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Impact properties of sisal–glass hybrid laminates

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Work of fracture (WOF) of unidirectionally aligned sisal–glass hybrid laminates, especially glass core – sisal shell (SGS) laminates, have been studied using flat charpy test. Keeping the volume fraction of sisal at about 0.4, the WOF of SGS laminates linearly increased from 80.2 to 228 kJ m^{-2} by varying the volume fraction of glass at the core ($V_{g\,core}$) from 0 to 0.2. However, further enhancement in WOF has been observed when the glass core is shifted from the midline towards the tensile side of the laminate with respect to impact. The specific work of fracture (165 kJ m^{-2}) of SGS laminate at $V_{g\,core}$ 0.2 is identical to that of glass-reinforced polyester composites containing 0.6 volume fraction of glass. Addition of glass facings to SGS laminates increased its WOF by 20 to 30 kJ m^{-2} when the volume fraction of glass in the facings ($V_{g\,facings}$) was about 0.04. The increase in resistance to compressive yielding that occurs by placing glass facings above a critical size ($V_{g\,facings} \simeq 0.04$ in the present case) adversely affected the WOF of SGS hybrid laminates.

1. Introduction

Investigations on ligno-cellulosic fibre composites have shown that their properties can be better utilized in hybrid composites [1–3]. Mohan and Kishore [2] report that jute provides a reasonable core material in jute–glass hybrid laminates. The glasss skins not only enhance the mechanical properties but also protect the jute core from weathering.

Clark and Ansell [3] report improvement of various mechanical properties of jute–glass hybrid laminates with different arrangements of jute and glass plies in the laminate. The cost per unit property of different constructions has also been compared. While jute core laminates are the most cost effective from the tensile and flexural properties view point, glass core laminates offer an exceptionally low cost per kJ m^{-2} of impact energy. Hence, the studies conclude that a five-ply laminate with glass at the core and in the facings has the most balanced set of properties compared on a cost basis with other arrangements.

The high impact performance of uniaxially aligned sisal fibre–polyester composites was reported earlier [4]. During the course of the present study on sisal–glass hybrid laminates, especially glass core–sisal shell laminates, improvement upon the impact properties with glass content was studied. The effect on the impact properties of placing glass facings on the above laminates is also studied and the results are reported in this paper.

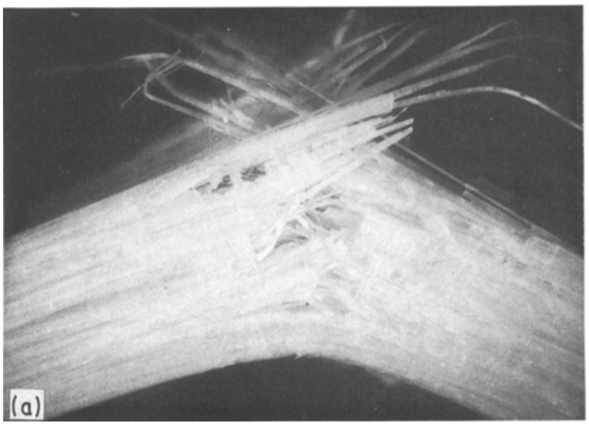
2. Experimental procedure

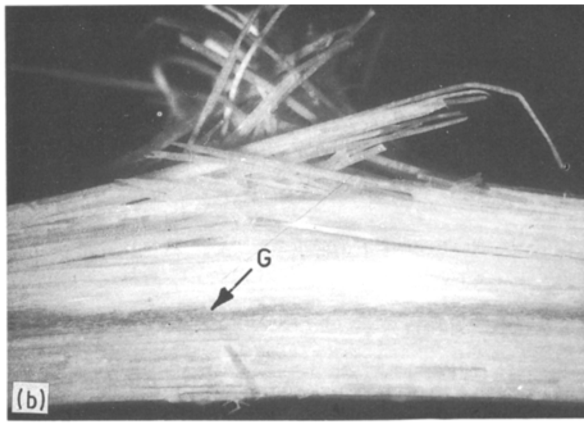
Polyester prepreg strips of unidirectionally aligned fibres were used for making sisal–glass hybrid laminates. The volume fraction of fibre in the prepreg strips was about 0.4. Test specimens measuring 4 mm × 6 mm × 50 mm and 2.4 mm × 25 mm × 70 mm for impact and flexural tests, respectively, were prepared by placing the strips of appropriate width at desired sequences in a leaky mould and then hot pressing as described earlier [4]. Glass core–sisal shell laminates and sisal core–glass shell laminates are generally designated as SGS and GSG laminates, respectively. However, a laminate specifically designated as 2S 2G 2S refers to an SGS system prepared using in total four layers of sisal/polyester prepreg strip in the shell and two layers of glass/polyester prepreg strips at the core. Similarly G 2S 2G 2S G refers to 2S 2G 2S laminate with glass facings of one strip on either side.

Volume fractions of fibre were calculated using the equation

$$V_f = \frac{(W_s/\rho_s) + (W_g/\rho_g)}{(W_s/\rho_s) + (W_g/\rho_g) + (W_r/\rho_r)} \qquad (1)$$

where W_s, W_g and W_r are the weight fractions of sisal, glass and resin, respectively, which were determined by knowing the weight of each component in the prepreg strips and weighing the laminates after curing and polishing the edges free of unreinforced resin formed in the leaky mould process. The density, ρ_g (2.55 g cm^{-3}) of glass was taken from the suppliers data sheet and ρ_r (1.21) of cured resin was determined by the water-displacement method. The density of sisal ($\rho_s = 1.05$) was calculated from the density of its pore-free composite following the method used by White and Ansell [5] for straw–polyester composites. The volume fraction of sisal in all the laminates was calculated to be around 0.4 and the variations were found to be within experimental error. Because the total volume of the laminated specimens was kept





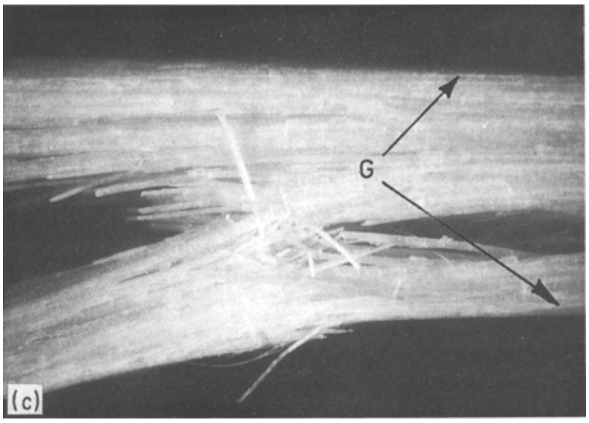


Figure 1 Fractographs of impact-tested (a) sisal–polyester composites, (b) glass core–sisal shell, and (c) sisal core–glass shell laminates.

constant irrespective of the number of prepreg layers of glass, each layer contributed about 0.02 volume fraction of glass in the hybrid laminate.

The work of fracture (charpy method) of unnotched specimens was measured using a pendulum impact tester. Flexural properties (three-point bending) were measured at a cross-head speed of $2\,\mathrm{mm\,min^{-1}}$ by employing a span-to-depth ratio of 16 according to ASTM D 970. Photographs of the fractured specimens were taken in a stereo microscope.

3. Results and discussion

3.1. Work of fracture of sisal–glass hybrid laminates: SGS compared to GSG

The results of impact testing of SGS and GSG hybrid laminates are given in Table I. SGS hybrid laminates showed higher WOF compared with GSG hybrid laminates of equivalent volume fraction of sisal and glass fibre as also observed with jute–glass hybrid laminates [3]. It can also be seen that less than 0.08 volume fraction of glass at the core (2S 4G 2S) is sufficient to attain the WOF of $135\,\mathrm{kJ\,m^{-2}}$, that obtained for a 4G 4S 4G laminate where the volume fraction of glass in the shell is 0.16. It has also been experienced that while the WOF of SGS laminate increased with glass content at the core, that of GSG laminate showed a tendency to decrease when a high glass content was provided in the shell.

Observation of impact-tested specimens (Fig. 1) showed that SGS hybrid laminates failed with crack opening at the tensile side and with large fibre pull-out similar to that observed for sisal–polyester composite. On the other hand, failure in GSG hybrid laminates occurred by delamination (which becomes more prominent with the increase in glass content in the shell) by which contribution from fibre failure and pull-out from the matrix, towards toughness of the laminate is significantly reduced.

3.2. WOF of glass core–sisal shell laminates

3.2.1. Effect of glass content at the core

Fig. 1b also shows that glass at the core of SGS hybrid laminates acts as an effective barrier for crack propagation and a plot of WOF, W, against volume fraction of glass at the core (Fig. 2) shows a linear relationship following the regression equation

$$W = 697.5\,V_f + 91.3 \qquad (2)$$

with a correlation coefficient of 0.99 which is significant at the 1% level. The WOF measured of sisal–polyester composites of 0.4 fibre volume fraction was $80.2\,\mathrm{kJ\,m^{-2}}$. The values obtained for SGS hybrid laminate show that the increase in toughness by incorporating glass at the core is more than two-fold at 0.12 V_g (2S 6G 2S) and three-fold at 0.2 V_g (2S 10G 2S).

The WOF of sisal–glass hybrid laminate is better appreciated when compared to that of synthetic fibre composites. The data given in Table II show that the specific work of fracture of glass–polyester composite ($V_g = 0.6$) can be achieved with 2S 10G 2S laminate

TABLE I Work of fracture of sisal core–glass shell and glass core–sisal shell hybrid laminates

Laminates[a]	Designation	Volume fraction of glass	Work of fracture ($\mathrm{kJ\,m^{-2}}$)
Glass shell–sisal core	2G 4S 2G	0.08	105 ± 15.0
	4G 4S 4G	0.16	135 ± 16.6
	6G 4S 6G	0.24	93 ± 11.4
Glass core–sisal shell	2S 4G 2S	0.08	141.7 ± 8.3
	2S 8G 2S	0.16	204.2 ± 5.3
	2S 10G 2S	0.20	228 ± 5.2

[a] Volume fraction of sisal ~ 0.4.

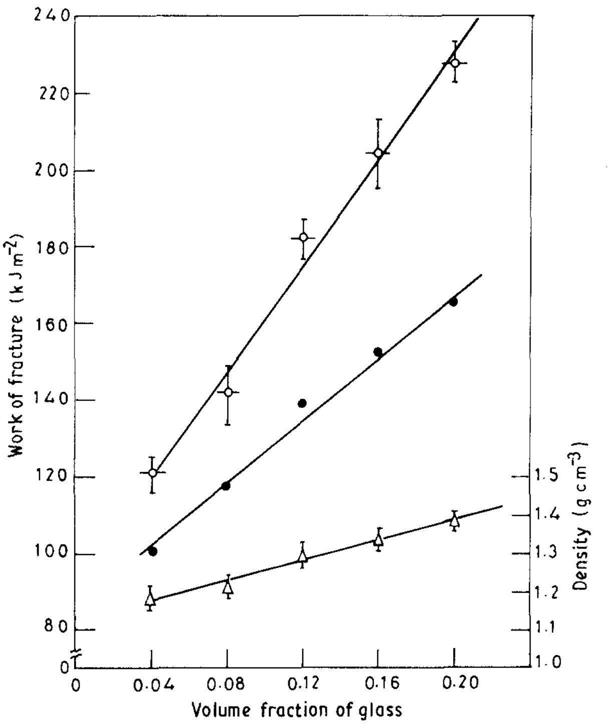


Figure 2 Work of fracture of glass core–sisal shell laminates plotted against glass content at the core (volume fraction of sisal ~ 0.4). (○) WOF, W, (△) density, ρ, (●) specific WOF, W/ρ.

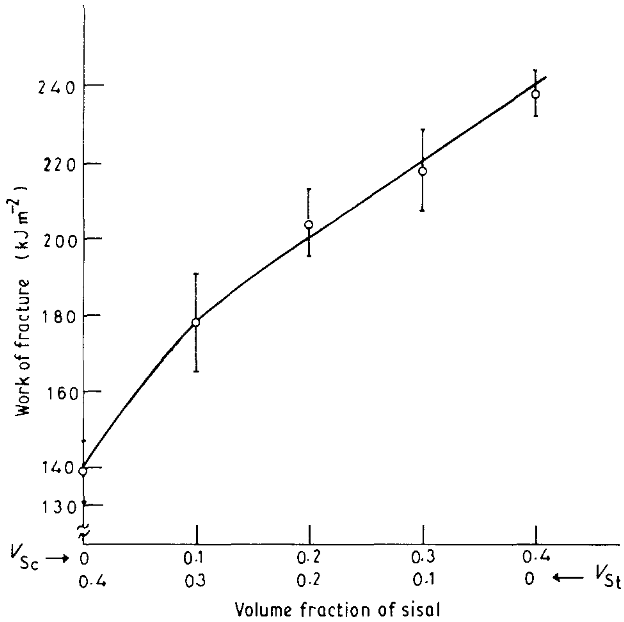


Figure 3 Variation in work of fracture of glass core–sisal shell laminates with shift of glass layer from midline (V_g = 0.16, V_s = 0.4. V_{Sc} and V_{St} denote volume fraction of sisal at the compressive and tensile side, respectively, with respect to impact).

which contains 0.4 volume fraction of sisal in the shell and 0.2 volume fraction of glass at the core. The WOF of the above laminate is also identical to ultra-high modulus polyethylene (UHMPE)/glass hybrid laminate [6] where the volume fraction of glass at the core is about 0.26.

3.2.2. Effect of asymmetry

The WOF of SGS hybrid laminates was found to be dependent on the position of the glass layer as evinced from the fact that toughness of the laminates varied significantly by shifting the glass layer from the midline. Fig. 3 shows that the toughness of the laminate increases when the glass layer is shifted towards the tensile side of the specimen with respect to the impact. The observed increase of WOF is essentially due to the tensile failure and pull-out of more glass fibre. Thus an asymmetrical arrangement with glass plies kept at the tensile side (Fig. 4) gives the maximum impact performance.

3.2.3. Effect of placing glass facings

Although glass core–natural fibre shell hybrid laminates have shown high impact performance, they are reported to have much lower environmental resistance compared to natural fibre core–glass shell laminates [3]. It is believed that the glass shell of the latter protects the natural fibre at the core from environmental attack. With this in mind, glass facings have been provided to SGS hybrid laminates. The effect on work of fracture of addition of glass facings of varying volume fractions of SGS laminates is given in Fig. 5. The results show that there is an improvement in WOF of SGS laminates by placing glass facings of fibre volume fraction ($V_{g\,\mathrm{facings}}$) of 0.04. Toughness then showed a decreasing trend with glass content in the facings. This decrease in WOF was found more

TABLE II Work of fracture of glass core–sisal shell laminates in comparison with synthetic fibre composites

Laminates[a] (polyester matrix)	Density (ρ) (g cm^{-3})	Work of fracture, W (kJ m^{-2})	Specific work of fracture, W/ρ (kJ m^{-2})
Sisal–glass (V_g ~ 0.2)	1.38	228	165
UHMPE–glass [5] (V_g ~ 0.26)	1.45	240	165
E-glass [5] (V_g ~ 0.6)	1.95	320	160

[a]Total fibre volume fraction ~ 0.6.

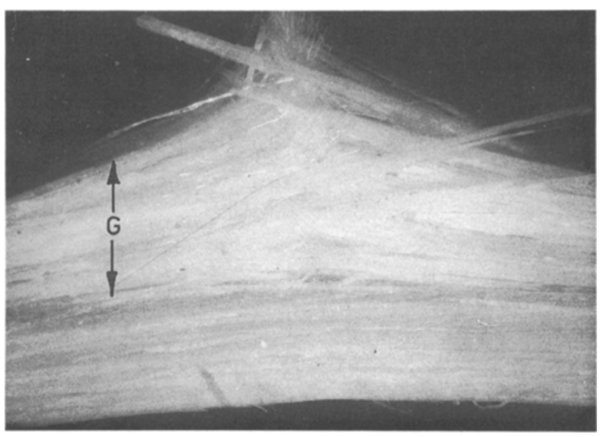


Figure 4 Fractograph of sisal–glass asymmetrical hybrid laminate tested with glass at the tensile side with respect to impact.

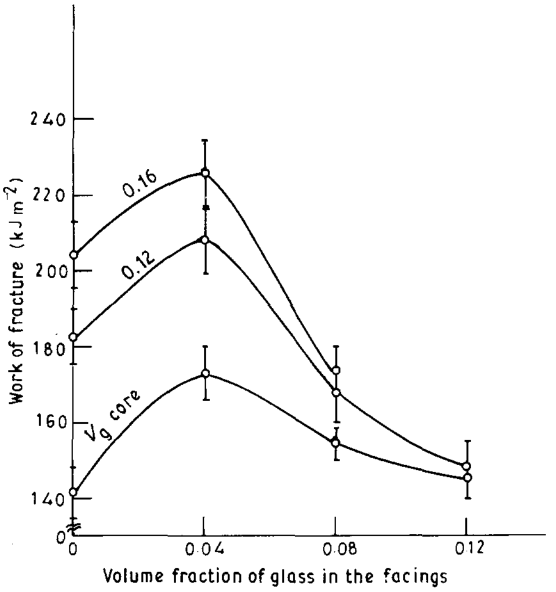


Figure 5 Effect on work of fracture of placing glass facings on glass core–sisal shell laminate containing different volume fractions of glass at the core.

TABLE III Work of fracture of glass core–sisal shell laminates with asymmetrical glass facings

Laminate[a]	Volume fraction of glass in the facings		Work of fracture (kJ m^{-2})
	Compressive side	Tensile side	
3G 2S 6G 2S 3G	0.06	0.06	148 ± 5.7
4G 2S 6G 2S 2G	0.08	0.04	137.7 ± 6.8
2G 2S 6G 2S 4G	0.04	0.08	169.2 ± 6.8

[a]Volume fraction of sisal ~ 0.4.

pronounced and drastic with increase in $V_{g\,core}$. However, by disproportionating the glass content in the facings by shifting more glass to the facings at the tensile side from that at the compressive side, the adverse effect could be made less severe (Table III).

The fractographs of the laminates with glass facings (Fig. 6) show that the glass facings prevent crack opening at the tensile face which resulted in delamination of the plies. When $V_{g\,facings}$ was kept low (0.04), delamination generally occurred in sisal layer near to the glass core as shown in Fig. 6a and there was no evidence of fibre breakage. Keeping the $V_{g\,core}$ at 0.08 and increasing the $V_{g\,facings}$ to 0.08 and above, the plane of delamination was found to be shifted to the vicinity of the glass skin. In addition to delamination, breakage of the fibres below the delaminated plane has also been seen when $V_{g\,facings}$ was 0.16 (Fig. 6b). Laminates in which both the $V_{g\,facings}$ and $V_{g\,core}$ are high were found to fail by multiple delamination (delamination in the sisal layer as well as glass core) as shown in Fig. 6c.

Flexural properties of SGS hybrid laminates given in Table IV show that the modulus of the laminates depends more on the glass content in the facings than at the core. This is essentially due to having stiffer glass in the outer layers of the former which take a greater proportion of the applied load [7]. However, the decrease in WOF observed with increase in glass content in the facings of SGS laminates can be attributed to the variations in energy absorption mechanisms as generally observed with hybrid laminates of different constructions [8] where compression damage near the load points appears to make a significant contribution for the laminates containing organic fibre composites as one of the constituents.

Marom and Chen [9] have shown that by placing glass fibre on an organic fibre composite the compressive yielding near the load points can be suppressed and this is effective at glass layers above an optimum thickness. Therefore, the initial increase in WOF of SGS laminates at $V_{g\,facings}$ of 0.04, which seems to be below the requirement to resist compressive yielding, can be attributed to the contribution from the glass fibre at the tensile side. The increase in glass content in the facings above 0.04 appears to give resistance to compressive yielding which significantly reduces its contribution towards energy absorption. As a consequence, decrease in WOF is experienced following the initial increase as shown in Fig. 5. The high WOF exhibited by asymmetrical hybrid laminates (Table III), where glass facings at the compressive side are kept low, confirm this observation. Hence the size of the glass facings provided at the compressive side, with respect to the impact, of the sisal–glass hybrid laminates should be kept below an optimum value to attain maximum impact performance.

TABLE IV Flexural properties of sisal/glass hybrid laminates

Laminates[a]	Volume fraction of glass at		Ultimate flexural strength (MN m^{-2})	Flexural modulus (GN m^{-2})	Work of fracture (kJ m^{-2})
	Core	Facings			
Sisal–polyester	—	—	192.0	7.52	80 ± 4.6
2S 8G 2S	0.16	—	280.7	12.20	204 ± 5.3
G 2S 6G 2S G	0.12	0.04	295.0	12.93	208 ± 9.0
2G 2S 4G 2S 2G	0.08	0.08	294.6	16.85	154 ± 3.7
4S 8G	Asymmetric with 0.16 glass at tensile side with respect to loading		299.2	22.79	238 ± 6.0

[a]Volume fraction of sisal ~ 0.4.

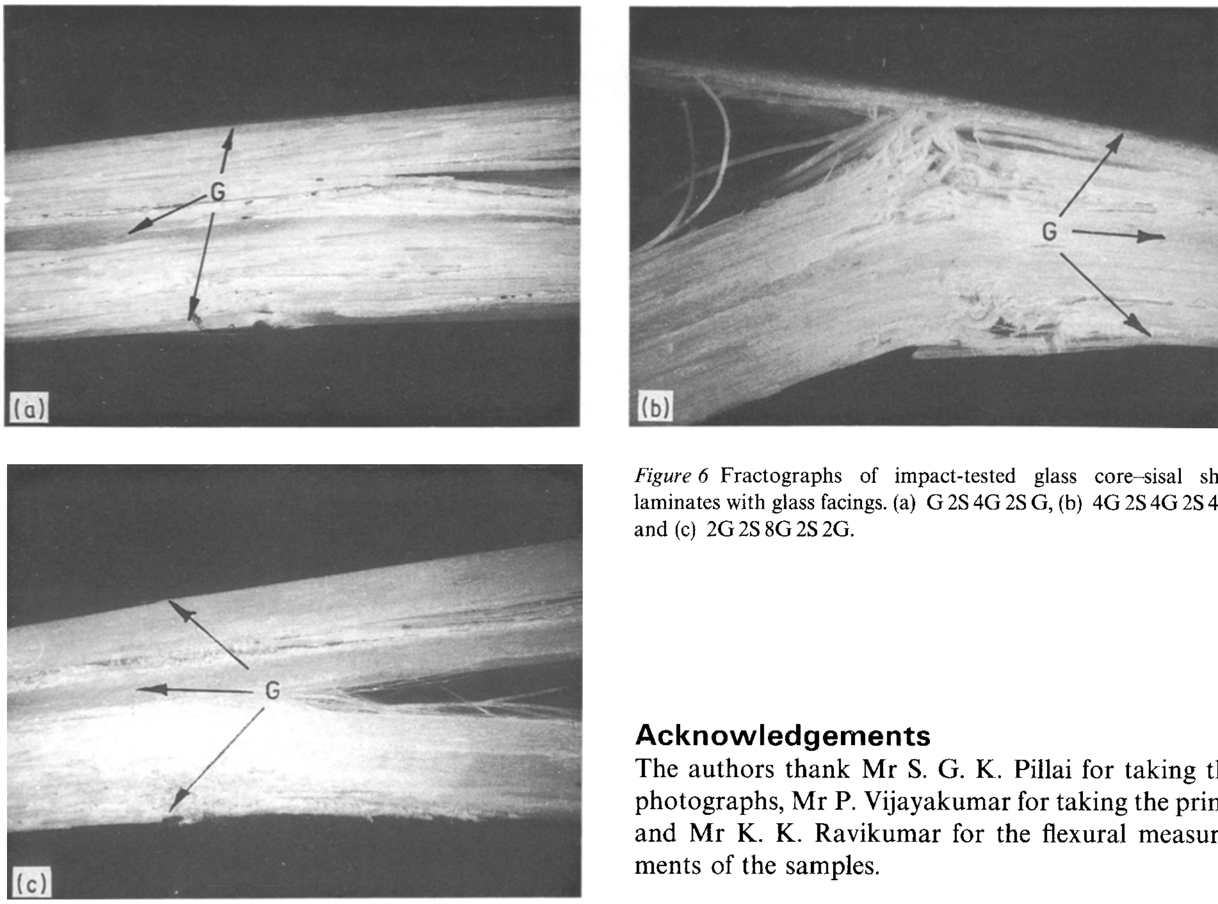


Figure 6 Fractographs of impact-tested glass core–sisal shell laminates with glass facings. (a) G 2S 4G 2S G, (b) 4G 2S 4G 2S 4G, and (c) 2G 2S 8G 2S 2G.

4. Conclusion

Hybridization of sisal fibre with glass in polyester composites, in view of improving the impact performance of the former, can be better utilized in glass core–sisal shell (SGS) laminates than in sisal core–glass shell laminates. The specific work of fracture of a whole GRP ($V_g \approx 0.6$) can be attained by an SGS laminate containing 0.4 volume fraction of sisal in the shell and 0.2 volume fraction of glass at the core. However, a still higher impact performance can be imparted to sisal–glass hybrid laminates by asymmetrically arranging the glass and sisal at the tensile and compressive side, respectively, with respect to the impact. The size of the glass facings provided to an SGS laminate, in view of improving its weatherability, should be kept below an optimum value (volume fraction of glass around 0.04), especially at the compressive side with respect to impact, to maintain its high work of fracture.

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