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Mechanical properties of polypropylene/glass weft knitted composites hot pressed in various structures and contents

Abstract: In this study, composites of knitted fabric made from side-by-side multiple glass and polypropylene yarns have been investigated. These composites have been produced by a new manufacturing method – the hot press method. By using various knitted fabrics made from different components of glass and polypropylene yarns, several types of knitted structures and yarn components were investigated: rib 1-1, full Milano and full cardigan. The mechanical properties of composites were measured in three directions. The results showed that hot-pressed knitted composites of glass and polypropylene yarns have high strength, impact resistance, work-to-break and elongation, simultaneously. The highest bending resistance and maximum stiffness are achieved for rib-knitted composites consisting of 8 wt% glass and 92 wt% polypropylene yarns. The highest impact energy absorption was obtained with 18 wt% glass content and 82 wt% polypropylene matrix.

Keywords: glass fibers; heat treatment; knitting; mechanical properties; textile composites.

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1 Introduction

In recent years, polymer/matrix composites have been intensively investigated in both industrial and academic fields. The polymer composite class of E type glass fiber is the most preferred for reinforcement despite its limitations [1]. Fiber-reinforced composites are usually used in engineering parts of automotive, aerospace, marine and engineering applications due to their several advantages such as mass productivity, low fabrication cost, good resistance to impact and high ability to conform to complicated contours [2, 3]. Polypropylene, which has low cost and high-throughput ability, has been used in hot press molded parts [4]. Recently, composite application has been focused on weft knitted structures. The use of weft knitted composites for ultra high-strength applications has many advantages. They have high production rate and ease of handling, can be formed by deep drawing technique, and have high drop ability and possibility of forming double curved structures with integral 3D forms [5].

A thermoplastic composite made of glass fiber-polypropylene has good impact resistance and stiffness [1]. A crucial parameter for the design of composites is the fiber component, as it controls mechanical and thermomechanical properties [6]. Many researchers have tried to make multiple glass/polypropylene composites prior to 1996 [7–9]. In 1996, Karger and Czigany studied the interfacial effect on the dynamic mechanical behavior of plain weft knitted glass/polypropylene composites produced by commingled yarns [9]. They also investigated the effect of interphase on the fracture and failure behavior of plain knitted fabric reinforced composites [6]. In 1998, Hamada et al. investigated the influence of sizing condition on the bending properties of continuous glass fiber reinforced polypropylene composites [10]. Mouzakis et al. [11] and Wakeman et al. [12] investigated optimum conditions to produce composites of woven fabric. In 2000, Ramakrishna et al. studied the development of a novel flexible composite material. They investigated the mechanical properties of interlock knitted polyester/polyurethane composites [13–15]. Other researchers have carried out similar studies on weft knitted reinforced composites, but they manufactured composites in simple rib or plain structures of knitted fabrics [5, 16–20]. After 2001, researchers studied the effect of glass component in 3D composites. They also investigated the effect of incorporation of grafted brominated monomer in glass fiber reinforced polypropylene [2, 21–29]. Many attempts have been made to produce a polymer matrix in laminate form [1, 3, 30]. In 2005, Khondker et al. investigated the impact and compression after impact performance of weft knitted textile composites [31]. The impact of humidity on the durability of E-glass polymer composites was investigated [32]. In recent years, 3D fiber reinforced polymer composites were investigated [33]. However, there is no research on the effect of knit structure on the mechanical properties to improve the impact behavior of glass/polypropylene weft knitted composites.

The aim of the present research is to manufacture better weft knitted composites made of glass and polypropylene yarn with optimum mechanical properties, bending properties, impact resistance and stiffness by investigating the combined effect of knit structure and component percentage.

2 Experimental

Weft knitted fabrics were produced from glass yarn (E-glass; linear density 110 dtex, density 2.5 g/cm^3, diameter 14 μm) and polypropylene yarn (linear density 160 dtex, density 0.9 g/cm^3) by the CMS 400 knitting machine (Stoll GmbH; gauge 5, feed 4, double cylinder) in three different structures: rib 1-1, full Milano and full cardigan. The fabric structures can be seen in Figure 1. The polypropylene matrix was modified with maleic anhydride. After that, knitted fabric samples were manufactured by the hot pressing method under optimized processing parameters (temperature 200°C, pressure 4 MPa, holding time 5 min, full press cycle 80 min). Optimized processing parameters were found by trial-and-error method to reduce porosity in composite samples. The glass fiber content in composites was determined by the combustion method (Table 1).

Mechanical experiments were applied to composite samples in the wale, course and biaxial directions. The coding of experiments has been demonstrated as following summarized codes of rib structure in the wale, course or biaxial direction (R w,c,b), full Milano structure in the wale, course or biaxial direction (M w,c,b), full cardigan structure in the wale, course or biaxial direction (C w,c,b), and content of volume percentage for each composite (no. 1–5). The knitted structure was characterized as having 10 stitches per centimeter in the wale and course directions. The mechanical properties of composites were obtained according to ASTM D638 [34]. The flexural strength and flexural modulus of glass fiber/polypropylene composites were obtained following the ASTM D790 standard test method [35]. These tests were done at room temperature using a three point bending setup with a specimen thickness of 2 mm, span of 24.4 mm and a crosshead speed of 1 mm/min. Charpy impact tests were done according to ASTM D3029 [36]. Toughness test was done with EQUTIP G type with boundary support conditions, e.g., 40-mm-diameter ring that gives L number [35]. Average values of five specimens are reported with standard deviation of <5%.

3 Results and discussion

There are three steps in the stress-strain curve of all composites. First, the matrix component of glass/polypropylene has elastic deformation. Second, the polypropylene matrix enters the plastic state but glass yarn remains in

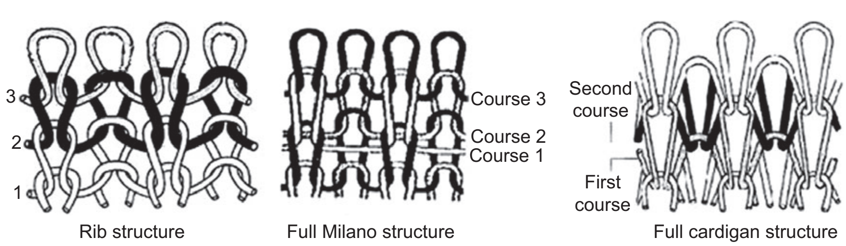

Figure 1 Knitted fabric structures.

Composite number	Feed yarn no. to CMS		Weight portion (%)		Volume portion (%)	
	Glass	Polypropylene	Glass	Polypropylene	Glass	Polypropylene
1	1	3	19	81	8	92
2	1	2	23	77	10	90
3	1	1	37	63	18	82
4	2	1	58	42	33	67
5	3	1	68	32	44	56

Table 1 Polypropylene and glass fiber content in composites.

the elastic state with increasing stress. This step continues up to breaking of the yarn, which is the majority of the curve. Third, glass yarn is broken with increasing stress; therefore, the matrix is unaccustomed to maximum stress. Figure 2 shows the stress-strain curves of composite samples. The curves show that rib structure improves the strength of composites and cardigan structure has more strain in comparison with other structures of composite fabrics. Figures 3–8 represent the mechanical properties of composites. Figure 3 shows that elongation modulus has maximum value in rib structure, whereas it has a minimum value in full Milano structure. Elongation modulus decreases with increasing glass yarn content in all knitted composites. Also, values of elongation modulus are highest in the wale direction and very low in the course direction.

Figure 4 demonstrates that increasing the glass content up to 18% in rib and full Milano structures leads to increasing yield stress. Yield stress decreases when glass content is >18% because a higher glass content leads to less adhesion between the glass yarn and the polypropylene matrix. However, yield stress decreases for the full cardigan structure with increasing the glass content. The rib structure presents more yield stress in comparison with the full Milano and full cardigan structures. This is seen for the wale direction compared to the course direction. A full stitched structure of rib is more symmetric compared with structures of skip stitch or tuck stitch components. This leads to better resistance against local stresses.

Yield strain has opposite results in comparison with yield stress (Figure 5). The results are very interesting because increasing the glass content and decreasing the knit element portion lead to increasing yield strain. It may be because of more slippage between the glass and the polypropylene phase in rigid samples. It should be mentioned that skip stitches and tuck stitches create a rigid structure. Also, using more glass content leads to more rigidity in composites. It seems that adhesion between the glass yarn and the polypropylene matrix plays an important role.

Observations in strength tests show that the mechanical properties of composites are reduced by increasing

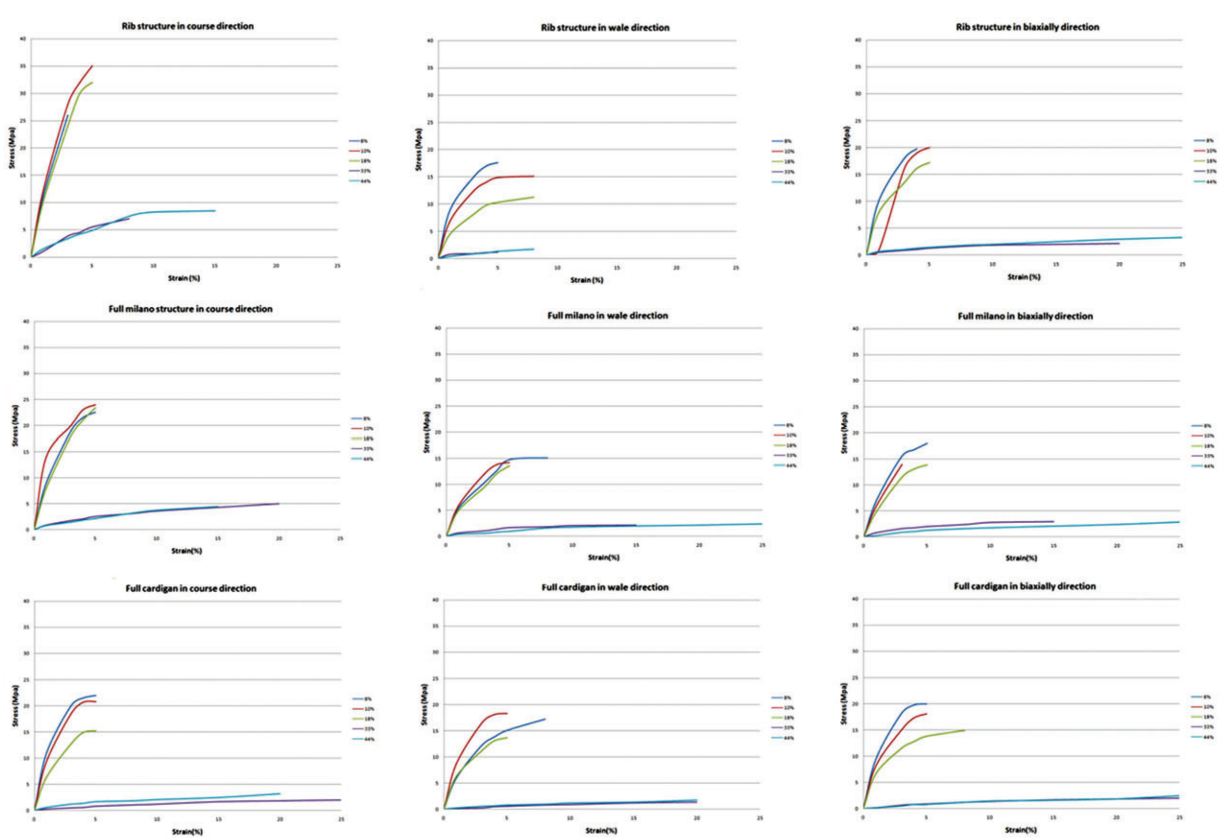

Figure 2 Stress-strain curvatures of fabric composites.

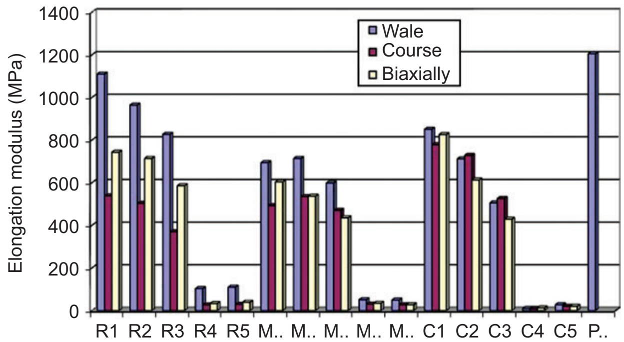

Figure 3 Results of composite's elongation modulus.

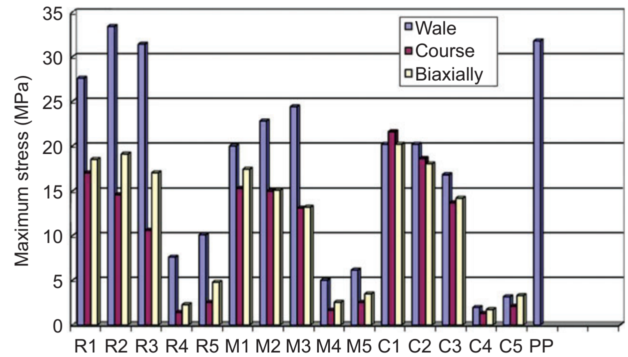

Figure 6 Results of composite's maximum stress.

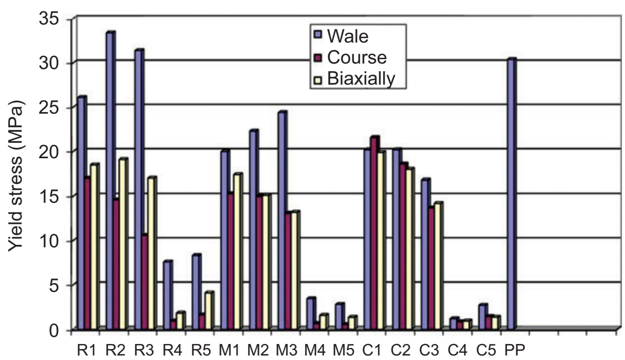

Figure 4 Results of composite's yield stress.

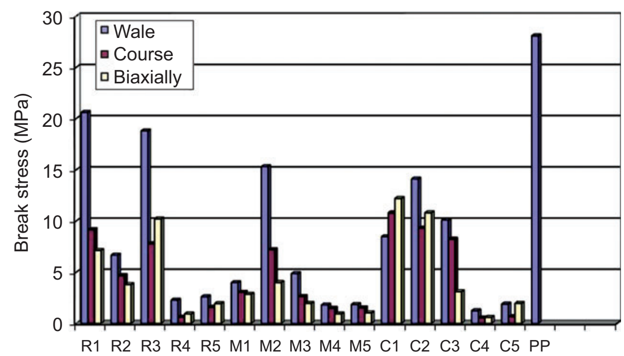

Figure 7 Results of composite's break stress.

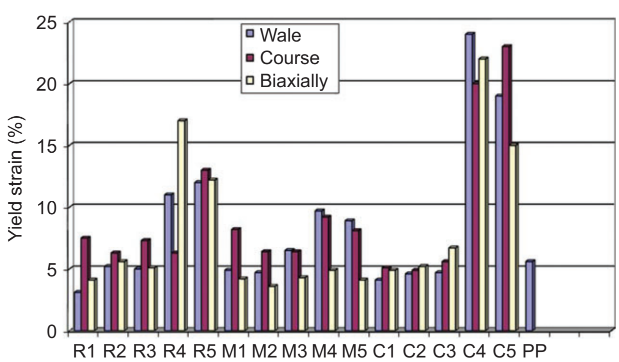

Figure 5 Results of composite's yield strain.

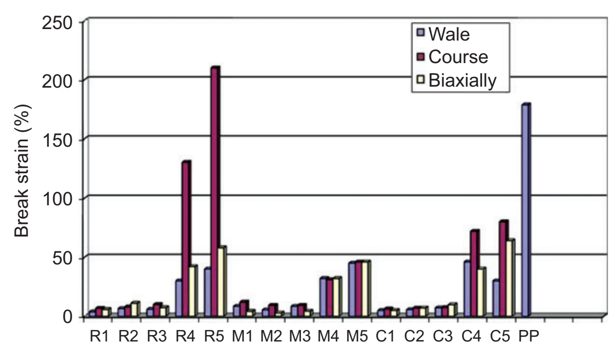

Figure 8 Results of composite's break strain.

the glass yarn content by more than 18%. The strength and stiffness of knitted composites are inferior due to the limited utilization of fiber stiffness and strength resulting from the several bent fibers in the knit structure [15]. Rib knitted composites have a symmetric structure; therefore, stress force acts in the biaxial direction. This increases the breaking stress for rib composites compared with other structures. Tuck and skip stitches make the fabric asymmetric because the tuck stitch is a semiloop stitch that is tightened in the next course stitch, and the skip stitch is a straight yarn without any loop that is located behind the next course stitch. Therefore, full Milano and full cardigan composite structures have less strength. Full Milano structures have skip stitch in their structure; hence, by increasing stress, more time is needed to lock the stitches together. This occurs more often in full cardigan structures. The maximum stress of rib structure is more than that of other structures (Figures 6 and 7). The cumulative strength of full cardigan is more than that of full Milano. It is clear that the force in the course direction stretches the skip stitch. Regarding the full cardigan structure, stretching force in the course direction deforms the tuck stitch shape; the majority of this force opens the tuck stitch structure. After the tuck stitch is opened, a portion of force is increased on each knit stitch. In this part, stitches lock together and more force is needed to open the locked stitches. The full cardigan structure has stronger mechanical strength properties than the full Milano structure because more force is needed to stretch the tuck stitch in the course direction. However, this occurrence is reversed in the wale direction.

Results showed that contact forces between knitted stitches are generated in contact points when knitted composites are stretched and their stitches are locked together. When a knitted composite is stretched in the biaxial direction, the force is separated to horizontal and vertical borders. In the first stage, these force borders lead to changing the stitch configuration. By deforming the stitch element, one part of the stitch becomes longer and straighter in the direction of the stretching force, whereas the part in the direction perpendicular to stretching bends and becomes shorter [5].

According to Figure 8, increasing the glass content by more than 18% leads to a big increase in strain at the break. If the knit has a lower degree of orientation in the stretch direction, it is more stretchable, and vice versa. The next stage of stretching is characterized by shifting the yarn contact point in the knitted structure. There is pressure between the yarns in the stitch contact point, which influences the friction force between them.

The maximum bending force test results (Figure 9) show that the highest resistance of bending force is obtained for the rib structure, which is the maxima in the wale direction.

The bending strength of full cardigan is more than that of full Milano. The knit stitch leads to locking of structures together in which its effect is more than the effect of the tuck and the skip stitches, respectively. This matter is justified because of movement freedom ability along stitches. Using more looped stitches creates more entanglement between knitted elements, thus leading to less movement freedom ability. Decreasing the movement ability leads to increasing bending resistance. The bending modulus result (Figure 10) is similar. In general, increasing the glass yarn content reduces the bending modulus of composites because glass yarn increases slippage. Stitches resist against the bending force to keep their primary shape. They can keep their primary shape in a symmetric structure; therefore, in knitted composites, decreasing the orientation of the structure leads to decreasing bending resistance. Generally, the bending resistance of knitted composites in the wale direction is more than that in the other directions. In the wale direction, there are more contact points along stitches. This leads to more resistance to the bending force due to the available forces in contact points. However, in the course direction there are less contact points along stitches; therefore, the bending resistance is less than that in the wale direction. In the biaxial direction, the force of bending acts in the asymmetric location of stitches. One part of the force couple acts on the head stitch and the other part acts on the sinker stitch (tail stitch). This asymmetry leads to a decrease in the bending force. However, the brittleness of knitted composites against bending force increased with increasing amounts of glass yarn.

The impact resistance of knitted composites is dependent on the knitted composite's resistance against breakage or structural damage. Figure 11 shows that the absorbed energy of impact is maximum in the rib structure, generally in the wale direction. Impact energy in the rib structure is more than that in the full cardigan and full Milano, respectively. This matter is justified because of the more bidirectional orientation of rib knitted composites in comparison with other combined knitted structures of full

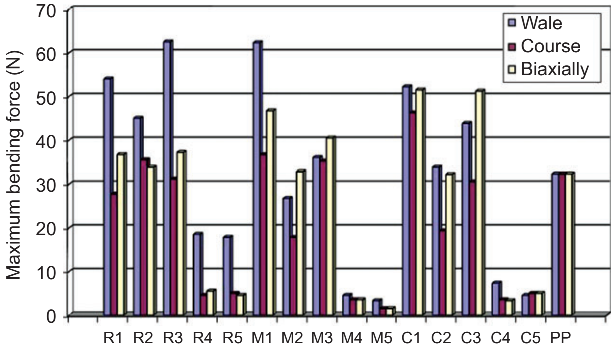

Figure 9 Results of composite's maximum bending force.

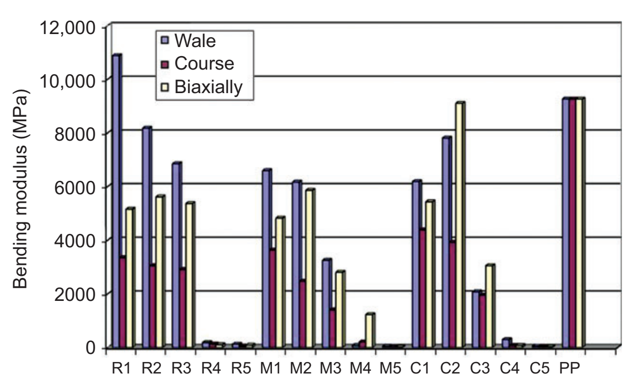

Figure 10 Results of composite's bending modulus.

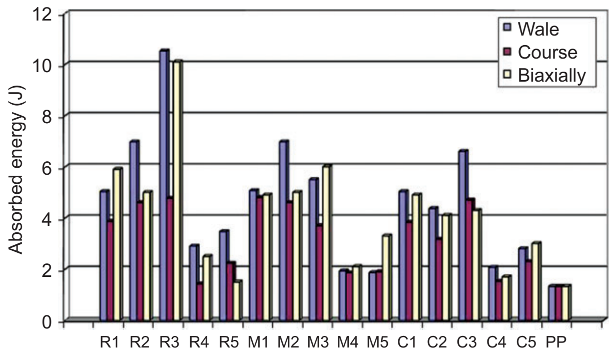

Figure 11 Charpy test results for composites.

Milano and full cardigan. Also, the strength and strain of these knitted structures are similar. Therefore, it is clear that multiplying the strength and strain plays a role in work of rupture and impact resistance.

Normal absorption energy of impact is shown in Figure 12 for samples of knitted composites. According to results of the impact energy absorption test (Figure 12), the impact resistance of knitted composites is increased by increasing the amount of glass content up to 18 wt%. By increasing the glass content more than 18 wt%, impact resistant is decreased intensively. A glass fiber content of over 18 wt% makes knitted composites more brittle. These findings are confirmed by previous results from strength and strain experiments in which the impact resistance is obtained by multiplying the strength and strain together. Less glass content makes the composite soft and leads to less strength against force especially over a short time. Also, more glass content makes the composite brittle with low stretching ability and leads to less strain in short time. Therefore, the optimum situation for composites is when both strength and strain are optimum. Results of impact resistance tests introduce a glass content of 18 wt% for samples of knitted composites in the above-mentioned conditions of production and experiments in this study. Of course, these results may differ in other conditions.

Test results for knitted composite stiffness indicate that rib knitted composites have more stiffness than the other structures. However, there is no noticeable difference between the stiffness of full Milano and that of full cardigan knitted composites. Results show that stiffness of composites is reduced when the glass content increases (Figure 13). These results are very close to strain results.

With regard to data and table of material stiffness, it is undeniable that knitted composites with 8, 10, and 12 wt% glass fiber content have stiffness similar to that of iron and steel. Components with 33 and 44 wt% glass fiber content have the same stiffness as aluminum sheets [37].

The important parameters for each composite were obtained by performing analysis of variance (ANOVA) on the data. ANOVA showed that the elastic and plastic moduli have been changed in different knitted structures. The same results were seen for the percentage of glass content. In general, there is a best condition for providing the knitted composite for each application based on the presented results. According to the results, knitted composites with rib structure and 18 wt% glass content have maximum values of elongation modulus, whereas full Milano structures with 33 wt% glass content have minimum values. Break stress is maximum in rib structure (8 wt%) and minimum in full cardigan (33 wt%). Test results of bending give a maximum value in full cardigan (10 wt%) and is minimum in full Milano (44 wt%). Regarding impact resistance, Charpy impact test showed that impact resistance of rib structure is maximum with 18 wt% glass content. The minimum condition of impact resistance occurred in brittle knitted composite of 44 wt% glass content in full Milano structure. The hardest knitted composite was produced with glass-polypropylene (8–92 wt%) in rib knitted structure. Stiffness test results suggest full cardigan knitted composite with 33 wt% glass content for soft applications.

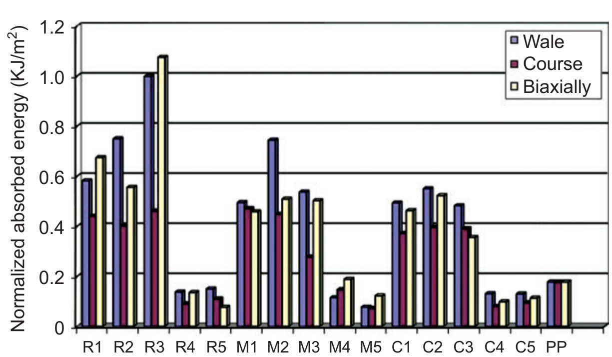

Figure 12 Normalized absorbed energy results for composites.

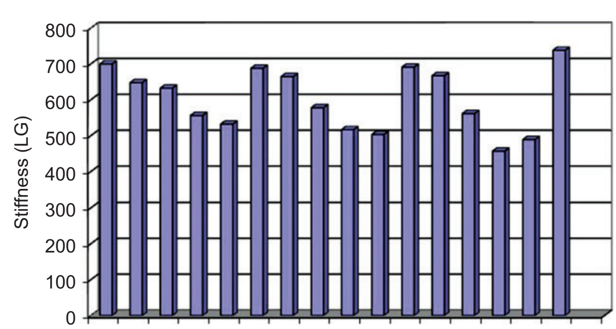

Figure 13 Stiffness results for composites.

4 Conclusion

It has been shown that the orientation of stitches in a knitted structure has key influence on the mechanical properties of knitted composites produced by hot pressing of glass and polypropylene yarns. Increasing the orientation of composites leads to increasing the strength and impact energy absorption. Due to the stitch geometry and inherent knit structure, the optimum condition for providing a high-strength composite and maximum stiffness is rib knitted composite consisting of 8 wt% glass/92 wt% polypropylene contents. The maximum value of impact energy absorption was obtained with the 18 wt% glass fiber content and 82 wt% polypropylene matrix in rib knitted composite. With regard to bending resistance, full cardigan with 10 wt% glass and 90 wt% polypropylene matrix is much better than other knitted samples. In addition, the present method of production for knitted composites is cheaper with shorter time of production in comparison with previous methods.

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