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A Review on Properties of Basalt Fiber Reinforced Polymer Composites

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Abstract Recent days natural fibers are increasingly projected as an alternative to traditional synthetic fibers (glass and carbon fiber) which has an adverse effect on the environment. Among the various natural fibers (plant, animal, mineral etc.) basalt fibers have extensively used in various fields of engineering and a lot of research activities has been carried out to study the material properties of basalt fibers by reinforcing it with polymer matrix materials. Basalt fibers are mineral fiber with mechanical properties near or above glass fibers and low cost when compared to carbon fibers. There is a need for research on composite materials which is indeed helpful in solving the problems of society/ industrial sector. This article presents an overview on material properties such as mechanical properties under static and dynamic loading, tribological properties and thermal properties of basalt fiber reinforced polymer composites.

Keywords Basalt fiber, Polymer composites, Natural fibers

1. Introduction

Composite materials are gaining a lot of attention in these days because of their unique properties which are being achieved by reinforcing fiber with a binding matrix material. There is a lot of scope and demand for composite materials in different fields of engineering. In the past few years, researchers are working for the development of sustainable composites, which can be reinforced with natural fibers. Natural fibers are found to be a suitable alternative to traditional glass fibers which can be used as a reinforcement material. Natural fibers have lot of advantages when compared to glass fibers because of their low cost, high strength-to-weight ratio, low density, low energy content, resistance to breakage during processing and recyclability etc. [1].

Basalt fibers are not biodegradable but still considered as natural, because they can be produced by using basalt rocks, which has been found globally. Basalt is a natural material that is found in volcanic rocks originated from frozen lava, with a melting temperature ranging from 1500°C to 1700°C [2]. Basalt fibers usually have a diameter ranging from 9 to 13 micrometers and are ideal for replacing asbestos fibers, since their diameter is significantly greater than the respiratory limit (about 5 micrometer) [3]. The process technology used to produce basalt fibers is almost similar to that of glass fibers. The manufacturing process used to produce basalt fibers do not requires additives to be added and consumes less energy, which makes it cheaper than traditional glass or carbon fibers [4, 5]. The rock is first pre-treated and then melted to obtain continuous basalt fibers. The melted basalt rock flows into one or more bushings which contain more number of orifices and filaments are formed as the molten basalt rock passes through these orifices [6]. Continuous basalt fibers are produced by spinneret method (Figure 1) similarly to glass fibers [5]. Researchers [2, 7] have reported about the melt spinning method on dielectric heating in order to produce basalt fibers on laboratory scale, which was proposed by several other authors.

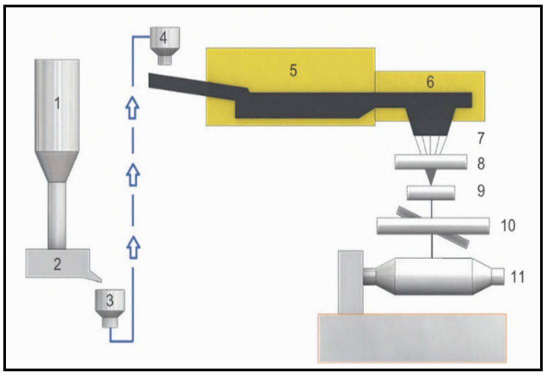

Figure 1. Steps involved in manufacturing of basalt fiber: 1) crushed stone silo; 2) Loading station; 3) transport system; 4) batch charging station; 5) initial melt zone; 6) secondary heat zone with precise temperature control; 7) filament forming bushings; 8) sizing applicator; 9) strand formation station; 10) fiber tensioning station; 11) automated winding station. [2, 7]

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As its discovery in 1923 by American scientists, basalt fibers have been found to be the material of choice for military research, defense and aeronautical applications during World War II by the United States (US), Europe and Soviet Union. In recent decades, an increasing research interest in the use of basalt fibers due to their enhanced mechanical properties has taken the polymer industry by storm. These fibers are now used in fabricating light, high-end hybrid composite materials for infrastructural and civil applications [8].

The chief constituents of basalt (Figure 2) are SiO_2 as the main part and Al_2O_3 as the second one, followed by Fe_2O_3, FeO, CaO [2, 9, 7]. Basalt fiber is also known as high-tech fiber and was developed by Moscow Research Institute of Glass and Plastic in 1953-1954. The physical, chemical and mechanical properties of these fibers are dependent on the type of raw material used, production process and characteristics of the final product [2, 6].

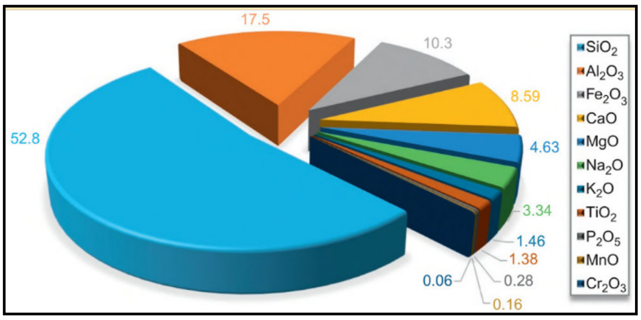

Figure 2. Chemical composition of basalt. [7]

Furthermore, basalt fibers are natural, non-combustible, eco-friendly, nontoxic, lightweight, good chemical resistance, high temperature resistance and low water absorption, alkaline, acids exposure, sound insulation properties, inexpensive and high strength, modulus and elongation to break these characteristic have made basalt fiber as a potential candidate to be used in manufacturing composites. Moreover, basalt fibers can be used from very low temperatures (i.e. about -260°C) up to the comparative high temperatures (i.e. in the range of 600 to 900°C) [8, 2, 3].

The present review focuses on basalt fibers reinforced with the thermoset and thermoplastic matrices and also their properties such as mechanical under static and dynamic loadings, tribological and thermal properties.

2. Literature Review

Several researchers have successfully reinforced basalt fibers in various matrix materials. The performance of basalt fiber reinforced with thermoset and thermoplastic polymer composites are discussed in brief.

2.1. Mechanical Properties under Static Loading

Lopresto et al. [6] compared the quasi static mechanical properties of Basalt Fiber Reinforced Polymer (BFRP) and Glass Fiber Reinforced Polymer (GFRP). The test results showed that Young's modulus value of BFRP was 35-42% higher than that of GFRP composites. Also BFRP shows better performance in terms of compressive and bending strength, impact force resistance and energy absorption capacity when compared to GFRP.

Dorigato et al. [10] compared the quasi static tensile and fatigue properties of epoxy based laminates reinforced with woven fabrics of basalt, E-glass and carbon fibers with the same areal density (i.e. 200 g/m^2). The experimental result showed that the elastic properties and stress at break of BFRP laminates were 20 and 30% higher than that of GFRP laminates. While the tensile strength values of BFRP laminates were near to that of carbon fibers based laminates. Moreover, fatigue behaviour of the laminates reinforced with basalt fabrics was found to be better, with the specific damping capacity 5-10% higher compared to glass fiber composites.

Asadi et al. [11] compared the BFRP and GFRP, the main intention was to reduce the weight and cost of the traditional GFRP sheet moulding compounds (SMC). Interfacial shear strength values of both 25 wt.% BF/epoxy (4.4±0.7 GPa) and 25 wt.% GF/epoxy (4.1±0.7 GPa) were found to be same and similar adhesion at the fiber-epoxy interface. The average modulus of the BFRP (87 GPa) found to be higher than that of GFRP (75 GPa). Furthermore, tensile and flexural moduli of BFRP were almost similar to that of GFRP. The impact strength of BFRP and GFRP were almost identical taking into account the coinciding standard deviation, even though a negligible difference of 6% in the average values.

Bulut et al. [12] studied the mechanical properties (tensile, flexural and impact resistance) of basalt fiber reinforced epoxy polymer composite laminate containing graphene nano-pellets (GnPs). The test results indicated that the incorporation of GnPs fillers at 0.1 wt.% shown higher performance in terms of tensile strength (240 MPa), flexural strength (273.91 MPa), impact strength (110 kJ/m^2) but it follows a decreasing trend for GnPs at 0.2 and 0.3 wt.% respectively. The decreasing trend in mechanical properties of the composites was mainly due to the agglomeration of fillers.

Chen et al. [13] studied the quasi- static properties of BFRP/epoxy composites. The quasi-static tensile test was conducted for BFRP composites the strength, failure strain and elastic modulus was 1642.2 MPa, 0.021 and 77.9 GPa respectively.

Scalici et al. [14] evaluated the mechanical properties of quasi-unidirectional basalt fabric reinforced with epoxy resin. Longitudinal Young's modulus and strength values were found to be increased by 7% and 10% when compared to RI and VB techniques respectively. The flexural modulus followed similar trend as that of tensile test. The main reason for such trend is that higher fiber fraction. In case of transverse tensile test, the Young's modulus value was increased by 8.5% when compared to RI samples and VB techniques respectively. The transverse tensile strength and flexural modulus values was found to be decreased by 5%

and 7% respectively, when compared to RI and VB techniques respectively. Poor impregnation of fiber might be the reason for the performance of composites. Shear test did not provided a significant difference in results of the composites.

Wu et al. [15] studied the tensile properties of BFRP/epoxy composites in corrosive environment. It was found that tensile strength and elastic modulus of BFRP composites are 47% and 16% higher than the basalt fibers. Moreover, the fracture properties of BFRP composites are governed by interface failure of fiber and the resin, which was found to be the critical factor rather than fiber only.

Shokrieh et al. [16] conducted stress corrosion study of BFRP, the test specimens were prepared by filament winding method, under bending loading and submerged in 5% sulphuric acid corrosive medium. The test specimen were tested under three states of stress, equal to 30%, 50% and 70% of the ultimate strength of composites showing that the strength of composites degrades by time. Degradation of bending modulus of elasticity for loading equal to 30% was found to be smoother but when the loading was more than 50% of the ultimate strength, the degradation of test specimens were at a faster rate. The test results were modelled using exponential functions.

Liu et al. [17] studied the tolerance of BFRP composites towards salt water immersion, moisture absorption, temperature and moisture cycling. The authors used two twill fabrics (i.e. basalt and glass) with the same weave pattern and yarn ratio in both warp and weft directions and two polymer matrix materials epoxy resin and vinyl ester were used to reinforce the composites. With respect to sea water resistance, the vinyl ester resins show comparable behaviour than epoxy composites. Furthermore, tensile and short beam test were also carried out, after 240 days ageing in salt water or water, it was found that a minor but considerable decrease in Young's modulus and tensile strength of BFRP was found. Up to 199 cycles freeze-thaw cycling did not change the shear strength significantly, but ageing in hot salt water (40°C) made the shear strength of basalt composite to decrease. The results show that the ageing of BFRP requires much more modifications.

Sfarra et al. [18] compared the damage features caused by impact on glass and basalt fiber reinforced laminates. The test results show that there was increased directionality of impact damage observed in BFRP composites, slightly superior to GFRP composites. The experimental results suggest that the production of glass/basalt fiber hybrids in different configurations, though presenting an increased manufacturing complexity, would nonetheless present additional advantages in allowing a better predictability of impact damage patterns.

Mingchao et al. [19] studied the chemical durability and mechanical properties of unidirectional basalt fiber reinforced epoxy composites. The composites were immersed in eight kinds of chemical mediums (i.e. 30% vitriol, 5% hydrochloric acid, 5% nitric acid, 10% sodium hydroxide, saturated sodium carbonate solution, 10% ammonia, acetone and distilled water) for 15, 30, and 90 days at room temperature and the monitoring of the flexural properties was carried out after each period of immersion. Experiment results showed that the corrosion behaviour of the composites differs greatly due to the different corrosion mechanisms of basalt fiber in acid and alkali mediums. In alkali mediums, the flexural modulus is very close to original value but the flexural strength declines gradually. In acid mediums both these properties declines gradually. The test results showed that the tensile strength of BFRP (640 MPa) was much lower when compared to GFRP (1029 MPa) composites. The compressive strength values were found to be closer for BFRP (836 MPa) and GFRP (895 MPa) composites. The flexural strength of BFRP is about 80% of the flexural strength of GFRP composites. Furthermore, the specimens were destroyed by tension and compression in case of BFRP and GFRP respectively. The test results of interlaminar shear strength of BFRP was higher when compared to that of GFRP, there was greater adhesion between the interfaces of BFRP composites to withstand the compressive load.

Kim et al. [20] analyzed the possibility of utilizing basalt chopped fiber in order to prepare a thermally stable fiber reinforced composites. Bi-component resin system epoxy and benzoxazine monomer were used to reinforce the basalt fibers. Copolymerization of epoxy resin upon curing with benzoxazine is carried out in the absence of a strong catalyst.

Kim et al. [21] has used basalt chopped fiber reinforced with epoxy composites with different curing systems to investigate their thermal characteristics. Two different curing systems for bisphenol F type epoxy resin an epoxy-amine curing system and an epoxy-anhydride curing system was used. It was found that tensile and flexural properties of epoxy-anhydride were found to be improved with 10% of fiber content.

Espana et al. [22] studied the influence of different silane coupling agents on the mechanical properties of basalt fiber reinforced with bio based epoxy resins. Compatibility between basalt fibers and epoxy resin was found to be increased through addition of silanes. Furthermore, the addition of silanes leads to increase in tensile strength properties by 220% when compared to that of untreated silane composite samples.

Chen et al. [23] has analyzed the importance of incorporation of functionalized multi walled carbon nanotubes (MWCNTs) into epoxy/basalt composite laminates, as a result mechanical properties of the composite laminates were improved. The elastic properties of the composite laminates, particularly in fiber direction were improved. This work also demonstrated the in situ alignment and dispersion of functionalized nanotubes in multi-scale epoxy based laminates reinforced with basalt fibers.

Kim et al. [24] analyzed the effect of the silane and acid treatments of multi-walled carbon nanotubes on the flexural and fracture behaviours of basalt fiber reinforced epoxy composites. The test results showed that the flexural modulus and strength of silane-treated carbon nanotube/epoxy/basalt composites were approximately 10% and 14% higher than those of acid-treated carbon nanotube/epoxy/basalt composites, respectively. The fracture toughness of silane-treated carbon nanotube/epoxy/basalt composites were 40% higher than those of acid-treated carbon nanotube/epoxy/basalt composites.

Lee et al. [25] investigated the tensile and thermal properties of modified carbon nanotube reinforced with basalt/epoxy composites. In this study silane modified carbon nanotube in 1% weight/woven basalt/epoxy composites were compared with the unmodified and acid modified (oxidized) carbon nanotube based composites. The test results showed that tensile strength and Young's modulus of silane modified CNT/basalt/epoxy composites were 34 and 60% higher respectively, than that of unmodified CNT/basalt/epoxy composites.

Subargia et al. [26] studied the effect of different tourmaline micro/nano particle loading (0.5 to 2 wt.%), with and without a surfactant to enhanced dispersion of the tourmaline particles, on the mechanical properties of BFRP/epoxy composite laminates. The test results revealed that incorporation of tourmaline particles in the BFRP/epoxy composites improved the tensile and flexural strength and modulus. It was found that at 1% in weight of tourmaline loading with surfactant has provided the best results. Moreover, the enhanced performances of the laminates was mainly due to good dispersion of tourmaline particles in the epoxy matrix that provided increased surface area for strong interfacial interaction and better load transfer.

Colombo et al. [27] studied the static and fatigue properties of BFRP by reinforcing it with vinyl ester and epoxy resins polymer matrices. The test results of basalt/epoxy composites showed the ultimate tensile strength, compressive strength, elastic modulus and strain at failure (due to compression) was found to be increased by 29, 84.3, 13.6 and 86% respectively, when compared to that of basalt/vinyl ester composites. Fatigue curves of basalt/epoxy composites revealed better performance.

De Rosa et al. [28] compared the post-impact performance of two woven fabric laminates, basalt/vinyl ester and E-glass/vinyl ester composites. From the test results it was found that for maximum impact energy applied (22.5 J), degradation of specimens were not exceeding more than 15% in terms of flexural strength and modulus. Furthermore, it was found that there was much more delamination area in case of E-glass/vinyl ester than on basalt/vinyl ester laminate composites.

Yusriah et al. [29] compared the effects of hollow polymeric microspheres (PHMS) on specific mechanical properties and thermal properties of glass, basalt, and carbon woven fabric reinforced vinyl ester composites. The test results showed the specific flexural strength of the carbon woven fabric/vinyl ester was found to be the significant one which shows a 193% increase in specific flexural strength when compared to that of the neat vinyl ester resin. The increasing trend in terms of specific flexural strength was followed by woven basalt and woven glass fabric reinforced with vinyl ester composites, respectively. Furthermore, the flexural modulus also shown an increasing trend for woven carbon fabric/vinyl ester followed by woven basalt and woven glass fabric reinforced with vinyl ester composites, respectively.

Manikandan et al. [30] investigated the effect of surface modifications (NaOH and H_2SO_4) on mechanical properties of BFRP/unsaturated polyester composites. It was observed that the tensile strength of BFRP composites for untreated, acid treated and base treated were found to be 9.8, 24.5 and 35.45% greater than that of GFRP composites, respectively. The impact tests showed that acid treated BFRP composites had 69.33% greater impact strength than GFRP composites.

Zhang et al. [31] studied mechanical and thermal stability of BFRP/poly (butylene succinate) (PBS) composites. The tensile test results of composites were found to be increased by 48.3% when the basalt fiber loading increased from 3 vol.% to 15 vol.% and tensile modulus of PBS matrix was found to be increased by 100% when the fiber loading was 3 vol.%. Furthermore, it was also found that adding basalt fiber to PBS matrix has remarkably increased the flexural strength and initial flexural modulus by 280% and 580% respectively, as the basalt fiber loading increased from 3 vol.% to 15 vol.%.

Černý et al. [32] studied the mechanical properties of BFRP composites prepared by partial pyrolysis (650 to 750°C in nitrogen) of precursors as polysiloxane matrix. The test results revealed that the flexural strength of the BFRP composites ranges from 620 to 820 MPa or from 405 to 510 MPa for composites pyrolyzed to 650 or 750°C, respectively. The Young's and tensile modulus ranges from 50 to 80 GPa, shear modulus ranges from 10 to 22 GPa. The shear modulus was found to be increased when pyrolysis is beyond 750°C, which indicates the increasing integrity and stiffness of the material.

Černý et al. [33] has investigated the elastic and plastic response of continuous basalt fibers (filaments or fabrics) reinforced with polysiloxane composites which were found to weaker when compared to glass fibers composites under the tensile load at elevated temperatures. The R-glass fiber retains its modulus up to 450°C and loses but 8% of its room-temperature value at 600°C which was found to be the best one when compared to basalt fibres with significant losses of modulus (10-13%) even at 450°C. After heat treatment to 750°C, the X-ray diffraction revealed that basalt fibres were affected by onset of crystallization.

Botev et al. [34] studied the mechanical behaviour of series of commercial-grade polypropylenes (PP) filled with different contents of short basalt fibers. The impact strength was four times higher than that of unfilled PP. Adhesion between the PP matrix and the basalt fibers was found to be poor. The interfacial interactions were further improved by addition of poly(propylene-*g*-maleic anhydride) (PP-*g*-MA). Furthermore, the tensile strength for the obtained materials was found to be increased by 10%, 21% and 40%, and impact strength was found to be increased by 13%, 24% and 29% with increasing of the amount (5, 10 and 20wt.%) of

PP-*g*-MA in the blend, respectively.

Szabo et al. [35] studied the static behaviour of polypropylene composites reinforced with different short fibers (basalt and ceramic) with varying in proportion of reinforcements (5%, 15% and 25%), the basalt and ceramic fibers were produced by compression moulding. It has been observed that the mechanical properties of composites are strongly influenced by fiber content and the direction of fibers. Results of scanning electron micrographs of fractured surface of samples showed that the damage form is pull out in transverse and debonding in longitudinal directions. The reason for debonding is mainly effected by manufacturing process used as observed in SEM images.

Eslami-Farsani et al. [36] compared the tensile properties of clay reinforced thermoplastic polypropylene (PP) nanocomposites (PPCN) and chopped basalt fiber reinforced PP -clay nanocomposites (PPCN-B). The thermal conditions under which specimens are tested includes: the room temperature (RT), low temperature (LT) and high temperature (HT). Addition of nanoclay particles (up to 5 wt.%) improves the Young's modulus and yield strength of PPCN and PPCN-B at RT, HT and LT and it is mainly due to the improved dispersion of clay layers in PP matrix, whereas it reduces the ultimate tensile strength. Furthermore, the Young's modulus of the PPCN were found to be improved with the addition of chopped basalt fibers (10 wt.%). For PPCN and PPCN-B the Young's modulus and the yield strength values were found to be significantly high at LT (-196 °C), descend at RT (25°C) and then low at HT (120°C).

Bashtannik et al. [37] has studied the effect of adhesion interaction on the mechanical properties of thermoplastic basalt plastics based on a high-density polyethylene (HDPE) and a copolymer of 1, 3, 5-trioxane with 1, 3-dioxolan. The surface modification of basalt fibers in acidic and alkaline media intensifies the adhesion of thermoplastics to them owing to a more developed surface of the reinforcing fibers after etching. In case of HDPE-based composites, the optimum interaction temperature is 200 to 210°C at an interaction time of 10 to 15 min, whereas in the case of thermosensitive binders based on copolymers of formaldehyde are 200°C at an interaction time of 10 to 15 min. Moreover, etching of the composite specimens in the acidic medium is more efficient and significantly improves the mechanical properties of basalt plastics by 20%.

Akinci et al. [38] studied the mechanical and morphological behaviour of basalt filled in low density polyethylene (LDPE) with 10 to70 wt.% polymer composites. Properties such as hardness, flexural strength, elastic modulus and density have been improved with addition of basalt filler (30-70 wt.%) to LDPE composites. It has been found that increased in addition of basalt filler to the LDPE results in a decrease in elongation at break values. The X-ray diffraction analysis showed that inclusion of basalt fillers found to increase degree of crystallization in LDPE composites. It has also been observed that the mechanical properties can be improved by adding coupling agents to basalt and LDPE mixtures.

Song et al. [39] studied the mechanical properties of basalt fiber reinforced polyamide (PA) 1012 composites were prepared by melting blending method. Test results showed that the optimal tensile and flexural strength of silane treated BFRP/PA1012 were 83.4 and 120 MPa, respectively.

Song et al. [40] studied the mechanical properties of basalt fiber reinforced with PVDF/PMMA (70:30) polymer composites. The tensile strength and flexural strength of BFRP/PVDF/PMMA composites showed an increasing trend with 37 to 62 MPa and 41 to 102 MPa, respectively. This trend was limited up to a basalt fiber content of 0 to 20% in composites and beyond this range of basalt fiber it has shown a decline in trend.

Zhu et al. [41] investigated the quasi-static (0.001 s^{-1}) and high strain rate (3000 s^{-1}) tensile test for basalt filament tows. The basalt fiber is a strain rate sensitive. From the stress strain curves it was observed that with the increase in strain rate (in log scale -3 to 4 approx) the tensile strength (approx 2000 MPa) and modulus were found to be increased, while the failure strain (approx 3.8%) decreased with same strain rate.

Kizilkanat et al. [42] investigated the mechanical and fracture behaviour of basalt and glass fiber with same volume fractions 0.25, 0.5, 0.75 and 1.0 wt.% reinforced with concrete. Experimental results revealed that basalt fiber reinforced concrete (BFRC) and glass fiber reinforced concrete (GFRC) showed highest compressive strength of 66.6 MPa at 0.5% inclusion and 67.6 MPa at 0.75% inclusion, respectively. It has been observed that addition of fiber has no effect on the modulus of elasticity of BFRC (41,860-44,415 MPa) and GFRC (41,237- 42,831 MPa). With the fiber dosage up to 1% the flexural strength was more significant in case of BFRC, In case of GFRC beyond 0.50% dosage, it was insignificant. With the dosage of 0.25% a minor increase in fracture energy was observed for BFRC and GFRC. However significant increase was observed beyond 0.5% dosage and with the 1% dosage the fracture energy was increased by more than 50%.

Soares et al. [43] studied the mechanical properties of BFRP/unsaturated polyester (UP) composites. Experimental results revealed that tensile test agrees with analytical results with relative error of 1.32%. The modulus of elasticity in case of compression has been found to be 24% higher when compared to that in bending. In case of tensile, compression, and flexural tests sudden failure has occurred to the furthest layer of composites.

De Vergara et al. [44] studied the low velocity impact behaviour of basalt fiber reinforced furan composites, the comparisons were made for thermal cured and microwave (MW) cured furan/basalt composites. The test results for MW cured composites in terms of interlaminar shear stress, delamination threshold force, maximum load and penetration threshold were found to be 13.11%, 5.2%, 17.8% and 14.5% higher than that of thermal cured furan/basalt campsites.

Shishevan et al. [46] compared the low velocity impact performance of BFRP/epoxy and CFRP/epoxy composites.

The low velocity impact tests were carried out in 30, 60, 80, 100, 120 and 160 J energy magnitudes. Basalt fibers have shown higher toughness, it is also observed that a better low velocity impact performance of BFRP when compared with CFRP. The results of tested new fabricated materials revealed that the change of fabrication process and curing conditions improves the impact behaviour of BFRPs up to 13%.

Wang et al. [45] investigated the fatigue behaviour of high strength BFRP tendons used in pre-stressing applications in civil infrastructure. It has been found that the fatigue life of BFRP tendons has significant affect on stress range of cyclic loading. As per whitney's method stress range was found to be limited from 68 MPa to 899 MPa and it ensured to be 95% reliable.

Babu et al. [47] the quasi static tensile, compressive and inter-laminar shear properties of the composites were investigated. Experimental results showed that the tensile, compressive and inter-laminar shear strength of BFRP was found to be 23%, 43.8%, and 48% higher than that of GFRP composites. Furthermore, there was also good bonding between fibers and epoxy resin for BFRP, determined by inter- laminar shear strength and Young's modulus had a positive influence on the abrasive wear behaviour whereas for GFRP due to poor bonding between fibers and resin has shown unfavourable results.

Varley et al. [48] has compared the surface modification techniques to understand the influence of matrix fiber interaction on the mechanical properties of BFRP/epoxy composites. Moreover, a hybrid approach was used to combine these two strategies, further these hybrid functionalized surface was again modified by addition of aliphatic triethylene-tetramine (TETA). Results of single ply composites showed that when the properties were fiber or fiber/matrix dominated, the sol-gel or epoxy silane method gave the largest improvement in ultimate tensile strength increasing 66% and 27% for uni-weave 0° and 45° laminas. The hybrid approach method of surface modification has shown an increase of 45% and 13% for the same laminas. When properties were matrix dominated, the hybrid approach was found to improve the ultimate tensile strength by 55% compared with 37% for sol/gel modification. For 16-ply plain weave laminates, epoxy silane surface treatments produced the maximum improvements in terms of compressive and interlaminar shear strengths, increasing 52% and 21%, respectively. This correlated with fiber and fiber/matrix-dominated results from single ply laminas. The surface modification technique by TETA approach was found to decrease shear and compressive strength by about 20%.

2.2. Mechanical Properties under Dynamic Loading

Chen et al. [13] has also studied dynamic properties of BFRP/epoxy composites. As the strain rate increases from 12 to 259 s^{-1} the tensile strength and failure strain was found to be increased by 78.1% and 58% respectively. The material properties such as tensile strength, elastic modulus and failure strain was found to be increased rapidly with the strain rate, when the strain rate was beyond 120 s^{-1}. The dynamic strength of BFRP was found to be two times than that of quasi static strength.

Zhang et al. [1] analyzed the dynamic mechanical properties of BFRP/epoxy composite. The dynamic tensile test for the composite specimens were conducted at strain rates ranging from 19 to 133 s^{-1} and the test results for BFRP composite specimens showed that tensile strength, toughness and maximum strain increased 45.5%, 17.3% and 12.9% respectively, as strain rate ranges from 19 to 133 s^{-1}.

Yao et al. [49] has compared the dynamic tensile behaviours of unidirectional basalt, carbon, glass and plain-woven aramid fibers were tested under strain rates (25, 50 and 100 s^{-1}). Experimental results revealed that for carbon and aramid fabrics the tensile strength, Young's modulus and toughness values were found to be high. High ductility was found to be for glass fabrics. Basalt fabrics values were at intermediate levels and were found to be competitive when compared to other materials. As the strain rate (25 to 100 s^{-1}) increased the tensile strength increased from 1095 to 1743 MPa and toughness was also found to be increased.

Varley et al. [48] has also studied the dynamic mechanical thermal analysis (DMTA) of the BFRP/epoxy laminates. The test results revealed that the glass transition temperatures remained unaffected irrespective of the type of surface treatment employed, apart from the colloidal/silane/amine three-step method shows a reduction in glass transition temperature by 6°C. Moreover, this reduction in glass transition temperatures in thermosets is mainly due to increased miscibility of different phases or plasticization. The scanning electron microscopy (SEM) evaluation and dynamic mechanical thermal analysis (DMTA) attributed this to increased resin ductility and plasticization.

2.3. Tribological Properties

Babu et al. [47] has also studied the two body abrasive wear behaviour for BFRP and GFRP using pin-on-disc apparatus. The wear test was conducted for BFRP and GFRP specimens for 5, 10 and 15 N load with an abrading distance of 100 m. The composite specimens were made to slide against SiC grit paper. The BFRP showed the minimum specific wear rate under all loads when compared with GFRP composites, the main reason for BFRP to show low wear rate is that high hardness and presence of Fe which in turn resists the abrasive wear.

Kim et al. [50] has studied the effect of carbon nanotube addition on the wear behavior of basalt fiber reinforced epoxy composites. The test results showed that the addition of the acid-treated carbon nanotubes enhances the wear resistance of basalt/epoxy woven composites, due to the homogeneous load transfer between the composites. Particularly, the friction coefficient of the BFRP/epoxy composite was stabilized in the range of 0.5-0.6 whereas for basalt/carbon nanotubes/epoxy composites it lies in the range of 0.3-0.4. The wear volume loss of the basalt/epoxy composites was approximately 32% higher than that of the basalt/carbon nanotubes/epoxy composites.

Akinci et al. [51] has compared the friction and wear performance of pure LDPE and basalt filled (filler content of 10, 30, 50 and 70 wt.%) with LDPE composites were tested under dry sliding conditions. Wear tests were carried out at room temperature under 5, 10 and 20 N loads and at 0.5, 1.0 and 1.5 m/s sliding speeds. Test results showed that up to 30 wt.% of basalt content in basalt filled LDPE composites the coefficient of friction of LDPE decreases with increase in basalt content, and beyond 30 wt.% of basalt content shows steady state behaviour. Coefficient of friction of the LDPE was found to be decreased from 0.51 to 0.13 with increase in basalt content, depending on applied loads and sliding speeds. The wear rates of pure LDPE and basalt filled composites were increased with the increase in loads and sliding speeds. The wear rates of the basalt filled composites were extensively dependent on the basalt content. Wear rates of the LDPE was found to be decreased from 2.596×10^{-3} to 6.8×10^{-5} mm^3/m with increase in basalt content. In case of pure LDPE and basalt filled LDPE composites, wear rates were found to be increased with the increase in applied load and sliding speed, whereas in case of basalt filled LDPE composites more the basalt content resulted in lower the specific wear rate.

Wang et al. [45] has studied the wear behaviours of water lubricated polytetrafluoroethylene (PTFE) -based composites reinforced with carbon fibers and basalt fibers sliding against stainless steel under water lubrication were investigated and compared with pure PTFE. It has been observed that dendritic PTFE nano-ribbons as interface between CFRP/PTFE composites revealed that there is a good bonding between them, whereas basalt fibers were poorly bonded with the PTFE matrix it is mainly due to long interfacial free space. Crystallization has been promoted by basalt fiber in PTFE matrix, but crystallization is inhibited by carbon fiber in PTFE composites. With the highest crystallinity of BFRP/PTFE composite shows much higher water absorption when compared to pure PTFE. Due to poor fiber/matrix interfacial adhesion on the water absorption for CFRP/PTFE composite lead to matrix plasticization and degradation of fiber/matrix interface. Wear test was conducted for pure PTFE and its composites were made to slide against stainless steel 316 under water lubrication condition, due to the serious matrix plasticization and the failure of fiber reinforcement by BFRP/PTFE composites lead to highest wear rate (approx 65×10^{-5} mm^3/Nm). On the other hand with highest resistance to water plasticization and friction stress lead to better fiber/matrix interfacial adhesion for CFRP/PTFE composites showed lowest wear rate.

Zhang et al. [52] have studied the friction and wear behaviour of short basalt fibers (BF) reinforced with polyimide (PI) matrix composites. Specimens were made to slide against GCr15 steel using ring-on-block test rig under dry sliding condition. It has been observed that co-efficient of friction and wear rate of BF/PI composites can be enhanced by adding BFs in appropriate amounts (10 wt.%). During the friction process, the transfer film was formed on the counterpart surface which reduced the friction coefficient and wear rate of the BF/PI composites. Test results revealed that BF/PI composites showed improved tribological properties with a higher load (200 N) and sliding speed (0.862 m/s).

Zhang et al. [53] has investigated tribological performance of BFRP/solid lubricants (MoS_2 and graphite) filled PI composites. The resulting composites were fabricated by means of hot-press moulding technique and made to slide against GCr15 steel using ring-on-block test rig under dry sliding condition. It has been found that inclusion of MoS_2 and graphite as fillers significantly enhanced the wear resistance of the BF/PI composites. The optimal volume content of fillers MoS_2 (40%), graphite (35%) in the BF/PI composites was found to be the best combination. Furthermore, the tribological behaviour of the filled BFs/PI composites was closely related to sliding speed and applied load. Experimental results revealed that the MoS_2 (40%) and graphite (35%) filled with BF/PI composites showed better tribological properties under higher product of applied load and sliding speed (PV) product, whose values ranging from 100 to 400 Nm/s.

2.4. Thermal Properties

Asadi et al. [11] have studied the thermo mechanical properties of 25 wt.%BF/epoxy and 25 wt.%GF/epoxy composites. The test results showed that storage modulus of 25 wt.%BF/epoxy was found to be 22% greater than that of 25 wt.%GF/epoxy composites.

Zhang et al. [1] has also studied effect of temperature on the dynamic tensile properties of BFRP/epoxy composites and it was found that tensile strength was independent of temperature ranging from -25°C to 50°C but it was found decreased between 50°C to 100°C.

Kim et al. [20] has also investigated the thermo gravimetric analysis (TGA) of the epoxy-benzoxazine copolymer resin and its composite, it was found that the incorporation of basalt fiber in composite has lot of advantages. Furthermore, the apparent char yield and net char yield gain of the composites were evaluated using TGA thermo grams. Based on the results of differential scanning calorimetry (DSC) and TGA, it is suggested that the favourable thermal properties can be obtained by preparing the composites with the range of 20 to 50% of epoxy content with 10% of basalt fiber.

Kim et al. [21] has also observed the TGA of BFRP increased by 15°C and 20°C for epoxy-amine and epoxy-anhydride composites respectively. Through the evaluation of TGA and thermal degradation behaviour of both systems, it was deduced that the type of curing system as well as basalt fiber reinforcement have a great advantage in preparing the high performance composites.

Kim et al. [50] also analyzed that glass transition temperature of basalt/carbon nanotubes/epoxy composites was higher than that of BFRP/epoxy composites.

Lee et al. [25] reported that silanized composites had shown better thermal stability with a higher storage modulus

7049 (MPa) and glass transition temperature (Tg) than that of the unmodified and oxidized composites. The development of the mechanical and thermal properties of silanized CNT/basalt/epoxy composites is mainly due to better dispersibility and strong interfacial interaction between the silanized CNTs and the epoxy in the basalt /epoxy composites.

Yusriah et al. [29] indicated that the incorporation of carbon fiber into the vinyl ester resin showed a prominent effect where it reduced the co-efficient of thermal expansion (CTE) of the vinyl ester resin by 92% when the CTE for neat vinyl ester reduced from 71.85 ppm/°C to 7.05 ppm/°C below the glass transition temperature. It was observed that upon the inclusion of PHMS fillers into the composites the CTE value was found to be decreased for all woven fabrics reinforced with vinyl ester composites. Test results showed that the thermal stability of the neat vinyl ester was improved by addition of woven glass, woven basalt fabric and woven carbon fabrics. It was also found that there was decrease in thermal stability with the inclusion of PHMS (5 wt.%) fillers into the composites owing to the tendency of the PHMS fillers to undergo ablation process when subjected to intense heat.

Zhang et al. [31] has also studied the effect of basalt fiber on the thermal properties of PBS composites test results reveals that the heat deflection temperature of the BFRP composites increases with the basalt fiber loading. The heat deflection temperature and Vicat softening temperature (VST) of the BFRP composites were found to be increased by 40% and 13.5% respectively, when compared to those of neat PBS.

Song et al. [39] has also observed that the PA1012 γ structure was not modified by addition of basalt fiber. Up to 20 wt.% of basalt fiber content, the melting point of PA1012 increased and further it got decreased. The melting enthalpy also showed a similar trend like melting point. Moreover, the presence of basalt fibre improved the nucleation ability of PA1012 since the crystallization temperature of PA1012 in composite (10°C) greater than neat PA1012. It was observed that the crystallization of PA1012 was accelerated due to basalt fiber and it eliminated the cold crystallization phenomenon of PA1012.

Song et al. [40] evaluated the heat resistance of the materials by vicat softening temperature (VST); it has been observed that the VST of composites increases with increase in basalt content and the PVDF/PMMA/basalt fiber (20%) composites showed a better VST of 146.1°C.

Cao et al. [54] has investigated the tensile properties of carbon fiber, glass fiber and basalt fiber reinforced polymer (epoxy resin) composites at a temperature ranging from 16°C and 200°C. It was observed that with the increase in temperature (55°C to 200°C) tensile strength of different fiber reinforced polymers (FRP) has been reduced, while the elastic modulus did not shown significant reduction. Beyond glass transition temperature (T_g) of polymers (epoxy resin) it has been found that the tensile strength remains a stable higher values for CFRP, BFRP and GFRP composites (average tensile strength ratios at 200°C is 70.25%, 65.73% and 62.23% respectively). However, these higher values signify the role of polymers to protect and unify the fibers.

Wu et al. [55] has studied the mechanical and thermal properties of BFRP rebar at elevated temperatures (from 25 to 350°C). Beyond glass transition temperature (T_g) it has been found that the tensile strength and stiffness values were 50% higher when compared to room temperature for BFRP rebar.

Sim et al. [56] has studied the performances of S-glass, carbon and basalt fiber as a structural strengthening material. When compared to all fibers, only basalt fiber was able to sustain its volumetric integrity and 90% of the strength, when the fibers were tested beyond 600°C.

3. Conclusions

Basalt fiber has been found to be a potential candidate to be used as reinforcement material with different polymer matrices. Due to its unique properties, it has become an emerging cost effective replacement to traditional glass and carbon fibers. The wide spread use of basalt fiber polymer composites demands detailed study of their behaviour with several matrices, different orientation, varying fiber content, processing methods, aerial density and different loading conditions. With the thorough investigations, the possibility of its use can be explored.

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