MECHANICAL PROPERTIES OF CROSS-PLY BANANA-GLASS FIBRE REINFORCED POLYPROPYLENE COMPOSITES

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ABSTRACT

Banana fibre is a secondary crop fibre that could be profitably used in the manufacturing of fibre reinforced composites because they possess attractive mechanical and physical properties. The mechanical properties of banana-glass fibre reinforced polypropylene composite were studied. The composites were prepared using a hot press with four types of stacking sequence. Mechanical tests were carried out according to American Society for Testing and Materials (ASTM) D3039 for tensile test, ASTM D790 for flexural test and ASTM D6264 for quasi-static indentation. The results showed that banana fibre (B) reinforced composite was enhanced by incorporating glass fibres (G) by 302.27% and 24.45% for GBG, in terms of tensile and flexural strength respectively. For quasi-static indentation, the energy absorbed increased by 122.22% with the incorporation of glass fibre for GBG. The results show a positive hybrid effect on the mechanical properties, where hybrid GBG is comparable to GGG in the flexural application.

Keywords: *Natural fibre; hybrid composite; mechanical properties; banana fibre; glass fibre.*

1. INTRODUCTION

Environmental consciousness, as well as government legislations around the world, has encouraged the academic and industrial researches to develop eco-friendly, sustainable, and biodegradable composite materials, thus often referred to as green composites (Baillie, 2005). Natural fibre reinforced composites are currently dominating the composite field, which support the notion of creating a greener future. Natural fibres offer better specific stiffness and strength, biodegradability, availability, sustainability in production, and low cost per unit volume (Herrera-Franco & Valadez-Gonzalez, 2004). Many types of natural fibres such as kenaf, jute, hemp, sugar palm, sisal, pineapple leaf, coir, abaca and kapok, have been used as reinforcement in polymer composites (Mohammed *et al*., 2015). Environmentally friendly composites are more frequently applied to military applications, transportation, building and construction industries (Saba *et al*., 2014). Extensive research and investigations are dedicated to natural fibre reinforced polymer composites due to their advantageous features, such as biodegradable, recyclable, lightweight and cost-effective (Subramonian *et al*., 2016). Physical and mechanical properties of composites are dependent on the length of the fibre, matrix ratio, fibre arrangement, number of layers and fibre directions (Arthanarieswaran *et al*., 2014; Subramaniam *et al*., 2017).

One way to improve the mechanical properties of natural fibre reinforced composite is through hybridisation. There is a growing need for composite materials for use in military and civil applications, and there is a global search for materials with desirable structural characteristics (Razali *et al*., 2017). The study of woven banana and kenaf fibre composites by Alavudeen *et al*. (2015) showed that hybridisation of kenaf with banana fibres increase the mechanical properties which are superior to those of the individual fibres. Woven hybrid composites namely jute / sisal / glass and jute

/ banana / glass were tested, and the results showed that high strength hybrid composite made of jute / banana / glass has better mechanical properties and is applicable for a wide range of applications (Parandaman & Jayaraman, 2015). Venkatasubramaniam *et al*. (2014) studied the mechanical properties of the randomly oriented mats of abaca, banana and glass fibres and their hybrids. The result showed that abaca-glass composite had the highest tensile properties while abaca/glass/banana hybrid composite had better flexural and impact properties. Srinivasan *et al*. (2014) investigated the mechanical properties of woven flax, banana, glass and their hybrids. The results showed that the banana / glass composite had a higher tensile strength than the flax / glass composite. However, the flexural and impact properties of the banana / glass composite were slightly higher (15.79%) and lower (8.33%) respectively lower than the flax / glass composite. Navaneethakrishnan *et al*. (2015) investigated the mechanical properties of glass / banana fibre reinforced silica nano-particles with epoxy composites. The impregnated layers were made for six different types of composites with 0 - 5 % of silica, where each type composed of two layers of banana fibre and four layers of glass fibre. The results showed that the composite with 3% silica had the highest tensile strength. It was concluded that banana fibre in combination with glass fibre has proven to be excellent for making a cost-effective composite material. Samal *et al.* (2009) investigated the performance of banana / glass fibre reinforced polypropylene hybrid composites. The samples were fabricated using melt blending with different fibre ratio. The results showed that the mechanical properties of hybrid composites were enhanced to the maximum when the fibre was 15%:15% (glass: banana). Thiruvasagam *et al*. (2016) evaluated the mechanical properties of woven roving hybrid banana, jute and glass fibre reinforced polyester composite. The result showed that glass / banana / jute had the highest tensile properties followed by glass / banana and glass / jute. However, for the flexural test, glass/banana composite had the highest flexural strength since its strength increases with an increase in interfacial adhesion.

Rodriguez *et al*. (2016) studied the water uptake, chemical characterisation and tensile behaviour of modified woven banana plantain fibre and their polyester composites. The results showed that silane treated banana fibre increased the tensile strength by 11.32%. Kumar *et al*. (2013) investigated the mechanical properties of short banana fibreglass reinforced hybrid polypropylene composites with different fibre weight fraction. Based on the results, the tensile strength was maximum when the fibre weight fraction was 7.5%, and 10% for flexural strength. The composite can be regarded as a useful lightweight engineering material and reduces the manufacturing cost by adding banana fibre hybridised with glass fibre to the matrix. Rahman *et al*. (2018) investigated the mechanical properties of chemically treated banana and pineapple leaf fibre reinforced hybrid polypropylene composites. The short fibres of banana and pineapple leaf were alkali treated before fabrication. The results showed that the best mechanical properties were obtained when polypropylene was reinforced with 5 wt.% pineapple leaf and banana fibre at a ratio of 3:1. This is due to pineapple leaf fibre containing higher cellulose content as compared to banana fibre, thus making composite with more pineapple leaf fibre having better bending properties.

Boopalan *et al*. (2013) studied the mechanical and thermal properties of cross-ply jute and banana fibres reinforced in epoxy resin. The results showed that the mechanical properties increased up to a certain limit, then decreased due to poor interfacial bonding. The highest tensile and flexural strengths were observed for the composite with a 50/50 weight ratio of jute / banana fibres. Amir *et al*. (2017) studied the effect of fibre configuration on the mechanical properties of banana fibre / polypropylene (PP) / maleic anhydride grafted polypropylene (MAPP) reinforced composites. The composites were reinforced with different types of banana fibres; raw fibre, banana yarn and banana in mat form. The results showed that the PP / banana yarn had the highest tensile and flexural properties. This was because the yarn fibre is continuous in the composite and commingled by its configuration. Heckadka *et al*. (2018) compared the mechanical properties between jute / glass and banana / glass reinforced epoxy composite laminates. In this research, the tensile and flexural strengths of jute / glass composite was higher than the banana / glass composite. The hybridisation of natural and synthetic fibres enhanced the mechanical properties of the composite through the acquirement of the advantages of one fibre to overcome the disadvantage of another fibre, such as hydrophilicity (Dhar Malingam *et al*., 2017; Subramaniam *et al*., 2017).

However, thus far, the research on the hybridisation of cross-ply banana-glass fibre thermoplastic composites is scarce, especially on the effect of stacking on the mechanical properties. Thus, this paper investigates the mechanical properties of hybrid banana-glass fibre reinforced polypropylene composite in terms of its tensile, flexural and quasi-static indentation properties.

2. EXPERIMENTAL SETUP

2.1 Materials

J.C. Overseas Incorporation, India supplied cross-ply (0/90°) banana (B) fibre with the areal weight of 342.5 g/m^2. ZKK Sdn Bhd, Malaysia supplied cross-ply (0/90°) glass (G) fibre with the areal weight of 600 g/m^2. Al Waha, Saudi Arabia supplied polypropylene (PP) pellets with a density of 0.95 g/cm^3. The typical properties of banana fibre, glass fibre and polypropylene are tabulated in Table 1.

Table 1: Typical properties of banana fibre (Agarwal *et al*., 2003; Paul *et al*., 2008; Bhatnagar *et al*., 2015;), glass fibre (Wallenberger *et al*., 2001) and polypropylene (Maddah, 2016).

Properties	Banana Fibre	Glass Fibre	Polypropylene
Tensile Strength (MPa)	550	1700-3500	22-41.4
Young's Modulus (GPa)	22-32	65-72	1.5-2
Elongation at break (%)	3-4	3	3-700
Diameter (μm)	80-250	5-25	-
Density (g/cm^3)	1.35	2.58	0.89-0.95
Cellulose (%)	60-65	-	-
Hemicellulose (%)	6-19	-	-
Lignin (%)	5-10	-	-
Softening point, T_q (°C)	-	-	-10 to -23
Melting point, T_m (°C)	163	-	160-176

2.2 Composite Preparation

PP granules were compressed at 168 °C and pressure of 4.9 MPa in a hot press to form a thin film with a nominal thickness of 0.2 mm. The cross-ply glass and banana fibres were cut and stacked in four different sequences alternated with PP thin film in a picture mould frame with dimensions of 250 x 250 x 3.5 mm. A total of three layers of cross-ply fibres were fixed in a single composite laminate. The mould was then placed in a hot press and preheated at 170 °C for 5 min. Then, the composite was compressed at 170 °C for another 10 min at a constant pressure of 3.5 MPa and then left to cool for 15 min. The composites were divided into hybrid and non-hybrid composites, referred to as banana / banana / banana (BBB), banana / glass / banana (BGB), glass / banana / glass (GBG) and glass / glass / glass (GGG), as illustrated in Figure 1. BBB and GGG are the non-hybrid banana and glass fibre reinforced polypropylene composites. BGB is a hybrid composite with banana fibre as the skin layer, while GBG is the hybrid composite with glass fibre as the skin layer.

Table 2 shows the fibre and matrix volume fractions of the composites. The following Equation 1 is used to calculate the fibre volume fractions (V_{fibre}):

$$V_{fibre} = \frac{\frac{w_{banana}}{\rho_{banana}} + \frac{w_{glass}}{\rho_{glass}}}{\frac{w_{banana}}{\rho_{banana}} + \frac{w_{glass}}{\rho_{glass}} + \frac{w_{pp}}{\rho_{pp}}} \quad (1)$$

where w_{banana} and ρ_{banana} are the weight and density of banana fibre, w_{glass} and ρ_{glass} are the weight and density of glass fibre, and w_{pp} and ρ_{pp} are the weight and density of PP.

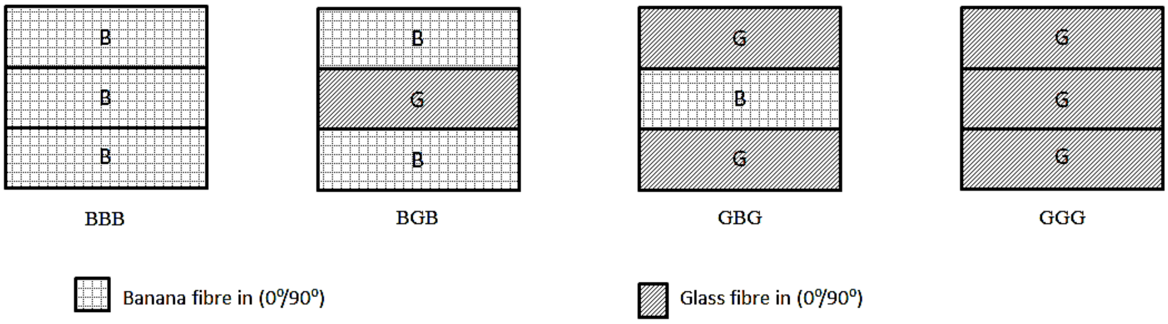

Figure 1: Stacking sequence of the composites.

Table 2 : Fibre and matrix volume fractions in the composites.

Composite	Fibre volume fraction (%)	Matrix volume fraction (%)
BBB	24.36	75.64
BGB	22.99	77.01
GBG	19.35	80.65
GGG	18.92	81.08

2.3 Mechanical Properties

Tensile and flexural tests were conducted according to American Society for Testing and Materials (ASTM) D3039 and ASTM D790 using a universal testing machine (UTM) model Instron 8872 with a 25 kN load cell. The composites were cut into dimensions of 200 x 25 mm and tested with a crosshead speed of 2 mm/mm until fracture. For the quasi indentation test, the samples were cut into dimensions of 100 x 100 mm according to ASTM D6264. The test was conducted using a UTM Instron 5585 with 150 kN load cell at a crosshead speed of 1.27 mm/min using a custom made fixture and 12.7 mm diameter stainless steel hemispherical tip indenter. Five samples were tested for each type of composite. The penetration energy absorbed by the composites was calculated based on the area under the penetration force-displacement curves. Following these tests, the tensile, flexural and quasi-static indentation fracture surfaces were examined using scanning electron microscope (SEM).

3. RESULTS AND DISCUSSION

3.1 Tensile Properties

Figure 2 shows that the tensile strength of the composite increases when the layer of glass fibre increases. The ultimate tensile strength for each layering sequence was determined, and the highest value was found for GGG at 191.27 MPa, while the lowest was observed for BBB at 38.80 MPa. The tensile strength for the BGB was 123.12% higher than BBB. GBG tensile strength was 80.29% and 302.27% higher than BGB and BBB respectively. This is due to the incorporation of glass fibre with higher strength and modulus as compared to banana fibre. The strength of the layered hybrid composites depends on the fibre stacking sequence in the composites (Dhar Malingam *et al.*, 2018a). The load applied on the composite was carried axially by the high strength fibres before multiple fractures occurred and beyond, where the load was redistributed to the PP matrix. The composite with higher fibre strength at the skin material is prone to yield an optimum mechanical property (Agarwal *et al.*, 2003). The normalised tensile strength also followed the same pattern of tensile strength, where non-hybrid GGG had the highest value of 1,235.59 MPa/ (g/cm^3), followed by the GBG, BGB and BBB composites with 1,059.57, 617.49 and 285.54 MPa/ (g/cm^3). Figure 3 shows the tensile modulus of the fabricated composites. The BBB sample exhibited the lowest tensile modulus of 0.37 GPa. The addition of glass fibre in the BGB sample showed an increase in the value of tensile modulus by 56.76%, while for the GBG sample, there was a 232.43% increase when compared to the BBB sample. The composite stiffness increased with the increase of glass fibre layup.

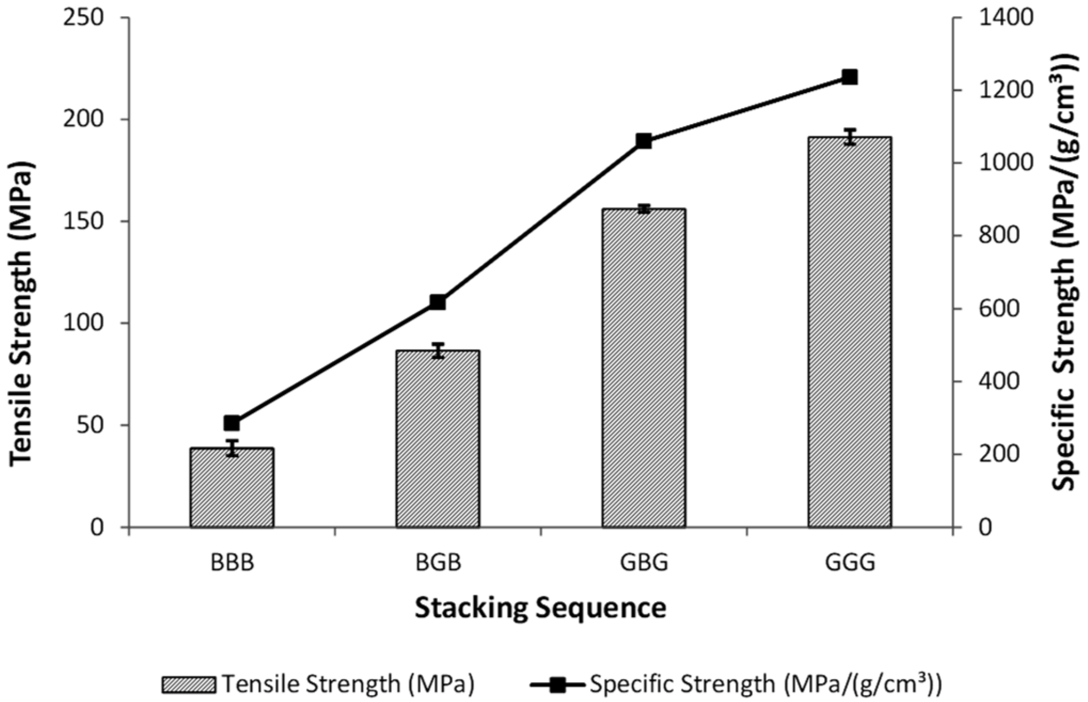

Figure 2: Tensile strength and specific tensile strength of each stacking sequence.

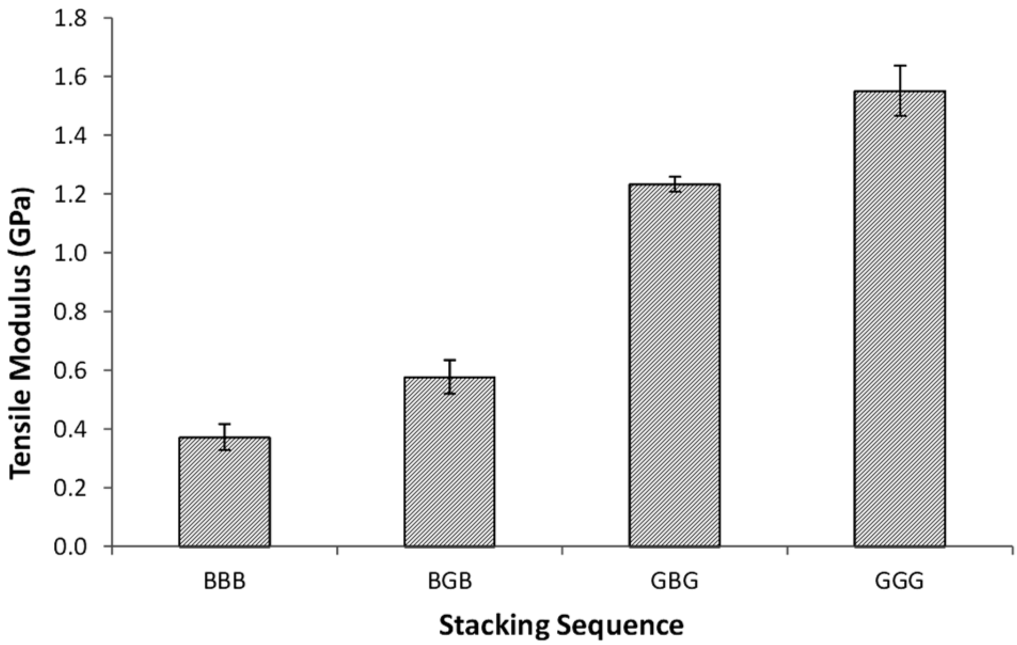

Figure 3: Tensile modulus of each stacking sequence.

3.2 Flexural Properties

Flexural strength is the combination of tension and compression stress, which vary with the inter-laminar shear strength. Figure 4 shows the flexural strength of each type of samples. The increasing glass fibre in the composites increased the shearing resistance and thus, increased the flexural performance (Sreekala *et al*., 2002). However, the GGG composite had a flexural strength of 68.26 MPa, which is 16.40% lower than the hybrid GBG composite due to poor interfacial adhesion between the fibre and matrix. Higher flexural strength in the hybrid composites is due to higher dispersion of banana fibre, where the glass fibre can pack well in the interstitial spaces available leading to a close-packed composite structure (Haneefa *et al*., 2008). Kretsis (1987) reviewed the flexural properties of hybrid fibre reinforced plastics, who found that flexural properties not only depend on the hybrid composition but also the arrangement of the material layers. The results depict that hybrid GBG has the highest flexural strength of 81.65 MPa when compared to hybrid BGB. This enhancement in flexural strength may be attributed to the ability of the fabric to withstand bending forces during the three-point bending test (Dan-mallam *et al*., 2015). The increased flexural strength of the hybrid composites with the loading of glass fibre was mainly owing to the increased resistance to shearing of the composites due to the inclusion of rigid glass fibre (Haque & Hasan, 2016). Failure of the composite was characterised by fibre breakage and matrix cracking, which was initiated from the tension side of the specimen, with fracture occurring in the middle of the beam (Jawaid *et al*., 2011). Once the compression failure occurs, the flexural stress in the composite is reduced as the fibre breakage, and matrix cracking continues to propagate along the fibre-matrix interphase. As stated in Sathish *et al*. (2015), composites made from banana fibres have high flexural strength and hence, can be used in various automotive applications such as seat trims and transmission covers. The flexural modulus in Figure 5 increased with increasing glass fibre in the composite. Joseph *et al*. (1999) attributed the increase in the flexural strength and modulus to the increasing fibre-to-fibre contact when the fibres were impregnated.

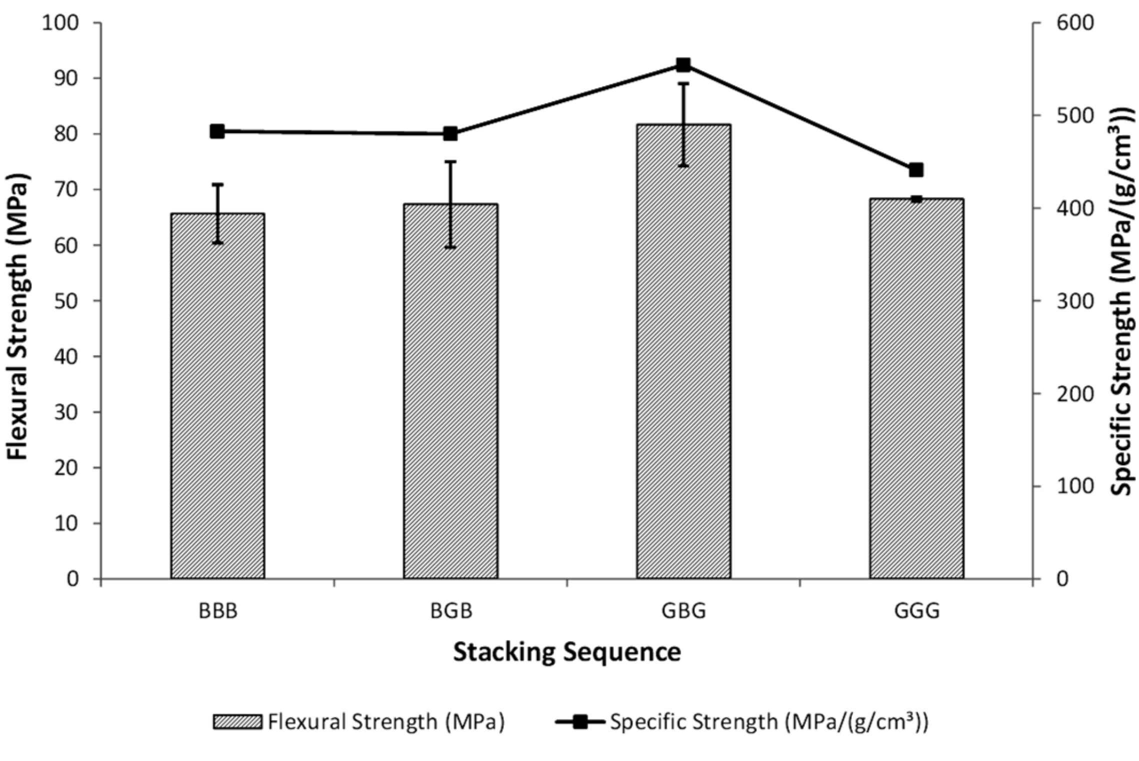

Figure 4: Flexural strength and specific flexural strength of each stacking sequence.

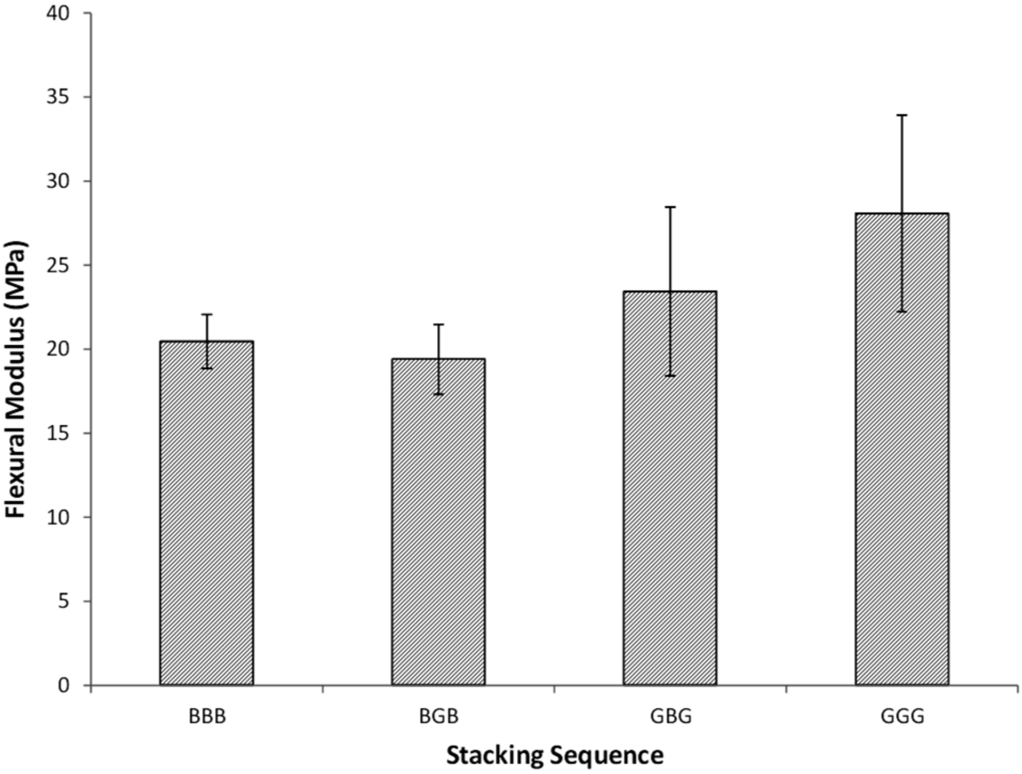

Figure 5: Flexural modulus of each stacking sequence.

3.3 Quasi-Static Indentation Properties

The average load-displacement curves of the indentation of the hybrid and non-hybrid composites are shown in Figure 6. The results of the test were analysed based on the force-displacement curves, total energy absorption and normalised energy absorption. Initially, the curve showed a linear behaviour, where it increased along with displacement until reaching a maximum peak load. This is due to a dent forming on the top surface of the composite, which eventually initiated a crack (Subramaniam *et al*., 2017). The indenter then moved through the thickness of the composite by pushing the matrix and fibres through the rear surface. Then, when the indenter penetrated the rear surface of the composite, the curve dropped drastically, which indicates that the specimen has failed (Saw *et al*., 2011).

Based on Figure 6, the GGG composite has the highest resistance to indentation for up to 6.65 kN. This is due to the strength of glass fibres, which resist the formation of a shear plug (Dhar Malingam *et al*., 2018b). However, the peak loads of the hybrid composite GBG was only 24.5% less than the GGG composite at 5.02 kN, followed by BGB and BBB at 3.07 and 2.25 kN respectively.

The area under the load-displacement curves in Figure 6 was calculated up to the peak load to determine the indentation energy absorbed by the composites. Figure 7 illustrates the energy absorbed and normalised energy absorption of the composites. The trend showed a positive hybrid effect where incorporation of glass fibre as the skin layer had greater energy absorption and load resistance. The glass fibre requires more force and elongation to fail, thus placing glass fibre as the skin layer of the composite enhance the energy absorption. The highest energy of 46.14 kJ was absorbed by GGG, followed by GBG and BGB with 32.30 kJ and 16.82 kJ respectively. BBB had the lowest energy absorption capability of 13.19 kJ. BBB had the lowest normalised energy of 0.36 kJ/g followed by BGB, GBG and GGG at 0.43, 0.80 and 1.04 kJ/g respectively. Hybrid GBG was 86% higher than hybrid BGB.

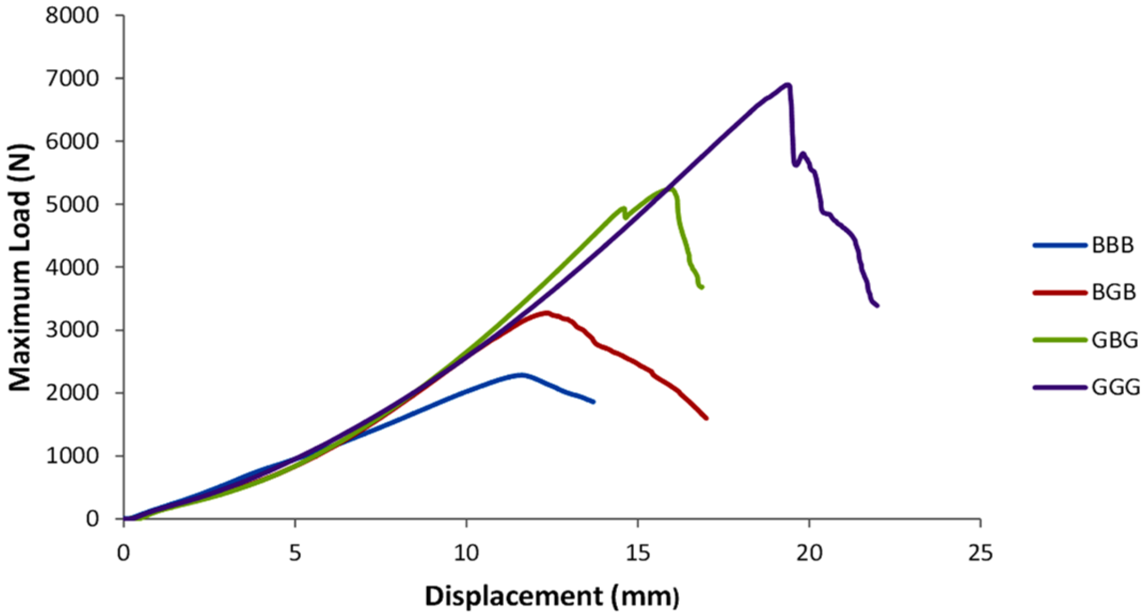

Figure 6: Load-displacement curve for each stacking sequence.

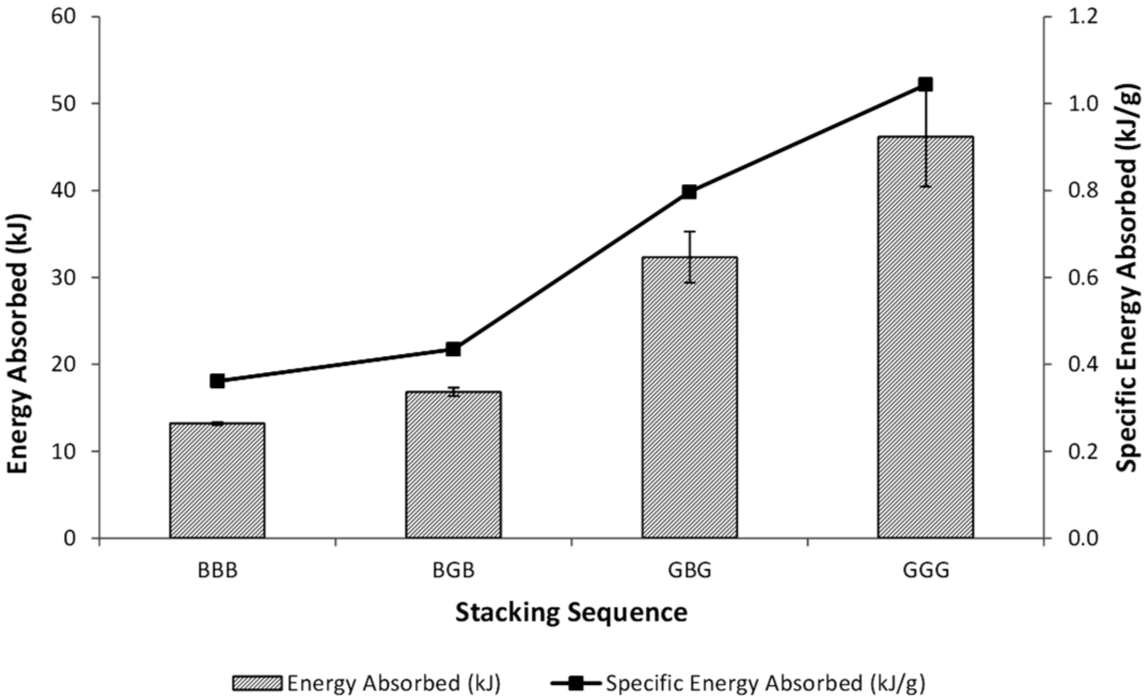

Figure 7: Energy and specific energy absorbed for each stacking sequence under quasi-static indentation.

3.4 Characterisation

Figure 8 depicts the SEM images of the failure surface of cross-ply composite due to tensile loading. The interlocking mechanism in both natural and synthetic fibres play an important role in resisting the load applied (Dhar Malingam *et al.*, 2017). Based on Figure 8(a), it is apparent that fibre pull-outs occurred making the stress transfer between matrix and fibre less efficient. Figure 8(b) also shows banana fibres pull-outs and fractured glass fibres in BGB. Figure 8(c) has fewer fibre pull-outs but has traces of some delamination and matrix cracking in the composite GBG. Incorporation of glass fibres into the banana fibre reinforced composite increased the mechanical properties of the composites as the stresses were efficiently transferred from the matrix to the fibres for tensile and quasi-static. The staggered fractured matrix surface indicates the ductile behaviour of the matrix. Figure 8(d) shows the smooth surface of glass fibre, which indicates inefficient fibre wetting and matrix fracture. The matrix surface has few edges, which indicates that the composite is more brittle than the GBG composite in Figure 8(c) and thus, immediate failure occurred. A stronger fibre at the skin layer has better properties as compared to hybrid and BBB composites, thus resulting in hybrid GBG exhibiting better tensile properties when compared to hybrid BGB.

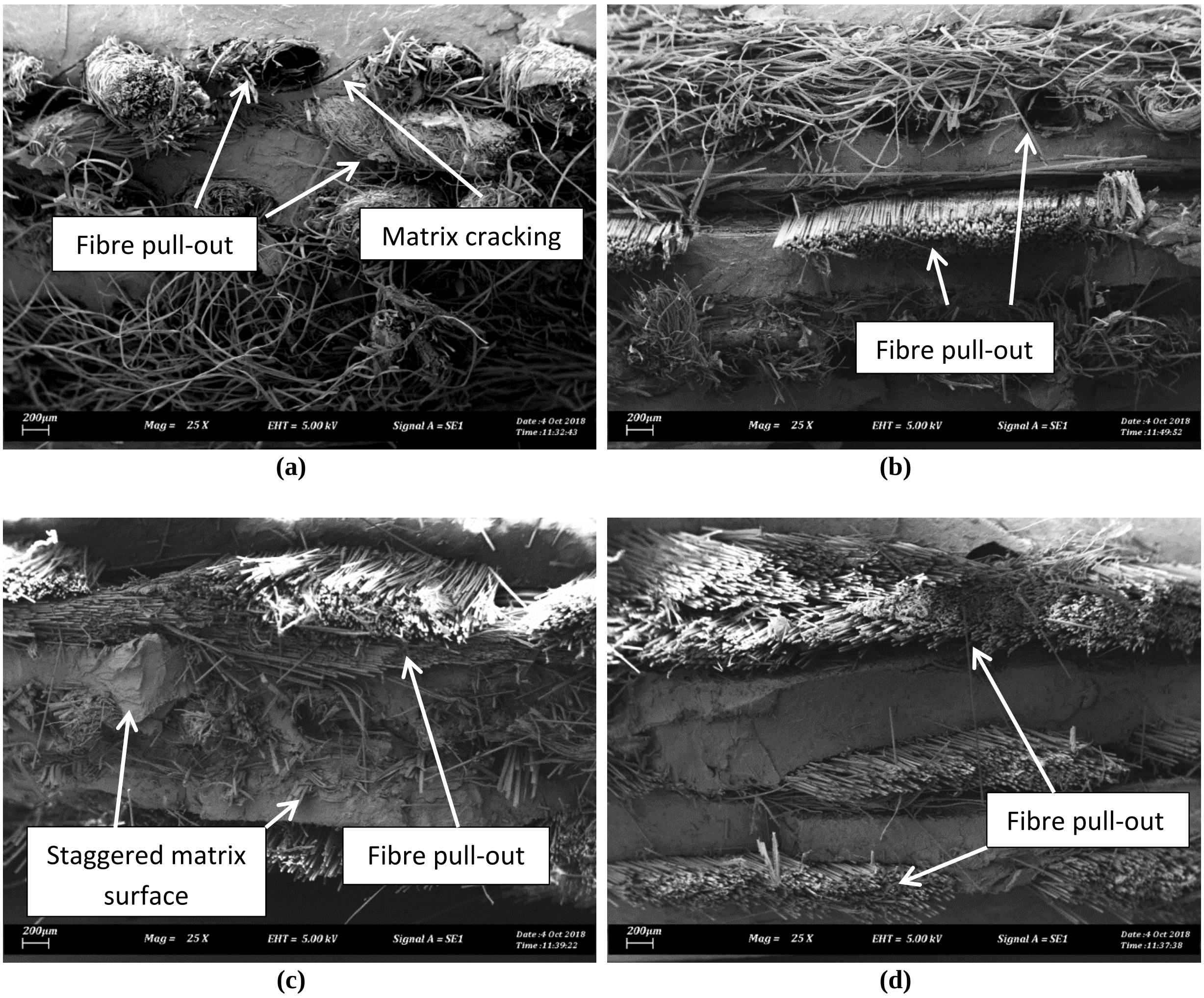

Figure 8: SEM micrograph of each stacking sequence (a) fibres pull-outs in BBB composite (b) banana and glass fibres in BGB composite (c) good adhesion between fibre and matrix of GBG composite (d) glass fibres in GGG composite.

4. CONCLUSION

Tensile, flexural and quasi-static indentations of hybrid banana / glass fibres in different stacking sequences were investigated. The tensile, flexural and quasi-static indentation properties were compared between hybrid and non-hybrid composites. The highest tensile strength was achieved by non-hybrid GGG composite with 191.27 MPa, which is 392.96% higher than non-hybrid BBB composite. Incorporation of glass fibres in the banana fibre reinforced composite showed enhancement of 302.27% and 123.12% for GBG and BGB respectively. The highest flexural strength was observed for hybrid composite GBG with 81.65 MPa, which is 21.32% higher than hybrid BGB. The highest energy absorbed is seen in the non-hybrid GGG composite with 46.14 kJ, which is 249.81% higher than non-hybrid BBB composite. The hybrid GBG composite had 32.30 kJ, which is 92.03% higher than hybrid BGB. Based on the results, the hybrid banana / glass fibres showed better mechanical properties with the incorporation of glass fibres, especially in flexural properties.

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