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Hybrid Polymer Composites Of Bio-Based Bast Fibres With Glass And Basalt Fibres For Structural Applications—A Review

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Abstract

Natural fibres, as replacement of engineered fibres, have been one of the most researched topics over the past years. Composites with reinforcements based on bast fibres such as flax, hemp, jute and kenaf offer many advantages such as weight reduction, improved specific impact, flexural, acoustic properties, biodegradability, renewability and their abundant availability. Their position is well established, especially in the nonstructural applications. However, in structural applications of composites, their mechanical property profile is not comparable to the dominant reinforcements such as glass and carbon fibres. The low mechanical properties of these composites could be improved by hybridization that involves adding high-performance fibres to the bast fibre composites. The review presented in this article provides an overview of the developments in the field of hybrid polymer composites composed of bio-based bast fibres with glass and basalt fibres.

Keywords: Bast fibres, Basalt fibre, Hybrid Composites, Mechanical Analysis, Synthetic Fibres

Introduction

Currently, there is an increasing trend to use natural fibres as reinforcements in polymer composites due to their advantages of combining low density, low cost, environmental friendly, good thermal and acoustic insulation and acceptable specific mechanical properties in addition to the renewability, biodegradability and abundant availability[1–4]. Natural fibres (as flax, jute, hemp, bamboo, kenaf, sisal, ramie etc.) are largely investigated as an alternative, involving total or partial substitution of synthetic fibres (as glass, carbon, kevlar etc.) in several applications[5,6]. Despite the attractiveness of natural fibre reinforced composites (NFRCs), they exhibit some drawbacks, such as large variability, lower mechanical properties, lower impact resistance and poor moisture resistance compared with synthetic fibre reinforced composites (SFRCs)[7-9]. Among these natural fibres, flax fibre is considered one of the most promising materials because of its wide commercial availability in the required form at a low cost and the comparable specific mechanical properties to those of glass fibres[10-12].

In recent years, basalt fibre, which is a natural mineral fibre obtained from basaltic volcanic rock, have often been proposed as an alternative to glass, in view of some significant advantages such as high mechanical strength, high temperature resistance, high chemical stability, good resistance to weather, non-combustibility and non-toxicity. Due to these merits, several studies have reported on using basalt fibres as a reinforcement phase in polymer matrix composites[13–15]. The major disadvantages of basalt fibre are its higher density and cost compared with E-glass fibre. Hybrid composites are designed to maintain the advantages of its constituents and alleviate some of the disadvantages[16–17]. The hybridization of different fibres is a successful approach to address the lack of the ductility in composites[19].

Hybridization of natural fibres with stronger synthetic ones can overcome the drawbacks, i.e. can enhance the strength, stiffness and moisture resistant behavior of the composite[20]. Hybridization of flax fibre reinforced composite with glass fibre revealed a much higher impact performance with the benefits of having lower environmental effects than pure glass fibre reinforced laminates[21-24].

Table 1. Mechanical Properties And Sustainability Characteristics Of Carbon, Glass, Basalt And Bast Fibres[18,25,26].

Fiber	Density	Diameter	Tensile Strength	Tensile Modulus	Cost [18]	Elongation at Break	Renewability	Health Risks
	(g/cm^3)	(µm)	(MPa)	(MPa)	(€/kg)	(%)		
Carbon	1.80	5–10	2000–5000	200–600	26–34	1.5–2	No	Yes
Glass	2.50	5–25	1700–3500	65–72	0.42–2.56	2.5	No	Yes
Basalt	1.40	10–20	2800–3100	80–90	0.34–3.42	3.1	Yes	No
Flax	1.2–1.5	12–20	400–600	12–25	1.3–1.4	1.2–1.6	Yes	No
Hemp	1.3–1.5	25–500	300–700	20–70	5–10	1.6	Yes	No
Kenaf	1.1–1.2	30–40	150–250	10–20	1–3	2.7–6.9	Yes	No
Jute	1.3–1.5	17–20	350–780	20–30	1.2–1.6	1.8	Yes	No

The aim of this paper is to review the literature contributions about the hybridization of bast fibres with high-performance, synthetic (glass and carbon), and natural (basalt) fibres in polymer matrices and the influence of their hybridization on the composite properties.

Hybrid Composites

Hybrid composites have two or more different fibre types simultaneously as reinforcement in one matrix[27,28] and the choice of the hybrid reinforcements depends upon which shortcoming of the composite needs adjustment in a particular application. The properties of the hybrid composites depend upon several factors such as fibre content, fibre length and orientation, fibre–matrix interaction, fibre stacking sequences, and the properties of individual constituents of the composites. Important factor is the proportions of the different fibre types in the reinforcement[29,30]. Hybridizing natural fibres with high strength fibres in polymer composites provides an excellent opportunity to improve their property profile for structural applications[31,32].

Another attractive reinforcement that is slowly making its mark in the composites is basalt. Basalt fibres (Figure 1) are natural inorganic fibres made from basaltic rocks. Table 2 shows a comparison of the chemical composition of glass and basalt fibres.

Figure 1. Various Basalt Products (Fibres, Rocks, Laminates) From Basaltex Displayed At Composites Europe, Stuttgart, Germany 2019

Table 2. Chemical Composition Of Basalt And Glass Fibres[46].

Element	Oxide	Basalt Fibers		Glass Fibers	
		Element (m%)	Oxide (m%)	Element (m%)	Oxide (m%)
Al	Al_2O_3	9.17	17.35	6,3	11.86
Si	SiO_2	19.76	42.43	27.24	58.25
Ca	CaO	6.35	8.88	15.05	21.09
Fe	Fe_2O_3	8.17	11.68	0.21	0.30
K	K_2O	1.94	2.33	0.36	0.43
Mg	MgO	5.70	9.45	0.32	0.54
Na	Na_2O	2.81	3.67	0.22	0.30
Ti	TiO_2	1.53	2.55	0.25	0.41

Additional advantages of basalt over glass fibres are their better environmental profile and no health hazards during processing. They are inert and have been classified as non-toxic and non-carcinogenic. In Europe and the US, they are available as safe material. However, care in handling is recommended [33-38].

Factors Affecting Hybridization Of Natural Fibres In Polymers

The properties of natural fibre reinforced polymer composites are influenced by certain factors associated with the natural fibres:

Hydrophilicity

Natural fibre reinforced composites tend to take up moisture from the environment because of the hydrophilic nature of the natural fibres. They can absorb up to 5–15 wt % of moisture. Moisture absorption can cause dimensional variations, poor fibre–matrix interaction and poor fibre dispersion in the matrix[39]. These issues with natural fibres result in composites with inferior mechanical properties.

Poor Thermal Resistance

Natural cellulosic fibres are mostly used in low-temperature applications because of their low thermal stability. Their maximum processing temperature is usually 200^0 C. This limits their applications because they cannot be processed by all the manufacturing methods, especially those involving high-temperature exposure[40].

Naturally Existing Variations And Biodegradability

The mechanical, physical, and chemical properties of cellulosic fibres depend strongly on the harvest, climate, location, weather conditions, and soil characteristics. These are naturally occurring irregularities and almost impossible to control[41].

Literature Review

The use of bast fibres is common in non-woven fabrics, molding compounds and composite components especially in the automotive industry as door panels, headliners, seat backs, etc. They have very similar microscopic structure as can be seen in Figure 2.

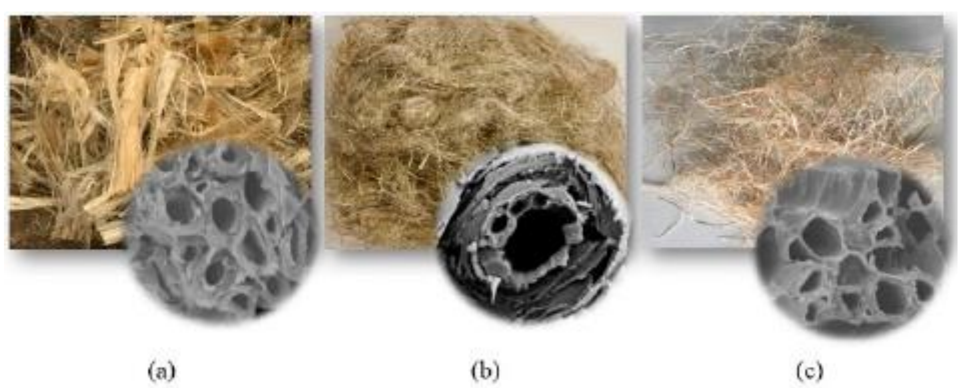

Figure 2. Short (a) Kenaf, (b) Flax and (c) Hemp Fibres And Cross Section Of A Fibre Bundle (Modified Illustration)[4].

The choice of a single fibre for a certain application depends upon factors such as availability or part geometry e.g. flax is flexible and preferred for complicated geometries.

Hybrid Bast/Glass Composites

The stiffness of some of the bast fibre reinforced composites is found to be superior to the glass fibre reinforced composites. The mechanical performance of bast fibre reinforced composites could be improved by replacing a part of bast fibres with glass fibres, which have high strength and reproducible characteristics[42].

Flax/Glass

Barvarz et al.[43] investigated the mechanical and aging properties of flax/glass hybrid composites of PP. The results showed that the mechanical properties improved by increasing the glass fibre content. There was a significant improvement in the tensility, impact resistance, and hardness of the hybrid composites. However, the strain at yield and the elongation at break were almost unaffected by adding glass fibres. Glass fibres also enhanced the water resistance of the flax reinforced composite. The analysis of the composites by UV ageing test showed that the glass fibres accelerate the degradation of the PP matrix, but flax fibres can protect the composites.

Saidane et al.[44] presented a hybrid composite of glass and flax fibres in the epoxy matrix. They reported a positive hybridization effect manifested by the increased tensile modulus and strength for hybrid composites. The composites were immersed in water at 55^0 C for the analysis of water resistance and the acoustic emission coupled with scanning electron microscope was used to identify the typical damage mechanism. They evaluated the damage mechanism by hit number and acoustic energy. The results showed that even if the number of hits associated with fibre failure was less, their contribution to the failure was significant in terms of cumulative acoustic emission energy.

Calabrese et al.[45] studied the mechanical stability and durability of hybrid flax/glass epoxy composites. The aim was to use these materials for structural applications in the marine environment. The hybrid composites were compared with the individual glass and flax fibre reinforced composites, as well. All samples were tested for aging in a salt–fog environment for 60 days. The hybrid composites showed improved flexural strength, modulus and an improved aging resistance indicating a positive effect of hybridization.

Kumar et al.[46] studied the hybrid composites of biaxial glass and woven flax fabrics in vinyl ester resin. The composites with various stacking sequences were manufactured via vacuum-assisted resin transfer molding. The mechanical properties such as tensile, flexural and charpy impact energy were better for hybrid composites. The tensile strength of pure glass fibres composite was lower than the hybrid glass/flax composite.

Jute/Glass

Abdullah et al.[47] presented their work based on hybrid composites of jute and glass mats as reinforcement in unsaturated polyester resin. They reported improved mechanical properties by the addition of glass fibres in the jute fibre reinforced composites. The composite with a jute to glass ratio of 1:3 was best in the mechanical performance. They showed an increase of 125% in tensile strength, 49% in modulus, 162% in flexural strength, and 235% in flexural modulus over the jute composites. The glass and carbon fibres were treated under UV radiation of various intensities, as well. The properties of treated fibres hybrid composites were higher and impact strength was nearly equal to that of only glass fibre reinforced composites.

Ahmad et al.[48] studied the hybrid composites of jute and glass fibres as woven mats in the polyester matrix. The composites were prepared by hand layup method at room temperature. The composites were studied for their impact, tensile, flexural, interlaminar shear strength, and water resistance properties. It was found that the addition of glass fibres to jute fibre composites improved all the measured properties.

Braga et al.[49] described the investigations on hybrid composites of jute and glass fibres in an epoxy matrix. The analysis of the composites showed a significant improvement of the tensile, flexural, and impact strength with a decrement in the moisture absorption for the hybrid composite.

Hybrid Bast/Basalt Composites

Hybrid composites of bast/basalt fibres provide an excellent opportunity to improve the mechanical property profile of bast fibre reinforced composites without reducing the amount of their natural content.

Flax/Basalt

Boria[50] investigated the experimental study to model the falling weight impact properties of thermosetting composites. Despite the complexity in the model, it was possible to predict the contact forces and final deformation of the composites. The composites were manufactured using a partially bio-based vinyl ester resin with flax and basalt reinforcement by hand layup and resin infusion. The curing was done in an autoclave by applying heat and pressure. The composites were tested for their tensile and flexural properties. The tensile performance showed a significant improvement when the flax fibre layers are used as the core between basalt fibres. The advantage of this combination was that it reduced the stiffness and brittleness of the basalt fibres.

Zivkovic et al.[51] studied the hybrid composites of basalt and flax in a vinyl ester matrix. The composites were prepared by hand layup process. The mechanism of energy absorption was studied by SEM analysis of the damaged surface and cross-section. It was found that the hybrid composites had significantly improved impact properties compared to the single flax fibre composite.

Sarasini et al.[52] manufactured laminates with a hybrid intraply woven fabric based on flax and basalt fibres. The aim was to improve the low-velocity impact response of natural fibre composite. They used both thermoset (epoxy) and thermoplastic matrices (PP) for the production of the laminates. It was observed that the energy absorbed and the damage mechanism is significantly affected by the matrix used. The influence of low transverse strength of flax fibres on impact response was counteracted by the hybrid fibre structure, irrespective of the matrix type. Thermoplastic laminates showed better quasi-static properties, energy absorption, peak force, and perforation energy compared to the epoxy-based composites.

Jute/Basalt

Amuthakhanan et al.[53] studied various stacking sequences of basalt and jute fibres in hybrid composites prepared by compression molding. The composites were analyzed for their tensile, flexural, and impact behaviour properties. It was observed that the tensile and flexural properties were better for the composites having alternating layers of basalt and jute fibres. SEM was used to study the fracture morphology.

Parasath et al.[54] manufactured composites of basalt and jute fabric in a polyester matrix by compression molding. The composites were prepared in various stacking sequences. They were analyzed for their tensile, flexural, and charpy impact properties. It was concluded that the hybrid basalt composites have higher tensile and flexural properties than the jute composites, whereas the jute fibre composites have better impact properties.

Fiore et al.[55] studied the aging resistance of jute/basalt hybrid laminates. The composites were manufactured by vacuum-assisted resin infusion. The influence of the aging time on the mechanical properties was studied by flexural and low-velocity impact analysis. It was found that the substitution of the external jute layer with basalt layer (sandwich-like arrangement) gave the best results to enhance the durability of the composites exposed to salt-fog conditions.

Gangapa et al.[56] manufactured hybrid jute/basalt composites to combine the high tensile and modulus properties of basalt with antistatic properties of jute in polyester resin. The composites were manufactured by hand layup and compression molding technique and tested for their tensile and flexural properties in warp and weft direction. They compared the results of the 2- and 3-mm thick hybrid composites with each other. The tensile properties of 3 mm thick sample were less than the 2 mm thick samples, whereas, 3 mm thick sample had higher compression strength. This increase and decrease of the properties were attributed to the variation in fibre reinforcement.

Applications Of Hybrid Composites

The most widely used composites in automotive industry are glass fibres reinforced composites. Hybridization provides an opportunity to substitute partially, if not fully the glass fibre content of the composites with natural fibres[57]. Furthermore, natural/glass fibre hybrid composites have manifested reduced moisture absorption compared to the natural fibre composites increasing their chances in structural applications[58,59]. Flax/glass hybrid composite in epoxy was studied for marine applications and showed enhanced aging durability in marine environmental conditions[58].

Basalt fibres are considered a natural alternative of the glass fibres. Hybridizing basalt fibres with bast provides a completely natural alternative to the hybrid bast/glass fibre composites. Basalt fibres other than providing enhanced mechanical strength and environmental benefits, improve the high-temperature resistance of the composites. An important parameter for safety is the inflammability of the materials. Basalt fibres, along with enhancing the mechanical property profile of the composites, have the potential to improve their inflammability characteristics[60]. Their use in other applications is also attractive and efforts are ongoing to apply them in, for example in the biomedical area[61] or even construction sector, as well.

Conclusions

Hybridization of natural fibres with glass, carbon, or basalt is a good opportunity to manufacture bast fibre composites with enhanced mechanical properties. There is good possibility to overcome the limitations of bast fibre composites in structural applications. The main findings of the review are:

1. Hybridization improves the properties of hybrid composites compared to the conventional single bast fibre composites and is an effective method that can be employed to tailor properties of bast fibre-reinforced composites for structural applications.
2. Hybrid composites of bast fibres with high strength fibres show a simultaneous increase in mechanical property profile and reduction of water absorption.
3. The fibre layers and their stacking sequence have a significant influence on the mechanical performance.
4. Hybridization with basalt fibres instead of carbon or glass provides a more sustainable alternative for the improvement of mechanical properties because of the environmental friendliness and sustainable properties of basalt fibres.

It is recommended that future research in this field should not only be driven by the automotive applications of hybrid bast composites, but also their applications in other important fields such as construction and biomedical need exploration. Modern analysis methods, such as X-ray photoelectron spectroscopy or atomic force microscopy and analytical models, are required for the optimization of their widespread applications.

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