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Emerging Trends in Traditional and Technical Textiles

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Editors

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Preface

Textile industry has continuously evolved itself through development of new materials, technology, processes and smart products for diverse applications. Continuous activities on deliberations and dissemination of knowledge keep everybody abreast of these developments. This book publishes the peer-reviewed selected full papers presented during the 3rd International Conference on Emerging Trends in Traditional and Technical Textiles (ICETT 2023). The contents of the book bring together the latest developments and applications in the field of textile materials, with a special focus on technical textiles. Technical textile industry works in diverse raw materials, processes, products and applications. It is not possible to cover all the areas of this diverse field but a few of the interesting papers presented during the conference and covered in this book include protective textiles, natural fibre geotextiles, medical and healthcare textiles, military textiles, polymer composites and nonwovens, smart and wearable textiles. Rapidly growing consumer preferences towards sustainable products have forced several textile manufacturers to restructure their businesses and invest in manufacturing facilities that target sustainable products. Looking into the latest trend, a few papers on sustainability including recycling of textiles, ecofriendly textile materials and consumer perspectives on green textiles are also presented. The book also discusses the natural dyeing on chitosan treated cotton fabrics, digital printing and fastness properties of the textile materials. Finally, it covers the noise reduction analysis in the industrial environment using various acoustic materials.

This is the second book bringing the selected full papers presented during the conference series *Emerging Trends in Traditional and Technical Textiles.* The book has contributions from a number of authors with wide experience in academic, research and industry. We are thankful to the authors for their contributions and cooperation during the publication of the book. The generosity of several publishers and authors in permitting the reproduction of material from their published work is gratefully acknowledged.

The book can be a valuable reference for beginners, students, researchers and professionals working in the area of technical textile applications.

Jalandhar, India — Vinay Kumar Midha
Braga, Portugal — Raul Fangueiro
Bolton, UK — S. Rajendran

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About the Editors

Dr. Vinay Kumar Midha is Professor in the Department of Textile Technology at National Institute of Technology, Jalandhar (India). He obtained his B.Tech. from REC Jalandhar and M.B.A. from Punjabi University Patiala. He did M.Tech. (Textile Engineering) and Ph.D. from the Department of Textile Technology, IIT Delhi. His academic and research experience spans over 29 years after having one year of industrial experience. His specialization and field of work are sewing dynamics, nonwovens and technical textiles, spinning systems and textile project management. He has been involved in several research projects funded by MHRD and DST. He has guided eight students for their dissertation work, who have been awarded Ph.D. degree. He has held various administrative assignments like Head of the Department of Textile Technology and Dean Faculty Welfare at the Institute during these years.

Prof. Raul Fangueiro is currently Vice-Dean of the School of Engineering, University of Minho, Portugal. He is Full Professor and Senior Researcher with expertise in advanced materials (nano, smart, composites) and structures (3D, auxetic, multiscale). He is Mentor and Head of FIBRENAMICS, Institute of Innovation on Fiber-Based Materials and Composites (www.fibrenamics.com). He has more than 200 published papers in international reputed scientific journals (Google Scholar H factor: 47), 500 conference publications, 36 books and 40 patents and also appears in the top 2% Stanford's world most influential scientists. He is Scientific Coordinator of several national and international research projects on advanced fibrous and composite materials, mainly for building, defense, architecture and healthcare applications.

Prof. S. Rajendran moved to the University of Bolton, UK, in 1998 after 17 years of service at the South India Textile Research Association (SITRA), India. Since then he has been actively involved in healthcare, polymeric and biomedical textile devices research, teaching and consultancy assignments at the Institute for Materials Research and Innovation, School of Engineering. He is currently Emeritus Professor at the University of Bolton, UK. He has previously held the position of Professor of Biomedical Materials and STEM Champion. Professor Rajendran has 42 years of

academic experience and has published 181 research papers that include 11 books and eight patents. Recently he has been honored with a prestigious medal by the Textile Institute for his devotion to the furtherance of scientific knowledge concerning fibrous materials.

Development of Multi-layered Stab Protection Fabrics Using UHMWPE, a Blend of UHMWPE/Polyester and HPPE UD Laminate Material



Priya Kumari, Vinay Kumar Midha, and Nandan Kumar

Abstract Protective body armor that offers protection against stabs has long been the subject of intense interest. A lightweight and flexible body armor can satisfy fit, comfort, and protection. This study was conducted on single and multilayer fabrics of UHMWPE and a blend of UHMWPE/polyester (70/30) plain woven fabric with HPPE unidirectional laminate. A comparative study has been done between these two developed fabrics concerning their tensile, tear, abrasion, cut, and stab resistance. The stab testing of UHMWPE and UHMWPE/polyester fabric was done according to the standard VPAM KDIW 2004. The evaluation was based on determining the depth of penetration for both woven fabric and HPPE UD laminate against the knife strike. The present work indicated that the combination of UHMWPE woven fabrics and HPPE UD laminates can improve stab protection. The optimum combination of woven and HPPE UD laminate layers was found respectively.

Keywords Armor · UHMWPE · Stab resistance · Cut resistance · HPPE UD laminate

1 Introduction

A stab-resistant body armor system should protect users against injury from a knife, edged, and sharp-pointed weapon penetration while allowing the wearer to move freely. The protected area protects vital organs, specifically the heart, liver, spine, kidneys, and spleen [14]. As assaults using sharp objects like spikes and edged objects like knives are on the rise worldwide, frontline police officers are increasingly vulnerable to attacks involving sharp instruments like knives and spikes, which

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can cause piercing, striking, and cutting injuries. Studies have shown that sharp objects, rather than guns, are responsible for the majority of violent injuries sustained by law enforcement officials. This has prompted a growing focus on the design of stab-resistant armor as a critical component of protective gear for law enforcement worldwide [20]. The stab/puncture-resistant protective textiles are required for many applications, such as police and defense personnel, industrial safety wear and gloves, inflatable structures, and tamper-proof packaging to name a few. Threats from stabbing can be categorized into: cuts or punctures [8] The term “puncture” describes the use of tools with sharp ends but no cutting edges, such as ice picks or awls, to penetrate critical body parts such as the neck area. Since it is quite simple to improvise sharp instruments, correctional guards are most concerned about these risks. Contact with blades that have a continuous cutting edge is referred to as a cut [2]. The metal ring mesh is most commonly used for commercial jackets for cut protection, also known as "chain mail, however, this ring mesh does not offer puncture protection against spike attacks. The layers of Titanium foil have also been used in other commercial designs, providing both cut and puncture resistance but they are very heavy and not easy to assemble [3, 4]. The contemporary body armor designed to protect against knives and spikes utilizes specialized fabrics treated with resin, such as para-aramid or UHMWPE-based fabrics, in addition to extra layers that may include Titanium foil. Although these stiff armors provide protection against stab, their mass, and rigidity make them unpleasant to wear and challenging to conceal while wearing especially in the Indian weather conditions [5, 10].

Further, the outer layers are not cut-resistant so the panels can be easily removed by cutting the outer layers. Moreover, the currently available stab-resistant jackets are not comfortable for female para-military forces in India. Therefore, it’s important that body armor should be designed using lightweight materials to reduce the burden of carrying the armor during operations and promote ease of movement for the user [13].

This work aims to develop a lightweight and flexible stab-resistant panel with a cut-resistant outer layer that can be easily used to manufacture stab-resistant jackets for both male and female forces.

2 Materials and Methods

In this study, two types of woven fabric were developed at the CCI sampling loom, JCT Phagwara. In order to reduce the number of layers, the HPPE Unidirectional (UD) laminates were used in between the layers of woven fabric of UHMWPE. To make 100% UHMWPE woven fabric the multifilament yarn of 200 deniers of UHMWPE is used with an initial modulus of 4842.8 cN/Tex and 4.68% elongation is used. The tensile strength of the developed fabric is 1054 N and 883 N in warp and weft direction respectively.

The second sample was prepared using composite multifilament yarn of 200 deniers UHMWPE (70%) and 75 denier polyester (30%) in this composite yarn

Table 1 Specification of all samples

Sample	Weave	Warp set (EPI)	Weft set (PPI)	Areal density	Thickness (mm)	Image
100% UHMWPE	1/1 plain weave	67	40	103g/m^2	0.195	
70% UHMWPE/ 30%Polyester	1/1 plain weave	67	40	153g/m^2	0.2995	
HPPE UD laminate (0°/90°/0°/90°)	Unidirectional	–	–	106g/m^2	0.3	

the color of UHMWPW filament is white and the color of the Polyester filament is fluorescent yellow-green. Yarn denier is 288 with an initial modulus of 2726 cN/Tex and 4.69% elongation. The tensile strength of the developed fabric is 1030 N and 878 N in warp and weft directions respectively.

The HPPE UD laminate is used in this study, it is a form of nonwoven fabric made up of parallel strands of HPPE filament (UHMWPE) at 0°/90°/0°/90° angles with a flexible resin(binder), in this study 4UD layer of HPPE UD laminate is used. They are free of interlacement and crimp, which means that most of the impact of stress propagates on the fabric plane, with limited transmission to the fabric layers at the back [6, 7]. Sample specification is given in Table 1.

2.1 Composite Sample Preparation

The composite fabric is developed by incorporating 10, 13, 15, or 17 layers of woven fabrics along with 8 to 10 HPPE UD laminates. The optimal combination of woven and UD fabric is determined to record the minimum penetration at different strike angles. During the strike, the fabric is at 0°, 45°, and 90° (warp yarn orientation with respect to knife blade cut position). A comparative study of 4 samples has been made to determine the best results with an optimal combination.

2.2 Dynamic Stab Resistance Test

The stab resistance test is performed on all 4 combinations of composite samples according to the VPAM KDIW 2004 standard, this standard is used by CRPF/RAF and police personnel across India [9]. for determining the targeted protection. For The targeted protection of K1, the armor must not allow a more than 20 mm depth of penetration when stabbed with a standard knife at energy 25 Joules. For accurate evaluation of knife penetration backing material is used. A backing material consists of 4 layers of neoprene sponge (6 mm), 1 layer of polyethylene closed-cell foam (30 mm), and 2 layers of rubber (6 mm) as shown in Fig. 1. It is placed under the sample during the strike [11] the mass is dropped from a certain height to attain 25 Joules as shown in Fig. 2. If the penetration is more than 20 mm then the sample is considered to be insufficient for providing protection level K1 [19].

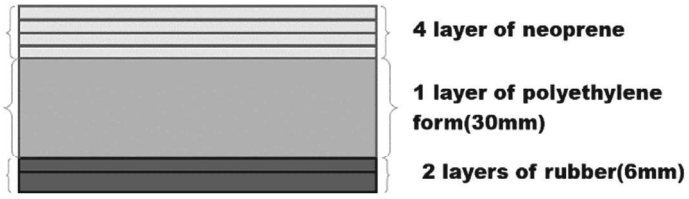


Fig. 1 Layers of backing material

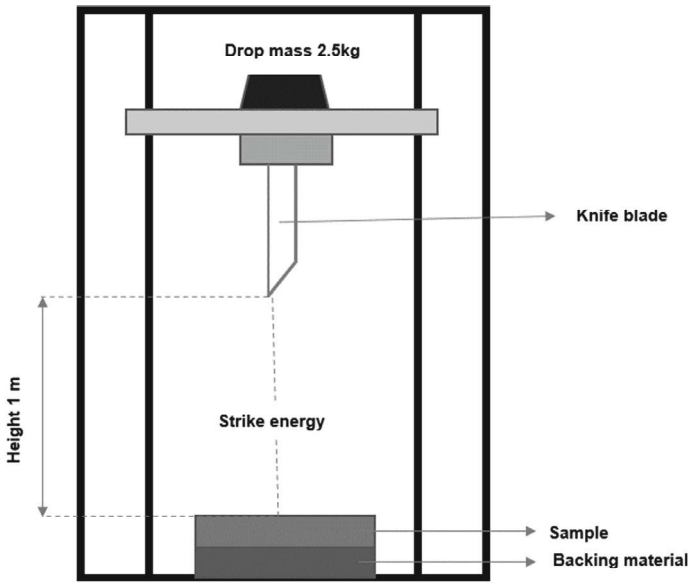


Fig. 2 Sample and knife arrangement for stab testing

2.3 Testing of Flexural Rigidity

The sample is tested for its flexibility as per ASTM D 1388- 18 on the Shirley stiffness tester. This is primarily used for assessing the bending resistance or stiffness of fabrics. It calculates the fabric's bending length or inclination based on the principle of the cantilever instrument. The sample size of 200 mm × 25 mm is fixed in the instrument's rectangular strip for measuring the bending length of multilayered fabric (ASTM D1388-18) and the following equation is used for calculating the same [17].

$$\mathrm{G} = W * C^3$$

where:
G = flexural rigidity, mg. cm,
W = fabric mass per unit area, mg/cm^2, and
C = bending length, cm.

2.4 Tensile Strength

The tensile strength is measured according to ASTM D 5035-11. The sample is 35 mm wide and 150 mm long whereas the jaw is set to move at 300 mm/min, the gauge length was maintained at 75 mm maximum load that the material could bear in one direction before breaking is recorded [16].

2.5 Tear Strength

The sample's tear strength is measured as per ASTM D 5587 (trapezoid method) The test requires a fabric sample 75 mm long and 150 mm wide, on which a 15 mm cut is made at the centre. Two lines are used to create a trapezium on the sample, with the top and bottom jaws 25 mm apart. The sample is mounted on the machine and subjected to a traverse speed of 300±10 mm/min. The cut spreads across the sample until it reaches the opposite end. The test is considered complete once the sample tears completely, and the average of the top five peaks in the stress-strain curve is recorded [18].

2.6 Cut Resistance

The cut resistance of woven fabrics is determined in accordance with ISO 13997-1999. In this method, a straight-edged blade is used to cut-through the test at a

particular load. After conducting multiple tests, the load is determined to generate a 20 mm cut-through distance (EN ISO 13997:1999).

2.7 Abrasion Resistance

The abrasion resistance of fabric is evaluated as per ASTM D3884. This test is used for measuring the abrasion resistance of fabrics through a double-head rotary platform. The test assesses the durability and wear resistance of fabrics by subjecting a rectangular specimen to a controlled load and a specific number of abrasion cycles on a rotating platform. The test conditions are standardized based on the type of fabric being tested. After completing the test, the fabric specimen undergoes a visual inspection for any damage or wear, and the abrasion resistance is calculated based on the amount of mass loss. This test provides a quantitative measure of a fabric's ability to withstand abrasion and wear, which is essential for assessing its suitability for specific end-use applications [15].

3 Results and Discussion

3.1 Dynamic Stab Resistance

The test results indicate that the woven fabric of sample 1 can provide adequate stab resistance with at least 34 layers. However, more number of layers resulted in a bulky composite which is more stiff and difficult in donning even after having favorable results. In this study, the ply angle is changed and studied in three different angles 0°, 45°, and 90° as shown in Fig. 3.

(A) 0° angle when the warp yarn is parallel to the knife, i.e., when the knife cuts the fabric the width of the cut is parallel to the warp yarn (Fig. 3a).
(B) 45° angle between the warp yarn and the knife blade, i.e., when the knife cuts the fabric the width of the cut is inclined diagonally to the warp yarn (Fig. 3b), and
(C) 90° angle between the warp yarn and the knife blade, i.e., when the knife cuts the fabric the width of the cut is perpendicular to the warp yarn (Fig. 3c):

As shown in Fig. 4, blue shows a layer of woven fabric, and white shows a layer of HPPE UD laminate (A) the combination C of 15 layers of woven fabric and 10 layers of HPPE UD laminate are stacked. The first three layers and last three layers consist of woven fabric while starting from the fourth layer, an alternating pattern is followed with one layer of HPPE UD laminate and one layer of woven fabric. And (B) the combination B of 13 layers of woven fabric and 12 layers of HPPE UD laminate are stacked. The first 2 layers and last 2 layers of woven fabric whereas the

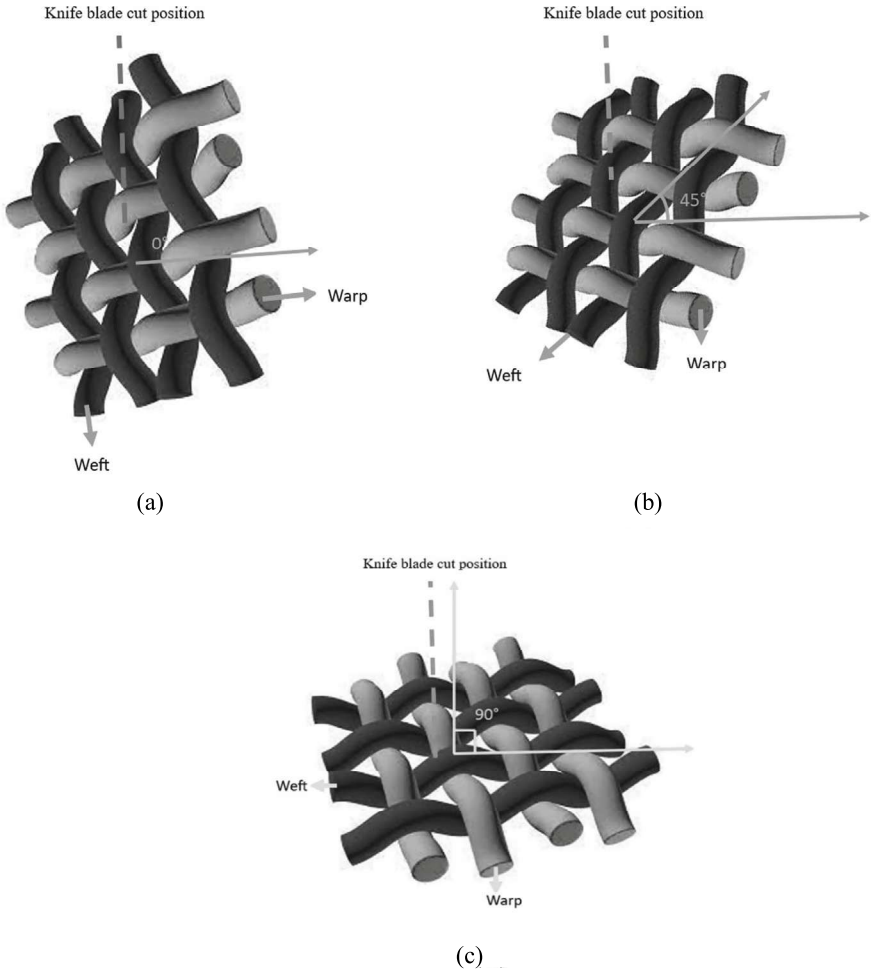


Fig. 3 **a** Warp yarns aligned at 0° to the knife, **b** warp yarns aligned at 45° to the knife, **c** warp yarns aligned at 90° to the knife

first third and last fourth layers are of HPPE UD laminate, while the remaining are placed in an alternating pattern.

Here sample 1 is indicated as S1 and sample 2 is indicated as S2. Further, in order to reduce the fabrics layer HPPE UD laminate is used and it is observed that in S1, 15 layers of woven fabric and 10 layers of HPPE UD laminate, and in S2, 13 layers of woven fabric and 12 layers of HPPE UD laminate offer K1 level protection at a 90° angle.

The combination C and B of both samples S1 and S2 yielded better results compared to other combinations, this is because layers of the fabric are more effective at stopping a penetrating knife when it directly opposes the force it may be because

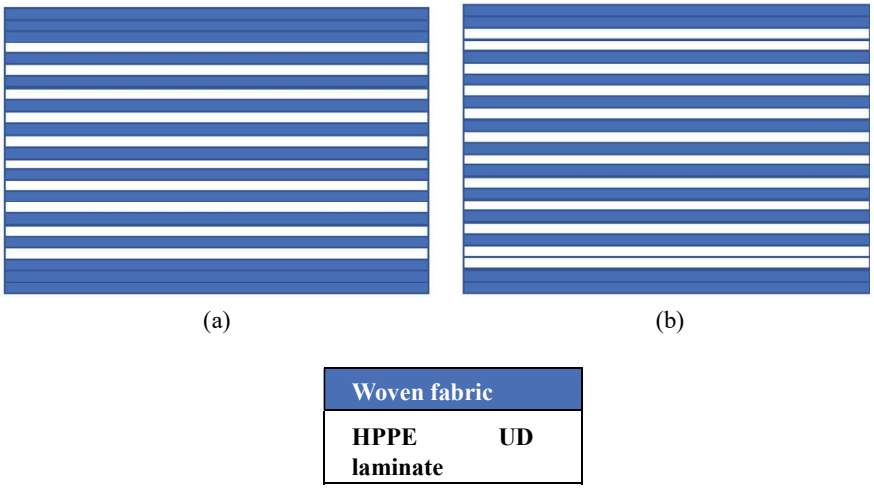


Fig. 4 Layer of combination, **a** 15 woven layers with 10 layers of HPPE laminate, **b** 13 layers of woven fabric with 12 layers of HPPE laminate

at 90° the warp yarns are more and binding point is more due to this the resistant to stop the stab impact is more. And more yarn is present to absorb the impact energy during the stab. The layers can absorb and distribute the energy more efficiently in this orientation and it resist the penetration of the knife. The average depth of penetration of combination C and B of S1 and S2 is 16.77 mm. The depth of penetration can be measured by two methods;

(1) The first method involves measuring the cut length width of the first layer of backing material and then using the cut length value in (Eq. 1) to calculate the penetration depth,

$$\text{where penetration depth (mm)} = \text{length of cut (mm)} \times 2.396 \quad (1)$$

(2) The second method involves directly measuring through the vernier scale by measuring the distance between the sample and the tip of a knife through the underside of the specimen [1].

The method is also illustrated in Figs. 5 and 6.

The depth of penetration at a particular angle along with the flexural rigidity and Areal density of all combinations are given in Table 2 and test results are represented in Fig. 7.

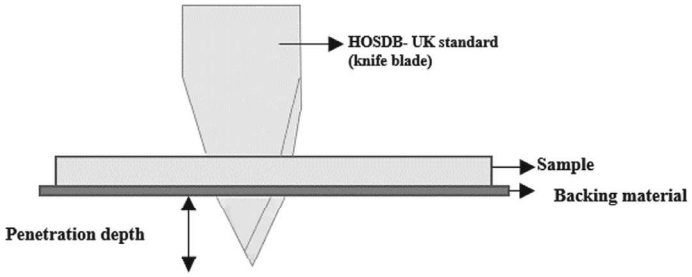
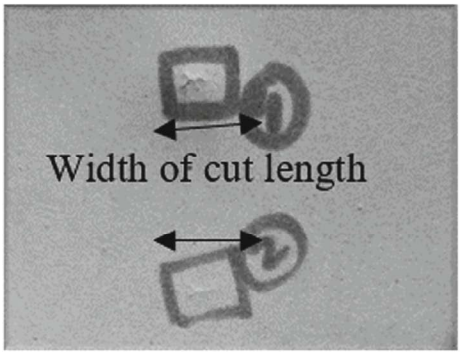


Fig. 5 First layer of backing material below the sample

Fig. 6 Measurement of Penetration depth using vernier scale



3.2 Flexural Rigidity

The results obtained from the Shirley stiffness tester as per ASTM D 1388-18 revealed that the combination A having 10 layers of woven fabric and 9 layers of HPPE UD laminate had the lowest flexural rigidity. However, this sample failed to achieve the K1 protection level. On the other hand, combination C, consisting of 15 layers of woven fabric and 10 layers of HPPE UD laminate has lower flexural rigidity as shown in Table 2, and other combinations exhibited higher flexural rigidity.

3.3 Tear Strength

It was observed from Table 3 the tear test results that Sample 1 has more resistance to tear (in both the warp and weft directions) than Sample 2 instead of having the same End Per Inch (EPI) and Pick Per Inch (PPI). Sample 1 is made from 100% UHMWPE yarn whereas sample 2 is made from composite yarn of 70% UHMWPE and 30% polyester. The elongation and braking tenacity of 100% UHMWPE yarn are 4.68 and 209.12cN/tex respectively whereas 70% HPPE and 30% polyester yarn

Table 2 Depth of penetration with Flexural rigidity and Areal density of all combinations

Comb	No. of layer		Depth of penetration (mm)						Flexural rigidity mg.cm		Areal density g/m^2	
			90°		45°		0°					
	Woven	HPPE laminate	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
A	10	9	28.75	31.14	31.14	33.54	35.94	38.33	1103.8	1533.3	1984	2484
B	13	12	14.37	16.77	16.77	19.16	21.56	21.56	1287.5	1686.5	2611	3261
C	15	10	16.77	19.16	19.16	19.16	21.56	23.96	1175	1634.3	2605	3355
D	17	8	19.16	21.56	23.96	23.96	28.75	28.75	1490.4	1739.7	2575	3425

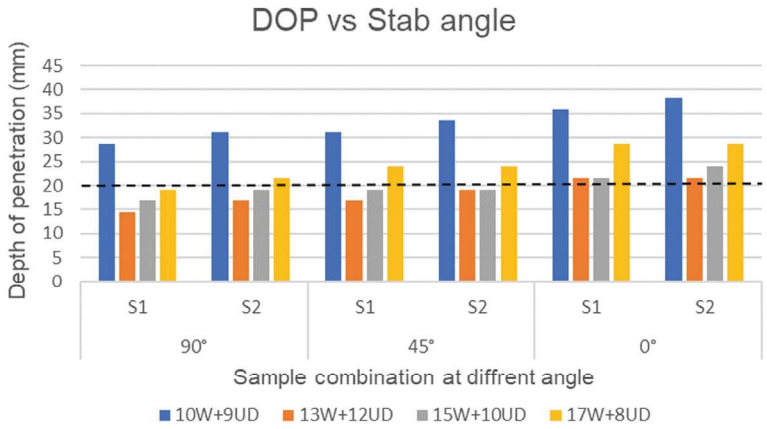


Fig. 7 Graph between depth of penetration and sample at different angles

Table 3 Tear strength of sample 1 and sample 2

Tear direction	Sample 1 (100% UHMWPE woven fabric)	Sample 2 (70% UHMWPE and 30% polyester)
Warp	1176N	1115N
Weft	2065N	1402N

have the same elongation but braking tenacity was 139.64 cN/tex, the yarn resists tearing in the delta zone of the fabric.

A high tear strength ensures that the multilayer fabric withstands such forces without ripping apart, maintaining its integrity and protective capabilities.

3.4 Cut Resistance

The TDM-482 cut test machine is used to test the cut-resistant behavior of woven fabrics according to the standard ISO 13997-1999. In this test, the force required to cut-through a distance of 20 mm is 2N for both fabrics and the R2 value is 0.973 for sample 1 and the R2 value is 0.9522.nnn the load required to cut the samples at a cut though distance of 20 mm is measured and it is observed that both fabrics having almost similar cut protective performance. To cut the fabric for a 20mm cut-through distance 2N load is required as shown in Fig. 8, indicating that both fabrics meet cut protection level A according to the standard EN388 [12]. However, sample 1 showed slightly higher cut resistance than sample 2, because of 100% UHMWPE yarn used in developing this sample. The 100% UHMWPE yarn's strength and the orientation of its polymer molecules contributed to its ability to resist cuts and abrasions, preventing sharp objects from penetrating the material.

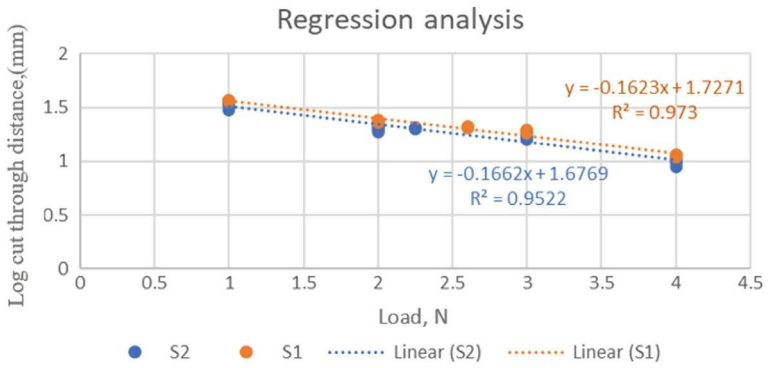


Fig. 8 Graph representing cut resistance of sample 1 and sample 2

3.5 Abrasion Resistance

The Martindale Abrasion Tester was used to determine the abrasion resistance of a fabric specimen in accordance with ASTM D 3884. The sample size is 150 mm × 50 mm. The test results showed that sample 1 has an abrasion resistance of 0.3% after 10 cycles, while sample 2 has a higher abrasion resistance of 1.51% after 20 cycles. It may be due to sample 2 being made from composite yarn which is made from UHMWPE Fiber and polyester Fiber. After 100 cycles, the HPPE UD laminate was abraded.

4 Conclusion

In this study, the experiment is done on woven fabric samples and their combination with HPPE UD laminates for multilayered fabric in body armor for protection against stabs. The study revealed that incorporating a higher number of HPPE UD laminates resulted in a reduced depth of penetration along with reduced flexibility. After conducting multiple tests on different samples, the optimum combination of woven fabric and HPPE UD laminates is found in combination C of sample 1 and combination B of sample 2 respectively for providing stab protection of K1 level. This combination has adequate flexibility that provides ease to the wearer. Additionally, the research highlights the importance of using square fabric with the same Ends Per Inch (EPI) and Picks Per Inch (PPI) to assess the effect of the angle on fabric position during testing it was found that at 90° (when the warp yarn and knife cutting position are intersecting by 90° is giving the less depth of penetration while maintaining a fixed testing angle. The fabric's cut resistance is evaluated and determined to have passed Level A according to standard EN 388, indicating low to medium cut resistance at a load exceeding 2N and a distance of 20 mm.

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A Review on Challenges in Developing the Military Uniforms



Meghana Kammeta, Arunangshu Mukhopadhyay, and Monica Sikka

Abstract Military uniforms are characterised by unique designs and colours that represent their country or branch of service, making them an essential component of modern-day warfare. The military forces carry out a wide range of activities, such as running, jumping, climbing, falling, and crawling, during the defence and physical training in different environmental conditions, which demands uniforms that provide high serviceability and comfort. Along with these properties and according to MIL standards, the designed military uniform has to be lightweight. With advancements in fields, the armed forces are demanding camouflage patterns in different terrains to protect themselves from their preys. As military personnel fight and survive in different environmental conditions (fire, heat, cold, wind, and rain) it is very important for them to protect themselves from these conditions by wearing uniforms that have protective finishes. Designing military uniforms with all these combined requirements is a very challenging task, as the requirements for camouflaging/dyeing can have an adverse impact on the tear strength and overall durability of the materials. On the other hand, improvement in the durability of clothing material through structural modification can lead to heat stress and can also affect mechanical comfort during military activity. In order to maintain all these requirements in the combined proportions, the adequate selection of materials and the manufacturing technique is a crucial process. This review article provides an overview of the mechanical and comfort behaviour of military uniforms. The contribution of all the factors toward the mechanical and comfort properties, the current trends, and advancements in the field of military uniform design and development are also discussed, including the use of advanced materials, such as high strength fibres, to improve durability and functionality. The importance of military uniform design, including comfort, is also highlighted.

Keywords Military uniforms · Durability · Comfort · Challenges · High performance materials · Design

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1 Introduction

Military armed forces are organisations responsible for the defence and security of a country or nation. The role of textiles in national defence is more important and far-reaching as they are used for uniforms, tents, sails, saddle pouches, caparisons, parachutes, camouflage nets, and more [11, 19]. Military uniforms are one of the most basic and pervasive textile materials used by the Department of Defence to protect themselves from external threats, as they serve as the only barrier between the elements and the armed forces. They are characteristic garments worn by the armed forces during combat, training, parades, and non-field duty purposes. According to the research of the US Army NSRDEC, the work of the soldiers is treated as an entire soldier system which has the capability of maximising the protection, sustainment, mobility, command, and control of the individual soldiers to counter the threats. In the overall 'Soldiers system', the first step is to engineer a basic fabric, that proves the ability to manufacture the protective clothing [48], that embraces three areas: protection against the environment, concealment from observation and protection against enemy munitions [19].

The literature survey reveals that there has been extensive research on various aspects of military textiles that covers developments and new technologies related to thermal comfort, camouflage, mechanical protection, wearables, chemicals, and biological attacks [1, 47]. A general review was conducted on the development of materials to lower the wear and tear due to the harsh military environment faced by the warfighters during the war [38].

The aim of this review paper is to discuss the complex challenges that are encountered during the development of military uniforms for tropical and subtropical climates. Military uniforms play a key role in modern-day warfare by providing special requirements such as durability, comfort, protection, ease of movement, and camouflage. Designing a uniform considering all these factors is not a simple task as it demands a striking balance between various design factors. This paper seeks to explore the challenges related to material and garment construction, highlighting the implications involved during the selection of appropriate fibre types and blends to achieve the specific requirements. Additionally, the paper will address the difficulties in optimising the yarn parameters, fabric parameters, pre-processing techniques, dyeing, and finishing techniques. The challenges faced during designing a well fit garment for different body shapes of military personnel are also discussed.

2 Design Requirements

Depending on the purpose, each uniform has a different requirement, and choosing an appropriate textile material plays a critical role in achieving the design requirements. The common requirements for all types of military uniform are durability, light weight, and comfortability. For the soldiers working in the fields of different climatic

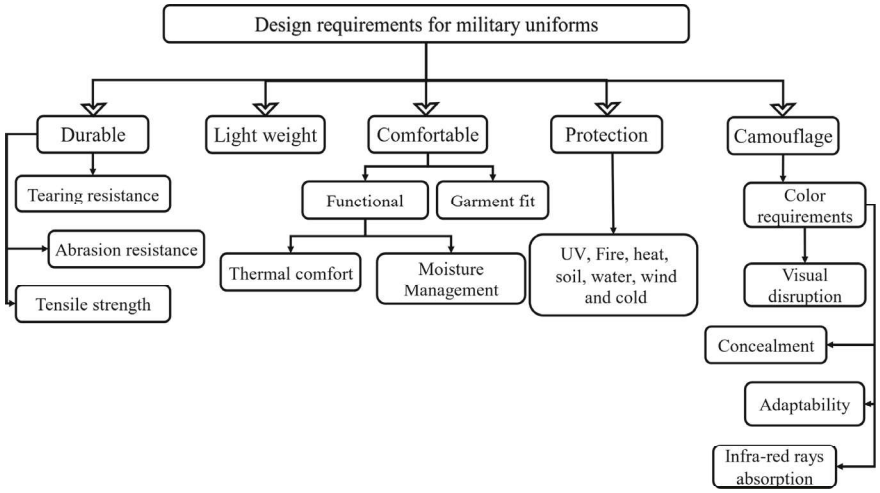


Fig. 1 Requirements of military uniforms

conditions and terrains, protection and camouflage are the demanded requirements along with common requirements. Each requirement has its own specific properties, as mentioned in Fig. 1.

2.1 Durability

The military personnel engage in highly intensive activities such as running, jumping, crawling, climbing, and falling during their missions and training that demand uniforms of high durability. The durability of a military uniform is directly related to the fabric resistance to stresses generated during their activities in different locations of the garment as shown in Fig. 2. The failure in distributing the generated stress uniformly across the axis of the garment may lead to wear and tear of the fabric which in turn results in compromising the overall structural integrity of the uniform. As the uniform undergoes continuous stretching, bending, and abrasion during the activities, the failure in distributing the stress may also lead to loss in mechanical properties of the uniform, resulting in increased stress concentration in specific areas such as the crotch area, seat seam, and knees in trousers, and at the elbows in the case of the shirts.

Considering these circumstances as well as the deployment of soldiers to live, survive, and fight in extreme climatic conditions has put new demands on the functions of military clothing for high serviceability [31]. Higher serviceability is essential to ensure that the uniform can withstand the stresses and that military operations can subject it to tearing and abrasion. It is said that military clothing systems require a higher resistance to strains than normal garments [42].

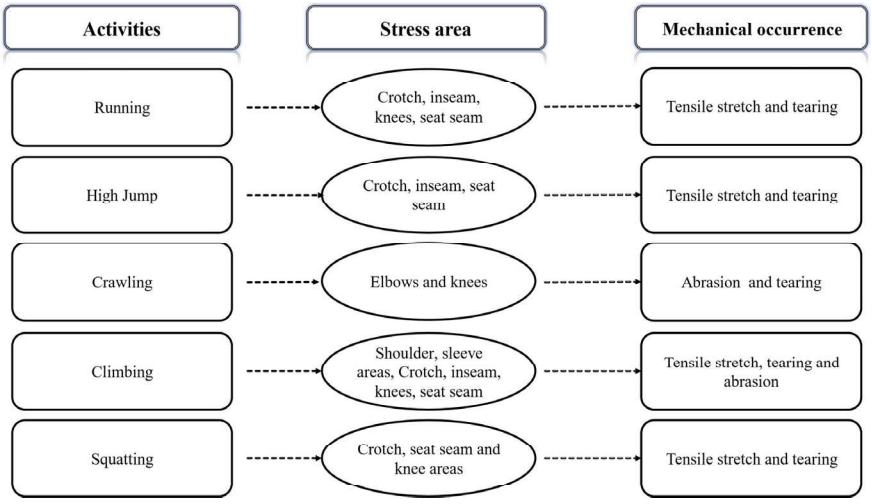


Fig. 2 Mechanical occurrences in military uniforms

2.2 Tensile Properties

Military uniforms necessitate the use of fabric with a higher tensile strength to withstand the forces that lead to tearing and failure. When it comes to the serviceability of a military uniform, the tensile strength of the fabric is less significant than the tearing strength, but the tensile strength of the seam has a significant impact on how long the military uniforms last because seams keep the garment's overall integrity. Choosing a durable seam, and sewing yarn that achieves 80% seam efficiency is a difficult task when designing military uniforms.

The tensile properties of the yarn such as strength and elongation also affect the durability of the fabric. When military uniforms are subjected to rapid and intense forces with loads greater than the ultimate breaking forces, there is a possibility of yarn breaking due to the shorter time available for the fabric to contract, ultimately resulting in fabric failure.

2.3 Tearing Strength

Among the three mechanical properties tearing has a high impact on the serviceability of the military garment because the dynamic forces during military actions may lead to tearing, and a torn garment has more chances of causing injuries when exposed to sharp objects or environmental hazards, which will hinder the mobility of the military personnel by limiting the range of motion and obstructing the functionality of accessories attached to the garment.

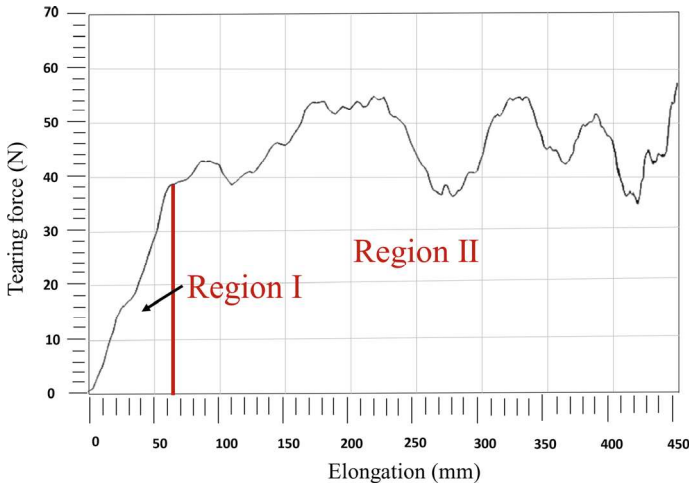


Fig. 3 Stages of tearing mechanism

During designing a military uniform, it is vital to ensure that the value of tearing strength is according to the MIL standards because, during the manufacturing and processing of the fabric, there are many possibilities which negatively impact the tearing strength. The highest negative impact on tearing strength occurs during the pre-processing techniques, such as scouring and bleaching, and post-treatment techniques, such as sanforizing, dyeing, printing, and finishing.

The evaluation of the tearing resistance of the fabric under lab conditions is also challenging. The mechanism of fabric tearing undergoes two stages as explained [49] in Fig. 3.

Tearing initiation (Region I)—is the initial work necessary for the material to reach the tearing point and

Tearing propagation (Region II)—propagation of the crack in the material

This process of tearing can occur in two different conditions. The first condition is rapid tearing, which occurs when a sharp object snags the fabric or military personnel perform high jumps or encounter sudden forces. In such cases, the fabric tears quickly, causing immediate damage. The second condition is slow tearing, which happens when the fabric is stretched repeatedly. The fabric becomes abraded and weakened over time, resulting in gradual tearing.

2.4 Abrasion Resistance

After tearing, abrasion is the second most important property determining the garment's durability in military uniforms. During crawling in combat conditions, military personnel encounter various obstacles, including fences, tank traps, trenches,

gravel roads, and so on. When a fabric meets such abrasive surfaces, friction and rubbing forces are produced. If the uniform lacks sufficient abrasion resistance, repeated contact and movement against abrasive materials can cause wear, pilling, and fabric damage. In environments with extreme weather conditions, abrasion resistance is also vital. For instance, soldiers operating in desert regions may encounter sandy or gritty terrain, while those operating in forested regions may experience abrasive contact with tree branches, thorns, or underbrush. The fabric may encounter rough surfaces such as frozen ground or ice-covered obstacles in snowy or icy conditions.

Designing a military uniform that can withstand the forces when exposed to all these different obstacles is also quite challenging part because it is very unpredictable to know the rubbing forces and to increase the abrasion resistance in general; the thread density and cover factor of the fabric are increased this may result in increasing the stiffness of the garment, thereby restricting the movement of the wearer.

2.5 Comfort

Comfort is a state of physical, psychological, and emotional ease and satisfaction that differs from person to person and it is another major requirement for military uniforms as the soldiers have to wear their uniforms for longer periods, and discomfort can hinder their performance. The soldier's survivability, mobility, and stamina are closely linked with thermophysiological comfort and fit of the clothing [42] because the soldiers perform various activities in different climatic conditions.

2.5.1 Thermophysiological Comfort

Thermophysiological comfort is a heat and moisture transfer exchange mechanism between the body and the environment and it is very important for military uniforms to maintain the balance in heat and moisture transfer from the skin to the environment as the soldiers are exposed to temperatures ranging from average temperature to scorching desert temperatures and from cold to freezing conditions. The designing of uniforms for different climatic conditions is a challenging task as each uniform component has its role in providing thermal and moisture comfort. Wearing a wet weather jacket in tropical conditions to protect from rain may impair heat loss and result in heat stress during physical activities [26]. Improving both thermal and moisture at the same time is quite challenging because if the sweat is converted to vapour form on the skin itself, then the transmission of vapour takes place only through fibres, and the pores at this time allow the air to pass through the fabric for maintaining the thermal comfort. But if the sweat is transferred to the fabric surface in liquid form, the pores get blocked with the liquid and restrict the movement of air by creating uncomfortable for the wearer. The structural modification of the fabric

for improving durability can have a negative impact on the exchange of heat through fabric, thereby causing heat stress to the wearer.

2.5.2 Fit Comfort

In civilian lives, the fit of the garment also has a more significant impact on the performance of the wearer. The range of motion during physical activities is the primary consideration while designing the military uniform. The designed uniform must have the ability to allow a full range of motion, and this is only possible by providing well-fitted garments to the armed forces. A too-loose fitting has the risk of getting caught during activities like crawling, and a tight-fitting will decrease the ease of movement during running, jumping, and climbing [42]. The ill fit of the garment also creates discomfort for the wearer. While designing the military uniform, parameters such as height, weight, and body shape are also to be considered because all military personnel come with different body shapes.

Fit is essential among all other characteristics such as durability, appearance, protection, feel, and thermal comfort for all uniforms [43], and poor fit is the primary variable contributing to the dissatisfaction of the wearer during the activewear uniforms according to the studies [5, 9] and the findings of the studies also state that many military forces do not know their proper fit which leads to chafing problems in the crotch area, and experience abrasiveness which creates discomfort. The garment's proper fit depends on several body measurements [27].

During designing the garment, the fit of the garment alone is not considered; sensory responses are also considered as the judgement of the garment visually, the same role as the functionality of garments. Since combat uniforms are worn on a daily basis for more extended periods, their appearance and sense of feel have gained equal importance to protection and durability, prompting researchers to shift their attention to the less-studied tactile comfort aspect of military uniforms.

2.6 Camouflage

Over the last decades, camouflage has become the most important component of the military due to its ability to protect the first-line soldiers by blending the colour and pattern with the surroundings or changing the outline of soldiers (disruption) to reduce visibility [25, 51]. The principle of camouflaging has been taken from many animals that could conceal themselves to attack or protect themselves from their prey [3]. There are two main requirements for manufacturing camouflage fabrics: colour type and fabric type [37].

The colour to be selected has to have the property of blending with different terrains such as urban, woodland, deserts, and mountain environments as shown in Fig. 4, breaking the outline of the wearer by creating irregular and distorted patterns (visual disruption) and minimising the heat signature emitted from the body ranging



Fig. 4 Camouflage patterns for different terrain

between 3–5 and 8–14 μm to make it harder for detecting from the thermal imaging device and the colour should have the ability to be used in different terrains and environmental conditions. The wavelength of the electromagnetic spectrum in the visible region must lie at 400-800 nm and 750–1200 nm in the near-infrared region [15, 37].

The fabrics must be designed in such a way that they blend with nature while also minimising the wearer's infrared signals to the detector in both night and daylight.

2.7 Additional Requirements

Protection is an additional requirement that is given to the military uniforms in the form of finishes to protect the soldiers from the specific battlefields, flames, heat, water, soil, chemicals, biological agents, radiological substances, UV rays, and nuclear threats. The selection of finishes depends on the specific surroundings to which the soldiers are expected to be exposed. The application of these finishes typically takes place after the dyeing or printing process, which enables customisation as well as the addition of functional enhancements. The water-resistant, soil-repellent, UV resistance, and flame-retardant finishes have a negative impact on the breathability, drapability, mass of the fabric, and tear resistance.

3 Challenges in Considering Design Factors of Military Uniforms

Designing military uniforms is a complex task that involves various design factors to meet the needs of the wearer and material selection is a key element of the design factors because the inappropriate selection of material for the uniforms will result in failure of the product. The points to be considered while selecting the material are as follows.

- The selected material should have the ability to form into the desired shape of the product
- Material properties should be directly related to the performance of the product
- Material should undergo minimum changes in its properties over time
- It has to be biodegradable and recyclable and
- The whole process of manufacturing needs to be cost effective

During the material selection for military uniforms, the main factors as explained in Fig. 5 have to be considered to produce the product with high durability under mechanical and environmental conditions, strength-to-weight ratio, high strength, and low stiffness.

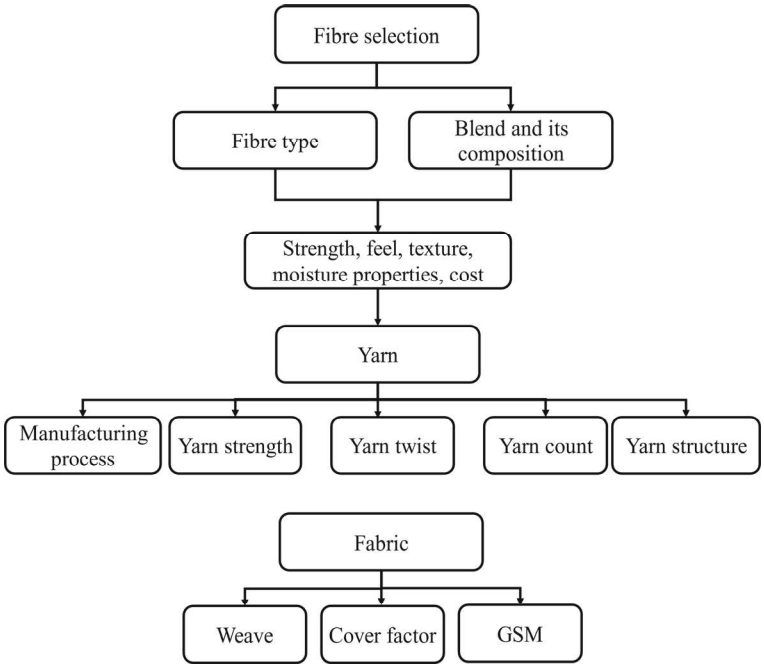


Fig. 5 Design factors for development of military uniforms

After the preparation of the fabric depending on the requirements the fabric undergoes some pre-processing treatments and finishing treatments. The garment fit and sewing performance also play a critical role in determining the functionality, durability, comfort, and visual appearance of the garment.

3.1 Fibre Properties

The selection of textile fibres for military clothing is based on three principal factors: the performance characteristics of the material to meet the end-user requirements, their cost compared to alternate textile materials which meet the functional requirements, and their availability in adequate supply within the country [19]. The choice of fibre type for military uniforms depends on the type of fibre, fibre quality, fibre blend, and its proportions. Fibre quality has a direct influence on the fabric's mechanical properties; the fabrics made of irrigated cotton fibres of high quality (50–65%) have a tearing strength which is 3 times the other cotton fibres of rain-grown varieties [39].

The type of fibre and its proportion in the blend become essential variables when considering the climatic conditions for which the uniform is intended. For military uniforms the usage of 100 % cotton fibre was the best option for the natural feel and absorption, making it a popular choice in warm climates. However, problems arise when cotton alone cannot meet all the requirements for a military uniform, such as durability and light weight when soldiers are exposed to hot climatic conditions for an extended period due to high humidity in the environment allows the fibre to retain the moisture by creating dampness and allowing the fabric to dry for a longer time. To address this problem, scientists experimented in the 20th century by blending cotton with synthetic fibres like polyester and nylon in varying proportions to improve moisture wicking and durability. The pure synthetic fibres in the blend also enlighten the camouflage requirement by reflecting IR rays.

Uniforms for the Indian armed forces and paramilitary forces are typically made from polyester-cotton blend with a variety of blend proportions such as 20/80, 68/32, 50/50, and 67/33 [20, 22, 28, 30, 36]. And Armed forces wearing polycot uniforms on the battlefield risk melting the polyester component on their skin, leading to burn injuries caused by the fire-ravaged surroundings. To deal with these situations, the polyester component is replaced with nylon to strengthen the uniform. The commercial name of the blend is NYco**,** which is a 50/50 blend of nylon and cotton [35]. To handle these types of situations, the polyester component is tried to be replaced with nylon to make the uniform stronger. Nylon is blended with cotton at a ratio of 50/50, and the commercial name of the blend is NYco [4]. Combining cotton with small amounts of synthetic fibres with high tenacity [8], either through intimate blending or core yarn techniques [40] for meeting the majority of military requirements.

3.2 Yarn Properties

The yarn properties such as yarn strength, yarn twist, yarn count, the structure of yarn, and the yarn manufacturing process are the major factors affecting the mechanical and comfort properties of the military uniform.

The yarn structure and yarn manufacturing process have an impact on the mechanical properties of the fabric, such as tensile, tearing, and abrasion resistance. Ring spun yarn is used in the fabrics of military uniforms, and studies so far state that the fabrics constructed of ring spun yarns have better mechanical properties in terms of tenacity, tear strength, and abrasion resistance than compared to that of the rotor spun yarns [2, 17, 52]. The rotor spun yarn also exhibits higher tearing strength depending on the linear density and direction of tearing [17, 41]. The tearing strength of both ring and rotor yarns reaches down to the same point after the pre-treatment process [31].

The level of yarn twist has a direct impact on the strength of the yarn which has to be high to provide maximum durability and flexibility with high porosity. The optimum level of twist has to be selected for the yarns where the (military uniforms and work wear) fabric needs high strength with better comfort properties and economical costing.

3.3 Fabric Structure

Fabric weave is another important parameter that cannot be overstated; by changing the weave, the overall performance of the garment can be changed. Choosing the right structure of the fabric is very crucial in achieving the goal, as military uniforms are designed to withstand harsh conditions such as wear and tear. The inherent strength and high resistance to tearing of weave structures like ripstop and twill, when compared to plain weave, make them popular choices for military uniforms. Ripstop weave, as shown in Fig. 6 is constructed with reinforcing threads woven into the fabric at regular intervals to stop small tears from becoming larger ones. The diagonal pattern of the twill weave, as in Fig. 6, on the other hand, makes the fabric more robust and long-lasting. Plain weave [20, 23], in addition to ripstop and twill weave, can also be preferred for military uniforms due to its better moisture management properties. However, the low tearing strength of the plain weave fabric creates problems because a balance between breathability and durability must be maintained. A fabric can be tightly woven/knitted to make the fabric durable and improve its water and soil-repellent properties, but at the same time, with an increase in the tightness, the breathability of the fabric will decrease, which results in causing discomfort to the military personnel during hot weather conditions.

Numerous studies have been conducted, keeping the aim of maximising the performance, longevity, and comfort of military uniform fabrics in all conditions. And these studies found that a fabric made of combining plain and ripstop weaves, sateen, and

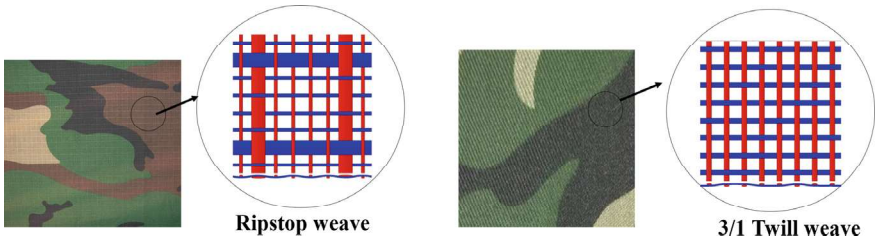


Fig. 6 Weave patterns of military uniforms

basket weave improves a fabric's resistance to abrasion [14, 18, 22]. High breaking strength and elongation are found in the twill weave when compared to that of the plain weave [30], and high tearing strength can be found in the basket weave when compared with the twill and plain weave [14].

3.4 Pre-processing and Finishing Treatments

Before being dyed, fabric goes through a series of pre-processing treatments (singeing, de-sizing, scouring, bleaching, and mercerization) for the improvement in quality. Singeing is the process of removing protruding fibres to achieve a more uniform appearance and colour after dying. Desizing removes the sizing agents from the fabric, making it more pleasant to use. Scouring improves absorbency and dye uptake by removing impurities like oils and waxes. Bleaching is a process used to get rid of a fabric's natural colour or stains so that the fabric appears white or uniform. Mercerization boosts a fabric's performance and aesthetic appeal by increasing its durability, sheen, dye affinity, and dimensional stability. All these steps improve the fabric's durability and functionality. The fabric is dyed after the mercerization process. The dyed fabric is then allowed to go through the sanforizing process to reduce potential shrinkage during frequent laundering and usage.

Fabric treatment procedures often have positive effects on the fabric's quality; however, they might also have adverse impacts on the fabric's mechanical behaviour. The tensile strength and tear resistance of a fabric are altered by treatments like scouring, bleaching, dyeing, and sanforizing. The process of scouring and bleaching has a negative impact on the tearing and tensile strength (see Fig. 7) of the fabric due to the presence of scouring chemicals and hydrogen peroxide in bleaching that degrades the cellulose. Though the mercerization improves the mechanical properties by increasing the packing fraction of fibres, reducing the yarn diameter, and smoothening the thread surface, but when the fabric undergoes the dyeing process again there is a reduction in the mechanical properties [33, 34].

In most cases, tearing strength suffers more than tensile strength from the dyeing process. Tearing strength gets diminished by the addition of auxiliary chemical

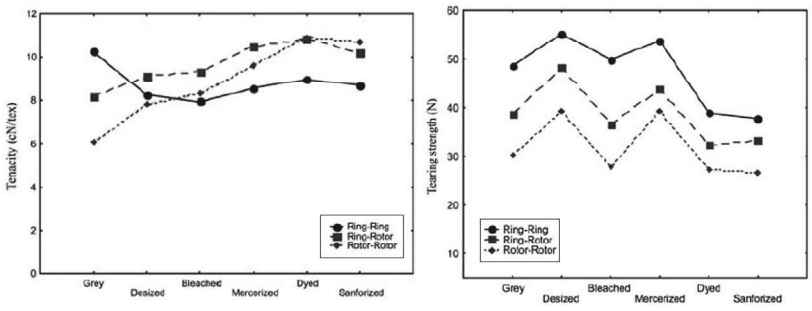


Fig. 7 Effect of pre-treatments on tenacity and tearing strength of military uniforms [31]

reagents [45], modifying the pH, increasing the dyeing temperature or time [24], or increasing the dyeing speed with mechanical agitation.

The usage of vat dyes for the military uniforms, increases the yarn stiffness by decreasing the yarn elongation, resulting in a reduction in tearing strength [31]. This can be problematic for fabrics used for military uniforms, which rely extensively on durability.

In order to improve the tearing strength of military uniforms and to achieve the values according to the MIL standards, the fabric is sanforized which reduces the shrinkage.

A study found that the order in which these procedures were performed also affected the fabric's functionality. The seam strength, modulus, and work of rupture of sanforized stitched and washed military garments are superior to those of the other routes [29] shown in Fig. 8.

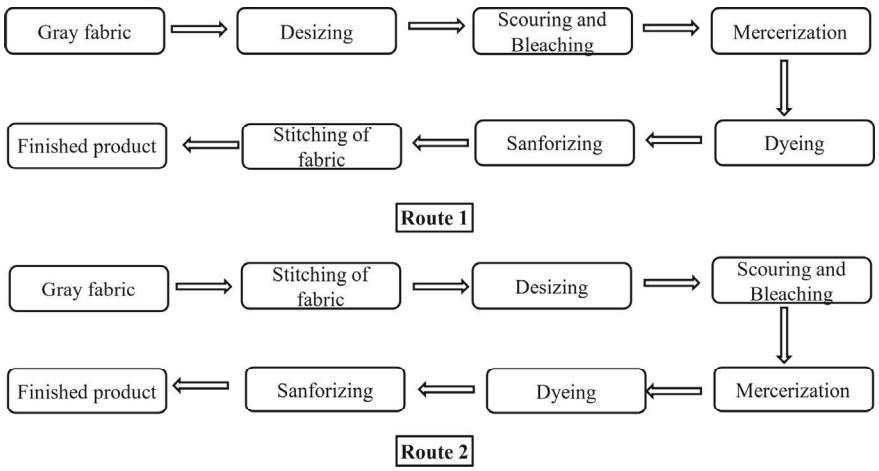


Fig. 8 Processing the fabric through two different routes [29]

Printing treatment

A key component of military uniform design is the fabric camouflaging technique, which ensures that soldiers are effectively hidden and protected in a variety of surroundings. In this process, dyeing is crucial because it gives the fabric specific colours that enable it to blend in with the surroundings. For example, if the army forces operate in dusty terrains, the uniform may be dyed in the shades of the sand to blend with it. The shade that matches and blends with the sand is the khaki colour. To get blended with the jungle environment, the uniforms are to be dyed with the shade of green. The selection of colour is not only based on the surroundings; it is also dependent on the fibre type in the fabric because nowadays, a wide range of fibres are used for military uniforms, and each fibre has its own characteristics and requirements.

The dyes used are different for different fibres. The uniform colouration also has an impact on the functionality of military uniforms, if there is no uniformity in dyeing, the colour may bleed during the washing and can also fade out during the long exposure to the UV light. Therefore, designers must carefully select dyes that are colourfast and can withstand the wear and tear of military use. Vat dyes are most widely used for dyeing cellulosic military uniforms due to their excellent wash and light fastness properties [21, 50].

The khaki fabrics were dyed in a combination of Novelon Brown and Solanthrene vat dye [29, 31], and the olive green hue was dyed with a combination of yellow acid and green acid dyes. With the increase in technologies, the demands and requirements of military uniforms are also increasing. One of the requirements is the concealment from observation, and this requirement is not achieved by the solid colours; this led to the transition from solid colour dyeing to camouflage dyeing. Individual camouflage is considered to be the most important as it is used for different types of terrains, vegetation, and seasons of the year.

The camouflage patterns are printed on the fabric by various printing methods such as screen-printing, pigment printing, dye-sublimation heat transfer printing, inkjet printing, and digital printing. Printing the camouflage pattern onto the fabric according to the terrain is a difficult task, because blending the pattern with the surroundings to the same level requires a lot of expertise. To achieve the pattern the steps explained in the Fig. 9 as to be followed.

Finishing treatments

For further improvement in the mechanical properties and according to the requirements, finishes are applied on to the fabric. Since tearing strength of fabrics has a direct impact on the serviceability of the miliary uniforms, works are going on to improve the tearing strength by finishing the fabrics with polyethylene emulsions, polyethylene wax emulsions [13], and silicon emulsions.

Depending on the additional requirements the military uniforms are treated with water repellent finishes and oil water repellent finishes, but these repellent finishes have a negative impact on the fabric's breathability. A study was conducted where the Battle dress uniforms (BDU) were treated with different types of DWR (durable

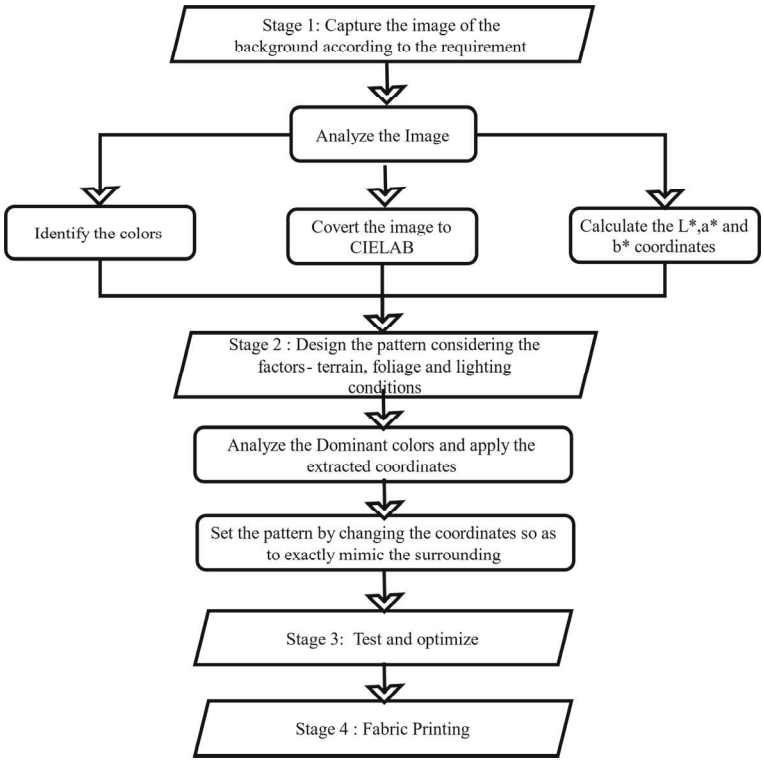


Fig. 9 Process of camouflaging the fabric

water repellent) and Quarpel (oil and water repellent treated) repellent finishes and their effect on breathability was evaluated. It was found that treating the outer layer of the fabric with the finish while the inner surface retains its moisture characteristics, the comfort properties where improved [12].

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Designing military clothing for each season is difficult, especially in the summer, where sweat discharging and ventilation are the most important. To overcome this problem, the thermal regulation of the fabrics is improved by coating them with the Phase changing materials (PCMs). The mechanism of PCMs is changing from liquid state to solid state and vice versa on exposure to different temperatures of the body area and surroundings. Then increase/decrease in the temperature of the human

body or the surroundings tends to store or release the heat in the form of latent heat. Microencapsulation is a technique used for encapsulating the PCM in the capsule which will enhance heat transfer by facilitating faster heating or cooling processes, improve thermal stability by protecting from any leakages, unwanted reactions, and contaminations, controls the rate of heat transfer which is very important where the specific temperature range has to be maintained.

Kimn [20] worked on microencapsulating the octadecane PCM as a core material and melamine formaldehyde as the outer layer of the capsule. The mixture of microcapsules and the binders were printed onto the fabric by the screen-printing method, and the fabric was evaluated for its heat storage/release and mechanical properties at different concentrations of microcapsules (6, 12, 18, 24, and 30 %) and curing temperatures (95–115 °C). It was found that with the increase in the concentration of microcapsules, the heat storage/release (ΔHf heat fusion and ΔHc crystallisation) properties were increased. Still, when the curing temperature was increased, there were chances of capsule leakage, which resulted in a slight decrease in heat fusion and crystallisation. The mechanical properties, such as tensile strength and elongation at break, decreased with increasing the curing temperature. The toughness of the fabrics increased with an increase in the concentration of microcapsules due to an increase in high add-ons. The best results were found at 110 °C curing temperature and 24% concentration of microcapsules. But to optimise the treatment conditions to acquire maximum heat storage/release properties and less friction sound, a response surface methodology (CCD) was applied to the experiment. The results were optimised to a curing temperature of 113 °C with a 12.5% concentration of microcapsules.

Further, the study was extended by Eugene considering the optimum treatment conditions, the thermal properties, water vapour permeability, skin temperature, skin humidity, and clothing microclimate were measured. The thermal properties of the garment increased with an increase in the concentration of microcapsules, but the water vapour permeability was reduced due to the coating, which covered the open spaces in the fabric, thereby reducing the microclimate of the treated garments. The skin temperature and humidity range were the comfort zone when compared with the untreated fabrics. Still, with an increase in the concentration of microcapsules, the thermal performance of the garments decreases because the fabric is becoming stiffer, thereby reducing the still air layer to decrease the thermal insulation [23].

3.5 Fit Comfort and Tactile Comfort

Garment fit and sensory comfort are equally as important for military uniforms as are the thermophysiological comfort, protection, and durability characteristics. Fit and sensorial comfort are related to the overall physical and psychological well-being of military personnel, just as thermophysiological comfort is related to controlling body temperature and moisture management.

The fit of the garment depends on various factors which include the garment construction (type of seam, seam angle), ease of allowance, body shape and size,

pattern design, and fabric design. Selecting the right fabric, and designing the uniform with sizes of wide ranges according to different body types and gender is also a challenging task.

The Fabric design includes the structure of the fabric (woven/knitted), the amount of Lycra in the fabric which helps in better fitting. Lycra is most widely used in the workwear fabrics (Denim) to improve the comfort in the weft direction, but it's not used in the military uniforms as it deteriorates the tearing strength. Since the construction of workwear fabrics and military uniforms are similar research works are going on improve the fit comfort of the military garments by adding optimum percentage of Lycra in the weft direction so as to maintain the tearing properties according to the standards.

In a study conducted by [44] on the behaviour of fabric with different elastane % under tensile load and it was found that the wear comfort of the garment is depended on the tensile load developed at lower extension levels, so with increase in elastane content, the tensile load developed at lower extension decreases thereby improving the wear comfort.

Few studies have been conducted to improve the fit of the garment, by customising according to the customer preferences which includes the pant hem, sleeve length, waist fit, etc., and by incorporating the ergonomic principles into the uniform by choosing the right position for placing the seams and stretch panels, and finally by taking feedback from the customers about how they personally feel the garment.

The combinations of two types of fabric (Plain and twill) and two types of seams (plain and lap felled) with three different fit types (Straight, regular, and slim) were evaluated for their tensile properties. The angle of cut for regular and slim-fit trousers varies from 0° to15° with respect to warp direction. It was found that the slim-fit trouser with twill fabric and lap felled seam has better performance than the regular fit; this is due to the higher angle orientation of yarn (yarn angle above and below seam line) in the slim-fit trouser in different fits as explained in Fig. 10 [30].

The garments of the female wearers are different from the male wearers due to their different body dimensions, so it is very important to design the uniforms for

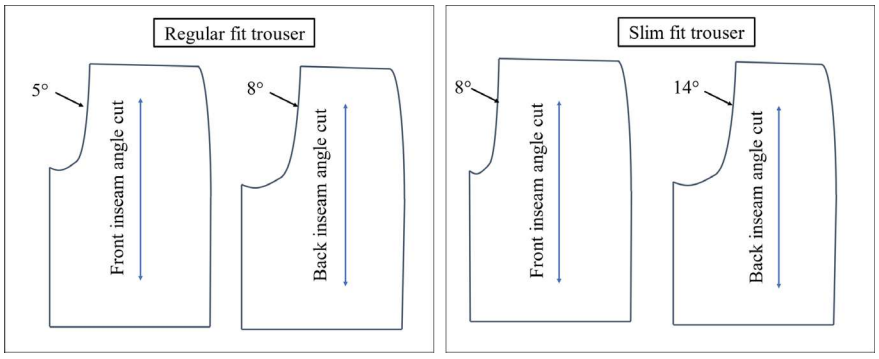


Fig. 10 Inseam angle cut of regular and slim-fit trousers

the women's military forces. Nicolene Smit worked on the African warrior project contracted by the South African National Defence force, where the project was to explore and describe the fit of the female upper garments (closely fitted jacket and loosely fitted combat shirt). The objectives of this study are to find out the tolerance levels of the fit that satisfies the functional requirements, the suitability of dimensions in the current size designation, and the evaluation of sizing systems. Individual preferences influenced satisfaction with the fit, according to the study. In some areas, insufficient or excessive fabric caused discomfort and restricted movement. The size designation's key dimensions did not provide enough comfort. It is recommended that waist and hip dimensions be included to accommodate different body shapes and improve size allocation [46].

Another method for improving garment fit is to optimize the military uniform sizing system by selecting the appropriate methods. To improve the upper garment size system, the first study combined support vector clustering (SVC) with genetic algorithm (GA) models. The study improved fit and reduced inventory costs by optimising parameter values and reducing the number of size groups [16]. The second study used a mathematical model of garment fit and nonlinear optimisation techniques to present a novel approach to apparel sizing systems. The study achieved significant improvements in fit compared to existing sizing systems by incorporating endogenous size assignment and relaxing the stepwise size structure [27]. The third study employs laser scanning technology to examine body measurements and movements in PPE. To acquire accurate data for designing effective uniforms and equipment, advanced techniques such as 3D scanning and contactless anthropometry are used. Non-contact anthropometric methods and CAD/CAM systems are used to collect and process information necessary for designing effective military uniforms and equipment [7].

The surface characteristics of the fabric have a direct influence on tactile comfort. A study was conducted by Armand and Les, where a predictive relationship between the fabric properties, sensory perceptions, and consumer comfort is studied for better understanding and quantifying the factors with both descriptive analysis (KES-F) and hand method (HSDA), which contributes to the tactile comfort of military clothing. The results of both studies suggest that the tactile comfort of military clothing is affected by the fabric's shear, bending, compression/friction, tensile, surface roughness, and sensory attributes like surface texture, volume, and noise. Higher values of specific properties, such as graininess, grittiness, compressional resilience rate, fabric weight, and coefficient of friction, were consistently identified as influential factors in both studies, with lower perceived comfort levels correlating with higher values. Both studies' R^2 values (0.94,0.924) indicate that a considerable amount of variation in ratings of tactile comfort can be attributed to the identified factors [4, 48].

3.6 Sewing Performance

Seam Quality is an important parameter in deciding the performance of any garment. The mechanical performance of the seam is a key factor for designing military uniforms as the seam encounters sudden impact forces and cyclic loading forces with high amount of stress during the activities performed by the military personnel on the battlefields and physical training. To sustain these stresses the seam strength of the military clothing should have 80% of seam efficiency [10]. The efficiency of the seam is affected by the type of seam, sewing thread strength, and fabric parameters (weight and construction of fabric) [32].

The seam is the joining of two pieces of fabric and is an integral part of any garment. In military uniforms, the seam must be strong, durable, and able to withstand the rigours of combat and other physical activities. A poorly constructed seam can cause the garment to tear, rip, or fray, which can be a safety hazard for the wearer. The choice of the seam will depend on the type of fabric and the intended use of the uniform. The recommended minimum seam strength for combat clothing is 14,900 N/m [6]. The double lap seam, is commonly used in military uniforms that require high durability, as it is a strong and robust seam which satisfies the 80% seam efficiency in both the warp and weft directions, when compared to that of the safety seam, serge seam, and combinations of safety and topstitch seam, serge and topstitch seam and it is suitable for all types of fabrics ranging from light weight plain fabric to heavy weight twill fabric [6]. The combination of twill fabric with the lap felled seam has the highest breaking strength, compared to that of the combination of plain fabric with lap felled seam and plain fabric with plain seam [30].

Sewing thread, attaches the various parts of the uniform together, and it is another vital component. Seam failure is often caused by thread breaking, so choosing the right sewing thread is crucial to the durability and aesthetics of the seams. Synthetic sewing threads such as 100 %polyester and nylon are stronger and have high resistant to abrasion and chemicals, and on the other hand, cellulosic sewing threads such as cotton have high resistance to heat. Since the military forces are exposed to various kinds of situations like long exposure to heat, abraded surfaces, and cyclic stretching, it is essential that the thread utilised for sewing military uniforms is strong enough to protect the wearer during rigorous activities. From the studies, it was found that the utilisation of polyester-cotton core spun thread and 100% polyester thread is prevalent in military uniforms owing to their durability, resistance to unravelling, and capacity to endure the demanding conditions involved in military operations [6, 30]. Seam strength is affected by the linear density of the yarn in addition to the fibre type and thread construction. Fabrics sewn with coarser yarns have greater seam efficiency and seam strength than those sewn with finer yarns [28]. The selection of thread size is influenced by the weight of the fabric. Smaller thread sizes are less susceptible to abrasion compared to coarser yarns, as the smaller threads become embedded within the seam.

The service life of the seam is also affected by the stitch type. Various locations in the garment employ a wide range of stitch types, each possessing unique properties.

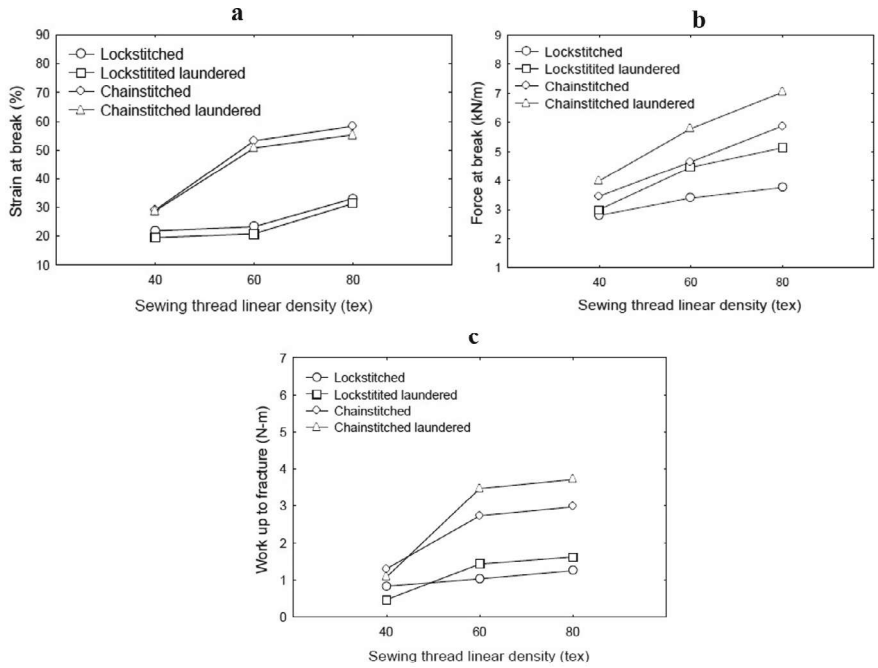


Fig. 11 Effect of linear density of sewing yarn on **a** force at break kN/m, **b** work up to fracture (N-m), and **c** Strain at break % [28]

The lockstitch with its characteristic interlocking pattern, results in a particularly strong and reliable seam. The chain stitch, on the other hand, is elastic because it uses loops formed on the wrong side of the fabric. Both types of stitching help make military trousers last longer and perform better in harsh conditions. The performance of chain stitch seam is much better in case of strain at break, work of rupture, and force at break than compared to that of lockstitch, as shown in Fig. 11 [28].

4 Conclusion

The present review discusses the challenges in developing military uniforms in terms of durability, comfort, and environmental protection. There are various kinds of military uniforms, and each uniform demands for specific requirements. The performance of military uniforms relies on a complex interplay of factors, including mechanical performance, thermophysiological behaviour, lightweight construction, camouflage effectiveness, and protection.

The successful integration of these elements is essential to meet the demanding requirements of modern warfare and ensure the well-being and effectiveness of military personnel, but at the same time, balancing all these requirements is a challenging task. The following points need attention for developing military uniforms;

Durability is crucial for military uniforms to withstand the harsh conditions of combat environments and prolonged use, and it is improved by selecting highly resistant fabrics, strong seams, and finishes. However, the variables considered for improving the durability of military uniforms may have an adverse impact on the weight of the fabric and comfort properties of the uniforms, thereby restricting mobility and causing discomfort to the wearer during extended wear. Camouflage and protection are also essential requirements demanded in military uniforms, but the process of camouflaging and application of finishes for protection may have a negative effect on the mechanical performance of the fabric, mainly on the tearing strength.

Additionally, testing of military uniforms presents its own set of challenges as the behaviour of fabric in laboratory conditions may differ from real-life scenarios. It is crucial to simulate realistic situations to accurately assess the performance of the uniforms.

With increase in global competition, the textile industries are facing a lot of challenges in developing a product with minimum cost and high performance. During the designing of military uniforms, it is very challenging for meeting the multi-targeted responses with the simultaneous optimisation of process and parameters at each stage. Future work in this area can focus on Multi Objective Decision Making (MODM) algorithms, where the optimisation problems involving more than one objective function can be optimised simultaneously.

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A Critical Review on Two-Dimensional MXenes and Their Applications in Wearable and Multifunctional Smart Textiles



Jagriti Thakur and Arobindo Chatterjee

Abstract MXenes, discovered in 2011, are two-dimensional transition-metal carbides, nitrides, and carbonitrides that have attracted considerable attention owing to their promising features and applications in flexible and wearable smart textiles. They show superiorities such as ionic conductivity, hydrophilicity, mechanical flexibility, optical properties, robust surface functional groups, large surface area and unique surface chemistry. Several novel synthesis strategies have been investigated to obtain MXene-based flexible devices with various functions and tailored structures. Since its recognition, more than 30 distinct arrangements have been produced via selective etching of various MAX phase precursors. In this review paper, a comprehensive discussion on structural patterns, synthesis of the most researched MXene titanium carbide ($Ti_3C_2T_x$), properties, recent developments, and applications in smart textiles are presented. The major applications include healthcare, flexible energy storage, smart thermotherapy, supercapacitors, electromagnetic interference (EMI) shielding, water purification, biomedical, electrocatalysis, etc. In addition, existing challenges, and future research of MXene enabled e-textiles are also outlined.

Keywords MXene · Synthesis · Wearable smart textiles · $Ti_3C_2T_x$ · 2D nanomaterials

1 Introduction

With the current demand and rapid development of portable and intelligent wearable textiles, traditional textiles have been fundamentally changed through the integration of their inherent flexibility and novel functionalities. The latest advances in flexible electronic devices are due to their unique qualities, such as being light, easy to make,

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and comfortable to wear. Smart textiles enabled devices play a major role in wearable electronics, that can be used in energy storage, sensors, real-time healthcare monitoring, electromagnetic interference (EMI) shielding, biomedicine, etc. [4, 5]. Numerous electroactive materials have already been explored to produce innovative e-textiles, including carbon nanotubes, boron nitride, graphene, nanoparticles, conducting polymers, etc. [4, 5]. Due to their intrinsic properties, 2D materials have always been of interest to researchers, and as a result, more 2D materials have been successfully produced in recent years [12]. However, there are certain hindrances in the fabrication of electronic clothes, including the adhesion of sensors to clothes, the comfortability of garments having devices on them, and unreliable performance due to improper connection. The sensors cannot be directly placed on the textile material through embroidery, sewing, etc. As it will lead to inadequate adhesion of sensors to garments, resulting in the easy fall of devices when worn by the user [12]. This necessitates the exploration of a new material that can be incorporated into the textile material using existing or new fabrication methods to produce electronic textiles. Recently, the novel two-dimensional (2D) material MXene has attracted tremendous attention from the research community due to its intrinsic properties. In 2011, researchers at Drexel University discovered MXene and introduced it to the family of two-dimensional materials [6]. MXenes are 2D layered materials denoted as $M_{n+1}X_nT_x$, where M represents the transition metal, T represents functional groups such as hydroxyl, oxygen, or fluorine, X represents carbon or nitrogen, and n represents an integer. Approximately 30 distinct stoichiometric MXenes, such as $Ti_3C_2T_x$ (the most thoroughly investigated), have been synthesized by etching and exfoliating various MAX phase precursors, and the structures and features of many are being investigated [10].

MAX phases are ternary carbides or nitrides, denoted as $M_{n+1}AX_n$ or max phases that belong to the hexagonal system, where A represents the A-group element. There are currently over 90 MAX phases, including Ti_3SiC_2, Ti_3AlC_2, Ti_2AlC, V_2AlC, Ti_2AlN, etc., and others [17, 18]. MAX phases have a crystal structure where M and X atoms are tightly packed and occupy octahedral sites to create ceramic-like layers separated by metal-containing A layers resulting in MAX phases containing ceramic and metallic features. MAX phases behave like metals showing conductivity, and resistance to thermal shock and behave like ceramics, having high-temperature strength, and thermal stability [17, 18]. The current optimal synthesis conditions of MXene produce extremely high conductivity (up to 20,000 Scm^{-1}) and capacitance per unit volume (up to 1,500 Fcm^{-3}) [10].

MXene has excellent intrinsic properties such as flexible surface properties, adjustable surface termination, electrochemical, conductivity, optical, and hydrophilic properties, redox capability, and graphene-like structure. These interesting properties endow MXenes with quite promising applications, including wearable electronics, photodetectors, power generation, joule heating, breath monitoring, sensing, electrochemical energy storage, conductive electrodes, and so on [8]. MXene is superior to other nanomaterials, due to the abundance of functional groups on the MXene surface, which creates a strong adhesion between the textile surface and MXene. Due to the strong bond formation of MXene with textiles, it does not come

off easily from the fabric, even after washing [8]. MXene can be fabricated onto the textile material by different processes including 3D printing, coating methods such as dip, spray or brush coating, screen printing, the layer-by-layer assembly method, electrospinning, and wet spinning with or without the addition of binders or surfactants due to its hydrophilic surface. In addition, a better comprehension of its rheology and ability to form dispersion in many organic solvents has opened the door to the processing of MXenes into novel structures and geometries. MXene has just been introduced to the market, so the research is in the preliminary stage and has several limitations [4, 5]. There are certain issues with oxygen stability, scalable production, aggregation in specific solvents and poor mechanical properties which still need to be addressed. The cost of nanomaterials is very high, and their behaviour is unpredictable as while the processing of nanomaterials if any problem arises it shows insufficient conductivity [4, 5]. In this review, the criteria of high quality MXenes is outlined along with recent developments of flexible MXene based textiles for wearable devices. The influence of different synthetic methods on surface functional groups, fabrication of multifunctional smart textiles, performance and application is also summarized. In addition, the properties of MXenes have been discussed [14].

2 Structural Characteristics and Properties of MXene

The MAX term denotes the MAX phase precursor in the synthesis of MXene, denoted by $M_{n+1}AX_n$, where A represents GA, Si, In, Pb, Cd, As, etc. "M" atoms are tightly packed in a hexagonal structure, having the same space group ($P6_3/mmc$), where "X" atoms are tightly packed in octahedral structure [17, 18]. Many MAX phases have been synthesized (such as Ti_2AlC, Ti_3SiC_2, Ti_2AlN, Ti_2AlC, and Cr_2AlC and Ti_3AlC_2) reaching up to 70, and others are also being produced. MAX phases have high thermal and electrical conductivities, ease of processing, high hardness, low density, corrosion resistance, etc. [15]. MXene and textiles form strong bonds and adhesion due to their hydrophilic groups (oxygen, fluorine, hydroxyl, etc.) and surface chemistry. The adhesion between MXene-MXene layers and MXene-textile substrate can be increased by performing functional treatments such as UV Ozone and oxygen plasma and using conducting binders [12], such as poly(3,4-ethylenedioxythiophene) polystyrene sulphate (PEDOT: PSS). MXene has a unique structure and possess high surface area making it a perfect candidate for manufacturing of smart textiles. Due to the presence of metal layers, MXene possesses metallic conductivity [1]. Researchers have reported electrical conductivity of MXene up to 20000 Scm^{-1}. It has extremely high mechanical properties, such as a single layer's Young's modulus of up to 330±30 GPa and tensile strength of up to 17.3±1.6 GPa [4, 5]. Films of $Ti_3C_2T_x$ absorb light energy in the UV-visible region at a wavelength between 300 nm and 500 nm [9] (Fig. 1).

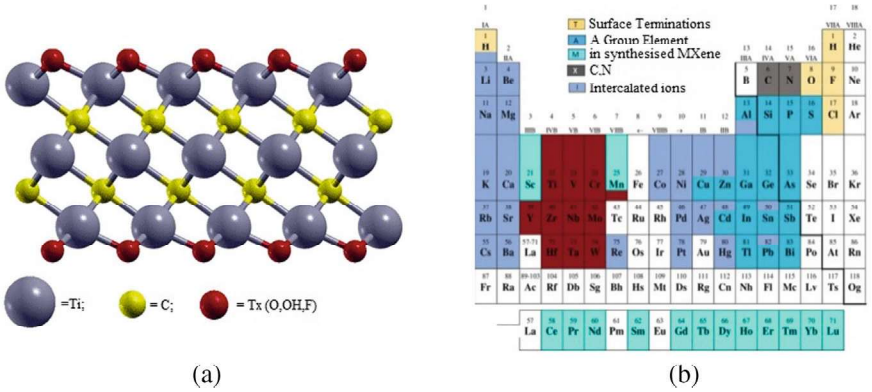


Fig. 1 **a** Atomic structure of MXene, **b** Periodic table depicting compositions of MXene and MAX phases

3 Synthesis of MXene:

Synthesis of $Ti_3C_2T_x$ is done from Ti_3AlC_2 MAX phase precursor by several routes using different starting materials [10]. Till now 30 or more MXenes have been synthesized by selective etching of Ti_3AlC_2. The selection of method depends on the required product and the desired properties such as size, morphology, and the overall performance of the material. MAX phases are the starting material, and the process is completed in two steps: etching of MAX phase then delamination of the exfoliated MXene layers. 3D MAX phase such as Ti_3AlC_2 is selected, and its etching is done using an acid etchant [1]. The very first MXene was synthesized by selective etching of Ti_3AlC_2 fine powders in the presence of hydrofluoric acid (HF) etchants. Ti_3AlC_2 was added to a solution containing 50% concentrated HF for 2h at room temperature. The aluminium atoms are removed from MAX phase, and MXene is terminated with –OH, –O and -F atoms. Ti–F, Ti–O, or Ti–O bonds replace Ti-Al bonds, resulting in multilayered MXene flakes. This process requires a separate step for intercalation and delamination of multilayer MXene to obtain the monolayer MXene [13] (Fig. 2).

Other techniques, are used in which in situ HF is formed where an etching solution is prepared using deionized water, HCl and LiF, in which Ti_3AlC_2 is immersed. Li^+ ions are formed which promoted etching of aluminium, and convert MAX phase to MXene with rheology like clay in a single step [11]. The clay like MXenes is

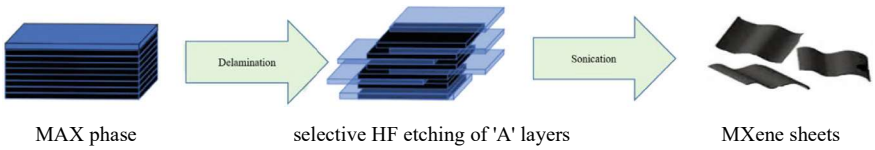


Fig. 2 Formation of MXene by etching of MAX phase with HF acid-based etching

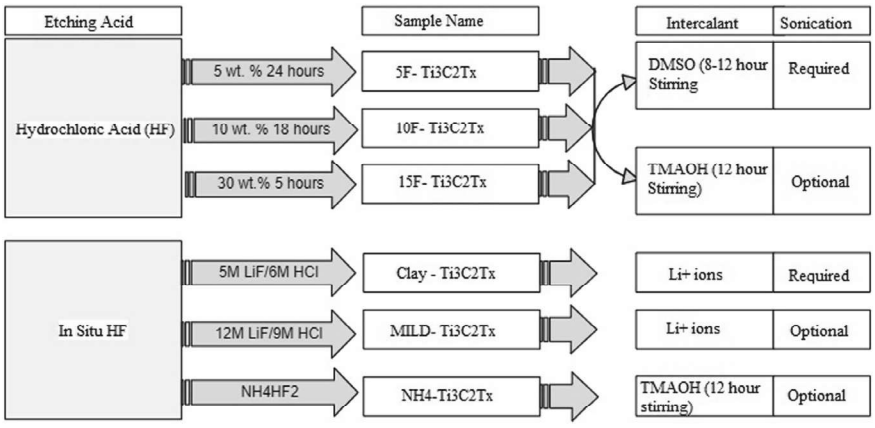


Fig. 3 Describes routes for synthesis of most studied MXene $Ti_3C_2T_x$

collected, centrifuged optional and washed until pH of supernatant approaches ≈6. Several fluoride salts can be used as etchants to obtain in situ HF and avoid use of toxic HF [1]. MXenes are prepared by exfoliation by etchants including HF, molten salt, in situ HF, HCL and fluoride free etching. Intercalating agents are used to promote easy delamination by increasing the distance between two MXene layers and produce pure MXene sheets. The agents include DMSO, tetramethylammonium hydroxide (TMAOH), hydrazine, urea, and isopropylamine [7]. Another method named hydrothermal treatment is used as it is environmentally friendly and successfully produces multi-patterned 2-D MXene. Other methods such as hydrothermal treatment and electrochemical etching can be used to obtain fluorine free MXenes [10]. The Fig. 3 shows the general routes for the synthesis of the most studied MXene $Ti_3C_2T_x$.

4 Factors Influencing the Preparation of MXene Enabled Smart-Textiles

To produce MXene integrated smart textiles some of the factors are to be considered to ease the processibility. MXene flakes are applied on the textile material to form smart textiles so the size of MXene plays a very crucial role in deciding the physical and electrical properties of the final product. In a recent study it was observed that textile coated with large size MXene flakes shows an increase in conductivity as compared to the small size flakes.

It occurs due to the deposition of large sized MXene flakes on the surface of textile material while the small sized flakes penetrate the textile material and contains more defects. But the use of large sized flakes results in less flexibility and poor adhesion between the MXene sheets [2, 3]. To overcome this several binders are present

which can be used to improve adhesion. The textile material and MXene should have some affinity towards each other for the application of MXene on them. Mxene cannot be directly applied on the fibers as the interaction between the fiber and MXene is required as well as between the MXene flakes. The textile material can be functionalized using treatments such as oxygen plasma and ultraviolet (UV) ozone, or binding agents such as poly(3,4-ethylenedioxythiophene) polystyrene sulphate (PEDOT: PSS) can be used to improve the adherence [12]. Mxene is applied on the textile substrate by various methods which also include coating. In this method, the MXene is coated on the textile material in dispersion form. Dispersing agents such as DMSO, DMF, hydrazine, urea, and isopropylamine can be used. DMF and DMSO have shown the best dispersibility than aqueous medium, but the conductivity observed was less than the aqueous medium. The choice of accurate sized flakes, solvent and dispersing agent is important for the processibility of material into different textile structures [16].

5 Fabrication Techniques

Several procedures are followed for incorporating MXene into textile substrates to obtain the required functionality. One approach involves coating fibers, yarns, and fabrics with an aqueous MXene dispersion. Depending on the textile substrate and the MXene properties, it may infiltrate into the textile material [2, 3]. MXene-based fibers such as monofilaments, nonwoven mats of fibers, or yarns can be produced using melt spinning, electrospinning, biscrolling etc. can be used [10] (Fig. 4).

5.1 Coating

This method is the most facile, scalable, and cost-effective way to make electronic textiles. In this method MXene is directly applied to natural fibers, synthetic fibers, carbon-based fabrics, yarns, woven, nonwoven and knitted textiles. A MXene dispersion is prepared and applied on textile using coating methods such as dip coating, spray coating, spin coating, and drop casting [10]. In a study, researchers coated cotton/linen fabrics with MXene by dipping in aqueous dispersion of MXene. The results showed a strong bonding between the fabric and MXene. Similarly, in another study, polymeric textile was dip coated in MXene and they reported a strong interaction between MXene and substrate due to hydrogen bonding [12]. Another method to apply MXene directly on textile surface is drop casting where the material is constantly dispersed to obtain the required coating. Dop casting of MXene on silver plated nylon have also reported promising results in terms of electrical conductivity. In a recent study, AgNWs and MXene were applied on the textile material to produce electronic textiles. To increase the surface conductivity, MXene content should be increased on the surface of textile. High mass loading requires repetitive coating of

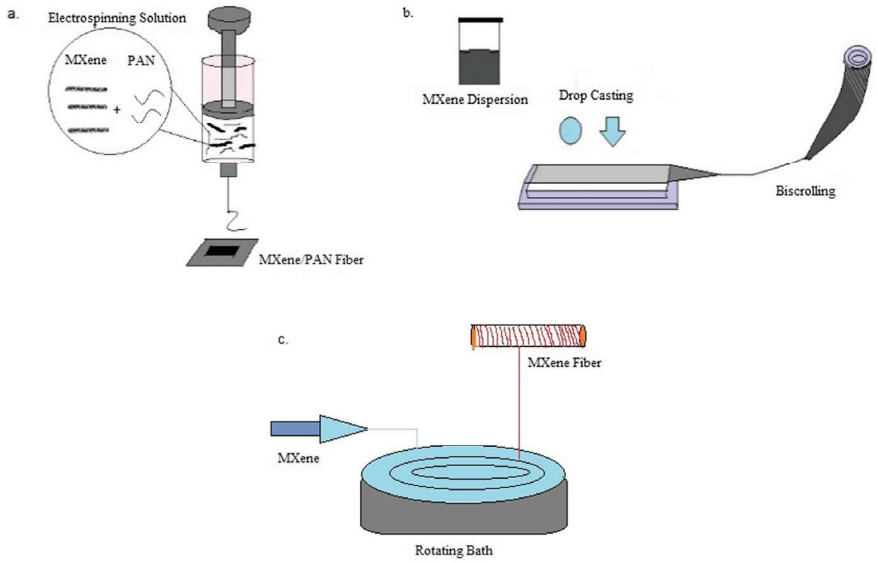


Fig. 4 Schematic diagram of fabrication methods to produce smart textiles: **a** Electrospinning, **b** Drop casting and Biscrolling, **c** Wet spinning

MXene which results in excessive deposition of MXene flakes on substrate. This necessitates to explore other methods for application of MXene on textile substrates [2, 3].

5.2 Vacuum-Assisted Filtration (VAF)

Vacuum assisted filtration is used to produce MXene/polymer composite. The desired amount of polymer and MXene are mixed in a polar solvent under continuous stirring or sonication, followed by vacuum filtration. Dispersing agents are used to increase the bonding of MXene/polymer composite for proper stacking of MXene flakes in polymer composite. The weight percentage needs to be controlled as the polymer may get washed away resulting in inadequate composition of MXene/polymer composite. To avoid these issues, other processes such as hot pressing, solvent evaporation, and the layer by layer (LbL) method, can also been explored to produce MXene/polymer composites with a controlled thickness and composition [3, 4].

5.3 Electrospinning

Electrospinning is extensively being used to manufacture polymer composite fibers by adding MXene into the dope solution. Various researchers have studied the production of electrospun MXene-nanofibers having large surface area-volume ratio including, chitosan, polyethylene oxide (PEO), polyvinyl alcohol (PVA), alginate, and PAN. Organic solvents, are used to form dispersion of MXene including DMF, ethanol, trifluoracetic acid, water, and alginate-based solutions, to spin the composite fibers. This technique is less explored for wearable electronics due to some problems such as the decrease of contact among MXene layers due to polymer intercalation and the restriction of mass loading using electrospinning [12].

5.4 Biscrolling

The unconventional technique of biscrolling can be used to make MXene-yarns. In this method, CNT sheets serve as hosts and MXene is injected into the spinnable substrate and both MXene and CNT sheets are scrolled to produce yarn. Before inserting a twist, MXene is injected into the spinnable substrate using drop casting process or, deposition during synthesis, or dip coating [10]. The particles get entrapped in the scrolls of CNT, and create voids of different diameters enabling the penetration of electrolytes into the scrolls [3, 4]. This approach offers up to 98 wt.% nanoparticle loading in yarns with regulated diameter and porosity.

5.5 Wet Spinning

Wet spinning is an effective method for producing efficient, scalable, and long functional fibers using a spinneret. A spinning solution is introduced into a coagulation bath through a spinneret, causing the fibers to concentrate and solidify. Resultant fibers are extracted from the bath, cooled, and wounded on a winder. A wide variety of solvents, such as PCL, polyurethane (PU), PEDOT: PSS, and GO, are introduced to the dope solution to improve the processibility of flakes into fibers.

Advanced application of Ti_3C_2-based Textiles

In recent years, Ti_3C_2-based MXene versatility has led to the development of some major applications. Due to its excellent properties, such as its young modulus, good electrical conductivity, adjustable band gaps, chemical stability, etc., MXene has been incorporated into several devices. Integrated MXene textiles are used in thermotherapy, sensors, EMI shielding, energy storage, biomedical applications etc. MXenes have hydrophilic terminated surfaces, easing their application on fabrics through coating. In this section, some potential applications of MXene enabled wearables are outlined [12] (Fig. 5).

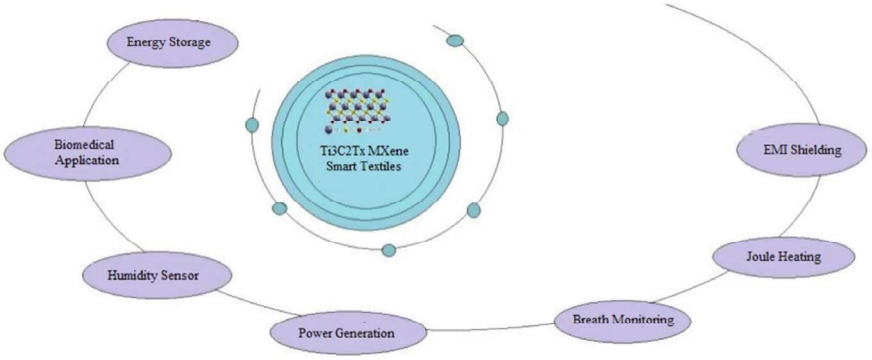


Fig. 5 Schematic diagram showing emerging applications of Ti_3C_2. based MXene integrated smart textiles

5.6 Joule Heating for Thermotherapy

Joule heating is used in thermotherapy to impart comfort from serious health problems such as muscular pain, fibrositis, backaches, injuries caused by excessive sport activity. MXenes are electrically anisotropic and have recently been used in thermoregulation devices to relieve pain. Heating systems produced by MXene senses and react to the changing environment due to the formation of a microclimate near the skin. Smart textiles serve as respiratory monitoring systems, by responding to humidity generated by the contraction of MXene flakes due to presence of water particles [12]. The generated heat is transferred homogeneously to the infected skin, and wounds are healed. A flexible MXene enabled heating device can be developed by assembling MXene flakes on fibre surface. Knitted heaters are also produced due to their excellent heating performance. The MXene fabric heater, when attached to the human wrist, effectively increases the body heat, and circulates it along the arm, leading to a potential MXene-based wearable thermotherapy [3, 4].

5.7 EMI Shielding

EMI shielding is very important to block the undesired electromagnetic radiations to protect human health and the life of electronic gadgets. It can cause chronic illnesses such as asthma, heart disease., cancer, etc. The connection between the charge carriers and electromagnetic field is broken to prevent the EM radiation from penetrating [12]. MXene has shown impressive results for this application. In comparison to existing materials such as graphene and conductive materials, MXene has shown better results due to its low density, high conductivity, large surface area and excellent metallic and hydrophilic surfaces [3, 4]. MXene acts as a shielding material and prevents the penetration of high-frequency radiation. Many MXene based textile interfaces are

developed using various methods such as layer by layer method, dip coating, spray coating, Vacuum-Assisted Filtration etc.

5.8 Energy Storage

MXene is also used as energy storage material. MXene enabled energy storage materials are used in batteries and supercapacitors, due to its excellent metallic conductivity, redox reaction active surface and properties like metals and semiconductors [13]. Reported data has shown the promising results of using MXene for storage capacity as compared to other 2D materials.

6 Challenges and Future Perspective

Despite many excellent properties, MXene has certain issues about chemical stability, orientation, precise fabrication technique, solvent selection, etc. Several challenges need to be resolved, such as the fact that using HF for MXene synthesis is extremely dangerous and toxic, and it should be avoided, and new, less toxic methods should be adopted, such as HCl and LiF, which can be used in place of HF [3, 4]. Other methods, such as electrochemical, and molten salts etching, can replace the existing dangerous methods. By changing structural compositions, various colored MXene can be produced. The oxidation stability of MXene is poor, and it affects the properties of MXene and fabrication of MXene on textiles. The life of MXene can be improved by storing the colloidal solutions at a very low temperature (5 °C) in hermetically sealed, Argon bottles or by storing the films obtained after the filtration of the colloidal solution. Lack of adhesion between textiles and MXene is another challenge that needs to be resolved. Large-sized MXene flakes coated on textiles produce more conductivity but lack flexibility and adhesion. To overcome this problem, Mxene-treated textiles should be functionalized using cross-linking agents, which increase the adhesion and mechanical strength of the product. O_2 plasma and APTES can be used to improve adhesion [12]. Textile materials are cleaned by washing only, and when MXene is applied to the textiles, some standard washing techniques are to be followed to avoid deterioration of the textile due to twisting, distortion, etc. Up until now, major studies have been done on $Ti_3C_2T_X$, which necessitates the investigation of other MXenes. More fabrication techniques should be developed, such as the printing of MXenes onto textiles, which can be used to produce portable, separate, wireless e-textiles. Highly functional optical fibers can be produced by thermal drawing. Textile technology is leading to reality and upcoming developments in Internet-of-Things (IOT), artificial intelligence, virtual reality, and cloud computing [3, 4]. New wearable electronic textiles are to be made to replace the

existing knitted sensing fabrics. The internet of textiles has become the new extension of the Internet of Things. MXene-integrated e-textiles can be used to produce supercapacitors, sensors, thermotherapy, etc.

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Study of Multi-layered Fabrics for Thermal Insulation in Extreme Cold Weather Apparel



Jameer Aslam Bargir and Monica Sikka

Abstract The value of textiles in maintaining a comfortable internal body temperature cannot be overstated. Through metabolic processes, the human body generates heat constantly at a rate between 40 and 440 W/m^2 depending on the nature of their activities. The thermal insulation that is provided to the person wearing the severe cold weather apparel ensemble comes from the employment of high-bulk nonwovens that are arranged in the form of layers. In this research, two different multi-layered fabrics have been studied with the same inner and outer layers but varying middle layers. Polyester knitted fabric is used as the inner layer, and PU-coated nylon fabric is used as the outer layer. Two different types of hollow fibers are used for the middle layer in the form of waddings. The hollowness percentage of these fibers is calculated by using Scanning Electron Microscope (SEM) analysis at different magnification levels and found that the hollow polyester (3.33 Tex) fiber shows a higher hollowness percentage than Thermolite® fiber (0.15 Tex). Thermal properties such as thermal resistance, thermal conductivity, thermal diffusivity, thermal absorptivity, and value of heat flux have been evaluated for both fabrics using the Alambeta instrument. Along with that the effect of areal density (GSM), porosity, and thickness of the middle layer on multi-layered fabric structure with respect to thermal properties also have been studied in this research. The results of both fabrics are analyzed using ANOVA and it is concluded that multi-layered fabric with Thermolite® fibers waddings as the middle layer shows lower thermal conductivity, thermal absorptivity, and higher thermal resistance and thermal diffusivity with respect to the fabric with hollow polyester fibers waddings.

Keywords Alambeta · SEM analysis · Thermolite® · Hollow polyester · Thermal resistance · Thermal conductivity

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1 Introduction

Protecting the wearer from the cold is the major goal of clothes designed for use in cold climates. For regular folks, thermal insulation is all that's needed in terms of constructing protective clothing, but for members of the armed forces and other paramilitaries, a number of other needs are also vital. These include the ability to handle fight and operational hazards with minimal effort, to complete their mission while wearing the clothing, and to be protected from the elements such as wind, snow, and rain when doing so. The protective clothing must fulfil all of these criteria while also being comfortable to wear [1]. It has always been difficult for scientists to design textiles that can withstand freezing temperatures [2]. The human body's metabolic functions are a constant source of internal heat. A person's internal heat generation might range from 40 to 440 W/m^2 depending on the level and duration of their workout. Clothes allow the body's heat to escape into the environment via convection, conduction, radiation, and evaporation [3]. In order for the wearer to keep their body heat, the clothes must prevent the chilly air from the surrounding atmosphere [4]. This problem cannot be solved by using just one sort of fabric at any time. Putting on multiple layers of textiles that are designed to be worn as garments [5]. The layering of materials, when worn combined, has a significant impact on the attributes of the layered clothes, including permeability to air, thermal conductivity, and thermal resistance [6–8].

Layered clothing's ability to transport heat is of the utmost significance because it is one of the primary factors that determines how comfortable one will be in terms of temperature. These multi-layer structures typically consist of three layers, with every layer performing a unique function and contributing to the overall goal of achieving thermal physiological balance [9]. The inner layer's primary role is to prevent heat from escaping the body by trapping it and removing moisture from the skin & and transferring it to the outer layer [10]. This layer is ideal for fast-drying materials like polypropylene and polyester. The main function of the assembly's core material is to act as insulation for the complete fabric. In order to prevent the body from losing too much heat, various materials are employed to provide insulation around it, including feathers, nonwoven, and other similar items. The outermost layer is breathable and serves as a barrier against snow, wind, and rain. It needs to be permeable to air and water vapor for comfort.

PU-coated nylon, Windstopper®, Gore-Tex®, and Trinity® can be used for the outer layer [5, 11, 12]. According to research by Kasturiya et al., wearers of multilayer garments can stay warm and comfortable even in sub-zero temperatures [1]. Shen et al. found that the middle layer between two fabric layers helps with insulation in extremely cold weather. They also found that rough materials trap air [13]. Barker et al. and Maurya examined how fabric bulk density and thickness affect thermal insulation. They found that with thickness fabric's thermal insulation increased. The design of the nonwoven layers as well as the temperature in the surrounding area both play a role in the heat transfer that occurs through the layers. Porosity, fiber fineness, and cross-section of fiber all contribute to the structure, which in turn

affects the fiber surface area and compressional resiliency of the nonwovens [14]. The pores of the nonwoven material have an effect on the rate of heat transfer by conduction and, consequently, the thermal resistance of the material. Different-sized and shaped fibers can be used to create each nonwoven layer. Hence, it was decided to study the impact of sub-zero temperature variations on the thermal performance of nonwoven fabric assembly featuring nonwoven layers consisting of fibers of varying deniers. In this study, the experiment is carried out on non-woven webs which are made up of two different kinds of polyester fibers with different deniers but the weight of both webs is the same. Thermal properties such as thermal conductivity, thermal absorptivity, thermal diffusion, thermal resistance, and, heat flux value of both fabrics have been studied using the instrument Alambeta [15]. The porosity of different layers is calculated through numerical methodology whereas thickness is calculated by Alambeta itself [15].

2 Materials and Methods

For this study, a multi-layered fabric construction with breathable PU (Polyurethane) coated nylon fabric, waddings of Thermolite® fiber and hollow polyester, and interlock polyester fabric is used. Six samples have been produced in which the inner and outer layers are the same and made up of interlock polyester fabric and breathable PU (Polyurethane) coated nylon fabric respectively. The middle layers are made up of waddings of Thermolite® and hollow polyester fibers with three different GSM of 350, 400, and 450. The specifications of all the materials are given in Tables 1 and 2 displays the layering configuration that results from using these materials. All of the samples used in this study were subjected to measurements that determined their thickness (ASTM C518), mass per unit area (ASTM D3776), bulk density, and porosity, among other fabric properties. When determining the bulkiness of a fabric, the important physical characteristics to take into account are its mass per unit area as well as its thickness. Thickness is measured in Alambeta itself and the ASTM D3776 standard is used to measure areal density [5, 15]. Equation 1 is used to measure the bulk density of fabric in gm/cm. i.e.

$$\text{Bulk density (D)} = W/T \tag{1}$$

where,

W = GSM of the fabric in gm/cm^2

T = Thickness of fabric in cm

And porosity is the amount of air that is prevented from escaping from within the material which is found by Eq. 2. i.e.

$$\text{Porosity } = 1 - D/d * 100 \tag{2}$$

where,

D = Bulk density of fabric (gm/cm^3)
d = Density of fiber (gm/cc)

Ten readings of all samples have been taken and an average of those values is considered as a result and tabulated in Tables 1, 2 and 3.

Table 1 Specifications of materials used

Parameters	Interlock polyester fabric	Thermolite® fiber wadding			Hollow polyester fiber wadding			Breathable PU-coated nylon
		GSM			GSM			
		350	400	450	350	400	450	
Fiber fineness (Tex)	1.11	0.15			3.33			7.78
Thickness of layers (mm)	0.70	17.03	19.79	20.97	15.12	17.38	18.64	0.096
Bulk density (Kg/m^3)	214.3	20.55	20.21	21.45	23.14	23.01	24.14	681.8
Porosity (%)	84.58	99.98	99.98	99.98	98.40	98.40	98.40	45.6

Table 2 Layering configuration of materials

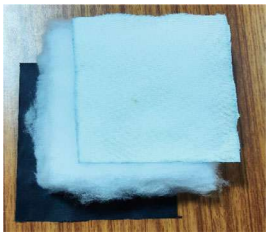
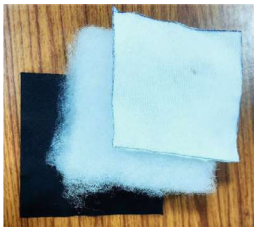
Parameters	Fabric I (ITB)	Fabric II (IHB)
Inner layer	Interlock polyester	Interlock polyester
Middle layer	Thermolite® wadding	Hollow polyester wadding
Outer layer	Breathable PU coated nylon	Breathable PU coated nylon
Images		

Table 3 Codes for a combination of fabrics

FL	Multi-layered fabric with 350 GSM
FM	Multi-layered fabric with 400 GSM
FH	Multi-layered fabric with 450 GSM
TH (Fabric I)	Multi-layered fabric with Thermolite® fiber web
HP (Fabric II)	Multi-layered fabric with Hollow polyester fiber web

2.1 SEM Analysis

Thermolite® and hollow polyester fibers both are subjected to SEM analysis to identify the difference in the hollowness of both fibers. The fibers have been cleaned and dried well because the fibers should be free from impurities and moisture before SEM. As the fibers were non-conductive in nature, the sputtering method was used to apply a 10 mm gold coating on these fibers to avoid the charging of fibers during the SEM analysis process [16]. The mounting of fibers is done by using double-sided tape such that the sample should be properly mounted on SEM stub. The SEM analysis has been done using the Carl ZEISS EVO 10 Scanning Electron Microscope works with SmartSEM software in which tungsten filament with a maximum acceleration voltage of 30 kV is used as an electron source, a powerful and versatile tool for high-resolution imaging of 3.5 nm at 30 kV for the secondary electron (SE) and 5.0 nm at 30 kV for the backscattered electron (BSE), magnification range between 5x to 300,000x with advanced imaging, and capability of the holder to tilt the sample up to 45° [17].

2.2 Thermal Properties

The Alambeta tester was used to determine the thermal characteristics of fabric in accordance with ASTM C518. In the absence of body movement and external wind flows, this instrument imitates the heat transfer (q) [W/m^2] from the body to the fabric during brief first contact. This instrument relies on a statistical analysis of the time course of heat flow flowing through the tested fabric because of the temperature difference of 10 °C between the bottom measuring plate and top measuring head. The Alambeta apparatus measures thermal properties at a contact pressure of 200 Pa, including thermal conductivity (λ), thermal diffusivity (a), thermal absorptivity (b), thermal resistance (R), heat flow (qm), and thickness (h) [15, 18]. Before being put to the test, each fabric sample is conditioned in a climate simulator at a tropical 27 °C ± 2 °C temperature and an RH of 65% ± 2%. The testing is carried out on the Alambeta (Fig. 1) instrument and the results are analyzed statically with the help of ANOVA.

2.2.1 Thermal Conductivity (Λ)

The capacity of a material to transport heat is known as its thermal conductivity [19] and it is most often represented by the letter k, however, the symbols λ are also acceptable alternatives. It is measured in W/mK and it is inverse to the thermal resistivity.

$$\text{Thermal Conductivity}(\lambda) = q/\Delta T \tag{3}$$



Fig. 1 Alambeta instrument

where,
q = Heat flux of fabric
ΔT = Temperature.

2.2.2 Thermal Diffusivity (a)

The term "thermal diffusion" is used to describe the passage of heat through the air as a characteristic of fabric structures. The thermal conductivity of a material has a direct impact on this value. It is measured in m^2/S. 10^{-6}

$$\text{Thermal!diffusivity(a)} = \lambda/\rho c \tag{4}$$

where,
λ = Thermal Conductivity
ρ = density of the material
c = Specific heat capacity

2.2.3 Thermal Absorptivity (B)

It's a scientific way to evaluate how warm or chilly a fabric actually is. Materials with a low thermal absorptivity rating retain heat well, whereas those with a high value do the opposite [20]. The range of thermal absorptivity lies in the range of 20–600. This is measured in W. s½ / m^2.K.

$$\text{Thermal absorptivity(b)}: \sqrt{\lambda \rho c} \tag{5}$$

where,
λ = Thermal Conductivity
ρ = density of the material
c = Specific heat capacity

2.2.4 Thermal Resistance (R)

The ability of a substance to act as an insulator against heat is referred to as its "thermal resistance." It is directly proportional to the thickness of the fabric and inversely proportional to thermal conductivity [13, 20]. It is calculated in form of m^2KW^{-1}.

$$\text{Thermal resistance(R)}:h/\lambda \tag{6}$$

where,
h = Thickness of fabric
λ = thermal conductivity of the fabric

3 Results and Discussion

3.1 SEM Analysis

The results of the SEM analysis has been shown in Figs. 2 and 3. Since this equipment analyses elements and produces high-resolution pictures of fibers. The hollowness percentage of both fibers has been found with a high-resolution image. As the hollow polyester fibers are a little coarser, these were magnified in the range of 130X, 2.00KX, and 2.00KX to get high-resolution images at 3.00 kV of electron source whereas, Thermolite® fibers were magnified in the range of 1.83KX, 3.00KX and, 4.94KX to get high-resolution images at 3.00 kV of the electron source.

From the result, it is observed that the hollowness of hollow polyester fiber is more than that of Thermolite® fiber. The hollowness percentage is found by using the formula

$$\text{Hollowness } \% = \frac{\Pi d^2}{\Pi D^2} * 100 \tag{7}$$

where,
d = Inner diameter of the fiber cross-section
D = Outer Diameter of the fiber cross-section

From the SEM analysis, it has been found that the inner and outer cross-sectional diameter of Thermolite® fiber was 4.31μm (d) and 12.75μm (D) respectively. The

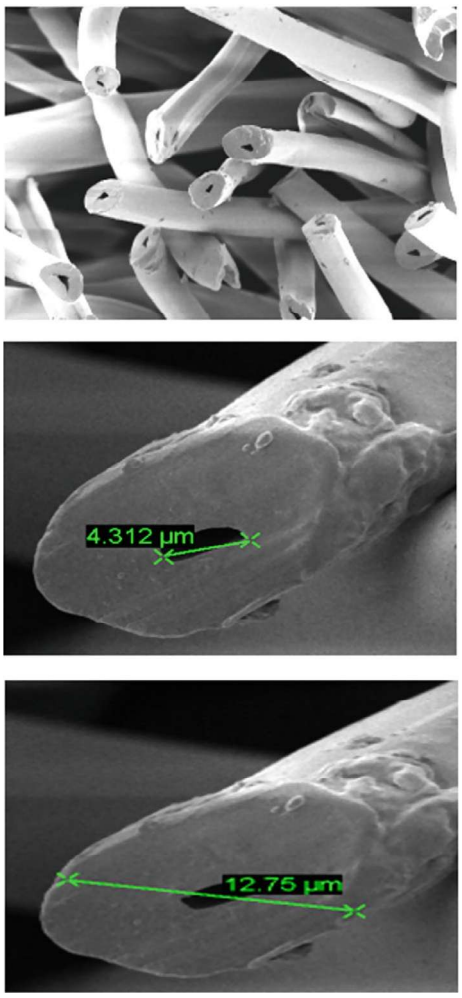


Fig. 2 SEM analysis of Thermolite® fiber

hollowness percentage of Thermolite® fiber is 11.4% Whereas in the case of hollow polyester fiber inner and outer cross-sectional diameters of fiber were 11.77 µm (d), and 29.75 µm (D) respectively. The hollowness percentage in the case of hollow polyester fiber is 15.64%. The hollowness percentage of hollow polyester is higher because of the coarseness of the fiber. Thermolite® fiber is nearly 23 times finer than hollow polyester fiber due to which it is showing lower hollowness of its cross-section. But in the case of the air gap, Thermolite® fiber will entrap a large amount of air because of the large surface area provided by a greater number of fibers per unit volume with respect to hollow polyester fiber.

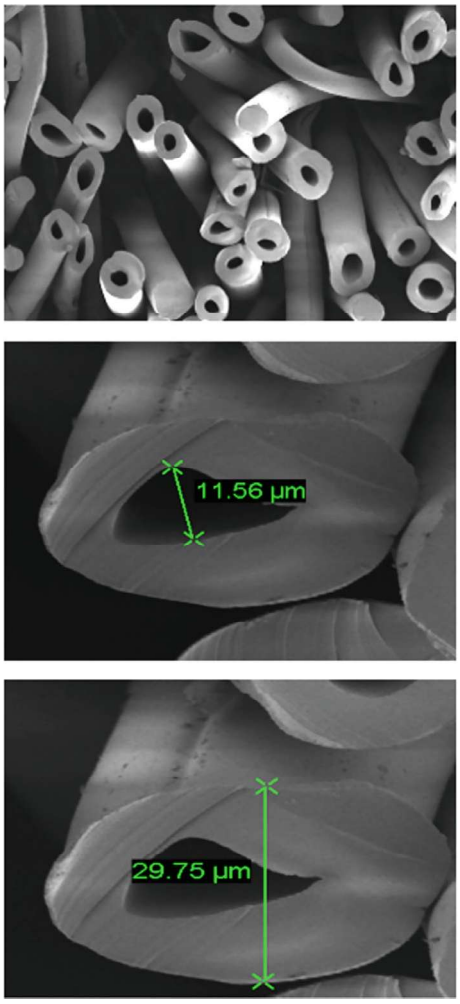


Fig. 3 SEM analysis of hollow polyester fiber

3.2 Thermal Properties

After the testing, the values of thermal conductivity (λ), thermal diffusivity (a), thermal absorptivity (b), thermal resistance (R), heat flow (qm), and thickness (h) have been noted and tabulated in Table 4.

3.2.1 Thermal Conductivity

The results of thermal conductivity obtained from this research have been shown with the help of the graph in Fig. 4. The thermal conductivity of the inner and outer layers

Table 4 Results of thermal properties of multi-layered fabrics in the dry state

Parameters	Inner layer	Fabric I (ITB)			Fabric II (IHB)			Outer layer
GSM	150	350	400	450	350	400	450	80
Thermal conductivity (λ)	0.042	44.98	45.29	46.26	51.46	52.19	53.69	12.53
Thermal diffusivity (a)	0.2	3.29	4.92	5.04	1.25	1.74	1.83	–
Thermal absorptivity (b)	97.85	20.13	20.84	24.71	36.05	43.23	45.59	–
Thermal resistance(R)	0.017	389.93	436.37	475.47	306.61	353.82	374.78	7.7
Thickness (h) in mm	0.70	17.32	19.56	21.96	15.30	17.79	19.96	0.096
q max. (qm)	493.96	261.73	219.69	169.71	279.25	224.53	173.31	1067.43

will remain the same but varies with the middle layers. The multilayer fabric with hollow polyester wadding (Fabric II) as a middle layer shows higher thermal conductivity than the fabric with Thermolite® fiber waddings (Fabric I). From Table 5, there is a statistically significant difference ($p<0.05$) between the results of these two fabrics at all three GSMs of 350, 400, and 450 (i.e. 51,52,53>44,45,46). It may be because of the lower thickness, bulkiness, and porosity of hollow polyester wadding with respect to Thermolite® fiber wadding [5, 21]. Also by comparing with Eq. 3, it can be seen that the thermal conductivity is directly proportional to heat flux. So, Fabric II is showing higher thermal conductivity because of the higher value of heat flux with respect to fabric I.

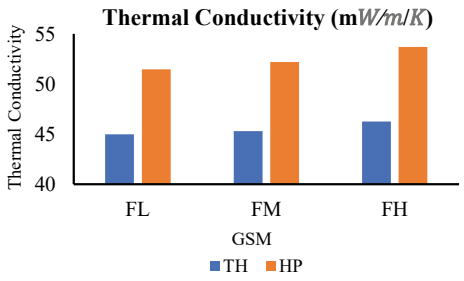


Fig. 4 Thermal conductivity of TH/HP

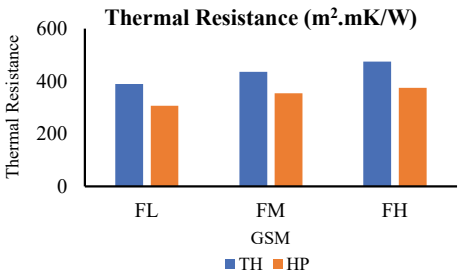


Fig. 5 Thermal resistance of TH/HP

3.2.2 Thermal Resistance

The results of thermal resistance obtained from this research have been shown with the help of the graph in Fig. 5. The thermal resistance of multilayer fabric with Thermolite® fibers waddings (Fabric I) shows the highest thermal resistance value with respect to multilayer fabric with hollow polyester wadding as a middle layer (Fabric II). From Table 5, there is a statistically significant difference ($p<0.05$) in the thermal resistance of both the fabrics at all three GSM of 350, 400, and, 450. As thermal resistance is directly related to thickness and porosity, Fabric I shows higher thermal resistance because of its higher thickness and higher porosity than fabric II at all three GSMs of 350, 400, and 450 [5, 21]. Thermolite® fibers contain air pockets because they are constructed of a blend of hollow-core and polyester fibers. These air pockets function as insulators, slowing the passage of heat across the fibers and increasing thermal resistance because air is a poor conductor of heat. Also, by comparing the relation of thermal resistance with thermal conductivity and thickness, the thermal resistance of fabrics has been increased with thickness and decreased with conductivity as per Eq. 6.

3.2.3 Thermal Diffusivity

It shows the movement of heat in fabric structure through the air [9, 21]. The results of thermal diffusivity obtained from this research work have been shown in Fig. 6 with the help of a graph. Multi-layered fabric with a hollow polyester web (fabric II) shows lower thermal diffusivity than fabric with a Thermolite® fiber web (Fabric I). Also, from Table 5, it is proved that there is a statistically significant difference ($p<0.05$) in the thermal diffusion of both fabrics at all three GSMs of 350, 400, and 450. This may be because of porosity, thickness, and bulkiness of the Thermolite® fiber web is more than the hollow polyester web along with that it has less pore size with a greater number of pores helping to entrap a large amount of air which acts as an insulator to the heat transferred from the body [22]. The high thermal diffusivity of thermal insulating materials allows heat to move rapidly toward the air pocket where it can be trapped and prevented from moving further due to the insulation property of air. By comparing with Eq. 4, it can be seen that the thermal diffusivity is

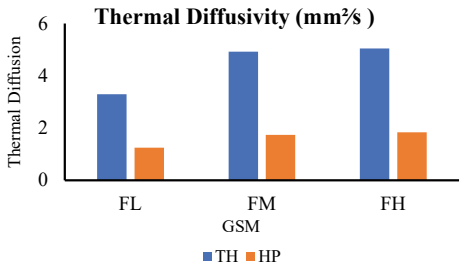


Fig. 6 Thermal diffusion of TH/HP

directly proportional to thermal conductivity but Fabric I is showing higher thermal diffusivity and Lower thermal conductivity because of its higher thickness and lower specific heat with respect to fabric II [23].

3.2.4 Thermal Absorptivity

This is a thermal property that shows the characteristics of the fabric when it comes in contact with the skin. It is directly related to the density, thermal conductivity, and specific heat of fabric. If the thermal absorptivity of fabric is more it means a cooler sensation will be there when the fabric comes in contact with the skin [5, 20]. The result of thermal absorptivity obtained from this research work is shown in Fig. 7. A multilayer fabric with a Hollow polyester web (Fabric II) shows higher thermal absorptivity as compared to a Thermolite® fiber web (Fabric I) at all the GSMs of 350, 400, and 450. From Table 5, it can be seen that there is a statistically significant difference ($p<0.05$) in the result of the thermal absorptivity of both fabrics. This may be because of the smoothness of hollow polyester fibers which increases the contact area with skin and which transfers the heat faster and sense cooler. On other hand, Thermolite® fibers are a blend of polyester and hollow-core fibers and are designed as highly reflective because of their hollow-core construction and reflective coating, Thermolite® fibers are particularly successful at lowering thermal absorptivity and minimizing heat movement through Fabric [24].

Table 5 Results of ANOVA with respect to p values

	Thermal conductivity			Thermal resistance			Thermal diffusivity			Thermal absorptivity			Q max		
	GSM			GSM			GSM			GSM			GSM		
	350	400	450	350	400	450	350	400	450	350	400	450	350	400	450
Between fabrics (p values)	1.8E-5	6.15E-10	4.47E-09	2.88E-13	1.17E-10	4.34E-10	7.901E-11	4.6 E-7	5.29E-08	3.30E-10	3.6E-11	1.08E-08	0.014807	0.0009	9.84E-5

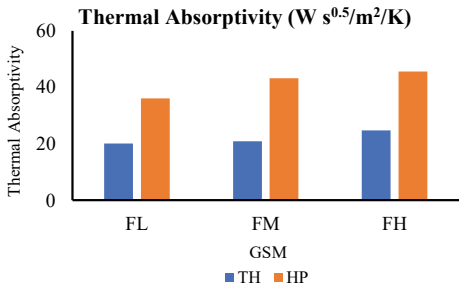


Fig. 7 Thermal absorptivity of TH/HP

4 Conclusion

Through metabolic processes, the human body generates heat constantly. Humans generate metabolic heat at a rate between 40 and 440 W/m^2 depending on the nature of their activities. The thermal insulation that is provided to the person wearing the severe cold weather apparel ensemble comes from the employment of high-bulk nonwovens that are arranged in the form of layers. In order for the wearer to keep their body heat, the clothes must prevent the chilly air from the surrounding atmosphere. Putting on multiple layers of textiles that are designed to be worn as garments consists of three layers, with every layer performing a unique function and contributing to the overall goal of achieving thermal balance. Therefore in this research work, two different types of multi-layered fabrics have been studied with the same inner and outer layer and varying middle layers. Two different fibers Thermolite® and Hollow polyester used because both are hollow and very fine, which helps to entrap large amounts of air and give better thermal insulation. The hollowness percentage in the cross-section of fibers is measured by Scanning electron microscope (SEM) analysis. The hollowness percentage of hollow polyester is higher which may be because of the coarseness of fiber but Thermolite® fiber will entrap a large amount of air as it is finer and provides a large surface area provided by a greater number of fibers per unit volume with respect to hollow polyester fiber. The waddings of these two fibers are used as the middle layer in fabrics. Among these two fabrics, the fabric with a Thermolite® fiber web as a middle layer gives higher thermal insulation and thermal diffusivity than the other one (389,436,475 > 306,353,374) and (3.29,4.92,5.04>1.25,1.74,1.83) at all three GSMs of 350,400 and 450. This is because of the higher porosity and thickness of the Thermolite® fiber web as compared to the hollow polyester fiber web. Whereas fabric with the hollow polyester web as the middle layer gives higher thermal conductivity (51,52,53>44,45,46) and thermal absorptivity (20.13,20.84,24.71>36.05,43.23,45.59) at all the GSMs of 350,400 and 450. So from this study, it can be concluded that the nonwoven web of fibers with higher porosity, thickness, and bulkiness gives better thermal insulation.

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Advanced Outer Shell Fabric for Bulletproof Jacket



Amar Srivastava, Biswa Ranjan Das, Subhankar Maity, Manoj Kumar Singh, Deepak Kumar Yadav, Ashok Kumar Yadav, and Mayank Dwivedi

Abstract In this study, various types of advanced-grade Polyester fabrics in digital camouflage and disruptive print were explored to find the most suitable one as the outer shell fabric (OSF) for bulletproof jacket (BPJ). These fabrics were developed in two different weave designs (rip stop and plain) with varying the areal densities (200 g/m^2, 232 g/m^2 and 253 g/m^2) and were also coated with thermoplastic-grade polyurethane (TPU). The results of the study showed that the Polyester fabric with an areal density of 232 g/m^2 was among the most suitable material for the OSF, based on the mechanical properties. However the other functional features are comparable with the two other fabrics (200 g/m^2 and 253 g/m^2). This fabric displayed improved durability in terms of superior mechanical properties; breaking, tear and bursting strength and excellent abrasion resistance (insignificant weight loss and no fibre damage) compared to the existing version OSF of IS: 17,051 and GSQR 1438. The colour characterization (x, y and z and ΔE) of the print pattern of the selected Polyester OSF is carried out for the assessment of extent of variation from the digital camouflage pattern.

Keywords Bulletproof · Camouflage · Defence · Fabric · Outer shell · Shelf-life

1 Introduction

Bulletproof jacket (BPJ) is considered as an important protective clothing that protects the wearer from various attacks and hazardous situations and is made up of different components i.e. soft armour panel (SAP), hard armour panel (HAP) and

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outer shell fabric (OSF). The OSF fabric is exposed to various harsh environmental conditions, such as rain, fire, and UV rays, and provides pockets for holding the SAP and HAP. They also help to safeguard the vital body organs (lungs, heart, liver, kidneys and backbone) from the physical trauma caused by the high bullet velocity [6, 7]. The function of the ballistic vest is to absorb the impact energy of the bullet and redistribute it across various fabric layers through stretching, breaking the material, and obstructing the bullet [6, 7]. The mechanism for absorption of energy depends on the fabric density, fabric structure, yarn material, velocity of the bullet and its impact angle [6, 7].

In earlier times, ceramic plates and heavy weight metals were used in bulletproof jackets for protection. However, with technological advancements, fibre-reinforced composites made of high strength/modulus fibres like ultra-high molecular weight polyethylene (Spectra, Dyneema) [3], Technora, Twaron etc. have been used [11]. The outer shell fabric is a prime component of the BPJ and needs to have specific characteristics including high mechanical strength such as breaking strength, tear strength, resistance to flexing and bursting strength to resist the impact of the bullets and chemical properties such as waterproofing, wind proofing, colour fastness to washing and light etc. to meet the essential requirement. The OSFs were generally coated with polyurethane (PU) -to achieve durability, stiffness, tensile and tear strength, and high abrasion resistance. Its chemical structure involves the reaction between di/poly isocyanate and a diol or polyol, forming repetitive urethane linkages [5].

This research focuses on exploring indigenous technology to develop advanced outer shell fabrics based on the Indian Army camouflage pattern. The existing version of Nylon 6,6 fabric meets the functional requirements but severe snagging issues were observed in the existing fabric. In this paper, three different varieties of high tenacity Polyester fabrics with areal density (200 g/m^2, 232 g/m^2 and 253 g/m^2) were used to find the most suitable one for use as OSF for bulletproof jackets matching the functional requirements (mechanical and chemical properties) as per the standard IS 17051:2018 (BIS Standard IS 17051 BPJ 2018 Specifications for Bulletproof Jacket.) Though, Nylon 6, 6 based OSF offers higher functional features but is a non-indigenous source for Indian defence. So, exploration of Polyester fabrics has been made as it being a popular, cost effective and indigenous material source to meet the demand of the growing defence forces. Moreover, the existing version of fabric had huge issues in snagging that causes the panels (HAP &SAP) of the BPJ to dislocate causing severe threats to the soldiers. High tenacity polyester fabric (7.0 gpd) with comparatively higher areal density (232 g/m^2) could be used due to their lower snagging tendency as areal density is an important factor responsible for snagging along with the cost effectiveness and and higher functional properties required for the intended application as OSF for BPJ. Moreover, efforts were made to develop a digital camouflage pattern similar to that approved by the Indian Army [1].

2 Experimental

2.1 Materials

High tenacity Polyester woven fabrics were developed in different areal densities (200 g/m^2, 232 g/m^2 and 253 g/m^2) in plain and ripstop weave construction [8]. Specialized aliphatic grade thermoplastic polyurethane (TPU) was used for coating. Disperse dye was used for dyeing and printing (camouflage designs) using pigment dispersions and thickeners in a Transfer printing machine.

2.2 Method

The woven fabric was prepared by using two sets of yarns, the warp and weft yarns in a sectional warping machine. These were prepared in three different areal densities (200 g/m^2, 232 g/m^2 and 253 g/m^2) and weave construction (ripstop and plain) [2]. The fabrics were scoured, acid washed and further dyed with khaki colour using disperse dye. They were coated with a specialized grade of 12% thermoplastic polyurethane (TPU) coating and camouflage designs (disruptive and digital) were printed with a transfer printing machine on polyester fabric (Fig. 1). The printed fabric was cured in the pressure ager and then washed with hot water at 75 °C. The mechanical properties of three camouflaged printed OSF are shown in Table 1



Fig. 1 Different varieties of Coated Polyester fabrics (left to right). **a** Polyester (200 g/m^2), **b** Polyester (232 g/m^2), **c** Polyester (253 g/m^2)

Table 1 Fabric sample plan

S No	Material parameter	Sample 1	Sample 2	Sample 3
01	Mass of finished fabric (g/m^2)	200	232	253
02	Nature of material	Polyester	Polyester	Polyester
03	Width (cm)	180.0	180.0	180.0
04	Nature of Yarn	Multifilament	Multifilament	Multifilament
05	Weave design	Ripstop	Plain	Plain
06	Denier of yarn 'g' Warp and Weft	334 and 381	591 and 609	750 and 676
07	Ends/dm and Picks/dm	214 and 162	185 and 126	162 and 130
08	Tenacity (gpd)	6.0	7.0	6.5

2.3 Evaluation of Functional Features of PU Coated Polyester Fabric

The standard test methods were employed to assess various physical properties of the fabrics. The mass of coated fabrics (g/m^2) was determined in accordance with IS: 7016 Pt-I standards.

Breaking strength (kgf) and tear strength (kgf) of the coated fabrics were measured using an Instron Tensile Tester, following the test standards IS: 7016 Pt-II and IS:7016 Pt-III. The bursting strength of coated fabrics was tested with a Diaphragm Bursting Strength Tester, adhering to the ASTM D 3786 M-18 standard. Waterproofness (water pressure of 30 cm for 30 minutes) of the coated fabrics was assessed using IS: 7016 Pt-VII standard. Colorfastness to washing and light for these coated fabrics was measured following IS: 687 and IS: 2454 standards, respectively.

3 Results and Discussion

3.1 Assessment of Physical Properties

Different physical properties of the coated fabrics such as mass (g/m^2), breaking strength (kgf), tear strength, bursting strength, water proofness, abrasion resistance, colour fastness to washing and light were evaluated according to the standard test method as shown in Table 2. It is observed from Table 2 that the coated Polyester fabric with areal density 232 g/m^2 displayed the most advanced functional features (mechanical and chemical properties) in comparison to the other two polyester fabrics. However, coated Polyester fabric denoted by sample 1 (200 g/m^2) did not give the required mechanical properties in terms of breaking strength (warp 105.3 kgf and 82.3 kgf) against the minimum requirement of breaking strength (warp 115 kgf and 95 kgf) as per IS:17051. Moreover, the Polyester fabric denoted by sample 3

Table 2 Comparative analysis of the functional features of three varieties of PU coated Polyester fabrics and existing Nylon 6,6 fabric (IS:17,051:2018)

Sl. No	Material parameter		Sample 1	Sample 2	Sample 3	Existing OSF (IS:17,051)
01	Mass of finished fabric (g/m^2)		200	232	253	160
02	Breaking strength (kgf) Warp and Weft		105.3 and 82.3	173.6 and 149.7	135.7 and 96.7	115 and 95
03	Tear strength (kgf) Warp and Weft		23 and 18.5	32 and 30	28.5 and 24	16 and 14
04	Bursting strength (kgf /cm^2)		14	29	26	–
05	Colour fastness to washing		4	4	4	4
06	Colour fastness to light		5	6	5	5
07	Waterproofness (30 cm water head pressure for 30 min)	Leakage (ml)	Nil	Nil	Nil	Nil
		Wetting of the outer surface	No wetting	No wetting	Few drops adhered at outer surface	No wetting

(253 g/m^2) failed in the waterproofness test as few drops adhered at outer surface due to lower concentration of PU coating substrate. As the coated Polyester (232 g/m^2) fabric turned out to be the most suitable one in terms of all the functional features, hence further exploration of other functional features is carried out for this specific fabric only.

3.2 Assessment of Abrasion Resistance

The abrasion resistance test done was at Martindale Abrasion tester at 12KPa pressure and for 6000 abrasion cycles. The HT-coated polyester fabric (232 g/m^2) showed insignificant weight loss and did not display any damage to its surface fibres. This demonstrates that the fabric exhibits excellent resistance to abrasion suitable for OSF.

3.3 Assessment of Hydrophobicity

A higher water contact angle of 103.70° and 93.10° (front and back side) was observed (as shown in Fig. 2) in the case of TPU coated Polyester fabric (232 g/m^2). It represents good hydrophobicity and is due to uniform coating with specialized grade TPU which is favourable for advanced outer shell fabric of BPJ.

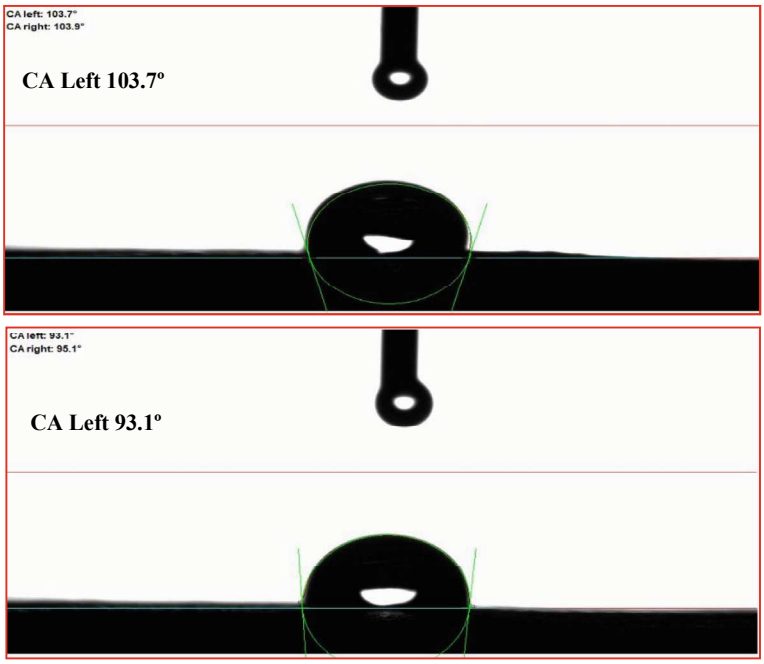


Fig. 2 Water contact angle of TPU coated Polyester fabric, **a** front side, **b** back side

3.4 TGA Profile of the PU Coated HT Polyester Fabric

The thermal stability of high tenacity (HT) polyester fabric (232 g/m^2) was evaluated and it was observed that weight loss due to degradation starts majorly at around 350 °C (as shown in Fig. 3). As the coated fabric has to be used as OSF, where the material would be subjected to a much lower temperature (200 °C) compared to the degradation temperature of the fabric, hence could be used as the OSF for BPJ.

3.5 Analysis of Colour Characteristics

The selected OSF fabric was printed in a digital camouflage pattern by following the standard digital print sample. It was done by finding the Pantone number of each colour (black, brown, green and khaki) from the standard digital printed sample and efforts were made to replicate these four print colours in the developed digital printed polyester fabric. The colour characteristics (x, y, z and ΔE) values of the selected OSF (sample 2) were analysed for observation of the colour difference and compared against the standard digital camouflage pattern [9]. Efforts were made to develop a digital print pattern like that of the digital camouflage pattern of the Indian Army

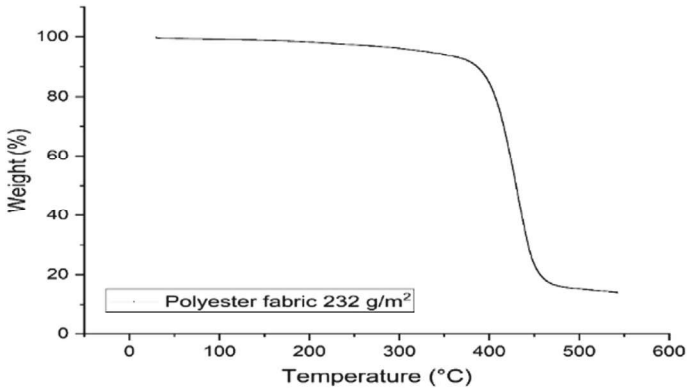


Fig. 3 TGA profile of PU coated HT Polyester fabric (232 g/m^2)

Table 3 Comparison of colour characteristics with Standard Digital Camouflage Pattern

S. no	Sample	X	Y	Z	ΔE
1	Std digital black	7.53	7.94	8.71	1.62
	Polyester black	7.69	7.91	9.12	
2	Std digital brown	10.13	10.04	9.19	2.65
	Polyester brown	13.72	13.35	12.12	
3	Std digital green	9.59	10.46	10.12	7.74
	Polyester green	9.86	10.51	10.58	
4	Std digital Khaki	16.46	16.65	14.78	3.29
	Polyester Khaki	26.51	27.43	23.96	

and the comparative analysis was done as shown in Table 3. Although the colour difference (ΔE) for coated black, brown and green colour values were comparable with the standard digital camouflage pattern, yet the khaki colour pattern needs further improvement [10].

4 Conclusion

The objective of this study was to explore three different grade high tenacity polyester fabrics finished with thermoplastic polyurethane (TPU) coating. High tenacity polyester fabric with areal density 232 g/m^2 was found to be most suitable material among all three fabric samples for its use as outer shell fabric of BPJ. It meets the required benchmark as per IS:17051 with enhanced mechanical properties in terms of breaking, tear and bursting strength. Moreover, improvement in light fastness and wash fastness was obtained in this case as compared from the

existing fabric version (IS:17051 and GSQR 1438) of the Indian Army. Furthermore, the developed fabric also demonstrated higher water contact angle (103.7°) that shows good hydrophobic behaviour of the fabric. Excellent abrasion resistance with no surface fibre damage and insignificant weight loss on the abraded surface was observed in the developed outer carrier fabric. The efforts were made to print the selected polyester OSF in a digital camouflage pattern and it was concluded that the three colour values (black, brown and green) were comparable with the standard digital camouflage pattern which could be depicted from the colour difference (ΔE) values, though khaki colour print still requires further improvement. This study demonstrates that high tenacity TPU coated polyester fabric (tenacity-7.0 gpd) could be used at a higher areal density (232 g/m^2) against Nylon 6,6 fabric (160 g/m^2) as it results in advanced functional properties (tensile, tear and bursting strength) against the existing fabric with reference to the standard IS:17051 and GSQR 1438.

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Development of Polymer Composites Using Recycled Polymer Waste of Textile Industry: A Review



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Abstract The use of synthetic fibre has increased exponentially in the textile industry to fabricate textile products. The most common method of synthesis the man-made fibre is melting the thermoplastic polymer followed by drawing and winding. The generation of enormous amounts of waste during the processing of the fibre formation and the end life of the fibre-reinforced polymer composites is a major issue which causes environmental impact. Therefore, it is essential to identify the potential application of waste fibre generated during the composite material development process and the end life of the composite recycling through mechanical and chemical processes. A significant improvement is observed in polymer composites by using this short and continuous waste and recycled fibre. This study presents an extensive review on the work done by various researchers to utilise waste textile fibre to develop composite material for numerous applications.

Keywords Man-made fibre · Reinforcement · Composites · Textile waste · Polymer

1 Introduction

The construction, automotive, and aerospace industries have widely adopted man-made fibres, particularly glass fibre-reinforced polymer (GFRP) composites, due to their exceptional strength-to-weight ratio, corrosion resistance, and capacity for customisation or targeted application development [1–3], (Chin 1996). The GFRP

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pultrusion industry in Europe produces various waste products, which are often challenging to recycle due to their composition and properties. Therefore, these waste materials, such as scrap pieces, trimming residues, and end-of-life products, are typically sent to landfills. This disposal method can lead to environmental pollution and resource depletion, as landfills rapidly fill up and significantly threaten public health and the ecosystem. Consequently, the GFRP pultrusion industry should focus on developing sustainable waste management strategies, such as reducing waste generation, promoting recycling and reuse, and exploring alternative disposal methods, on minimising their impact on the environment and society. These unsustainable practices are primarily caused by many constituent materials (such as glass fibres, organic matrix, and various kinds of inorganic fillers) and the cross-linked properties of thermoset resins, which make remoulding a nonviable process option [4, 5].

The three primary recycling procedures can be utilised to extract value from fibre-reinforced polymer (FRP) thermostable materials, according to published scientific literatures: (a) partial incineration, energy recovery from the heat produced during the combustion of the organic component; (b) thermal and/or chemical recycling, such as solvolysis, pyrolysis, and similar thermal decomposition processes, with a partial recovery of reinforcing fibres; and (c) mechanical recycling, which involves the breakdown of the composite by shredding, milling, comminution, or other similar mechanical processes, resulting in size reduction to fibrous and/or powdered products that can be reincorporated in the polymer matrix [6]. Comparing mechanical recycling to the other suggested recycling procedures, considerable economic and environmental benefits exist. Mechanical size reduction does not result in water pollution from chemical solvent effluents or atmospheric pollution from petrol emissions, nor does it necessitate the use of sophisticated and presumably expensive equipment like those used by the other procedures (Bartholomew 2004).

Three types of polymer are used in textile industry for the fabrication of yarn.

Natural Polymer: Polymers that are present in naturally occurring sources such as plants and animals are referred to as natural polymers. Examples include the starch and cellulose found in vegetables, the protein found in animals, and the latex found in plants.

Synthetic Polymer: Synthetic polymers are made artificially in laboratories from lower molecular weight compounds. The industries generate them on a commercial basis in response to market demand. Synthetic polymers such as nylon, polyester, PVC, and polyethylene are often created and used in daily life.

Semi-synthetic Polymer: Polymers created by altering naturally occurring polymers. Certain polymers, such as vulcanised rubber, treated with sulphur to create cross-links between the polymers, are also significant commercially. Another illustration of a semi-synthetic polymer is cellulose acetate. Cellulose acetate is a cellulose derivative that is created when naturally occurring cellulose polymers are acetylated [7].

Over the past few decades, there has been a significant increase in the global population, and during the same time, overall living conditions have improved. The consumption of textiles has expanded as a result of these two advancements, leading to an increase in textile output. Over 110 million tons of textile fibres and clothing are

produced worldwide each year, which results in a significant amount of textile waste being produced. Using a circular economy model is crucial to ensuring sustainability and minimising environmental impacts in the textile and clothing industry. A circular model can not be implemented without the recycling of textile waste. The management of textile waste is generally evaluated in this study with an eye on sustainability and reducing environmental effects (Burçin et al. 2020).

Production of clothing and textiles plays a significant part in this worldwide phenomenon. 1.2 billion tons of CO_2 equivalent of greenhouse gas (GHG) were released in 2015 as a result of textile production-related greenhouse gas (GHG) emissions. This amount is higher than the combined emissions from all international travel and maritime shipping, two essential modes of transportation. Long-distance sea transportation is required to transfer finished goods made in developing nations to stores in rich nations, which raises the overall amount of non-renewable fuel consumed (Choudhary 2014). In the event that the sector's actual trends remain unchanged, the textile industry will account for 26% of the carbon budget and 300 million tons of crude oil by 2050—a substantial increase from 2% and 98 million tons, respectively, in 2015 (Ellen 2017). The textile sector uses a lot of energy, yet it is not very efficient. While the spinning and weaving parts of the production largely use electrical power, the chemical processing leg of the production uses thermal energy to heat water and dry fabrics [8]. It is estimated that around one trillion kilowatt hours of electricity are needed annually to create 60 billion kg of textiles worldwide. In addition, the production of textiles releases volatile organic compounds (VOCs), NOx and SOx emissions, and solvents during coatings drying or cleaning procedures [9].

Another significant issue is the waste produced during the production and consumption of textiles. Global textile usage is estimated to reach more than 100 million tons [10]. Nonetheless, recycling rates are not very high: After use, just 13% of the total material intake gets recycled in any way. Less than 1% of this 13% recycled material is used to make new clothes. The remainder is recycled into lower-value products like mattress stuffing, cleaning cloths, and insulating material (Ellen 2017).

In the case of waste, polymeric fibre obtained during yarn and fabric formation can be used directly as reinforcement in a polymeric matrix. No further process is required to use the waste fibre or yarn as reinforcement. The end use of the composites depends upon the characteristics of the waste fibre and the recycled fibre. The composite fabricated using waste textile or recycled fibre can be used for structural and automotive applications. The application area of waste/recycled textiles is presented in Fig. 7.1.

In this study an extensive review of the work done by various researchers to utilise waste textile fibre as well as recycled fibre from composite scrap to develop composite materials for numerous applications.

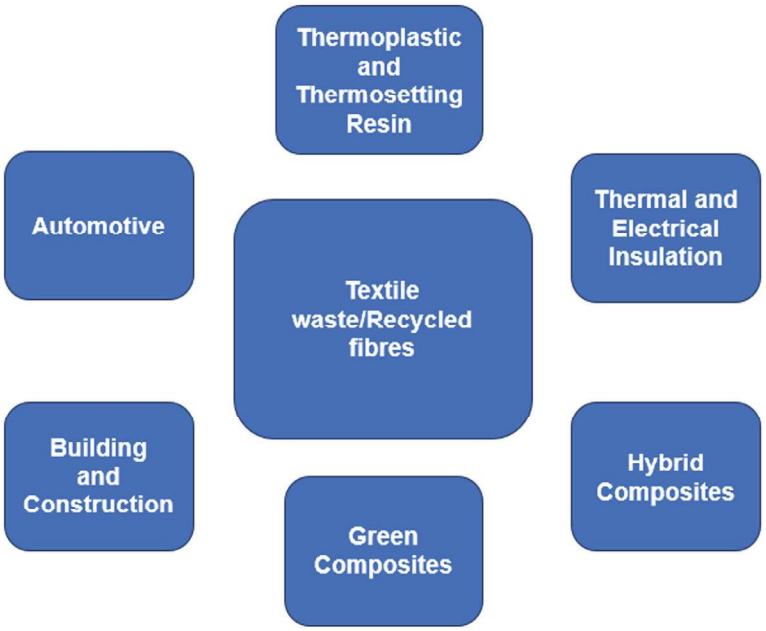


Fig. 7.1 Application and use of textile waste

2 Extraction of Synthetic Fibre from Polymeric Composites

The process of removing the reinforcing fibres from the polymer matrix in composite materials is known as fibre extraction from polymeric composites. This operation is usually carried out when the composite material reaches the end of its useful life or when recycling is necessary. Reusing the removed fibres in new composite materials reduces waste and conserves resources [11]. The general procedures for removing fibres from polymeric composites are as follows:

2.1 Collection and Preparation

Gather the composite materials that require processing first. Composite panels, FRP pipelines, and other components are examples of items made from these materials.

If required, eliminate any impurities or non-fibre elements from the composite, including coatings, adhesives, and other substances [12].

2.2 Mechanical Separation

Mechanical separation, which requires disassembling the composite into its constituent parts, is a popular technique for extracting fibres. Grinding, crushing, and milling are a few of the techniques that can be used to produce mechanical separation. By physically shattering the polymer matrix, these techniques liberate the fibres [13].

2.3 Chemical Separation

Chemical procedures that dissolve or weaken the polymer matrix can be used to make it easier to extract fibres from polymeric composites. This is especially helpful when a cleaner fibre separation is sought or when mechanical separation is ineffective on its own. In order to facilitate fibre extraction, polymeric composites can be chemically treated using the following typical methods:

Chemical Solvents: The composite is treated with particular solvents that have the ability to dissolve or soften the polymer matrix. The type of polymer employed in the composite determines the solvent to be utilised. For certain thermoplastic composites, for instance, acetone, methylene chloride, or toluene can be utilised. It is simpler to separate the fibres when the solvent dissolves or softens the polymer.

Chemical Degradation: The polymer matrix can be chemically broken down using chemicals or chemical methods. This may entail reactions that weaken the chemical bonds of the polymer and weaken its structural integrity. For some polymers, for instance, alkaline or acid hydrolysis can be employed. But not all composites can be treated with this technique, and caution needs to be used to avoid damaging the fibres.

Thermal Decomposition: In some circumstances, the polymer matrix can be weakened using heat breakdown or pyrolysis. The polymer breaks down at high temperatures, making it possible to mechanically remove the fibres from the weakened matrix. Composites that exhibit stability at high temperatures are more suited for this technique.

Enzymatic Treatment: Enzymes are catalysts generated from biological processes that can be utilised to degrade particular polymers in a composite. Though less popular, this technique provides an eco-friendlier way to break down polymers.

Supercritical Fluids: Supercritical carbon dioxide and other supercritical fluids can be used to remove polymers from composite materials. These fluids' special qualities enable them to dissolve or swell polymers with ease.

The chemical process selection is influenced by the kind of composite, the polymer matrix composition, and the necessary quality level for the extracted fibres. To minimise any negative impacts, these chemical processes have safety and environmental concerns that need to be carefully evaluated. Additionally, post-treatment steps may be necessary to eliminate any leftover chemicals before the extracted

fibres are repurposed [14, 15] (Mariana and Silvia 2012; Mallic 1997; Hull et al. 1996; Callister 2003).

2.4 Separation of Fibres

Mechanical techniques, including sifting or air classification, can be used to separate the fibres from the remaining polymer matrix after the composite has been broken down or processed.

Sometimes additional cleaning or processing is required to get rid of any impurities or polymer residues that may still be present in the fibres [16].

2.5 Collection and Reuse

The quality and qualities of the extracted fibres may be evaluated to make sure they match the necessary standards for reuse.

The extracted fibres are collected and can be utilised again in the creation of new composite materials or other goods (Muller 2016).

2.6 Disposal of Residues

Get rid of any pollutants or extraction-related wastes in an ecologically friendly way, such as the polymer matrix.

It's crucial to remember that different fibre extraction methods and procedures may be used based on the kind of composite material, the composition of the polymer matrix, and the intended application of the extracted fibres. Fibres from polymeric composites can be recycled and repurposed to help cut waste and promote sustainability in a number of industries, including construction, automotive, and aerospace [17] (Muller 2015).

2.7 Composites from Waste Synthetic Textile Fibre

In terms of mechanical performance, synthetic fibres outperform cellulosic fibres and exhibit less product quality variation. Synthetic fibres also benefit from greater thermal stability, which enables higher processing temperatures. In contrast, when exposed to high temperatures, cellulosic natural fibres exhibit a significant loss of mechanical capabilities [18]. The strength and modulus often increase when fibres are introduced to polymers, while elongation significantly decreases. Although a

decline in strength is observed at high fibre concentrations, the composite characteristics continue to follow these trends with increasing fibre content [19, 20]. Synthetic fibres are frequently employed as a reinforcement ingredient in polypropylene (PP) based composites due to their good balance between cost and properties. However, the stability and strength of the polymer-fibre interphase play a crucial role in determining their final qualities. Poor adhesion can render fibres ineffective as a reinforcing material. Moreover, harsh environmental conditions, such as high temperatures, excessive wetness, and stress fields, can readily compromise the adhesion between phases [21].

Glass fibres (Gf) are the most common reinforcement for polymeric matrix composites. They offer several advantages, including low cost, high tensile strength, excellent chemical resistance, and insulating qualities. However, they also have some disadvantages, such as low tensile modulus, relatively high specific gravity, sensitivity to handling abrasion, low fatigue resistance, and high hardness.

E-glass and S-glass fibres are the most frequently utilised fibres in the fibre-reinforced plastic industry. E-glass fibre is the most affordable of all commercially available reinforcing Gfs and is widely used in the industry. S-glass, which was initially developed for missile casings and aviation parts, has the highest tensile strength of any currently used fibres. However, its increased manufacturing cost and different composition make it more expensive than natural fibre composites (Swift and Willes 2004) [22–24]. Various application products made from textile waste are presented in Table 1.

Table 1 Recent research studies based on the incorporation of waste and recycled fibres in the polymer matrices for a large range of applications

Matrices	Fillers	Source	Applications	References
Polyurethane foam	Polyamide, polyacril and modal	Textile waste from knitted clothing	Materials to reduce noise pollution levels	[28]
Two component epoxy adhesive	Polyamide microfibres	Waste from tyre industries	Waste disposal problems	[29]
Chitosan	Miscanthus fibres/ recycled textile fibre	Recycled second-hand jean	Non-flammable and insulating building materials	[30]
Epoxy resin	Polyamide fibres and rubber particles	Process of tyre recyclation	Tyres Industries	[31]
Recycled polyester Low melting point polyester	Carbon, basalt, and aramid plain woven fabrics	High Strength polyester selvages	Protective clothing field and geotextiles field	[32]
Cement–clay admixture	Polypropylene fibres	Waste bags	Compacted pavement base/ subbases	[33]
Portland cement	Polypropylene fibres	Waste carpet fibres	Concrete composite exposed to corrosive ambient	(Lazar et al. 2023)

The production and utilisation of polymers have become a widespread phenomenon over the past six decades, resulting in the generation of enormous amounts of polymer waste. Most polymers utilised are non-biodegradable, which poses a significant environmental threat. These non-biodegradable polymers can persist in the ecosystem for hundreds or even thousands of years, causing long-lasting environmental damage. This has led to a growing concern about the accumulation of polymer waste and its impact on the environment. Therefore, innovative approaches must be developed to address the issue of polymer waste and promote the use of more eco-friendly alternatives. This may include implementing recycling and upcycling practices, developing biodegradable polymers, and exploring sustainable materials that can replace non-biodegradable polymers. Such actions can help to minimise the accumulation of polymer waste and promote a more sustainable and eco-friendly future.

Recycling is considered the most favourable approach among other alternatives. By utilising recycling polymers, both reinforcement and matrix materials can be produced. Various methods can be employed to convert polymer composites into fibres or particles suitable for use in the polymer matrix. Mechanical milling is one of the simplest and most commonly used methods for crushing and producing reinforcement from waste polymer composites, as reported in literature (Fazli and Rodrigure 2022) [25–27]. Figure 7.2 illustrates the fibre recycling process from GFRP composites.

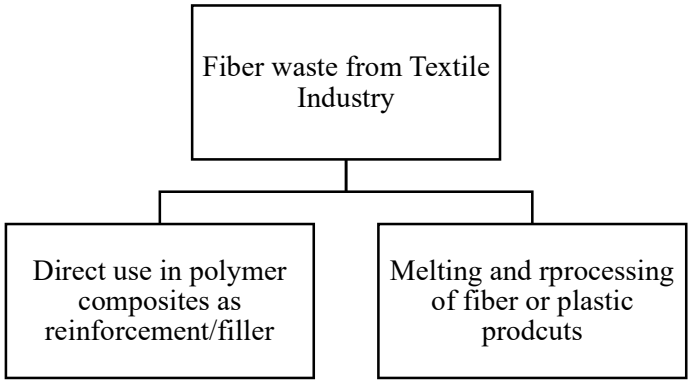


Fig. 7.2 Flow chart of recycled synthetic fibre and plastic materials

3 Manufacturing Methods of Polymer Composites

3.1 Open Moulding Process

Generally, hand layup and spray up techniques are frequently used for the fabrication of the polymer composites due to the simplicity of the process and capability to fabricate large size components or products. In spray up technique the resin mixed with chopped glass is sprayed over the mould of the product to fabricate the composite parts. In the case of sandwich composite, core material may be used in between the laminate layers. However, Glass fibre volume is typically 15 wt. % when sprayed on and 25 wt. % when laid by hand.

3.2 Resin Infusion Processes

The industry is under pressure to replace manual layup with alternative fabrication procedures due to the ever-increasing demand for quicker production rates. Additionally, fabricators are being encouraged to automate these operations whenever possible.

Resin transfer moulding (RTM), often known as liquid moulding, is a popular substitute. The RTM method is quite straightforward. It starts with a matching, closed, two-part mould composed of composite or metal. RTM manufactures components of superior quality without the need for an autoclave. A part intended for a high-temperature use, however, normally goes through post-cure after being cured and demoulded. High-pressure RTM (HP-RTM), a more recent RTM variation, is attracting interest due to its potential for producing automobile parts rapidly. High production potential is shown by HP-RTM's capacity to quickly fill a mould filled with a preform using a resin that cures quickly. This technology is typically integrated into fully automated systems with mould shuttles. The HP-RTM process still uses a closed mould, press, fibre preform, and resin injection system; however, the resin injection system is now an impingement mixing head, similar to the ones that were initially created in the 1960s for use in PU foam applications.

Reaction injection moulding (RIM) injects a fast-curing resin and a catalyst into the mould in two different streams, as opposed to RTM, which premixes the resin and catalyst before injecting them under pressure. Mixing and the ensuing chemical reaction occurs in the mould rather than in a dispensing head. Automotive industry suppliers have used fast preforming techniques and structural RIM (SRIM) to create structural parts that don't need a Class A finish. Achieving fibre quantities of up to 68% is feasible, and automated controls guarantee reduced voids and reliable preform reproduction without the need for trimming.

3.3 Vacuum-Assisted Resin Transfer Moulding (VARTM)

Refers to a group of associated procedures that make up the moulding technology that is expanding fastest. The primary distinction between RTM and VARTM-type procedures is that resin is pumped in under pressure, but in VARTM, a preform is merely sucked into by means of a vacuum. High heat or pressure is not necessary for VARTM. Because of this, VARTM uses inexpensive tooling, enabling the production of massive, complicated parts at a low cost in a single shot. In order to create a vacuum-tight seal, fibre-reinforcements are inserted into a one-sided mould and covered with a covering (usually plastic bagging film). Usually, the resin enters the structure through feed lines and ports that are positioned carefully—a process known as "manifolding." It is pulled through the reinforcements by vacuum through several channels built in to help with fibre wetout. The final product may have as much as 70% fibre. Applications today include infrastructural components, land transportation, and maritime.

3.4 Resin Film Infusion (RFI)

A dry preform is inserted into a mould either on top of a layer of high-viscosity resin film or between layers of the film using the hybrid RFI method. Even with high-viscosity, hardened resins, the resin liquefies and is pulled into the preform under applied heat, vacuum, and pressure. This short flow distance leads to a uniform resin distribution.

3.5 High-Volume Moulding Methods

Compression moulding

Compression moulding is a thermoset moulding technology with high-volume production that utilises metal dies that are costly but extremely robust. When production quantities exceed 10,000 pieces, it is a suitable option. Using sheet moulding compound (SMC), a composite sheet material created by sandwiching chopped fibre-glass between two layers of thick resin paste, up to 200,000 components can be produced on a set of forged steel dies. The resin paste is transferred onto a moving film carrier by a metering system to make the sheet. Glass fibres that have been chopped fall over the paste, and another film carrier covers the glass with another coating of resin. Rollers press down on the sheet to release trapped air and saturate the glass with resin. Initially, the resin paste has a consistency similar to molasses (20,000–40,000 cps); over the course of the following three to five days, its viscosity increases, and the sheet takes on the appearance of leather (approximately 25 million cps), making it perfect for handling.

Injection moulding

A quick, high-volume, low-pressure, closed process, injection moulding is most frequently used to fill thermoplastics, like nylon, with chopped glass fibre. But in the last 20 years, makers of metal casting and thermoplastics have lost part of their businesses to automated BMC injection moulding. For instance, the BMW Mini and Peugeot 207 engines were the first to use BMC-based electronic throttle control (ETC) valves (which were previously only moulded from die-cast aluminium). This was possible because TetraDUR GmbH, a division of Bulk Moulding Compounds Inc. (BMCI, West Chicago, IL, US), provided a specially formulated BMC that offered dimensional stability.

One example of the search being conducted by the automotive sector is hybrid injection moulding/thermoforming. With just two robots, the process can be easily automated. It saves 40–50% of the weight compared to a steel seat back and costs less than $5/kg more per kilogramme of weight saved. Even though the continuous CF/PA12 tapes offer customised strength and stiffness, half of the mass of the seat back is made of less expensive injection moulding material. With no extra operations, the one-shot technique creates a geometrically detailed part in around 90 seconds. A PA12-impregnated mat composed of recycled carbon fibre (RCF) served as the base layer of the organosheet preform, reducing part cost and carbon footprint in the process.

Filament winding

Continuous fabrication techniques like filament winding have comparatively cheap material prices and can be highly automated and reproducible. A mandrel is a long, cylindrical tool suspended horizontally between end supports. The fibre application instrument, or "head," rotates along the length of the mandrel and applies fibre in a predefined configuration to the tool. There are filament winding machines that are computer-controlled and have two to twelve axes of motion.

Pultrusion

Similar to RTM, pultrusion has been utilised for many years with polyester and glass fibre resins; however, throughout the past ten years, the technology has also been applied to sophisticated composites. The reinforcing fibre (often roving, tow, or continuous mat) is frequently dragged through a heated resin solution in this relatively easy, inexpensive, continuous process. As it goes through one or more forming guides or bushings, it is subsequently moulded into precise forms. After that, the material passes through a heated die, curing and taking on its net shape. After cooling, the resulting profile is trimmed to the appropriate length further downstream. Smooth finished pieces from pultrusion usually don't need postprocessing. Pultrusion produces a broad variety of continuous, reliable, solid, and hollow profiles; the procedure can be specially designed to meet the needs of certain applications [34].

4 Properties of Recycled Polymer Based Composites

4.1 Physical Properties

X-ray Diffraction pattern of recycle polyethylene has been performed in some studies [35, 36]. It was observed when the recycled polyethylene is used as reinforcement on polymer matrix composites the crystallinity of the matrix improves satisfactorily in the developed composite. The Fourier-transform infrared (FTIR) spectroscopy of recycled synthetic fibre viz., Polyethylene and Polypropylene reinforced epoxy-based composites shows that the FTIR plots imply some peak shifting for various bonds and no significant peak appears in the plot. This confirms that the bonding between the synthetic fibre and matrix is basically the mechanical bonding which ultimately improves the mechanical properties of the composite [11, 37–39], Kaya and Geri (2021).

4.2 Mechanical Properties

Fu et al. [40] investigated the mechanical characteristics of short recycle Kevlar fibre (KF)-reinforced PP and an MA grafted PP (MA-g-PP) composite by altering the KF modification procedure. Enhancing the interfacial contact and mechanical characteristics of the resulting composites was the aim of the modification. Three distinct modifications were made to the KF: (1) KFs were directly hydrolyzed at room temperature using a 10 wt. % aqueous solution of sodium hydroxide. With an increase in KF content, the yield strength of the composites gradually increased before declining. Interfacial adhesion between the KFs and the PP matrix may be responsible for the various enhancing effects [41].

4.3 Thermal Analysis

The deterioration of materials at high temperatures was assessed using thermogravimetric analysis (TGA). Three temperature interval zones were found in the TGA study of recycled polyethylene/bamboo composites: below 200 °C, between 200 and 490 °C, and above 490 °C. The composite weight loss % remains essentially constant in the temperature range below 200 °C. However, a significant weight loss was noted in the 200–490 °C temperature range, which is caused by the deterioration of recycled polyethylene [42].

4.4 Thermo-Mechanical Testing

In an investigation, the epoxy/synthetic fibre-reinforced composites' dynamic mechanical analysis (DMA) has been performed. These composites are extensively used in the automotive, aerospace, energy, and other production industries. The mechanical properties of single fibre-reinforced polymer composites for epoxy/synthetic composite can be enhanced through the carbonisation process. The study also shows how the epoxy/synthetic fibre composites' dynamic mechanical properties can be improved using high elongating fibres. On the other hand, the dynamic mechanical analysis (DMA) tests exhibit a shift in the synthetic carbon fibres composites' glass transition temperatures, which may be useful for these fibre-reinforced high-temperature applications of composites [43].

4.5 Water Absorption Measurement

There are three major mechanisms of water absorption in fibre-reinforced polymer composites: diffusion, capillary, and transport of water molecules, respectively. Diffusion mechanism occurs inside the micro gaps between the chains of polymers. According to reports, the water absorption in recycled polyethylene epoxy composite is mainly caused by transport of water molecules through the micro gaps of recycled fibre which are generated during extraction of fibre from polymer composites. Higher filler concentrations result in higher water absorption [44].

5 Conclusion

In conclusion, this review article highlights the potential of recycled fibres obtained from textile waste as reinforcement for polymer matrix composites. The study shows that a significant amount of polymeric waste generated from the textile industry can be effectively reused and transformed into useful products, thereby reducing the negative impact on the environment. The mechanical and chemical processes used to recycle these waste polymer composites can lead to the production of high-quality reinforcements for polymeric matrices. It is also revealed that waste polymer composites as reinforcement in polymeric matrices can significantly enhance their mechanical properties and make them suitable for various industrial applications. These composites can be utilised in the automotive, construction, and electrical industries to create high-performance and sustainable products. The potential of recycled fibres obtained from textile waste to be used in composite materials suggests new ways to deal with the growing environmental issue of waste management. The study encourages researchers and industry experts to explore the possibilities of using recycled materials in product development and adopting sustainable practices.

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Thermal Regulation Through Clothing: Balancing Comfort and Insulation



Sakshi Singh, Vinay Kumar Midha, and Monica Sikka

Abstract "Clothing is an important aspect of human comfort in a variety of climates, particularly in cold weather conditions where protection from wind chill and maintaining a comfortable skin temperature of around 33°C are essential." While civilians want simple cold protection, military troops require insulation, mobility, and protection from the elements. Extensive research is being conducted to balance these objectives while maintaining comfort. Strategies incorporating multi-layered designs and material improvements aim to improve thermal protection by trapping air and boosting insulation qualities. This study explores the delicate trade-off between weight and warmth in clothing, which is crucial to designing clothing for cold locations. Beyond this, the complex world of human adaptability in this type of environment, highlights the variables that affect efficient insulation from the cold, and pinpoints the materials that are most resilient to these extreme conditions. It is necessary to understand these intricacies in order to maximise the comfort and safety that cold weather clothing may provide.

Keywords Thermoregulation · Thermal insulation · Fabric comfort · Heat loss prevention · Adaptability

1 Introduction

Clothing is a basic human need that provides physical covering and protection from various environmental situations. These circumstances vary considerably around the world, from extreme cold to hot and humid locations, making it difficult to provide universal protection and comfort with a single form of apparel. Warm-weather clothing is often loose and lightweight, allowing for easy sweat evaporation, whereas cold weather clothing is typically heavy and layered, providing thermal insulation and wind protection. Human survival is based on basic requirements such

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as food, shelter, and clothes. Clothing now serves more than one purpose in modern society, symbolising money, prestige, culture, employment, and gender [1]. Social, economic, environmental, and physical variables all influence clothing choice, which has a huge impact on comfort and general well-being. Clothing generates a microclimate that aids the body's thermoregulation, guaranteeing comfort in the face of changing temperatures [2]. This highlights the importance of textiles in protecting people from harmful environmental conditions while also improving comfort.

Researchers emphasise physiological processes in regulating body temperature in their varied definitions [3, 4]. As a psychological, physiological, and physical state of balance between a person and their surroundings, comfort is commonly understood to be the absence of discomfort. Examining variables like thermo-physiological components, sensory/tactile characteristics, physiological parameters, and fitting comfort are important steps towards understanding fabric comfort). The movement of heat and moisture is included in thermo-physiological comfort, whereas the feel of the cloth against the skin is measured by sensory comfort.

Concerning the thermal retention: The role of clothing as a barrier, except in high temperatures and heavy physical activity, ambient temperatures are usually lower than the body's normal temperature. As a result, clothing obstructs the outward flow of body heat to the surrounding atmosphere. For example, at ambient temperature of approximately 27 $\pm$ 2 °C, minimum clothing layers are sufficient for heat balancing owing to minor temperature changes between skin and surroundings. As temperatures fall lower, the body loses heat more quickly, giving the impression of being chilly. Adding insulating layers helps counterbalance heat loss, dramatically lowering body heat loss via clothes, especially in freezing situations below -20 °C, where maximising clothing's thermal insulation becomes critical to avoid heat loss.

2 Basic Factor of Thermal Comfort

Air temperature is the most often used indication of thermal comfort (it is simple to use and most people can relate). However, while air temperature is an essential signal to consider, it is neither a valid nor an accurate predictor of thermal comfort or thermal stress. The temperature of the air should constantly be weighed against other environmental and human considerations.

Environmental and human variables both influence thermal comfort (Fig. 8.1). These elements may be unrelated, yet they all contribute to a person's thermal comfort.

2.1 Environment Factors

(a) *Air temperature*- The warmth or coldness of the surrounding air is represented by the air temperature. It has a major impact on how human body and the

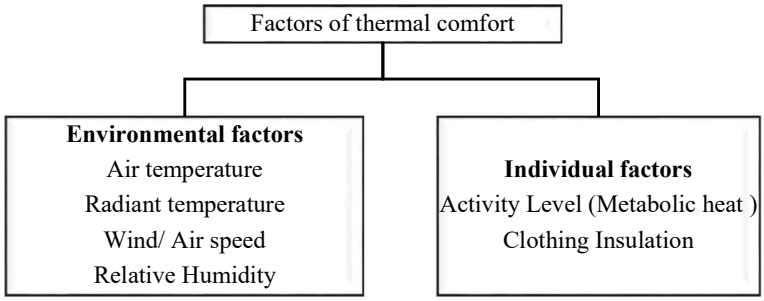


Fig. 8.1 Basic factors of thermal comfort

environment exchange heat. Compared to skin temperature, our body sheds heat more quickly at low air temperatures. On the other hand, our body tend to retain heat in warmer climates. As a result, a key factor in this heat exchange process is air temperature.

(b) *Radiant temperature*- Radiant heat is emitted by heated things such as a fire, heater, or any hot surface, and has a substantial impact on human thermal comfort. It is more influential than air temperature in determining how humans absorb or lose heat. Our skin absorbs radiant heat like a matt black object, raising our body temperature. Wearing luminous clothes helps to reduce heat absorption, keeping us cooler. Fire, heaters, ovens, and hot surfaces are common sources of radiant heat. Firefighters wear reflective coated garments to reduce radiant heat exposure. These textiles should be noiseless, breathable, highly reflective, comfy, washable, heat-dispersing, and lightweight.

(c) *Air velocity*- Air velocity has a considerable impact on body cooling. Cooler air rushes over the body, cooling it immediately, similar to standing in front of an air conditioner. Increased air movement promotes convective heat loss, which aids in bodily cooling independent of ambient temperature or humidity. Stuffiness is created in stagnant interior situations, particularly in warm rooms, preventing heat dissipation. Movement increases convective heat loss in warm, humid circumstances, providing cooling without changing air temperature. Physical exercise increases air movement, which increases convective heat loss and contributes to a cooler feeling. The perceived coolness is affected by adjusting air velocity based on activity levels.

(d) *Humidity*- Thermal comfort is unaffected by relative humidity levels ranging from (40–70) %. Sweat evaporation is hampered in hot situations with humidity levels above 70%, preventing body temperature from lowering and creating discomfort. High humidity reduces sweat evaporation, which affects cooling, particularly in hot and humid situations. High humidity can cause pain, although airflow can help. Airflow aids perspiration evaporation, which is essential for heat dissipation. Poor vapour permeability in protective equipment, such as firefighter gear, limits sweat evaporation, reducing comfort.

(e) *Evaporation*- In high-temperature situations, sweat evaporation is the principal means of heat disposal. As a result, in hot weather, lesser humidity is better to minimise discomfort. Wearing vapor-impermeable Personal Protective Equipment (PPE) in high humidity and hot circumstances causes pain because sweat evaporation is hampered. This discomfort arises when PPE lacks holes or has insufficient vapour permeability, resulting in excessive humidity within the garment's microclimate and significantly lowering comfort.

2.2 Insulation Characteristics of Clothing

Clothing affects how heat is exchanged with the surroundings. For comfort, it can adjust to various conditions or act as insulation. Thermal control is aided by layering, which modifies heat retention. The choice of clothing has a significant influence on comfort depending on the climate and individual requirements, enabling varying degrees of insulation.

(a) *Metabolic heat*- It fluctuates according to exercise level and personal circumstances. Knowing one's metabolic heat helps in clothing choices. Increased physical activity creates more metabolic heat, requiring improved heat dissipation to avoid overheating. When weight, age, fitness, height, and individual physical attributes are taken into account, metabolic rate has a substantial impact on thermal comfort.
(b) *Thermoregulation through clothing*- Conduction, convection, radiation, and perspiration evaporation all contribute to heat transfer. Moisture-related heat is released as latent heat via condensation, evaporation, freezing, or melting, whereas dry heat dissipates through clothes via conduction, convection, or radiation. Heat and moisture transport are substantially influenced by the structure of clothing and trapped air. Without increasing the material amount, effective regulation of entrapped air inside garments affects insulation and moisture transfer.

3 Thermal Comfort of Clothing

"The body reacts differently to external conditions in winter and summer, influenced by factors such as temperature, vapour pressure, air velocity, and clothing insulation." Skin temperature is affected by several factors. Changes in the external environment might cause pain during physical exercises. Skin and body temperature are greatly influenced by environmental temperature and humidity [5]. The human body operates within a restricted temperature range, normally sustaining (37±0.5) °C. Thermal comfort is determined by a combination of clothes, weather, and physical activity. Body heat output varies depending on exercise and clothes. Clothing protects against external effects and helps to regulate body temperature [6]. Heat balance includes

the body's heat generation equaling heat transmission via numerous methods such as conduction, convection, radiation, evaporation, and respiration. Clothing has a considerable impact on both body heat loss and individual comfort.

3.1 Heat Exchange Through Clothing

The amount of heat energy generated by metabolism and the pace at which heat is removed from the body should be equal under a steady-state heat balancing condition of the human metabolism system. The transmission of body heat occurs by radiation evaporation, convection, respiration, and conduction. According to [7–9], the universal heat balance equation expresses the fundamental thermodynamic process in heat exchange per unit body surface area (W/m2) between humans and the environment,

$$M - W = C + Ck + Cres + R + Eres + Es$$

M (metabolic rate), W (external work), C (heat loss by convection), Ck (heat loss by conduction), Cres (sensible heat loss due to respiration), R (heat loss by radiation), Eres (evaporative heat loss due to respiration), and Esk (heat loss by skin evaporation) are all terms used to represent the thermal dynamics between the human body and the environment. In most circumstances, external work (W) is minimal and generally disregarded, whereas metabolic rate is dependent on metabolic activity.

The transport of moisture in a textile material is usually by two common methods namely: diffusion and convection. Diffusion is the result of random molecular motion from an area of high concentration to an area of low concentration. The moisture usually diffuses into the textile material through interstices between fibres or yarns in a fabric. The number of interstices is determined by yarn linear density, yarn twist, ends/inch, picks/inch, weave, etc. Fabrics having more air spaces, allow more diffusion to occur. Other phenomenon like adsorption, absorption, or desorption also helps in moisture transfer between the fibres and surrounding air [3].

3.2 Transient Heat Flow and Warm–cool Effect of Fabrics

Transient heat conduction is the cause of the sense of warmth or coolness that occurs when human skin comes into contact with another surface. The skin's temperature decreases and thermoreceptors in the dermal layer of the skin are stimulated when it comes into contact with clothes, which is normally colder than the skin. The degree of the chilly feeling is influenced by the rate of this heat flow, which is dictated by the material's thermal characteristics. Typical values of rate of temperature changes for warm and cool fabrics. Higher thermal inertia fabrics, as indicated by density, specific heat, and thermal conductivity, dissipate heat more efficiently and feel colder to the

touch [4]. The warm or chilly sensation is mostly determined by the characteristics of the fabric surface.

Surface features, as well as material type, influence fabric warmth or coolness [10]. Kawabata and his colleagues invented Qmax, which determines the highest heat flow from a heated plate to cloth upon contact [11, 12]. The concept of qmax, which denotes the maximum heat transfer after contact, serves as a reliable indicator of the sensation of warmth or coldness experienced when touching objects. Additionally, this measure demonstrates a strong correlation with findings from human studies. This number shows transitory heat conduction and is related to the warm/cool sensation. It fluctuates with moisture content, with linen having the highest qmax and wool having the lowest up to a certain point. Higher qmax values equate to a colder feel, and they are affected by fabric surface characteristics, water content, and geometry. Heat conduction qualities, which are determined by parameters such as material density, thermal conductivity, and heat capacity, have a direct effect on qmax [11]. Skin contact with items of varying temperatures alters the distribution of skin temperature, generating warm or chilly feelings via thermoreceptor reactions.

4 Factors Affecting the Thermal Properties of Cold Weather Clothing

4.1 Effect of Fibre Morphology

The fibre shape of a material has a major impact on its thermal insulation. The term "fibre morphology" describes the properties and physical structure of the fibres used in textiles. The impact of fibre shape on thermal insulation is as follows:

Fibre Diameter- Generally, a fabric with thinner fibres has more air spaces, which improves insulation. More air is trapped between the fibres in fabrics with finer fibres, slowing down heat transmission and improving insulation.

Surface Area- Greater surface area fibres, such as microfibres or fibres with asymmetrical forms, can trap more air in the fabric, leading to increased insulation. Increased surface area enhances the fabric's insulating qualities by allowing more air to be trapped inside.

Porous Structure- A fibre's structure, such as its hollow or porous fibres, helps to improve insulation. The insulating qualities of air allow hollow fibres to retain more air inside their cavities, improving insulation.

Fibre Crimp- A fabric's thermal insulation is enhanced when it has more air pockets due to the crimped or textured fibres. By increasing the fabric's loft, the crimp helps it capture more air and lessen heat transmission.

Fibre Density and Arrangement- A fabric with a higher fibre density or a more compact arrangement of fibres will have fewer air gaps and less insulation. On the other hand, by allowing more air to be trapped between fibres, looser patterns or lower fibre density might improve insulation.

4.2 Effect of Yarn Parameter

Structure modification of yarn- The structural modification of yarns involves the addition of supplementary micro-pores within the yarn body, further increasing yarn porosity and subsequently impacting fabric thermal characteristics. Fabrics containing micro-pores within the yarn demonstrate decreased thermal conductivity when compared to a reference fabric sample made of 100% cotton [13]. The removal of PVA fibres generates micro-pores within the yarn structure, increasing trapped air. Air, being a poor conductor of heat compared to fibres, impedes heat transmission through the fabric [14].

Woven fabrics made from staple twist-less and hollow yarns significantly impact comfort-related properties like air permeability, thermal conductivity, water vapour permeability, wicking, and water absorbency. Fabrics using standard yarn show higher thermal conductivity, while those with hollow yarns exhibit the lowest values. The reduced thermal conductivity in hollow yarn fabrics is due to their bulky structure, trapping air within the hollow spaces and acting as insulation, preventing heat transfer from the inner to the outer layer [15]. So, the studies indicate that finer yarns in knitted fabrics lead to a decrease in both thermal resistance and thermal conductivity. An inverse relationship exists between thermal resistance ($R = h/\lambda$; where R is thermal resistance, h is fabric thickness, and λ is thermal conductivity). Surprisingly, the investigation revealed that as thermal resistance decreases, thermal conductivity also decreases. This contradiction is attributed to variations in fabric thickness. (Nilgün et al. 2007).

Fineness and hairiness of yarn- Finer yarns in fabric decrease yarn diameter and thickness. If the reduction in thickness surpasses reduced thermal conductivity, thermal resistance decreases. As yarns become finer, thermal absorptivity drops. Higher yarn twist coefficients are associated with lower thermal resistance, likely due to finer yarns resulting in decreased fabric thickness [15]. Reduced fabric hairiness enhances the surface area between the fabric and skin, resulting in a cooler sensation. Fabrics made from carded yarns exhibit higher thermal resistance compared to those from combed yarns, attributed to the increased hairiness in carded yarn fabrics. Higher yarn hairiness contributes to a larger amount of static air, which hampers heat transfer.

4.3 Effect of Fabric Parameter

Fabric thickness- It affects thermal resistance significantly, with more thickness contributing to increased warmth due to lower heat transfer [16]. The thicker fabric allows for greater fibre density or trapping of stagnant air layers, which increases heat resistance. A rise in fabric thickness, on the other hand, coincides with a reduction in heat transmission. Fabrics with various thicknesses and yarn linear densities may have comparable thermal transmittance.

Fabric weight- Because it represents mass per unit area, fabric weight has a direct impact on insulating properties. Higher mass per unit area frequently increases material content, resulting in higher fabric insulation and lower heat transmission for comparable fabric thickness. However, in the case of knitted fabrics, the combination of lesser weight and higher fabric tightness results in reduced heat transmission.

Fabric tightness factor- The degree of fabric tightness has a big impact on heat transmission. Slightly more tightness within the same tex increases thermal transmittance, mostly influencing conduction-based heat loss. Increased conduction of heat is made possible by tighter textiles that don't have any air spaces. Conversely, materials with open structures allow for more convective and radiative heat. When combined with structural tightness, yarn jamming improves heat transfer mainly by conduction. Moreover, increasing twist levels in the yarn structure reduces interior air pockets, which increases heat loss through conduction.

4.4 Effect of Microclimate Thickness on Thermal Transmission

The overall heat input from the human body reduces as the thickness of the microclimate increases. This is due to an increase in the air layer, which acts as an insulator. The contribution of radiation to total heat flow increases as microclimate thickness increases. This is owing to the fact that radiation heat transfer is independent of microenvironment thickness. It has been observed that the influence of fabric thicken Chemical procedures that dissolve or weaken the polymer matrix can be used to make it easier to extract fibres from polymeric composites. This is especially helpful when a cleaner fibre separation is sought or when mechanical separation is ineffective on its own. In order to facilitate fibre extraction, polymeric composites can be chemically treated using the following typical methods: than microclimate thermal conductivity, and hence the outcome is less sensitive to fabric thickness than microenvironment thickness. When the thickness of the microclimate is lower, the influence of fabric thickness is greater [17].

5 Different Methods for Cold Weather Protection

The wearer values comfort above the material used in cold-weather clothing. Preferences for such clothing vary according to activities and climate conditions. Thickness, heat resistance, compressibility, and air permeability are all significant factors to consider when purchasing cold-weather clothing. Thermal resistance increases with thickness [18]. These costumes may be layered or worn as separate pieces piled on top of each other. More layers improve heat resistance, with the outer layer's air permeability having the greatest impact. The inside layer is usually a

knitted wool/cotton blend, while the outside shell is woven polyamide [19]. Wool/cotton blends, polyamide, and polyester constructions are among the other layers. This design carries moisture from the skin's surface to the outer layers, resulting in reduced skin humidity but higher humidity inside the body.

5.1 Phase Change Materials (PCM)

Phase Change Materials (PCMs) are an upcoming fashion in cold-weather apparel. They function by storing energy during the change from a solid to a liquid and then releasing it when they return to their initial form [20]. The goal of PCM technology development was to improve textile materials' ability to withstand heat. In order for PCMs to melt, heat from the environment or the body must be absorbed. The encapsulated PCM solidifies at temperatures below a certain transition point, producing heat and having a warming effect. Before starting the heat exchange process, the wearer must physically exert themselves to bring the PCM layer within the garment to this transition temperature [21].

Several techniques, including coating, finishing, laminating, melt spinning, injection moulding, and bi-component synthetic fibre extrusion, can be used to apply PCM to textiles. Encapsulated paraffin wax is present in some goods' micro-encapsulated phase change material (microPCMs). The capacity of PCM to store latent heat is quite great. Paraffin wax has a melting point of 27 °C, which is quite close to body temperature. Because it melts readily when heated by the body, it is used as PCM for clothes intended to withstand cold temperatures.

For protection in cold weather, a unique four-layer clothing system has been devised in (Fig. 8.2). Cotton fabric is used to produce the inner layer, and polyester is used to create a nonwoven first insulating layer that has been treated with micro PCM. It is paired with a second nonwoven polyester insulating layer, and the outer layer is made of breathable, waterproof material. This ensemble has been tested on a bionic skin model at (-15±5)°C in a climate room. The PCM turns into a liquid and stores energy when the temperature of the PCM layer climbs over its melting point. Liquid PCM transforms into a solid and releases energy at temperatures below 27 °C [22].

5.2 Extended Cold Weather Clothing System (ECWCS)

The United States has developed a new cold-weather clothing system, known as the third-generation ECWCS. This system asserts its capability to enhance survivability across diverse climatic conditions. The GEN III ECWCS encompasses seven levels of system features aimed at providing heightened protection, as shown in (Fig. 8.3). Polypropylene undershirt and underwear, polyester fibrepile shirt and bib, nylon/cotton trousers, Gore-Tex trousers, trouser liners, snow camouflage trousers cover,

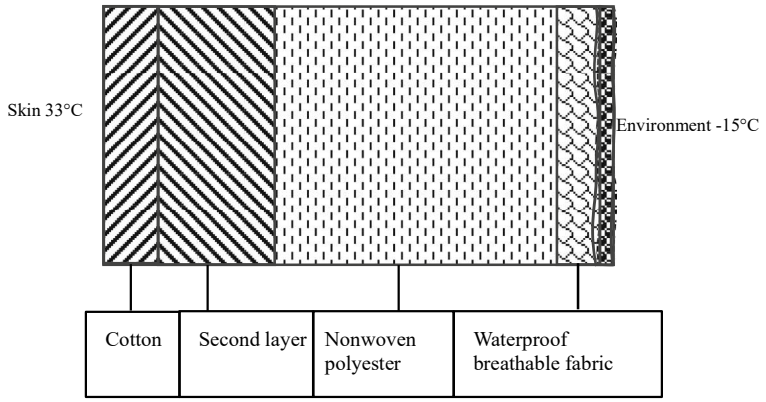


Fig. 8.2 Structure of PCM clothing assembly



Fig. 8.3 Extended cold weather clothing system

gloves, glove inserts, mittens, mitten inserts, mitten shells, snow camouflage mitten shells, cap, balaclava, nylon socks, cold weather vapour barrier boots, extreme cold weather vapour barrier boots, and M-1950 trouser suspenders were all assembled in detail for the first generation of ECWCS clothing. The arrangement of the layering system was as follows: Gore-Tex clothing served as the exterior layer, polyester shirt/bib, liners, and cotton/nylon pants as the intermediate layer, and polypropylene undergarments as the inner layer [23].

5.3 Biomimetics Method

Applications for outdoor apparel are another area where biomimetics is used. It involves applying biological ideas to the world of humans. The Greek origins of

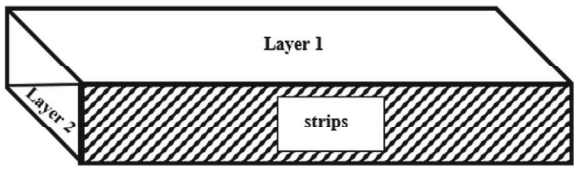


Fig. 8.4 Structure of two layers Biomimetics fabric assembly

this term are bio-, which means life, and mimesis, which means to copy [24]. A British team conducted research to find out if penguins can withstand extremely low temperatures. It was discovered to be the outcome of their coat, which is made up of both flesh and feathers. Through the use of a muscle attached to the feather, they may change the waterproof or insulating properties of their skin. The skin becomes waterproof when this connecting muscle contracts, and becomes an air-filled windproof garment when it is released, and this phenomenon is "adaptive insulation".

The phenomena of adaptive insulation in clothing have been attempted to be understood. The resulting structure consists of two layers of fabric connected together at an angle to the plane of the two layers by textile material strips. A skewing of the volume of air trapped between these parallel layers diminishes, leading to reduced insulation, as illustrated in (Fig. 8.4). PTFE has been used in the production of a jacket called Airvantage. The membrane is combined with a polyester framework (24% PTFE, 76% PE), enabling the user to regulate the amount of air necessary for appropriate insulation [24].

5.4 Shape Memory Polymer Coating

Shape memory polymer coatings, based mostly on polyurethane (PU), are a subject of current study in the field of insulating materials. At the molecular level, these polymers adapt dynamically and exhibit an elastic memory effect. Body heat and vapour escape through the polymer coating's tendency to expand or open when the wearer's body temperature rises. On the other hand, when the atmosphere gets colder, the molecules in the material constrict or close, which stops heat from escaping into space.

This is an inventive polymer coating that is multipurpose and works on cotton, silk, polyester, and nylon fabrics. Mitsubishi has created the resultant fabric, which is known as "dream cloth," and it has tremendous promise in the field of advanced textiles [25]. Employing SMPS (Shape Memory Polymers) in clothing amplifies the air gaps between layers, consequently enhancing thermal insulation. Integrating shape memory materials into garments provides superior flexibility, particularly in extremely cold conditions, as shown in (Fig. 8.5).

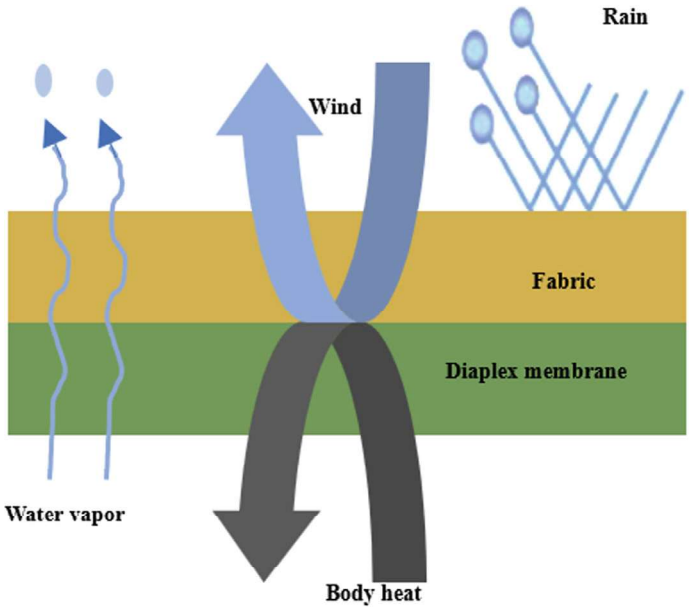


Fig. 8.5 Structure of shape memory textile

5.5 Multi-Layer

When it comes to wearing protective clothes for cold weather, wearing several layers works far better than wearing one heavy one. This unique layering method makes lots of air pockets in the fabric, which efficiently traps air and provides body insulation. Moreover, this configuration helps sweat to be transferred away from the human body, which improves comfort levels all around. The layering system usually consists of three different groups, each having unique features, as indicated in (Fig. 8.6):

The base layer, being the innermost layer, specialises in wicking, efficiently drawing moisture away from the skin and transmitting it to the upper layers. Polypropylene, Polartec®, and polyester microfibre fabrics are used for the base layer because of their quick-drying qualities. The importance of this layer in keeping the skin dry considerably improves user comfort. The wicking principle extends to foot protection as well, with thin polypropylene socks worn as inner layers beneath wool socks to keep the feet dry and warm.

Middle Layer: This layer acts as an insulation layer, capturing the warmth created by body heat while letting sweat to travel away from the body. Rather than a single layer, the insulating layer is usually made up of many. Polartec®, Windstopper®, PowerStrech®, fleece, pile, wool, or thicker polyester may be used for this layer.

Outer Layer: As the outer shell, this layer primarily protects against wind and rain while also allowing for ventilation. The outer layer is commonly made of cordura, Gore-Tex®, Cloudburst®, Windstopper®, Trinity®, eVent®, and Precip®.

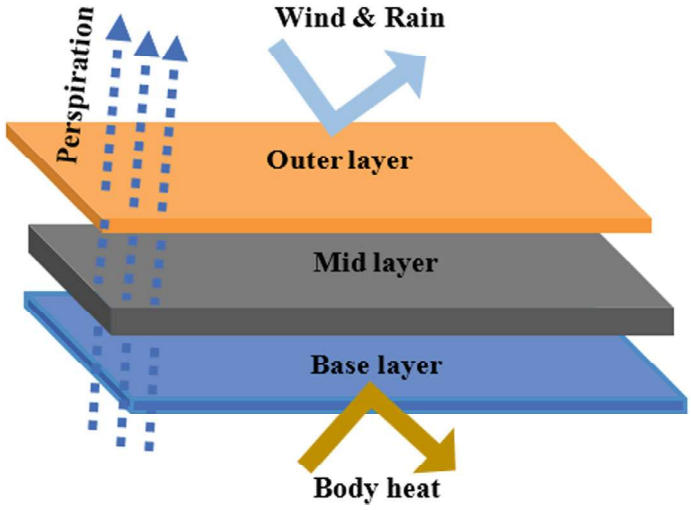


Fig. 8.6 Structure of multi-layer clothing assembly

The efficient usage of layered clothing is critical. Adjust layers according to activity level; remove some layers before beginning vigorous exercise and reapply them during breaks for extra insulation when body heat output reduces. This reduces moisture accumulation in the inner layer, improving comfort.

Clothing comfort and thermal protection are greatly influenced by design aspects. High collars provide additional neck protection, while insulated hoods reduce heat loss from the head. Elastic sleeve cuffs help to keep heat in the arms, and overlapping upper and lower body clothing or one-piece suits are recommended. To reduce internal moisture in cold weather clothes, ventilation is critical [26]. The efficiency of protective gloves against convective and contact cold is critical. Flexibility and water impermeability are other important characteristics for optimal performance.

6 Specific Materials and Textiles for Cold Protection

The cold weather protective garments can be classified into the following categories on the basis of their specific end use:

Natural and synthetic fibres- Textiles with significant moisture absorption capacities, such as wool and wool blends, can handle modest quantities of moisture without impairing their insulating characteristics. Wool is a good base layer fabric because it keeps your skin dry. However, once soaked, its ability to manage moisture deteriorates. Cotton absorbs moisture as well, but when wet, it sticks to the skin, making it unsuitable for close-to-skin use in freezing temperatures. Many synthetic materials resist water while still allowing moisture to pass from the skin to the next layer. As a result, while sweating, the skin's microclimate swiftly becomes humid, causing

discomfort and needing user changes. The fundamental effect and goal of employing vapour barrier textiles next to the skin.

Waterproof and Breathable- These are often the most functional and costly garments, ideal for heavy rain and strenuous work scenarios. They are not ideal since workers who perspire heavily nevertheless feel wet due to the limited pace at which moisture moves through waterproof/breathable membranes. Such gear includes laminate fabrics with nylon or polyester on the inner and outer layers and a waterproof breathable membrane in the core. The idea behind breathable fabrics, which are materials that repel water but allow sweat to escape, is that microscopic holes in the material are too small for water droplets to pass through yet wide enough for water vapour (perspiration) to escape [23].

Water Resistant and Breathable- These are optimal for high activity levels during warm weather and light rain. They typically consist of tightly woven materials offering wind and light rain resistance. These fabrics often feature a DWR (Durable Water Repellent) coating, like Teflon®, on the outer surface to repel water. However, the effectiveness diminishes with frequent washings.

Waterproof and Non-Breathable- These clothes, which are often composed of PVC or another coated fabric, are perfect for rainy days with light duty jobs. It has a low tear strength and lacks breathability, which might make workers uncomfortable. It can be an ideal solution for scenarios such as being worn for short periods of time, needing to be disposed of due to contamination, or having a minimal workload.

Soft Shells- These shells are water and wind resistant, as well as highly breathable. Soft shells also provide insulation and weather protection. Stretch fabric or stretch panels are commonly used in this garment for additional comfort. They are appropriate for light rain and heavy workloads, and are now available with naturally fire-resistant textiles. Soft shell jackets come in a variety of forms, including single layer and composite construction with many layers.

Insulated- These forms of clothes have an insulating layer built in, making them excellent for cold and damp climates. It lowers adaptability in areas where temperatures and precipitation might vary. Outer layers containing FR materials are available for work settings where accidental flame contact is a concern. The structure may include a Nomex® knit inner, a PTFE membrane, FR polyester, FR modacrylic, or Lenzing FR® [23].

7 Properties Required in Cold Weather Clothing

Clothing is the primary means of protection against cold, and it should be adapted to individual working and climatic situations. When creating cold-weather apparel, consider factors such as the duration and kind of physical activity, activity intensity, temperature, humidity, wind conditions, and anticipated rain or snowfall.

It is important to consider the following material characteristics when determining if clothes are appropriate for cold weather-

(a) *Thermal Insulation*- It is commonly stated in units of Clo and represents the resistance to heat transfer provided by the clothes. The primary factors influencing the insulation value are the material's thickness, its capacity to retain air within clothes, and its level of dryness. The air that is trapped serves as a heat-insulator.

1.Clo = 0.155 K-m^2 /W

(b) *Evaporative Resistance*- Sweating produces moisture on the skin. In hot weather, perspiration evaporates, removing body heat and providing a cooling effect. In the cold, heat loss by evaporation is unnecessary; the important issue is to move perspiration from the skin to the outside via clothes. Condensed perspiration is absorbed by the material's hydrophilic fibres and transmitted to the clothes surface, where it evaporates.

The capacity of clothes to allow the passage of vapourised moisture through the material is expressed by its permeability. If moisture movement is not facilitated via the material, the thermal insulation of clothes drops by 30-50%.

(c) *Water Resistance*- It describes a clothes capacity to keep liquid moisture from the outside environment from penetrating the fabric. As was previously said, less water penetration into the clothes will help to preserve its insulating qualities and, eventually, the wearer's comfort.
(d) *Wind Resistance*- The ability of a material to resist wind passage. Convection transports heat from the skin's surface along the air flow through the material [26].

8 Conclusion

The study highlights how important clothing is to human life as a basic need and how it serves a variety of purposes beyond simple physical defense. The statement highlights the difficulties in designing clothing that is appropriate for various climates because these variables vary greatly around the world. Fashion has a big impact on people's comfort and well-being since it is a social status, cultural, and identity marker that is shaped by a number of different sociological, economic, and environmental circumstances. In order for the body to adjust to fluctuating temperatures, textiles are vital in controlling the human body microclimate. Factors like fitting, physiological, and sensory elements must all be taken into account in order to fully comprehend fabric comfort. The talk emphasises how clothes may act as a barrier against heat loss, especially in colder climates, and stresses how important sufficient insulation is to preserving thermal equilibrium.

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Design of Top Surface of a Partly Reusable Sanitary Napkin Based on Fluid Flow Across the Plane



Tanya S. Herle and Subrata Ghosh

Abstract Menstruation, the monthly shedding of the uterine lining, makes women vulnerable to diseases caused by inadequate hygiene. Medical textiles heavily employ disposable menstrual sanitary items, which assist in management of menstrual flow and preserve hygiene. Sanitary napkins, a popular menstrual hygiene product, have three layers: top, inner (including a distribution layer), and bottom, each with different features and uses. The top surface of the napkin directly contacts the skin and absorbs menstrual flow across the plane, leaving the surface dry and comfortable with minimal back flow. Scientific studies have been done to simulate the napkin's partially reusable characteristics. The study examined polyester monofilament and multifilament plain woven top-surfaces of different constructions to understand the intrinsic influence of yarn type, pore size, drop size and horizontal wicking in terms of diameter on fluid flow across the plane and the problem of liquid drop flow through the top surface of sanitary napkins to the core. A mathematical model will be formulated to understand the mechanism of flow. Therefore facilitating selection of an optimal top surface to create a more environmentally friendly, cost-effective, and partially recyclable product.

Keywords Sanitary napkin · Environment friendly · Top-surface of SN · Menstrual hygiene

1 Introduction

Menstruation is a normal occurrence in females who lose blood for one week every month from the age of maturity till menopause [1]. Women belonging to economically backward communities are observed to use cloth pads due to the unavailability and high cost of sanitary products. These cloth pads are extensively made from

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either waste fabrics or by buying cheap fabrics for meager rates. Despite significant advancements in water and sanitation, the needs and wants of teenage girls and women remain overlooked [2]. Study into the management of these menstrual hygiene products showed a very small percentage of the population was found to reuse the fabric and found disposing them off or even burying them for the fear of embarrassment or other superstitions. The small percentage of women found to reuse them were also found to not be confident about their hygiene due to the marks left by the discharge even when it is found to be clean [3]. Problems faced by the women in question can be diligently solved through a systemic approach to the problem. Philanthropic work towards menstrual hygiene of economically backward women already include the education and distribution of sanitary products and their maintenance yet, these efforts fall short of follow through. Hence a sustainable option to support such efforts is attempted upon. Today, disposable menstrual hygienic products which help in managing the menstrual flow and maintaining hygiene are classified as technical textile products with technological developments that are used intensively in the field of medical textiles [4]. One of the widely used menstrual hygiene products is the sanitary napkin, which consists of three layers, namely top layer, inner layer or core (including a distribution layer) and a bottom layer each with distinct properties and functions. The top surface of the sanitary being in direct contact with the skin has an important function of immediately absorbing the menstrual flow across the plane leaving the surface dry and comfortable to the wearer with minimal back flow [5]. In commercial disposable sanitary napkins an extensive use of non-woven, perforated polypropylene or polyester sheet is observed. These top surfaces of disposable sanitary napkins are found to have exceptional liquid transport properties, low cost and easy production process but pose a problem in terms of impossible re-usability and most importantly with respect to their non-biodegradability, the waste generated and ultimately have very questionable sustainability.

Scientific studies have been conducted in order to achieve a proper simulation for the behavior of the napkin under use with partly reusable possibilities. Within the scope of the study, polyester mono filament and multi filament plain woven top-surfaces of different constructions have been studied upon to understand the intrinsic influence of type of yarn, pore size, drop size on the flow of fluid across the plane along with the horizontal wicking in term of diameter to get an insight into the problem of liquid drop flow through top surface of sanitary napkins to the core of it. A mathematical model in this regard will be formulated to understand the mechanism of flow, facilitating selection of the top surface in terms of optimum function and reproducibility in order to achieve a better environment friendly, cost friendly and partly reusable product.

2 Experimental

2.1 Materials

Three types of polyester plain woven fabrics are tested for liquid transmission and wicking out of which two fabrics are composed of multifilament yarns while the other is composed of monofilament yarns. The specifications of the samples are given in Table 1. Comparative studies of these fabrics with reusable possibility is done with top surfaces of commercial disposable sanitary napkins for more insight into the fluid flow through the media.

Liquid transmission of monofilament fabric with different pore sizes (0.2, 0.6, 0.8, 1.8, 2mm) have been studied with a tentatively standard drop size (≈2mm) to understand the mechanism of fluid flow through the fabric.

Methods

Liquid transmission properties of fabrics were tested with the apparatus setup according to the horizontal wicking test (AATCC 198) but the observations made are tilted towards the number of drops passing through the fabric with respect to the number of drops falling on the top of the surface. The experimental part of the study observes each drop falling on the fabric at a constant rate (8ml/min) and consecutively, the number of drops passing through the fabric is found which is not found to be equal to the drops made to fall on the top since the liquid is also found to spread. Hence the diameter of spread after each consecutive drop on the top of the fabric is measured to accurately obtain the rate of spreading at constant intervals and influence of each drop. Correlation with the rate and amount of spreading and the number of drops falling down is found and the more efficient top surface adhering to minimum spread and maximum flow through the fabric is selected.

Eliminating the negligible amount of wicking (spreading) in plain woven fabric consisting of monofilament yarns a study into the behavior of drop with different pore sizes is observed. The manipulation of the pore sizes and careful measurement

Table 1 Details and specifications of samples under study

S No	Fabric sample	Sample code	Fabric areal density (g/m^2)	Structure	Thread	Density	Pore size (dia in mm)	Yarn linear density (Denier)	
					EPCM	PPCM		Warp	Weft
1	Polyester 50GSM fabric	P50	50	Plain weave	19	16	0.2	100D	85D
2	Polyester 75GSM fabric	P75	75	-do-	25	20	0.1	80D	80D
3	Polyestermonofilament fabric	MF	90	-do-	16	18	0.25		

is done with the help of Leica image porosity microscope device. The observations from this study have been applied into the mathematical modeling regarding the fluid flow through porous media.

3 Results and Discussion

It is imperative that when a fabric surface comes in contact with a fluid, the interaction is mainly in two ways wherein the drop tries to pass through the pore of the fabric but influence of wicking due to capillary spaces in the yarn and the fabric interstices cause the liquid to move along the fabric plane. When a saturation of wicking in the particular point is achieved, the drop is found to escape through the fabric pore. When the possibility of wicking is reduced to a minimum, the drop can be observed to pass through the fabric in minimum time as soon as the specific tension of the fabric is surpassed by the weight of the drop. In the top surface of the sanitary napkin it is desirable that a drop is immediately transported to the core through the top layer leaving the top dry with minimal wicking. The property of negligible wicking is observed in the fabric of monofilament yarn, it is considered to be an ideal case for the top surface of sanitary napkins. Results of a drop to drop analysis of fabric fluid flow characteristics done on the three samples (polyester 50GSM fabric, polyester 75 GSM fabric and polyester multifilament fabric) resulted in the following plots shown in Fig. 9.2.

It is to be noted that the monofilament fabric cannot be used as a top surface due to its stiffness and surface roughness. The plot in Fig. 9.2 represents the increase in

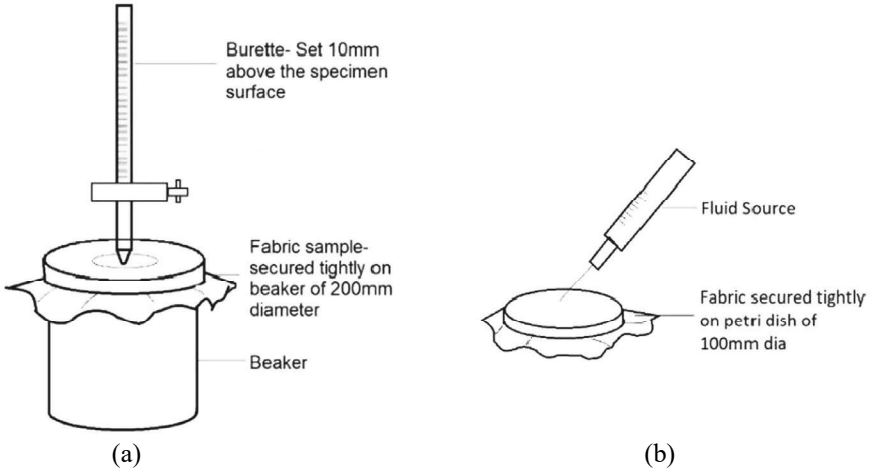


Fig. 9.1 Experimental setup for liquid transmission study **a** setup according to AATCC198 for study of diameter of spread and fluid flow through **b** set up for pore size versus number of drops study

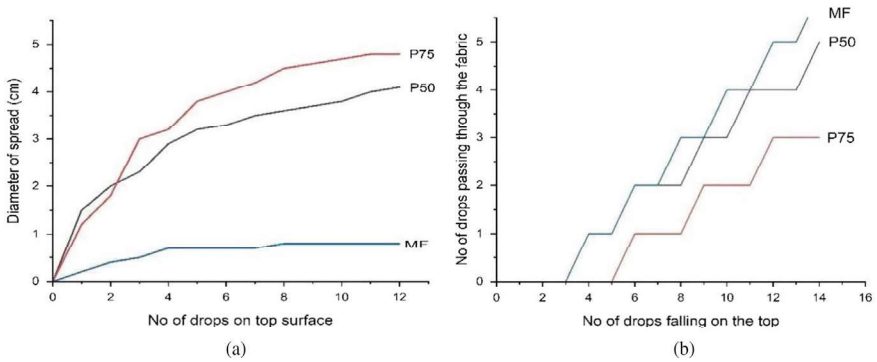


Fig. 9.2 Plots of results obtained in study of fluid flow through the three different media under study **a** plot of diameter of fluid spread on the top surface with each consecutive drop **b** plot of drops flow through the fabric after each consecutive drop

diameter of spread of the fluid after each consecutive drop of fluid falling on the top surface of the sample. It can be assumed that for the optimum function of the top surface minimal wicking (spreading) is desirable as observed in the monofilament fabric which shows a very minimal amount of spreading along with the number of drops hence it can be assumed to be the ideal case. In this study it can be observed that among the P50 and P75 samples which are relatively less stiff and pose a less possibility of discomfort to the wearer, P50 fabric has a lesser tendency of spreading. Similarly, an observation of the number of drops required by the fabric to effectively undergo wicking then overcome the surface tension and get transported across the plane of the fabric. Monofilament fabric shows the trend with maximum fluid flow across the fabric when compared to the multifilament fabrics. The point noted was that the P50 fabric was found to show flow across its plane quite close to that of the monofilament fabric. This may be an indication of better properties than P75 fabric in both aspects i.e. minimal wicking and more across the plane flow of fluids.

The above observations have led to further curiosity on the influence of the pore size of the fabric with respect to the drop size and its intrinsic mechanism. To further study upon this, an analysis of drop versus pore size is done to with across plane flow of liquid is shown in Fig. 9.3.

For a tentative drop size of 2mm, the pore size equal to it results in the passing of each drop through the pore as it does not face any resistance to flow from the yarns. As the pore size is decreased gradually the flow of fluid also is observed to decrease gradually. It has been noted that in the trend between pore sizes of 0.8 to 0.6, a drastic exponential decrease in flow is observed.

Modeling

Considering the fabric surface of a woven fabric, the interlacement of yarns forms rectangular pores between them Fig. 9.4a. When a fluid is dropped on the pore it is mainly supported by the highest points of the unit of the fabric i.e., the four points

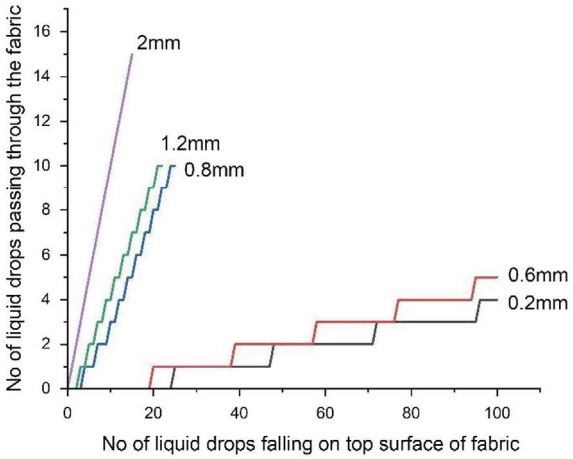


Fig. 9.3 Results of drop to drop analysis of drop versus pore size of plain woven monofilament fabric (for drop size ~ 2 mm)

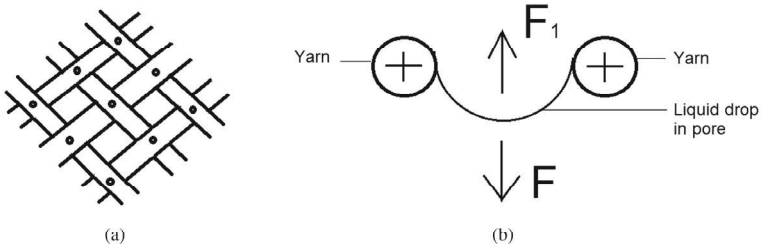


Fig. 9.4 **a** Geometrical representation of woven fabric surface **b** cross sectional view of drop in a unit cell of a fabric

of interlacement hence a cross sectional view of the drop versus pore interaction can be represented as in Fig. 9.4b.

When a drop of size equal to the pore size of the fabric falls on a unit cell of the fabric, it passes through without any resistance but decrease of the pore size causes the drop to be suspended forming a meniscus on the bottom of the unit. This system is temporarily in equilibrium as the force acting downwards i.e. F which is the mass of the droplet is less than F1 which is the force resisting the drop from falling down. Force F1 is the force acting on the drop due to the surface tension and pore size of the fabric.

Hence for the drop cannot escape from the pore until F1 $\geq$ F, it is required for the force F1 to be less than F (F1< F) for the drop to fall down from the surface of the unit cell of the fabric.

Therefore a mathematical model formulates to derive the relationship between surface tension and geometrical parameters of the fabric through this means.

$$\Delta P = \frac{4\gamma\gamma\gamma\gamma\gamma\gamma\gamma(\gamma-\gamma)}{\sqrt{2\gamma} - \gamma\gamma\gamma\gamma\,\gamma} \tag{1}$$

So, the pressure exerted by the meniscus depends on γ (surface tension), P distance between the threads (diagonal), d, yarn diameter, θ (contact angle)

$$Y = R - I\sqrt{4}\gamma^2 - \gamma^2 \quad (2)$$

The drop of the droplet is y and R is the radius of curvature of the meniscus and c is the length of the cord drawn at the points of hang of the drop.

These two equations obtained through the mathematical modeling significantly explains the parameters influencing the pressure exerted by the meniscus on the liquid. Since the meniscus formation is mainly influenced by the geometrical parameters of the fabric, the optimum parameters that are physically possible to attain desirable fluid flow properties on any given fabric with a given construction can be determined.

The significance of the droop of the drop on a fabric is that the amount of distance that the drop can hang on its weight purely due to the surface tension of the fabric gives the maximum amount of distance the second layer of a system can be kept at in order to efficiently absorb the fluid. Hence a second layer kept at any distance less than y will effectively absorb the fluid wherein, a distance higher than y would render the layer useless or inefficient as the drop is found to fall down under its own weight until this point is reached. Further, the sudden increase in flow of drops with a normal increase in pore size between 0.6 to 0.8 mm Fig. 9.3 can be explained on this basis that there is a sudden decrease in the surface tension posed by the pore and thus easing the flow of fluid through the unit cell of the fabric.

Therefore, the study and mathematical modeling not only finds the better of the materials under study but also paves way to set parameters for further research which may aim at finding a more efficiently performing top surface of a sanitary napkin.

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A Review on Implications of Fiber Pretreatments on the Characteristics of Eco-Friendly Textile Materials



Akanksha Dobriyal and Swati Sarkar

Abstract Creating a sustainable environment requires usage of the natural fibers as composite reinforcements. Natural fibers are likely to include toxins and other unfavorable elements when collected from a plant, soil, or animal. Reinforcements take over as the primary means of carrying loads in a composite material as output of removal of these undesirable components and improvement of green fiber strengths, aiding the composite in attaining significant mechanical qualities. As a requirement, various pretreatment techniques are used for green fibers like jute, banana, kenaf, flax fibers etc. The techniques include a variety of chemical processes as well as drying, heating in a flame, and other steps. These processes aid in enhancing the green fiber's surface coarseness enhancing the connection between the fiber and matrix. This paper provides an understandable picture of the various pre-treatment methods employed in various studies and their effects on the physical composition of the composite (blended) elements.

Keywords Reinforcement · Matrix · Composite materials · Pretreatment

1 Introduction

Natural fibers are strengthened in a synthetic or natural resin and molded into the necessary forms to create a green fiber-based composite material. There are several variables that affect how these novel materials behave. A key consideration that determines the quality of the composite material is the reinforcing properties and resin properties [1–3]. In addition to this, the pretreatment techniques used, and the manufacturing circumstances have a remarkable impact on the composite qualities. Natural fibers are obtained from a diversity of sources, including animals, plants,

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and minerals. Since they are readily a fibers have received most of the attention from researchers in the last ten years among the three categories. Mineral fibers are brought out from earth and specific rocks, and plant-based fibers are produced from diverse plant components including fruits leaves, grains stems and roots [4, 5]. Before being used as the right reinforcement in composite material, impurities have been removed in several natural (green) fibers. Table 1 lists several significant natural fibers and their attributes [6–11]. The chemical makeup of natural fibers on the other hand, has a major impact on the fiber qualities. When a natural or green fiber is reinforced in polymeric composites, cellulose, a semi-crystalline material with numerous hydroxyl groups, gives the surrounding matrix hydrophilic characteristics [12]. In contrast, hemicellulose has its open structure and several acetyl hydroxyl groups that make it naturally hydrophobic and soluble in water. As a result, the matrix begins to preoccupy moisture from the surrounding air [13]. Amorphous lignin has phenyl propane components in chemical composition. It enables this to acquire a slight inertness to the immersion of water among other ingredients [14]. In terms of chemical composition, cellulose gives nearly all attributes to fiber—aside from water (H_2O) resistance—while hemi-celluloses, wax, ash, and lignin lessen features of green natural fiber. To get rid of undesirable elements, chemical pretreatment is essential for all green natural fibers. Alkali treatment is one such procedure that gives green fibers additional qualities while removing undesirable elements [15]. Pretreatment not only enhances the fiber's characteristics but also significantly increases the machinability of composites made of green cloth [15, 16].

Table 1 Significant of natural fibers and their characteristics (6–11)

Fiber	Density (kg/m^3)	Young's modulus (GPa)	Diameter (mm)	Failure strain (%)	Tensile strength (MPa)
Bamboo	880–1100	18–55	100–200	1.3	391–713
Abaca	1500	12	10–30	3–10	400
Banana	1350	12–20	50–250	5–6	500–550
Cotton	1500–1600	5–13	20	7–8	287–597
Grewia Optiva	500–1250	8.34	800	-	128.56
Date palm	1000–1200	2.5–5.4	14–18	2–4.5	97–196
Flax	1500	50–70	50–100	2.7–3.2	345–1035
Coconut	800	4–13	100–450	15–40	131–175
Jute	1300	23–27	260	1.4	393–773
Hemp	1100	35	120	1.6	389–900
Coir	1200	4–6	10–16	30	175
Wool	—	2.3–3.4	20–30	25–35	120–174
Spider silk	14	11–13	2–8	17–18	875–972
Linen	1400	50–70	12–60	2.7–3.5	800
Nettle	1500	38	20–80	1.7	650

Table 2 Significant natural fibers' primary chemical compositions (18–20)

Fiber	Cellulose (%)	Fat/wax	Hemicellulose (%)	Lignin (%)	Pectin (%)
Hemp	77.07	0.7	14–22.4	3.7–13	0.8
Sisal	84.93	0.3	10–24	7–11	0.8
Oil palm	65	–	–	19	–
Linen	82	–	2	4	–
Ramie	91	0.3	5–16.7	0.7	1.9–2.1
Grewia Optiva	58–62	–	22–24	14–16	–
Cotton	92–95	0.6	5.7	–	1.2
Nettle	53–82	–	–	0.5	0.9–4.8
Banana	63–64	–	18.6	65.2	–
Pineapple	71.6	4–7	80.5	10.5	2–4
Abaca	56–63	0.2	15–17	7–9	0.5
Jute	63.24	0.5	13.6–21	12–26	0.2–4.4
Coir	43	–	1.7	45	3–4
Flax	62–71	1.5	16–18	2–2.5	1.8–2

There is a plethora of fibers with beneficial properties available all around. However, people don't consider and utilize such potential elements. Some researchers are working on natural fibers so that they can convert natural fibers into wearable fabric, though in some fibers there is a lack of certain properties which are helpful in converting natural fibers into textiles. These techniques can aid researchers in the creation of innovative textiles made from various fibers. Table 2 lists several significant natural fiber's primary chemical compositions [17–19].

1.1 Fiber Treatment Methods

Treating the fiber is a very primary approach to make the fiber into a wearable fabric. Various research works have addressed various treating methods to transform the fiber into wearable textiles. These treatments are done by researchers with some natural fibers, some of the treatment methods discussed in this section are given below.

1.2 Acryl Treatments

Following the treatment with alkali, sequential process called acrylation has been carried out with aid of ($C_3H_4O_2$) acrylic acid). The process Acrylation aids in lowering fiber's hydrophilicity, increasing the fiber's strength. According to the

study on the effects of acrylation on reinforced phenolic polymers of sisal, acrylation increased two crucial parameters, namely the flexural and tensile strengths, by 37 and 34%, respectively. Moreover, acrylation contributed to a 37 and a 43% improvement in the composites' volume resistance and electrical strength, respectively. The substitution of molecule of hydrophilic vinyl-ester which is present in the form is also observed to reduce the composite's capacity to absorb water [20]. Banana fibers have been pretreated with acrylic acid, and composites made of unsaturated polyester are strengthened by the acrylic acid. Studying the physical and mechanical and characteristics of the generated composites revealed that, compared to treated of composites with alkali, treatment with ($C_3H_4O_2$) acrylic acid significantly increased the bending strength, impact strength, bending modulus and the water resistance of composites. To improve the physical and mechanical characteristics of the composites, treatment with acrylic acid is therefore preferable to treatment with alkali [21]. Bamboo cloth mats have been pretreated with acrylonitrile (C_3H_3N), which is also utilized as reinforcement in polyester resins and epoxy for making composites. A typical study of manufactured materials revealed an increase in both resins' tensile modulus and tensile strength. The composite's ability to absorb water was also significantly decreased after being treated with acrylonitrile, going from 75 to 14% [22]. To learn more about mechanical qualities, a research study on the effects of treating abaca fiber with acrylic acid was conducted. As opposed to alkali and permanganate treatment, treatment with acrylic acid significantly increased the bending strength and tensile strength of compounds. Moreover, it has been claimed that benzene diazonium treatment of abaca textiles might increase strength even more [23]. Another study that looked at the impact of grafting of (C_3H_3N) acrylonitrile of the Sugar Cane fiber found that the degree of the modification of the chemical was a key factor in determining the attributes, including swelling behavior, chemical resistance, and water resistance [24]. Another study used graft copolymerization to modify the surface of bleached jute textiles, and it found that the change significantly increased the fabric's thermal stability, breaking strength, and dye ability [25]. The strength of the composite is heavily influenced by the length of the fiber. When different lengths of hemp fiber were compared—3, 5, 7, and 9 mm—and treated with acrylonitrile, samples reinforced with 5 mm fiber had the maximum tensile strength. Also, it is indicated that the composites' maximal strengths cannot be reached with just 3 mm of length [26].

1.3 Alkylation

Alkalization is the process of removing hydroxide groups from compounds, such as potassium hydroxide, sodium hydroxide (NaOH), and others [15, 16]. Many studies have examined the effects of treatment with NaOH on mechanical potency and some other characteristics of composite of natural fibers. All of them have demonstrated that the process alkalization is the most popular pre-treatment technique and may be used for natural green fibers that are entirely natural. Jute fiber has been treated

with alkali before being reinforced in the form of compound plates within the natural rubber matrix. After evaluating the mechanical properties, it was discovered that treatment with alkali improves more bonding (interfacial) among the jute fiber and natural rubber matrix. This significantly enhances the stress transfer process, increasing the composite's qualities including tensile strength, hardness, and tensile modulus [27]. To make composite samples, the polyester matrix is reinforced with vegetable fibers that have undergone an alkali treatment initially. It has been shown that the treatment with alkali also improves adhering bonding between fiber and matrix [2]. Before being reinforced in the epoxy matrix, three distinct green fibers—flax, linen, and bamboo—underwent an alkali treatment. According to a study, alkali reduced the flexile modulus and flexile strength of all three natural green fiber yarns. In addition, it is noted that bending-strength and flexile -strength and of the composites have increased by 16% and 22%, In comparison to samples that are untreated. It has been reported that treatment with alkali increased the adhesion strength between the matrix and green fiber [28]. On the other side, flax and linen treated with alkali increased their cohesive strength and torsion modulus of composites while decreasing their damping ratio and impact strength. As a result of the fiber and matrix's reduced interfacial adhesion following the alkali treatment, the damping ratio and impact strength have decreased [28]. Equation 1 depicts the green fiber's reaction in the process of alkalization.

$$Natural\ Fiber - OH + NaOH \rightarrow Natural\ Fiber - 0^{-}\,Na^{+} + H_2O \quad (1)$$

Equation 1 Reaction with the green fibers in the process of alkalization (31)

1.4 Peroxidation

Alkali has been used as a pretreatment on sisal fibers, and then H_2O_2 has been added. In order to create composite samples, the treated natural (green) fibers were strengthened in a polylactic acid matrix, and the mechanical properties of the samples were examined. According to the findings, peroxidation improved the composites' impact strength, tensile strength, and flexural strength. A testimony on treated fiber composites' enhanced thermal resistance, and it is further deduced that the treated fiber composites absorb water significantly less than untreated fiber composites do [29]. PPF (palm-pressed fiber) is given peroxidation and strengthened in a matrix of PBS (Poly Butylene Succinate)) in the form of a sheet. After testing, it was discovered that peroxidation has increased the tensile strength, fracture strain, and tensile modulus of sheets by 54, 43, and 830%, respectively [30]. With more exposure days, green fiber will absorb water at a faster rate. Because hemicellulose and lignin have been removed from the green fiber by peroxidation, composites reinforced with coconut husk are typically stable against water absorption [31]. One method for eliminating the lignin content from green natural fibers is to treat them with peroxide. As a result, the composites' thermal and tensile strengths are elevated

when peroxidized natural green fibers are applied as reinforcement [32]. Equation 2 depicts the reaction of the peroxide along with the green natural fiber.

$$\begin{aligned} &HO - OH \;\rightarrow\; 2HO' \\ &HO' \;+\; Natural\ Fiber - H \;\rightarrow\; HOH \;+\; Natural\ Fiber' \end{aligned} \tag{2}$$

Equation 2 The Reaction of the peroxide with the green natural fiber (31)

1.5 Benzoylation

Using a benzoyl chloride solution, benzoylation aims to improve all the significant properties of green fiber (C_6H_5COCl). The green natural fiber is first treated with Sodium-Hydroxide (NaOH) before being submerged for several hours in a benzoyl chloride solution. After that, the fibers are dried in an oven after being cleaned with distilled water. Equation 3. Depicts the chemical interaction between fiber and benzoyl chloride. Three distinct chemical processes—alkylation, peroxidation, and benzoylation—were compared in an examination of laminates reinforced with vetiver, and it was demonstrated that benzoylation was remarkably effective in increasing the composite's mechanical properties [2].

$$\begin{aligned} &Natural\ fiber - O'Na^{+} \;+\; C_6H_5C \\ &=\; OCI \;\rightarrow\; Natural\ Fiber \;-\; C_6H_5C0_2 \;+\; NaC1' \end{aligned} \tag{3}$$

Equation 3 Benzoylation process of green fibers (31)

1.6 Acetyl Treatments

Acetic acid and Acetic anhydride ((CH_3CO) 2O) are used in the process of acetylation (CH_3COOH). The green fibers are first alkalinized before this chemical treatment, which is then followed by acetylation. The green fiber's OH group is reacted with acetic anhydride during the acetylation process to produce acetic acid. Piassava fibers are mechanically characterized after acetic anhydride pretreatment. The outcomes show that the storage modulus of composites is mostly impacted by the treatment with the chemicals. The composites' glass transition temperature is lower, and the adherence of fibers to the matrix is better. At the glass transition temperature, chemical treatment has no effect on the storage modulus and is instead predominantly governed by the fiber volume percent [33]. During the creation of the composite, flax fibers were acetylated with acetic anhydride ((CH_3CO) 2O) and afterward strengthened in the polypropylene matrix. The acetylation procedure increases the inertness to water absorption by 50% and thermal stability by a significant amount, according

to a water absorption analysis on the manufactured materials. The degree of acetylation is acknowledged to be a key factor in determining mechanical strengths, and 18% acetylation is recommended for getting a maximum 25% increase in the flexural and tensile strengths of the composites [34]. One more study on the Musa fruit bunch fiber reinforced (PPC) polypropylene composites noted a similar pattern. In increasing the mechanical parameters and interfacial shear strength including impact strength tensile strength and tensile modulus, it has been found that the process of acetylation is superior to treatment with alkali. Also , the procedure of acetylation aided in ensuring that the fibers were dispersed uniformly over the matrix, preventing flaws like voids and micro holes, among others [35].

1.7 Enzymatic Treatments

One type of protein found in living things is an enzyme. In biological processes, enzymes are released by the source and work as catalysts to speed up reactions without altering the reaction itself. Helicase, lipase, xylanase maltase, laccase, lactase, amylase, trypsin, and other enzymes are among those present in living organisms. The treatments with enzymes considerably enhance the characteristics of green natural fiber during the creation of the composite, Xylanase and laccase, two different types of enzymes, are used for processing fiber before it is strengthened in a matrix made of (C3H6) n-polypropylene [29]. The hemicelluloses, lignin, and pectin found in green natural fibers are extremely effectively destroyed by enzymes, which reduces the diameter of the fiber and increases the aspect ratio of the fiber. Hence, the treatments with enzymes increase the area of the fiber or matrix contact, which improves the adherence of fiber to the matrix. A composite material's mechanical characteristics are improved through increased adhesion [36]. Enzymes also facilitate the spinning and weaving of the green fiber during the production of the cloth. The circumstances under which enzymes function determine a composite material's properties as well. It has been studied and determined that 45 °C, 4.5 pH, and 6 hours are the best conditions for banana fiber's enzymatic treatment [37]. Enzymes also facilitate the spinning and weaving of the green fiber during the production of the cloth. The circumstances under which enzymes function determine a composite material's properties as well. The optimal temperatures and pH levels for treating banana fibers with enzymes are found to be 45°C and 4.5, respectively, for a period of 6 hours [38]. Treatments with enzymes reduce the green fiber's diameter. When flaxseed fibers are tested after being treated with the enzyme (pectinase), this is learned. The fiber produces smooth fibers because of the pectinase enzyme removes pectin from the fiber. The rate at which wax in the green natural fiber is taken out at the time of treatment with enzyme varies on the exposure time. Pectinase is more appropriate for treating flaxseed fibers since prolonged treatment with enzymes is required to provide improved impact and tensile characteristics [39]. Treatment with enzymes increases the surface area of Linum fibers which are exposed to the matrix around

them, improving the fibers' thermal stability, water resistance, and crystallinity index [40].

2 Treatments with Chromium Sulfate and Sodium Bicarbonate

Lady finger plant fiber is segregated and then treated with alkali, chromium sulfate, and a mixture of chrome sulfate and sodium bicarbonate. Comparing the three methods demonstrated that while the other treatments reduced external coarseness by adding a thin layer to the fiber and strengthening the chemical bond between the cellulose in the fiber, the alkali treatment increased surface coarseness by removing hemicellulose (hydrophilic) that was already present in the fiber. Also, it should be highlighted that the surface treatments have boosted the fiber's tensile strength and tensile modulus. Tensile strength and Young's modulus decrease with increasing span length, but thermal stability does not change significantly. As compared to single-stage treatments and alkali, the complete performance of the double-stage treatment with chemical is determined to be the most satisfactory chemical treatment [41].

3 Hydrochloric Acid Treatment

Green fibers can also be pretreated with hydrochloric acid (HCl), another chemical, by soaking them in an aqueous solution of HCl for roughly two hours. The green fibers are then heated in the furnace after the treatment to eliminate moisture. Oil palm fibers that have undergone HCl treatment exhibit little swelling in the presence of moisture, which results from refinement in cross-linking density among the polymer and fiber. The dynamic mechanical characteristics, load-bearing capacity, and aging resistance of composites all improve because of this fiber-polymer interaction, this might be shown by improved storage modulus and a lower mechanical loss factor. As a result, HCl (Hydrochloric acid) is a useful chemical for improving the properties of composites strengthened with oil palm fiber [42]. Nevertheless, as compared to NaOH. HCl did not increase the (ILTS) inter-laminar cohesive strength of the kenaf (Guinea) fiber in the pull-out test of a single fiber. As a result of the hydrochloric treatment, fiber fails brittlely and ductility during the test [43].

4 Treatment with ($NaClO_2$) Sodium-Chlorite

($NaClO_2$), Sodium chlorite is used primarily to fade or bleach natural fiber in the solution of acid. Chlorine dioxide is created by $NaClO_2$ during the process. After that, hydrophilic hemicellulose and the lignin in the natural fiber react with chlorine dioxide, removing lignin from the fiber. Ultimately, fiber loses its hydrophilic quality and develops a hydrophobic quality. Delignification also increases flexibility and decreases the stiffness of the green fiber [44]. Together with increasing the hydrophobicity, $NaClO_2$ and alkali increase the tensile strength of the material and make it more suited for use in damp environments [45].

5 Conclusion

The basic properties of the natural fiber will be modified to make it more appropriate for reinforcing in polymer-based products. Several chemicals can be used to modify the surface of the fiber, each with a unique effect on the fiber. Inter-laminar shear strength, mechanical strengths, moduli, bonding ability, flammability, water and chemical retention, thermal strengths, and so on are examples of essential qualities. This is supported by research on a variety of fibers, including jute, banana, kenaf, flax fibers and others. Silanes and some other compounds, such as acetic acid acrylic acid, and other coupling agents, can also improve some of surface qualities of green natural fibers. Each one chemical has an enormous effect on increasing the fiber attribute. As a result, the choice of chemicals is determined by the normal implementation of natural fiber materials. Depending on the environment, two or more chemical treatments may be required to make the fiber suitable for use. Working factors such as chemical concentration, temperature, time, etc., must be taken seriously during treatments because they have a direct impact on the fibre's characteristics. As a result, prior to composite production, a chemical treatment with correct working conditions becomes more essential for green fibers.

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Noise Reduction Analysis in the Industrial Environment by Acoustic Materials



Charanjeet Singh and S. Deswal

Abstract Millions of individuals experience negative effects from noise pollution every day and it can cause stress and major health problems including permanent hearing loss. A significant research area is now focused on creating sound-absorbing materials that are effective and affordable for noise reduction in big spaces, buildings and vehicles. This paper show that the analysis of how noise reduction take place after addition of different type of material in CNC and Robotics lab of NIT Kurukshetra, under different operating conditions where individual and multiple machines operate. The machines in CNC lab are Maxmil, Maxturn and Handling Cell and in Robotics lab are Spot Welding Cell, MIG Welding Cell and TIG Welding Cell. For the purpose of taking readings sound level meter (CEL-620B1) was used. The reading was taken in accordance with IS 10988–1984 standards. The results were obtained before and after use of acoustic materials in individual and combination of machines are presented in form of tables and graphs and both the result were compared to measure the effectiveness of the acoustic materials. Glass and curtain were used as acoustic materials. Readings were taken at appropriate stations for each source and time interval depending on the nature of source. Multiple readings were taken on same station to avoid errors. In order to provide light on future research approaches towards enhanced acoustic materials, opportunities and challenges are explored while engineering applications from the built environment to the industry were done.

Keywords Acoustic material · Noise reduction · Combined noise · Sound absorption · Sound transmission loss (STL)

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1 Introduction

As we know that due to fast expansion of industrial operations, noise pollution has emerged as one of the most significant environmental problems facing by human society. Over exposure to noise is bad for health of people and animals. Noise pollution is defined by the World Health Organization (WHO) as noise exceeding 65 dB and the noise standards according to central pollution control board (CPCB) are mentioned in Table 1. The WHO states that prolonged or severe noise exposure has been linked to everything from hearing loss to cardiovascular disease, ineffective communication, poor concentration and sleep disorder. It is a known fact that urbanization, a lack of well-organized infrastructure, increase in population and increase in the number of industrial developments cause greater noise problems in the cities particularly in our country. Unfortunately, the maximum buildings do not have adequate insulation to block outside noise and they also contain a lot of internal noise sources however there are not enough methods for reducing noise for the community. Since noise has a major impact on urban residents so it has become the most talked environmental concern. Consequently, the development of effective acoustic or sound absorption materials is essential for noise abatement. Despite their common interchange in everyday conversation, the terms "sound insulation" and "sound absorption" have different meanings. Sound-absorbing materials aim to improve sound quality by reducing reflections and changing the direction of sound waves. Sound-absorbing materials don't reduce noise; instead, they absorb heat and improve sound quality by reducing echo and bothersome reverberation within a space. However, sound insulation blocks sound waves from entering or exiting a space, acting as an acoustic barrier to the source of the sound [1]. Porous and resonator materials are the two categories into which sound-absorbing materials fall. Sound waves can pass through porous materials because they feature interconnected pores, including polyurethane foams, nonwoven textiles and thermoplastic foams.

The frictional heating that occurs between the vibrating air molecules and pore surface is what essentially dissipates the sound energy. Additionally, the porous material wall contacts experiences energy transfer [2]. A sound wave can go through a material less or more deeply depending on the size of the pores.

Table 1 Permissible limits of noise levels laid by central pollution control board (CPCB)

Area/Zone	Category of zone	Limits in dB(A) L_{eq} Day Time	Limits in dB(A) L_{eq} Night Time
A	Industrial area	75	70
B	Commercial area	65	55
C	Residential area	55	45
D	Silence zone	50	40

Note Day Time 6:00 am to 10:00 pm and night time 10:00 pm to 6:00 am

The sound wave can pass through pores of the right size and be numerous times reflected within the pore, preventing it from being reflected back and allowing the material to absorb additional energy. A too-small pore size results in less energy transfer into solid materials and thus, less sound reduction foams and other porous materials have the advantages of relatively easy processing, low cost and a broad range of sound absorption [3–5]. The overall target of this study is oriented to reduce the noise problems which are caused by the excessive noise generated now a days and this is done with the use of acoustic materials which will damp and absorbs the noise vibrations as the form of heat as discussed above.

1.1 Literature Review

Author discussed about various properties, working mechanism and designing of different type of sound absorbing material such as Polyurethane foam, thermoplastic foam, nano fibers, fabric and textile-based material. Metamaterials are also discussed i.e., metallic foam and graphene foam. And also discussed the application of materials in automobile, interior and infrastructure. Material used is not eco-friendly and manufacturing cost of these materials is little bit high and here author do not try all type of combination of Acoustic materials. Author mentioned that sound reduction can be done by without use of acoustic material we can reduce noise by electrical signal and electromagnetic signals [6]. In order to improve the combination's ability to absorb sound, this paper discusses the use of multiple perforated plates (PP), air gaps, and coir fibre. Here, the absorption coefficient of each individual and combination was estimated using the Johnson-Allard model and Acoustic Transmission Analysis (ATA). Impedance tube measurements are made to confirm the analytical findings. Results indicate that the porosities of the applied PPs control the panel's absorption coefficient. Higher porosity allows sound to gradually enter and be absorbed in the inner compartments, whereas lower porosity of the face PP causes incident sound to reflect back. When two PPs are used in multilayer panels, low porosity inner PPs supported by an air gap yield the best results and here is the analysis that coir fiber is very good in sound absorption [7].

In this paper author find out the insertion loss [$IL = L_{wo} - L_{wc}$] in different type of enclosure at different ranges of the frequency. Enclosure is taken as rectangular box made up of aluminum and other one is fibrous glass covered with rockwool layers. Noise sources are taken as the loud speakers and noise source is kept inside the enclosure. The results are obtained by the theoretical model and are presented in tables and graphs how insertion loss varies with different range of frequencies [8]. This paper deal with the study of the combined noise and individual noise producing from 6 construction machines i.e., Breaker, bulldozer, excavator, pile driver, earth auger and payloader. L_{Aeq} parameter is used for the correlating the noise between combined and Individual of the machines. Here reading of 3 minutes is taken on binaural microphone and 30 people (19 male and 14 female) are selected of mean age of 23.6 year and all the people has to listen that recorded sound and give the rating

according to their experience. The rating scale consist reading 0 to 10 (0 means no effect and 10 means extreme) and for sound above 85 dB everyone rates it 8 to 9 [9]. In this paper author discussed about the metamaterials. Metamaterials are referred as the artificial composite material which consist of periodic arrangements and they are different from the conventional acoustic materials because they can reduce even very low frequency noise which is not possible by conventional one. Author discussed about the physical mechanism, classification and design trend of the metamaterials. They can be design by programing depending on the frequency of noise.

In this paper there is comparison between passive acoustic metamaterials and active acoustic metamaterials [10]. Here author calculate the acoustic properties of material i.e., sound absorption coefficient, airborne and impact sound insulation data. The material used are natural and recycled i.e., cotton, sheep wool, clay and rubber, plastic, carpet respectively. Analysis of the paper showed that airborne sound insulation of natural material i.e., recycled cellulose fiber is much similar to the glass. Bamboo and coco fiber show good sound absorbing performance and production of these material is easy and not has harmful impact on human health [11].

2 Methodology

2.1 Study Area

The study was carried out at Siemen Centre of excellence at NIT Kurukshetra, a lab used for teaching students and for researcher works containing CNC and Robotics section in Nit Kurukshetra, Haryana. Machines like Maxmil, Maxturn Plus used in CNC lab for cutting and finishing metal. A handling cell was present in the CNC lab for pick-and-place operations. On the other hand, in the Robotics lab, Spot Welding Cell, Mig and Tig Welding Cell are used for different types of welding. Figure 12.1 shows the CNC and Robotics machines. There are six machines three in CNC and three in Robotics lab. The running machines cause wear and tear to the equipment used for operations also welding and cutting of metals all make a contribution to vibrations which cause the noise in the work place [12]. These factors work together to increase the noise levels generated by machine tools. The sound Transmission loss (STL) is calculated on appropriate locations of the lab by using different type of the acoustic material. The Industrial Hall was marked with the following trade symbols for milling machines are 828D, KR10 R1420, KR210 R2700, KR10 R1420, KR16 R1610 and 828D.

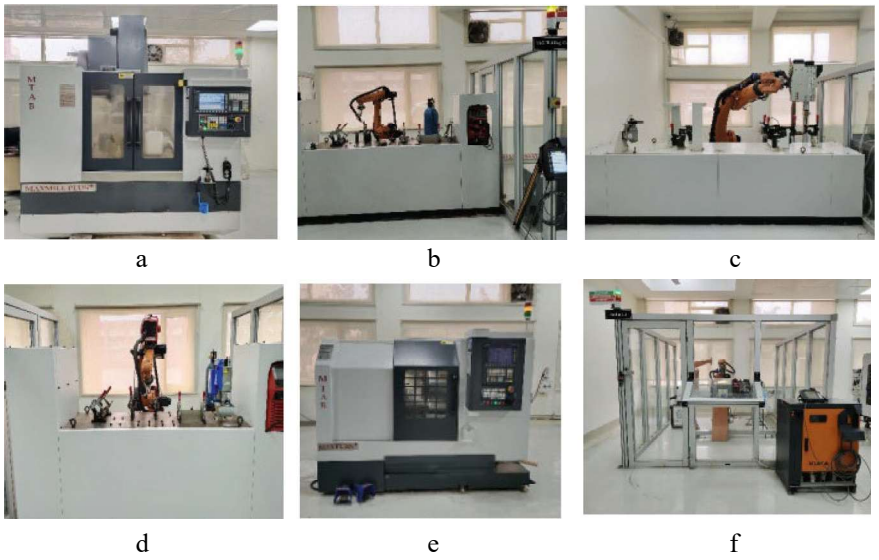


Fig. 12.1 Images of CNC and Robotics Machines **a** Maxmill, **b** Maxturn, **c** Handling cell, **d** Mig Welding, **e** Tig Welding, **f** Spot Welding

2.2 Instrument Used in the Study

Sound level meter (SLM) Casella CEL-620B1 was used, where 'B' stands for 1/1 octave band and 1 stand for class 1, to monitor noise levels in the CNC and Robotics lab at appropriate location. The instrument used to measure the noise levels in the "A" and "C" weighting network was held between 1.3 to 1.5 meters above the ground and between 3.0 to 3.5 meters away from any reflective surfaces [13]. Calibration was performed at 114 dB (A) both before and after sampling using a Casella CEL-120/1 class 1 acoustic calibrator.

2.3 Measurement and Analysis

Noise reading is taken at 5 stations shown in Fig. 12.2 around the machines with and without the use of different acoustic materials i.e., glass and curtain. These stations are selected so that maximum noise can be analysed. The thickness of the glass is 3mm and curtain is 1mm. The run duration of the SLM is 3 minutes so that machines get stabilize on a constant vibrations and variation of noise can be accurately monitored. The parameters are used for the calculation are L_{Aeq}, L_{Ceq}, L_{AFmax}, L_{ASmin}, LAF_{min}, L_{ASmax}, L_{Apk} and L_{Cpk} and mentioned in Table 2. Sound Transmission Loss (STL) is calculated by given expression (*Sound Transmission Loss Analysis on Building Materials*, n.d.):

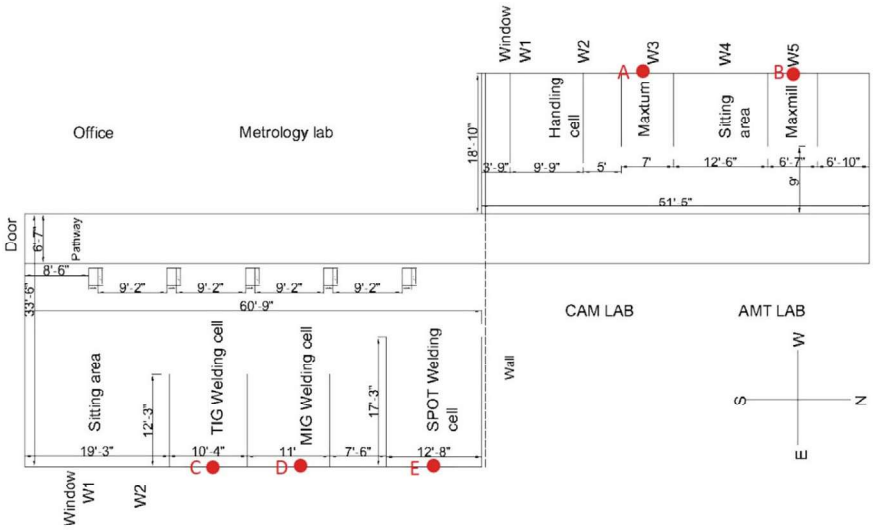


Fig. 12.2 Layout of the CNC and robotics lab with measuring points

Table 2 Observed noise levels

Stations	L_{Aeq}	L_{Ceq}	L_{AFmax}	L_{ASmax}	L_{AFmin}	L_{ASmin}	L_{Apk}	L_{Cpk}
A	77.3	78.5	85.3	81.6	73.1	73.2	97.4	98.9
B	75	79.3	82.5	78.3	69.8	70.4	94.6	97.4
C	61.53	64.02	73.9	68.3	58.1	60.1	90	91.2
D	78.32	77.43	86.2	85.3	54.2	56.8	109.3	107.9
E	67.58	68.96	77.2	73.8	57.2	59.2	89.8	90.4

$$STL(dB) = SPL_{Ref}(\text{dB}) - SPL_{tr}(\text{dB}) \tag{1}$$

SPL_{ref} = Noise without use of acoustic

SPL_{tr} = Sound after transmission

All the parameter are playing very crucial role while noise analysis that is L_{Apk} which shows that the maximum loudest noise generated on station may be for milli second but this parameter shows that value also and similarly the L_{AFmin} show the minimum value. Parameter used for STL calculation is L_{Aeq} (Equivalent Noise Level of weighted parameter A) and on the basis of the STL the efficiency of the acoustic material is determined. The machines are running on RPM (Revolution per minute) of 1500 and feed rate is 10mm/revolution. Cutting of Aluminum take place in the maxturm and maxmill while taking the readings. The noise monitoring is done on each marked location while the metal cutting and welding process is going on and at

each station three set of reading should be taken so that chances of error will be not there [14]*: Method of Measuring Noise from Machine Tools (Excluding Testing in Anechoic Chambers)*, n.d.). The L_{Aeq} of three reading is calculated by the following formula [15]:

$$L_{eq} = 10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} 10^{\frac{Li}{10}}\right] \tag{2}$$

n = Number of readings

L_i = Noise Level

From the recorded reading set of three the logarithmic value is calculated on the basis of expression 2 and the final calculated value is used for the calculation of the STL. For the others parameters the maximum values are choose for max and minimum for min and that analysis shows the variation of overall parameters with noise standards for industrial standards.

3 Result and Discussion

The noise levels are recorded at different stations and different parameters are recorded mentioned in Table 2 and graphical analysis is mentioned in Fig. 12.3. The highest peak value is 107.8dB at station D and minimum peak value is 88.1dB at station C of A weighted network. As we know the 75dB is industrial standard according to CPCB but here some stations noise levels are crossing the standards.

Sound Transmission Loss (STL) is calculated in Table 3 and the graphical representations are shown in Fig. 12.4.

In the Fig. 12.4 blue curve show that the variation of noise without using any material. And after using curtain as acoustic barrier noise reduction take place and that variation is mentioned by red curve. Purple curve shows variation of noise after using glass. The straight dotted line is the standard noise level mentioned by CPCB for Industrial environment is 75 dB for day time.

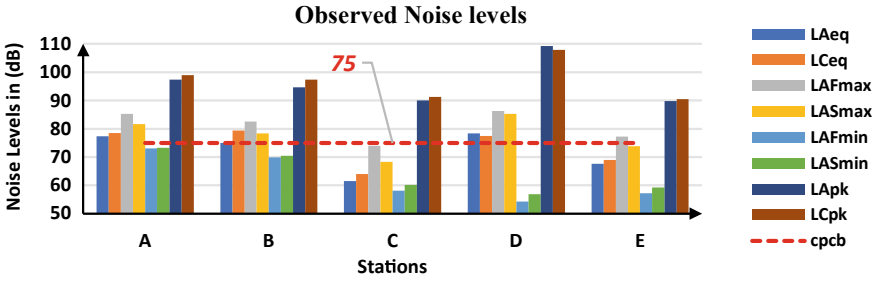


Fig. 12.3 Measured noise levels

Table 3 Sound transmission loss

Stations	L_{aeq}	L_{aeq} (Curtain)	STL (curtain)	L_{aeq} (Glass)	STL (Glass)
A	77.3	72.2	5.1	53.8	23.5
B	75	70	5	56.8	18.2
C	61.53	57.57	3.96	47.27	14.26
D	78.32	73.52	4.8	60.52	17.8
E	67.58	63.4	4.18	51.78	15.8

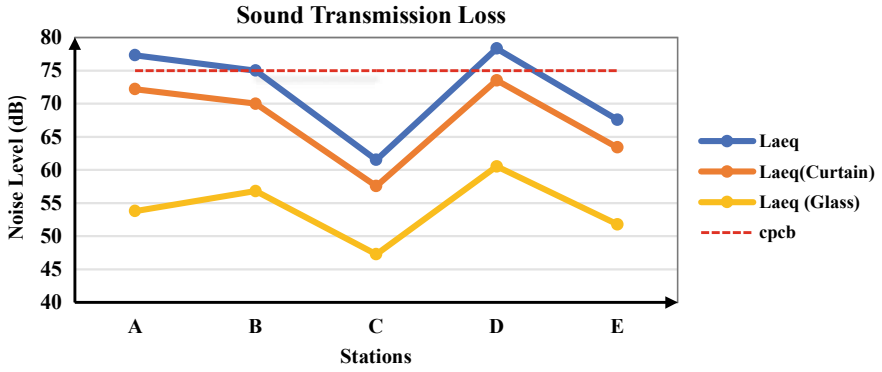


Fig. 12.4 Variation of STL

4 Conclusion

Here, the sound transmission loss by using glass and a curtain varies at different stations depending upon the intensity of the noise, the STL at stations A, B and D is higher than that at stations C and E. On stations A, B and D the noise levels are crossing the CPCB standards but by using acoustic materials, the noise levels fall under the permissible range. The STL values are 5.1, 5, 3.96, 4.8 and 4.18 by curtain on stations A, B, C, D and E respectively. Similarly, STL values are 23.5, 18.2, 14.26, 17.8 and 15.8 by glass on station A, B, C, D and E respectively. The STL values of curtain are not much higher but still it can use as acoustic material as it is very hard in nature so don't cause hindrance while working hours in the industry. And both together cause enough reduction so that noise fall under CPCB standards. As this is situated in NIT Kurukshetra educational institute, there should be a silence zone near classes and offices. So, there is a very much role for the acoustic material so that internal noise in the industry do not go outside and create noise. Here, proper glasses and curtains are used for sound reduction but the operator working inside should wear ear protection while operating the machines.

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Performance Assessment of Coir Geotextile as Green Geosynthetic in Improving Soil Subgrade—A Review



Harrajdeep Singh, Davinder Singh, and Sanjeev Kumar

Abstract The construction sector accounts for 39% of global carbon emissions, so global attempts are being made to decarbonize this sector. Geosynthetics is one such field, traditionally utilizing polymeric resins, which are neither energy-efficient nor sustainable. Herein, Coir geotextile (CGT) is considered an ideal green geosynthetic. Comparative studies of natural fibers under-line their relative advantages. Coir Fiber (CF) is composed of lignocellulosic material that imparts strength, durability, and ductility while keeping it sustainable and economical. Its role is suitable for low-cost construction applications, including strengthening soil subgrade. This paper has reviewed the existing scholarship to examine the soil-coir geotextile interactions. Experimental investigations suggest that the subgrade's dry density, shear strength, and CBR increase noticeably while moisture, settlement, and plastic deformation decline with CGT reinforcement. This study suggests geotextile placement above the subgrade, which aids soil consolidation while reducing pavement thickness due to enhanced subgrade characteristics.

Keywords Coir fiber · Green geosynthetics · Decarbonization · Lignocellulosic fiber · Soil subgrade

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1 Introduction

Environmental concerns have taken center stage in the global geopolitics. The latest estimates set the emission levels to 33.8 Gt in 2022 against 23.1 Gt in 2000. Considering the sectoral analysis of CO_2 emission contribution, a major contender is the Construction Sector, accounting for 39% of global emissions in 2018 [1]. Hence, to effectively realize the goal of Carbon Neutrality, it becomes imperative to decarbonize this sector as a primary weapon for a clean climate.

The emerging crisis has renewed interest in the field of Green geosynthetics. These are made of naturally occurring materials or eco-friendly, biodegradable polymeric resins that maintain performance throughout use, including strength, durability, and hydraulic properties. Afterward, they decompose, leaving minimal negative impact on the soil structure beyond the service time. One of the main components of green geosynthetics is lignocellulosic Fibers, as opposed to artificial Fibers primarily used in traditional geosynthetics. Figure 1a provides a comparative assessment of artificial and natural Fibers. It can be noted that coir fiber is durable in tension, with minimal warming potential, even in comparison to other natural fibers.

Considering the focus on Coir, its global annual production has been approximately 650,000 MT, in which India accounts for a staggering 46% of production (FAOSTAT). Due to its abundance, it has found wider usage in fertilizers, ropes, and brush industries, while in the construction sector, it is used as an insulator, sound absorbent, or geotextile soil reinforcement. Therefore, considering its unique potentialities in the decarbonizing construction sector, with competitive physical properties and comfortable economic advantage, it becomes a potential candidate to be explored as a green geosynthetic material.

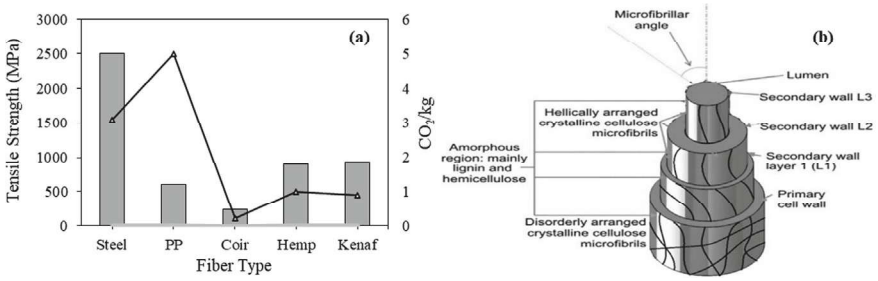


Fig. 1 **a** Tensile strength (MPa) and CO_2/kg emission of fiber [2-4] and **b** Lignocellulosic structure of coir fiber

2 Coir Fiber

Coir Fiber (CF) has a cylinder-like structure consisting of three components—a lumen in the middle, a secondary wall in the inner periphery, and a primary wall at the outer end (Fig. 1b). The primary wall is principally an amorphous region consisting of pectin, lignin, and hemicellulose with proneness to swelling. The secondary wall (L) is further distinguished in the L1, L2, and L3 layers. Herein, cellulose is abundantly available. The microfibrillarangles (MFA) point to the angle made by cellulose microfibrils with the cell axis.

According to Djafari Petroudy, a fiber's strength in tensile is directly correlated with the cellulose content in Fiber and has an inverse correlation with MFA [6]. Thus, in consideration of high MFA (30–50˚) and low cellulose (32–44%), CF exhibits relatively inferior tensile strength against its natural fiber counterparts (Table 1); however, its higher strain at failure (29–51%) underlines a better ductility with characteristics comparable to Steel.

Furthermore, Coir has a high lignin content (40–45%). Since lignin depicts a hydrophobic nature, its high content makes Coir better resistant to wet conditions and fungi against other plant-based fibers. It directly correlates with enhanced durability, raising the service life of Coir Fiber in a range of 1–3 years while all other fibers degrade in a shorter span of approximately one year only [7]. Hence, based on inferred evidence, CF's mechanical performance in wet conditions can be comfortably acknowledged, further affirming its suitability in tropical weather conditions. Since durability is a significant factor when applying any reinforcement material, Coir becomes a suitable candidate.

3 Coir Geotextiles (CGT)—A Green Geosynthetic

One of the prominent families of geosynthetics is geotextiles. These are textiles in the conventional sense, primarily composed of engineered fibers. However, they are also prepared to utilize natural Fibers. Developing embankments and pavements on soft soil are among the most common geotextile applications [10]. The critical concern on rural roads is rutting, which causes subsequent potholes caused by defects, particularly in the subgrade layer. The usage of polymeric geotextiles has been observed to address the problems above significantly. Despite the wider accessibility of these geosynthetic solutions, the volume of carbon footprint makes its application unsustainable. Thus, recognizing green geosynthetics necessity, the government of India recently included CGT in the construction of rural roads under PMGSY-III [11]. The Indianized connotation of this geotextile is "Coir Bhoovastra," prepared according to the BIS standards test code IS 15868 (Part 1–6)—2008 [12]. A coir bhoovastra has three main functions on unpaved road constructions—Filtration, Separation/Drainage, and Reinforcement. The properties of Coir Bhoovastra have been provided in Tables 2 and 3.

Table 1 Typical characteristics of selected natural fibers

Fiber	Biochemical characteristics			Physical and Mechanical characteristics					References
	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Service Life (years)	Moisture gain (%)	Tensile Strength (Mpa)	Microfibril-larangles (u)	Failure strain (%)	
Coir	32–44	0.1–0.3	40–45	1.0–3.0	5.0–13.0	110–250	30–50	29–51	Kumar et al. [4], Chandrasekaran and Rmakrishna [8], Noaman et al. [9]
Jute	61–72	12–25	11–13	1.0	12–14	310–850	6–10	1.0–1.8	Yan et al. [3], Noaman et al. [9]
Sisal	60–78	10–15	7.5–12	0.5–1.5	9.5–14.0	501–960	10–20	1.0–7.5	Yan et al. [3], Chandrasekaran and Ramakrishna [8], Noaman et al. [9]
Flax	60–79	15–21	2–2.5	0.5–1.5	8.0–12.5	300–1500	5–10	1.2–3.5	Yan et al. [3], Chandrasekaran and Ramakrishna [8], Noaman et al. [9]

Table 2 Properties of coir geotextiles (CGT)

Parameters		Range of values	References
Mass per unit area, ρ_A (g/m^2)		365–1286.56	Subaida et al. [10], Subaida et al. [13], Nithin et al. [18]
Thickness (mm)		6.46–9	Subaida et al. [10], Subaida et al. [13], Nithin et al. [18]
Tensile strength (kN/m)	Warp	9.08–36.00	Subaida et al. [13], Lal et al. [14], Bhole et al. [16], Sayda et al. [19]
	Weft	7.5–20.70	Subaida et al. [13], Lal et al. [14], Bhole et al. [16], Sayda et al. [19]
Failure strain (%)	Warp	10.30–36.12	Subaida et al. [13], BIS for Coir Geotextile; Bhole et al. [16]
	Weft	9.70–31.45	Subaida et al. [13], Lal et al. [14], Bhole et al. [16], Visvanathan et al. [17]
Number of ends/dm		4.6–18.90	Subaida et al. [10], Bhole et al. [16], Visvanathan et al. [17])
Number of picks/dm		3.9–10.90	Subaida et al. [10], Subaida et al. [13], Bhole et al. [16], Visvanathan et al. [17]
Puncture Resistance (N)		440–920	Visvanathan et al. [17], Nithin et al. [18]

3.1 Tensile Behavior and Failure Strain of CGT

It had been experimentally determined that a woven CGT with a higher ρ_A value, lesser aperture size, and placement position of CGT positively correlates with tensile strength. Moreover, CGT displays better strength in the longitudinal/warp direction than in the transverse/weft direction. It is possibly due to the higher yarn thickness and quantitative value of yarns in that direction. Subaida et al. [13] found that the high interface friction creates efficient interlocking of CGT with subgrade resulting in increased stress resistance. The similarity is also noticed in the failure strain of CGT with dependence on ρ_A value, weaving patterns, thickness, and variation in strain rate. The failure strain increases with a higher ρ_A value in the warp direction, while there is no clear trend in the weft direction [13].

3.2 Durability Studies of CGT

Studies on strength degradation at three different pH levels (5, 7, and 9) have shown that the alkaline media significantly impacts the loss of strength (45%), enhancing the degradation rate relative to acidic or neutral conditions. This is due to removing the waxy coating over the CGT surface when subjected to alkali action, leading to more

Table 3 Properties of Coir Geotextiles (CGT)

References	Parameters studied/ Tests conducted	Optimum Geotextile Location	Remarks (↑—improve, ↓—reduce)
Subaida et al. [13]	Placement position, geotextile stiffness	H/3 of base course thickness	↑ Bearing strength, ↓ Plastic surface deformation
Harinder et al. [20]	CBR, wheel tracking test	H/2 of sub base	↑ Bearing strength, ↓ Plastic Deformation, Slow Settlement, ↑ Service Life, ↓ Maintenance cost
Sumi et al. [21]	Surface treatment	–	↑ Long-term performance and durability
Lal et al. [14]	Form of geotextile—planar/ geocell	H/4 of soil layer	Geocell is 35% better than the Planar form of reinforcement
Tiwari and Satyam [14]	Lime treatment	Interface	↑ Shear strength, ↑ Bearing strength, ↓ Upward swelling pressure, ↑ Angle of shearing resistance, ↓ Pavement thickness
Subaida et al. [13]	Pullout and shear test	Interface	↑ Pullout resistance, ↑ Shearing strength, ↑ warp / longitudinal direction
Visvanathan et al. [17]	Properties of geotextile	–	High mass/unit area (ρ_A), high tensile strength, and less aperture size are preferred
Sayda et al. [19]	Deflection test	–	↑ Rigidity, ↑ Load-bearing capacity, ↓ deflection
Nithin et al. [18]	Settlement	Interface	↑ Bearing strength, ↓ Settlement
Tiwari et al. [22]	Swelling of soil	–	↓ Upward swelling pressure and expansion of clay
Babu et al. [23]	Cost optimization and bearing capacity	Interface	Increased thickness of layer reduces membrane effect

excellent moisture absorption. Pre-treatment of CGT provides an additional coating that reduces strength loss up to 17–23%. Additionally, the geotextiles remained immune from saline exposure and durable to rigorous freeze-thaw and wet-dry cycles. However, the studies show significantly reduced strength losses with changing CGT's placement position. It is due to the higher moisture content and microbial activity that leads to rapid strength deterioration, while CGT at greater depths is exposed to biologically less active soils [21].

3.3 Mechanical Behavior of CGT

The CGT-reinforced soil's bearing capacity was shown to be higher than that of the unreinforced soil in the results of monotonic and cyclic load testing [4, 13, 20]. The reinforced section's bearing capacity increased between 40 and 75% compared to the unreinforced. Subgrade improvement is a function of various parameters, including the subgrade type, CGT position, ρ_A value, etc. To illustrate, placing CGT at H/3 depth rather than at the base-subgrade interface may increase bearing strength by about 66.8% [24].

Additionally, studies observe that the thickness of the upper pavement layers has an inverse relationship with the improving CGT reinforced section's bearing capacity [14]. The CBR value of CGT reinforced subgrade could rise to 121% greater than that of unreinforced under both soaked and unsoaked situations. This could be due to changes in the dry weight of soil and the load spread across a larger area [13]. Applying CGT might significantly lessen plastic deformation and elastic-plastic settling by 15–87% and 40–60%, respectively [13, 19]. The development of these parameters is similar to trends in bearing capacity. This finding suggests that CGT with a higher ρ_A value (greater than 700 g/m^2) is preferred for strengthening soil subgrade applications [13].

4 Conclusions

The review attempts to scientifically address the utility of CGT in strengthening subgrade. Experimental data reveals CGT's potential as a green geosynthetic material and holds promising results in enhancing the mechanical behavior of village roads. The presence of cellulose, hemicellulose, pectin, and lignin in fibers impacts their overall physical and mechanical characteristics. Besides, the environmental and soil parameters typically influence the quality of Fibers. Due to its strength and durability, Coir is the preferred lignocellulosic Fiber for making green geosynthetics across all natural Fibers. It allows Coir to display higher resistance to microbial deterioration than other lignocellulosic Fibers. The variables that control CGT's strength are the durability of CGT, the thickness of CGT, ρ_A value, strain rate, the position of placement, chemical treatment, aperture size, and weaving patterns. According to laboratory tests, the subgrade's dry density, shear strength, and CBR increase noticeably, while moisture, settlement, and plastic deformation decline with CGT soil reinforcement. This study suggests geotextile placement above the subgrade, which aids soil consolidation while reducing pavement thickness due to enhanced subgrade characteristics.

5 Competing Interests

The authors have no competing interests to declare relevant to this article's content.

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Technology in Pursuit of Maternity Wearables



Rupika Nanda and Neha Sah

Abstract Maternity clothing has become a popular trend among Indian women in the past few decades. Initial developments that happened in maternity wear were mostly focused on adding volume to clothing by introducing gathers or excess fabric to support physical growth with less scope for styling. The idea was more about concealing the grown body silhouette with loose maxi kind of dresses. The clothing range was further improved with the use of stretchable fabrics which gave freedom to introduce more style features while balancing comfort for pregnant women. Adaptability, comfort, and style were found to be some of the key features summarized by researchers who have been working to explore the needs, psychology, and physiology of women during and post-pregnancy periods. As we have stepped into the technological era, the wearable device industry is revamping the market for maternity wear and care. To monitor the health and physical activities of the mother and the fetus, as well as to lower risk during pregnancy, numerous wearable sensors and gadgets have been developed. While some wearables concentrate on the mother's health and physical activities, others monitor the fetus's development and growth. Many maternity wear companies are incorporating smart fabrics into their designs, which are breathable, moisture-wicking, and support the mother's growing belly. This paper explores and interprets the emerging trends and current state of knowledge in health care textiles for smart maternal services, woman's expectations towards maternity wear, and the present market scenario of maternity clothing.

Keywords Pregnancy · Maternity wear · Wearable technology · Health sensors · Smart fabrics · Antenatal care

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1 Introduction

Each year, more than 200 million women throughout the world become pregnant [1]. Every year, almost 140 million babies are born. In 2019, less than 81% of births were attended by trained medical workers [2]. A time of life that entails quick physiologic and behavioral changes is pregnancy [3]. Lifestyle, behavior, and physical activity can have an impact on both the mother's and the fetus' health throughout pregnancy. Therefore, if there is a risk or a complication develops, regular monitoring is frequently needed [4]. Pregnancy problems pose a serious threat to both the mother and the unborn child's health, increasing the likelihood of outcomes like miscarriage, premature birth, stillbirth, and low birth weight. Every year, problems related to childbirth kill over 295,000 women globally [2].

The increased body proportion lasts for several months after the child is born, until she regains her original body proportion. Clothing is one of the most pressing issues that pregnant women dealing now a days. In today's fast-paced world, a pregnant woman who goes shopping, to work, or to a party prefers clothing that is both comfortable and easy to care for [5]. Pregnant women require clothing that is as comfortable, non-demanding and as easy to maintain as possible. Many devices and sensors have been created to remotely monitor health states and measure health parameters in everyday surroundings thanks to recent advancements in communications and technology. Mobile apps, wearable sensors, and other wireless devices like smart watches create new opportunities for tracking behavioral and physiological events [6]. These tools make it possible to reliably monitor biometric data such as blood pressure, heart rate, blood glucose level, and others [9].

Technology also gives expectant mothers all the resources they need to keep track of their pregnancies. By enabling pregnant patients to communicate with doctors from the comfort of their homes, it helps to cut down on in-person appointments. To give the comfort with specially designed clothing and embedded technology into the garments the needs and problem areas has to be understood. Physiological changes take place during pregnancy to support the growing fetus and get the mother ready for labor and delivery. While some of these modifications affect biochemical levels that are considered to be normal, others may resemble symptoms of a medical condition. Aside from the standard changes, the exact changes during pregnancy are dynamic and vary from person to person. Several studies have been conducted over the years to examine the bodily changes that the mother goes through during the pregnancy phase [10-12].

Considering the growing reach of technology in every spheres of human life it is imperative to critically review its application in maternal healthcare. The paper begins by exploring and interpreting the emerging trends & current scenario in health care textiles for smart maternal services followed by women's expectations towards maternity wear and in the last section summarizes about the present market scenario of maternity clothing. A woman's life is fundamentally changed by pregnancy and with increasing self-awareness, the integration of tech with maternal wear can promote two-way communication between expecting mothers and doctors while significantly

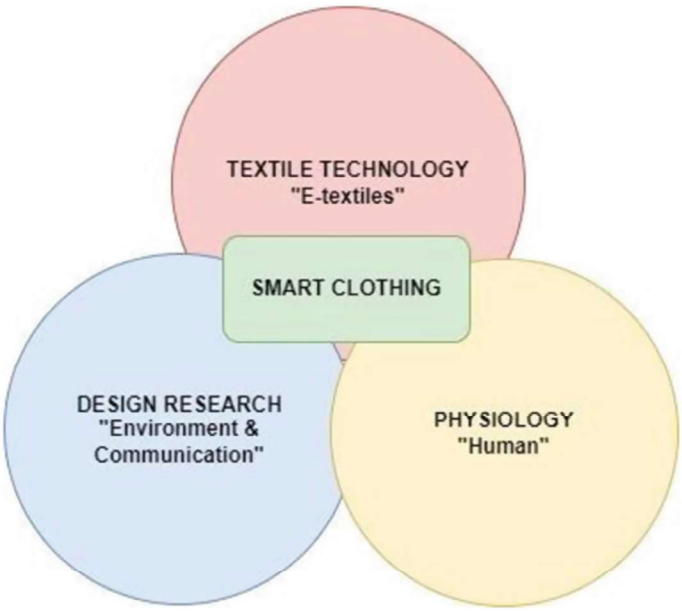


Fig. 1 Multidisciplinary approach to smart clothing [35]

reducing the workload of medical staff, increasing work efficiency, and making it easier for pregnant women to keep a track of their health while ensuring a safe growth environment for the unborn child.

Emerging trends and current state of health care textiles for smart maternal services

By incorporating sensors and data-transfer devices into textiles or fabrics, many wearable technology products have been created. These new wearable electronic system classes are created to meet cutting-edge consumer applications in the sectors of sports, military, public safety, fitness, and healthcare [13]. For a very long time, clinical practice has made extensive use of wearable mobile medical devices [14]. Sphygmomanometers, oximeters, and routinely used electrocardiographs, for instance, are all portable and usable. Data can be read and analysed by computers once a patient has been found. In the age of information and digitization, this category of equipment is referred to as the first generation of wearable medical devices. They produce tremendous clinical medical value; however, their utility and comfort are still a matter of discussion and improvement. Most consumer-based wearable technologies available today do not specifically target pregnant women. Instead, they assess physical activity, track other lifestyle changes, and continually monitor physiologic indicators (including blood pressure) [15].

The most difficult issue from a textile perspective is the compatibility of different qualities in technology and clothes. Figure 1 illustrates the integration of textile

technology, design research, and physiology contributing to the multidisciplinary nature of smart clothing.

1.1 Textile Technology

Most primitive attempts to present customers with satisfactory products have been odd looking. The infusion of technology with good outer aesthetics has been a key challenge as these two are considered oddly apart from each other. For instance, if a portable gadget, such as a laptop computer or a cell phone, requires a longer power supply, it must also be equipped with large, unsightly batteries [16].

1.2 Design Research

User-centric designs are crucial for developing smart products. Abstract ideas transform into reality with the right design approach. Though design requires creativity, the steps leading to great designs can be controlled and made apparent [18, 19]. A personalized more accurate user experience can be achieved by intelligent integration of technology with design aesthetics during the design development phase itself [18].

1.3 Physiological Consideration

Practical clothing that serves both function and comfort must be the base of smart clothing design. The integration and application of smart techniques should neither introduce unnecessary burdens to the wearer nor hamper their mobility [20].

Smart clothing, also known as e-textiles or smart textiles, has been an evolving field that integrates technology with traditional textiles. This involves embedding sensors, data transfer devices, and other electronic components into fabrics to add functionalities beyond traditional clothing. Here are some relatable studies mentioned below:

Pregnancy-related wearable technology gained popularity in major American and European hospitals during the 1990s. They gradually left hospitals after 2010 and joined families. With the use of big data [35] and cloud computing [36, 37], they were enhanced to provide more focused and individualized care, moving the focus of mother and child healthcare from treatment to prevention. A study conducted in 2021 in which author presented a cutting-edge and innovative Internet of Things (IoT) paradigm for intelligent maternal healthcare services utilizing wearable technology and related technologies [38]. It also explores its applications and monitoring and management modalities in hospital obstetrics departments at home.

In another study [39] two smart textiles products were introduced- the belly band and the baby band with focus to replace the medical devices in hospitals, clinic and home. The belly band is a band of cloth that covers a pregnant woman's lower abdomen and is worn like a "tube top," as the name would imply. Using a tiny RFID chip sewed into the belly band, the threads function as antennas, transmitting data regarding fetal heart rate and uterine contractions to other computer knowledge systems. The baby band which is still in progress, a band which collects the data and send to parent's smart phone, to a baby monitor or to hospital data systems and staff. Both bands did medical monitoring of mom and baby at home and in every day's life. In 2019 additionally [40], a device "Lifebelt" designed for monitoring parameters such as abdomen growth, maternal heart rate, oxygen saturation, blood pressure, temperature, and weight suggests a comprehensive health monitoring system for pregnant women which is as protective as predictive too. A recent study conducted by the researchers [41], in which a device was introduced named chest strap device and with the help of the device activity tracking can be done which means step count and heart rate.

In some recent studies [42] the adoption of Industry 4.0 principles has the potential to transform industries, making them more efficient, adaptive, and technologically advanced. However, it also presents challenges related to data security, workforce skills, and the need for substantial investments in technology infrastructure. As Industry 4.0 heavily relies on the Internet of things (IOT) and Wireless sensor networks (WSN). The integration of IoT (Internet of Things) and WSN (Wireless Sensor Networks) in various control systems for applications such as environmental monitoring, home automation, and chemical/biological attack detection.

Women's expectations towards maternity wear

Maternity clothing is typically cut loosely with elastic, tabs, and stretchy materials like elastane and spandex to give the wearer greater comfort throughout her pregnancy. Many women continue to wear maternity apparel after giving birth until they have dropped the pregnancy weight and can once again fit into regular clothing. This is a key factor in why a mother's need for this niche continues long after her maternity leave (Fig. 2).

Maternity clothes are important for the mother's feelings as well as the unborn baby's comfort. Pregnancy is a wonderful time in one's life, and it's important to dress appropriately. Clothing that is cut to accommodate the growing belly and does not cut off circulation is critical. Too-tight clothes that constrict are bad for the physical and mental health, as well as a display of your proud accomplishment to the rest of the world [21].

When determining the best maternity apparel based on the preferences of pregnant women's age groups, it has been shown that younger women are more concerned with cost and contemporary design than older women. However, it was crucial for older women to ensure the safety of the mother and the fetus [22]. Many social theorists believe that the body is a crucial aspect of self-definition in modern Western culture, especially considering consumer culture's emphasis on the body's outward appearance as a carrier of symbolic worth [23] [24].

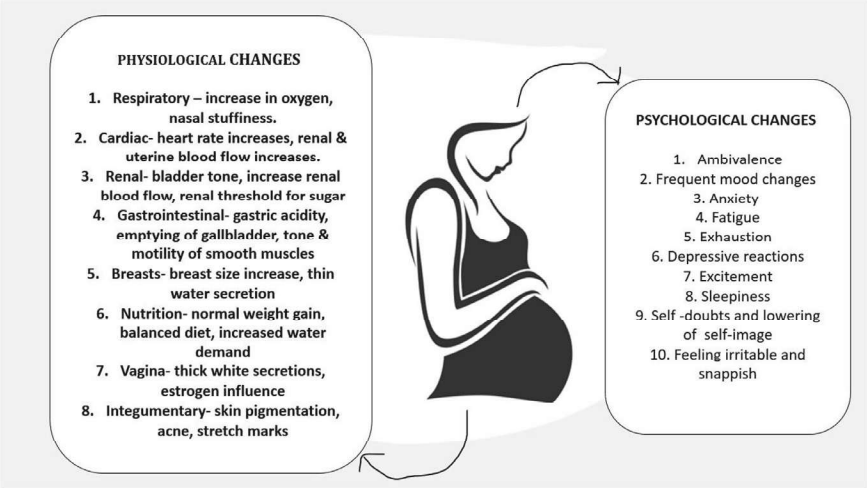


Fig. 2 Physiological and psychological changes during pregnancy. From [11, 16]

It has been claimed that an individual's sense of identity, values, attitude, and mood all have an impact on how they dress [25]. The importance of body image in relation to clothing was recognized by the author [26], who included a body image dimension in the proximity of clothing to self-scale. They claimed that clothing can affect body image and self-esteem whereas clothing can affect body image and behavior when it comes to dressing. Therefore, our perception of our bodies affects how we dress.

Customers frequently experience frustration while trying to find clothing that is both comfortable and fits them well [27]. Because it is usual for women going through their first pregnancy to be uninformed of the changes that their bodies will go through throughout pregnancy, pregnant clients struggle even more to find well-fitting clothing. Furthermore, every woman's body changes during pregnancy differently. For instance, it is usually difficult or impossible for petite and large-framed women to obtain maternity wear that fits their body types and caters to their individual demands [28]. Cotton cloth, according to Shaft, should be used in maternity wear. He believes that this type of clothing is fluffy, gives the user a sense of comfort, and effectively balances heat and humidity. Furthermore, the permeability of cotton clothing eliminates the need for proper ventilation due to increased perspiration during pregnancy. Woollen cloth has also been suggested for preparing close fitting garments for winter clothing because such clothes keep the body temperature constant and help maintain the body temperature by absorbing [29].

Based on women's needs and expectations, various designs for maternity clothing have been proposed. One of the proposed designs, dubbed 'durable' clothing, has been suggested to continue wearing maternity clothes after pregnancy. Stretch fabric is used in this design to accommodate body changes during pregnancy while exposing the body to the least amount of pressure [30].

The present market scenario of maternity clothing

According to the Mylo survey, the popularity of maternity clothing among Indian women increasing day by day, however, the market lacks fashionable and inexpensive solutions [32]. From the standard slouchy maxis, maternity fashion has advanced significantly. If celeb-inspired fashion is any indication, maternity is the time to step up your personal style. Mommies-to-be, allow us to lend a helping hand if those social media images of Sonam Kapoor and more recently Alia Bhatt, both of whom are expecting, are inspiring you to purge your closet of out-of-style clothing and go shopping. Shop from these leading Indian companies for beautiful, comfortable pregnancy clothes that will only enhance the baby's radiance [33] (Table 1).

From global perspective:

From 2021 to 2028, the size of the global maternity wear market is projected to grow at a CAGR of xxx. This market is growing due to a variety of causes, such as an increase in the number of working women, more breastfeeding awareness, and rising demand for high-end maternity wear.

Pregnant women wear maternity clothing while they are carrying a child. A woman's wardrobe needs to be changed to accommodate the numerous changes her body goes through throughout pregnancy. Maternity clothing comes in a wide variety of styles, including dresses, shirts, bottoms, and lingerie. Maternity clothing should be stylish as well as comfortable. Many expectant mothers want to feel secure and look nice during their pregnancies. They are capable of doing that with the proper maternity clothing (Fig. 3).

Table 1 Online Source; Women's fashion from [33]

Sr. no.	Name of the brand	Brands and their offering under maternity wear
1.	House of Masaba	This brand deals in casual as well as occasion wear maternity clothing which includes Anarkalis, Dresses, Kaftans, Shirt, Tops, Kurta dresses, Sharara sets and Palazzo sets
2.	Morph maternity	This brand offers comfortable range of maternity work wear along with a box set of essentials including anything from pregnancy pillows to back support belts
3.	Mama couture	This brand contains beautiful, cozy and considerable clothing for the postpartum phase in which nursing apparel and belly control trousers are include
4.	Momzjoy	They offer tops, bottoms, nursing gowns, kurtas, swimwear, bottoms, and new mother necessities. (Nursing stoles, diaper bags, nursing bras)
5.	Mystere Paris	To accentuate the growing baby belly this brand offer dresses, bottoms and shirts with interesting prints and bold colors
6.	The mom store	This brand offers both casual maternity and nursing dresses in classic design and colors
7.	Mom to be	This brand offer variety in Kurta which can be worn as casual wear as well as for ethnic purpose having regard to the tummy area

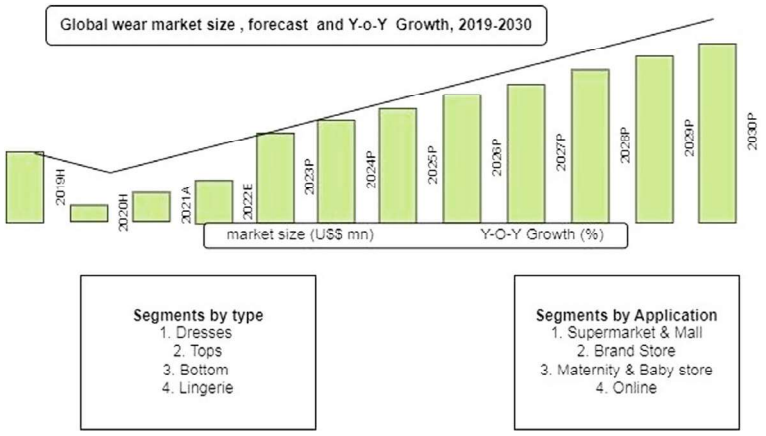


Fig. 3 Maternity wear market report, global forecast 2020–2030 [33]

From Indian perspective:

The evolution of maternity wear as a distinct and fashionable category is indeed an interesting aspect of the fashion industry. Until a few years ago, maternity wear was often limited and not as widely available or stylish as regular clothing and maternity wear reflects a broader trend in the fashion industry towards inclusivity and recognizing the diverse needs of consumers. It also underscores the significance of understanding and catering to specific life stages and experiences, such as pregnancy, within the realm of fashion.

If reports are to be believed, the Indian market for maternity wear is estimated to be around Rs 2000 crore and is expected to expand at a compound annual growth rate of 15–17%. In fact, according to a Statistic analysis, the global maternity wear market is expected to reach USD 7 billion by the end of 2023, up from USD 6.1 billion in 2016. During the projection period of 2016–2023, this represents a compound annual growth rate (CAGR) of almost 2%. These figures suggest that India has jumped on the maternity clothing bandwagon and is catching up faster than before. This indicates that the new category that is emerging inside the retail fashion market has a ton of potential.

High-street clothing has suddenly become more popular, and modern consumers' growing demand has put pressure on companies and stores to up their game and offer chic, stylish looks without sacrificing comfort. The days of expectant mothers hiding their bumps with large waistcoats, masculine shirts, uncomfortable saris, and classic baby doll outfits are long gone. Particularly, nursing-friendly clothing has gained popularity and is greatly favored by working mothers. These recently added categories have resulted in a notable increase in the per capital spending on "mother and baby care." India's market for mother and baby care is expected to grow at a compound annual growth rate (CAGR) of 11.11% to reach 26.35 billion by 2025.

In addition to the category's ongoing growth and diversity, labels and designers are making great efforts to guarantee that wearing maternity clothing is memorable,

stylish, and comfortable. In addition to serving the metropolitan population, they are progressively focusing on tier-1 and tier-2 cities, where there is a need for maternity clothing but a poor paying capacity.

2 Conclusion

Smart clothing helps understand and recognize changes in the human body under the influence of external factors, environment, and physical activity. In the modern world, intelligent clothing is used in a variety of contexts, including sports, medicine and health care, military equipment, security, and even entertainment. Maternal healthcare is a segment where the addition of smart technology can make the entire experience hassle-free, safe, and comfortable on physical and psychological fronts for pregnant women. The development of more comprehensive functions, comfortable clothing patterns, diverse technologies, and intelligent materials can promote a positive body image among women on utilitarian grounds. As technology continues to evolve, we can expect to see even more innovative products that further enhance the pregnancy experience for mothers during their antenatal journey.

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Effect of Natural Dyeing on Chitosan treated Cotton Fabric Using Selected Sources



S. Greeshma, Sadhna, and Rajesh Kumar

Abstract Dyeing, the process of applying colours to the textile material involves natural and synthetic dyes. The application of natural dye to textile materials is reduced since the introduction of synthetic dyes. World sustainability paved the way back for the usage of natural dyes in textiles. The natural dyes extracted from various natural sources are dyed with the help of mordants known as fixing agents. In this study, Aloe vera is used as a natural mordant, to fix the dye extracted from the marigold flowers on 2 × 2 cotton fabric. Since the cellulosic fibres have less affinity to the natural dyeing than protein fibres, chitosan which is known for its good absorption and adsorption is used to pre-treat the cotton fabric in the dip and dry method to check the affinity of the natural dye to the cotton. The dyeing was carried out with different dyeing methods and tested for its properties.

Keywords Natural dyeing · Mordant · Aloe vera · Chitosan · Marigold

1 Introduction

The process of applying colour to textiles through a variety of dye types and techniques is known as textile dyeing. It uses both artificial and natural processes. The importance of natural dye techniques declined as synthetic dyes became more widely available and more affordable, making natural dye methods less common [1]. The health risks associated with synthetic dyes are substantial and can cause symptoms such as wheezing, coughing, asthma, and skin conditions like skin cancer and allergies. In addition, unfixed dyes—which are frequently released during washing—contribute to the production of dye effluents from textiles. These effluents are dangerous to the environment because they contain dangerous materials. In order to lessen these negative effects on human well-being and the ecosystem, the textile industry must adopt sustainable alternatives and ethical business practises. The detrimental impact extends to health issues and environmental degradation [2]. Amid

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growing global sustainability concerns, natural dyes are experiencing a resurgence in use. Derived from plants, minerals, and insects, these dyes can be obtained from various sources like flowers, leaves, roots, or the entire plant. Marigold flowers, for instance, serve as a notable natural dye source. This renewed interest in natural dyes reflects a broader commitment to environmentally friendly practices, signalling a shift towards more eco-conscious alternatives in various industries [3].

2 Review Literature

2.1 Marigold

Marigold extracts have long been recognised for their antibacterial and antimicrobial qualities, which make them an excellent choice for textile colouring. Research has validated the efficaciousness of lutein, a naturally occurring textile colourant present in marigold flowers. For textile colouring, marigold phytochemistry—especially that of the naturally occurring colourant lutein—is essential. Lutein, a carotenoid pigment present in marigold flowers in large quantities, gives textiles vibrant yellow and orange tones when used as a dye.

This compound is what gives cotton fabrics their colour when marigold extract is used as a natural colourant. The superior light and wash fastness of marigold dye also ensures that the colour will not bleed even after washing and exposure to light. The eco-friendliness, renewable nature, and skin-friendliness of marigold dye contribute to its appeal as a natural textile colourant. These qualities draw attention to the adaptability and environmental benefits of marigold, which makes it a desirable choice for sustainable and environmentally friendly textile dyeing. When taken as a whole, these features highlight the adaptability and potency of marigold as a natural textile dye that is both visually appealing and useful [4].

2.2 Mordants

When it comes to natural dyeing, mordants play a vital role because they help the dyestuffs and fibres bond together. This bond not only increases the dye's colorfastness but also its overall fastness, guaranteeing vivid and long-lasting colours. The fundamental function of mordants is to create a bond between the fibre and the dye, which enables the dye to thoroughly ingrain itself into the fabric. For cellulose fibres like cotton, which are frequently mixed with tannins to ensure strong bonding, this procedure is extremely important.

Although there are significant dyes that don't require mordants, most natural dyes work better and last longer when mordants are used. Usually metallic salts, mordants are necessary to achieve a wide range of colours. However, because of safety and

environmental concerns, it is not recommended to use certain heavy metal mordants, like chrome, as they can be toxic. A crucial step in the natural dyeing process, the selection of mordants and their mixtures can also affect the dye's final colour [5].

In the realm of textile dyeing, natural mordants are becoming more and more of an eco-friendly option as a result of research into sustainable alternatives to synthetic ones. The potential use of aloe vera in textile dyeing has drawn a lot of interest. Research indicates that aloe vera gel, renowned for its adaptable qualities, can function as a natural mordant with efficaciousness, augmenting the fastness characteristics of natural dyes. This environmentally friendly strategy fits in with the textile industry's increasing focus on sustainability. Studies reveal that aloe vera can function as a biomordant during the vegetable textile finishing process, which enhances the colorfastness of natural dyes. Improvements in washing fastness and colour strength values have been shown with simultaneous mordanting with aloe vera. These results highlight aloe vera's potential to improve the overall performance of natural dyes on textiles and position it as a promising bio-mordant for natural dyeing [6].

The transition to natural mordants, such as aloe vera, highlights textile dyeing's dedication to environmentally responsible and sustainable methods. By using these substitutes, the sector can lessen the harm that synthetic mordants cause to the environment and join the larger push for more environmentally friendly, socially conscious methods. Natural mordants are still being explored, and incorporating them into textile processes has the potential to improve dyeing efficiency while also encouraging peaceful coexistence with the environment.

2.3 Chitosan

As a sustainable and environmentally friendly substitute for synthetic adsorbents in textile dyeing, chitosan, a biopolymer derived from chitin, has been thoroughly investigated for its potential as a dye adsorbent. Chitosan-based hybrid materials have shown promise as adsorbents for a range of textile dyes, such as sunset yellow, methyl orange, and methylene blue. Changes that improve the physio-chemical characteristics and adsorption capacity of chitosan increase its adaptability. These changes make a wide range of applications possible, including hydrogels, aerogels, gel beads, and Schiff base derivatives, as well as chitosan compositions with metals, clays, and polymers [7].

Chitosan's properties can be modified, which makes it suitable for adsorbing a variety of dye types. Use of chitosan as a dye adsorbent has several benefits, including inexpensive cost, easy availability, simple operation, and quick results. Given its ability to effectively adsorb dyes, this natural adsorbent is a highly attractive option for textile dyeing.

Beyond its usefulness, chitosan usage is in line with environmentally friendly and sustainable practises. Its natural origin and environmentally beneficial qualities make it a desirable alternative to synthetic adsorbents, demonstrating the textile industry's dedication to ethical and ecologically friendly practises. As chitosan's

uses in dye adsorption are investigated further, its many advantages help to change the textile dyeing industry's perspective in favour of more environmentally friendly and sustainable methods [8]. Thus chitosan being an adsorbent is chosen to pretreat the cotton fabric.

2.4 Cotton

As a plant-based substitute for animal-based protein fibres, cellulosic fibres are more economical and environmentally friendly, fitting in with natural dyeing methods. Cellulosic fibres provide advantages, but handling them has drawbacks as well. Because of their poorer substantivity and affinity to natural dyes, they complicate the dyeing process and require more time and extensive preparation to achieve desired results. However, when combined with natural dyes, protein fibres show greater dye-ability, allowing for the creation of vibrant, dark, and saturated hues as well as subdued neutral tones. On protein fibres, the addition of mordants frequently improves colorfastness; this step is less important for direct dyes on cellulosic fibres.

Cellulosic fibres have environmental benefits in terms of sustainability and affordability, which makes them a commendable choice even though they may take more time and effort to dye naturally. The choice between the two types of fibres frequently depends on the desired result. In the complex art of natural dyeing, protein fibres offer rich colour potential and simplicity, while cellulosic fibres offer a more environmentally friendly option. The stability of the dye/fiber complex determines how well dyes work on textile materials. Natural dyes have poor affinity and substantivity for cellulose fibres, which makes dyeing difficult. On the other hand, because protein fibres have ionic groups in their structure, they have a higher affinity for natural dyes and form stronger bonds with those that do [9].

The fundamental cellulosic fibre, cotton, is thus the subject of a study to determine whether finishing cotton with a natural adsorbent enhances the affinity of natural dyeing in cotton textiles.

3 Methodology

3.1 Preparation of Dye and Mordant Solutions

Preparation of dye solution: The freshly collected flowers were shade dried, and crushed. 500 g of crushed flowers were added to the soxhlet extractor to extract the dye solution. The extraction cycle was carried out for 48 h at room temperature. The dye was extracted with the aqueous solution (Fig. 1).

Preparation of mordant solution: The aloe vera leaves were collected, and washed and the outer skin was peeled off to collect the white gel mass separately. The



Fig. 1 Soxhlet extraction—the dried and crushed marigold flowers are kept on extraction for 48 hours

collected gel was crushed with the help of an electric motor and strained to collect the liquid mass.

Preparation of chitosan solution: Chitosan was purchased from Hi Media Laboratories Pvt. Ltd with less than or equal to 75% degree of deacetylation. Three grams of chitosan was added to 1500 ml of distilled water followed by 6ml of acetic acid. The solution was allowed to sit overnight. The solution was then stirred in a hot plate magnetic stirrer to obtain clear solution at 40 °C for 30 mins and filtered.

Fabric Dyeing Procedure: The desized cotton fabric was first pre-treated with chitosan solution. The fabric was dipped in the chitosan solution for 2 hours and then added in the padding mangle for fixation. The pretreated fabric(Chitosan treated) and untreated fabric(not treated with chitosan) was dyed in pre, post and simultaneous dyeing procedures with aloevera solution as a mordant. The procedure was carried out with an M:L ratio of 1:40 at 30% dye concentration and 10% mordant concentration.

4 Results and Discussion

4.1 Colour Strength

The dyed samples were evaluated for reflection, color strength, and K/S values using spectrophotometric tests, with the data summarized in Table 1 and visualized as a chart in Fig. 2.

In the spectrophotometric test, the K/S values of chitosan-treated fabric are 26.201 for pre-mordanting, 9.422 for post-mordanting and 19.815 for simultaneous mordanting fabrics. The K/S values of untreated fabric are 17.307 for pre-mordanting, 13.811 for post-mordanting and 13.128 for simultaneous mordanting. Chitosan-treated pre-mordanting and simultaneous mordanting cotton fabrics had a higher

Table 1 Effect of colour on chitosan-treated and untreated samples

Fabric	Dyeing procedure	L	a	b	C	H	K/S	Reflection
Chitosan treated	Pre mordanting	50.623	2.956	11.870	12.233	75.985	26.201	12.268
	Post mordanting	49.344	3.475	8.731	9.397	68.270	9.422	25.242
	Simultaneous mordanting	51.509	3.276	13.285	13.683	76.117	19.815	14.393
Untreated fabric	Pre mordanting	49.465	2.161	9.564	9.805	77.237	17.307	17.665
	Post mordanting	50.259	2.799	20.960	11.312	75.643	13.811	19.575
	Simultaneous mordanting	52.474	2.881	13.608	13.910	78.015	13.128	16.815

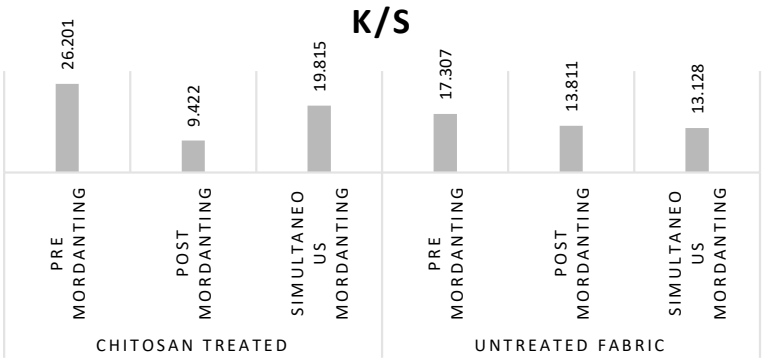


Fig. 2 Comparison of K/S values between the samples

affinity to the dye than untreated pre-mordanting and simultaneous mordanting fabrics. Whereas, in post mordanting technique untreated cotton fabric had a higher affinity to the dye than chitosan-treated fabrics. Among all the samples pre-mordanting of chitosan treated cotton fabric has higher affinity to dyed samples.

4.2 Colour Fastness

The dyed samples were tested for their various colour fastness tests which is given in Table 2

In the colour fastness test, pre-mordanting of chitosan treated cotton fabric has showed good fastness properties in wash fastness, crocking fastness and light fastness among all the dyed samples. Whereas, chitosan treated post mordanted fabric showed the poor fastness properties. The remaining pre, post and simultaneous dyeing of untreated cotton fabric and simultaneous dyeing of chitosan treated cotton fabric showed average colour fastness to different tests.

To sum up, the results of the spectrophotometric and colour fastness tests have given important information about how well cotton fabrics treated with chitosan perform in different dyeing processes. The K/S values showed that fabrics that were pre-mordanted and simultaneously mordanted with chitosan had a better affinity for dye than fabrics that were not treated. Among all the samples, the cotton fabric treated with chitosan showed the highest affinity for pre-mordanting. The post-mordanting method, however, revealed a different pattern, with cotton fabric that had not been treated demonstrating a greater affinity to the dye than fabric that had been treated with chitosan. This variation highlights the complex effects of chitosan treatment on various dyeing techniques.

Table 2 Fastness properties of the samples according to wash fastness, crocking fastness, and light fastness

Fabric	Dyeing procedure	Wash fastness		Crocking fastness		Light fastness
		Change in shade	Staining on fabric	Dry	Wet	
Chitosan treated fabric	Pre mordanting	4	4	4	3-4	6
	Post mordanting	2	2–3	2–3	2	3
	Simultaneous mordanting	3–4	3–4	3–4	4	5
Untreated fabric	Pre mordanting	3–4	4	3–4	4	5
	Post mordanting	3	3–4	3	3–4	4
	Simultaneous mordanting	3	3–4	3	3–4	4

On the other hand, post-mordanted fabric treated with chitosan showed relatively poor fastness properties. Average colour fastness was shown by the simultaneous dyeing of chi-tosan-treated fabric and the untreated cotton fabric under pre, post, and simultaneous dyeing techniques. These results highlight how intricately dyeing methods, chitosan treatment, and the final fabric properties interact. Although fabrics treated with chitosan may exhibit improved dye affinity under specific circumstances, the post-mordanting procedure may introduce variables that impact colour fastness. This complex knowledge is essential to optimising dyeing procedures and producing textiles that satisfy the necessary requirements for durability and fastness in addition to having vivid colours.

As the textile industry continues to explore eco-friendly practices, these findings contribute to the ongoing efforts to strike a balance between aesthetic appeal and functional performance in dyed fabrics.

5 Conclusion

Dyeing, a transformative process in the textile industry, involves imparting colours to fabrics through various methods and dye complexes. These complexes encompass both synthetic dyes and natural dyes, each contributing distinct characteristics to the coloured textiles. The advent of synthetic dyes marked a decline in the utilization of natural dyes, primarily due to their superior colour-fastness properties. However, driven by global environmental consciousness, natural dyes are experiencing a resurgence in the textile industry. Natural dyes have gained prominence for being non-allergenic, non-toxic, and eco-friendly. Their resurgence aligns with a broader societal shift towards sustainable practices and a heightened awareness of the impact of industrial processes on the environment. Unlike their synthetic counterparts, natural colorants boast enhanced biodegradability and compatibility with the environment. Moreover, certain natural dyes exhibit remarkable properties, such as being antimicrobial and antifungal, adding an extra layer of functionality to dyed fabrics.

One distinguishing feature of natural dyes is their heightened affinity for protein fibers compared to cellulosic fibers. Among these fibers, cotton stands out as a widely used cellulosic material in textile production. To optimize the interaction between natural dyes and cotton fabrics, various pretreatment methods can be employed. Chitosan, a versatile natural polymer derived from chitin, proves to be an effective agent in enhancing the affinity of cellulosic fibers for natural dyes. Pretreatment techniques, such as dip and dry or dip and pad, involve applying chitosan to cotton fabrics before the dyeing process. This treatment imparts a greater affinity to natural dyes, resulting in dyed fabrics that not only showcase vibrant colors but also align with the principles of eco-friendliness. The chitosan pretreatment not only enhances the dye uptake by the fabric but also contributes to the overall sustainability of the process.

The synergy between natural dyes and chitosan-treated fabrics yields textiles that are not only aesthetically pleasing but also environmentally responsible. As the textile industry navigates the evolving landscape of consumer preferences and environmental regulations, the revival of natural dyes and innovative pretreatment methods becomes crucial. These approaches contribute to the development of eco-friendly fabrics that resonate with the growing demand for sustainable and ethically produced textiles.

In conclusion, the resurgence of natural dyes in the textile industry represents a paradigm shift towards sustainable and environmentally conscious practices. The unique properties of natural colorants, coupled with effective pretreatment methods like chitosan application, pave the way for the creation of eco-friendly fabrics. As the industry embraces these changes, it moves towards a future where aesthetics and environmental responsibility coexist harmoniously in the realm of textile production.

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Production of Multi-Walled Carbon Nanotubes by AC Arc Discharge in Air



Abhishek Kumar Sinha and S. K. Chaudhary

Abstract Carbon nanotubes (CNTs), is one of the most wanted materials in the field of nanotechnology research. Multi-walled carbon nanotubes (MWCNTs) nowadays have paramount importance in the field of industrial and aerospace applications owing to their high tensile modulus (>1TPa), thermal conductivity, chemical resistivity, high aspect ratio, ultra lightweight, etc. MWCNTs are used as an additive nanomaterial in polymer composite, metal-matrix composite and ceramic-matrix composite to enhance their properties. This work emphasizes on the synthesis of MWCNTs in air by arc discharge technique involving AC power supply using graphitic electrodes having purity of 99.99%. The cylindrical movable electrode was used as an anode while the stationary rectangular electrode as cathode. The overall process is coherent with respect to manual metal arc welding except, for polarity. Due to the continuous vaporization of carbo-cations in the plasma zone soot deposition took place on the cathode which consisted of MWCNTs along with some impurities. Finally, after oxidation of powdered soot in muffle furnace, the morphological characterization of the same was done using FESEM, XRD and Raman spectroscopy. Results indicated that MWCNTs produced have length 120–280 nm and diameter 20–50 nm.

Keywords Multi-walled carbon nanotubes · Air · FESEM · XRD · Raman spectroscopy

1 Introduction

Carbon nanotubes (CNTs) that were discovered as a byproduct of fullerenes is a material of utmost importance in the field of nanotechnology research [1]. The discovery of carbon nanotubes by Iijima in 1991 has attracted immense experimental and theoretical studies on it. CNTs seem to have unlimited potential both from fundamental point of view and future aspect [2]. Continuous research and development in this field has a positive and wide impact in the field of biomedical imaging, drug

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delivery, biosensing, semiconductors, design of functional nanocomposites, in the field of aerospace (due to lightweight), sensing devices, fuel cells, polymers [3], etc.

CNTs have extensive application in textile industry such as in ballistic protection fabrics, CNT doped textiles with electromagnetic shielding, and ultraviolet absorption capabilities are meeting the market demands, high-load carbon nanocomposites (HNCs) are being used to protect against electromagnetic interference.

The two well-known crystalline forms of pure carbon are diamond and graphite. In diamond, the carbon atoms exhibit sp^3 hybridization forming a regular tetrahedron shape which is extremely rigid. In graphite, sp^2 hybridization occurs in which each atom is evenly connected to three carbons (120°) in the x-y plane and a weak π bond is present in z-axis. This sp^2 hybridization forms the hexagonal (honeycomb) lattice of a sheet of graphite (graphene) [3]. In this type of hybridization bonding takes place between 1s orbital and 2p orbitals, two single bonds and one double bond between three atoms form and the three hybrid orbitals come together in a triangular arrangement. AC arc discharge technique involving manual arc welding setup is used to produce highly crystalline MWCNTs that has hexagonal (honeycomb) lattice. In most cases related to carbon nanotube production DC supply along with controlled environment was used making the system complicated and costly but, this method of MWCNTs production in air is less complex and economical. In order to promote the formation of MWCNTs there is no requirement for metals to be used as a catalyst in anode [4] (Fig. 1).

According to [5], the use of alternative current (AC) instead of DC has been seldom reported, in such a case the discharge was always made between two graphite electrodes of different diameter with the deposition taking place on the electrode having larger diameter.

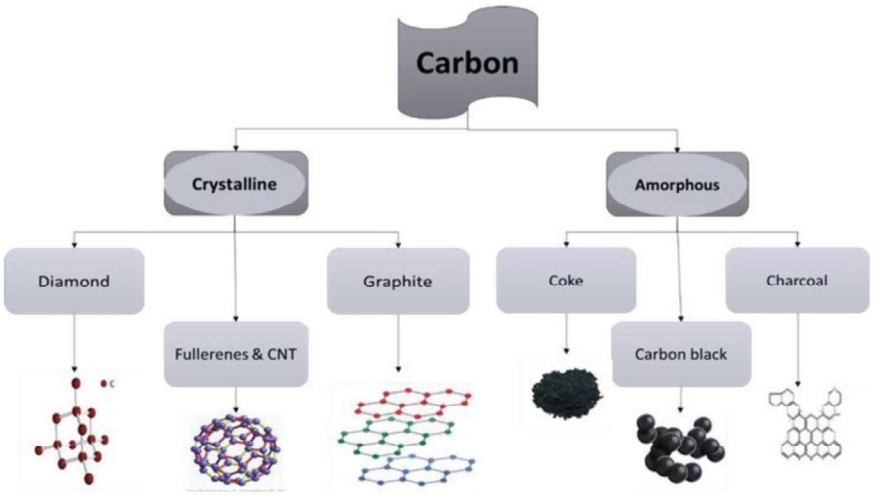


Fig. 1 Allotropes of carbon

1.1 Properties of Carbon Nanotubes

Carbon nanotubes exhibits a combination of superlative mechanical, thermal and electronic properties. The amazing and excellent mechanical properties of CNTs is because of the strength of the sp^2 carbon-carbon bonds.

Carbon nanotubes can have densities as low as 1.3 g/cm^3 which is 1/6th of that of stainless steel.

Young moduli (measure of material stiffness) is superior to all carbon fibers with values greater than 1 TPa which is approximately 5 times higher than steel.

CNTs are 100 times more robust than steel on molecular level.

Highest measured tensile strength/breaking strain for a carbon nanotube is upto 63 Gpa which is around 50 times higher than steel.

Additionally, CNTs have good chemical and environmental stability and high thermal conductivity (~3000 W/mK, comparable to diamond).

It has superior electrical conductivity (comparable to copper).

It has high aspect ratio and ultra-light weight.

Its electronic properties vary from metallic to semi-conducting.

1.2 Uses of Carbon Nanotubes

Carbon nanotubes are versatile and can be put into use for wide range of applications in the fields of polymers, displays, engineering plastics, thin films, coatings, anti-corrosion paints, transparent and non-transparent conductive electrodes, hydrophobic coatings, batteries, solar cells, fuel cells, advanced devices, water desalination, optics and semiconductors.

2 Experimental Details

The entire experiment comprised of two different dimensions of movable cylindrical graphite (99.99% pure) rods used as anode in which, the length to diameter ratio was kept as 10:1. Similarly two different dimensions of stationary rectangular graphite (99.99% pure) plate was used as cathode for which the length: width: height ratio was kept as 10:5:1. The soot deposition from cylindrical rod of length 40 mm and diameter 4 mm, and length 60 mm and 6 mm was obtained in the rectangular plate of length 40 mm and 60 mm respectively.

A manual metal arc welding setup with AC supply having current rating 39-500 A of the General Electric Company was used. The process is initiated with arcing of movable cylindrical graphite rod on the stationary rectangular graphite plate in open air and the current is maintained at 105 A, 133 A for rods of length 40 mm and 60



Fig. 2 Positioning of electrodes during arcing

mm respectively but, the voltage remains constant at 80V. A continuous directional arc with very little splatter was observed and an arc length of 3–4 mm (Fig. 2).

was maintained for 5–8 mins. Further, it was observed that the arc length was reduced as current was lowered. During arcing as the anode evaporates the deposition of soot takes place on the graphite plate which was then air-cooled naturally i.e. slow cooling in order to avoid any thermal cracking resulting in hard crust that was scrapped away by the steel blade and collected.

Subsequently, the soot was converted into fine powder in pulverizer. Afterwards, fine powder was heat treated in muffle furnace to get rid of amorphous carbon, traces of moisture and other impurities. In muffle furnace the sample was kept at a temperature of 550 °C for 30 mins (Fig. 3).

Figure 4 shows the deposit formed on cathode which is in the form of small disc having diameter 10–13 mm. The deposit shows two regions, one is the inner black core and other is an outer rim with irregular morphology.

3 Result and Discussion

During the entire experiment AC power source was used for deposition of soot on the cathode and the current and voltage requirement was noted down which is presented in a tabular format (Table 1).



Fig. 3 Image showing soot formation after slight cooling



Fig. 4 Irregular morphology and bubble-like structure in outer rim of soot after cooling

Table 1 Current and voltage requirement during arc discharge

Length of cylindrical graphite electrodes (all values in mm)	Current (I) (all values in ampere, A)	Voltage (all values in volt, V)
60	133	80
40	105	80

Current density calculation

Current density is the measure of the amount of electric charge per unit time that flows through the unit area of cross-section. Current density (denoted by J) is a vector quantity. Formula used: J = I/Ac, where, I = current flowing through the conductor in amperes, Ac = Cross section area of cylindrical electrode in mm^2 (Table 2).

The above data shows that current density in 4 mm diameter electrode is greater than 6 mm diameter electrode. This trend shows that current density depends upon the electrode diameter (Table 3).

Morphological characterization

For the morphological and structural characterization of carbon nanotubes (CNTs) following analysis are carried out:

Field emission scanning electron microscopy analysis (FESEM).
X-ray diffraction analysis (HRXRD).
Raman spectroscopy analysis.

Fesem analysis

FESEM analysis was conducted using Carl Zeiss Sigma 300 to observe the size and visualize the very small topographic details. In FESEM, the microscope works with electrons instead of light. The object was scanned by electrons according to a zig-zag pattern. The electrons are liberated by a Schottky field emission electron gun where the working distance (the distance between sample and gun) was kept as 3 mm and the extra high-tension voltage was maintained at 5 kV.

Within the high vacuum column these so called primary electrons are focused and deflected by electron lenses to produce a narrow scan beam that bombards the object. As a result, secondary electrons are emitted from each spot on the object. A

Table 2 Current density for the cylindrical electrodes

Length (in mm)	Diameter (in mm)	Area of cylindrical electrode (A_c) (in mm^2)	Current (I) (in ampere)	Current Density (J) (in A/mm^2)
40	4	12.5663	105	8.3556
60	6	28.2743	133	4.7039

Table 3 Total yield calculation

Length of cylindrical rod (in mm)	Mass of deposited soot on cathode (in gm) [Initial mass]	Mass of soot after pulverization and heating in muffle furnace (in gm) [Final mass]	Total yield = [Final mass/Initial mass] (in %)
40	1.6157	1.4674	90.82
60	5.1854	4.7402	91.41

detector catches the secondary electrons and produce an electric signal. This signal is amplified and transformed to a video scan image that can be seen on a monitor or to a digital image that can be saved and processed further.

For FESEM analysis of the fine powdered sample, it was coated with carbon using Quorum sample coating machine (Q150R ES). During the sample preparation current was kept as 20 mA, while the chamber pressure was maintained at 1×10^{-1} mbar. The total time involved in preparing the sample was about 8 min 44 secs.

Finally, images of different samples were obtained after the analysis which are illustrated in the figures given:

Figure 5 shows the presence of agglomerated carbon nanotubes obtained from 60 mm diameter cylindrical electrode which might have occurred owing to the presence of Van der Waal's force of attraction among nanotubes. Coherent morphology has been reported by [6].

Figure 6 shows oxidation of certain CNTs obtained from 40 mm diameter cylindrical rods which occurs simultaneously while the oxidation of impurities was carried out which is a major disadvantage, still oxidative treatment is considered a good way to remove the carbonaceous impurities [7].

There may be a huge possibility of partial oxidation of CNTs taking place during the arcing process. The oxidation occurs as the entire synthesis process was carried out in open atmosphere where oxygen is in abundance. Smaller length CNTs might appear owing to insufficient amount of plasma density and temperature thereby, leading to insufficient electron emission. [8], therefore, reported that the lesser heat produced is not optimal for growth of CNTs.

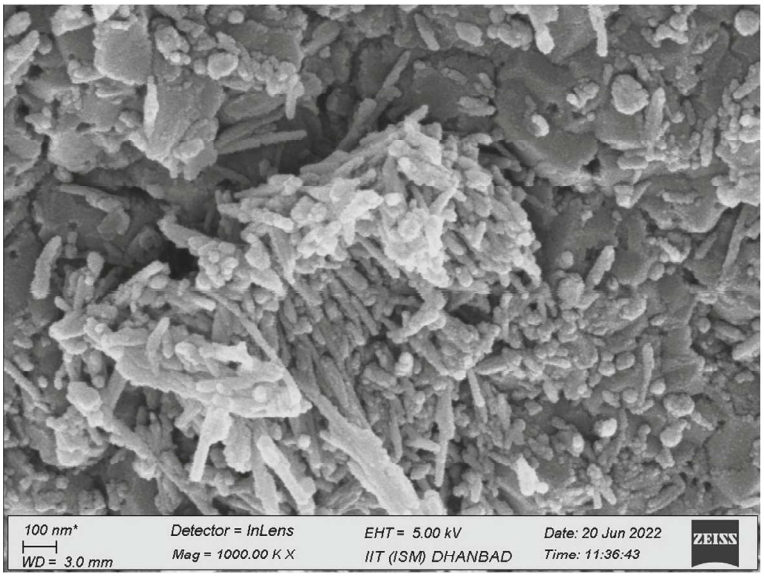


Fig. 5 Image showing presence of agglomerated carbon nanotubes

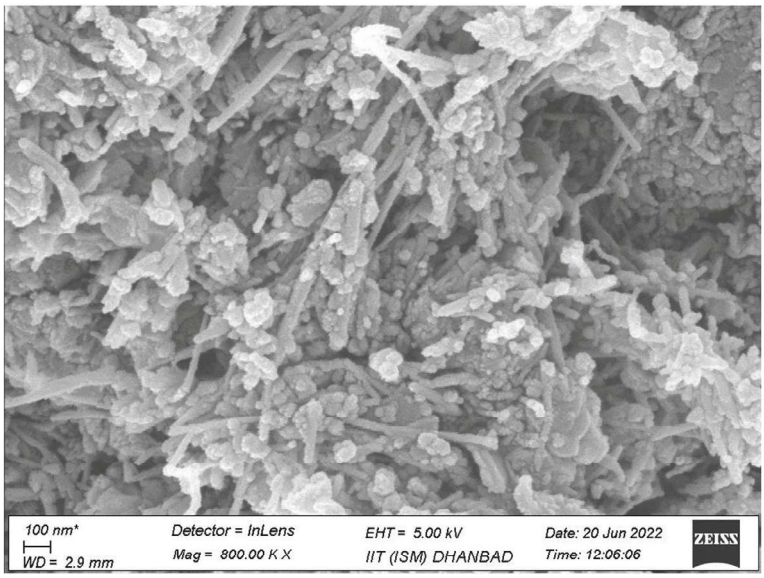


Fig. 6 Image showing presence of oxidized carbon nanotubes

The FESEM images shown in Fig. 7 revealed different types and shapes of randomly oriented CNTs. The different types of curvature observed here may be due to fluctuation of temperature and splitting electric field during the arc discharging process [8].

HRXRD Analysis

X-Ray diffraction analysis is a non-destructive technique used generally in the field of material science to determine the crystallographic structure of a material. XRD works by irradiating a material with incident X-rays and then measuring the intensities and scattering angles of the X-rays that leaves the material.

For performing the XRD analysis, Rigaku Smartlab X-ray diffractometer was used. The Rigaku Smartlab is a multipurpose high resolution X-ray diffractometer (HRXRD) automated with guidance software (Smartlab Studio II). The software is capable to perform automated phase/composition identification, qualitative and quantitative analysis, residual stress analysis. X-ray powder diffraction can reveal the local and global features of microstructure's lattice and crystalline phases, domain size and impurities [9].

During the XRD analysis a very small amount of fine powdered sample was taken which was first washed using ethanol to remove the impurities. The parameters while performing the analysis in Rigaku smartlab X-ray diffractometer were kept as:

Scan speed = 5°/ min.

2θ range = 10–80°.

Step size = 0.02°.

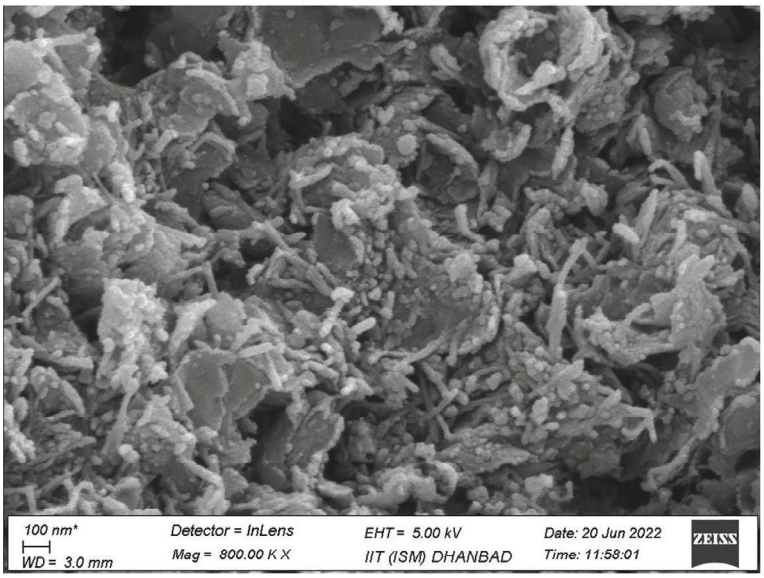


Fig. 7 Presence of carbon nanotubes of different curvature and shapes

Scan time = 15 mins (approximately), it depends on scan speed and 2θ range.
Scan mode = 1D scan.

Figure 8 and 9 respectively represents the graph plotted for intensity (arbitrary units) vs diffraction angle (in degrees). The strong sharp peak (002) for both the samples namely cylindrical rod of length 40 and 60 mm can be clearly seen at 26.2° and 26.18° respectively. The (002) peak for both the samples occur at slightly different degrees which is due to the variation of full width at half maximum (FWHM) that depicts inverse diameter relation.

The peak indicates that CNTs are made of graphite and are crystalline in nature. Its occurrence may also be attributed to the presence of inter layer stacking of graphene sheets nested together [5]. Besides, it also confirms that the nanotubes present are multiwall in nature.

Raman spectroscopy analysis

Raman spectroscopy for the heat treated finely powdered pure graphite sample was performed using Horiba Scientific LabRAM HR-UV-Open model where the samples are first pressed and flattened uniformly over a glass plate before the commencement of the analysis. During our analysis the laser excitation wavelength was taken as 785 nm; the working distance (the gap between the laser aperture and sample) was kept as 8 mm and magnification available was 50X (for powder) and 100X (for film). Since, our sample was in powder form thus, we used 50X magnification.

Raman spectroscopy is a non-destructive light scattering technique that provides detailed information about chemical structure, phase, crystallinity and molecular

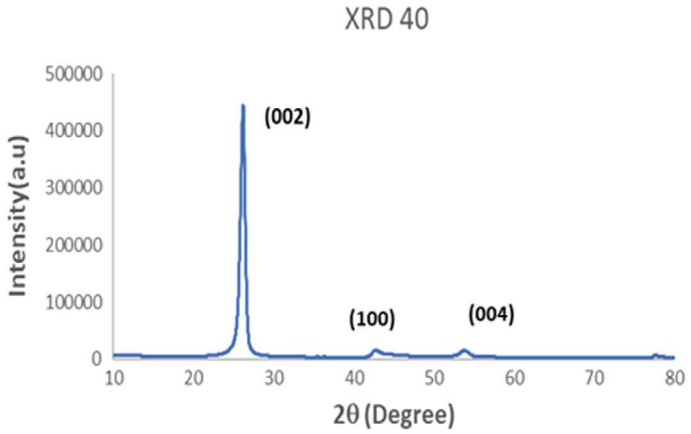


Fig. 8 XRD pattern of powdered CNTs obtained from 40 mm length anode

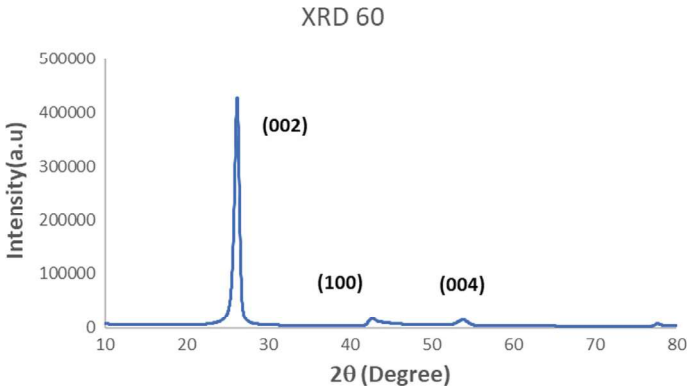


Fig. 9 Intensity versus 2 θ plot for powdered CNTs obtained from 60 mm length anode

interactions. In this technique, a molecule scatters incident light from a high intensity laser light source. A small amount of light (0.0000001%) is scattered at different wavelengths which depends on chemical structure of analyte-this is called Raman scattering.

The figures illustrated below depicts the Raman spectrum obtained for our sample while performing the analysis.

Figure 10 shows the Raman spectrum for the first sample (cylindrical rod of diameter 4 mm and length 40 mm). The D- band can be observed at 1352.6 cm^{-1}. A strong peak can be observed at 1576.65 cm^{-1}. The second order peak or G' band occurs at 2695.38 cm^{-1}.

Similarly, the Raman spectra for the second sample (cylindrical rod having diameter 6 mm and length 60 mm) is shown in Fig. 11. This graph depicted D-band, G-band and G'-band at 1347.83 cm^{-1}, 1579.74 cm^{-1} and 2695.38 cm^{-1} respectively.

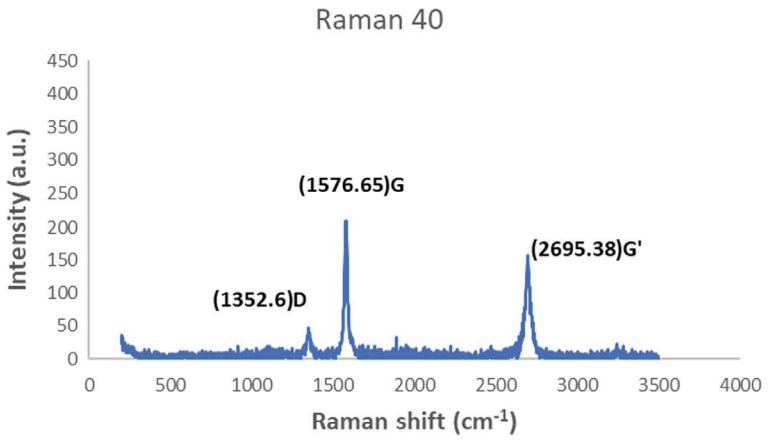


Fig. 10 Intensity vs Raman shift

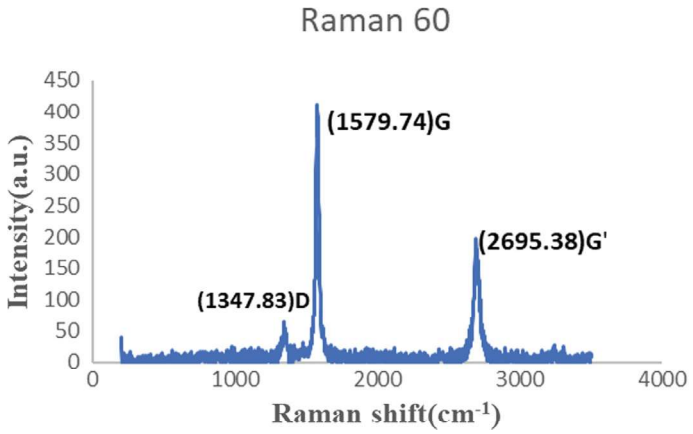


Fig. 11 Raman spectra showing presence of D, G and G' band

The presence of D-band depicted disorder in the carbon system as well as breathing of hexagons. Moreover, the sharp narrow high intensity band or the G-band corroborate high crystallinity of graphite. The G-band is associated with C-C tangential stretching mode and it is a characteristic of the graphitic phase, indicating presence of crystalline graphitic MWCNTs [10]. The occurrence of G'-band characterizes graphene with more layers and is an overtone of 1st order D-band.

In both samples the absence of radial breathing mode (RBM) indicated the presence of MWCNTs and the absence of SWCNTs.

Jiao et al. [11], reported the intensity ratio (ID/IG) as 0.38, 0.30 and 0.28 for single, bi and tri- layered graphene respectively. But, in this work the (ID/IG) ratio obtained was 0.8578, 0.8531. It is known that D to G-band intensity ratio (ID/IG) is

sensitive to structural defects in the MWCNTs [10]. The relation among D-band, G-band, G'-band and RBM plays a significant role in determining the different variant of CNTs [8]. Raman analysis provides information about presence of disorder in CNT samples [12].

In conclusion, the G-band frequency of MWNTs decreases with increasing tube diameter for diameter less than 20 nm, beyond which it is almost constant [13]. The slight variation in the Raman spectra of both the samples may be attributed to the interlayer spacing of MWCNTs and presence of slight impurities [13].

4 Conclusion

Multiwalled carbon nanotubes of length 120–280 nm and diameter 20–50 nm were successfully synthesized by AC arc discharge technique in open air under ambient conditions without the use of an external catalyst.

The Field emission scanning electron microscopy (FESEM) analysis revealed the presence of randomly oriented agglomerated carbon nanotubes. The nanotubes present had different curvature and shapes. The images obtained through FESEM also confirms the partial oxidation of nanotubes.

The graph plotted on the basis of X-ray diffraction (XRD) analysis revealed that the carbon nanotubes produced are crystalline in nature and is made of multi layer sheets of graphene.

The Raman spectroscopy analysis revealed that the carbon nanotubes present are multi walled in nature and has high crystallinity.

This method involved in the synthesis of multi walled carbon nanotubes is free from the requirements of maintaining a controlled atmosphere as observed in the conventional arc discharge method for producing of carbon nanotubes. This helps in increasing the ease of production of carbon nanotubes by manifolds in addition to the reduced cost of production. Major drawback which can be associated with this production method is possible contamination of soot and partial oxidation of the nanotubes as the entire synthesis is carried out in open air.

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A Review of Consumer Perspectives on Green Apparel



Meghna Gupta, Mithilesh Pandey, and Amit Kakkar

Abstract The rapid expansion of human activities, particularly after industrialization, created significant environmental and social challenges. Depletion of natural resource, climate change, population growth, and unsustainable consumption practices have all resulted in significant environmental damage around the world. The rising environmental impacts are due to excessive water usage in textile manufacturing, contamination from processing chemicals, and the amount of waste generated during disposal. In a world where social and environmental issues are becoming increasingly important, the fashion industry is in dire need to lessen and monitor its environmental and social impact. Amidst several innovative approaches to contribute to sustainable growth, many apparel manufacturers and designers are now providing clothing options labelled green textiles to consumers. Green clothing is also being produced to reduce the waste of natural resources like water, plants, energy, and land. Furthermore, Indians are becoming more interested in green or organic clothing brands which will most likely contribute to the apparel sector's revenues. The current study reviews the concept of green apparel, consumers' awareness of green fashion, the drivers that impact their purchase decision and choices, and the common dilemma of consumers' preferences for green products. It will emphasize the importance of understanding barriers to more sustainable production and consumption systems. Consumers can be educated about environmentally friendly attributes and benefits, resulting in a favorable understanding of green apparel benefits and value. Thus, the proposed work would lead to policy making as retailers and manufacturers can benefit through more focused strategies for environmental safety to reduce non-green branded products while educating their consumers about green apparel.

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Keywords Green textiles · Apparel and retail sector · Sustainable sourcing · Ethical production · Consumer attitude · Purchasing intention

1 Introduction

The fast expansion of human activities, particularly after industrialization, created enormous environmental and societal concerns [18, 52]. For example, such activities contribute to global warming, natural resource depletion, other environmental challenges, and economic disparities between different parts of society [32]. The high environmental implications are attributable to high levels of water usage in textile manufacture, contamination from processing chemicals, and the volume of waste generated during disposal [5, 15, 27]. In a world where social and environmental issues are becoming increasingly important, the fashion industry prioritizes environmental and social issues. In recent decades, sustainability has become essential to a successful firm. As a result, many organizations have implemented various sustainability programs in response to the social and environmental challenges caused by corporations, ranging from green marketing to the CSR Programme. The sustainable way of life in the fashion business is dependent on the efforts of all parties involved in the sector to enhance their commitment.

Therefore, more than a single step is required for change, which requires the formation of a robust ecosystem based on the collaborative efforts of regulators, consumers, NGOs, and other stakeholders. In terms of sustainability, the textile industry has enormous potential for advancement. While client attitudes towards green products and services have improved in recent years, both in general and in garments, the market share of clothes created in eco-friendly and socially responsible ways remains low. There has been a substantial surge in public interest in garment sustainability in recent years. Adjustments in current consumption and production patterns are required to compensate for and reverse environmental damage. Human actions must be improved [25].

As a result, businesses have begun to engage in energy reduction and water usage by adding realistic solutions to monitor energy and wastewater consumption from traditional to renewable energy sources, enhance lighting and air-conditioning systems, and install meters. These actions enforce in various businesses, shops, and distribution sites.

Customers need help with purchasing sustainable items. Analyzing client perspectives is, of course, vital to maintaining a transition in fashion development. Fashion companies are gradually adopting sustainable clothing, and buyers are increasingly linking eco-friendliness with fashion [5].

Sustainable goods with social, economic, and environmental features are in sustainable transactions [12]. According to [18], household purchases contribute 40% of ecological deterioration. Consumers can help to reduce or prevent environmental deterioration by purchasing sustainable items [4]. Therefore, sustainable

purchasing is essential, and research has demonstrated that it should be supported and investigated [6, 30, 40].

Environmental degradation in companies is now minimizing its effects [49]. Sustainable goods and energy-efficient equipment, have recently gained popularity, but their associated benefits outweigh increased consumption [52]. The existing literature reveals a rapid increase in environmentally conscious customers, although the extent to which they adopt sustainable items varies [50, 52]. Over time, more consumers were willing to embrace sustainable consumption behaviors [54], but their purchasing behavior did not reflect this willingness [2].

When purchasing products, people neglect their activities' environmental and social consequences. This gap between cognition and action is a sustainable behavior gap [27, 32, 42, 53] proposed that various variables could influence the linkages of sustainable behavior investigated. Understanding the attributes of sustainable shopping will enable the development of effective marketing strategies to address the sustainable behavioral deficit and promote sustainable product purchases. During the last few years, sustainability has progressed from a drop to a mainstream problem for manufacturers, managers, marketers, and other stakeholders. The shift in consumer mindsets and increased awareness of their environmental impact prompted a study to understand better green shopping behavior [47]. Nonetheless, sustainable apparel consumption remains marginal: Consumers over 35, in particular, were found to be neutral rather than supportive of sustainable fashion. Moreover, in the apparel sector, most customers fail to transform their overall green attitude into green activities [2], even though studies typically took macro-perspective, only factors such as perceived increased pricing and perceived aesthetic risk [43] prevent customers from purchasing sustainable clothes.

Green Apparels

The textile clothing business aims to make wear reusable, recyclable, and toxin-free to remove the industries' adverse environmental effects. Environmental concerns have developed in recent years, particularly in the textile and garment industries are not environmentally friendly. Every textile product emits environmentally hazardous wastewater. The traditional textile business consumes many natural resources and pollutes the environment through production and processing. Using rayon for clothes has contributed to the rapid deforestation of forests and has led to the creation of sustainable natural fibers such as Cotton, Hemp, and Bamboo fibers. Organic textiles like cotton and wood, recycled materials, minimal packaging, and raw materials are more energy efficient.

Green textiles are clothing and accessories made with organic and recycled materials, less packaging, and less energy. Other than organic raw materials like linen, silk, soybean fibers, and marine timber fibers, hemp and bamboo are critical environmental sources favorable to the environment since they proliferate without wasting resources. Reduced environmental effects of fabric over its whole life cycle or the use of reduced-impact products can help improve the issue. They are environmentally conscious. The Global Organic Textile Standard (GOTS), produced by the United States, the European Union, and Japan, grants organic certification for garment production. Green

fashion provides consumers with healthier and more environmentally sustainable apparel options [36].

Attitude

The theory of Planned Behavior is essential in forecasting an individual's behavioral intentions. Attitude can be defined as favorably or unfavorably appraising cognitive ideas about a specific concept, person, object, event, or behavior [13]. In today's society, an *attitude* is an individual's appraisal of a specific thing [22, 26]. Therefore, attitude is considered a critical antecedent of behavior, which is an intrinsic component of various behavior models such as TRA [14, 22].

Sustainable attitudes are transformed into purchasing activity, resulting in weak or insignificant connecting attitudes [10, 37]. On the other hand, researchers emphasize the importance of behavioral determinants in attitudes. Environmental behavior influences customer purchasing intentions. Researchers say a favorable attitude towards an environmentally friendly product leads to a purchase intention [11]. The position also impacted a specific action, which ultimately reinforced the aim of doing so. According to the literature, more environmentally conscious consumers buy more sustainable goods [11, 33]. Policymakers can stimulate consumer demand for sustainable clothing by raising awareness about the environmental impact of conventional clothes versus sustainable clothing through public campaigns. Provocative graphics and documentation demonstrate the social benefits of sustainable clothing. Furthermore, sustainable clothes could be subsidized or taxed to boost consumer demand [43].

Awareness

When discussing green clothing, the environment precedes health issues because it is directly related to the environment. People who have environmental difficulties are willing to change their environmental conservation behaviors. Researchers also discovered that when it comes to purchasing items, most US customers are still concerned about environmental issues. Top companies also expand their product portfolios by utilizing numerous sustainability methods to influence clients' green apparel purchasing decisions. However, only some studies have examined consumer motivations for purchasing eco-friendly clothes [33, 35].

According to [39], Indian consumers have several environmental concerns. Therefore, the study also emphasized the various elements that influence the selection of green goods. They investigated how customers interpreted the organic concept and discovered that purchasing incentives link to environmental and health information. Perceived Environmental Awareness (PEK) is a cognitive measure capable of understanding issues related to climate or sustainability, such as air pollution, water pollution, land pollution, electricity and energy usage and production, recycling, waste generation, and its social and environmental impact [7, 38, 47]. Environmental awareness uses two types of knowledge: subjective and objective assessments. Subjective awareness measures a person's perception or self-evaluation of what they are aware

of the green phenomena, also known as abstract knowledge. On the other hand, *environmental awareness* defines the ability to recognize diverse symbols, concepts, and conduct relating to ecological elements [24].

According to [34], information influences and aids in processing a product's message (in this example, an environmentally viable product). Petty et al. [44] Elaboration Probability Model (ELM) provides principles for investigating the relationship between environmental understanding and attitude. The objective in these circumstances may also alter depending on the level of environmental attitude established by a range of environmental awareness.

Suppose the environmental argument is more potent due to increased awareness. In that case, the attitude toward environmentally friendly goods is more solidly entrenched, according to the Elaboration Probability Model [44] and vice versa. Kim et al. [29] developed a model to investigate the impact of environmental concerns and its awareness on the purchase behavior of clothes buyers. Market awareness of apparel-related environmental issues had a minor impact on purchasing behavior. However, general concerns about ecologically friendly purchasing activity were highly associated. In addition, consumers' eco-friendly acts influenced their environmentally friendly purchase habits [20]. Barr [2] emphasized educating consumers about environmental and social issues in sustainable and recycled clothing. In addition, their clothing represents individuals' social, personal, and community identities. As a result, correspondence on organic clothing might investigate the benefits and personal significance of using environmentally friendly clothing for clients.

2 Subjective Norms

Subjective norms are an individual's opinions that emerge significantly from peers, society, or the family [31]. According to [14] *subjective norms define* a way of thought in which certain behaviors, endeavors, or actions are accepted and rejected. Individuals not only conduct themselves under social stress but also learn about the acceptability of the activities under evaluation under subjective standards [23]. The societal milieu is pressuring people to purchase such items. A subjective norm foreshadows a behavioral purpose in TPB [12, 31]. It may be a fantastic goal indication. However, it demonstrates that social influences have significantly influenced an individual's purchase decisions [31, 51]. Moreover, because Indian society is one of the wealthiest and most diversified cultures, many religions and traditions might influence a person's lifestyle choice [28, 31]. Researchers have reviewed subjective norms during the study [3] as evidenced by various studies.

3 Perceived Warmth

The theory of social decisions emphasizes the relevance of Warmth in customer perceptions of organizations and brands [17, 45]. Perceived Warmth is cooperative businesses and noble intentions. In addition, warm judgments necessitate a sense of honesty, compassion, morality, and friendliness, and they make clients feel confident with the brand [1, 17]. According to recent research, Warmth is an essential determinant of favorable consumer attitudes and behavior [45].

Warmth behavior findings include purchase intention and brand commitment, customer participation and relationship [17], and positive brand perceptions and purpose [1]. According to the literature, perceived Warmth contributes to the efficiency of CSR communication between organizations. Literature reveals that CSR programs favorably alter warming expectations, increasing customer satisfaction and behavioral goals [16]. Sustainability initiatives are suitable for generating company warmth inferences since they direct company resources toward enhancing social welfare by resolving social or environmental problems [17, 28].

4 Price Sensitivity

Commodity prices are among the most critical aspects of examining the consumer decision process. Payment is "the reasonable cost of a commodity for which the customer is willing to pay" [21, 48]. The cost of green items influences Indians' willingness to consume green products [8, 9, 44]. There is also a recurrent discussion of high pricing for items and associated market economies as the primary purchase barrier in sustainable clothes [15, 22].

Premium pricing, according to some scientists, is not a significant barrier to sustainable purchasing because consumers appear to be more ready to pay for sustainable goods and services [10, 19, 22, 41]. Customers are unwilling to pay more for green projects and practices. However, [46] pointed out that young Indian customers are paying exorbitant prices for green goods. These young consumers are ecologically conscious, and a strong relationship exists between price sensitivity and purchasing intent. As a result, price sensitivity is a premium for eco-friendly clothes [31].

5 Conclusion

After lodging, transportation, travel, and food, the EEA (European Economic Area) ranked the apparel, textiles, or footwear industry fourth on its list of high-environmental-impact industries. Demographic changes and the availability of global clothing brands have resulted in several unhealthy practices like short-term

recurring purchases, overuse of cheap materials, and unethical production environments in the Indian apparel industry. Green textiles are clothing and accessories made with organic and recycled materials, with less packaging and energy. Global and national apparel manufacturers have launched organic clothing lines for environmentally conscious consumers. Consumers' eco-sensitive attitudes and behavior analyze their intention to purchase. This review study investigates the impacts of attitude, awareness, perceived warmth, subjective norms, and pricing on customers' purchase intentions. There have been few studies on green purchasing. Consumers are willing to pay more for durable, a low-emission product, and an environmentally friendly manufacturing process.

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Digital Printing: The New Era in Fashion and Textile Design



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Abstract Digital printing has become an increasingly popular method for printing on textiles in recent years. It has shown a significant impact on fashion and textile design, offering new design, customization, and sustainable possibilities for designers and manufacturers. This study is an effort towards understanding of how the method of digital printing on fabric apparently has been more useful and by employing it more spontaneous designs or patterns can be achieved. In terms of future potential, digital printing has several opportunities for growth. Use of sustainable and eco-friendly materials for digital printing is one such area. As consumers become more conscious of their environmental impact, the demand for sustainable textiles and printing methods is expected to increase. Digital printing can offer a more sustainable alternative to traditional printing methods, as it generates less waste and requires fewer chemicals and lesser water and energy usage. The growth of the digital textile printing industry not only caters to the creative aspects but also can contribute to better economic growth of a nation by creating jobs, increasing exports, generating revenue, promoting innovation, and encouraging sustainability. India is one of the leading countries in the global market for digital printed textiles. India has a long history of textile production and has been investing in digital printing technology in recent years. As technology advances and customers become more aware of its advantages, the demand for digital printing in fashion is predicted to increase. As a result, more designers and producers are anticipated to include digital printing into their manufacturing procedures, expanding the variety of distinctive and customised designs available in the fashion sector. This paper tries to analyse the importance of digital printing industry and its potential growth in coming times in the global platform of fashion and textile design.

Keywords Digital printing · Fashion · Textile · Sustainability · Economic growth

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1 Introduction

Digital fabric printing technology is a relatively new printing process that has revolutionized the textile industry by allowing for the production of customized and personalized fabric prints. The demand for digital printing in fashion has been steadily increasing in recent years, as more designers and manufacturers look for new and innovative ways to create unique and personalized designs. It involves printing digital designs directly onto fabrics using inkjet printers that are specially designed to handle different types of fabric substrates. At the moment, ink development and head technology have seen significant advancements in textile printing. This procedure is comparable to the computer-controlled paper printers used for office applications, but it is carried out on a large scale with many complex variables being regulated to get the best results on fabric. The following factors must be coordinated for successful digital fabric printing: files and colour management, printer and Raster Image Processor (RIP) technology, fabric pre- and post-treatment procedures, inks/dyes, and client requirements.

2 History

The history of digital fabric printing technology can be traced back to the 1990s when inkjet printers first began to be used for printing on fabric. Initially, the technology was limited to printing on paper that was then transferred onto fabric using heat and pressure. However, with the development of better inkjet printers and advances in ink technology, direct-to-fabric printing became possible. The first commercially successful digital fabric printing technology was introduced in the early 2000s. These early printers were designed for printing on cotton and other natural fibres and used water-based inks.

While these printers were limited in terms of colour range and print resolution, they offered greater flexibility and customization than traditional screen-printing methods [1].

In the following years, digital fabric printing technology continued to improve, with advances in inkjet printer technology and the development of specialized inks for printing on a wider range of fabrics. By the mid-2000s, digital fabric printing technology had become more widely adopted in the textile industry, particularly in the production of fashion and home decor products. In the last decade, new inkjet printers have been developed that are capable of printing on a wide range of fabrics, including polyester and other synthetic fibres, and specialized inks have been developed for achieving specific finishes, such as metallic or fluorescent effects.

3 Methodology

To create a digital fabric print, a design is first created digitally using software. The design is then printed onto fabric using inkjet printers that are specially designed to handle different types of fabric substrates. The printers use either dye-based or pigment-based inks that are formulated to bond with the fabric fibres and produce bright, long-lasting colours.

There are two main types of digital fabric printing technologies:

Direct-To-Film (DTF)—A printed artwork on paper is transferred to fabric using a straightforward heating procedure. The employed dyes have a strong affinity for the fibres of the cloth because they can vaporise under the process's hot conditions. Polyamide and polyester have long been the subject of transfer printing.

An intermediate paper substrate is used in transfer printing, which increasingly is ink jet printed with sublimating or other dyes. During the transfer process, the paper's dye either sublimates onto fabric composed primarily of polyester or is trapped behind a "film" on fabric made of diverse fibre types [2].

Direct-To-Garment (DTG)—Direct digital fabric printing involves printing on rolls of fabric with large-format ink-jet printers. Printer heads with numerous little nozzles spew tiny ink droplets onto pre-treated fabric in a manner similar to a desktop computer printer. The demand for natural fibres and nylon has driven the development of direct digital printing. To aid in the adhesion of the print by the fibres, fabrics are pre-treated with chemicals. After being digitally printed, the fabric undergo post-treatment to permanently fix the colour during high-heat pressing.

Direct digital fabric printing enables the printing of many colourways and designs along or within a single roll of fabric, just like with digital sublimation printing on polyester fabrics. The cost of printing is unaffected by the quantity of colours used in a design; instead, it enables quick turnaround, short run sampling, large run printing, placement, and engineered designs.

Direct digital fabric printing is a quick and comparatively simple procedure that involves loading data into specific print software before sending them to the printer [3] (Fig. 1).

4 Processing

The process of digital fabric printing technology can vary depending on the specific printer and ink used, but here are the general steps involved:

Design Creation: The first step is to create the design that will be printed onto the fabric. This can be done using graphic design software or by scanning an existing design.



(a) (b)

Fig. 1 **a** *Source* https://subli-star.com/wp-content/uploads/2021/06/dtf-a3-process-819x1024.jpg. **b** *Source* https://www.rainbow-inkjet.com/uploads/dtg-process.jpg

Pre-treatment: Depending on the fabric type, it may be necessary to pre-treat the fabric before printing. This can involve washing and drying the fabric or applying a special coating that helps the ink adhere to the fabric.

Printing: The fabric is then loaded onto the inkjet printer, and the design is printed onto the fabric using specially formulated inks. The ink is applied to the fabric in a series of tiny droplets, and the printer head moves back and forth across the fabric to create the design.

Drying and Fixation: Once the design has been printed, the fabric is typically dried using heat or air. Depending on the ink used, it may also be necessary to fix the ink to the fabric using a process called fixation, which involves applying heat or steam to the fabric.

Finishing: After printing, the fabric may undergo additional finishing processes, such as steaming, washing, or ironing, to achieve the desired texture and finish.

Depending on the specific printing technology used, the process may vary slightly. For example, some printers use reactive inks that require the fabric to be steamed after printing to achieve optimal colourfastness. Others may use pigment inks that require no additional fixation process. It's worth noting that the digital fabric printing process allows for greater flexibility and customization than other printing methods. Multiple colours, gradients, and even photo-realistic images can be printed onto the fabric, and the process is faster and more environmentally friendly [4] (Fig. 2).

5 Discussion and Critical Appraisal

Here are some arguments in favour of digital fabric printing technology:

Greater Flexibility and Creativity: Digital fabric printing technology offers greater flexibility and creativity in design. Designers can create intricate patterns, gradients,



(a) (b) (c)

Fig. 2 **a** Versace shirt. **b** Urban Monkey T-shirt. **c** Masaba saree

and photo-realistic images that are difficult to achieve using traditional screen printing methods. This has opened up new possibilities for designers to create unique fabric prints and to produce small print that runs economically.

Faster Turnaround Times: Digital fabric printing technology has significantly reduced the turnaround time for fabric printing. The process is faster than traditional printing methods because there is no need for printing plates, screens, or other setup materials.

Reduced Setup Costs: The setup costs for digital fabric printing technology are lower than traditional printing methods. There is no need to create printing plates or screens, which can be a significant expense for small businesses.

Environmental Benefits: Digital fabric printing technology uses less water, energy, and produces less waste than traditional printing methods. This makes it a more sustainable option for fabric printing.

Greater Accuracy and Consistency: Digital fabric printing technology offers greater control over the design and production process, providing for more accurate colour matching and consistency in print quality.

On the other hand, here are some potential arguments against digital fabric printing technology:

Limited Durability: Digital fabric prints may have limited durability compared to traditional screen prints, especially in high-wear or high-traffic applications.

High Initial Investment: The initial investment for digital fabric printing technology can be high, making it difficult for small businesses to adopt the technology.

Limited Fabric Compatibility: Not all fabrics are compatible with digital fabric printing technology. Some fabrics may require special treatment or coatings to achieve optimal printing results.

While there may be some limitations to the technology, the benefits it offers make it a valuable tool for designers and manufacturers in the textile industry [5].

Table 1 Product range for digital textile print

Clothing (shirts, T-shirts, kurtis, dresses, pants, jerseys, etc.)	Fabric banners	Car covers	Curtains
Swimming costumes	Flags	Chair covers	Table cloths
Uniforms	Tents	Window blinds	Napkins
Fabric accessories (shoes, bags, etc.)	Sails	Upholstery	Light shades

6 Future Scenario

The market requirement differs from person to person. The intended use of the fabric is the most significant beginning point for determining precisely what is required to achieve a given result. Fabric can be made from natural yarns or synthetic fibres. The majority of fabric printing in the textile business is done traditionally, but there is growing interest in digital printing on fabrics.

Here below are some potential product categories for textile prints, of which some are already utilizing it and others show great possibilities in terms of consumer demands (Table 1).

While fabric is still associated with clothing and home furnishings, the fabric business as a whole is one of the world's major printing industries, with a wide range of products. Because of various technological advancements and increasing usage, the need for Digital Fabric Printing for garments and home furnishings is rapidly increasing [6].

7 Conclusion

To conclude the study, here are some ways that digital fabric printing has made a significant contribution to the economic growth of the textile industry.

Increased Flexibility: Digital fabric printing allows textile manufacturers to produce smaller runs of custom-designed fabrics. This flexibility allows manufacturers to respond more quickly to changing trends and to offer a wider range of designs to customers.

Reduced Waste: Digital fabric printing technology reduces the amount of water, energy and waste generated during the printing process, as there is no need for intermediate transfer paper.

Increased Efficiency: Digital fabric printing technology is faster and more efficient than traditional printing methods, allowing manufacturers to produce larger volumes of fabric in less time leading to cost savings and improved productivity.

Expanded Market Opportunities: Digital fabric printing has opened up new market opportunities for textile manufacturers, particularly in the area of custom-designed fabrics. This has led to the growth of niche markets, such as printed textiles for

interior design and home decor, as well as for industrial applications such as medical textiles and automotive fabrics.

Overall, the use of digital fabric printing technology is promising to the growth and expansion of the textile industry in coming times, providing new opportunities for manufacturers and designers, and offering consumers a wider range of fabrics and designs to choose from. It is worth noting that digital fabric printing technology has evolved significantly over the years and continues to improve [7].

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Recycled Sewing Thread Based on Waste PET Bottles



Prashant Kumar, A. K. Choudhary, and Vinay Kumar Midha

Abstract In today's scenario plastic waste bottles are used to manufacture different sustainable textile products like shoes, beg, jackets, and garments by using advanced recycling process. Waste PET bottles can be converted into fiber and then into the yarn. Sewing threads play a major role in apparel and garment industry. Almost 50% of apparel markets depend of sewing thread so this area have enough space for this recycled PET sewing thread. This study presents new approaches to recycle the PET bottle waste to sewing threads. This study discusses approaches for collection, segregation methods for PET bottle waste. It discusses process of manufacturing sewing thread using PET bottle waste and various process parameters that affect the sewing thread performance. The study emphases advantages of PET bottle based sewing threads and their future scope.

Keywords Plastic · Waste · Recycle · Textile · Sewing thread · PET

1 Introduction

Plastic was invented to serve our society but as with every invention, plastic has its pros and cons. In today's scenario, majorly cons are faced by our society. Recently found some micro plastics in human blood [15] also found plastic in glaciers of the Tibetan Plateau. It means it is possible that plastic is available in our environment, food, and also available where we can't imagine. This condition is very much dangerous for human being. Plastic is on it high alert in today's condition. The problem of plastic trash affects both industrialized and poor nations. The entire globe is currently looking for an affordable and long-term solution to the plastic waste problem. Despite the fact that there have several researches on how to recycle plastic waste. Many varieties of plastic are available on the market, but there are primarily seven: Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Polystyrene (PS), Low-Density Polyethylene (LDPE), Polyvinyl Chloride

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(PVC), Polypropylene (PP), and Others (BAS) [2]. The majority of the plastic in these categories is recyclable. Except for HDPE and PET, however, all other categories have extremely poor recycling rates of less than 1–2% [11]. Any plastic recycled product's low recycling rate is a key challenge for sustainable development. To boost the recycling rate, people should give it some thought and make the necessary contributions. Encourage individuals to dispose of their garbage properly to make the recycling process simpler. Government has to take some initiative to educate people about the need of recycling and to assist maintain a system for efficient waste management.

Textile is a very big area which continually serves our society. Textile offers enough opportunity for reducing methods of replacing plastic waste. Nowadays, all types of synthetic fibers, which are mostly made from various types of plastic, may also be generated from plastic waste, which are known as recycled fibers [8]. Many recycled items, including coats, t-shirts, shoes, and more, are made from polyester that is recycled from PET bottles [17]. There are several instances of businesses right now using recycled plastic in their goods. Decathlon [12] manufactured its recycled polyester items in large part, Nike [3] created its wearable shoes and t-shirts, and AMMAN and Coats prepared recycled sewing threads [4, 7]. Plastic garbage and waste from the fashion industry make up the majority of these goods' raw materials [16].

The fashion industry is growing quickly in our culture, which leaves a tremendous quantity of garbage in its wake. The fashion industry has a dark side, and this is it. Textile items are being shifted from being core human necessities to secondary goods as a result of rapidly expanding fashion trends [13]. Consequently, as a result of this occurrence, the lifespan of all clothing is decreasing, which leads to significant fashion waste. Plastics, which are recyclable, make up the majority of this waste's components. Polyester is mostly produced from waste bottles. Water bottles with the exception of the cap are made of polyester. The cap section is typically constructed of recyclable HDPE [9]. Waste from the fashion industry made of polyester includes things like coats, films, fake goods, threads, wires, and dresses, among other things [6]. In the garment industry, there are typically two types of sewing threads used. The first is natural-based cotton, which accounts for about 20% of the total sewing thread area, and the second is plastic-based polyester, which accounts for roughly 60% of the entire sewing thread area. Since that polyester sewing thread is a kind of plastic, it may be produced through the recycling of used plastics. Recycled polyester sewing thread (Fig. 1) used less energy than virgin polyester sewing thread, at least economically speaking.

2 Process of Recycled Polyester Sewing Thread

The cyclic process, how plastic waste convert into threads is represent in Fig. 2.



Fig. 1 Recycled polyester sewing thread

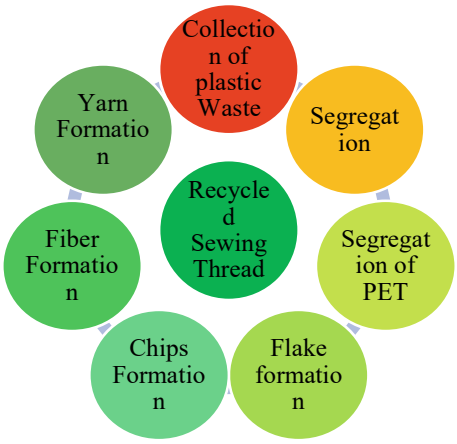


Fig. 2 Process of recycled polyester sewing thread

2.1 Collection of Plastic Wastes

In practically all developed and developing nations, waste collection is mostly handled by governmental bodies and a few private ones. In a developing nation like India, the municipal corporation is the name of the government agency that operates in each state and is primarily responsible for collecting all types of trash. It was known as MSW (Municipal solid waste) [14].

MSW contributes 22% of the overall garbage, with plastic making up around 16% of that waste. This plastic garbage is made up of many plastic types. Hence, the Municipal Corporation designates certain individuals to collect the MSW. The work team has a variety of tools and machinery for such job, including covered trash cans that are put within residential areas and utilized by residents to dispose of their trash.



Fig. 3 Indian railway waste collections

The municipal works then collects the waste from these boxes at a regular interval. Large covered vehicles are used to collect these wastes.

The waste is finally sent to the segregation facilities so that it may be separated. Several Indian government agencies are involved in this waste collection field, such as Indian Railways [5], which has a dedicated department to this task and ensures that waste is collected from trains and railway stations in a certain manner. The Indian Railways has implemented various measures to gather more plastic, such as installing garbage bottle crushing equipment on mostly Indian stations shown in Fig. 3. This effort was also done by certain local NGOs and commercial enterprises [1]. People in certain developing nations, such as India, Africa, and Vietnam gather plastic waste in order to make money from it. Poor and developing nations frequently engage in these practices [18].

2.2 Collection of Plastic Wastes

Plastic waste primarily consists of seven different types of plastic: Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Polystyrene (PS), Low-Density Polyethylene (LDPE), Polyvinyl Chloride (PVC), Polypropylene (PP), and others shown in Fig. 4. Most of these subcategories of plastic can be recycled. It becomes very difficult to separate all these distinct plastic categories from the plastic

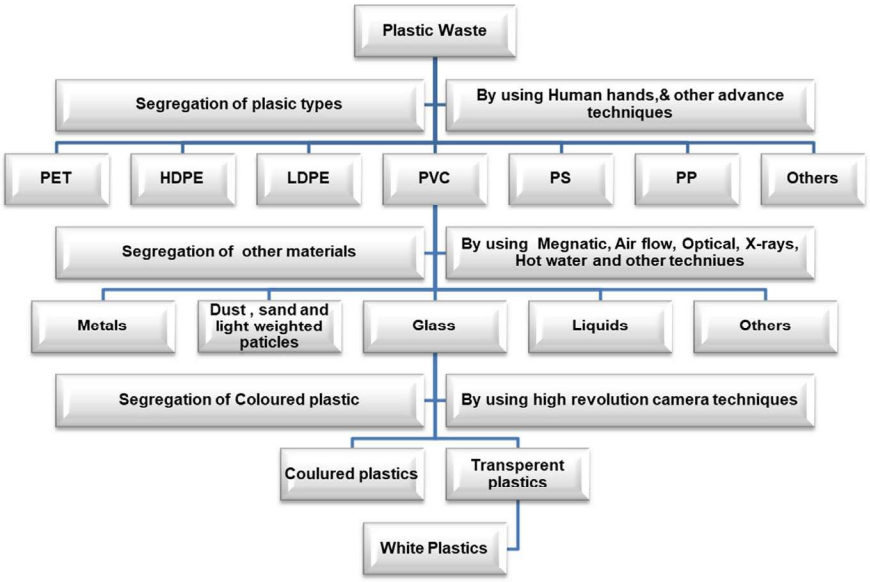


Fig. 4 Plastic waste segregation

waste since it contains so many of them. Various types of plastic have distinct molecular structures, masses, and lengths of molecular chains. If we don't take the segregation process seriously and move on to the melting phase right away, the material we produce won't have favorable qualities. Separation is particularly crucial since, in addition to plastic waste, there are metal pieces, liquids, mud, and other substances contained in used plastic bottles and containers that may affect our subsequent processes. For the extraction of dust and other light particles, air flow is employed. To remove the metal components found in the waste plastic, magnetic separation is used. The most popular chemical procedure for removing undesirable compounds from plastic trash is hot water washing. Human hands or other methods, such as X-ray techniques, are used to separate the various kinds of plastic [10].

2.3 Segregation of PET

The main source of polyester is waste plastic bottles. After recycling, this is utilized as the raw material for recycled sewing thread. To enhance the mechanical qualities of recycled polyester, de- and re-polymerization are occasionally used. Polyester is present in plastic bottles, with the exception of the cap and its leveling film. Usually caps are constructed of high-density polyethylene (HDPE) shown in Fig. 5. So, the cap section needs to be removed before continuing with the procedure since



Fig. 5 Waste PET bottle

otherwise, it would prevent you from getting the end recycled polyester product as favorable as possible.

2.4 Flake Formation

Waste PET bottles that had been hot washed and dried were compressed into large bales after the segregation stage. These bales are prepared for the procedure of forming flakes. These bales are moved to the shredder machine during the process of forming the flakes, which cut the bottles into tiny pieces. These tiny particles are referred to as flakes shown in Fig. 6, and they are eventually moved for further melting process. Transparent bottles and colored bottles are shred separately since shredding them together results in colored particles that are difficult to dye. After forming into flakes, these flakes are sent to various melting units where they undergo de- and re-polymerization to become polyester chips or cubes.



Fig. 6 Shredded waste polyester

2.5 Chips Formation

Flakes are conveyed to melting units where the de-polymerization and re-polymerization process has been completed in order to transform polyester chips shown in Fig. 7. Re-polymerization is carried out to enhance the superior physical qualities. Re-polymerization is possible in buildings with reactors. The market offers these recycled chips in a variety of categories based on how well they have been recycled. Recycled fibers, which are then utilized to create recycled polyester sewing thread, are typically made from high-quality recycled polyester chips.



Fig. 7 Recycled polyester chips

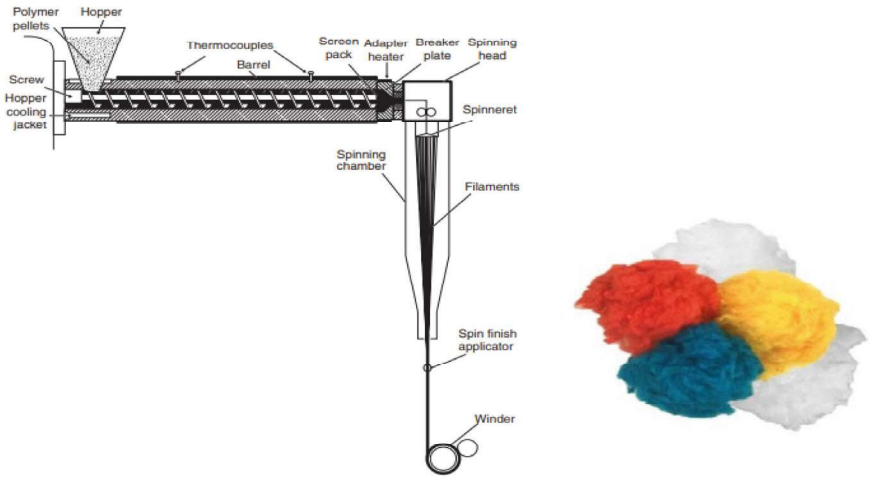


Fig. 8 Melt spinning process for recycled polyester staple fiber [19]

2.6 Fiber Formation

The well-known melt spinning method is used to create recycled polyester fiber shown in Fig. 8. Recycled chips of the highest quality are placed in the extruder, where they will melt in various zones at high temperatures. The substance is combined with several necessary chemicals during this procedure. Brightening agents are used to enhance the dullness of recycled polyester's color because after being exposed to sunshine, the polyester product develops a yellowish hue. To address this color issue, several brightening agents are often used. By adding these brightening chemicals, some tinted color or, as we would say, some blue color also reflects in the finished recycled fiber. By virtue of this tint, recycled polyester fiber consistently underperformed in terms of the whiteness color index value. After the operation was complete, the ready-melted mixture was delivered to the spinnerets zone, where it was stretched to attain its desired qualities. The two types of fiber are filament and staple. In general, staple fiber is used to make recycled polyester sewing threads.

2.7 Yarn Formation

The same well-known ring spinning method that is used to create conventional virgin polyester sewing threads is also employed to generate recycled polyester sewing threads. Particularly for the recycled polyester, this spinning process has not undergone significant modifications. In compared to virgin polyester sewing thread, recycled polyester sewing thread has more faults because there is greater variety or imperfection in the recycled materials during different phases of spinning.

Table 1 Physical property comparison between vPET and rPET sewing thread

Properties	Tenacity (gpd)	CV (%)	Elongation at break (N)	CV (%)	Color
Virgin PET sewing thread	8.34	5.55	43.1	5.29	White
Recycled PET sewing thread	7.23	8.49	46.5	7.56	Tinted

3 Experimental

3.1 Material and Methods

Virgin PET sewing thread and recycled PET sewing thread prepared from waste PET bottles are used as samples in this experiment. Virgin PET sewing thread and Recycled PET sewing thread having the same count, 30 Tex. Mechanical performance (tensile test) test is done to determine the breaking strength and elongation at break by following the standard ASTM D2256.

3.2 Results and Discussion

Table 1 and Fig. 9 shows the physical property comparison between vPET and rPET sewing thread. As per the representation rPET sewing thread shows the less physical properties in comparison with vPET.

4 Conclusion

The recycled PET sewing thread exhibits good strength, better extensibility. Although it have little bit smaller vales in comparison to virgin PET thread but it is an energy saving and sustainable product and also sufficient and very much capable to fulfil all the requirements of sewing industries.

5 Challenges, Benefits and Applications of Recycled Sewing Thread

In aspect of physical appearances, Instead of being white, recycled polyester sewing yarn is tinted. Recycled polyester sewing yarn has a bullish color because optical brighteners were included in to remove the dullness color. Darker dye colors face

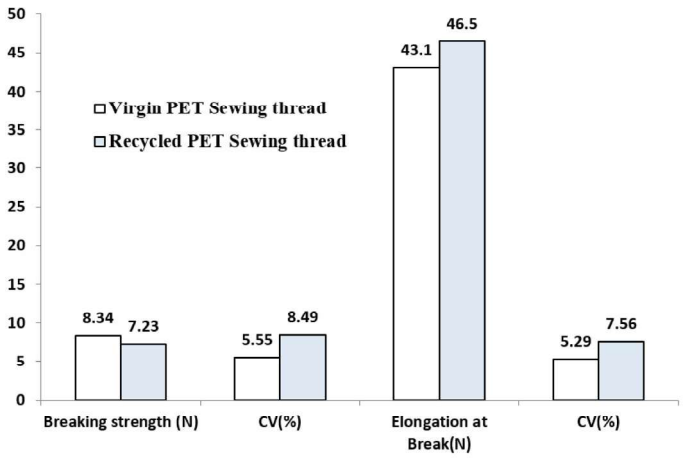


Fig. 9 Graphical representation of physical property comparison between vPET and rPET sewing thread

no issues, however lighter dye colors do cause some issues. In aspect of handle property recycled polyester yarn has more faults than virgin polyester so it has a harsher feel when used for sewing. And in aspect of physical property, compared to virgin polyester sewing thread, recycled polyester sewing thread has poorer physical characteristics. Several businesses employ the re-polymerization procedure to make up for this difference in physical property. This method has enhanced the physical characteristics of recycled polyester sewing thread. Recycled sewing thread has consumed almost 35–40% lesser energy in comparison to virgin sewing thread. It helps to replacement of plastic waste into textile sector. It also contributes as a sustainable product in circular economy. Recycled sewing thread has no skin harms and also not fading with the time. Due to recycling reason it is an eco-friendly product of sewing industry. Also have no shrinkage with water. Nowadays recycled sewing threads are present in the marks with different shades and colors so any one can use these with their different projects like embroidery etc.

Advantages with recycled sewing thread;

- Easier heat stabilization
- Better crimp and tensile properties
- Raising bending and shear rigidity
- Good adhesion

Many kitting garments, apparel industries, interior deigning (furniture), in garment industry like casual wears, shoes, different embroidery projects.

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Effect of Fiber Blend on Properties of Grey Needle Punched Composite Nonwovens



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Abstract This research explores the potential of combining dissimilar materials and substrates using needle punching to create composite nonwoven fabrics with superior properties. The study focuses on the effect of different fiber denier and structures on the performance of grey composite needle-punched nonwoven fabrics. Recycled polyester staple fiber and virgin polyester staple fiber are used with three levels of fiber blend composition and two levels of woven fabric as reinforcement for needle punched composite nonwoven. The six samples are analyzed for properties like air permeability, pore size, thickness, bursting strength, tensile strength, and elongation, shrinkage. The study concludes that a tailored approach can be employed to select blend ratios and scrim fabric to achieve the desired properties for required applications. The anti-static property can be used to control the electrostatic charge accumulation in the filter media. The findings suggest that the combination of different technologies can create multi-functional and economical composite nonwoven products.

1 Introduction

Nonwoven have noticeable advantage over woven fabric for dry filtration usage due to their unique feature such as random orientation, porous structure, bulkiness of fabric, high flowing rate, three-dimensional structure [1, 2, 8 9] it shows good efficiency in collection of dust particles without reducing flow rate or increase in pressure drop. Needle punched fabric is mostly considered for producing such dust filters as they can meet certain requirements [3] and considerably used for producing composite nonwoven fabric which will perform much better than only nonwoven fabric having same weight per meters. Composite nonwovens are already being used significantly

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in many markets, including hygiene, wipe, medical, filtration, automobile, geotextile, and agriculture. Baby care, feminine care, and adult incontinence products are applicable for nonwoven product. Dry filters are used in Mining, Cement Industry, Iron and Steel Industry, Aluminum and Non-Ferrous Industry, Ceramic Industry, Quarrying, Plastics, Milk Powder, Flour Mills (Applications under dry conditions up to temperatures of 150 °C) [3, 5, 6, 12, 15]. Bulk and physical property (better air permeability, porosity, and bursting strength) of needle punched fabric determine the suitability of fabric for the requirement [13]. Properties of such fabrics are influenced by many factors such as fiber properties, web characteristics, machine design parameters, machine variables and finishing properties [2, 4, 9]. Calendering needle-punched material helped in achieving desired compactness and air permeability in filter. Fabric after heat setting, thickness and air permeability of filter is increased. But breaking strength and elongation did not change at different stage (needling, calendering, heat setting). Bilayer nonwoven fabric is more suitable for air filtration [10]. Air permeability of fabric decreases for more fabric thickness. Bursting strength is more for bilayer nonwoven fabric. Filtration efficiency increased as increase in thickness and GSM.

Needle punched fabric shows good physical characteristics compared to thermal bonded fabric. Higher nonwoven fabric strength and presence of scrim fabric improve strength and abrasion resistance provided with suitable needle punch density. Air permeability, porosity, pressure drop is also affected by scrim fabric [14].

Composite nonwovens frequently exhibit enhanced product characteristics and performance when compared to conventional materials. Paired with their cost-effectiveness and high production rates, the future outlook for composite nonwovens seems promising. Nonetheless, this growth trajectory necessitates heightened emphasis on energy and cost efficiency during production, as well as a commitment to minimizing environmental impact and promoting the development of energy-efficient products.

2 Experimental

2.1 Raw Material

Needle punched nonwoven fabrics were manufactured using following fibers.

Recycled Polyester fiber [3 den × 51 mm in blend ratio (80, 65, 50%)]
Virgin Polyester fiber [1.4 den × 51 mm in blend ratio (20, 35, 50%)]
Woven fabric (Scrim) Parameters:
Normal Scrim—
1000 denier Multifilament Polyester;
Ends per inch (EPI) * Picks per inch (PPI) = 11 * 13;
Gsm—110;
Fabric Thickness—0.2 mm;

Fig. 1 Normal scrim

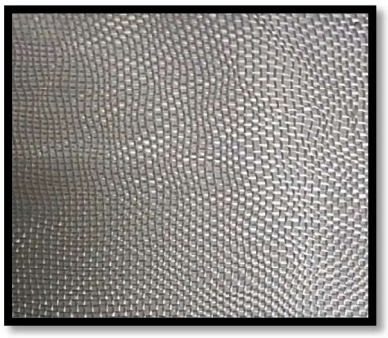
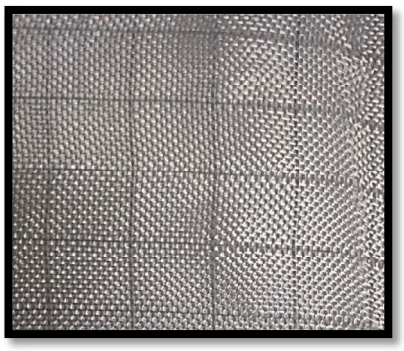


Fig. 2 Antistatic scrim



Fabric Weave—1 * 1 plain.
Antistatic Scrim—
1000 denier Multifilament Polyester and $2/20^{s}$ Polyester—Stainless Steel spun yarn.
Ends per inch (EPI) * Picks per inch (PPI) = 11 * 13;
Gsm—110;
Fabric Thickness—0.23 mm;
Fabric Weave—15 * 15 ripstop;
Surface Resistivity value of antistatic scrim is 10^2 to 10^3 Ohms/square.

2.2 Machine

See Fig. 3.

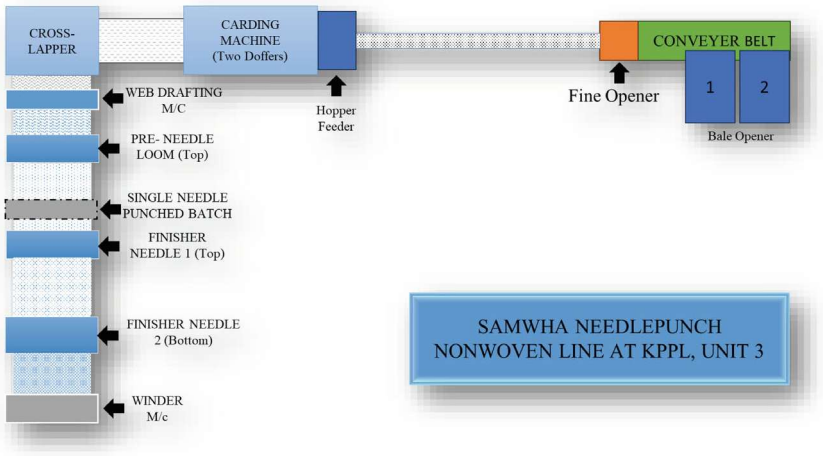


Fig. 3 Plant layout of project sample manufactured

2.3 Methodology

Six Composite Needle Punched Nonwoven samples were produced using polyester fiber for top and bottom layer with blend ratio of 80:20, 65:35 and 50:50 for blend of 3 denier recycled and 1.4 denier virgin fiber, by sandwiching multifilament fabric (scrim) of 100% polyester filament and antistatic polyester filament by keeping all the needling parameters same for both the fabrics. The samples were prepared by needle punched machine of SAMWHA line as mentioned in Fig. 3. The constant parameters mentioned in Table 2 were used to produce nonwoven fabric samples on machine. The machine line consists of two bale openers used for the blend of two different fiber deniers. The fine opener of the bale opener was used to open the fiber and forward the opened fiber to hopper feeder of carding machine. The carding machine had two doffers which gives two webs to cross-lapper. The cross-lapper is capable of laying 90″ fabric layer for set fabric weight throughout the line. Drafting machine was present in line but not used for drafting; it was used as transmission medium from cross-lapper to pre-needler loom. The pre-needler machine punches the fiber web from top side and forms fabric which was used for top and bottom layer in composite nonwoven fabric. The scrim fabric beam was kept after pre-needling of nonwoven fabric which get combined with nonwoven fabric at finisher needler 1 that is needled from top side. The Finisher needler 2 punches from bottom side and is used after both layer of nonwoven are sandwiched with scrim fabric and collected at the winder.

Table 1 shows the design of experiment and number of grey needle punched composite nonwoven produced.

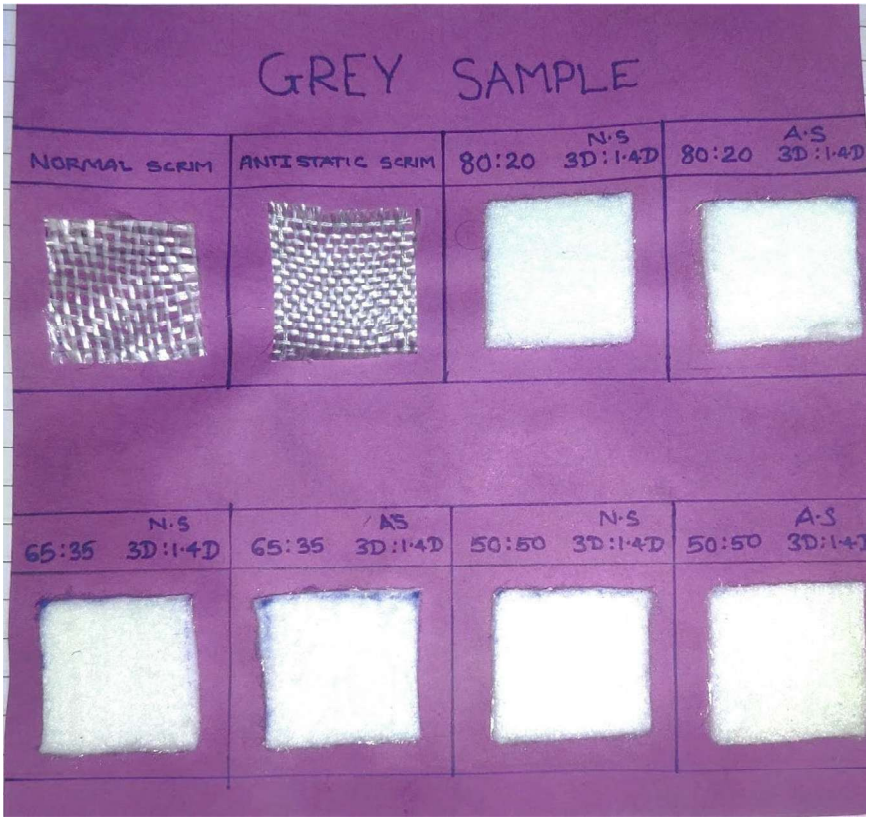


Fig. 4 Photograph of normal scrim, antistatic scrim and six needle punched composite nonwoven produced

Table 1 Design of experiment for grey sample

Scrim cloth	Blend ratios of 3 den recycled and 1.4 den virgin for top and bottom layer of needle-punched nonwoven fabric		
	80:20	65:35	50:50
Normal	1	3	5
Antistatic	2	4	6

3 Material Testing

Following test were conducted for the six grey samples produced and analyzed for various properties.

Table 2 Needle punch line constant process parameters: (needle used—standard felting needle—RF Barbs)

Needle loom	Pre-needle	Finisher 1	Finisher 2
Needle punch density (/cm^2)	254	283	310
Needle gauge used	38	38	40
Needle penetration depth (mm)	11	11.2	6.9
Needle stroke speed (stokes/min)	560	650	700
No. needles/meter in board	10,000	10,000	10,000
Distance between stripper plate and bed plate (mm)	24	18	18

Table 3 Testing and standards

Sr. no.	Testing	Machine	Standards
1	GSM	Weighing balance	ASTM D3776
2	Air permeability (AP)	Tex FX 3300—III	ASTM D737-96
3	Thickness	Digital thickness gauge	ASTM D1777-96
4	Strength and elongation	KMI—3151-201 T	ASTM D885
5	Micron/Pore size	Capillary flow porometer	ASTM D3359
6	Bursting strength	Digital bursting tester	ASTM D6797
7	Shrinkage	Dry air oven	ASTM D2259-02

4 Results and Discussion

The work was carried out as per the plan of work discussed above. Six grey samples were manufactured on Needle Punching Machine with three different Blend ratios and two types of scrim fabric. The samples were then tested for different characteristics described in material testing. The results were analyzed using two-way Analysis of Variance (ANOVA) without repetitions to know the effect and significance of fiber blends and type of scrim fabric on properties of grey needle punched composite nonwoven fabric samples.

4.1 Effect of Fiber Blend and Type of Scrim on Air Permeability of Grey Needle-Punched Composite Nonwoven

Mean Air Permeability values of six samples with three blend ratios and two types of scrims are shown in Table 4. Using two-way ANOVA without replication, there is significant of effect of blend ratios and types of scrims on mean air permeability. From Fig. 5, it is clear that the 80:20 blend shows highest value for both scrims,

Table 4 Mean air permeability (Ltrs/dm^2/min)

Scrim	Air permeability (Ltrs/dm^2/min)		
	80:20	65:35	50:50
Normal	374	335	290
Antistatic	295	283	239

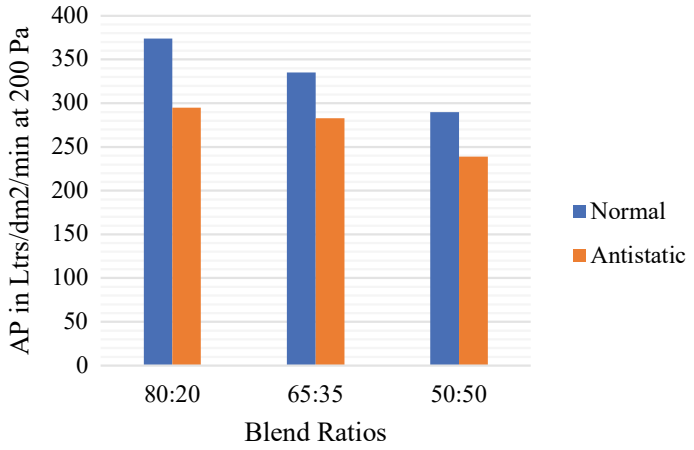


Fig. 5 Mean air permeability

while the 50:50 blend ratio shows the lowest air permeability. Since the average fiber denier for the 80:20 blend is coarser, and the average fiber denier for the 50:50 blend is finer, the increased surface area in the 50:50 blend creates more resistance to air permeability. Additionally, the weave of normal scrim is plain weave, which provides more air permeability than ripstop weave. Therefore the air permeability of the normal scrim nonwoven sample is higher than that of the antistatic scrim nonwoven sample.

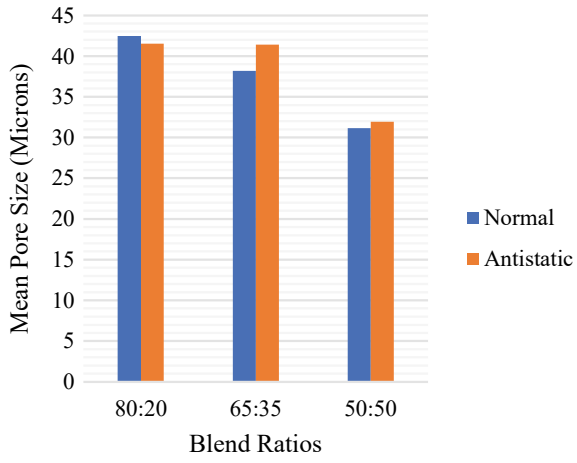
4.2 Effect of Fiber Blend and Type of Scrim on Pore Size of Grey Needle-Punched Composite Nonwoven

Mean Pore size values of six samples with three blend ratios and two types of scrim are shown in Table 5. Using two-way ANOVA without replication, there is significant of effect of blend ratios but no significant effect of type of scrim on mean pore size. From Fig. 6, it is clear that the sample of 50:50 blend for each scrim has less pore size compared to other four samples which also affects the air permeability of fabric. The 80:20 blend has highest pore size and the 50:50 blend has lowest pore size because average fiber denier for the 80:20 blend is coarser and average fiber denier

Table 5 Mean pore size (μm)

Scrim	Mean pore size (μm)		
	80:20	65:35	50:50
Normal	42.4781	38.1942	31.1291
Antistatic	41.5465	41.4093	31.9389

Fig. 6 Mean pore size



for the 50:50 blend is finer. The 50:50 blend sample can be used where filtration of below 30 μm particle size is needed whereas other four samples can be used for the particle size range of 30–50 μm.

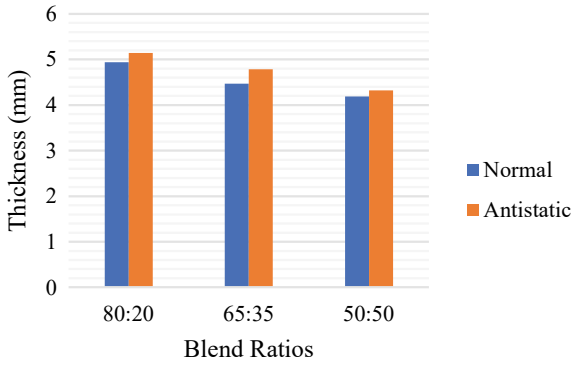
4.3 Effect of Fiber Blend and Type of Scrim on Thickness of Grey Needle-Punched Composite Nonwoven

Mean Thickness values of six samples with three blend ratios and two types of scrim are shown in Table 6. Using two-way ANOVA without replication, there is significant of effect of blend ratio and type of scrim on the mean thickness. The decreasing trend of thickness is shown in Fig. 7, as the percentage of finer fiber increases in the blend ratio and the proportion of coarser denier fibers decreases, which influences the overall thickness of the nonwoven fabric. The thickness of sample is also varied due to type of scrim, as the antistatic scrim nonwoven fabric has slightly more thickness than the normal scrim nonwoven fabric for all the blend samples due to weave type—ripstop and spun yarn used in the antistatic scrim.

Table 6 Thickness (mm)

Scrim	Thickness (mm)		
	80:20	65:35	50:50
Normal	4.94	4.47	4.19
Antistatic	5.14	4.785	4.32

Fig. 7 Mean thickness



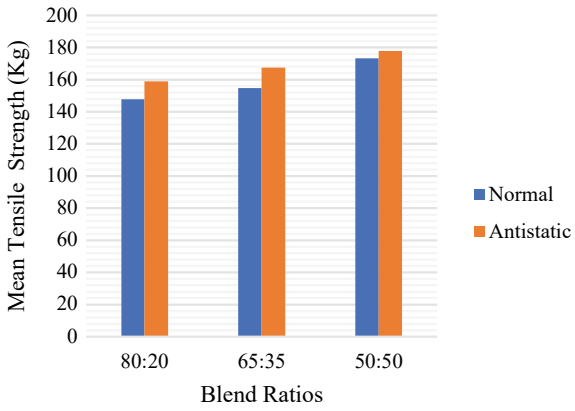
4.4 Effect of Fiber Blend and Type of Scrim on Tensile Strength (MD) of Grey Needle-Punched Composite Nonwoven

Mean Tensile strength in machine direction (MD) values of six samples with three blend ratios and two types of scrim are shown in Table 7. Using two-way ANOVA without replication, there is significant of effect of blend ratio on the mean tensile strength of the fabric in the machine direction, as well as a significant effect of scrim on tensile strength. However, for tensile strength in the cross direction, there is no significant effect of blend ratio or scrim type on the fabric. It is observed that tensile strength increases as the blend ratio shifts from 80:20 to 50:50, as shown in Fig. 8. As the proportion of virgin polyester increases in the blend ratio, the tensile strength tends to increase. Virgin polyester typically has higher tensile strength compared to recycled polyester. As the average fineness increases in the 50:50 blend, the number of fiber will be greater than in the 80:20 blend so strength will be higher for the 50:50 blend.

Table 7 Mean tensile strength

Scrim	Tensile strength (MD)		
	80:20	65:35	50:50
Normal	147.8	154.817	173.293
Antistatic	158.905	167.559	177.75

Fig. 8 Mean tensile strength



4.5 Effect of Fiber Blend and Type of Scrim on Elongation, Bursting Strength and Shrinkage of Grey Needle-Punched Composite Nonwoven

The mean elongation, bursting strength and shrinkage of six needle punched nonwoven samples are shown in Table 8. Using two-way ANOVA without replication, there is no significant of effect of blend ratio or type of scrim on elongation in both direction, bursting strength, or shrinkage. In Table 8, there are some variations in elongation, bursting strength, and shrinkage, but no significant changes in values. Some variation in shrinkage in both direction was observed, as the samples were not heat-treated, the shrinkage of fibers might have occurred due to the use of 3 denier recycled fibers.

Table 8 Average of test results

Sr. no.	Fabric type	Scrim type and blend ratio					
	Scrim type	Normal			Antistatic		
	Parameters	80:20	65:35	50:50	80:20	65:35	50:50
1	Bursting strength (kg/cm^2)	48.2	50.8	51.3	46.9	47.2	48.5
2	Elongation (%)	22.86	22.71	22.54	24.33	23.55	21.24
3	Shrinkage (%)	5.58	5.16	4.91	5.5	5	4.5

4.6 Comparison of Surface Resistivity of Normal Scrim and Antistatic Scrim Grey Needle Punched Composite Nonwoven

Surface resistance for the fabric sample with antistatic scrim displayed electrical resistivity values of 10^8 and 10^9 ohms/square, indicating its capacity to dissipate static electricity effectively during usage. In contrast, the normal scrim fabric shows relatively higher electrical resistivity value of 10^{12} ohms/square, signifying its inadequacy in dissipating static charge. Hence, the developed antistatic grey needle-punched composite nonwoven fabric can be used in applications where static charge generation is higher, such as in the bag house of coal, carbon, and cement industries. On the other hand, the normal scrim grey needle-punched nonwoven fabric can be used in filter application where static charges are not a significant concern.

5 Conclusion

This study aims to understand the effect of fibre blend and type of scrims on properties of grey needle punched composite non-woven fabric made by 3 denier recycled and 1.4 denier virgin polyester staple fibres. The study applied Analysis of Variance (ANOVA) for two factor without replications, and the following are the conclusions:

There is a significant effect of fibre blend and scrim fabric on air permeability, pore size, thickness, and tensile strength (MD). There is no significant effect of blend ratio and scrim type on bursting strength, shrinkage, and elongation in both directions.

Effect of Fibre Blend—Blend ratio has a significant effect on air permeability, pore size, thickness, and tensile strength (MD).

Effect of Scrim Fabric—Scrim fabric has a significant effect on air permeability, thickness, antistatic values. The weave of anti-static scrim is ripstop, which results in slightly more thickness for all blend samples compared to plain weave normal scrim. Air permeability is also affected by the anti-static scrim due to the change in weave and yarn type, as the plain weave scrim provides higher air permeability than the ripstop weave scrim.

The 80:20 blend ratio shows the highest air permeability for both scrim types, with the highest pore size, while the 50:50 blend ratio shows the lowest air permeability with lowest pore size. This blend composition can be used for suitable application.

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Surface and Total Hand Value Properties of Sericin Treated Fabric



D. Kamalraj, V. Subramaniam, and Bhaskar Mitra

Abstract The total hand value properties responses to a series of sericin treated polyester fabric were investigated. The fabric surface properties response includes, coefficient of friction, mean deviation of friction and surface roughness. Bulk density of sericin treated fabrics are also investigated. The fabrics were produced with different treatment including plasma treatment. Bulk density of sample C fabric without alkaline treatment followed with sericin and glutaraldehyde is characterized by lower value and sample D alkaline followed by plasma treatment accompanied with sericin and glutaraldehyde applied fabric exhibits highest value of bulk density. Coefficient of friction shows a reduction in all samples. Surface roughness is lower for fabric samples D and E alkaline treatment followed by sericin with glutaraldehyde treated fabric and highest value of surface roughness is obtained for fabric sample C. It was observed that all sericin treated fabric shows an increase in Total hand value and sample C (fabric is treated with Glutaraldehyde with sericin), shows highest total hand value. Thus, the sericin treated polyester fabric is suitable for sportswear application.

Keywords Fabric hand value · Sericin treated fabric · Bulk density · Hybrid fabric

1 Introduction

The experimental work of Gupta [6, 7] is contained in lengthy papers, giving results on sericin application to polyester and cotton fabrics. Doakhan et al. [3] have studied the influence of sericin titanium dioxide (TiO_2) nano composite on cotton fabric. Application of sericin to cotton fabric, the paper by Kongdee et al. [9] deserves special mention. The presence of sericin was confirmed by dyeing of treated fabric with acid

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dyes and measuring K/S values. Kosawatnakul et al. [10] have reported on chemical finishing of cotton fabrics by silk fibroin. It has been found that with increasing concentration of sericin, wrinkle recovery improves and dye uptake follows the same trend. Bhandari et al. [1] have studied the effect of sericin treatment on the dyeability of cotton fabrics at various concentrations of sericin treatment, temperature, treatment time, material to liquor ratio, concentration of citric acid, concentration of sodium hypophosphite, drying temperature, curing temperature and curing time.

Gulrajani et al. [5] have carried out a pioneering study on the application of sericin to polyester fabric. They have tested the fabric for moisture absorption property, crease recovery and bending length. Khalifa and Ladhari [8] discuss the application of sericin to modify cotton and wool fabrics. While sericin showed affinity for wool, no such effect was noticed in cotton. The treatment has also improved the antibacterial property for wool. Martinez et al. [11] have characterized sericin obtained from cocoon and silk yarns. Chaudhary et al. [2] report on multifunctional dyeing and finishing of polyester with sericin and basic dyes. Polyester fabric was treated with sericin alone with GTA (Glutaraldehyde) following irradiation using UV light. The treated fabric samples were dyed using basic dyes and their dye uptake was measured. Antimicrobial activity against *S. aureus* was found to be good. Hence, it is pointed out that sericin has been found to be useful in imparting multifunctional properties to polyester fabrics. El-Newashy et al. [4] investigated the Comfort Attributes of Polyester Knitted Fabrics Treated with Sericin, Vidya et al. [12] have studied the moisture management properties of the polyester knitted fabric and found that its properties are improved with the oxygen plasma treatment. A great deal of work has been done on the application of sericin to polyester and cotton fabrics and their many properties have been studied. There is an absence of work related to coefficient of friction, mean deviation of friction and surface roughness.

2 Experimental

A 380D polyester filament having an elongation of 27.23 are used and made100% polyester fabrics from the Industry. Five samples of polyester fabrics were used in this study. The details are given in the Table 1.

2.1 Alkaline Hydrolysis

The polyester fabric sample were pretreated with alkali 1M (40g/l) NaoH at 80 °C for 45 min with 1 : 100 material to liquor ratio to create functional groups on their surface, before applying sericin onto them. This formed the control sample A.

Table 1 Fabric treatment applied to polyester fabric

Sample code	Treatment applied
Sample A	Alkaline treated polyester fabric
Sample B	Without alkaline treatment sericin applied fabric
Sample C	Without alkaline treatment sericin with glutaraldehyde fabric
Sample D	Alkaline treatment followed by plasma treatment accompanied with sericin and glutaraldehyde applied fabric
Sample E	Alkaline treatment followed by sericin with glutaraldehyde treated fabric

2.2 Sericin Application

20g/l of sericin solution was used. Alkali treated fabric were padded with the sericin solution in a laboratory padding mangle by a 2 dip 2 nip process. The padded fabric was dried at 80 °C for 3 min and cured at 130 °C for 2 min. Cured samples were then washed and dried. Glutaraldehyde was used as a crosslinking agent to attach sericin to alkali modified polyester. This is called as sample E.

2.3 Plasma Treated with Glutaraldehyde (GA)

The alkali-treated polyester fabric was cut to the desired size of 54 × 54 cm and weighed. The pressure within the plasma chamber was reduced to zero bars before this fabric was put between the two plates and secured to the frame. Then, 2 bar of pressure worth of oxygen gas was passed into the chamber. The top side of the cloth was initially subjected to 1.06 A of plasma current at 350 V and 290 °C for 5 min. The fabric was then exposed for 5 min to a plasma current of 1.53 A, a plasma voltage of 300 V, and a temperature of 290 °C. After the process, the fabric was weighed again to determine the weight loss percentage. Weighing the fabric to determine its required dimension, it was then wetted in water with a wetting agent (TRO), treated with a solution of sericin 25% (owf), GA 20g/l, magnesium chloride 10g/l, and acetic acid using a material-to-liquor ratio of 1:9, padding it, and curing it. This sample is referred as D.

2.4 Without Alkali Treated Polyester

Without alkali treated polyester fabric are padded with sericin alone with the same procedure mentioned above, which forms the sample B. In the same manner without alkali treated polyester fabric are treated with sericin and glutaraldehyde by pad dry and cure method, forms the sample C.

3 Result and Discussion

Fabric surface properties decides the fabric handle and comfort properties. It includes coefficient of friction (MIU), mean deviation of friction (MMD) and surface roughness (SMD). Table 2 shows the values of MIU, MMD and SMD of all samples. Coefficient of friction shows a reduction with sericin treatment for all face and back side and mean as shown in Table 2. Surface roughness (SMD)is lower for fabric samples D and E. Highest value of SMD is obtained for fabric sample C.

Plasma treatment increases the roughness and the area of fibre surface compared with the control fabric. Morphological changes induced by plasma treatment can be attributed to fibre etching which occurs as a consequence of bombardment of the fibre surface by energetic and reactive particles generated by the plasma.

3.1 Coefficient of Friction (MIU)

MIU of sericin treated fabric of face, back and their mean are given in Table 3 with confidence interval. Figure 1 illustrate the MIU of mean of sericin treated fabric.

The drop in coefficient of friction following sericin treatment is due to decrease in area of contact caused by sericin. Plasma treatment causes surface etching which will change the surface due to bombardment of the surface.

Table 2 Surface properties of sericin treated sample

Surface properties	Sample A	Sample B	Sample C	Sample D	Sample E
Surface MIU	0.270	0.195	0.192	0.177	0.195
Surface MMD	0.0834	0.0674	0.0614	0.0617	0.0728
Surface SMD, μm	9.826	10.31	12.082	8.746	8.826

Table 3 MIU of sericin treated fabric in face, back and mean.

	Face	Back	Mean
Sample A Warp	0.282(±0.05)	0.258(±0.01)	0.27(±0.03)
Sample B	0.1995(±0.02)	0.191(±0.15)	0.195(±0.06)
Sample C	0.2025(±0.004)	0.181(±0.02)	0.1915(±0.01)
Sample D	0.197(±0.01)	0.1575(±0.004)	0.177(±0.01)
Sample E	0.2195(±0.03)	0.1705(±0.006)	0.195(±0.02)

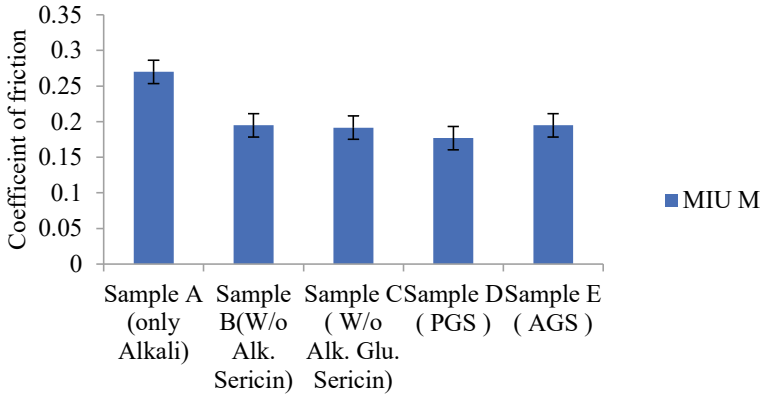


Fig. 1 Mean of MIU of sericin treated fabric

Table 4 MMD of sericin treated fabric (face, back and middle)

Sample	Face	Back	Mean
Sample A	0.09125(±0.001)	0.07565(±0.01)	0.08345(±0.003)
Sample B	0.0763(±0.04)	0.05855(±0.03)	0.0674(±0.03)
Sample C	0.06655(±0.04)	0.05625(±0.03)	0.06135(±0.04)
Sample D	0.0721(±0.04)	0.0514(±0.03)	0.0617(±0.03)
Sample E	0.07445(±0.02)	0.0712(±0.02)	0.0728(±0.02)

* () refers to confidence interval

3.2 *Mean Deviation of Friction (MMD)*

MMD of sericin treated fabric of face, back and their mean are given in Table 4 with confidence interval. Figure 2 illustrate the MMD of mean of sericin treated fabric.

3.3 *Surface Roughness*

SMD of sericin treated fabric of face, back and their mean are given in Table 5 with confidence interval. Figure 3 illustrate the SMD mean of sericin treated fabric.

3.4 *Bulk Density and Total Hand Value*

Bulk density of fabric determines the insulating properties of fabric. Figure 4 shows bulk density of samples from which it is noticed that fabric samples C is characterized

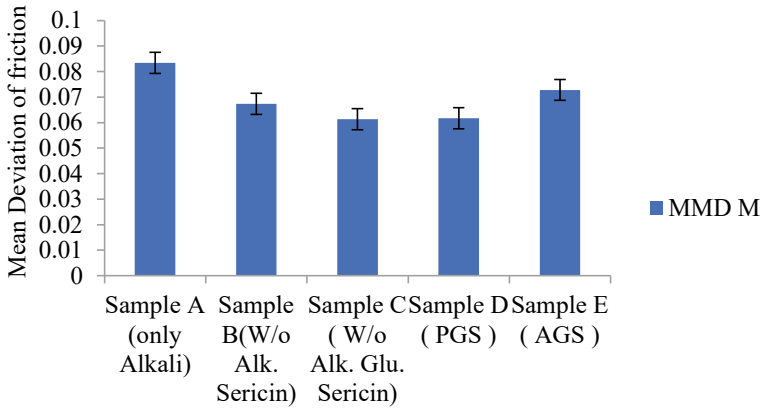


Fig. 2 Mean of MMD of sericin treated fabric

Table 5 Surface roughness (SMD) values of sericin treated fabric

Sample	Face (μm)	Back (μm)	Mean (μm)
Sample A	9.725(±0.56)	9.93(±0.24)	9.8265(±0.39)
Sample B	10.665(±0.38)	9.955(±1.11)	10.31(±0.75)
Sample C	11.565(±0.50)	12.615(±0.05)	12.091(±0.27)
Sample D	8.955(±0.54)	8.54(±0.61)	8.7465(±0.58)
Sample E	8.82(±0.14)	8.835(±0.58)	8.826(±0.22)

* () refers to confidence interval

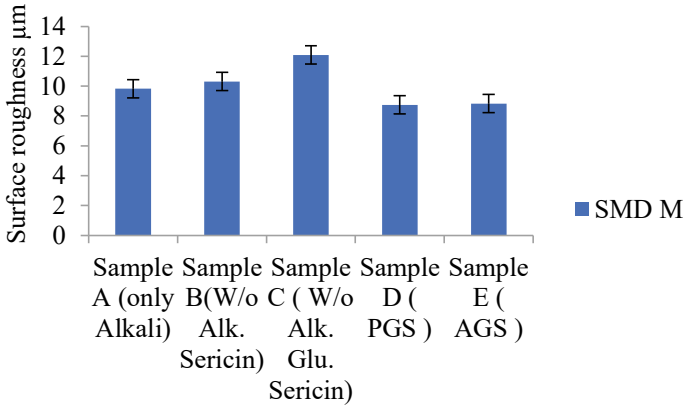


Fig. 3 Mean of SMD of sericin treated fabric

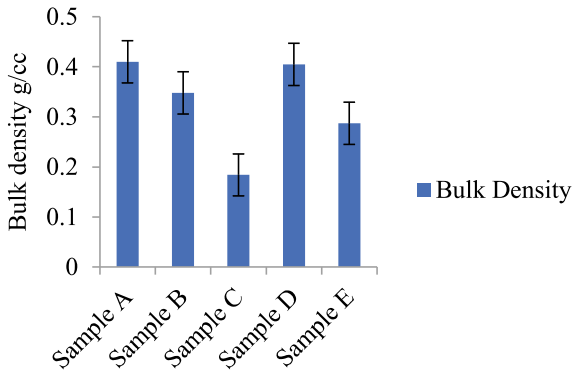


Fig. 4 Bulk density of sericin treated fabrics

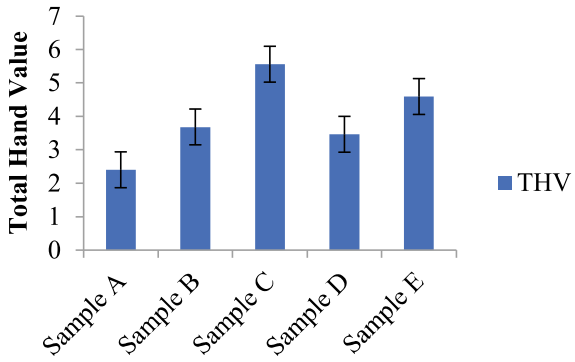


Fig. 5 Total hand value of sericin treated fabrics

by lower value. When the bulkiness of fabric reduces, thermal conductivity of the fabric increases. The sample D exhibits highest value of bulk density. Fabric sample C, shows highest THV (Total hand value) and sample A shows the lowest value as given in Fig. 5. All the treated samples show an improvement in handle in comparison to Sample A as illustrated in Fig. 5, which is evident that the sericin treated polyester fabric can be used as sportswear.

4 Conclusion

The results of this study shows that Coefficient of friction shows a reduction with sericin treatment for all face and back side and mean. Surface roughness (SMD) is lower for fabric samples D alkaline followed by plasma treatment accompanied with sericin and glutaraldehyde applied fabric and sample E, alkaline treatment followed by sericin with glutaraldehyde treated fabric. Highest value of SMD is obtained for fabric sample C, without alkaline treatment sericin with glutaraldehyde fabric. Bulk density of samples noticed that fabric samples C is characterized by lower value.

Highest value of bulk density is attained by Sample D. There is improvement in handle of the fabric in all the cases, but the fabric treated with sericin and glutaraldehyde has shown best handle property among all the fabrics. Based upon the information pertaining to above mentioned properties, the sericin treated polyester fabric can be used for sportswear application.

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Influence of Recycled Polyester Wool Blended Yarn Parameters on the Thermophysiological Properties of Woven Fabrics



Anant Gupta and A. K. Choudhary

Abstract Clothing is one of the fundamental requirements of human beings which gives the required comfort and protects from extreme climates. There are numerous interactions between fabric and human skin that influence comfort level. The nature of the fabric, its blend and thermal and moisture management behaviour largely affect the comfort level of the fabric. Woven fabrics are one of the essential clothing components in our everyday life. In recent times large volumes of plastic waste is generated which brings with it a colossal challenge of waste management. Refurbishing plastic waste into value-added textiles is one of the potent options for handling waste as well as resource conservation. There is a need to design fabrics from recycled materials. This paper focuses on the impact of incorporating recycled Polyester fibre in woven fabric. This research aims to explore the effect of yarn blend, linear density and twist multiplier on the thermophysiological properties of woven fabrics made from Recycled Polyester wool blends. The assessment of the thermal comfort of fabrics was done on the basis of instrumental parameters such as air permeability, water vapour permeability, thermal conductivity, thermal resistance, thermal absorptivity, etc. It was observed that with increasing yarn fineness and twist level the air permeability, as well as water vapour permeability, were found to increase whereas thermal comfort properties showed a close association with wool content.

Keywords Recycle polyester · Fabric comfort · Thermal comfort · Air permeability · Water vapour permeability

1 Introduction

Comfort is one of the prime requirements of the clothing industry and has been largely emphasised by several researchers. Due to improvements in the living standards of people, the expectations from clothing have also increased manifolds. Today clothing

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is not just used to protect the body from weather, heat, chemicals and injuries but also must cater to fashion and comfort requirements [1]. Many studies and researches have been conducted to develop clothing which offers a balance between protection and comfort [2]. Customers are demanding clothes which are having a combination of good comfort, care properties, handle and are pocket friendly [3]. The Comfort is a feeling of pleasant state experienced by an individual owing to harmonious interactions between human beings and environment [4]. Also the dynamic interactions of clothing with body movements influence the comfort experienced by individuals [5]. Clothing comfort mainly encompasses the fabric's thermoregulation and moisture transfer capacity [6]. Broadly comfort is classified as thermophysiological, sensorial, physiological and fit comfort [7]. Amongst these thermophysiological comfort has gained significant attention owing to the huge requirement of maintaining thermal balance in a variety of climatic conditions [8]. The human body continuously produces metabolic heat which requires proper regulation and dissipation [9, 10]. Human body requires to maintain an average body temperature which is achieved through thermoregulation. In any environment, the human body heat balance is governed by the amount of metabolic heat generated and heat dissipated by various means like convection, radiation & conduction [11]. Thermophysiological comfort includes the transmission of heat and moisture from the skin through the clothing [12]. The clothing has a profound influence on the thermal comfort by the way it buffers and rejects body heat and moisture. The properties of fabric like thermal insulation, vapour transmission and liquid transport are considered very critical for thermal comfort of clothing.

Fabric geometrical parameters significantly affect thermal comfort of fabric [10]. According to ISO 7730 thermal comfort is defined as a condition of mind which expresses satisfaction with the thermal environment. Clothing helps maintain a microclimate between body and environment due to which body exhibits necessary thermoregulatory responses [13]. Fabric breathability which includes movement of air, heat and moisture affects fabric thermal comfort. In cold climate, clothes are expected to maintain necessary thermal insulation along with moisture transmission to achieve desired levels of comfort. The clothing along with the air it encapsulates affects the thermal aspects, especially insulation. During strenuous activities large amount of heat is generated and in order to maintain average body temperature body employs perspiration which needs to be dissipated into the atmosphere. Therefore moisture transmission is of paramount importance when dealing with thermal comfort. Another important property is absorptivity which gives an idea about the warm-cool sensation perceived when fabric is touched [4]. Textile's thermal comfort is measured in terms of parameters like thermal resistance, conductivity and absorptivity and they are a function of fibre type, spinning method, yarn blend, twist, hairiness, fabric structure, weave, cover, thickness, surface finishes used, etc. [14, 15].

The factors influencing thermal properties generally fall under three levels. At the microscopic level, the factors include fibre type, chemical composition, morphology, fineness, cross section, etc. The mesoscopic level includes yarn structure, properties and other features and fabric structural features and finishes come under macroscopic level [16]. From a comfort viewpoint, Polyester's benchmark still remains

untouched owing to its excellent wicking and moisture transmission features. Moreover Polyester is a cheap, non-toxic thermoplastic possessing good mechanical and chemical resistance properties. Around 60% of produced PET is consumed in textile industry and 30% in bottle industry [17]. In present times Polyester is widely used for knitting, weaving and a variety of other applications [18]. Studies have revealed that blends of natural & synthetic fibres have immense potential in improving the thermal and wash care properties of fabric. Polyester wool combination is amongst those combinations which are widely used for aforesaid applications [19]. Due to ever increasing demands of growing population and fast fashion concept worldwide, enormous quantities of waste are being generated due to which waste management has become an issue of serious concern globally. Moreover, in recent times environment, protection norms have become increasingly stringent due to which sustainability and environment-friendly options are largely focused worldwide. Recycling is one of the potent solutions to mitigate the environmental adverse effects posed by large volumes of waste. Recycling not only promotes resource conservation but helps in reducing emission of greenhouse gases. There is a need to design fabrics from refurbished materials. Polyester is one such commonly used synthetic fibre whose manufacturing requires depletion of natural resources. These days large number of PET bottles are discarded, recycling this waste mechanically or chemically into polyester filament is one of the healthy disposable techniques. Mechanical processes involve crushing PET bottles followed by melting and extrusion into PET filament. Table 1 lists out the minimum requirements of PET flakes to be refurbished. Chemical recycling involves breaking down plastic into simpler monomers but this process is not environment-friendly. In order to enhance the functional properties of recycled PET they are blended with other fibres and spun into yarn via Ring, Friction and Rotor spinning technologies [8]. This paper is an attempt to investigate the thermal comfort properties of woven fabrics made from Recycled PET wool blends as a function of yarn linear density, blend and twist.

Virgin & Recycled Polyester fibre:

- Thermal properties—Studies conducted on DSC have shown that virgin PET having high degree of crystallinity exhibits higher melting temp. Around 253 deg. Celsius as compared to recycled fibre which shows melting at around 241 deg. Celsius. From the DSC thermogram, it was concluded that fresh polyester fibre showed higher crystallinity of 51% and Recycled polyester showed crystallinity of 48%. Moreover, Virgin fibre had a melt crystallisation at 213 deg. Celsius and Recycled fibre showed value around 202 deg. Celsius. In TGA analysis it was observed that thermal degradation onset temperature was around 390 degrees for both virgin & recycled PET fibres.
- Tensile properties—The virgin fibres exhibited high strength of 5.6 gpd whereas Recycled fibres showed 4.8 gpd strength. The recycled fibres had higher elongation of 13.7% as compared to virgin fibres which gave elongation values of 11.9%. The higher crystallinity of virgin fibres may be the causative factor for their higher strength. Moreover, r-PET has been subjected to remelting process which causes chain cessation which is responsible for low strength of r-PET [17].

- Moisture regain—More moisture regain is observed in r-PET owing to more amorphous regions.

2 Experimental

The yarn samples were produced in three variations of blend, count and twist. Recycled Polyester/ wool yarn in 80/20, 70/30 and 60/40 blends were produced. For each blend 10's, 20's, 30's count yarn was made. The single yarn were plied to produce 2/10's, 2/20's and 2/30's yarns. In each count three TM values of 3.0, 3.5, 4.0 was employed. In this manner, 27 samples were produced. Woven fabrics were produced on sample looms. Fabric sett for 2/10's is 30 × 30 per inch, for 2/20's is 44 × 44 per inch and 2/30's is 52 × 52 per inch. Plain weave was used in all fabric samples.

Methodology

Fabrics—For each fabric sample, areal density and thickness was calculated. Areal density was calculated by weighing 10 sq. cm fabric pieces. Fabric thickness was measured using the Alambeta instrument. Apart from these other instrumental parameters like air permeability, water vapour permeability, Thermal comfort properties, Moisture management, fabric roughness and coefficient of friction was checked.

Air permeability—The samples of size 20 cm^2 were tested following ASTM D737 on YG461E-I air permeability tester. Air permeability was measured in $cm^3/cm^2/s$. The air pressure is kept at 125 pascals. Ten readings were taken for each fabric sample and mean value was calculated.

Thermal comfort properties—Alambeta instrument was used for measuring Thermal conductivity, resistance and absorptivity for each fabric samples. Ten readings were taken for each fabric sample and mean value was calculated.

Water vapour permeability—This parameter was measured on SDL ATLAS (M261) water vapour permeability tester. It works on the principal of cup method. For each sample, six specimens were tested and mean value was found. This process incorporates BS 3424 standard. All tests were conducted in std. atmospheric conditions ie 20°C and 65% RH.

Moisture management—As per AATCC Test Method 195–2009, the fabric samples were tested on Moisture Management Tester (MMT), SDL ATLAS M290. Accumulative one-way transport index (O.T.I) was recorded from moisture management tester. For each sample, three specimens were tested and mean value was found.

Fabric roughness & coefficient of friction—This test was conducted on KES FB-4 evaluation system. For this test 20 sq.cm fabrics were used. Six readings were taken for each specimen and mean value was obtained.

3 Results and Discussion

The Thermal comfort of Recycled Polyester wool woven fabrics was evaluated in terms of Thermal conductivity, resistance, air permeability & water vapour permeability.

Thermal Conductivity:

The ability of a fabric to conduct heat is one of the important properties. The heat flow from different materials is different and primarily depends on thermal conductivity. This parameter was measured on Alambeta instrument shown in Fig. 1. The movement of heat between different fabric layers occurs mainly through conduction process via air gaps. Thermal conductivity was found to be maximum for P/W 80/20 blend ratio and minimum for P/W 60/40 blends. Since Polyester fibre has high thermal conductivity so fabric with polyester rich blend gave high values of thermal conductivity. Moreover, wool fibre gives good insulation effect so fabrics with wool rich blends showed less heat conductivity. It was also observed that coarse count fabrics showed high thermal conductivity as compared to finer counts owing to the fact that coarse count specimens had lesser fabric sett thus increasing fabric porosity and hence thermal conductivity. Also positive relation was observed with yarn TM and thermal conductivity because as twist increases yarn diameter reduces and more spaces are generated in the fabric thus aiding in heat flow.

Thermal Resistance:

Thermal resistance is the ability of a fabric to obstruct heat flow. It gives an idea about the insulating capabilities of a fabric. Measurement of thermal resistance is important



Fig. 1 Alambeta thermal conductivity tester

because entrapment of necessary heat is essential, especially for cold climates. In this study, it was observed that with increasing wool content thermal insulation was found to increase owing to excellent insulation properties of wool. Thermal insulation was highest for P/W 60/40 fabrics and least in case of P/W 80/20 blend fabrics. Previous researches have shown that a linear relation exists between fabric thickness and insulation property and in this case, also same observation was noted. Thermal insulation was found to be higher for coarser count fabrics and diminished as the count became finer. Moreover, with increasing TM values, thermal insulation was found to reduce. This is because the increasing twist reduces yarn diameter permitting more heat to flow from fabric and consequently reducing fabric insulation.

Air permeability:

Air permeability depicts fabric's ability to allow passage of air. It is the rate of airflow through a certain area of fabric under specified air pressure. This property is measured on Air permeability tester (Fig. 2) to evaluate the breathability of fabrics. Since air permeability increases with increase in synthetic fibre content, it was observed that air permeability was higher for P/W 80/20 blend fabrics and becomes lesser as wool content increases. Air permeability was found to be lesser for coarser count fabrics because fabric thickness and air permeability are inversely related. In addition to this, results indicate that increasing TM values influenced air permeability positively because as twist increases, fabric porosity also increases which facilitates more airflow through the fabric.

Water vapour permeability:

This parameter denotes the fabric's ability to allow body perspiration to be transmitted in vapour form through the clothing. This property was measured on water vapour permeability tester which is shown in Fig. 3. Fabrics with high thermal retention ability and low vapour permeability may be uncomfortable to the wearer hence this is an important property in assessing the comfort aspects of clothing. Vapour transmission abilities of fabric are a function of macro-porous structure of component fibre. It is well known that polyester fibre possess good wicking capabilities and being finer gives better packing fraction and hence contributes towards fabric vapour transmission capability due to which vapour transmission was found to be highest for P/W 80/20 blend ratio and least for P/W 60/40 blend fabrics. Medium values were obtained for P/W 70/30 blend fabrics. This is also because wool being a natural fibre has high moisture absorption tendency which restricts passage of vapour through fabric thus contributing towards low vapour permeability. It was found that vapour permeability values are highest for 2/20's Ne, mid values are obtained for 2/10's Ne and least values are obtained for 2/30's Ne fabrics. The probable reason for this observation may be attributed to fabric sett which is highest in 2/30's Ne fabrics thus retarding vapour transmission abilities. In case of 2/20's Ne fabrics, fabric sett is not sufficiently large which leads to more voids in the fabric thus promoting vapour transmission. Results also indicated that a strong positive correlation exists between water vapour permeability and yarn twist multiplier. As yarn twist levels were increased a corresponding increase in vapour transmission was also observed



Fig. 2 Air permeability tester

because increased twist reduces yarn diameter which generates more spaces in the fabric which permits more vapour transmission.

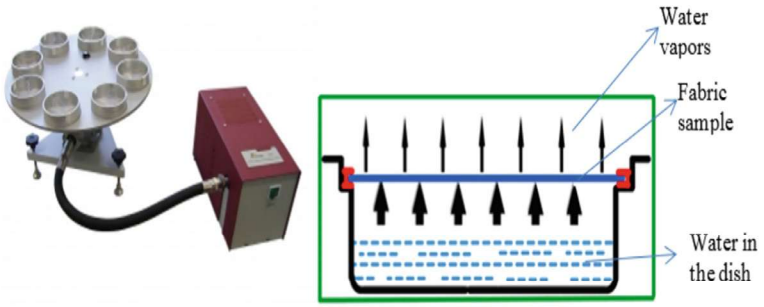


Fig. 3 Water vapour permeability tester

4 Conclusion

This research was undertaken to investigate the influence of recycled polyester blend ratio, yarn linear density and twist multiplier on thermal comfort of recycled polyester and wool blended fabrics as well as to develop an understanding of the dynamics of various heat transfer and moisture transfer mechanisms occurring in the clothing assemblies. Following conclusions have been derived from the above experimental research work and are given below:

1. Fabric in all samples whereas thermal resistance was found to reduce. Fabric surface roughness was found to geometrical parameters including fabric GSM, thickness and cover were analysed. Thermal comfort was measured in terms of instrumental parameters like thermal conductivity, resistance, absorptivity, air and water vapour permeability. Sensorial properties were studied by measuring fabric surface roughness. In addition to this moisture management was also studied to determine fabric's ability to effectively handle moisture build up.
2. The factors-recycled polyester blend ratio, yarn linear density and yarn twist multiplier have a significant influence on thermo physiological comfort of fabrics.
3. As recycled polyester content was increased in the blend ratio thermal, air and moisture transmission properties got enhanced whereas better thermal insulation was obtained in higher wool blends. Thermal absorptivity was also found higher in polyester rich blends.
4. Comfort properties like thermal conductivity, air transmission, water vapour permeability and moisture management show an increasing trend with yarn fineness whereas thermal resistance was higher in coarser count samples. Coarser count samples displayed higher surface roughness and thermal absorptivity.
5. With increasing yarn twist multiplier thermal, air, moisture transmission, thermal absorptivity and overall moisture management were found to increase increase with increasing twist levels.

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Improving Performance of Concrete Structures with Textile Reinforcements



Nabo Kumar Barman, Alagirusamy Ramasamy, and Someshwar S. Bhattacharya

Abstract The application of fabric as a reinforcement and strengthening material for building elements has gained significant attention in recent times. The unique characteristics of fabric structures, such as light weight, tensile strength, flexibility, and durability, have been widely acknowledged. The development of textile reinforced concrete (TRC) requires a comprehensive understanding of fabric parameters to enable engineers to design and construct TRC structures that meet specific end use requirements. The most commonly used fabrics in TRC are 2-D woven, 2-D knitted, and 3-D spacer fabric structures. This chapter reviews important fabric parameters, including fiber type, weave design, reinforcement ratio, embedment length, yarn fineness, pick density, loop size, inlay yarn, grid opening, resin-coated fabric, and hybrid fabric. These fabric parameters significantly impact the mechanical behaviour of TRC in terms of pull-out load, tensile strength, ductility, strain hardening behaviour, flexural strength, impact resistance, toughness, multiple cracking behaviour, crack width, and crack spacing. Woven fabrics are generally deemed more suitable due to the stable fabric structure, which provides mechanical anchoring and resistance against pull-out force inside the concrete matrix through warp-weft interlacement. However, certain special 3-D warp-knitted and spacer fabric structures have also gained wide acceptance as concrete reinforcement. Furthermore, resin-coated fabrics have demonstrated improvements in strength utilization of constituent yarns in cementitious composites, leading to improved mechanical behaviour of TRC.

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1 Introduction

Demand for sustainable and durable building structures has increased to prevent excessive material expenses and repair costs. Concrete inherently possesses excellent compressive strength, necessitating reinforcement to enhance its tensile strength. However, metallic reinforcements such as steel rebars are prone to corrosion, demanding a thick concrete cover for protection. This challenge arises when aiming to create thin concrete elements with metallic reinforcement. In contrast, alternative materials such as high-performance textiles (basalt, carbon, aramid, glass, etc.) are corrosion-resistant and require minimal cover [28, 71]. Incorporating textile reinforcement in concrete facilitates the production of slender, lightweight, and durable structures, providing heightened design flexibility and the ability to manufacture structural parts with complex shapes and predetermined properties [21]. Additionally, it offers the potential for cost savings through reduced material consumption. Compared to steel bars, the utilization of delicate textile reinforcement enables shorter anchorage lengths and finer crack distribution, as the large surface area of the yarns facilitates the transmission of high bonding forces. Ultimately, textile reinforcements made from AR-glass or carbon, with tensile strengths up to 2,500 MPa in concrete, are considerably stronger than conventional reinforcing steel (400–550 MPa) [8].

Textile reinforced concrete (TRC) combines concrete's compressive strength with textile materials' tensile strength, flexibility, and durability. TRC is a composite material consisting of cementitious matrix and embedded textile fabrics. According to Naaman [44] 'Textile reinforced concrete is a type of reinforced concrete commonly constructed of hydraulic-cement matrix reinforced with several layers of closely spaced continuous 2-D textiles, or one or several layers of 3-D textiles. At least one textile layer should be placed near each of the two extreme surfaces of the resulting structure. The textiles may be made of polymer, synthetic, metallic, organic or other suitable materials. The fineness of the cementitious matrix and its composition should be compatible with the textile armature system it is meant to encapsulate. The matrix may contain discontinuous fibers or microfibers of appropriate dimensions.'

Textile structures, as a reinforcement component in concrete, offer a unique ability to customize structures based on external load requirements. This customization includes variations in fiber/filament type, yarn linear density, the number of yarns per unit length (warp and weft), yarn fineness in warp and weft directions, yarn orientation (unidirectional, bidirectional, multidirectional), through-thickness reinforcement (3-D or spacer fabric), and the use of hybrid yarn and fabric [3, 4, 71]. The common fabric structures used for TRC applications are illustrated in Fig. 1.

Further, incorporating 3-D structures as concrete reinforcement streamlines construction, saving time and reducing labor costs compared to placing multiple 2-D fabric layers. The 3-D textile acts as an armature system, placed into a mould and encapsulated by a cement-based matrix, producing a thin, flat reinforcement sheet in an open box-shaped mould. 3-D textiles, with thicknesses ranging from 5 to 50 mm, are ideal for thin RC products, including ferrocement. Advances in research and technology enable variable thickness and curvatures in two directions, making textiles more versatile. They can serve as primary or secondary reinforcement (shear strengthening) or as a supporting structure for high-performance materials like carbon yarns or steel strands. For this supporting function, cost-effective materials such as polypropylene (PP) may be used [43].

Different types of fabrics, such as glass, carbon, basalt, and aramid can be utilized for textile reinforcement in concrete [23, 39, 63, 67]. Compared to steel reinforcements, textile reinforcements offer corrosion resistance, lightweight, higher strength to weight ratio, design flexibility, and formability [3, 4]. Structures reinforced with

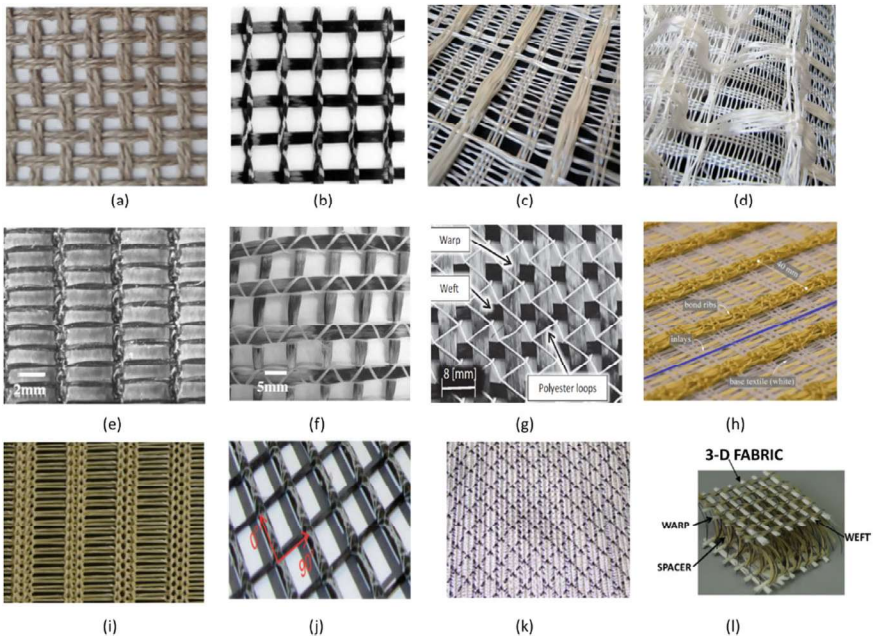


Fig. 1 Different fabric configurations used for reinforcement (strengthening) of concrete elements: **a** flax woven fabric (mat weave) [16], **b** basalt woven fabric (leno weave) [69], **c** interwoven geocomposite [7], **d** 3-D woven geogrid [7], **e** short weft-warp-knitted polyethylene fabric [70], **f** weft insertion warp-knitted carbon fabric with pillar stitch [70], **g** weft insertion warp-knitted carbon fabric with tricot stitch [38], **h** interlock weft-knitted fabric with inlays and ribbed texture [35], **i** interlock weft-knitted aramid fabric [37], **j** stitch-bonded carbon fabric (also recognized as non-crimp fabric) [22], **k** triaxial braided fabric composed of E-glass and high modulus carbon yarns [20], **l** 3-D warp-knitted spacer fabric composed of aramid, AR-glass, and polyester (PET) yarn [57]

textile materials have shown improved resistance to flexure, impact, fatigue, and seismic events [60]. TRC structures have better durability, longevity, and reduced maintenance and repair costs over time. TRC is used to reinforce beams, columns, walls, and slabs, and create thin-shell structures and precast elements [52]. Its excellent properties make it an ideal material for infrastructure projects.

The adoption of textile reinforcement in concrete is growing rapidly, and standardization efforts on TRC could lead to increased adoption of this innovative material in the construction industry. This chapter provides a comprehensive understanding of 2-D (woven and knitted) fabric and 3-D spacer fabric parameters and their influence on TRC behaviour. The role of textiles in shear strengthening, flexural strengthening, concrete confinement, and seismic retrofitting is also explored.

2 2-D Woven Fabric

To produce woven fabrics, weaving operations are carried out on a loom. Weaving involves the interlacing of warp (the yarn that runs lengthwise along the machine) and weft (the yarn that runs across the machine) at right angles. The term "weave" refers to how the warp and weft threads intertwine with each other. The most frequently used weave patterns include plain, twill, satin, sateen, leno, gauge, and triaxial.

The weaving process induces crimp in the fabric structure, resulting in underutilization of the reinforcement potential of filament yarn. Crimped geometry in woven structures may reduce reinforcement efficiency, and stress concentrations in the matrix may occur due to yarn curvature [50]. However, the special curvature present in the structure improves mechanical anchorage with the cementitious matrix, especially for synthetic yarns [47]. Improvements in pull-out load and flexural behaviour have been reported for woven fabric reinforced cementitious composites due to the special crimped geometry of woven fabrics [46, 47]. The fabric parameters should be optimized to achieve the desired mechanical properties of woven TRC, which are determined by the yarn diameter, number of ends/unit length, number of picks/unit length, and fabric construction [46]. The flexural behaviour of fabric reinforced cementitious composites depends on two factors: reinforcement content (volume fraction, V_f) and cementitious matrix penetration into the fabric structure. Optimizing these factors enhances flexural properties, including higher load capacity, toughness, multiple cracking, and greater ductility [24].

2.1 Fiber Type

TRC reinforced with carbon, AR-glass, and polyethylene (PE) was dynamically tested at 0.25 m/s. Carbon fabric has superior tensile and ductility properties in both fabric and cement composite forms. The carbon fabric's reinforcing efficiency is not fully utilized due to multifilament yarn and insufficient matrix penetration in the yarn

bundle, resulting in multiple cracking and fiber pull-out behaviour in carbon TRC. In contrast, AR-glass TRC exhibited effective stress transfer without fiber slippage, as the fibers were bonded by size. No such failure behaviour was observed in PE TRC [70].

Glass fabric reinforced concrete slabs show higher displacement, better residual capacity, and less scabbing than basalt textile reinforced concrete slabs under impact loading [18].

2.2 Reinforcement Ratio and Number of Fabric Layers

Increasing the number of fabric layers and using coarser yarns in concrete specimens increases the reinforcement ratio, resulting in improved flexural behaviour such as higher load-bearing ability, strain hardening behaviour, and ductility [68]. For example, low modulus nylon fabric reinforced concrete specimens with 430 tex yarn and 1.15% reinforcement ratio showed strain hardening behaviour under flexural loading [59]. Ductile failure with multiple crack formation occurs in specimens with an increased number of fabric layers under flexural loading [59, 68]. Four-layer carbon fabric reinforced RC slab showed 3.5 times higher load-bearing capacity than unstrengthened RC slab. Fabric-enhanced slab specimens exhibited finer, smoother, and smaller crack patterns, compared to the large cracks seen in unstrengthened RC slabs. Increasing the number of fabric layers resulted in a more distributed crack pattern with smaller crack spacings [58].

The impact strength of AR-glass reinforced cement composites was higher for six layers (V_f 2.7%) than for two layers (V_f 0.9%), with strengths of 29.8 and 11.5 MPa, respectively. PE fabric had good impact performance compared to carbon and AR-glass, and could withstand higher impact loads with minimal damage and no composite failure. To improve impact performance, reinforcing the tension side (bottom face) of cement composite specimens is recommended. Another study found that the impact resistance of basalt fabric reinforced concrete slabs decreased with increasing number of layers due to delamination and crack formation. The optimal number of layers for both glass and basalt fabric was five, with insignificant improvement beyond this number. Basalt demonstrated better post-peak impact response than glass reinforced TRC, and increasing the number of layers improved residual capacity in both cases. Furthermore, repeated impact loading resulted in minimal scabbing and no fragmentation of both basalt and glass TRC specimens [18].

2.3 Embedment Length

A plain-woven fabric with polyethylene monofilament yarn and varying picks/unit lengths was subjected to a pull-out test at a speed of 0.25 mm/s. The effect of embedded length on the pull-out load was investigated using three different lengths

(10, 15, and 20 mm), and it was found that the 20 mm embedded length provided the highest pull-out load due to greater depth of yarn and fabric embedded in the concrete. Crimp yarn and fabric outperformed straight yarn due to their crimp structure and mechanical anchorage [46].

2.4 Twisted Yarn Configuration

For strain hardening in concrete specimens, twisted yarns need higher reinforcement ratios than untwisted ones. Although twisting can enhance bond behaviour, its reinforcing efficacy decreases. Nylon yarns used in reinforced concrete shrink by 2–3% in alkaline cement pore solutions, leading to post-tension stress in the concrete. As a result, the uncracked zone in reinforced concrete exhibits greater strength than unreinforced concrete [68].

2.5 Yarn Fineness

Fabrics with yarn fineness of 213 tex and 430 tex have similar flexural strength at lower reinforcement ratios (one layer). However, increasing the reinforcement ratio has a greater impact on flexural strength, and thicker yarns improve the flexural behaviour of fabric reinforced concrete specimens. In addition, using 430 tex yarns instead of 213 tex improves the flexural behaviour of concrete specimens, including load capacity, strain hardening behaviour, and crack pattern. Coarse yarns also have better bonding and higher pull-out load in concrete [59, 68].

2.6 Yarn Geometry and Pick Density

The wave length and amplitude of the weft and warp yarns are influenced by fabric density, which in turn affects the fabric-matrix bonding in cement composites [5]. The bond strength between the fabric and matrix is enhanced by increasing weft density and yarn crimp curvature, resulting in better composite performance. However, the flexural properties of fabric composites are inferior to those of crimped untied yarn composites due to reduced penetration of the cementitious matrix inside the fabric structure, which is more pronounced in fabrics with higher weft densities. In cement composites, reinforcement using fabric and crimp yarn removed from the fabric showed superior performance in comparison to straight yarn. This may be due to the mechanical anchorage provided by the crimp geometry of the yarn, particularly in the case of fabric and crimp yarn removed from the fabric, as shown in Fig. 2a. It was reported that, fabric reinforced cement composite with a weft density of 5 yarn/cm exhibited a higher pull-out load compared to those with 8 yarn/cm and 9 yarn/cm,

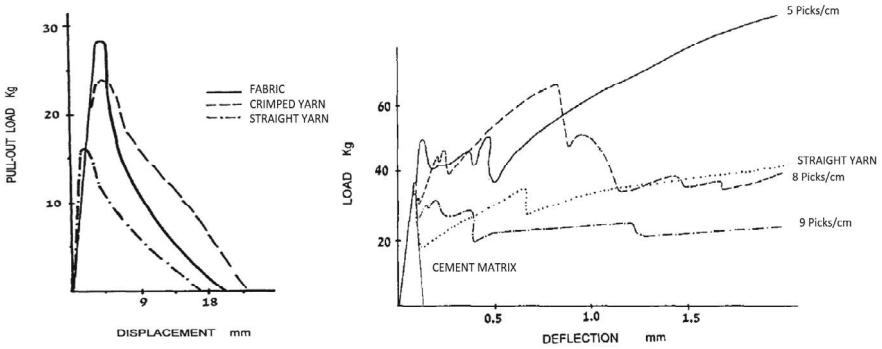


Fig. 2 Pull-out load–displacement graphs: **a** Performance of fabric, crimped yarn removed from a fabric and a straight yarn embedded 20 cm in a cement composite, and **b** Behaviour of a cement matrix reinforced with polyethylene fabric and variable picks per unit length (pick density), as well as a straight yarn reinforced in cement composite under pull-out loading (Copyright © 1994 [46]. Reproduced with kind permission of Elsevier Ltd.)

indicating improved cement matrix penetration due to the fabric structure, as shown in Fig. 2b [46].

The microstructural view of cement composites with varying weft densities shows that a lower weft density of 5 yarn/cm has denser cement penetration and no defects compared to a higher density of 10 yarn/cm, which exhibits lower matrix penetration and the presence of voids, as shown in Fig. 3 [47]. To improve the compaction and flexural behaviour of cementitious composites, the authors propose modifications to the manufacturing process [47].

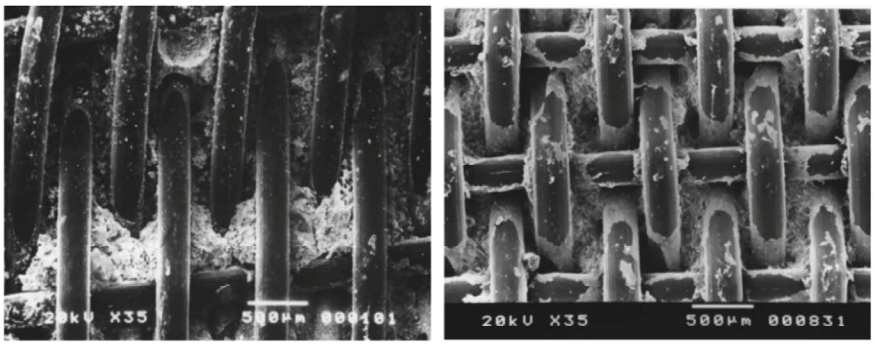


Fig. 3 SEM microstructure images depict cement composite reinforced with polyethylene monofilament woven fabrics of varying picks density: **a** 5 picks/cm, and **b** 10 picks/cm (Copyright © 1999 [47]. Reproduced with kind permission of American Society of Civil Engineers)

The AR-glass leno fabric had a fixed warp density but different weft spacings (10, 20, 30, and 50 mm). Fabrics with a small weft spacing of 10 mm were prone to weft defects, resulting in the lowest first cracking strength of 3 MPa. Increasing the weft spacing led to tension stiffening, with the first cracking strength reaching around 7 MPa. The stiffness of the multi-cracking zone was higher for weft spacings of 30 mm and 50 mm, as the longer bond length prevented longitudinal delamination. The specimens with 10 mm weft spacing had higher ultimate strain due to the presence of longitudinal cracks, allowing the roving to stretch. The peak load was similar for all weft spacing configurations, with only tension stiffening being affected, not the efficiency factor value [10].

2.7 Fabric Mesh Opening

As the mesh size of fabric specimens decreased from 10 mm × 10 mm to 5 mm × 5 mm while keeping yarn fineness constant, the number of reinforcing yarns and reinforcement ratio increased. This led to better performance under flexural loading, with higher flexural load, greater ductility, and strain hardening behaviour observed in the fabric specimens with a mesh size of 5 mm × 5 mm. Small mesh sizes resulted in higher flexural load and ductile behaviour, as evidenced by multiple cracks with small crack width [68].

The fabric specimen with a 2 mm mesh size showed the highest flexural load due to strain hardening behaviour and multiple cracking. However, with increasing mesh size, the volume fraction of the fabric decreases, leading to pseudo-deflection hardening behaviour for mesh sizes between 2 and 10 mm and strain softening behaviour for 20 mm mesh size. A fabric specimen with 0 mm mesh size exhibited poor filament-matrix bonding, resulting in lower flexural load despite having the highest volume fraction. SEM analysis revealed that increasing mesh size allows for free water flow and better fiber-matrix bonding. For specimens with a larger mesh size, lower flexural behaviour is associated with lower reinforcement content. Maintaining a volume fraction between 0.19% and 1.34% increases toughness by 5.6 to 52-fold compared to unreinforced specimens. Further, fabrics with varying mesh sizes of 2, 4, 6, 8, and 10 mm were created with a similar weight (approx. 15g) and volume fraction (0.6–0.7) by combining multiple carbon yarns. All specimens showed similar curves with strain hardening behaviour, indicating that mesh size does not independently influence the flexural behaviour of reinforced cementitious composites. The filaments' interaction with the matrix determined the flexural strength and toughness of the specimens. The specimen with 2 mm mesh size had significantly higher flexural toughness and toughness indices at the post-cracking point than the others, suggesting that fabric volume fraction significantly influences composite flexural properties. Increasing fabric mesh size at a constant textile volume content reduces the sample toughness indices [24].

The impact behaviour is affected by the grid size or fabric openness, where open AR-glass fabric leads to multiple cracking without complete specimen failure due

to improved mechanical anchorage of filaments-matrix provided by better cement matrix penetration into the fabric structure. However, the closely packed AR-glass fabric structure causes a reduction in impact strength after specimen failure [49].

2.8 Weave Design

Twill fabric structure has fewer interlacing points, resulting in lower tensile strength and slightly lower limit of proportionality (LOP) values under flexural loading compared to plain fabric structure. Modulus of rupture (MOR) values were significantly higher in concrete reinforced with plain and twill fabric structures with higher thread density due to an increase in the number of warp yarns in the load direction, contributing to higher flexural load. The weave design has no significant effect on MOR values as the warp yarn has already decrimped under tensile load at higher bending loads. Weft yarns perpendicular to the loading direction can affect bending load. The impact of weave design on toughness characteristics is less noticeable at higher bending deflection due to warp yarn de-crimping effect. During bending deflections of composites, tensile behaviour of warp yarn is crucial [64]. The plain weave pattern is widely utilized in TRC owing to its exceptional stiffness and strength. The twill weave pattern is better suited for applications that require high deformability, whereas the satin weave pattern offers superior flexibility and drapeability. In TRC, the leno weave pattern is preferred for forming open scrim fabric, which enables ease of matrix flow and penetration within the interstices of the fabric.

2.9 Woven Hybrid Fabric

Hybrid fabric structures are similar to hybrid yarn structures in that they combine different fibrous materials to achieve synergistic performance. This can be accomplished through (1) using reinforcement of two or more fabric layers, each made of distinct constituent fibrous materials in concrete, or (2) using a single fabric composed of yarns made from distinct constituent fibrous materials, oriented in various directions [52]. Hybridization allows for the combination of low-cost, low modulus yarns (such as PP, PE, and PET) with high-cost, high modulus yarns (such as carbon, aramid, basalt, and AR-glass) to achieve excellent mechanical properties at a reasonable cost [71].

The type of fabric used affects the impact behaviour of TRC slabs, with glass fabric showing the least damage due to high energy absorption, followed by basalt fabric. Hybrid TRC showed larger spalling and local failure. However, combining basalt and glass (hybrid fabric) showed the highest impact resistance, absorbing more energy at lower levels (50 J). Mid span deflection was lowest for hybrid textiles at higher energy levels (100 J and 200 J). Full factorial analysis showed a significant interaction between fabric type and energy levels for all TRC types [19].

Carbon-polypropylene hybrid woven fabric reinforced concrete beams exhibit flexural toughness 6.5–40.75 times higher than that of unreinforced concrete beams [64].

2.10 Resin-Coated Woven Fabric

The flax fabric was treated with epoxy resin and different hardener-epoxy ratios (0.6, 0.8, 1.0) were used. The compressive strength of concrete was increased by 2–4 times, impact resistance was increased by 5–10 times, and impact crack propagation was increased by 1.1–2.3 times when reinforced with resin-infused flax fabric compared to unreinforced concrete. The specimens with a lower hardener-epoxy ratio of 0.6 exhibited an improved impact response [13].

3 Knitted Fabric

Knitted fabrics are produced on a knitting machine through the intermeshing of loops. The formation of loops is determined by the knitting technique, resulting in either weft or warp knits. The structure and properties of the fabric are influenced by knitting parameters including course density, wale density, yarn characteristics, and stitch design [11]. Further, the geometric parameters of the knitted fabric, such as yarn and fabric orientation, grid spacing (yarn density), yarn bundle size (fineness), stitch loop size, stitch loop type, number of filaments in yarn cross-section, and fabric pre-tension, have a greater influence on the mechanical properties of the knitted fabric reinforced cement composite.

3.1 Fiber Type and Number of Filaments in Yarn Bundle

Three types of weft in-laid warp-knitted fabrics were produced with high modulus Kevlar®, low modulus polypropylene (PP) multifilament, and polyethylene (PE) multifilament yarns used for weft insertion, and polyester multifilament yarn used as warp (binding yarn). Microstructural analysis showed that a yarn bundle with fewer filaments (such as Kevlar® with 325 filaments) results in better cementitious matrix penetration in fabric structure than a bundle with a larger number of filaments (such as PE with 900 filaments), leading to improved bond behaviour in cement composites. In Kevlar® composites, external filaments remained bonded to the matrix, while internal filaments exhibited pull-out slippage. However, in the PE composite, pull-out slippage occurred, and the groove remained free of filaments. According to the results, the flexural performance of various fabrics such as Kevlar®, PE, and PP showed that the Kevlar® composite exhibited significantly greater average flexural

strength and load-bearing capacity after cracking than the PE and PP composites [45].

Warp-knitted fabric used as reinforcement in concrete increased flexural strength, with AR-glass and carbon fabric yielding strengths of 8.1 and 9.5 MPa, respectively, compared to unreinforced concrete at 5.2 MPa. AR-glass had a higher pre-cracking peak on the flexural stress–deflection curve, while carbon had the same peak as unreinforced concrete. Carbon reinforcement exhibited strain hardening behaviour after pre-cracking and increased in strength with deflection, outperforming AR-glass in terms of reinforcing efficiency. Carbon reinforcement is suitable for high flexural loads without breaking at very high strains, making it ideal for seismic-resistant structures in sensitive areas [66].

Biaxial warp-knitted fabrics were constructed using aramid weft insertion yarn and warp yarns of aramid, AR-glass, HDPE, and PP, with PP serving as the binding yarn. At low tensile strain values (1–2%), aramid TRC outperforms HDPE composite by 15–30% without significant differences in efficiency factors. HDPE is more efficient at higher strain values (>2%). Glass TRC was found to be brittle compared to other TRC composites, but at 1% strain, it showed the highest tensile stress with a greater efficiency factor over three times that of aramid and HDPE composites, making it effective for low strain applications. Aramid has the strongest bonding, followed by AR-glass and high density polyethylene (HDPE), with PP composites having the weakest bonding. The high bonding strength of glass with cement matrix caused brittle failure under tensile load, while HDPE and aramid TRC were more ductile and failed at higher strain levels. The higher modulus and hydrophilic chemical nature of glass and aramid contribute to strong bonding in cementitious matrices [51].

3.2 Yarn and Fabric Alignment

Specimens with fabric aligned in different orientations, such as warp (0°) and weft inlay (90°), are subjected to tensile tests. Composite specimens with fabric aligned at 90° exhibit 20% higher strength compared to those with fabric aligned at 0°. The loose holding of weft inlay yarns (90°) creates a flat cross-section, while binding stitches tightly hold the warp yarns (0°), allowing warp (90°) oriented specimens to have better bond performance of the inner filaments and more homogeneous activation of the rovings' total cross-section, resulting in greater reinforcement effectiveness in concrete [29].

The retrofitting of unreinforced masonry walls was investigated using a cement-based matrix-grid (CMG) system with AR-glass coated fabric. Proper alignment and orientation of the fabric reinforcement during installation significantly affect the load carrying capacity of the system. An increase in the orientation angle from 0° to 6° results in a relative increase in bond between the fiber and matrix. However, as the angle is further increased to 12°, the load on the yarns is no longer transmitted directly and the tensile force must be transferred to the matrix [42].

3.3 Yarn Fineness

Fabric specimens with constant properties showed that finer 1200 tex roving had higher average ultimate strength compared to the coarse 2400 tex roving, due to an increased surface-to-cross-sectional area ratio [28].

The impact of different yarn bundle sizes (fineness) on HDPE knitted fabrics with larger and smaller loop sizes was investigated. The larger bundle size (140 tex) composite had higher tensile strength than the smaller bundle size (90 tex) for both loop sizes, attributed to the higher reinforcement content (V_f) in the 140 tex composite. However, the smaller bundle size (90 tex) was more efficient in reinforcing the knitted fabric cement-based composite at different strain levels for both loop sizes. Increasing the loop size and using a finer yarn bundle strengthens the fabric's anchorage in the cement matrix, and both factors can increase the size of the open spaces between the yarns [51].

3.4 Inlay Yarn

Increasing the number of carbon weft inlay rovings in a warp-knitted fabric reinforced concrete beam improves its flexural characteristics, including flexural load, strength, toughness, displacement, deflection hardening behaviour, and ductile failure. The number of fabric layers (one or two) does not significantly affect the flexural behaviour. Epoxy impregnated fabric specimens perform better than non-impregnated fabric reinforcements in terms of flexural load, fiber performance index (FPI), and failure mechanism. Spotted epoxy impregnated fabric specimens with 8 and 10 carbon rovings show the highest displacement and flexural load, respectively. However, the specimens with 10 rovings fail catastrophically due to debonding failure of concrete specimens, likely due to the smaller mesh size and reduced fiber-matrix bonding [31].

3.5 Loop Size (Stitch Length) and Knitting Tension

The influence of 2 mm and 4 mm stitch loop sizes on HDPE knitted fabrics made with 140 and 90 tex yarn was investigated. Fabrics with 140 tex yarn and 4 mm loops had 20% higher tensile strength and better multiple cracking behaviour, as shown in Fig. 4a. The smaller 2 mm loops had lower tensile behaviour despite higher fiber volume, likely due to poor cement matrix penetration. However, a fabric composite with a 90 tex bundle size and 2 mm loop size performed well due to higher reinforcement content, as shown in Fig. 4b. The 4 mm loops were more efficient and had stronger fabric-matrix bonding, while the smaller loops produced denser fabrics

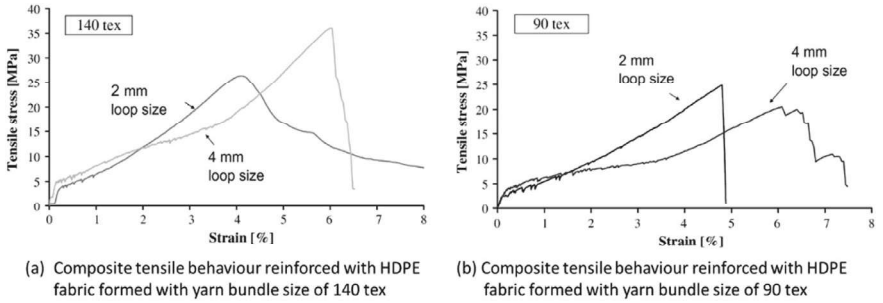


Fig. 4 Influence of stitch loop size on the tensile properties of fabric reinforced cement composites utilizing two different bundle sizes (yarn fineness): **a** 140 tex, and **b** 90 tex (Copyright © 2007 [51]. Reproduced with kind permission of Elsevier Ltd.)

with lower bond strengths. Overall, the 4 mm loops outperformed the 2 mm loops in terms of tensile strength, fracture behaviour, efficiency, and bond strength [51].

Stitch density affects filament-matrix bonding by increasing the number of loops and anchoring points. However, high stitch density tightens multifilament bundles, reducing cement matrix penetrability. Smaller loop sizes resulting from increased stitching can further reduce penetrability and potentially decrease overall composite performance. Dense stitches can cause crimped yarn and stress dispersions, even if stresses do not develop in the loading direction. Loop size has a more pronounced effect on coarse yarn bundles due to improved cement penetrability between the reinforcing filaments [9, 51].

Stitch length and knitting tension significantly affect the deformation of tow cross-section, fiber packing density, cement matrix penetration, and mechanical properties of TRC. The impact of stitch length and knitting tension on TRC mechanical properties was studied using stitch lengths of 2.1, 4.2, and 6.3 mm and knitting tension levels A (high), B (moderate), and C (low). Increasing stitch length while maintaining low knitting tension decreases fiber packing density. The specimen with the lowest knitting tension (C) and the longest stitch length (6.3 mm) had the highest fiber efficiency and roving pull-out load due to better cementitious matrix penetration in the less densely packed roving bundle. The compact fiber strand structure limited cementitious matrix penetration, with only 30% of the fibers participating in load bearing [12].

3.6 Weft Knitting Patterns

Interlock structures, such as inter-flat and inter-ribs, in concrete reinforcement exhibited better tensile behaviour than rib structures, including 1×1 and 2×2. This is due to the dimensional stability of interlock structures, which have limited deformation in the width (course) direction. Interlock structures with bond ribs failed

prematurely in the warp direction because of poor integration, but the ribs in the weft direction had stable hardening behaviour until brittle failure occurred. Bond ribs improved the mechanical bonding of the fabric-concrete matrix and reduced the likelihood of concrete cover spalling. However, tension stiffening was less in bond rib structures than in flat texture specimens because the bond shear stress was higher without the ribs [34, 37]. Fabric reinforced beams with tall ribs (30 mm height) had the best flexural behaviour, whereas other rib configurations had limited impact on shear resistance due to their small height. These rib configurations were effective in preventing premature fabric delamination and significantly enhancing the load reached by beams with flat reinforcement without spatial features, which failed prematurely with poor inlay utilization [36].

3.7 Warp Knitting Patterns

The reinforcement's load-bearing capacity in a composite section relies on roving geometry and matrix penetration depth, both influenced by the fabric's knitting pattern. AR-glass warp knit fabric with tricot stitch produces a higher strength composite due to its flat geometry, as shown in Fig. 5a [28]. The pillar stitch in knitted fabric produces a circular roving cross-section that allows the cementitious matrix to flow through fabric layers and fill the formwork during the casting process. However, knitted fabric with pillar stitch and coarse roving bundles (linear density of 2400 or 3600 tex) have poor cementitious matrix penetration and low contact with concrete, as shown in Fig. 5b. To improve load distribution, impregnating the fabric with polymers is recommended. Tricot stitching produces a flat ribbon-shaped roving cross-section, which improves surface contact and requires less penetration depth for better matrix penetration and bonding, as shown in Fig. 5c. However, tricot stitching flattens the roving strand and reduces the mesh size, requiring lamination and spraying techniques for fabrication [30].

The pull-out and tensile behavior of textile reinforced concrete (TRC) reinforced with warp-knitted fabrics featuring different patterns was investigated [27]. Specimen 5–3 (0°/90°/0°, tricot basic offset 1, 2 × 400 tex warp) avoids warp deflection by arranging two warps symmetrically on the exterior of the extended stitch-bonded fabric. Its initial pull-out resistance is around 12 N/mm, which is higher than specimens 5–1 (0°/90°, 800 tex warp, double tricot pattern) and 5–2 (0°/90°, tricot basic offset 1, 1 × 800 tex warp) due to the three-layer arrangement and greater surface area between the warp threads and concrete. The frictional bond is also higher in specimens 5–2 and 5–3, possibly due to the improved friction effect of the binding yarn around the warp. However, higher warp deflection in specimen 5–1 does not result in increased pull-out forces. Tensile tests on fabric reinforced concrete specimens showed that specimens 5–2 and 5–3, produced with the extended stitch-bonding process, are stiffer than specimen 5–1. Specimen 5–1 exhibited spalling and lateral cracks, while specimen 5–2 had only minor cracks in the area of the weft yarn due to reduced deflection of the warp. Specimen 5–3, on the other hand,

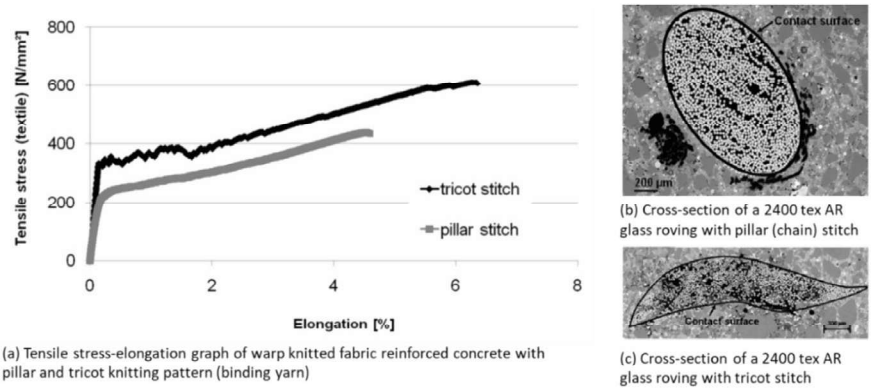


Fig. 5 **a** Influence of binding yarn on tensile stress-elongation graph of biaxial warp-knitted AR-glass fabric reinforced cementitious composite, **b** Cross-section of a roving with pillar stitch, and **c** Cross-section of a roving with tricot stitch (Reproduced from [30]. Copyright © 2010, RILEM)

had a crack-free concrete component. Specimen 5–3 also showed better realization of yarn strength to composite strength than specimens 5–1 and 5–2. These results suggest that the extended stitch-bonded method should be used to produce fabrics that can effectively reinforce TRC components and prevent spalling under service load [27]. Roving cross-section impacts concrete flexural behaviour. Cord and tricot stitches have flattened roving cross-sections and provide better bonding due to a longer contact surface, resulting in higher flexural strengths than pillar stitches with round rovings that offer insufficient stress transmission [53].

3.8 Knitted Hybrid Fabric

A weft inserted warp-knitted hybrid fabric was created by combining ductile, low-cost PP yarns with expensive, high-performance aramid yarns. The resulting fabric alternated equal amounts of PP and aramid yarns with 2 mm loops. The hybrid TRC composite exhibited comparable tensile strength to aramid-only TRC, despite using half as many Aramid yarns, as shown in Fig. 6. In fact, the hybrid TRC composite showed superior tensile behaviour to PP-only TRC. However, the hybrid system's bond strength was lower than aramid-only TRC, likely due to lower aramid yarn content. Overall, the hybrid TRC is cost-effective and comparable in tensile properties to aramid-only TRC [51].

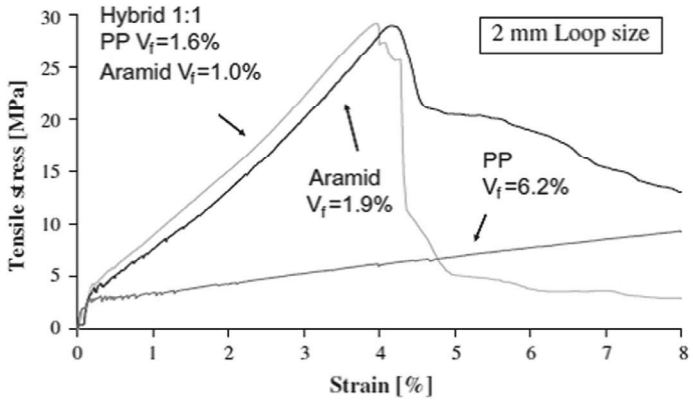


Fig. 6 Tensile stress–strain graph of hybrid fabric made up of polypropylene (PP) and aramid fibers compared with that of fabrics made up of the individual fiber types (Copyright © 2007 [51]. Reproduced with kind permission of Elsevier Ltd.)

3.9 Fabric Pre-tensioning

The tensile stress–strain behaviour of two composites, one with an unstretched fabric layer placed on the cementitious matrix paste and the other with an alignment pin holding the fabric in place during casting, was investigated. Since the matrix has low tensile strain capacity, the fabric cannot carry the load until after the matrix cracks. The freely placed unstretched fabric did not show any post-matrix crack stiffness, while the aligned and stretched fabric exhibited strain hardening and load carrying capacity higher than the first crack stress. The ultimate strength of the freely placed unstretched fabric was 2.5 MPa, while the aligned and stretched fabric had an ultimate strength of 4.0 MPa [42].

3.10 Resin-Coated Knitted Fabric

The load-bearing ability of reinforced fabric in cement composite is improved by activating and engaging the inner filaments of the roving strand. In a tensile test, unimpregnated AR-glass warp-knitted fabrics failed due to filament failure, with the maximum strength determined by the outer filaments. Epoxy impregnation increased the coefficient of efficiency from 0.25 to 0.66 for uncoated and epoxy impregnated AR-glass with similar fineness (2400 tex) and chain stitch [28]. However, acrylate impregnation did not enhance load-bearing capacity as effectively as epoxy impregnation, and it reduced the outer bond performance, leading to large crack spacings and crack widths [29]. The epoxy resin-impregnated fabric increased the bearing capacity to approximately 1200 MPa, which is almost three times that of the unimpregnated AR-glass fabric. The composite exhibited superior bond behaviour, with multiple

cracking and short crack distances in specimens with longitudinal cracks running along the reinforcement layer. Bond splitting can be avoided by incorporating the impregnated fabric in concrete immediately after resin impregnation (fresh-in-fresh) [28].

4 3-D Fabric Structure

A 3-D textile refers to a structure with yarns oriented in three orthogonal directions, whether produced in a one-step or multiple-step process. Unlike 2-D textiles, 3-D textiles have the advantage of incorporating yarns in three spatial directions, including through-thickness. Production processes involve one-step or multiple-step methods, with the latter including additional operations like cutting, laying, and joining. These structures offer cost-effective technology for composite material manufacturing, reducing labor costs [21]. 3-D fabrics can be produced through weaving, knitting, and braiding techniques. 3-D spacer fabric has found successful applications in civil engineering for various purposes. These include the construction of sandwich panels, façade elements, claddings, prefabricated wall panels, shell concrete members, retaining walls, slope protection, FRP reinforcement, and concrete canvas [25, 26, 56].

4.1 3-D Woven Fabric

3-D woven fabrics are employed in applications requiring high energy absorption, low crack propagation, good impact behaviour, and high tensile strength [21]. Mishra et al. [41] simulated the mechanical properties of various textile structural concretes, finding that 3-D woven reinforced concrete beams demonstrate remarkable ductility, making them promising for seismic-resistant buildings. Comparisons with plain concrete and other reinforcement structures showed that orthogonal fabric reinforced composites had the highest ductility and lower stiffness. The transition from plain concrete to orthogonal fabric increased ductility by 23.98%, enabling greater deformations and enhanced elasticity during earthquakes. Stress at fracture was highest in orthogonal fabric reinforced beams, emphasizing their superior strength and ductility compared to conventional concrete, with potential applications in earthquake-resistant buildings.

4.2 3-D Knitted Fabric

3-D knitted structures can be produced through weft-knitting and warp-knitting techniques, with the warp-knitting method being widely used in concrete reinforcement.

4.2.1 3-D Warp-Knitted Spacer Fabric

The warp-knitted spacer fabric is typically produced on a double needle bar raschel machine [56]. The incorporation of straight multifilament yarns in spacer fabric plays a crucial role for stability and strength of fabric structure. The machine concept involves creating a grid-like fabric surface, essential for cement and concrete applications, enabling easy cement penetration [55]. The upper and lower fabric surfaces consist of rovings laid at 0° and 90° angles, connected by warp-knitting yarn. Spacer yarns in the through-thickness direction bind the outer surfaces, offering open or closed structures with various mesh sizes for concrete reinforcement [56]. Spacer yarn length adjustments (varied up to 60 mm) allow for different fabric thicknesses based on composite geometry [54]. Spacer fabric properties are influenced by factors such as thickness, the number of inlay, and spacer yarns, laying angles, and knitting patterns [21]. Spacer fabrics with load-adapted design and optimized handling structures offer advantages in producing complex-shaped, thin-walled concrete elements with a single reinforcement textile [56].

Crossing pattern

The compression behaviour of spacer fabrics is influenced by the angles of the crossing patterns. As the angle of the crossing pattern decreases, the compression resistance decreases [56]. This flexibility allows for tailoring the compression behaviour of the textile to meet specific application needs, such as achieving the required stiffness for injection moulding processes.

Spacer yarn content

The quantity of spacer yarn in a given unit of spacer fabric area is determined by the threading of spacer yarns. Observations indicate that reducing the amount of spacer yarn in the unit spacer fabric area leads to decreased compression resistance [65]. Adjusting the aramid content as spacer yarn in the Z direction positively influenced toughness, stiffness, and tensile strength, especially in the vertical specimen arrangement [2].

Increasing the content of aramid yarns (0% to 100%) in the Z direction enhanced the flexural behaviour of cement-based composites. 3-D fabrics, when compared to 2-D fabrics, provide superior reinforcement with enhanced anchoring mechanisms and connections to the cement matrix. Additionally, epoxy treatment further improved composite performance by binding fabric elements and promoting uniform crack distribution [57].

Fabric orientation

The orientation of 3-D fabric influenced composite failure modes differently in warp and weft directions [23]. In the warp direction, flexure was the predominant mode, while in the weft direction, a combination of shear and flexure occurred. Shear cracks were observed exclusively when spacer yarns were perpendicular to tensile stress, indicating limited effectiveness in reinforcement. These cracks appeared only

in composites loaded in the weft direction, not the warp direction, possibly due to variations in spacer yarn angles throughout the composite thickness.

Spacer yarns play a crucial role in influencing the flexural behaviour of 3-D fabrics in composite materials. In both warp and weft directions, 3-D Ar100 (specimen with 100% through-thickness reinforcing aramid spacer yarns) composites show superior flexural performance compared to their 2-D fabric counterparts. The 3-D fabric composites exhibit increased strength, with improvements of 83% in the warp direction and 35% in the weft direction, highlighting the enhanced mechanical anchoring provided by the 3-D fabric structure [23].

4.2.2 3-D Weft-Knitted Spacer Fabric

Ma et al. [40] created aramid weft-knitted spacer fabrics using a high-speed computerized flat knitting machine. Aramid multifilament formed the outer layers, connected by elastic nylon monofilament as spacer yarns. Spacer yarn density increased with a lower ratio of surface course to spacer course, and tuck loops were anchored by the outer layers for structural stability. Aramid weft-knitted spacer fabrics have exhibited outstanding ductility and structural integrity in bending and impact tests, with spacer yarns playing a vital role in enhancing flexural strength, ductile deformation, and toughness, particularly in the weft direction. Impact tests show improved energy absorption and deformation capacity, especially with a high-density surface layer. The spatial interlock action of spacer yarns helps maintain structural integrity after severe impacts. These qualities make aramid weft-knitted spacer TRC suitable for various applications, including bridge piers, airport runways, protective barriers, shield structures, and blast hazard mitigation.

The bottom layer of polyester-based 3-D weft-knitted spacer fabrics was varied using different stitch patterns. Among the three fabric stitch types, the tuck stitch exhibited superior tensile strength and energy absorption compared to the knit stitch and miss stitch in calcium aluminate cement (CAC) mortar [1].

4.3 Mechanical Behaviour of 3-D Fabric Reinforced Concrete

The 3-D AR-glass fabric based cement composites demonstrated a 10% increase in impact strength, while the toughness values were an impressive 200 times greater compared to short AR-glass fiber cement composites [48].

The failure behaviour of fabric reinforced cement composites was compared between 2-D and 3-D Ar 100 fabric (specimen with 100% through-thickness reinforcing aramid spacer yarns) treated with epoxy [57]. The 2-D fabric composite showed complete failure, wide cracks, and delamination, indicating poor fabric-matrix bonding. In contrast, the 3-D Ar 100 composite displayed multiple cracks

and damage to the bottom zone, with less severe delamination than the 2-D fabric composite. The 3-D fabric also exhibited approximately 16 mm of deflection, suggesting improved bonding and mechanical anchoring within the cement matrix compared to the 2-D fabric.

Fabric reinforcement improved flexural properties of plain mortars, with polyester-based warp-knitted spacer (3-D) fabrics outperforming 2-D fabrics, showing 100% and 400% improvements in ultimate strength and strain capacity, respectively [17]. Spacer fabrics increased elastic modulus by 30%, and thicker fabrics with larger mesh enhanced flexural properties. Spacer fabrics redistributed loads, preventing matrix fracture, and fabric inclusion improved strength, modulus, and toughness without affecting water absorption or compromising durability.

El Kadi et al. [15] investigated the impact of 3-D textile typology, comparing knitted and woven transversal connections, and studied the influence of stress direction on mechanical response. Three fabric reinforcements were used: knitted 3-D TRC, woven 3-D TRC, and equivalent 2-D Planar TRC. In tension, transversal connections had no significant effect on post-cracking stiffness, while woven 3-D TRCs showed lower stiffness and higher failure strain in warp due to yarn waviness. In bending, all 3-D TRCs exhibited increased post-cracking stiffness compared to 2-D layup, highlighting the flexural anchorage mechanism and beneficial influence of the transversal fiber connections [14]. Knitted 3-D TRC consistently increased stiffness by 25%, while woven 3-D TRC was stiffer in weft during bending. This demonstrates woven 3-D textiles' effectiveness despite perpendicular transversal connections, indicating 3-D TRCs' potential for structural applications. Both layups' transversal connections were non-structural polyester.

5 Significance of Textile Reinforcement in Enhancing Concrete Performance

Textile reinforced mortar (TRM) and fiber reinforced plastics (FRP) effectively strengthen aging masonry structures. Unlike continuous fiber sheets in FRP, the open fabric structures of textiles in TRM enhance fiber-matrix bonding [61, 62]. Koutas et al. [32] emphasized that TRM effectively enhances flexural and shear capacity in concrete members with standard geometries. TRM contributes to improved stiffness, serviceability performance, and crack control, increasing axial deformation capacity and, to a lesser extent, compressive strength. The seismic retrofitting of RC columns or joints with TRM enhances ductility and energy dissipation, resulting in sturdier and more resilient masonry-infilled RC frames with improved seismic performance.

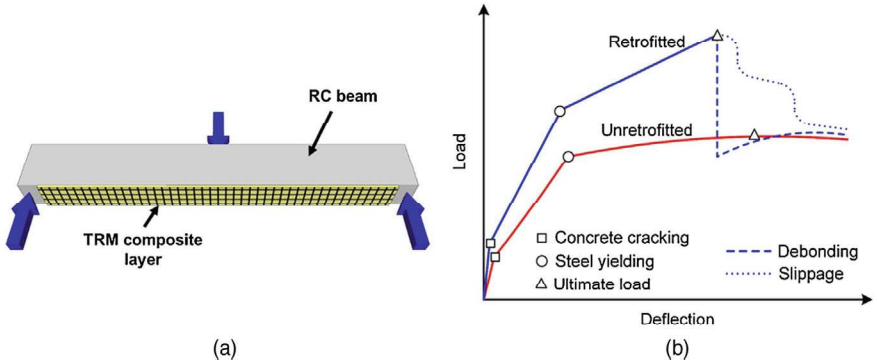


Fig. 7 **a** Flexural strengthening of an RC beam with TRM; and **b** strengthening effect on load versus displacement curves of RC members strengthened in flexure (Reproduced from [32]. ASCE published this article under Creative Commons Attribution 4.0 International license)

5.1 Flexural Strengthening

Beams or slabs are strengthened in flexure by bonding TRM layers to the tensile face—usually a beam's soffit or a slab's underside (Fig. 7a). Textile reinforcement is placed where extra moment capacity is required, along with sufficient anchorage length. Anchorage conditions can be enhanced using methods similar to FRP, such as U-strips or spike anchors.

In beam or one-way slab flexural strengthening, not all textile fibers bear tension; bidirectional textiles only use fibers parallel to the member axis for tension. However, for two-way slabs, fibers in both directions are effective [6, 32, 33].

Figure 7b depicts the generalized load–deflection curves, showcasing the flexural strengthening effects with textile reinforcement. Three linear segments describe flexural behaviour across stages: (1) pre-cracking, (2) cracked up to steel yield, and (3) plastic hinging for unstrengthened or full textile activation for strengthened elements up to ultimate load. Strengthening layers enhance initial stiffness, with greater effects seen in elements like slabs. Increasing cracking load activates tension fibers. Multiple cracks trigger second-stage strengthening, yielding stiffer behaviour and higher yield load than unstrengthened elements. TRM significantly boosts flexural resistance. TRM carries load till failure, except for shear or concrete crushing, causing gradual or sudden loss of strength. After a major reduction, capacity aligns with plastic moment of unstrengthened elements [32].

5.2 Shear Strengthening

Shear strengthening of RC beams or bridge girders is a common requirement for assessing strength under current codes. Insufficient shear reinforcement, corrosion,

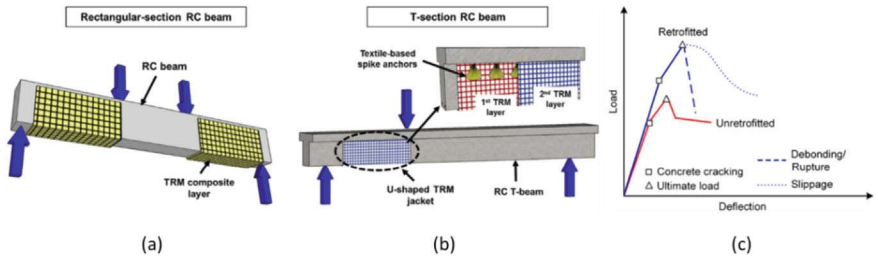


Fig. 8 Shear strengthening of a beam: **a** RC beam with U-shaped TRM jacketing subjected to symmetric four-point monotonic loading, **b** utilization of anchors in RC T-beams, showcasing the reinforcement technique; **c** strengthening effect displayed on load–displacement curves of shear-strengthened RC members (Reproduced from [32]. ASCE published this article under Creative Commons Attribution 4.0 International license)

low concrete strength, and increased loads drive this need. Additionally, shear strengthening ensures a ductile flexural failure mode. TRM is applied for critical shear spans through side-bonding (not recommended), U-wrapping, or full wrapping. Fully wrapped jackets are limited to shear-strengthening concrete columns due to infeasibility in beams or bridge girders with concrete slabs or decks. Anchorage systems, like mechanical devices or textile-based anchors, enhance anchorage conditions for side-bonded and U-shaped jackets, akin to FRP jackets. Figure 8a illustrates a beam strengthened with U-shaped TRM jackets, tested under symmetric four-point monotonic loading. Figure 8b displays a T-beam reinforced with U-shaped TRM jackets and textile-based anchors. Figure 8c displays simplified load versus deflection curves, indicating the strengthening effect observed in most studies. The shear behaviour is characterized by two linear segments leading up to the maximum load: (1) the uncracked stage until the initial concrete cracking point, and (2) the cracked stage until specimen failure. The descending branch may show a smooth, gradual load reduction (pseudo-ductile failure) or an abrupt load drop (brittle failure), contingent on the TRM's failure mode [32].

5.3 Concrete Confinement

The application of TRM layers for wrapping concrete elements (Fig. 9a, c) aims to impart passive confinement stresses under axial compression, thereby enhancing compressive strength and deformation capacity. Additional confinement is particularly needed for columns with low axial capacity and inadequate detailing. This method is typically applied using wet layup on suitably prepared surfaces. To prevent premature debonding (Fig. 9b), an overlapping layer is commonly added in the hoop direction. Bidirectional textiles, featuring fiber rovings in two orthogonal directions, are widely employed in the literature. However, in a 0°/90° configuration, only fibers in the hoop direction contribute to confining stress. This indicates the potential for

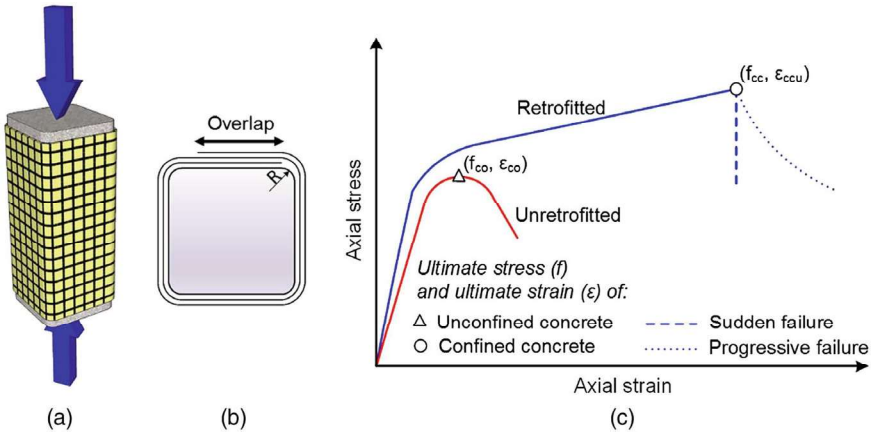


Fig. 9 **a** Concrete element under axial load confined with a TRM jacket, **b** overlapping of the final TRM layer, **c** enhancement of axial stress-strain curves due to strengthening (Reproduced from [32]. ASCE published this article under Creative Commons Attribution 4.0 International license).

optimizing textile geometries with distinct materials in each direction. Similar to FRP confinement, textile wrapping can be easily executed on circular or rectangular sections, provided the fibers remain uncoated and the corners of rectangular sections are adequately rounded. For textiles with coated fibers, specific conditions apply—limited coating impregnation and a relatively larger mesh size facilitate easier application [32].

5.4 Seismic Retrofitting

TRM jacketing confines plastic hinges in old-type RC columns with inadequate reinforcement detailing (Fig. 10a, b). During seismic events, such columns exhibit limited ultimate deformation capacity due to early failure at the column ends, particularly in lower floors. This failure is commonly attributed to bar buckling or bond failure in short lap splices. Full-height jacketing is employed for seismic shear strengthening of columns in high-risk areas (Fig. 10c).

The retrofitted columns, using both FRP and TRM, exhibited superior behaviour compared to their non-retrofitted counterpart, with deformation capacity more than doubled [32].

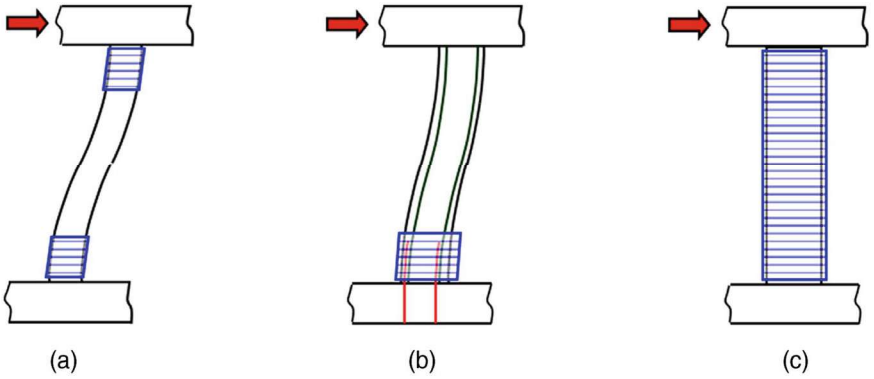


Fig. 10 Seismic retrofitting of RC columns using TRM: **a** enhancing concrete deformation capacity and/or delaying rebar buckling through local jacketing; **b** preventing lap splices failure with local jacketing; and **c** increasing shear resistance with full-height jacketing (Reproduced from [32]. ASCE published this article under Creative Commons Attribution 4.0 International license)

6 Conclusion

The geometry of woven fabric generates undulations that enhance mechanical anchorage in the concrete matrix. Optimal warp and weft density should be chosen to facilitate cementitious matrix penetration into the fabric interstices and achieve the desired bond strength. Knitted fabric parameters such as knitting patterns, loop size, and tension should also be carefully selected to ensure good filament-matrix bonding. When selecting yarn, finer yarn is preferable as it allows for better cementitious matrix penetration inside filament bundles. Hybrid yarn and fabric should also be considered to achieve cost-effective and synergistic mechanical performance. TRC has shown promise in civil engineering applications due to its unique properties such as high ductility, improved crack resistance, and enhanced durability. Further research is necessary to optimize TRC design and production and to develop appropriate design guidelines. TRC has the potential to revolutionize the construction industry by providing cost-effective solutions for repairing and strengthening existing structures, as well as for constructing new structures in seismic regions. It is expected that the popularity of TRC, particularly 3-D fabric-reinforced concrete, is expected to grow as researchers and engineers continue to explore its properties and applications.

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Assessing the Effects of Sweat and Water on Multilayered Fabric Assemblies for Enhanced Performance



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Abstract This study investigates the intricate relationship between moisture and thermophysiological comfort in multilayered fabric assemblies, particularly focusing on the impact of simulated sweat in comparison to distilled water. The multilayered fabric assembly under investigation consists of an outside layer of breathable nylon coated in polyurethane (PU), an inner layer of polyester knit fabric, and an intermediate layer with micro-polyester wadding, hollow-polyester wadding, or spacer fabric. The findings show that distilled water has a greater impact on thermal conductivity than simulated sweat, and this influence is considerable on the thermal characteristics of materials when they are wet. Additionally, the research emphasizes the substantial role of fabric construction and thickness in moisture behavior. Analyzing various layered ensembles, it is observed that polyester spacer fabric as the middle layer consistently outperforms hollow and micro-polyester waddings in terms of water vapor permeability, regardless of the moisture type (water or sweat). Also, it is found that heavier and thicker fabrics exhibit lower moisture vapor permeability. The study underscores the need for realistic sweat conditions in textile performance assessments.

Keywords Moisture properties · Thermal conductivity · Thermal resistance · Multilayered fabric · Water · Sweat solutions · Sportswear

1 Introduction

The quest for optimal thermophysiological comfort in textile engineering has gained paramount importance in the design and development of functional apparel, particularly in the domains of sportswear and activewear. As individuals engage in physically demanding activities, the interplay between the human body and the fabrics it adorns becomes a crucial determinant of overall comfort and performance. Among

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the myriad factors influencing this dynamic relationship, the impact of moisture, particularly sweat, and water, on multilayered fabric assemblies emerge as a focal point of exploration [2, 3, 5, 6, 8, 9].

In sportswear and cold-climate apparel, managing moisture is critical to prevent discomfort and hypothermia. Excessive sweat, especially in cold conditions, can reduce thermal insulation, leading to wet clothing and increased heat loss [1, 7]. Multilayered clothing, commonly used in cold climates, has distinct functions for inner, core, and outer layers. The fabric's structure influences moisture transmission, affecting thermal comfort and regulation. Severe environmental conditions, including sweat condensation in cold weather garments, pose challenges in moisture regulation.

Research on fabric thermal characteristics reveals the impact of parameters like thickness, weight, and porosity on thermal resistance. Moisture transfer qualities are crucial for outdoor garments in cold and wet environments, where stored moisture can freeze, compromising heat resistance. The composition and structure of each layer in multilayer garments influence moisture transmission, impacting thermoregulatory responses. Studies on the effects of saline water on fabric thermal behavior highlight the importance of understanding real sweat's impact. In the pursuit of elevated performance and wearer satisfaction, understanding how fabrics respond to the complex composition of human sweat, comprising salts, lipids, urea, lactic acid, carbohydrates, and minerals, becomes imperative. This research endeavors to unravel the intricate dynamics between multilayered fabric assemblies and moisture, scrutinizing the effects of both simulated sweat and water. The multilayered fabric assembly, incorporating elements like breathable outer layers, insulating middle layers, and moisture-wicking inner layers, serves as a microcosm reflecting the broader challenges faced in developing textiles for diverse environmental conditions.

By bridging the existing gap in research and delving into the intricacies of fabric behavior under diverse moisture conditions, this investigation seeks to contribute valuable knowledge that can inform the design of textiles for enhanced thermophysiological comfort and performance across a spectrum of applications.

2 Material and Methods

The fabric configuration utilized in this study consists of multiple layers, including a permeable exterior layer (composed of nylon coated with polyurethane), an inner layer (made of interlock polyester fabric), and an inner layer (comprising spacer fabric, micropolyester wadding, and hollow polyester wadding). The specifications and characteristics of individual layers used to create a multilayered composite are shown in Tables 1 and 2.

Measurements of thermal properties:

Hes and Dolezal's Alambeta tester, which offers a rapid evaluation of both steady-state and transient-state thermal characteristics, was used to examine the thermal properties [4]. This apparatus provides a somewhat accurate approximation of the

Table 1 Specifications and characteristics of individual layers

Fabric components	Layer	GSM (g/m^2)	Thickness (mm)	Filament/spun type		Cut length	Porosity (%)
Polyester knit (Interlock)	Inner layer	150 (1.48)	0.70 (0.013)	11.11Tex/144f		Not applicable	84.58
Spacer fabric	Middle layer	450 (1.36)	1.89 (0.009)	Outer (Multi-filament) 19.5 Tex	Inner (Mono-filament) 3.5 Tex	Not applicable	82.87
Micro-polyester wadding		450 (5.02)	8.58 (0.41)	0.1Tex		51 mm (±5 mm)	98.25
Hollow polyester wadding		450 (4.73)	10.2 (0.837)	0.33Tex		51 mm (±5 mm)	98.40
Breathable PU coated nylon	Outer layer	75 (1.002)	0.11 (0.002)	7.78Tex/24f		Not applicable	45.6

Table 2 Multilayer fabric assembly

Fabric sample code	Inner layer/bottom layer	Middle layer	Outer layer/top layer
ISP	Interlock fabric	Spacer fabric	Breathable PU coated nylon
IHP	Interlock fabric	Hollow polyester wadding	Breathable PU coated nylon
IMP	Interlock fabric	Micro-polyester wadding	Breathable PU coated nylon

heat flow (q) [W/m^2] from human skin to cloth during brief initial contact when there is no body movement and no external wind flow. Since the measuring head (32 °C) and bottom measuring plate (22 °C) are at different temperatures, the concept of this device depends on mathematical processing of the heat flow time course through the tested fabric. It merely takes a few minutes to measure. Because the sample moisture level stays relatively constant throughout the test, precise readings on wet fabrics are therefore possible.

Measurements of moisture vapor permeability

In accordance with BS 7209, the evaporative dish method was used to evaluate the moisture vapor permeability (MVP). For the test, a sample was cut with a diameter of 8 cm.

The test sample was sealed over the open mouth of a dish filled with water that was set up in the usual testing atmospheric conditions. A note was made regarding the dish's weight with the sample mounted on it. For recording the initial weight, the system will be stabilized after one hour, meaning equilibrium will be maintained. The following 4 h were dedicated to the test. The dish's weight was again recorded once the test was finished. Final weight was the phrase used. Equation (1) was used to calculate MVP and monitor the rate of water vapor passage through the fabric:

$$WVP = \frac{24 \times M}{A \times t} \tag{1}$$

M is the total assembly mass reduction, expressed in gram (g), over the designated time period.

The variable t denotes the interval in hours between successive assembly weighins.

The area of the exposed test specimen, A, is equal to the test dish's interior area (measured in m^2). In this case, specifically: A = 0.0054113 m^2.

3 Results and Discussion

The moisture vapor permeability (MVP), thermal conductivity, and thermal resistance of fabric constructions were examined individually and as layered components. This was done to assess the thermophysiological comfort of a multilayered system specifically developed for cold weather conditions. This section provides a comprehensive analysis of how the kind of liquid and type of middle layer impact the moisture and temperature behavior of the fabric assembly.

3.1 Thermal Properties of Individual and Multilayer Fabric Assembly

Thermal Conductivity:

The thermal conductivity of each individual layer is displayed in Table 3. Of all the middle layer fabric types, spacer fabric has the highest thermal conductivity, in contrast to hollow polyester wadding and micro-polyester wadding. Spacer fabric has less porosity than the other two types of middle layers, which helps to explain this.

The multilayered fabric assembly's dry and wet thermal conductivity values are shown in Fig. 24.1. The thermal conductivity values are 0.06, 0.05, and 0.04 W/m.K for ISP, IMP, and IHP, respectively. With a p-value of 0 (less than 0.05), the ANOVA findings show a substantial difference in heat conductivity across these three multilayered fabric assemblies. Notably, when compared to ISP and IMP, IHP exhibits lesser thermal conductivity. Because of its thinner layer than the other two samples, ISP has the highest thermal conductivity of the three. According to the results of different researchers, heat conductivity reduces with cloth thickness. Figure 24.1 shows a considerable rise in thermal conductivity upon wetting of the multilayered fabric. The increased water content in the fabric structure compresses the air pockets, causing this surge.

Table 3 Thermal conductivity and thermal resistance of individual layers

Tested/measured parameters	Polyester knit (interlock)	Micro-polyester wadding	Spacer fabric	Hollow polyester	Breathable PU coated nylon
Thermal conductivity (λ)/ (W/(m.K))	0.042	0.05	0.054	0.04	0.02
Thermal resistance (r)/ (m^2. K/W)	0.017	0.3	0.035	0.4	0.005

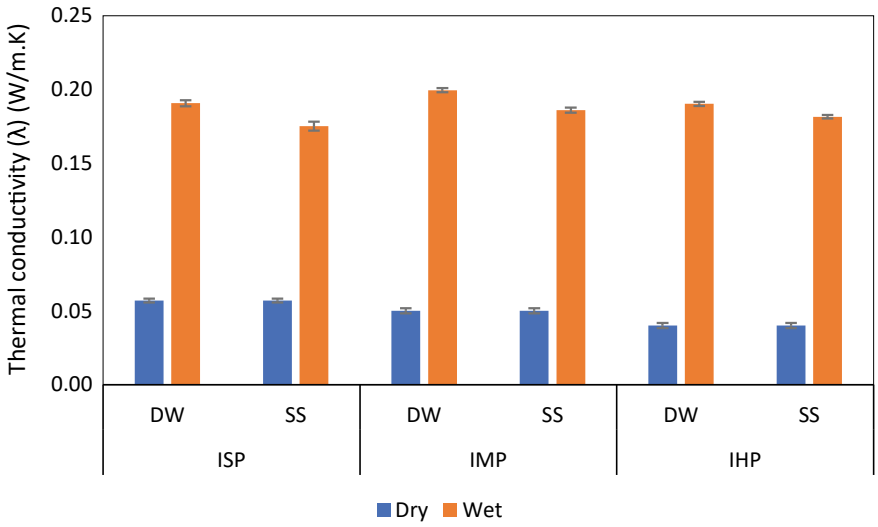


Fig. 1 Thermal conductivity of multilayered fabric assembly with sweat solution (SS) and distilled water (DW)

Thermal Resistance:

Hollow polyester wadding (refer to Table 3) demonstrates the highest thermal resistance among the materials listed, followed by micro-polyester wadding, spacer fabric, interlock fabric, and breathable PU-coated nylon. Fibrous waddings generally exhibit slightly higher thermal resistance compared to spacer fabric, which has a thinner thickness, resulting in lower thermal resistance. There exists a direct relationship between cloth thickness and thermal resistance.

As depicted in Fig. 2, materials experience a decrease in thermal resistance when wet, but gradually regain resistance afterward. Additionally, under both wet and dry conditions, ISP consistently displays the lowest thermal resistance among the three multilayered assemblies.

3.2 Moisture Vapor Permeability (MVP) of Individual and Multilayer Fabric Assembly:

Water vapor permeability is a crucial property in cold weather clothing, ensuring effective moisture management and breathability. It plays a vital role in keeping the wearer dry, comfortable, and protected from the chilling effects of trapped moisture.

In a recent study, various fabrics were evaluated for their water vapor permeability. Among these fabrics, spacer fabric stood out with an impressive permeability of 3158

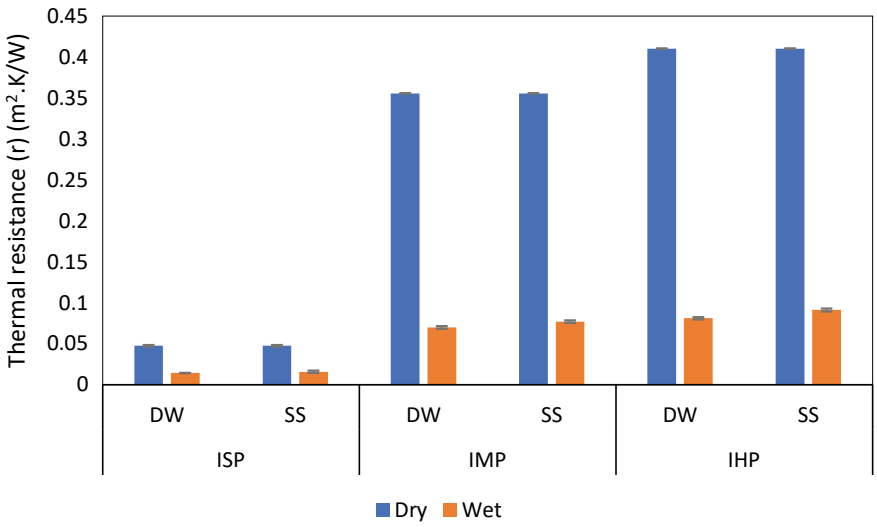


Fig. 2 Thermal resistance of multilayered fabric assembly with sweat and distilled water

g/m^2/day—the highest among all materials tested. The exceptional performance of spacer fabric can be attributed to its high porosity and low thickness.

However, other materials exhibited different characteristics:

Micro-polyester wadding and hollow polyester wadding had lower water vapor permeability compared to spacer fabric. Despite their higher porosity, their thickness hindered efficient vapor transmission.

Polyurethane-coated nylon, on the other hand, had the lowest water vapor permeability at 492.78 g/m^2/day. The presence of the coating reduced the fabric's porosity, restricting vapor transmission.

Interestingly, the type of liquid also influenced the permeability of fabrics and multilayer assemblies. When tested without fabric, distilled water, and sweat solution showed similar water vapor permeability values. However, in the presence of fabrics, the sweat solution exhibited considerably lower permeability than water. This discrepancy may be due to changes in pressure gradients caused by the interaction of sweat vapor and water across the material. Chemical components in sweat further contributed to this difference.

Additionally, the concept of Raoult's law—which relates a solvent's vapor pressure to its mole fraction in a solution—can help explain these phenomena in physical chemistry.

$$P(\text{solvent}) = X(\text{solvent}) \times P^{\circ}(\text{solvent})$$

where:

P(solvent) is the vapor pressure of the solvent in the solution.

X(solvent) is the mole fraction of the solvent.

P°(solvent) is the vapor pressure of the pure solvent.

According to Roult's law, as the mole fraction of the solvent increases, the vapor pressure of the solvent above the solution also increases. This means that the presence of a solute in a solvent will lower the vapor pressure of the solvent compared to its pure form.

The disparity between the vapor permeability of water and sweat solution significantly decreases in the case of multilayered ensemble (Fig. 3b). This decrease is significantly due to PU coated fabric as outer layer of the multilayered assembly. Also, the increase in overall thickness when fabric is layered and the air gaps that are formed within them, the pressure gradient at each layer further decreases, which in turn reduces the flow of moisture to the outer atmosphere. Comparing multilayered structures with polyester wadding to multilayered ensembles with spacer fabric, it has been observed that the latter exhibits greater vapor permeability when water is used.

4 Conclusion

The thermophysiological comfort of a multilayered fabric system designed for cold weather applications has been thoroughly evaluated in this study. By means of an extensive examination of moisture vapor permeability (MVP), thermal conductivity, and thermal resistance, we have acquired significant knowledge regarding the complex interplay between liquid kinds, fabric layers, and structural components. The examination of thermal characteristics revealed that spacer fabric has better thermal conductivity than hollow polyester wadding and micro-polyester wadding. This is because it has less porosity. Significant differences in thermal conductivity between the dry and wet states were observed in the multilayered fabric construction, highlighting the effect of thickness on conductivity. The results of the evaluation of thermal resistance indicate that breathable PU-coated nylon, spacer fabric, interlock fabric, hollow polyester wadding, and micro-polyester wadding were rated in order of highest ranking, confirming the direct correlation between fabric thickness and thermal resistance. Moisture vapor permeability, a critical factor in cold weather clothing, showcased spacer fabric as the most permeable due to its high porosity and thin profile. Conversely, micro-polyester and hollow polyester waddings, despite higher porosity, displayed lower MVP attributed to increased thickness. PU-coated nylon, with a restrictive coating, exhibited the lowest MVP. Notably, the type of liquid significantly impacted MVP, with sweat solution exhibiting considerably lower permeability than water when tested with fabrics. Raoult's law elucidated this phenomenon, linking lowered vapor pressure in sweat solution to the presence of various chemicals, resulting in decreased pressure gradients across the fabric. Disparities in vapor permeability between water and sweat solution diminished in multilayered ensembles, influenced by PU-coated fabric and increased overall thickness, leading to reduced pressure gradients and moisture flow. This research illuminates the complex dynamics of fabric behavior in response to environmental and structural

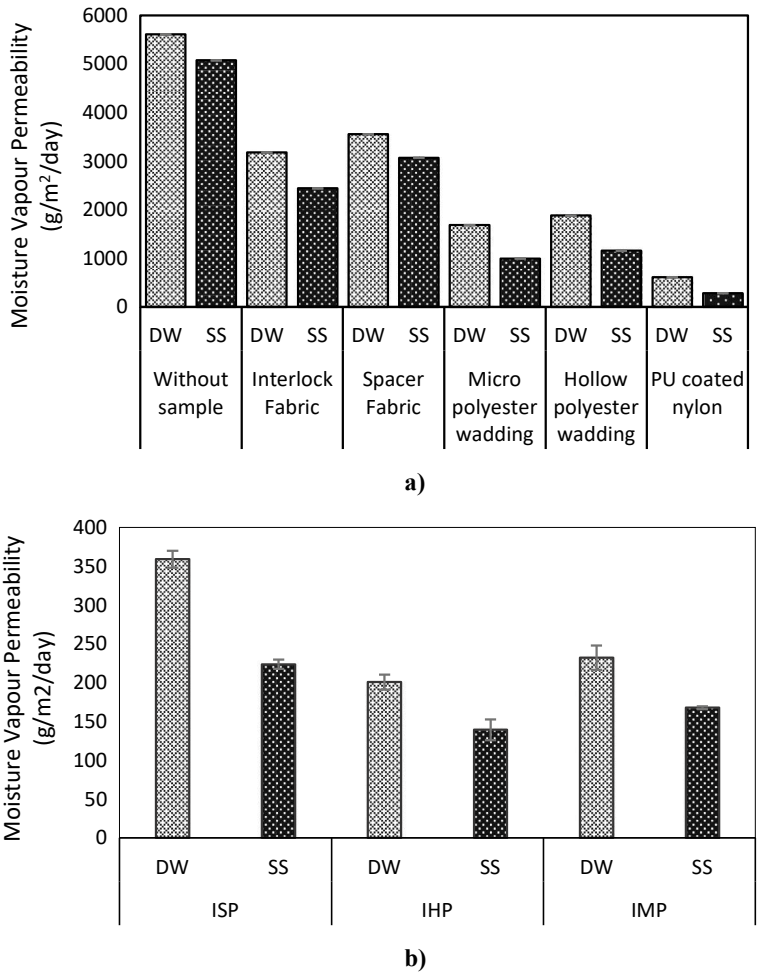


Fig. 3 Moisture vapor permeability with distilled water (DW) and sweat solution (SS): **a** Individual layers; **b** Multilayers fabric assembly

factors, offering critical insights for the meticulous design and development of cold-weather clothing systems. The findings contribute to advancing our understanding of thermophysiological comfort, paving the way for improved garment designs that prioritize optimal performance and wearer well-being in challenging cold weather conditions.

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Potential Applications of Jute and Coir Fibers in Geotextiles: Review



Jai Narain, Lalit Jajpura, and Vinay Kumar Midha

Abstract Ligno cellulosic fibers such as jute and coir have been used in varied applications for centuries. Jute fibers are derived from the stem of jute plant, while coir fibers are obtained from coconut husk. Owing to their sustainability and environmental friendliness, these natural geotextiles are attracting attention of scientists and researchers for use in cutting-edge technologies. These fibers possess good tensile, tearing, bursting strength, and UV resistance, which make them suitable for various industrial, geo, and civil engineering applications. Jute and Coir fibers alone or in special combinations have numerous applications in building retaining walls, filtration, drainage, and soil erosion control as well as for manufacturing plant pots &mulch mats, building railway lines, and building highways. Jute and Coir geotextiles have promising applications in the protection of slopes in earthen embankments, hill slopes, garbage dumps, and piles of granular waste like fly ash in thermal power. In this review, various forms of geotextile materials, their market status, characteristics, advantages, and limitations have been discussed with emphasis on potential applications of jute and coir as sustainable alternatives to synthetic geotextiles.

Keywords Jute and coir geotextile · Erosion control · Reinforcement · Filtration · Drainage · Separation

1 Introduction

Geotextiles are synthetic or natural fiber based textiles used to stabilize soil and prevent erosion [1]. Natural fibers such as jute and coir have gained popularity in geotextiles in recent years due to their environment friendliness, biodegradability, and low cost [7]. Jute is a cellulosic fiber extracted from the stem of jute plant and is a highly versatile fiber with several applications in industrial and technical textiles. Jute fiber is well-known for its strong tensile strength, limited elongation, and efficient

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moisture absorption. Coir fiber, on the other hand, is a lingo-cellulosic fiber derived from the husk of coconut. Coir fiber is also well-known for its strong tensile strength and good moisture absorption capabilities [28]. Geotextiles consisting of jute and coir fibers have several possible uses in which control in soil erosion is one of the most popular use. These applications include stabilization of soil on slopes, controlling surface water runoff & soil erosion [36], and reduction in sedimentation in rivers and streams [30]. Road and rail road construction is another possible application for jute and coir geotextiles [24]. They can be used to support soil in road embankments, prevent soil erosion, increase soil water retention and minimize the demand for irrigation. They can also be utilized to increase road subgrade stability and minimize the chance of pavement failure [36]. They can be used to strengthen the soil and prevent soil erosion in landscape areas [36]. In the present review, various types of geotextile materials, i.e., natural & synthetics; various forms of geotextiles, i.e., woven, nonwoven & knitted; their market status and future growth, characteristics, pros, and cons have been discussed with more emphasis on jute and coir as sustainable alternatives to synthetic geotextile.

1.1 Material Used in Geo-Engineering

There are many sorts of geotextiles used in field of geotextiles, in which some of them fall under natural renewable textiles such as jute, coir, sisal, hamp, cotton, etc., whereas others are synthetics such as polyester, nylon polypropylene, and aramid fibers. The advantages and disadvantages of natural textiles are given below (Antaby 2022):

Advantages of Natural geotextiles:

- Eco-friendly, renewable and biodegradable.
- Lighter and more resilient to tearing.
- Simple to install and provides dependable and predictable performance.
- Porous or permeable materials that permit liquids or gases to pass through them.
- They have appropriate durability and resistance to extreme conditions.
- Assist in stabilizing the soil and reducing erosion.
- Avoid soil saturation and facilitate easy drainage of water.
- Stimulate plant development and improve the permeability of the soil.
- Easy and abundant availability in market.

Some of the major advantages of natural fibers and their geotextiles are illustrated in Fig. 1.

Disadvantages of natural geotextiles:

- Prone to damage easily.
- They are not suitable for high-traffic regions.
- Inadequate for very stony and rough places.

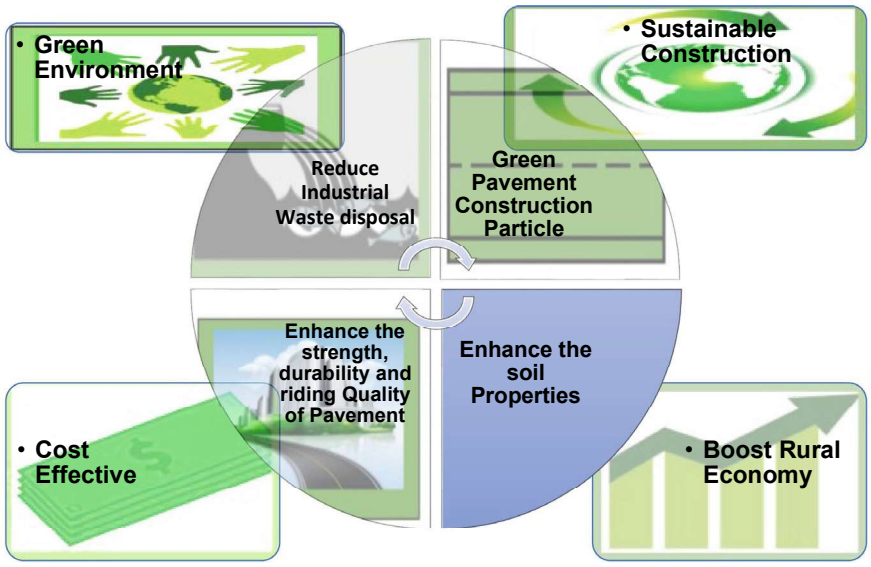


Fig. 1 Advantages of natural geotextiles [30, 43]

- They may accumulate clogs during the application that diminish their efficacy and necessitate maintenance.
- Susceptible to UV deterioration and eventually lose some of their usefulness.
- When installed improperly, they are particularly vulnerable to tearing.

The use of various synthetic fibers increased tremendously in geotextile over natural fibers as they became more cheaper than natural fiber due to their mass production and advancement in their production technology [16, 20]. Details of some of the common man-made fibers used in geotechnical engineering are as follows.

Polyester (PET): Polyester fibers are extensively used in geotechnical applications due to their comparatively higher strength and durability as well as resistance to UV degradation and chemical exposure. These properties make it suitable for reinforcement in soil stabilization projects, erosion control, and road construction.

Polypropylene (PP): Polypropylene is another common synthetic fiber used in geotechnical engineering. It is lightweight, has good resistance to biological degradation, and is often used in applications requiring filtration, separation, and soil reinforcement in road construction, embankment stabilization, and erosion control projects.

Polyethylene (PE): Polyethylene fibers are used in geotechnical applications for their strength and chemical resistance. They may be employed in situations where resistance to acidic or alkaline environments is necessary. Polyethylene-based geotextiles can be used for erosion control, soil reinforcement, and drainage applications.

Polyamide (Nylon): Nylon fibers are known for their high tensile strength and elasticity although less common in geotechnical applications compared to polyester and polypropylene. Nylon geotextiles might be used in soil reinforcement and stabilization projects.

High Density Polyethylene (HDPE): Similar to polyethylene, HDPE may be used in geotechnical applications such as in geogrids for soil reinforcement in retaining walls, slopes, and embankments.

Polyvinyl Alcohol (PVA): PVA fibers are sometimes used in geotechnical applications for their high tensile strength and resistance to chemicals. PVA geotextiles may be employed in projects where soil stabilization and reinforcement are critical.

Aramid (e.g., Kevlar): Aramid fibers, such as Kevlar, are known for their exceptional strength and resistance to wear being high performance fiber. Their use in geotechnical applications is rare due to cost considerations, although they may be used in specialized projects requiring high performance materials.

Man-made geotextiles, which are synthetic materials designed for various geotechnical applications, offer several advantages and disadvantages as mentioned below.

Advantages of Man-Made Geotextiles

- Provide high tensile strength, making geotextiles effective in soil reinforcement and stabilization.
- Mostly exhibit resistance to chemicals and ultraviolet (UV) radiation, ensuring stability in environments with exposure to aggressive substances.
- The manufacturing process and stringent quality control assure uniform performance across different batches.
- Synthetic fibers can be tailored to have specific characteristics, such as strength, elongation, and degradation rates, based on the requirements of a particular project.
- Many man-made geotextiles are lightweight, facilitating easy transportation, handling, and installation on construction sites.
- There is a wide range of synthetic geotextiles available, including woven, nonwoven, and knitted varieties, allowing engineers to choose the most suitable type for a given application.
- Synthetic geotextiles are generally designed for easy installation, offering flexibility and compatibility with construction equipment.
- While initial costs may vary, the long-term performance and durability of man-made geotextiles often justify the investment, making them cost-effective solutions for many applications.

Disadvantages of Man-Made Geotextiles

- The production of synthetic fibers involves the use of non-renewable petrochemicals, contributing to greenhouse gas emission and environmental concerns. Additionally, the disposal of synthetic materials can be an issue.

- While many synthetic fibers are resistant to UV radiation, prolonged exposure can lead to degradation over time. Special UV-resistant coatings or additives may be required for extended outdoor use.
- Some synthetic fibers may be sensitive to extreme temperatures, affecting their mechanical properties. This is particularly relevant in applications where temperature variations are significant.
- Unlike natural fibers, many synthetic fibers are not biodegradable, which can be a disadvantage in certain applications where biodegradability is desired.
- In certain drainage applications, synthetic geotextiles may have the potential to clog over time, reducing their effectiveness in allowing water to pass through.
- While man-made geotextiles may offer long-term cost-effectiveness, their initial cost can be higher than some alternative materials, such as natural fibers.
- Some synthetic fibers may have lower resistance to abrasion compared to natural fibers, impacting their performance in specific applications.

It can be seen that synthetic fiber has numerous advantages over natural fibers based on their performance and cost-effectiveness although they are not biodegradable, not renewable, and have disposal problems. Ultimately they are causing threats to the environment and ecology thus there is a dire need to replace these fibers with sustainable natural fibers, i.e., Jute and coir.

2 Market Data of Geotextiles Along With Jute and Coir Fibers

Global geotextile market was valued at USD 7.10 billion in 2022 and is expected to grow at a compound annual growth rate (CAGR) of 6.6% from 2023 to 2030 (http/www.grandviewreserach.com) [12]. Especially in the Asia-Pacific Region (APAC), rising construction activities in developing countries such as India and China will definitely raise utilization of natural geotextiles. National Green Highway Mission of India is expected to drive the demand of geotextiles in India (www.statista.com/statistics/679345/asia-pacific-jute-production-by-country) Nonwoven geotextiles are rapidly being employed in road, railroads and bridges construction and drainage and prevention of soil erosion. Natural geotextile helps in soil vegetation growth which reduces erosion in the long run.

India is the largest producer of Jute followed by Bangladesh as shown in Table 1. Jute primarily grows in West Bengal, Odisha, Assam, Meghalaya, Tripura, and Andhra Pradesh (Jute cultivation data—as per FAO). As per April 2022 study published by the Ministry of Textile, the global jute production was 384.1 lakh tons in 2022–23. India is also a leading producer of coconut and coir followed by Vietnam and Sri Lanka as shown in Table 2. Kerala state shares about 61% of coconut production in India. Coir products such as coir pith, coir fiber, tufted mat, handloom mat, coir geotextile, etc., products are extensively exported by India. As per estimate, only 2 to 5% of total production of jute and coir is used in geotextile.

Table 1 Jute production in the Asia–Pacific region in 2021, by country (in 1,000 metric tons) [10, 15]*

Sr no.	Country	Production in thousand metric tons:
1	India	1720
2	Bangladesh	1680
3	China	16
4	Nepal, Bhutan, etc.	50
	Global	3457

Table 2 Coir production in the Asia–Pacific region in 2020, by country (in 1,000 metric tons) [15]*

Sr No	Country	Production in thousand metric tons
1	India	586.69
2	Vietnam	390.54
3	Sri Lanka	161.08
4	Thailand	64.1
5	Malaysia	21.45
6	Bangladesh	10.31
	Global	1276

3 Functional Requirements of Geosynthetics Applications

Plant, animal, and mineral fibers are the three different categories of natural fibers in which plant fibers have emerged as the top option due to their extensive availability, flexibility in extraction, low cost, and high performance [46]. Jute and coir are two main plant-based geotextiles which are used extensively in woven, nonwoven, and knitted forms for different geo applications. Each form of geotextiles has certain pros and cons as discussed below.

Woven: The popular weaving techniques used for natural fiber based geotextiles are plain, twill, and satin weaves. The mechanical and structural qualities of woven textiles make them useful in geotechnical engineering for a variety of purposes due to the following reasons [34].

Strength and Durability: The strength and durability of woven fabrics are well-known. Thus, they are appropriate for uses requiring materials to support heavy loads, such as fortifying soil or building retaining walls.

Reinforcement: Soil constructions are typically reinforced using woven materials. For instance, these textiles can be incorporated into the soil to increase its capacity to support loads and stop erosion in operations involving soil stabilization or reinforcement.

Erosion Control: Woven textiles are used to reduce soil erosion on riverbanks, slop, and other locations that have propensity of soil erosion. These textiles can stop sediment loss, assist in maintaining the soil fertility, and facilitate vegetation.

Separation: Weaved textiles may be employed to provide a barrier between various soil levels or between soil and other materials. This keeps materials from combining and preserves the structural integrity of the building.

Filtering: Woven fabrics may act as filters, permitting water to pass through while preventing migration of fine particles. This is important in applications where water requires to be drained out keeping the soil particles intact in their location.

Flexibility: Since fabrics are frequently flexible, they may follow the curves of the underlying soil or structure. This adaptability is useful in a variety of geotechnical applications where uneven terrain may exist.

Cost Effective: They are comparatively affordable than other form of geotextiles for similar sort of strength and durability of product. Thus, they are an appropriate choice for many geotechnical engineering projects.

Ease of Installation: Woven fabrics are relatively simple to set up in engineering projects where a quick and basic installation is desirable.

Nonwoven: Nonwovens are produced by various techniques such as needle punching, chemical bonding, heat bonding and stitching. The nonwoven preform production process is more efficient and cost-effective than woven ones although have certain limitations. While nonwoven fabrics generally have lower tensile strength compared to woven fabrics still they are able to give the required strength for certain applications. Besides appropriate mechanical properties, they also have reasonable sound absorption capabilities [5, 31]. Nonwoven fabrics are frequently employed in geotechnical engineering for following applications [35].

Filtration: Nonwoven geotextiles are frequently employed in filtering applications. They hinder the passage of soil particles while permitting water to flow through. This has significant importance in situations when it's imperative to retain fine soil particles and have drainage.

Separation: The separation of several soil layers or of soil from other elements may be achieved effectively using nonwoven textiles. They preserve the structural integrity of the material by serving as a barrier and preventing material mixing.

Drainage: Nonwoven geotextiles can be conceived to have specific permeability features, allowing water to pass through easily. This drainage capability is useful in applications such as road and rail road construction, where water needs to be efficiently drained out to avoid damage to the road base.

Erosion Control: Nonwoven fabrics can be utilized to reduce erosion, on slopes and embankments. They lessen the chance of erosion by stabilizing the soil's surface and providing protection from surface water flow and rainfall.

Cushioning and Protection: Nonwoven geotextiles have the ability to protect and cushion underlying materials. They can be positioned, for instance, between a geomembrane liner and the soil to shield it from abrasions and punctures.

Vegetative Support: Nonwoven geotextiles can help plants develop by giving roots a secure place to take hold. This is especially helpful in applications involving erosion management, as vegetation aids in slope stabilization. Although compared to woven, they create hindrance in aeration of soil and growth of plants.

Ease of Installation: Nonwoven fabrics are frequently lightweight and easy to handle, making them convenient for quick and simple installation in the field.

Knitted: Knitting is another fabric type made by looping threads together, although this loop structure compromises some of the mechanical properties. Knitted fabric may either be weft or warp knitted [6]. Knitted materials are occasionally used in certain applications of geotextiles in comparison to woven and nonwoven textiles due to their elastic and flexible characteristic. The following are some of the potential applications of knitted textiles in geotechnical engineering.

Conformability: Knitted materials' intrinsic elasticity allows them to adapt to uneven surfaces and terrain. Because of this, they can be used in situations where the underlying surface is uneven or even flat.

Flexibility and Stretch: The stretch and flexibility of knitted fabrics can be beneficial in certain applications. For example, in slope stabilization projects, knitted fabrics may deliver a degree of flexibility that allows them to adapt to the modifying contours of the slope.

Soil Reinforcement: Soil reinforcement may be achieved by using knitted materials that have the right tensile strength. The flexibility of knitted materials can be advantageous in some soil stabilization applications, even if they might not have the same tensile strength as woven materials.

Drainage: Knitted materials can offer drainage abilities based on their pattern. They could offer some degree of soil retention while letting water flow through. In situations when regulated drainage is necessary, this may be advantageous.

Erosion Control & Vegetative Support: They are able to prevent erosion by acting as a barrier against surface water flow and precipitation and encourage the growth of plants. Knitted materials' elasticity may enable them to adapt to the soil's surface and withstand erosive stresses as well as facilitate roots growing via their open structure.

Selection of the proper geotextile material will depend on a number of factors, including intended engineering objectives, water conditions, slope angle, and type of soil. While woven and nonwoven materials are more common options, knitted materials might provide special benefits in some circumstances if their characteristics match the requirements of the project. The required geosynthetic properties differ depending on their end application. Each purpose necessitates the use of certain soil qualities. For Example, High tensile strength, chemical resistance, frictional characteristics, and frictional qualities are required for better reinforcement. The details of the degree of importance of required important properties of geosynthetics as per their intended end use are listed in Table 3.

3.1 Chemical Composition and Properties of Jute and Coir Fiber

The extensively used natural fiber is cotton but it consumes huge amount of water, fertilizers, and pesticides and thus needs sustainable alternatives [19, 42]. Studies show that bast, coir, etc., fiber needs less amount of water for irrigation as well as

Table 3 Details geotextiles functional application and properties

Geotextiles functions	*Tensile strength*	*Elongation*	*Chemical resistance*	*Flexibility*	*Friction properties*
Reinforcement	◆◆◆	◆◆◆	◆◆–◆◆◆	◆	◆◆◆
Filtration	◆–◆◆	◆–◆◆	◆◆◆	◆–◆◆	◆–◆◆
Separation	◆◆	◆◆◆	◆◆◆	◆	◆◆
Drainage	NA	◆–◆◆	◆◆◆	◆–◆◆	NA
Erosion control	◆◆	◆◆–◆◆◆	◆	◆◆◆	◆◆
Geotextiles functions	*Interlock*	*Tear resistance*	*Penetration*	*Puncture resistance*	*Creep*
Reinforcement	◆◆◆	◆	◆	◆	◆◆◆
Filtration	◆◆◆	◆◆◆	◆◆	◆◆	NA
Separation	◆◆	◆◆◆	◆◆◆	◆◆	NA
Drainage	◆◆	◆◆–◆◆◆	◆◆◆	◆◆◆	NA
Erosion control	◆	◆◆	◆◆	◆–◆◆	NA
Geotextiles functions	*Resistance to flow*	*Properties of Soil*	*Biodegradability*	*Water*	*Permeability*
Reinforcement	◆	◆◆◆	◆◆◆	◆◆◆	NA–◆
Filtration	◆	◆◆	◆◆◆	◆◆◆	◆◆–◆◆◆
Separation	◆	NA	◆◆◆	◆◆◆	◆◆–◆◆◆
Drainage	◆	NA	◆◆◆	◆◆◆	◆◆◆
Erosion control	◆◆◆	NA	◆◆◆	◆◆◆	◆◆
Geotextiles functions	*Burial*	*UV Light*	*Climate*	*Quality assurance and control*	*Cost*
Reinforcement	◆◆◆	◆◆	NA	◆◆◆	◆◆◆
Filtration	◆◆◆	NA	◆◆◆	◆◆◆	◆◆◆
Separation	◆◆◆	NA	◆	◆◆	◆◆◆
Drainage	◆◆◆	NA	◆◆◆	◆◆◆	◆◆◆
Erosion control	◆◆◆	◆◆◆	◆◆◆	◆	◆◆◆

◆◆◆—Highly Important, ◆◆—important, ◆—moderately important, NA—Not Applicable

less amount of fertilizers and pesticides hence they are more sustainable in nature [17].

Their use in apparels may have certain limitations due to stiffness and lack in softness but they have ample potential in industrial and relevant geotextile applications.

Natural fibers' characteristics are influenced by the composition and placement of their individual components [39, 40]. Natural fibers mostly consist of cellulose, hemicelluloses, lignin, and pectin as shown in Fig. 2 [23]. The properties of natural

fibers are determined by the composition and location of these aforesaid components [30].

Every natural fiber has a different composition of constituents. The three main substances that define a cellulosic fiber's physical characteristics are lignin, hemicellulose, and cellulose. In terms of organic content, cellulose is the strongest and toughest. An array of hydroxyl and acetyl groups can be found inside the open structure of hemicellulose. As a result, hemicellulose exhibits hygroscopicity and is partially soluble in water due to its amorphous structure. Phenyl propane unit polymers are the primary constituents of lignin. The cellulose and lignin contents of the fibers determine how long a natural geotextile will last; the higher the content, the longer the material will last. The orders of required chemical composition for different properties of fibers are given in Table 4. Whereas, the percentage composition of cellulose, hemicellulose, and lignin along with various properties of different cellulosic fibers are given in Table 5 [37]. Jute and coir are extensively used as natural geotextiles due to their remarkable chemical and physical properties, outstanding performance, and a variety of available commercial products.

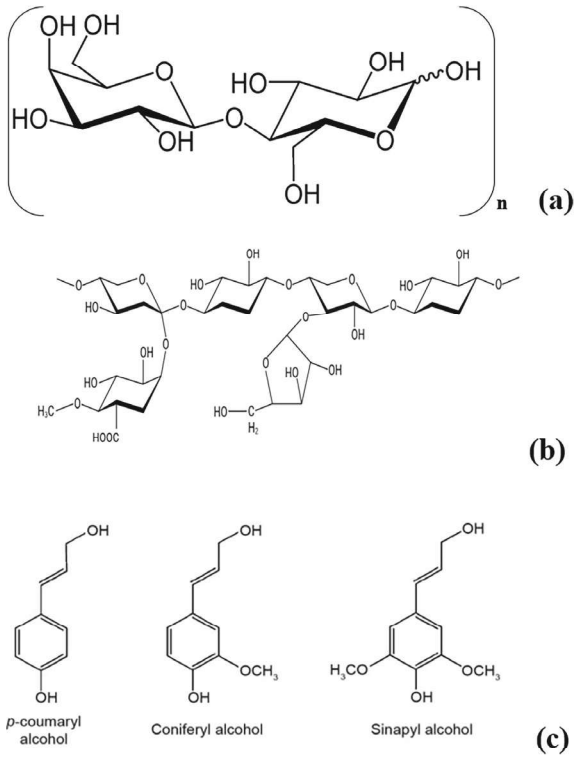


Fig. 2 Structure of **a** Crystalline cellulose **b** Hemicelluloses **c** Lignin components

Table 4 Required chemical composition for different properties of cellulosic fibers [46]

Importance level of Chemical Composition in Fiber Properties	Strength	Moisture absorption	Thermal degradation	UV degradation	Biological degradation
Crystalline cellulose	1	4	2	4	3
Non-crystalline cellulose	2	2	1	3	2
Hemicelluloses	3	1	–	2	1
Lignin	4	3	3	1	4

1—High, 2—Moderate, 3—Average, 4—Low

Table 5 Chemical composition and properties of different natural fibers for geotextiles application [2]

Properties / Fiber	Cellulose (Wt %)	Hemicelluloses (Wt %)	Lignin (Wt %)	Density (g/m^3)	Strain at break (%)	Tensile strength (MPa)	Young's modulus (MPa)
Jute	45–72	13–21	12–16	1.3–1.46	1.5–1.8	394–800	10–30
Coir	35–44	0.15–0.25	40–45	1.2	15–30	175–220	4–6
Flax	71–78	18.6–20.6	2.2	1.4–1.5	1.2–3.3	345–1500	27.5–80
Hemp	7–77	3.7–13	14–22.4	1.48	1.6	550–900	70
Kenef	31–57	15–19	21.5–23	1.2	2.7–6.9	295–930	22–60
Ramie	68.6–76.22	0.6–0.7	5–16.7	1.5	2–3.8	220–938	44–128
Sisal	47–78	7–11	10–24	1.33–1.5	2–14	400–700	9–38
Cotton	85–90	0.7–1.6	5.7	1.51	3–10	287–597	5.5–12.6

4 Various Applications of Jute and Coir Geotextiles

4.1 Natural Geotextiles Used for Prevention of River Bed

Riverbed erosion may be a severe issue that causes environmental harm and property loss. Natural geotextiles, also known as bioengineering materials, may help to keep riverbeds from eroding. Here are some natural geotextile samples that can be utilized for this purpose.

(a) Coir Mat: Coir matting is a common natural geotextile used for erosion prevention that is manufactured from coconut fibers. It is biodegradable and has a lifespan of up to 5 years. Coir matting is a simple material that is used to stabilize riverbanks and slopes [29].
(b) Jute Mesh: Jute mesh is another popular natural geotextile used for erosion prevention. It is biodegradable and has a lifespan of up to two years. Jute mesh is a lightweight material that is used to stabilize riverbanks and slopes.

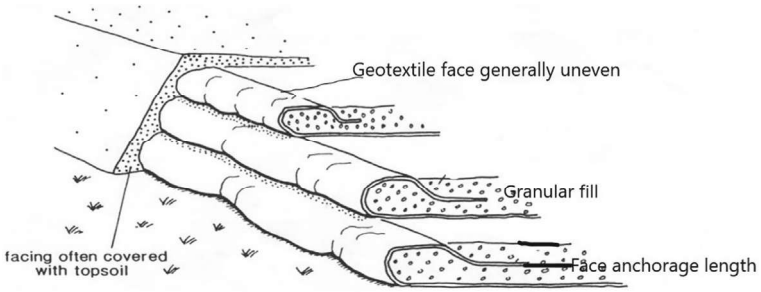


Fig. 3 Illustration of the field application of the geotextiles on river bed

Geotextiles are mostly formed of artificial fibers, although in recent decades natural fiber created geotextiles have been proven to be useful in enhancing geotechnical qualities of soil and are widely employed for a variety of technical end purposes, one of which is river bed prevention. Jute can efficiently filter and separate tiny particles in free flowing water, extending the life of various contain modifications [11]. The river bed's life can be extended by up to 600–700 days [29]. The durability of jute geotextile threads with environmentally benign additions is up to 4 years, and the tensile strength fulfills downstream application requirements. The impact of coir geotextile as a river bank protection measure is also outstanding, coir is environmentally friendly, and coir fiber has a life span of 4 to 5 years [3]. River bed construction with geotextile application is shown in Fig. 3. In this contraction there are three chambers of packet packed cover with geotextile.

4.2 Natural Geotextiles Used for Runoff Control and Vegetation

Vegetation is an excellent answer to a majority of steep soil erosion issues. Jute and coir have been shown to provide adequate soil loss protection [21]. Jute and coir are both utilized for runoff control and vegetation, although the jute geotextile performs better in terms of runoff management than the coir geotextile. Due to the increased water flow velocity and larger runoff volume under zero-infiltration conditions, the erosion control % under soil-infiltration conditions is lower at higher slope angles and rainfall intensity [26]. Due to the greater storage volume and restriction provided by the bigger diameter weft yarn of higher weight geomeshes, it has also been discovered that they produce reduced runoff and higher culmination [22]. Varying slope angles and weaves of jute and coir have varying effects on runoff, both reduce runoff, but more compact structures, such as plain weave, regulate more runoff [44]. Protective covering can be applied in a variety of ways, including mulching, spraying, and emulsion-like products, all of which fall under the general category of rolling erosion

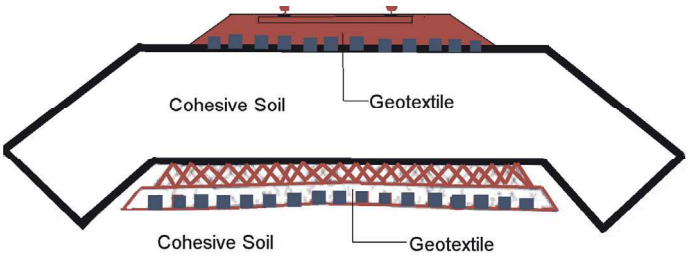


Fig. 4 Illustration of the field application of the geotextiles on reinforcement

control product (RECP). It is commonly acknowledged that permanent plant cover has long-term runoff management [39, 40].

4.3 Natural Geotextiles Used for Reinforcement

Geosynthetic reinforcement is used to provide additional stability in the construction of embankments of soft soil, roads, rail roads, etc. [32]. Natural geotextiles have excellent initial strength when used for road constructions. It is reported that jute geotextiles can increase the road strength by 67–68% in comparison to non-geotextile roads [4]. For long-term durability, the jute geotextile is particularly critical for the stability of subgrade reinforcement as illustrated in Fig. 4 [4].

4.4 Natural Geotextiles Used for Soil Erosion

Soil erosion is a key limitation in agriculture, affecting crop output and reducing environmental sustainability. Land degradation creates high erosion rates as a result of agriculture, grazing, mining, forest fires, or deforestation, resulting in economic, social, and environmental consequences for soil erosion control. Natural geosynthetic mattes are utilized with rolled-off erosion control blankets, such as open weave geotextile as illustrated in Fig. 5. Although Polyolefin, PVC, Nylon, and other synthetic polymers are used to minimize soil erosion, they are non-biodegradable which are detrimental to the environment [5, 25]. Jute geotextile may prolong runoff time and minimize runoff by 62.1% and erosion by 99.4%, respectively [41]. After 12 months of exposure to the environment, the tensile strength of untreated fibers remained at 23% tensile strength of starting sample [45]; Similarly, Coir has also applicability in runoff erosion although stiffness in fiber creates some problems in the application (Midha and Verma 2021).



Fig. 5 Illustration of the field application of the natural geotextiles on soil erosion **a** Coir geomesh **b** Jute geomesh **c** Combined coir and jute geomesh [8]

4.5 Geotextiles Used in for Sustainable Low-Volume Rural Road Construction

A growing number of sustainable low-volume rural road building projects are using geotextile as illustrated in Fig. 6. They fulfill a number of essential requirements mentioned below [33].

Separation: Geotextiles help to separate different layers of the road, preventing combining of materials.

Reinforcement: Geotextiles provide additional strength and stability to the road structure.

Filtration and Drainage: Geotextiles facilitate water drainage, thereby decreasing the risk of water damage to the road.

The application of geotextile may increase the lifespan, lower maintenance costs, and enhance the quality of rural roads. They also make it possible for the road to

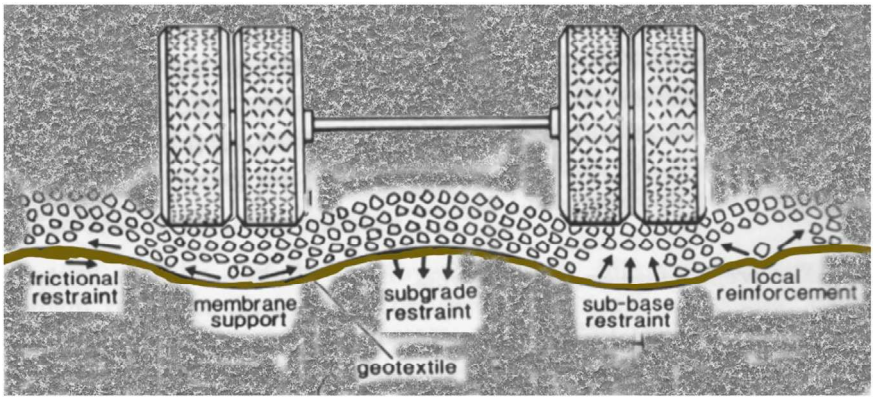


Fig. 6 Illustration of geotextiles applications in rural roads Constructions

endure weather-related natural disasters like floods and monsoon damage. Additionally, organic geotextiles like jute can support ecological equilibrium in the area [33].

The use of coir geotextiles has increased tremendously to improve all-weather rural road connectivity in India under a government program started in December 2000. In addition to upgrading 1.67 lakh km of existing roads, this initiative has offered connectivity over 4.66 lakh km. In the same context, guidelines for the use of coir geotextiles are included in the Rural Road Manual (IRC SP: 20–2002/2010) for design and construction, released by the Indian Road Congress [33].

4.6 Natural Geotextiles Used in Other fields

Jute, coir, and other natural fabric reinforced biodegradable geo membranes, medical disposable bags and wipes developed may be efficiently utilized for pond and canal lining, municipal solid waste management, hospital waste management, and other applications respectively [9]. Jute and coir fabric-based combined/multi-layered Tar Felt can also be utilized for prospective applications in civil engineering, particularly roof treatment. The use of jute-based composites for awnings, fake ceiling boards, cover walls of railway coaches, and even door panels for vehicles is becoming increasingly important for the diversification of jute goods. The potential of jute and coir fiber for all possible diverse fields may be explored further through appropriate R&D and marketing techniques [38].

5 Challenges of Geotextiles

Despite their numerous advantages, geotextiles also have certain drawbacks. One of the most difficult issues is keeping their integrity throughout time. Exposure to UV radiation, chemicals, and biological factors can cause geotextile to disintegrate early. This can endanger its efficacy and lead to the infrastructure project's collapse. A further issue is ensuring adequate geotextile installation and placement. Furthermore, geotextiles may be chosen depending on the project's unique needs, such as soil type, load capacity, and environmental conditions.

6 Studies to Overcome the Limitation of Coir and Jute Geotextiles

Definitely, biodegradability is the utmost required aspect in the textiles and geotextile products but they should at least perform their task for requisite time duration to economize the cost, labor, and energy involved in manufacturing and installation in associated projects. Thus, chemical modification of these natural geotextiles plays pivotal role in increasing their performance. It was observed that the transesterified jute geomeshes showed higher soil erosion control at all slope angles than untreated jute geomeshes, due to reduced flexural rigidity and improved percentage cover [27]. It was reported that the half-lives of the transesterified jute are around 3 to 5 times more than the untreated jute geotextile. Chitosan is the second most abundantly available cationic polysaccharide obtained as by-product of seafood industry and known for extraordinary antibacterial and microbial effects [16, 20].

Thus, chitosan and similar sort of sustainable chemical finishing on geotextiles using various cross linking agents such as citric acid improves their life span. Besides this, chitosan itself is renewable, biodegradable, and rich in nitrogen contents hence no adverse effect on soil fertility [18]. Longevity of jute geotextile can be also improved by a coating of bitumen or similar sort of products. It imparts rot resistance property to geotextiles.

Coir fiber has very high flexural rigidity due to lignin contents which hinders its applications in certain technical applications such as soil erosion control as coir geomeshes do not follow the contour of the soil. Thus, coir geotextile can be softened by applications of softening agents such as emulsified oils, waxes, soaps, hydrocarbons, and suitable surfactants. Besides these lignin contents may be reduced by alkali treatment which improves wettability and reduces flexural rigidity for better performance.

7 Future of Natural Geotextile

The population of the world is exploding with time and needs more productivity in cultivation, more construction of houses, dames, roads, etc., infrastructure which will increase the demand of soil, stone, cement, etc., inventories causing more soil erosion and related problems. Thus, geotextile's future especially of sustainable fibers is bright, as it continues to gain traction in infrastructure projects throughout the world. Technological advancements resulted in the creation of new geotextile materials with increased characteristics and durability. Furthermore, there is growing awareness of geotextile's environmental benefits that certainly boosting demand for more sustainable construction materials with less carbon emission. Sustainable jute, coir, etc., geotextile will continue to be a key asset to the civil engineering as well as agriculture industry since it provides a cost-effective and environmentally friendly solution to soil separation, reinforcing, and protection.

8 Conclusion

In this review work, characteristics and applications of natural geotextiles, particularly growing materials such as jute and coir geotextiles was discussed. These materials are environmentally safe, renewable, biodegradable, and widely available in Asian continents. Jute and coir are used in various applications like reinforcement, prevention of river bed, soil erosion, runoff control, vegetation, and several other applications. Because of the diverse range of natural geotextiles in terms of versatile designs, shapes, and compositions, they promote applications in various domains such as improving interactions with the soil, helping to delay crack development in asphalt, controlling erosion, and helping vegetative growth, reinforce pavement and railroad construction, etc. As the demand for sustainable materials is growing, the jute and coir geotextiles are likely to become more popular in the future as sustainable & biodegradable alternatives to synthetic geotextiles.

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