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REVIEW

Mechanical properties of biofiber/glass reinforced hybrid composites produced by hand lay-up method: A review

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Abstract: Hybrid composites utilize more than one kind of strands within the same matrix to urge the synergistic impact of both fibers' properties on composites' general properties. Hybridization can be performed from artificial, natural, and a combination of both fibers. The constituent filaments can be altered in numerous ways, driving to the variety in composite properties. Partial substitution of glass fiber with natural ones offers an advantage compared with glass fiber composites while permitting to obtain a mechanical performance higher than using pure natural fiber composites. Recently, researchers are tending towards the development of hybrid composites which will provide good static properties. In this context, a concise review has been done on the recent developments of natural/glass fiber-reinforced composites made by hand lay-up method. It includes a survey of the past research already available involving the hybrid composites and the effect of various parameters on composites' performance studied by various researchers.

Keywords: natural fiber, glass fiber, hand lay-up, mechanical properties

1 Introduction

Composite materials consist of two or more physically distinct phases whose combination produces aggregate properties different from those of its constituents [1] . Two significant types of fibrous materials are available: synthetic fiber and natural fiber, to enhance the properties of polymer [2] . After completion of the product life cycle, synthetic fiber-based composites show several demerits such as their recycling, reusability, and biodegradability [3] . Such properties are inevitable for sustainability in terms of environmental sensitivity. Due to these reasons, the concept of using natural fiber as the viable alternative of synthetic fiber was introduced [4] . Hybridization of the natural fiber (jute, sisal, banana, bamboo etc.) and synthetic fiber (glass, carbon, kevlar etc.) in the same matrix (thermoplastic or thermosets) is the only ways to take the best advantage from both fibers' following develop a superior but economical composite [5] . Attainment of balance in physical properties along with design flexibility is the significant advantages of hybrid composite [6] . Among various synthetic fibers, glass, carbon, and aramid, most of the researcher conducted their research on glass fiber-based hybrid composites. Physical properties of raw natural fibers, reported by researchers are listed in Table 1.

The hybrid fiber reinforced polymer composites can be manufactured by adopting various manufacturing techniques such as- hand lay-up, compression molding, injection molding, autoclave, and Vacuum Assisted Resin Transfer Molding (VARTM) process [21–23] . In order to get the desired mechanical properties of the composites, various types of matrix are usually used in hand lay-up technique. Significant mechanical properties of commonly used glass fiber and polymers are listed in Table 2.

Hand lay-up is a molding approach wherein reinforcements (woven, knitted, stitched, or bonded fabrics) are positioned by way of hand, and then polymer resin is poured or sprayed at the fiber. The present study provides a rigorous overview of recent research works conducted on natural fiber/glass biocomposites fabricated by hand lay-up techniques. Along with the brief description stated in the literature, corresponding significant mechanical properties are listed in tables. Section 2 discussed the mechanical properties investigations by the numerous researchers of mono fiber reinforced hybrid composites. Properties assessed for multi fiber reinforced biocomposites are analyzed in Section 3. Finally, concluding remarks are stated in Section 4.

Table 1 Mechanical properties of commonly used natural fiber as reinforcement in biocomposites

Fiber	Density (g/cm^3)	Diameter (μm)	Tensile strength (MPa)	Young's Modulus (GPa)	Elongation at break (%)	Reference
Sisal	1.45	50-200	468-640	9.4-22.0	3-7	[7]
Bamboo	-	10-330	440	-	1.4	[8]
Jute	1.3	25.2	393-773	26.5	1.5-1.8	[9]
Coir	1.15-1.46	10-46 mm	95-593	2-8	15-51.4	[10]
Kenaf	1.2-1.4	-	-	20	9.1-12.3	[11]
Palmyra	1.2	300-320	276$\pm$5	8.9$\pm$1.2	3.08	[12]
Flax	1-1.5	160-230	40-150	60-80	4.5-6.5	[13]
Banana	1.35	-	212	8	2	[14]
Oil Palm	0.7-1.55	50-500	100-400	1-9	8-18	[15]
Kapok	0.38-1.47	22.65	45-64	1.7-2.4	2-4	[16]
Silk	1.3-1.38	-	650-750	.016	18-20	[17]
Hemp	1.4-1.6	270-900	200-1040	23.5-90	1-3.5	[18]
Pineapple	1.52	-	413	34	1.6	[14]
Sugar Palm	-	99-311	190.29	3.69	19.6	[19]
Basalt	2.7	-	4840	89	3.15	[20]

Table 2 Mechanical properties of commonly used glass fibers and polymers for composite fabrication using hand lay-up method

Matrix	Density (g/cm^3)	Tensile strength (MPa)	Elastic Modulus (GPa)	Elongation at break (%)	Reference
E-glass	2.5	2000-3500	70	2.5-3.0	[24]
S-glass	2.5	4570	86	2.8	[24]
Epoxy	1.1-1.4	35-100	3-6	0.8-6	[25]
Polyester	1.16	8-19	0.58	1.6	[7]
Unsaturated Polyester (USP)	1.2	61	4	2.5	[9]

2 Mono fiber reinforced hybrid biocomposites

2.1 Sisal fiber

Sisal/Glass (S/G) epoxy biocomposites with fiber weight ratio 1:1 shows maximum tensile, flexural and compressive strength where the fiber length was 2 cm [26] . Alkali treated sisal fiber with 2 cm of length provided maximum strength [27] and it was reported that such specimen is more chemically resistant [28] . Characterization of silane treated S/G composite showed significantly superior tensile property [29–32] . Mechanical properties of the S/G unsaturated polyester biocomposites with the addition of chalk powder (as additive) decreases with the increasing of the chalk powder quantity [33, 34]. Hashmi et al. [35] assessed the properties of various sequenced S/G epoxy (chopped strand mat) composites and concluded that sisal paper could replace 84.5% of glass fiber to obtain an equivalent tensile modulus range. Palanikumar et al. [36] analyzed the fiber distribution (transverse and longitudinal) effects on the mechanical properties.

2.2 Bamboo fiber

Bamboo/glass (B/G) combination (4 layers) in the epoxy matrix improves the tensile strength [37] . The mechanical properties and water absorption behaviour of strand glass mat, woven glass mat reinforced epoxy, and polyester biocomposites were studied by Kushwaha & Kumar [38] . The epoxy matrix showed better tensile characteristics (increase of 19%) result than polyester matrix (increase of 15%) while reinforced with woven bamboo mats. Retnam et al. [39] investigated that the hybrid specimen with $\pm 45^\circ$ orientation yielded better mechanical (tensile, flexural and impact strength) properties. Vaghasia & Rachchh [40] prepared B/G unsaturated isopththalic polyester hybrid composites and it was found that the samples with 9% bamboo fiber showed best tensile, flexural and hardness properties.

2.3 Jute fiber

Jute/Glass (J/G) epoxy composites perform better for flexural loading (1.03 kN) [41] . Optimum tensile behavior of J/G epoxy composites were found for 30 wt % of jute fiber [42] . Gujjala et al. [43] prepared J/G composite specimens where the jute fiber direction varies (+45° to -45°) and studied the mechanical properties. Hybrid J/G composites with higher number of layers (10, 17, 18) were studied to analyze the mechanical properties [44, 45]. The addition of 16.5 wt% glass fiber in a total fiber weight fraction of 42% enhances the tensile, flexural, and interlaminar shear strength (ILSS) by 37, 31.23, and 17.6% respectively of J/G isothalic polyester composites [46] . Addition of fly ash in J/G epoxy samples enhances the tensile and flexural properties [47] . Trehan et al. [48] investigated that the alkali treatment, mixing and curing time did not significantly influence the tensile and flexural strength of J/G polyester composites. Mechanical properties of UV treated biocomposites were studied by Kafi et al. [49] .

2.4 Coir fiber

Jayabal et al. assessed the effect of different stacking sequences on mechanical properties of woven C/G unsaturated polyester composites [50, 51] and GGC and CGG combination showed maximum strength. C/G specimens with untreated coir fiber of 15 mm enhanced the mechanical properties [52] . Results concluded that surface modification of fiber, short, less/optimum fiber loading would give less water absorption, good mechanical properties, and exhibits good performances in normal conditions [53] . Untreated coir fiber length of 20 mm and fiber loadings of 40 wt% with an increase in the glass fabric content from 0 to 100% of C/G composites exhibit improved strength from 37 to 350% and for treated fiber, the strength improved by 50 to 313% [54] .

2.5 Kenaf fiber

Ramesh [11] showed that K/G composites exhibits higher tensile and impact strengths for the specimen contains 90° fiber orientation whereas 0° fiber oriented product showed flexural strength. Woven K/G unsaturated polyester composites of higher number (7) of layers with 3GK3G combination provided better performances [55, 56]. Fatigue properties were also examined by Sharba et al. [57] . Rozali et al. [58] reported that GKG unsaturated polyester biocomposites exhibits maximum flexural properties. On a contrary, KGK combination resulted in the highest water uptake and thickness swelling.

2.6 Palmyra fiber

Velmurugan & Manikandan [59] characterized the randomly mixed Palmyra/Glass (Pa/G) rooflite resin composites (disperse & skin-core type) and estimated optimum fiber length. Sravya & Sivaganesan [60] also reinforced Pa/G into the epoxy resin keeping Resin-fiber ratio at 90/10 %, while Pa/G fiber ratio was varied like 25/75%, 50/50%, 75/25%, 100/0%. Shanmugam et al. [12] found an increase of 33% in tensile, 55% flexural, and 50% in impact strength for benzoyl, permanganate, and alkali-treated bi-layer Pa/G composites, respectively, compared to untreated fiber composites. Karthikeyan et al. [61] prepared two specimens (15wt% / 10wt% and vice-versa) of Pa/G epoxy composites by varying the fiber weight ratio where epoxy percentages were 75% for both samples. Specimen with 15wt% showed the best performance compared to others.

2.7 Flax fiber

Meenakshi & Krishnaoorthy [62] reported that Flax/Glass (F/G) polyester composites showed equally good properties to conventional glass fiber composite and outperform the mono natural fiber composite. Santulli et al. [63] studied emphasized on the need to control void content and defects for better performance of F/G epoxy composites. Gupta [64] investigated the static behavior of F/G biocomposites and reported that the lay-up sequence GFGH was better than the FGFH arrangement in terms of tensile, flexural, compressive, and impact properties. Kumar et al. [65] determined the properties of 8-layered F/G epoxy composites. Ramesh [13] conducted the SEM analysis of F/G epoxy composites and reported that the specimens with 0° fiber orientation outperformed that of 90° fiber orientation. Interlaminar and sandwich structures comprising F/G sheets were used by Wang et al. [66] to study the lamination method's effect on properties.

2.8 Banana fiber

Joseph et al. [67] studied the enhancement of the physical properties of Banana/Glass (Ba/G) phenol-formaldehyde (PF) composites keeping total volume fraction constant (0.4). The maximum tensile properties were found for a vivid combination of both fiber, Tensile and impact properties of Ba/G polyester biocomposites were investigated by Pothan et al. [68] considering the volume fraction variation of glass fiber (0.03, 0.07, 0.11, 0.15, 0.16, 0.17). Batu & Lemu [69] fabricated NaOH treated false Ba/G epoxy composites and sample with volume fraction ratio 0.4 showed the highest strength. A selected length of 15 mm NaOH treated Ba/G epoxy composites showed an increase in banana fiber composition increases the high displacement to tensile load [70] .

2.9 Hemp fiber

Bhoopathi [18] and Prashanth et al. [71] fabricated Hemp/Glass (H/G) epoxy composites to evaluate various properties. Nano clay was used in the hybrid preparation to improve the composites' properties [72] . Shahzad [73] assessed the impact and fatigue properties of H/G polyester biocomposites.

2.10 Pineapple fiber

Pineapple/Glass (P/G) polyester composites was fabricated considering a constant volume fraction of fiber (P/G: 30%/70%) and analyzed the static [48] , dynamic mechanical properties [74] , and thermo-physical properties [75] . Mishra et al. [7] figured out the influence of various chemical treatments (Alkali, cyanoethylation) on P/G polyester composites' properties. Curaua fiber belongs to the pineapple plant family. Silva et al. [76] evaluated the mechanical properties degradation of curaua/glass hybrid composites due to water absorption. Water absorption of the composite was higher for distilled water (2.10%) than for seawater (1.95%). Samples exposed to distilled water showed superior tensile properties.

2.11 Kapok fiber

Reddy et al. [77] fabricated Kapok/Glass (Ka/G) polyester hybrid composites by varying the fiber ratio as 1:0, 3:1, 1:1, 1:3, and 0:1 and by keeping total fiber loading fixed at 9 vol.%. The flexural, compressive, and interlaminar shear resistance and hardness and tensile properties and impact properties of alkali-treated and untreated Ka/G composite samples were analyzed [78–80] . The Ka/G fiber ratio 1:3 gave optimum results in flexural, compressive, tensile, and hardness properties.

2.12 Silk fiber

Priya et al. [81] (Priya, 2006) experimented on Silk/Glass (Si/G) composite and evaluated the strength of the product. Within the sample, total fiber content was 25%, whereas investigation was made on the context of glass fiber. It was found that, at the fiber ratio of 50/50 the strength seemed to have almost doubled. Yang et al. [82] fabricated three groups of Si/G unsaturated polyester composites with small, medium and large fiber crepe to investigate the optical and mechanical properties and the investigated result reveals that the lamination structure does influence on the flexural property.

2.13 Sugar palm fiber

Sapuan et al. [19] fabricated Sugar palm/Glass (Su/G) reinforced unsaturated polyester composite for various fiber weight ratios (Su/G = 4:0, 4:1, 4:2, 4:3, 4:4, and 0:4) and characterized the specimen with respect to the fiber content. Among all samples, the 4:4 weight ratio exhibits the best result. The influence of chemical modification (Benzoylation) on flexural and compressive properties of Su/G epoxy hybrid composites were evaluated by Safri et al. [83] . They varied the Su/G ratio as 100:0, 70:30, 50:50, 30:70 and 0:100. Composition of 30:70 held the best flexural and compressive properties.

2.14 Basalt fiber

Sapuan et al. [84] investigated the physical properties of Basalt/Glass (Bas/G) unsaturated polyester biocomposites where longitudinal basalt fiber was used. Among all wt %, combination Bas22.5/G7.5 sample depicted optimum properties. Bas/G polyester composites characterization for various layering arrangement was reported by Patel et al. [85] . Sample with the mix stacking sequence showed better properties than plain basalt and plain glass polyester composite.

3 Multiple fiber reinforced hybrid biocomposites

Ramesh et al. [86, 87] evaluated that the S/J/G polyester samples with 0° fiber direction performed better than that of 90° oriented samples. Ramnath et al. [88, 89] figured out the influence of fiber orientation and composition variation on the mechanical properties with the volume fraction of the up to 0.40. It was found that the flexural modulus exhibits highest value.

The sample having a more significant percentage of abaca content with 45° fiber orientations resulted in optimum tensile and flexural properties. Study reported that the B/J/G reinforced epoxy composites shows better ultimate strength, flexural stiffness, percentage of elongation, and ultimate shear strength than B/G or J/G composites [90] . Rajesh & Pitchaimani [91] analyzed the B/J/G polyester biocomposites where glass fiber was used in woven format and natural fiber as the mat form. Results revealed that such hybridization enhances the impact and damping properties significantly rather than on tensile and flexural properties. Parandaman et al. [92] assessed the characteristics of B/J/G epoxy composites. Chandramohan et al. [93] examined the mechanical properties, water absorption resistance, and abrasion response of B/J/G polyester matrix with a fiber matrix ratio of 50:50. The maximum tensile, flexural, impact, and shear values were found for GBJBJG stacking combination. Pani et al. [94] fabricated six-layered biocomposites with fiber and epoxy ratio maintained 35%:65%. The $[G/B/J]_s$ specimen followed by the degradation of its flexural properties (strength by 42% and modulus by 33%). Bhoopathi et al. [95–97] characterized the Ba/H/G epoxy composites with and without the fiber chemical treatment where untreated combination revealed the maximum flexural and impact properties. Chaithanyan et al. [98] prepared C/S/G reinforced isophthalic polyester composites on a volume fraction basis of 0.4 & 0.5 and determined their mechanical properties. The breaking load of S/G biocomposites is 110% times greater than S/C/G composite. A/Ba/G bisphenol composites exhibit better flexural strength [99] and A/Ba/G reinforcement in resin of Ortho-Phthalic acid shows better tensile modulus [100] . Ramnath et al. [90] fabricated and characterized J/F/G composites and it was found that the specimens had excellent properties under tensile, flexural loading. H/F/G epoxy composites resulted better mechanical properties than J/G, H/G, F/G, J/H/G, and H/F/G epoxy composites [101] . Study on J/P/G epoxy composites revealed that the tensile and flexural properties were increased with the higher fiber content [102, 103].

Table 3 and Table 4 lists the significant mechanical properties of mono biofiber/glass fiber and multiple fiber reinforced hybrid composites, respectively.

Table 3 Reported works on mechanical properties of mono fiber/glass fiber reinforced polymer hybrid composites

Fiber	Matrix	Tensile strength (MPa)	Tensile Modulus (GPa)	Flexural strength (MPa)	Flexural Modulus (GPa)	Impact strength	Elongation at break (%)	Micro Hardness	Reference	Related Research(s)
Sisal	Epoxy	185.25	-	232.65	-	15.7 (J/m^2)	-	-	[37]	[104] [26] [27] [28] [35]
	USP	30.26	-	76.78	3.78	5.76 (J/m)	8.2	-	[29]	-
	Polyester	101	-	139 MPa	-	148 (J/m)	-	-	[105]	-
Bamboo	Epoxy	93	5.3	160	6.5	-	-	23.4	[106]	[37] [107]
	Polyester	243	10.75	-		-	-	-	[77]	-
	UIP	108	0.75	255	760.2 MPa	-	-	48.5	[40]	-
Jute	Epoxy	82	4.8	130	6.4	-	-	-	[43]	[86] [70] [45] [47] [108] [109]
	USP	32	1.85	-	-	40 (kJ/m^2)	-	-	[49]	[9]
	Polyester	125	12.5	160	12.5	-	-	-	[44]	[48]
Coir	Epoxy	17	1.8	62	-	-	-	22	[52]	[53]
	USP	49.4	1.45	71.4	2.88	97.5 (kJ/m^2)	12.5	-	[50]	[51]
	Phenolic Resin	33.63	6.97	170	9.75	-	-	-	[65]	-
Kenaf	Epoxy	69.86	-	162.566	-	6.66 (J)	-	-	[87]	-
	USP	195	95	275	195	-	2	-	[55]	[56] [57] [58]
Palmyra	USP	57.53	2.26	91	17.23	29.49 (kJ/m^2)	-	-	[12]	-
	IRR	138	4.80	245.56	8.47	10.80(J/cm^2)	-	-	[110]	-
	Rooflit Resin	26.3	1.31	39.85	1.34	1.76 (J/cm^2)	3.2	-	[59]	-
Flax	Epoxy	82.71	-	143.99	-	4 (kJ/m^2)	-	-	[13]	[64] [65] [66] [63]
	Polyester	83.75	-	83.75	-	14.33 (J/m)	-	-	[62]	-
Banana	Epoxy	132	1.35	165.5	-	-	-	-	[69]	[111] [70]
	Polyester	98	1.89	-	-	84 (kJ/m^2)	-	-	[68]	-
Oil palm	Epoxy	83	2.1	-	-	80 (kJ/m^2)	6.4	-	[112]	-
	PF	90	2.7	99	0.95	220 (kJ/m)	6.3	-	[15]	-
	Polyester	58	4.8	105	7.4	16 (kJ/m^2)	3.0	115.5 HRB	[113]	[114] [115]
Hemp	Epoxy	39.3	-	0.32 KN	-	6.45 (J)	-	-	[71]	[18] [72]
Pineappale	Polyester	102.1	2.73	-	-	1150 (J/m)	5.8	-	[48]	[74] [75] [105]
Kapok	Polyester	107	2.36	222.5	12.55	14.7 (J/m)	-	124 HRB	[?, ?]	-
Silk	Epoxy	84.04	1.0	115	5.40	-	14.33	-	[81]	[82]
Sugar Palm	USP	61.69	8.12	151.34	7.28	4.90 (kJ/m^2)	1.36	-	[19]	-
	Epoxy	-	-	56.93	3.57	15 (J)			[83]	
Basalt	Polyester	270	7.10	946.46	44.89	-	2.35	-	[84]	[85]

Notes: UIP = Unsaturated Isopththalic Polyester; IRR = Isophthalic Rooflit Resin; PF = Phenol Formaldehyde

Table 4 Reported works on mechanical properties of multiple fiber/glass fiber reinforced hybrid polymer composites

Fiber	Matrix	Tensile strength (MPa)	Tensile Modulus (GPa)	Flexural strength (MPa)	Flexural Modulus (GPa)	Impact strength	Elongation at break (%)	Reference
Sisal/Jute	Polyester	232.12	-	308.56	-	18 (J)	14.4	[87]
Sisal/Jute	Epoxy	23.29	2.08	59.80	3.14	15.01(kJ/m^2)	-	[92]
Abaca/Jute	Epoxy	57	0.29	12.1	1.45	12 (J)	18.182	[88]
Banana/Jute	Epoxy	42.24	2.65	72.93	4.70	26.35 (kJ/m^2)	-	[92]
Banana/Jute	Polyester	25.4	0.604	15.6	1.215	500 (J/m)	-	[91]
Bamboo/Jute	Polyester	78.86	3.581	133.68	2.75	24.59 (J)	-	[93]
Banana/Hemp	Epoxy	62.34	-	1.25	-	10 (J)	-	[97]
Coir/Sisal	IP	65	.360	132.15	0.99	1.4 (kJ/m^2)	34	[98]
Banana/Abaca	Bisphenol-A	57.32	.325	106.82	0.433	0.922 (kJ/m^2)	-	[99]
Banana/Abaca	PROC	97.28	.56	82.849	0.221	1.09 (kJ/m^2)	-	[100]
Flax/Jute	Polyester	56.88	0.33	134.05	1.233	1000 (J/m)	14.8	[89]
Hemp/Flax		45	1.5	43	0.6	4 (kJ/m^2)	5	
Hemp/Jute	Epoxy	43	1.47	90	0.75	7 (kJ/m^2)	4.6	[101]
Hemp/Jute/Flax		60	2	67	1.25	10 (kJ/m^2)	6	
Jute/Sisal/Flax	Epoxy	69.30	2.13	136.06	10.07	-	-	[113]
Jute/Pineapple	Epoxy	70	.82	240	-	-	-	[102]

Notes: IP = Isopththalic Polyester; PROC = Phenolic resin of ortho-phthalic acid

4 Conclusion

Hybridization of natural and synthetic fiber with hand lay-up technique outperformed others in terms of operational complicacy. Several key concluding remarks of this review works are (i) epoxy and polyester were used mostly as matrix rather than other polymers, (ii) specimen with glass fiber at the outer surface exhibits better characteristics than other stacking sequences, (iii) mechanical properties increase linearly for upto certain amount of fiber content, then decreases gradually, (iv) samples with 0° fiber orientation provided better results than other directional laminates or samples with chopped fiber, (v) surface modification of the fiber improved the mechanical properties of the composites, (vi) multiple fiber reinforced composites exhibit better quality than mono fiber-based product, (vii) jute fiber is most commonly used as one of the fibers in multiple fiber-based hybrid composites.

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