Indian Journal of Fibre & Textile Research
Vol.49, September 2024, pp. 344-351
DOI: 10.56042/ijftr.v49i3.12513

Influence of weave structure on mechanical properties of cotton fabrics reinforced with unsaturated polyester

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Received 31 October 2022; revised received and accepted 22 September 2023

The effect of weave structure on the mechanical properties of cotton fabric reinforced with unsaturated polyester (UP) resin has been studied. Cotton yarns are woven into four weave structures (plain 1/1, rib 4/4, twill 3/1 and satin 5/2 weaves) on a tappet loom. Fabrication of the composite is done using the hand lay-up technique. Results show that the twill fabric has an optimal strength of 15.21 MPa, while satin fabric shows the least tensile strength of 11.31MPa. The tensile and flexural strengths of the composites are improved by 47–140% and 44–49% when compared with neat polyester resin respectively. Composite with twill fabric shows the best tensile and flexural strengths of 48 MPa and 73.2 MPa, a tensile modulus of 0.37 GPa and elongation-at-break of 52.8%, which is closely followed by plain, rib and satin weave composites. Charpy impact test shows that the twill fabric composite absorbs more energy followed by the plain, rib and satin fabric composites. Moreover, the characterization of the composites evaluated by SEM and FTIR shows better bonding of treated fabric with the hydrophobic polyester and the presence of functional groups respectively.

Keywords: Cotton, Composites, Fabrics, Hand lay-up, Mechanical properties, Plied yarn, Polyester resin, Weave structure

1 Introduction

Natural fibre composites have continued to dominate the global market, especially in the lightweight, automotive and aerospace industries, owing to the renewability of the base materials, low density and biodegradability of the resultant composites[1]. However, the orientation of the natural fibres has a weighty effect on the final performance of the resulting composite. Natural fibres, such as cotton, linen, silk and flax have found applications using various fabric constructions, such as weaving, knitting and nonwoven. Fabrics are very much easier to handle and maintain better dimensional stability during composite formation, as compared to yarns and fibres[2-5]. Woven fabric is the most versatile fabric produced by the interlacement of two sets of yarn (warp yarn and weft yarn). Due to the variation in interlocking, it is possible to produce different designs, like plain, twill, satin etc.[6,7]. These variations of weave patterns have a significant effect on the mechanical properties of the fabrics[8,9]. For textile fabric, strength is described as the material's resistance to the external force causing a change in shape[10]. The response of textile materials depends on their mechanical properties; the way load and tension are applied. In designing, mechanical properties are important to account for materials' resistance to permanent deformation under applied stresses and subsequent uses[11-13]. Owing to their excellent mechanical properties like strength, rigidity, and dimensional stability, fabric weaves are useful in fibre-reinforced polymers. It is possible, with weaving know-how to construct high-density woven structures having load-oriented fibre setting[14,15]. The strength and rigidity of fabric-reinforced composites are dependent not only on the matrix and yarn properties but also on the structural factors of materials like weave pattern and fabric count[16,17]. The weave pattern indicates how the warp and the weft yarns are interlocked, while the fabric count defines the number of weft and warp yarns per cm[7,18].

In a study on the effect of weave design on warp and weft on the tensile strength of the fabric, Booth [10] compared the tensile strength of plain and twill fabrics and obtained that both warp-wise and weft-wise strengths of plain weave are higher than that of the twill weave. Doustar *et al.*[19] investigated the effect of fabric design and weft density on the bagging behaviour of cotton woven fabrics. They observed

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that shear rigidity and formability are significantly increased with the weft density. Li *et al.*[20] reported that excellent drapeability, reduced manufacturing costs and increased mechanical properties are the driving forces for the increased use of woven fabrics as compared to their non-woven counterparts, especially the interlaminar or interfacial strength. Jahan[6] who studied the effect of fabric structures (1/1 plain, 2/1 twill, 2/2 twill) on the mechanical properties of woven cotton fabrics, reported high tensile strength, abrasion resistance, stiffness and resistance to pilling in the plain weave as compared to those in twill weave as the number of interlacements of warp and weft yarns increases but with a decreasing the number of floating in the weave. However, the twill weave shows a high tearing strength because it is increased with the increasing number of floating with fewer interlacements. The effects of woven and nonwoven kenaf fibre on the mechanical properties of polyester composites using different types of performing structures have been reported by Ratim *et al.*[21]. Their study reveals that the strength and stiffness of the polyester-reinforced kenaf fibre composites, prepared by hand lay-up process with different fibre structures (plain, twill and mats) are largely affected by fibre structures. Patil & Turukmane [22] asserted that the more the interlocking, the higher is the fabric strength in line with the universal law of fabric. Hence, the plain weaves show higher strength than duck and basket weaves; and vice versa for elongation, tearing, and abrasion resistance. Achukwu *et al.*[23] in their study observed better tensile properties for composite reinforced with twill fabric as compared to plain and knitted fabric composites and better flexural properties for knitted fabric composite. Other studies on the use of natural fibres in fabric composites include woven banana[24], jute fabric[25], hemp fabrics[26], sisal fabric[27] and flax fabric[28].

This paper reports a study on the influence of weave structures on the mechanical properties of cotton fabrics/unsaturated polyester composites. Cotton fabrics of different weave constructions treated with sodium hydroxide and acetic anhydride are impregnated with unsaturated polyester resin using the hand lay-up technique. The mechanical properties of the resultant composites are determined. Also, the composites were characterized using SEM and FTIR. To the best of our knowledge, no work has been reported on the impregnation of modified and unmodified cotton fabrics of different weave structures using unsaturated polyester resin.

2 Materials and Methods

2.1 Materials

100% cotton yarns [2.5 Neβ (4ply) count, 9.97 % elongation, 5.73 harness index, 10.45 U% evenness, and 39.7N strength] were procured from Spintex Lagos, Nigeria. The sodium hydroxide and acetic anhydride were supplied by the Finn Laboratory, Owerri, Nigeria. The unsaturated polyester resin, cobalt and MEKP catalyst were supplied by NYCIL Nig. Ltd, Lagos, Nigeria. Four cotton weaves (plain 1/1, twill 3/1, 5 harness satin 5/2 and rib 4/4) were woven on a tappet loom (AD-A-Harnesss loom, model B4 D) at Zaria Industries Limited, Zaria, Kaduna State. The weave structures are shown in Fig. 1. The physical properties of fabrics used in this study are presented in Table 1.

2.1.1 Fabric Treatment

Desized cotton fabric structures of known dimensions (20 cm × 2.5 cm) were first soaked in 4% NaOH for 24 h at 25°C according to ASTMD1965. The fabrics were washed with distilled water and dried. The alkaline-treated fabrics were further

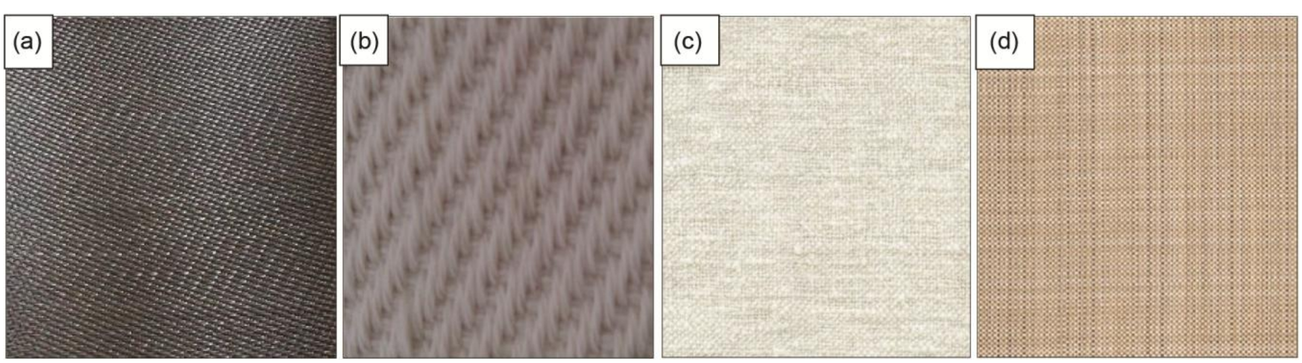

Fig. 1 — Pictorial representation of different weave structures (a) satin weave 5/2, (b) twill weave 3/1, (c) plain weave 1/1 and (d) rib weave 4/4

Table 1— Fabric properties

Fabric	Thickness, mm	Ends/in	Picks/in	Cover factor		
				Warp	Weft	Fabric
Plain	2.04	18.00	18.00	11.4	11.40	18.16
Twill	2.31	31.00	21.00	19.61	13.28	23.59
Rib	2.10	22.00	20.00	13.92	12.66	20.29
Satin	2.62	32.00	12.80	20.30	8.10	22.53

immersed in acetic acid for 1h at 25°C room temperature and thereafter soaked in acetic anhydride containing one drop of concentrated H_2SO_4 for 5 min [29].

2.1.2 Composite Preparation

The hand lay-up technique was used in the preparation of the unsaturated polyester/cotton fabric composites. The unsaturated polyester resin, Methyl ethyl ketone peroxide (MEKP) (catalyst), and naphthalene cobalt(accelerator) were used in the ratio of 100:1:1. Composites were obtained by impregnating the woven fabrics with the resin mixture at room temperature (27 ± 2°C) in a mould of dimensions 150 mm × 150 mm × 6 mm already smeared with a mould release agent. Finally, the composites were allowed to cure at the same room temperature and then stored in plastic bags for further use.

2.2 Mechanical Testing

The tensile strength of composites (ASTM D3039 08), composite modulus (ASTM 1822), flexural strength (ASTM D790 08), impact strength (ASTM D256 A) and tensile strength of different weave structures (ASTM D5035 11) properties were determined according to the mentioned standards. An average of five samples were tested for each property. The image morphology test of the composites was carried out using a scanning electron microscope (SEM) [Model MV 2300] and Fourier Transform Infrared (FTIR) spectrophotometer (BULK Scientific Model 550) to understand the bond interactions and functional groups present in the composites.

3 Results and Discussion

3.1 Mechanical Properties

The mechanical properties of the cotton weave structure, and polyester/cotton weave composites have been evaluated and the results are presented in Figs 2 and 3.

3.1.1 Tensile Strength of Cotton Fabrics

Figure 2 shows the tensile strength of individual weave structures or patterns. Twill weave shows the best tensile property (8.79 MPa), closely followed by

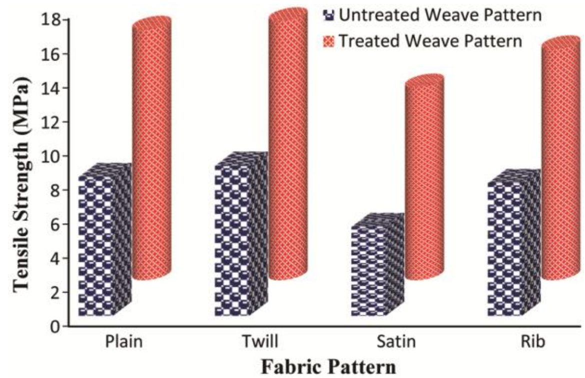

Fig. 2 — Tensile strength of different weave structures

plain weave (8.13 MPa), rib weave (7.77 MPa) and satin fabric (5.20 MPa). The high value of tensile strength associated with twill is due to the fact that in twill weave, yarns are disseminated over each other, thereby providing more strength. As plain weave has maximum crimp, there is very little amount of fibre slippage in the yarn, and this results in lower strength. On the other hand, satin weave possesses minor strength as compared to others due to the large float of its weave structure.Similar results have been reported by Ferdous *et al.*[30]. They observed that twill weaves possess the best tensile strength as compared to plain, diamond and satin weaves. Zupin & Dimitrovski [31] analysed the physical and mechanical properties of fabrics woven in twill and sateen weave and found that given identical constructive parameters and weaving conditions, twill weave gave a 100 N higher breaking force in the warp direction than a satin weave.

3.1.2 Tensile Strength of Unsaturated Polyester Composites

The tensile test is a method adopted to assess the reinforcing effect of cotton weave structures or patterns in polyester composites. Normally, the tensile strength and modulus of the composites are dependent on the tensile properties of the fibre and the quality of interfacial strength between the fibre and the matrix. In this case, the effect of weave structure on the tensile strength, tensile modulus and elongation-at-break of cotton weave/polyester composites has been studied and findings are presented in Figs 3 (a) – (c) respectively. The fabric improves the tensile strength of the composite as compared to the neat polyester (17 MPa) by 47–140% for different weave patterns (Fig. 3). The tensile strength of the composites is found to be the highest for twill fabric composite (48 MPa), followed by plain (40 MPa), rib (28 MPa) and satin (25 MPa) fabric composites. The highest value of tensile strength as exhibited by the twill

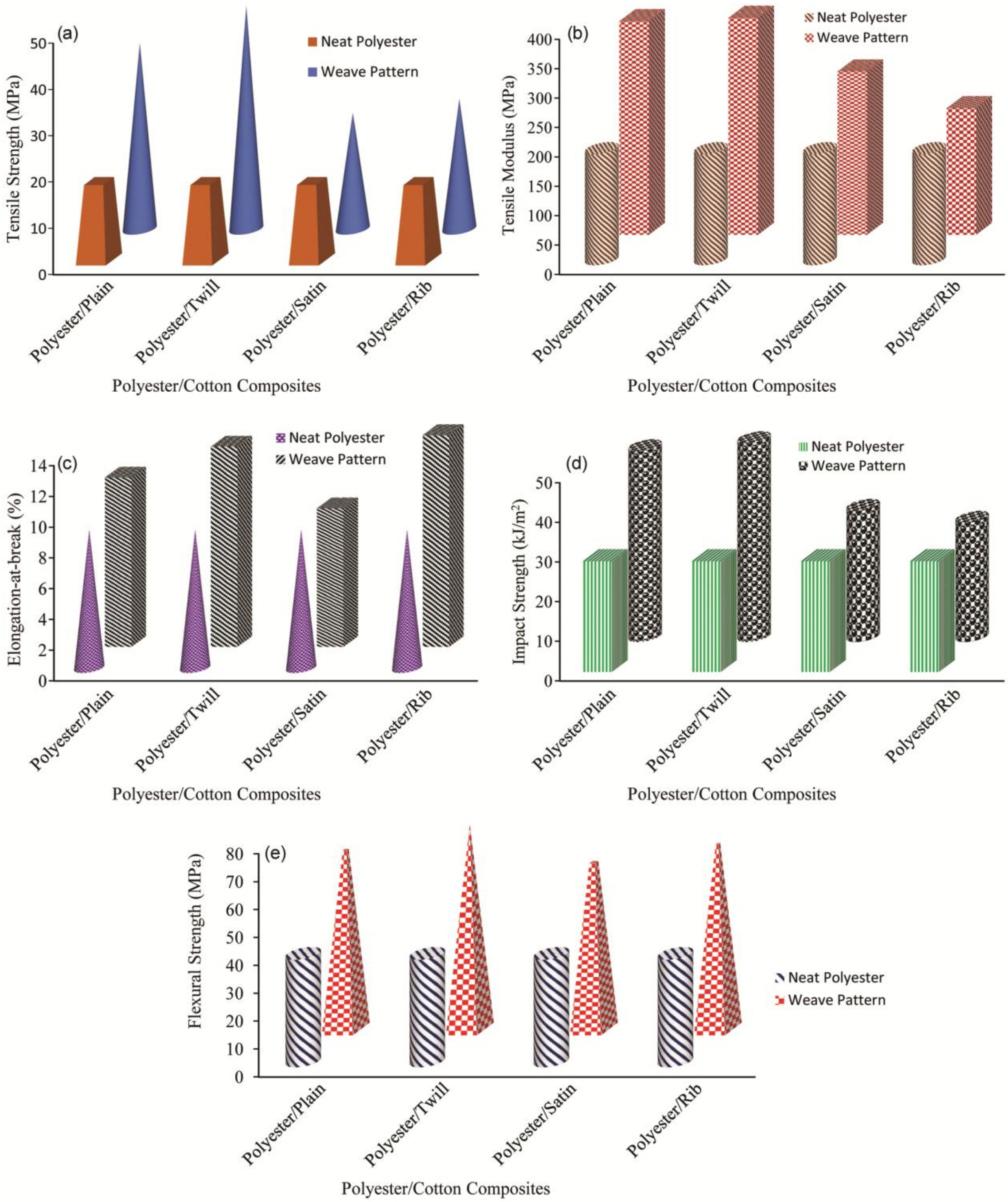

Fig. 3 — Effect of cotton weave structure on (a) tensile strength, (b) tensile modulus, (c) elongation-at-break, (d) impact strength, and (e) flexural strength of polyester composites

fabric is due to the presence of more yarns in the same volume fraction, which participates in load bearing. Similar trends have been reported by Ratim *et al.*[21], who studied the effect of woven and nonwoven fibre structures on the mechanical properties of polyester-reinforced kenaf composites. They reported that twill fabric reinforced composite possesses the best mechanical properties over other fabric structures. Achukwu *et al.*[23] investigated the effect of fabric pattern on the mechanical properties of cotton fabric/reinforced unsaturated polyester and observed enhanced tensile strength with the addition of cotton fabric with twill fabric composites exhibiting the highest strength value. The effect of fabric weave on the tensile strength of unsaturated polyester composite reinforced with woven kenaf fabric has been studied by Saiman *et al.*[32], who reported that the breaking strength of the fabric increases when different weave patterns with low crimp percentage is used as compared to Plain 1/1. Sapuan *et al.*[24] studied the mechanical characteristics of woven banana/epoxy composites and reported that woven banana composites exhibit an improved tensile strength. *Alavudeen et al.*[33]investigated the effect of woven fabric patterns and random orientation on the mechanical properties of banana/kenaf fibre hybrid polyester composites. They reported that regardless of fibre strength, the woven pattern reasonably affects the strength of the composites. A higher tensile strength value is obtained in twill weave fabric structure than in mat and plain weave fabrics, as reported by Ratim *et al.* [21]. They attributed the low tensile strength in mat composites to a contribution from non-crimped and inhomogeneous distribution of fibres. However, Pothan *et al.*[4] who studied the tensile and flexural behaviour of sisal fabric/polyester textile composites prepared by resin transfer moulding technique reported a decrease in the tensile strength values of plain and twill weave composites with respect to virgin polyester in all cases. They attributed the low values to the fibre volume fraction being lower than the critical value for effective stress transfer.

3.1.3 Tensile Modulus of Unsaturated Polyester Composites

The tensile modulus of different cotton weave reinforced polyester composites is shown in Fig. 3(b). It is observed that the tensile modulus of cotton weave composites is enhanced by 14 – 95.5% for different weave composites, which is higher than that of neat polyester (188.9 MPa). The tensile strength of composites is found to be the highest for twill fabric composites, followed by plain, satin and rib fabric composites. A similar trend is reported by Pothan *et al.*[27]. Both tensile and impact properties are found to be maximum for composites made with twill woven fabric where fibre bundles are used in the weft direction. The use of cotton and kapok fabrics as reinforcing materials in polypropylene matrix has been studied by Mwaikambo *et al.*[35]. Their study revealed that adding fabrics to the matrix enhanced the rigidity of the composite material. The woven composites show better mechanical properties for the same weight percentage than randomly oriented fibre composites, as also revealed by Rajesh & Pitchaimani[36]. They studied the mechanical properties of natural fibre braided yarn woven composites. Also in agreement with our study is the finding of Wang *et al.*[37] who worked on alkaline-treated fabrics reinforced epoxy and shows that the alkaline treatment enhances the tensile modulus of epoxy composites.

3.1.4 Elongation-at-break of Unsaturated Polyester Composites

Figure 3(c) shows the effect of cotton weaves on the elongation-at-break of polyester/cotton weave composites. It can be observed that the addition of cotton fabrics to the polyester increases the elongation-at-break of the composites by 0–52.8% with respect to neat polyester. The reason for higher elongation in fabric composites is that crimped yarns in the fabric tend to de-crimp and elongate more during tensile tests. Similar effects have been reported by Kaynak & Babaarslan[38], Özdemir *et al.*[39] and Realff[40]. The improvement in elongation-at-break is in agreement with the work of Achukwu *et al.*[23], who studied the effect of alkaline treatments on the breaking elongation of polyester/cotton composites and reported enhancement in the breaking elongation of the composites.

3.1.5 Impact Strength of Unsaturated Polyester Composites

Impact tests are carried out to determine the ability of composites made with different weave structures to absorb energy. The energy absorbed is a degree of a given material’s toughness and serves as a tool to probe brittle-ductile transition[41,42]. Figure 3(d) shows the impact behaviour of the various structures of cotton fabric-filled polyester composites. It can be seen that the fabric structures improve the impact strength of the composite by 18–79 % with respect to neat polyester (28kJ/m^2). Twill weave composite shows the highest impact energy absorption (50kJ/m^2)

due to the better drapeability of the twill weave structure than the plain pattern (48kJ/m^2). Achukwu *et al.*[23]reported a significant (105%) increase in the impact strength of the composite with respect to pure polyester knitted fabric composite, giving the greatest impact strength of 33.8 kJ/m^2. Ratim *et al.*[21] also reported a better impact strength of twill weave structure than plain weave pattern in their study on the effect of woven and nonwoven fibre structures on mechanical properties of kenaf fibre reinforced polyester composite. The results of the study on the influence of weave pattern and composite thickness on mechanical properties of bamboo/epoxy composites by Kanaginahal *et al*.[43] showed a 16% increase in energy absorbed for twill weave of thickness 5.4 mm over plain weave composites of similar thickness. Mariatti *et al.*[44] who also studied the mechanical properties of unsaturated polyester reinforced with banana and pandanus woven fabrics, reported that the flexural and impact properties of the reinforced composites were higher than that of neat polyester.

3.1.6 Flexural Strength of Unsaturated Polyester Composites

Flexural properties of composites are evaluated by studying the combining effects of the tensile, shear and compressive strength of the materials. The flexural strength of the polyester composites with different weave structures has been measured and the findings are shown in Fig. 3(e). It is observed that cotton weave structures have a great effect on the flexural strength of composites. A 44–49% increase in flexural strength for the different weave patterns with respect to virgin polyester is observed [Fig. 3(e)]. The flexural strength of the composites is found to be highest for twill fabric (73.20 MPa) followed by rib (66.42 MPa), plain (64.25 MPa), and satin (59.80 MPa) fabric composites for the polyester matrix (38.56 MPa). The observed behaviour is attributed to the nature of the different patterns and the good bonding of the fabric with the polyester matrix occasioned by the effective removal of lignin and other impurities without degrading the fibre strength during fabric treatment. Similar behaviour is reported by Achukwu *et al.*[23]. They reported a 20–47% increase in the flexural strength of different fabric structure composites when treated with NaOH. Bledzki *et al.*[45] also reported that the flexural strength of composites is found to increase with increasing degree of acetylation up to 18% and then decrease. Carmisciano *et al.*[46] explored the flexural properties of basalt woven and glass fibre-reinforced vinyl ester composites. The study reveals that basalt woven fibre composites give better properties than glass fibre composites. It is worth noting that the trend of the flexural strength in the case of the weave structures is similar to that of the tensile properties.

3.2 Morphology of Composites Surfaces

The image morphologies of the cotton weave polyester composites are determined using a scanning electron microscope (SEM) and the results are shown in Figs 4(a) – 4(d). From the images, less fibre pullout, fewer fibre breakages, more crystalline areas and fewer void spaces are observed in all the fabric composites. The SEM images show that the polyester resin exhibited a high coverage over the different weave structures, which makes the fibres less conspicuous. Besides, the images are obtained from the unfractured samples of the composites.

3.3 FTIR Analysis

FTIR analysis helps us to understand the bond interactions and the functional groups present in a material. The FTIR findings of unmodified and modified cotton weave/polyester composites are presented in Figs 5(a) and (b) respectively. Figure 5(b) shows the effect of surface modification on the cotton weave polyester composite, the broadband in 3200 – 3500 $\mathrm{cm^{-1}}$ signifies the stretching vibration of the OH group, showing possible hydrogen bonding between polyester and cotton weave. The bands in the range of 2900 – 3100 $\mathrm{cm^{-1}}$ correspond to the stretching vibrations of C-H groups, such as $\mathrm{CH_2}$ and $\mathrm{CH_3}$. It is noticed that the stretching vibration of the CH group has approximately the same absorption bands after curing the polyester with cotton weaves. A very intense band in 1754 $\mathrm{cm^{-1}}$ is observed due to $\mathrm{C=O}$ group vibration in the spectrum of cotton weaves/polyester composite. Weak bands at 1403 $\mathrm{cm^{-1}}$, 1341$\mathrm{cm^{-1}}$can be assigned to an aromatic ring. The band 1960-2893$\mathrm{cm^{-1}}$ shows the breakdown of hemicellulose and lignin due to the treatment of acetic anhydride. A similar report is published by José *et al.*[47]. The band vibrations at 1964 $\mathrm{cm^{-1}}$, 1341$\mathrm{cm^{-1}}$ and 1044$\mathrm{cm^{-1}}$ signify the presence of carbonyl $\mathrm{C=O}$ stretching of ester, $[\mathrm{C-H\ in\ -O(C=O)-CH_3}]$ and ($\mathrm{C-O}$ stretching of an acetyl group) respectively. This is due to acetic anhydride treatment on the cotton weave[48].

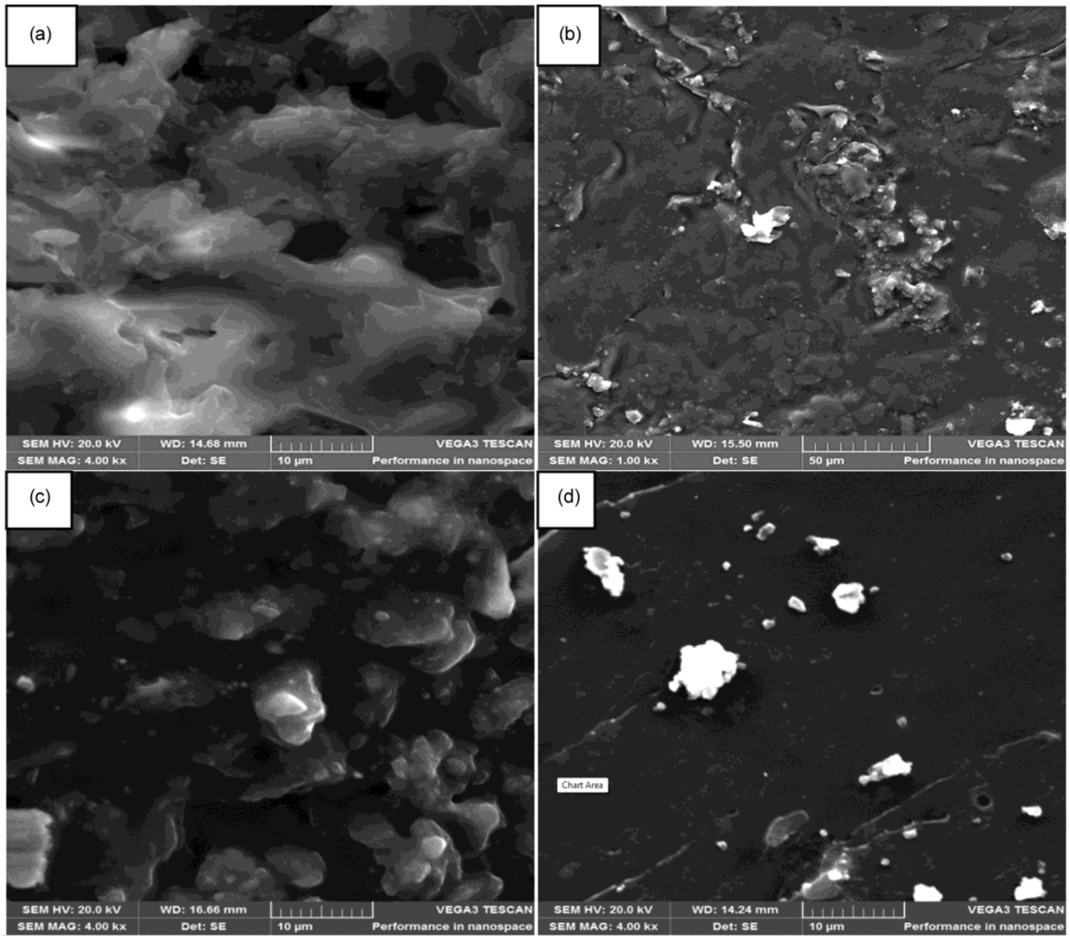

Fig. 4— SEM micrograph of (a) plain, (b) twill, (c) satin and (d) rib cotton weave/polyester composites

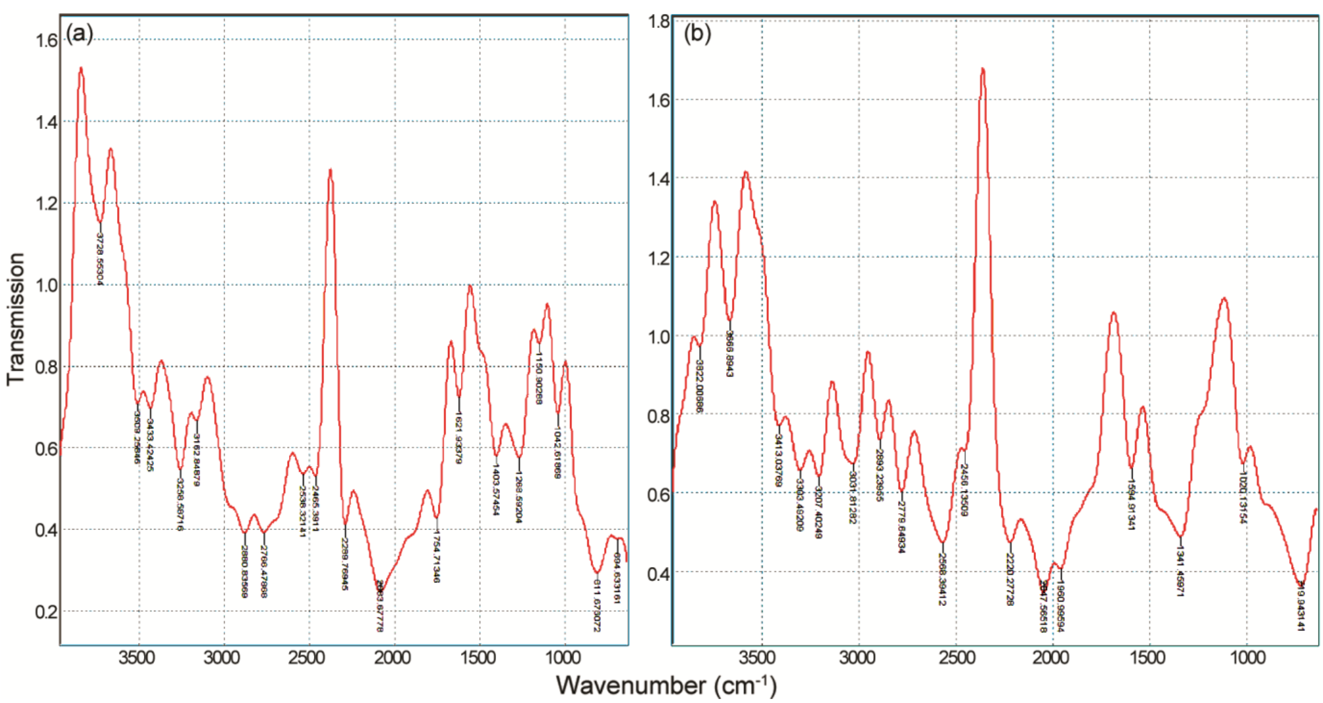

Fig. 5 — FTIR analysis of (a) cotton weave/polyester composite, and (b) effect of acetic anhydride treatment on cotton weave/polyester composite

4 Conclusion

This work successfully reports the effect of the weave structure on the mechanical properties of the cotton weave-reinforced polyester composite. The results show that weave structures have a significant impact on the mechanical behaviour of the resulting composite. Twill fabric tends to possess better mechanical properties when incorporated into polyester. SEM morphology shows a better inter-relationship between the matrix and the fibre due to chemical treatment, which improves the hydrophobicity of the natural fibre, less fibre pullout and less fibre breakage. The FTIR analysis shows the effect of modification on the cotton weave and its corresponding effect on the composite.

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