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Effect of directional loading on mechanical performance of HDPE warp knitted mesh fabric

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This study examines the mechanical properties of high-density polyethylene (HDPE) warp-knitted mesh fabrics under varying directional loads. Four distinct fabric structures have been produced using different lapping plans on a tricot warp knitting machine, with each structure tested under three directional loads (0°, 45°, and 90°). The findings show a significant improvement in breaking strength in the wales (0°) direction as compared to those in other fabric directions (45°, 90°) in all the fabric structures. Also, closed loop warp knit structure (S4) has greater bursting strength than the other samples due to its maximum stitch density.

Keywords: Fabric cover, High density polyethylene, Mechanical properties, Porosity, Tensile strength, Technical textile, Warp knitting

1 Introduction

The rapidly emerging market potential of industrial textiles has attracted manufacturers to utilize specialized warp knitted fabric in agriculture[1-3], construction[4], geotextile[5, 6], and automotive sectors[7, 8] to fulfill the demands efficiently. The advancement in warp knitting technology has expanded its possibility to produce innumerable structures ranging from nets, grids, monoaxial, biaxial, multiaxial, and 3D spacer[9-12]. The grid and net configuration have been used in high wall constructions, land reclamation, and embankments for gripping and holding the soil to increase the stabilization of the structure and to enhance the efficiency of the process[7, 8]. The warp knitted fabric has also found its application in textile-reinforced concrete, where a warp knit fabric reinforced composite is used to increase the stability of the structure. The knitted fabric is produced by intermeshing of loop of yarn rather than placing them horizontally and vertically, which is observed in woven fabric construction. The warp knitted fabric is characterized by the interlocking of loops in a vertical direction along the length of the fabric [Fig. 1 (b)]. The warp yarns are supplied to the guide bar, and the lapping movement determines the position and configuration of a series of overlaps and underlaps. The swinging and shogging movement of the guide bar controls the yarn movement, and forms overlap and underlap in the knitting structure. When the guide bar moves to the front of the needle, it forms overlap, but when moves back to the needle, it forms underlap [Fig. 1 (a)]. The amount of overlap and underlap determines the fabric properties, such as mechanical strength, thickness, and porosity. It can be manipulated to suit the need of a specific fabric in a particular application[13]. Yarn geometry and its interrelation with topological features greatly influence thermal, mechanical, and other properties. The influence of loop has shown immense influence on the load extension properties of the warp-knitted fabric. Stolyarov *et al.*[14] discussed the tensile properties of warp-knitted fabric by varying the stitch density and incorporating yarn roving for concrete reinforcement application. The tensile properties of tricot and cord stitches were higher than pillar stitches due to the cross-section of roving responsible for flattening and compacting the fabric. Besides, the indices of warp-knitted fabric influence the resistance to frictional forces. The number of underlapping due to the front guide bar creates opposition to sliding motion due to intermeshing, cavities, and projections because of the direction of motion.

The loop profile in the knitted fabric has more flexibility and elongation than straight yarn in woven structures. The yarn follows a zig-zag path in the

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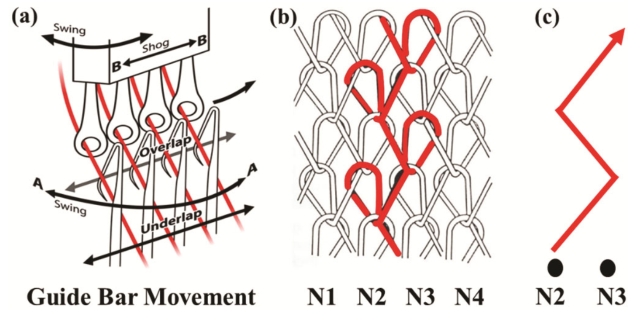


Fig. 1 — (a) Guide bar movement during overlap and underlap operation, (b) loop configuration in a warp knit structure, and (c) yarn path along the length of warp-knit fabric

loops of warp-knitted fabric and affects its mechanical strength as the yarn is not fully aligned in any direction [Fig. 1 (c)]. The warp-knitted mesh and grid structures, used to support and hold operations, do not give sufficient attention to applying these fabrics to utilize their optimum strength. The application of warp knit fabric in a particular direction can be advantageous to exploit its maximum strength.

Researchers have tried to study the effect of yarn alignment in different knitted structures on the mechanical properties of the fabric, such as tensile and bursting strength. Dahesh *et al.*[15] investigated the effect of different fabric structures on the bursting and tensile behaviour of knitted fabric. Five different structures with different amounts of overlap and underlap were prepared, including quasi sandfly, pin-hole net, tricot, sandfly, and quasi-marquissite. The tensile behaviour of structures was analysed in course-wise, wales wise, and in bias directions. The result showed that the tensile and bursting strength correlate well when tested in a bias direction. Luo *et al.*[16] analyzed the tensile and tearing properties of a biaxial warp knitted fabric under a biaxial load. The results depicted that the maximum load was observed in the warp direction due to most of the yarns being aligned in a warp direction. Deeken *et al.*[17] evaluated the strength retention of polypropylene, polyester, and polytetrafluoroethylene mesh by testing them in a longitudinal and transverse direction. They observed that all the structures displayed significant variation in the mechanical and physical properties when tested in different orientations, especially when the structure is anisotropic.

The literature has given very little justification to the orientational mechanical properties of the warp-knitted fabric. However, they have a significant impact on the ability of the fabric to sustain the load. Hence, this study investigates the effect of different structures and directions of testing on the mechanical properties of the warp-knitted fabric.

2 Materials and Methods

High-density polyethylene (HDPE) monofilament was used to fabricate each sample with various lapping plan. HDPE monofilament is exceptionally strong, which makes it ideal for use in applications that require strong and durable fabric. In addition, HDPE filament is highly resistant to UV radiation, and hence can be used in the application of outdoor fabric, such as shade netting or agriculture fabric. HDPE monofilament is procured directly from the Lakshmi Industry, Bangalore. All the specifications of filament are given below:

Property	:	Value
Tensile strength	:	40.95 cN/tex
Linear density	:	92 den
Modulus	:	35.38 gf/den
Strain at maximum load	:	18.05 %
Breaking load	:	4.32 N

2.1 Fabrication Method of Warp Knit Samples

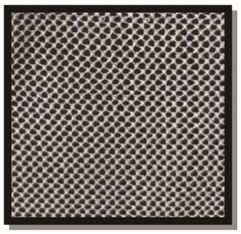
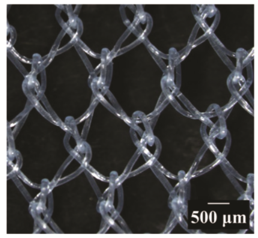
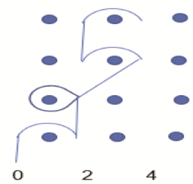
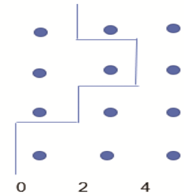
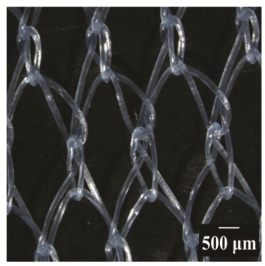
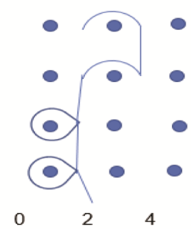
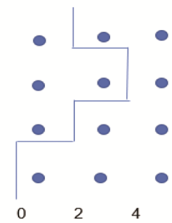
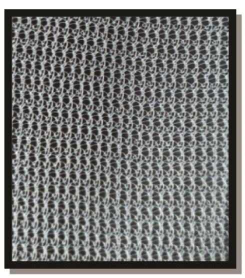
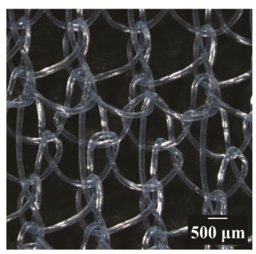
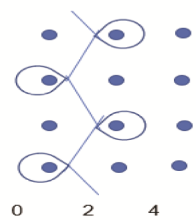
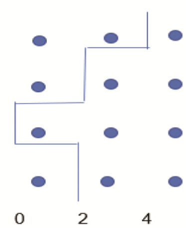
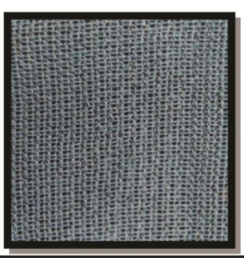
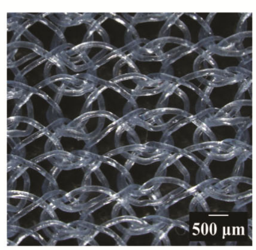
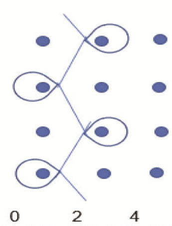
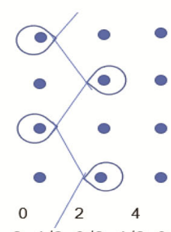
All the samples were produced using warp knitting technology. The tricot warp knitting machine with two guide bars (full threading) and 12 gauge was used to prepare the samples. Standard atmospheric conditions were maintained during the fabric sample preparation to avoid any effect on the physical properties of materials. Before testing, the fabric was allowed to relax in standard atmospheric temperature at 27±2 °C and 65% relative humidity for a minimum of 24 h.

2.2 Structural Features of Samples

The intermeshing of the loop of yarn in the length direction of the fabric is called a warp-knit fabric. Four samples were prepared on a tricot warp knitting machine using two guide bars. Each structure is prepared by the combination of underlap and overlap of yarn represented by the lapping diagram shown in Table 1. If the overlap and underlap motions are in the same direction, the result is an open loop, and vice versa, as depicted in S1 lapping plan. S1 is prepared by two guide bars on a tricot warp knitting machine using a latch needle in which the front guide bar of the machine forms an open and closed loop, whereas an open loop is formed by the back guide bar. When viewed through an optical microscope, structure S1 appears to be of a rhombus-like shape.

Similarly, S2 is also prepared with a combination of the open and close loop and back guide bar formed underlap. The front bar produced alternate two closed

Table 1—Fabric structure and lapping plan

Sample code	Fabric structure	Microscopic view	Lapping plan: Front guide bar	Lapping plan: Back guide bar
S1			 0-2/2-0/4-2/2-4//	 0-0/2-2/4-4/2-2//
S2			 2-0/2-0/2-4/4-2//	 0-0/2-2/4-4/2-2//
S3			 2-0/2-4/2-0/2-4//	 2-2/0-0/2-2/4-4//
S4			 2-0/2-4/2-0/2-4//	 2-4/2-0/2-4/2-0//

and two open loops in one repeat unit during the loop formation. An open rhombus-type fabric structure appears on the surface of the fabric in an optical microscope. Sample S3 was also prepared with two guide bars and a tight loop length. However, sample S4 was made using a closed loop in both guide bars. On the other hand, the appearance of the two samples (S3 and S4) is irregular.

2.3 Characterization techniques

2.3.1 Physical Characterization

The physical properties of the samples were characterized using various testing methods. The areal density and thickness of the fabric samples were calculated using ASTM D3776 and ASTM D1777-96 standard[18] respectively. Shrinkage percentage in wales during fabric preparation depends on the variation in the number of wales per unit length. If underlap of the fabric structure is more, then it shows more shrinkage in wales. The following expression calculates the shrinkage percentage in wales:

$$\text{Wales shrinkage (\%)} = \frac{\text{Number of wales/inch} - \text{Number of needles/inch}}{\text{Number of wales/ imch}} \quad \ldots(1)$$

Porosity is defined by the volume of air contained per unit of fabric, which depends on the thickness and areal density of the fabric samples[18-20]. Porosity of the sample was calculated using the following equation:

$$\text{Porosity}\ (\%) = \left(1 - \frac{m}{t \times \rho \times 1000}\right) \times 100 \quad \ldots (2)$$

where m is areal density of fabric; t,thickness of samples in mm; ρ, the density of HDPE monofilament (0.95 g/cm^3).

2.3.2 Fabric Cover

The fabric cover is defined by, how much area is covered by the yarn in the fabric. The fabric cover is an essential parameter for the light barrier properties of the warp-knitted product. The fabric cover is calculated by using digital image analysis software[21]. In this method, a clear and contrasting image of the samples is registered with the help of a camera. All normal images are transferred into the image software for converting into the binary image (Fig. 2).

The image of the samples is visible on the computer screen. In a binary image, the white part is the fabric cover, and the black part shows open space. Since the fabric cover is two-dimensional property of the fabric, it is therefore calculated by the binary image with the help of white and black pixels. The fabric cover is calculated in accordance with the following equation:

$$\text{Cover}(\%) = \frac{\text{Area of white pixels}}{\text{Total area(white + black) of pixels}} \times 100 \quad \ldots (3)$$

2.3.3 Mechanical Characterization

- ***Tensile Test***

The mechanical property of a fabric is determined by tensile testing. Furthermore, there are different types of forces applied in the axial direction of the fabric. There are three types of testing standard methods for evaluating tensile strength, viz grab test, modified grab, and strip test[22]. The tensile strength of fabric depends on its structure, design, type of yarn and type of fabric. In this research, strip test methodology is used for evaluating the tensile strength of the fabric. The tensile strength of the sample is evaluated according to the ASTM D5035-06 standard [23]. The sample is clamped in between the jaw of the instrument (250mm × 50mm). This testing standard includes ravelled strip and cut strip methods for evaluating the breaking force and elongation of all textile materials. All the tests are performed at a standard room temperature of 27°C (±2°C) and relative humidity of 65% (±2%). Tensile testing of samples is performed in three directions, viz course (90°), wales (0°), and diagonal (45°) direction.

- ***Bursting Test***

The bursting test confirms the mechanical strength of the warp-knitted fabric, which is important for

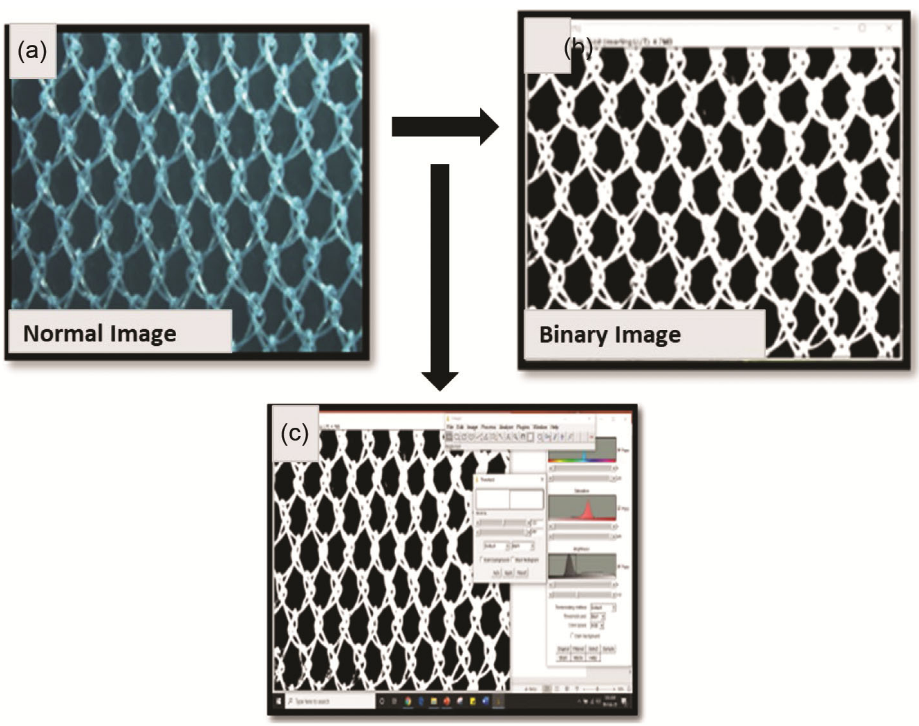


Fig. 2 — (a) Normal, (b) binary, and (c) software image of samples for determination of fabric cover

evaluating multi-directional forces on the sample. The bursting test is used for fabric that has no yarn aligned in any fabric's fixed direction, such as knitted fabric and nonwoven fabric. This testing was done according to the ASTM D3786-06 using a 125 mm ×125 mm sample size [24]. The sample is placed under a diaphragm of synthetic rubber with a diameter of 48 mm with a thickness of 1.8±0.05 mm. The fluid is displaced at the rate of 95±5 mL/min.

3 Results and Discussion

This study aims to examine the tensile and bursting strength of various warp-knit structures. The tensile strength of the sample is tested in three directions (0^0, 45^0, and 90^0). The mechanical properties of the warp-knitted fabric are affected by physical properties, such as porosity, cover, areal density, thickness, and stitch density of fabric. The physical properties of all samples are shown in Table 2. The mechanical and physical properties of samples are essential considerations when choosing a fabric for a certain application. Klosterhalfen *et al.*[25] reported that high porosity and light weight fabric are suitable for hernia repair applications. Variation in the orientation of the loop of warp-knit fabric affects the tensile and bursting properties during the application of load in the course and wales directions of the fabric.

3.1 Fabric Cover

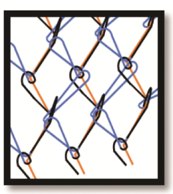
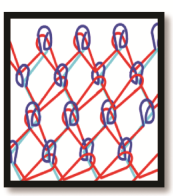
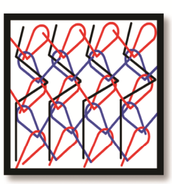
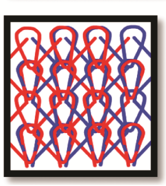
The digital image software evaluates the fabric cover (%) with the help of a high-resolution camera**.** Figure 3 depicts the variation in fabric cover (%) of different samples. In comparison to the other sample, S4 shows a higher fabric cover (%). It is explicable by the maximum stitch density (510 loops/inch^2), showed by sample S4, which indicates that sample S4 has the most coverage area.

3.2 Tensile Properties

3.2.1 Breaking Strength

The breaking strength in a course and diagonal directions is significantly less as compared to that in wales direction because the larger proportion of the yarn is aligned in the wales direction, contributing to load sharing. The amount of force required to break each sample is shown in Fig. 4. It is observed that the

Table 2— Physical and structural characteristics of prepared samples

Samples	Loop design	Thickness mm	Wales per inch	Courses per inch	Areal density gm/m^2	Porosity %	Wales shrinkage %
S1		0.514	18±2	24±2	56±10	88.53	28.57
S2		0.556	18±2	20±2	42±10	92.04	28.57
S3		0.480	17±2	18±2	51±10	88.81	21.42
S4		0.538	17±2	30±2	91±10	82.19	21.42

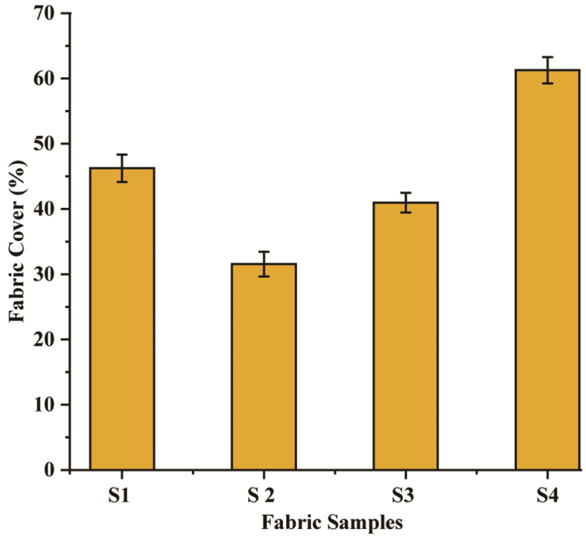


Fig. 3 — Cover of warp knitted structures

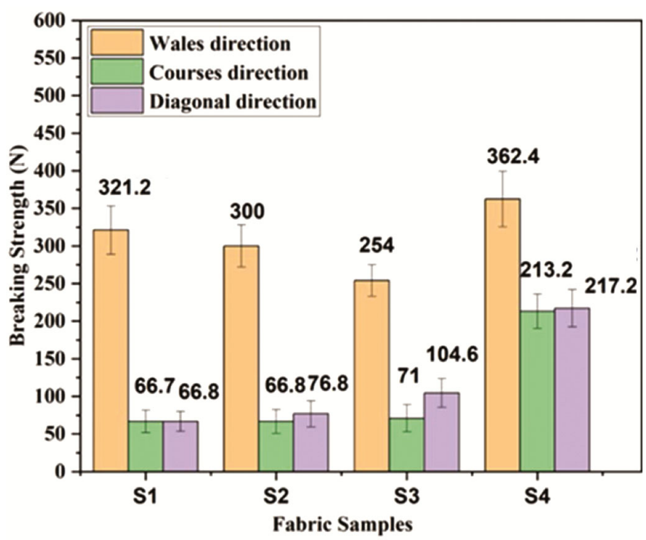


Fig. 4 — Breaking strength of warp knitted structures

breaking strength of sample S4 is 362.4 N in the wales direction of the fabric. Sample S4 showed higher breaking strength as compared to S1, S2, and S3 in the wales direction. It is due to the presence of closed loops in the front and back guide bars of sample S4. A closed loop is more resistant to breaking than an open loop due to more number of points of contact between the yarns when the loop is formed. The lowest breaking strength (254 N) is observed for sample S3, which is prepared by the open and closed loop. Despite the fact that the samples S1, S2, and S3 are prepared using a combination of open and closed loops, as stated in Table 1, the stitch density difference contributed to the variation in breaking strength. The higher number of courses per unit area results in a greater number of loops of yarn participating in bearing the load during the testing of samples. Sample S4 has a breaking strength of 217.2 N in the diagonal direction, which is lower than that in the wales direction but higher than that in the course direction. Owing to the closed-loop present in the wales direction through both guide bars and higher course density, the breaking strength is more in the diagonal direction.

3.2.2 Modulus of Elasticity

The modulus of elasticity is a measurement of a material's resistance to elastic deformation when a load is applied. It is determined by the slope of the stress-strain curve in the elastic deformation region[26]. The deformation of warp-knitted fabric involves two principal mechanisms. When the fabric is subjected to axial load, first the loops deviate from the central axis and deform in a loading direction. At this stage, higher extension is produced with less load; hence the curve flattens towards the strain axis. The fabric deformation is triggered when the wales become jammed as a result of the loop deformation. The load is dispersed over the entire fabric structure in this mechanism, and the curve slope extends towards the stress axis, increasing the fabric's modulus[27]. Figure 5 (a) depicts the deformation zone (1^{st} region- loop deformation region, 2^{nd} region- fabric deformation) in warp knitted fabric during tensile loading.

In the wales direction, the elastic modulus for the samples is recorded as 20.96 MPa for S1, 11.93 MPa for S2, 24.72 MPa for S3, and 6.73 MPa for S4, as shown in Fig. 5(b).The higher elastic modulus of S3 is attributed to the lower angle of the lap (α) 48° (Table 3), which affects the force required for loop deformation. Lower angle (α) implies that the time required for loop deformation is less; hence the load will be distributed across the fabric structure, and fabric deformation will start sooner, resulting in higher resistance to deformation.

Also, the yarn movement in S3 for the back guide bar is nearly a straight line as compared to that in S1, S2, and S4, as shown in Fig. 6 (c). In comparison to the loop yarn in the front guide bar, the yarn in the back guide bar contributes more load because it is in a straight form. As a result, the fabric undergoes a lower extension, thus realizing a higher modulus. The modulus in course and diagonal directions is much lower than in wales direction, because a larger proportion of yarn is aligned in the wales direction, leading to higher load sharing. The variation in

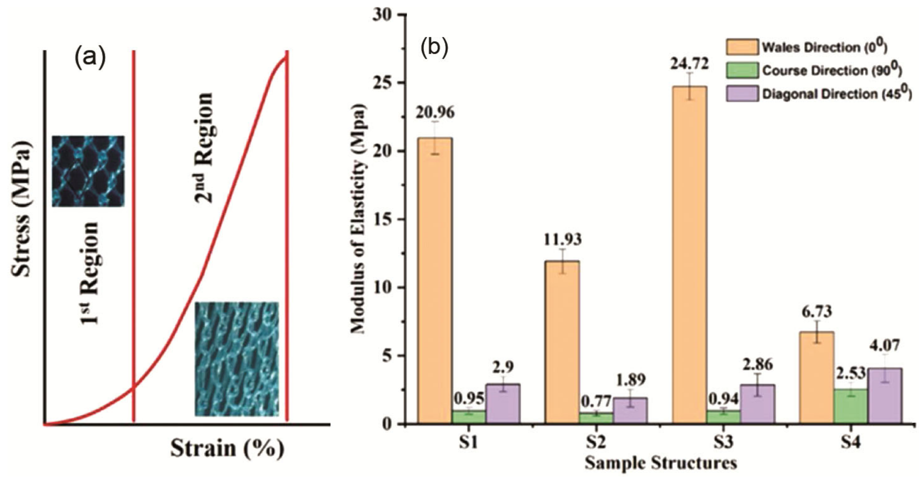


Fig. 5 — (a) Stress-strain curve for the fabric sample during tensile loading (1st region— loop deformation, 2nd region — fabric deformation) and (b) modulus of elasticity of warp knitted structures

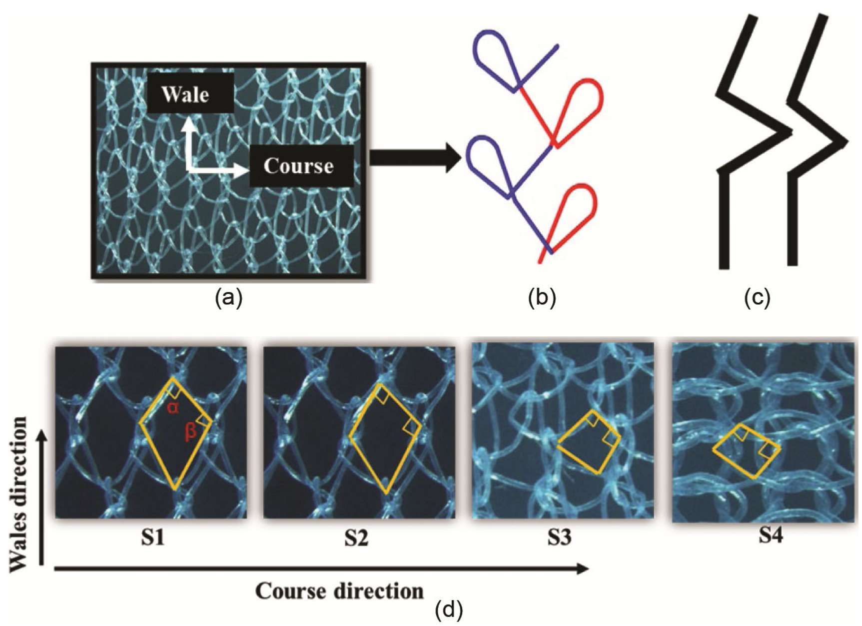


Fig. 6 — (a) Optical image of sample S3, (b) front guide bar yarn movement, (c) back guide bar yarn movement, and (d) angle of the lap in fabric samples

modulus in the course direction in samples S1-S4 also depends on the loop angle β, as shown in Table 3 and Fig. 6.

3.2.3 Bursting Strength

The bursting strength of a knitted fabric is an important property for a particular application. The fabric should be able to withstand the multi-directional force that is exerted on it during the application. The bursting strength of knitted fabric depends on the yarn type, structural configuration, stitch density, and extension property of warp knitted fabric. In this study, the bursting strength of the warp-knitted fabric is investigated, which is shown in Fig. 7. The bursting strength of sample S4 is 6.79 kg/cm^2, which is found higher as compared to the samples S1, S2, and S3. The number of loops per unit area is more in the case of sample S4, which shows the maximum stitch density of 510 loops/square inch, thus a greater number of loops participated in bearing the load during bursting strength testing. In addition, as demonstrated in Fig. 4, the breaking strength of S4 is higher in all directions as compared to S1, S2, and S3. The bursting strength of samples S1, S2, and S3 do not differ significantly. Sample S4 shows 16%, 17.6%, and 16.5% more bursting strength than samples S1, S2, and S3 respectively.

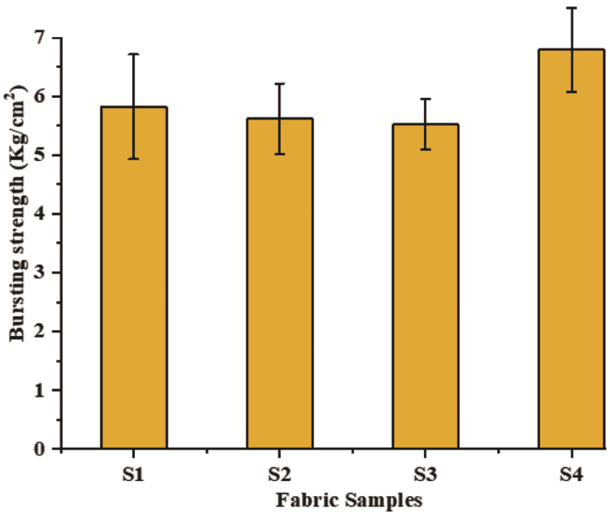


Fig. 7 — Bursting strength of warp knitted structures

4 Conclusion

In the present investigation, the physical and mechanical properties of different warp-knitted fabrics made from HDPE monofilament have been studied and analyzed. Different lapping plans have been proposed, and samples are prepared accordingly. Mechanical properties are characterized in various directions, such as wales (0°), courses (90°), and diagonal (45°). The result of the directional effect can be exploited while choosing the type of fabric for the required application and the nature of loading. The Maximum breaking strength of fabric sample is shown by the sample S4. Due to its high breaking strength, it is suitable for the construction of nets and geotextile applications. Sample S2 shows maximum porosity, which can be used for the hernia repair application. Sample S3 shows maximum elastic modulus in the wales direction as compared to samples S1, S2, and S4, owing to the nearly straight yarn formed by the back guide bar and lower angle of the lap. In addition, Sample S4 exhibits 16%, 17.6% and 16.5% higher bursting strength than samples S1, S2, and S3.

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