International Journal of Advances in Engineering and Management (IJAEM)
Volume 5, Issue 2 Feb. 2023, pp: 205-227 www.ijaem.net ISSN: 2395-5252

Basalt Fibre as Potential Reinforcement for Polymer Matrix Composites: A Review

Praveenan Dayalan[1,*], Prakash A Mahanwar[2]

[1] *Post Graduate Researcher, Department of Polymer & Surface Engineering, Institute of Chemical Technology, Mumbai, Maharashtra, India – 400019 ;*

[2] *Professor, Department of Polymer & Surface Engineering, Institute of Chemical Technology, Mumbai, Maharashtra, India – 400019 ;*

Date of Submission: 01-02-2023 Date of Acceptance: 10-02-2023

ABSTRACT

In recent years, fabrication of composites using natural fibres attracts the industrial applications and research worldwide due to its sustainability. One among the natural fibres, Basalt Fibre of mineral origin (from Volcanic Lava) gained more attention because of its outstanding physio-mechanical, thermal, chemical, sustainability, eco-friendly and non-hazardous properties as compared to conventional fibres in composite fabrication like Glass, Carbon etc. This review article describes the basics of composites and its fabrication techniques in detail. It also illustrates the basalt, manufacturing of basalt fibres and properties of basalt fibres are discussed in detail. Moreover the usage of basalt fibre in Polymer matrix and its hybridization with different properties and the recent advancement in Basalt Fibre Reinforced Composites (BFRC) research also reviewed based on different researchers findings. Further the industrial applications of BFRC are discussed.

Keywords: Basalt Fibre, Composite, BFRC, Physio-Mechanical, Thermal Properties.

I. INTRODUCTION:

Natural fibres have been used in polymer reinforcing composites in recent years as a result of an increasing interest in environmental issues.[1]–[5] Composite materials have been able to solve technological issues, and they have begun to attract industry attention, particularly in polymer-based composites. Steel and aluminum have been largely replaced by composites, which have improved performance in many cases. The use of composites resulted in a weight reduction of 60-80 percent compared to metals & 20-50 percent compared to Al, while maintaining the equivalent properties.[6]–[8].If the material consists of different nature of fibres, then the composite is said to be hybrid. Fiber-reinforced composites (FRC) were used for most of engineering and industrial applications for over the decades. The matrix is comprised of resins like polyester, vinyl ester, phenolic and epoxy resins, and thermoplastics, and other thermosets. The mechanical behavior of a fiber-reinforced composite basically depends on the morphological and geometrical properties of fibres. The reinforcing phase might be fibrous or non-fibrous (particulates) in nature, and natural fibres are those that are generated from plants or other living creatures. The creation of novel composite materials with more than one reinforcement that are biodegradable resources, such as natural fibres as a low-cost and environmentally acceptable alternative to synthetic fibres, has sparked tremendous attention as a consequence of environmental concerns. Many other processes have been used to remove these fibres, including mechanical decorticator, water retting, and chemical retting, and so on. Synthetic fibres are manufactured from chemicals and can be formed of glass, carbon, aramid, boron, ceramic fibres and etc. The appropriate orientation and type of fibres resulted in greater features, and a key characteristic of composite was comparable to metal, had higher strength and stiffness.[5], [9], [10] Natural fibres are fibres formed from natural substances (cellulose, hemicellulose, lignin, pectin, wax, and moisture), such as jute[11], flax[12], hemp[13]–[15], sisal[16], coir[17], banana[18], agave[19], snake grass fibre[3], and so on. The hybrid fibres in the composites can withstand higher loads in different directions based on the fibres, and the surrounding matrix keeps them in the correct position and direction, acting as a better load transmission medium than single-fiber reinforcements.This work discusses polymer matrix composites reinforced with hybrid fibres (either natural or synthetic fibres or natural/synthetic fibres). The major advantages of composites over traditional materials are lightweight, resistance to weather and harsh chemicals, high strength to weight ratio, flexible (wide range of material combinations used in composites), durable, and achieving a different and wide range of properties in a single product. Basalt fibres have better physical, mechanical strength & resistance to temperature, chemicals, weather, non-combustibility, and non-hazardous. Because of these advantages, BF has been utilised as reinforcement PMC in various research. When compared to E-glass fibre, the main disadvantages of basalt fibre are its higher density and expense. Therefore this review paper hopefully provides valuable information and comparative study on different basalt fibre reinforced composite (BFRC) materials and their hybrid composites with their manufacturing process available and discusses the industrial applications of BFRC.

II. COMPOSITE:

Composite material can be defined as the assembly of two or more materials and the final product having better properties of each constituent material. The matrix ensures the distribution and orientation of the stress. The resulting materials are very heterogeneous in composition and have anisotropic properties. The nature, the charge, shape, orientation, quality of the interface, and processing parameters of the matrix & fibers alter the properties of the composites.[3], [20]–[24]

2.1 Matrix:

In a fiber-reinforced composite site, the matrix is to align the fibres in appropriate location and geometry, to uniformly distribute stresses in fibres, to protect fibres from surrounding which degrades the fibres, to give protection for surface of fibres from physical degradation. [25] In a composite structure's tensile load-bearing capability, the matrix plays only a minimal influence. The choice of a matrix, on the other hand, has a significant impact on Compressive, Interlaminar and Inplane Shear properties of Composite.

It offers support against buckling of fibres under compressive stress, impacting the compressive strength of the composite material to a great extent. For constructions subjected to bending stresses, interlaminar shear strength is critical, whereas in-plane shear strength is critical for torsional pressures. In designing damage-tolerant structures, the interaction between fibres and matrix is also important. Finally, the fabrication and flaws in a composite are influenced by the matrix properties.

The liquid viscosity, curing temperature, and curing time, for example, are processing properties for epoxy polymers utilized as the matrix in various aerospace composites sites. Epoxy, UPR, and vinyl esters are widely utilized as matrix materials in FRC, owing to their low viscosity, which makes them easier to process. Thermoplastic polymers are more usually employed in injection-molded short fiber-reinforced composites; metallic and ceramic matrices are typically used in high-temperature applications.[26]

2.2 Fibers:

The main elements of a fibre reinforced composite material are fibres. Fig 1 describes the classification of fibres. A pure polymer usually possesses the low mechanical strength required for use in a variety of applications. The addition of high-strength fibres to the polymer gives it significantly improved mechanical characteristics, making fibre reinforced polymer composites (FRPCs) appropriate for a wide range of applications, from aircraft to sports. They contribute the largest proportion of a composite laminate's volume and absorb a major portion of the load bearing on the structure.The fibre type, fibre volume percentage, fibre length, and fibre orientation must all be chosen carefully since they affect the following qualities of a composite laminate [25], [26]:

1. Density
2. Modulus and tensile strength
3. Compressive modulus and strength
4. Fatigue strength and causes of fatigue failure
5. Electrical and thermal conductivities
6. Price

Over monolithic polymer materials, synthetic FRPCs have distinct advantages. In addition to enhanced mechanical properties, these composite exhibited an increased fatigue life and flexibility.Synthetic FRPCs may be improved further in terms of corrosion protection, resistance to abrasion, aesthetics, temperature-dependent behaviour, environmental stability, heat resistance, and conductivity.Different researchers have employed glass fibres as reinforcement. Despite their superior mechanical strength, SFRPCs have a number of major disadvantages, including high price, dense, non-recyclable, and non-biodegradability. Bio-fibers are proved to be competitive with glass fibre in several composite applications. The properties of natural fibre reinforced composites with thermoplastic matrix have been demonstrated in a variety of applications. Natural fibres are abundant and renewable bio-based materials. Natural fibres[1], [27]–[33] are a preferable alternative to synthetic fibres because of their properties (low density, abundance, and high specific strength). Jute, banana, sisal, hemp, and other natural fibres have been employed as reinforcement by various researchers.

III. MANUFACTURING OF COMPOSITES:

Manufacturing of a composite structure starts with the incorporation of a large number of fibres into a thin layer of a matrix to form a lamina (ply). Composite is fabricated by incorporating a huge proportion of fibres into a thin layer of a resin to produce a laminate[34], [35].Laminate’s thickness is generally between 0.1 and 1 mm. If continuous (long) fibres are used to create the lamina, they can be placed in a unidirectional, bidirectional, or multidirectional pattern. Weaving or other textile industry operations are employed to achieve bi- or multidirectional fibre orientation. For a laminate with uni-directional fibres, composite material has the maximal modulus and strength along the longitudinal axis of the fibres. However, its strength and modulus in the transverse direction are quite low. The strength and modulus of a bidirectional fibre lamina may be changed by utilizing variable quantities of fibres in the longitudinal and transverse directions. These qualities are the same in both directions for a balanced lamina. Discontinuous (short) fibres in a matrix can also be used to make a lamina. The discontinuous fibres can be placed in either a unidirectional or a random pattern. In the plane of the lamina, however, random fibre orientation allows for equivalent mechanical and physical characteristics in all directions. In a fiber-reinforced composite construction, the thickness necessary to carry a certain load or maintain a specific deflection is acquired by stacking many laminas in a defined sequence and then consolidating them to form a laminate. Fibers can run in one direction or in several directions in distinct laminas of a laminate. It's also feasible to make an interply or intraply hybrid laminate by combining different types of fibres.

The selection of right process for composite part manufacturing is a highly challenging job since. There are several raw materials and processing methods to choose from how fabricating the component. The process to be used is determined by the application's requirements. The selection criteria for a process are determined by the part's manufacturing rate, cost, strength, and size and form requirements.

BASALT FIBERS:

Basalt fibres are natural mineral fibres derived from basalt rocks. Basalt fibre is a continuous fibre created by melting basalt stone at 1450 to 1500 °C and passing it through a Platinum rhodium alloy bushing.Because of its golden brown tint, it's also known as golden fibre. Extruding melted volcanic rock based on basalt, which is present in flowing lava, produces basalt fibre. Basalt fibre is extruded in a considerably more energy-efficient and easy manner than rival fibres. The fibre dimensions are usually between 10 and 20 micrometres.Several of these qualities (such as basalt's tensile and compressive capabilities) outperform E-glass fibres while also being significantly less expensive.[36] As a result, basalt fibres are gaining popularity as a unique form of reinforcing material for hybrid composites and laminates. In polymer composites, they are frequently used as an alternative to glass fibre reinforcement. They are roughly 5% denser than typical glass fibres, but have 20% better tensile strength, modulus of elasticity and compressive strength. Basalt fibres are also better for the environment and your health than glass fibres since they are natural, inert, and non-toxic and non-carcinogenic. Furthermore, basalt fibres emit less pollution during manufacture and disposal than glass fibres, and their specific fusion enthalpy is lower. They also have a good flame resistance, temperature resistance over 500 °C (the fibre melts at 1450 °C), chemical resistance, and low moisture and water absorption.[36]–[39]

Basalt Fibres are manufactured from natural (volcanic) resources and no hazardous additives, solvents, pigments, or other hazardous ingredients are used in their creation, they can be considered as a eco-friendly material. Fig 2 shows different forms of Basalt available in market. Because the melting point of natural basalt powder is quite high, 1400°C, when the BFs in resin are recycled, the by-product is un melted basalt rocks that can be used again. This means that composites with basaltfibres are burned, and the by-product left is un-molten basalt that can be reused.[40]

Basalt fibres may be equivalent in price to glass fibres, depending on the fibre quality and production technique. Basalt fibre has significant applications in the manufacturing of BF-epoxy composites, have good load-bearing capabilities and lightweight which are helpful in the vehicle sector, based on their advantages. Due to its excellent mechanical qualities, CF composites are currently being widely used in the automobile sector. It is possible to minimize vehicle body weight by 40–60% by using this reinforcing material, but the costing for the entire procedure is presently more costly. As a result, it's critical to reduce production and delivery costs without sacrificing CFRP-based composite mechanical qualities. As previously said, basalt fibrespromising nature, cheap cost, and effective qualities may make them a suitable option for reinforcement in CFRP-based composites.

Basalt contains magnesium, calcium, sodium, potassium, silicon, and iron oxides, as well as traces of alumina. Depending on the geographical distribution, the chemical composition may differ. Basalt is very abundant, accounting for nearly 33% of the earth's crust. Pyroxene, clinopyroxene, olivine, and plagioclase minerals make up the fibres chemically. Magnesium, calcium, sodium, potassium, silicon, and iron oxides, as well as traces of alumina, are all found in basalt. Due to geographical location, the composition may vary.

Chemically, the fibres are made up of pyroxene, clinopyroxene, olivine, and plagioclase minerals. Tholeiitic basalt is a kind of basalt that is high in silica but low in sodium. Fig 3 shows the chemical composition of Basalt Fibres. Alkali basalt is defined as basalt with a high sodium content but low silica content. Furthermore, if the material contains more than 17 percent alumina, the basalt is classified as an intermediate between alkali basalt and tholeiitic. Boninite contains high content of magnesium with very low quantities of titanium and other trace elements.

Mechanical Properties:

Basalt fibres have gained more attention as a source of fibrous reinforcement than any other common filler (glass fibres) due to their improved mechanical qualities. The chemical composition and affi of the individual basalt fibres have a significant impact on the elastic modulus of the basalt fibre reinforced composite.[41] Basalt has a greater tensile strength and elongation at break than other rocks. Table 1 shows the comparison of mechanical properties of different fibres.

Chemical Properties:

BFs have high chemical resistance with acid and alkali steam resistance is far superior to glass fiberand belong to the first hydrolytic class.[29]Basalts are more stable in salt solutions, particularly water than glass, but they are less stable in strong acids. In alkaline solutions, the complete loss of tensile strength deprivation is due to pitting of the fibre in a large area. In acid solutions, the most important cause for the loss of the tensile strength is the damage or change in the chemical constituent of the fibres. The weight loss of basalt in alkali, boiling water, and acid is considerably low. BFs and their composites shows greater resistance to salt and water solutions as compared to glass fibre where as in acidic environment glass beat the basalt.[21]Table 2 shows the comparison of chemical properties of different fibresFor example, when Epoxy resins reinforced BFs and glass fibres were tested with a seawater solution, similar degradation was observed for epoxy based basalt fibre glass fibre. BFRP improves the strength of BFs by lowering the Fe^{2+} level. From the perspective of weightlessness rate & strength retention rate, basalt fiber has good alkali resistance.

Thermal Properties:

Basalt Fibres possess better thermal properties, sound insulation and less water absorption[23] Because of its superior properties, BF used as Fire resistant materials.[42]Basalt has a larger temperature range than E-glass (-60 to 450/460°C), ranging from -200 to around 650/800°C. Due to mineral composition and presence of a huge number of micropores, Table 3 shows the comparison of thermal properties of basalt with different fibres.BFs are passive fire protection and thermal insulation applications BFs are better than E-glass in terms of residual relative strengths (after heat treatment).[37]

In 300-500°C range, basalt outperforms E-glass in the stressed condition and can maintain integrity up to 1250°C in unstressed (used as fire/heat barrier) condition. Crystallization behaviour is the key factor in evaluating the heat stability of BFs. In basalt crystallisation occur in two phases first phase in which spinel structure is formed due to oxidation of ferrous cation (high of iron oxides in basalt), in second phase the diffusion of divalent cations (Fe^{2+}, Mg^{2+}, Ca^{2+}) take place where they come to surface to form Nanocrystalline layers of CaO, $(Mg,Fe)_3O_4$, MgO. Crystallization of basalt are often controlled by doping elements like zirconia. At hot temperature, high thermal stability of basalt fibers material is observed because of characteristics of natural basalt rocks, which nucleate. The basalt rocks, however, don't need but during the melting process, produce a usual nucleating agent like Fe_3O_4.

Electrical Properties:

When subjected to RF radiation, basalt fibres do not conduct electricity, and no fields are induced. Dielectric properties like volume resistance of Basalt Fibres are nearly equal to ones of glass fibres. So, switching from glass to basalt does not change radar transparency of construction. Compared with other types of fibre, the dielectric constant of basalt fibre is lower than that of other fibres. The dielectric loss of E-glass fibre, S-glass fibre and Kevlar fibre is in the same order of magnitude.[43], [44]

Insulation Properties:

In low-temperature technologies, basalt fibre is frequently employed as an effective thermal insulation material. Under the temperature of -96°C, the thermal conductivity of basalt fibre with a unit diameter of 1-3µm is 0.030W/(m•K), and the fiber's strength is not decreased after soaking in the cryogenic medium. The aviation, metallurgical, and machinery industries all employ acoustic absorption materials derived from basalt fibres, and the fibres are frequently used to build structural materials that combine insulation and sound absorption [45], [46]. This type of material is completely non-combustible, and no harmful substances or gases are released when heated.Temperatures of 600-700°C can be used. The temperature can exceed 1000°C when mixed with other material, such as weatherproof firewalls, safeguard fire doors, fire prevention buildings, cable hangers systems, and other industries.

IV. BASALT FIBRE REINFORCED POLYMER (BFRP) COMPOSITES:

Several researchers have investigated the usage of basalt fibre reinforced polymer in the manufacturing of composite materials for a variety of applications. Due to its advantages, the reinforcing fibre has greater mechanical characteristics than non-reinforced resin-based composites. Basalt is known for having better tensile strength and elongation at break, as well as increased impact strength and long-term durability. Table 4 describes the use of basalt fibres in different composites and its inference.

Using the VARI process, ArySubagia et al. [47] created BF/epoxy composites containing tourmaline micro/nano particles (0.5–2 wt%). The flexural and tensile strength of Tourmaline/BF/epoxy laminates enhanced by 16 percent, while the flexural and tensile modulus increased by 153 percent and 27 percent, respectively. Wang et al.[48]fabricated BF with a better method based on hybridization, and the design was optimized for usage in a cable-based long span bridge. The hybridization of the fibre resulted in an increase in total modulus, potential strength, and fatigue behaviour. Sarasini et al. [49] recently studied the impacts of BF hybridization on quasi-mechanical characteristics and low velocity impact behavior in carbon-epoxy based laminates. They also evaluated the interacting hybrid system by stacking two laminates with various sequences at 3 distinct energies.It was discovered that hybrid laminates made with an intercalated stacking sequence absorb more impact energy and are more resistant to damage than laminates made solely of carbon fibres.

Zhang et al. [50] made BF reinforced polybutylene succinate (PBS) composites with different fibre contents. They investigated the composite's thermal and mechanical characteristics. Because of the strength provided by the basalt fibres in the composite, the mechanical characteristics of the PBS matrix improved. They also observed that the composite's VST and HDT were much higher than the PBS matrix.

Kurniawan et al.[51] fabricated silane treated basalt fiber and effects of atmospheric pressure glow discharge plasma polymerization in it and assessed the thermal& mechanical properties of the basalt fiber/polylactic acid composite. The results revealed that the composite parameters of strength and modulus were raised by 45 percent and 18 percent, respectively, when compared to the untreated ones.

Chen et al.[52] recently investigated the dynamic tensile& quasi-static characteristics of BFRC. The results showed that increase in tensile strength with strain rate, and the dynamic strength is nearly twice that of the quasi-static strength.

The mechanical properties of surface treated BF using a low-temperature atm. O_2were studied by Kim [53]. They investigated the toughness and interlaminar fracture of BF/epoxy woven composites. The aim of the research was to study the wettability through contact angle studies. The results obtained from the study proved that the wettability of the fibers increasing remarkably with fiber surface functionalization through physical etching. The inter-laminar fracture test proved that there was a 16% increase in the strength than the untreated one.

Xu et al.[54]also has examined mechanical properties at low to intermediate strain rates using BFRP tendons. During tensile testing, the mechanical properties of BFRP are susceptible to strain.

Subsequently, Botev et al.[55]fabricated and improved the mechanical properties of BF/PP composites by treating short basalt fibers in polypropylene-g-maleic anhydride (PP- g-MA).

Bashtannik et al. [56]enhanced the adhesion strength of BF/HDPE Composite by etching basalt fiber in Sodium hydroxide (NaOH) and hydrochloric acid (HCl)solution. Czigány et al.[57] improved tensile strength of Vinylester/Basalt composites by modifying the surface of basalt fiber bysilane precursor as a coupling agent.

Kim et al.[58]fabricated BF/Epoxy composites with different weight fractionof natural graphite sheets (NGFs) and studied the thermal characteristics. The NGF significantly increases the thermal conductivity and thermal stability of composites, because NGFs have good compatibility and acts as heat radiatingmaterial. Lee et al. [59]enhanced the shear strength, fracture toughness and interfacial adhesion of BF/Epoxy Composite by treating basalt fiber in Potassium hydroxide (KOH) and Sulphuric Acid (H_2SO_4)solution. Zhang et al. [60]studied the mechanical properties of BFRP at differenttemperature and strain ratess. From the results, they concluded that the average tensile strength, maximum strain & toughnessincreases with increase in strain rate of the BFRP specimen. Tensile strength is decreases at 100 °C; this is because of the Tg (Glass transition temperature) of the epoxy group.

Mahesha et al. [61]fabricated BF/Epoxy composites with different content ofnanofillers (Nano-TiO2, nano-clay and nano-TiO2/nano-clay) and investigated the mechanical and wear loss of composites. The results proved that the tensile strength & dimensional stability increases whereas Wear loss decreases with the addition of Nano Fillers.Bhat et al.[62]compared the fire resistance of BF/Vinyl ester composites with that of E-GF/vinyl ester laminates. The results show that at the same radiant heat flux density, the tensile strength of GF composites is higher than those of BF composites. Both laminates have similar softening rates because of thermal softening, weakening of the fiber reinforcement & decomposition of the polymer matrix. The fireproof performance of BF composites is poor, because of itshigh emissivity.

Landucci et al.[63] fabricated Basalt Fibre composites by impregnating BF in matrices (organic & Inorganic). They studied the property of these materials during accidental flame impingement. They used the time and rupture sequence, temperature profile, and weight loss during the imposed conditions of flame impingement for studying the behaviour of various materials. The findings revealed that basalt composites had a low wall temperature and high residual strength, which slowed panel failure. They concluded that BF may be considered as a fundamental constituent for the manufacture of novel thermal shields for PFP.Czigány[64]investigated mechanical properties as well as its thermal properties and compared it with glass fiber (GF). Thermal resistance, acoustic insulation, chemical resistance, and low water absorption are all known properties of BF. BF has recently gained much attention due to its potential use as a reinforcing material in composites, as well as its use in thermoset-matrix based composites and fire-resistant thermoplastics.

Militky´et al. [65]studied the tensile properties of BF in different temperatures of 50-300 °C. Due to the thermal effect, there were some morphological and structural changes observed in fibers with change in tensile properties. They found that when the fibres were treated at temperatures below 300 °C for 1, 15, and 60 minutes, they showed strong tensile properties.Ozturk et al.[66]studied the how wear properties of hybrid composites of BF(0-40% Vf) and ceramics (10% Vf).By using a heated pin-on-disc apparatus, the wear friction properties were studied. They concluded that the wear test cof increases directly with an increase in disc temperature to 300 °C. They observed that with vary in content of basalt fiber, the friction coefficient of the hybrid composite also varies. They found that when the fibres were treated at temperatures below 300 °C for 1, 15, and 60 minutes, they showed strong tensile properties.Medvedyev and Tsybulya[67]showed the effective use of BFRC in hot gas filtration. They increased the life span by 7-10 years by incorporating basalt fibers in the fabrication of a bag house.

Wang GJ et al.[68]measured the acidity coefficientand pH value of BFs. They concluded that Al_2O_3 content in BFs is relatively high.Garima et al. [69]enhanced theinterfacial properties of BF/epoxy composites by grafting CNTs. CNTs enhanced the interface strength between the fibre and matrix, so the chain entanglement of the polymer chains was minimized, and the CNT-grafted BF/Epoxy Composites exhibits high thermal stability.Manikandan et al.[70]investigated the effect of corrosion on physical properties of Basalt Fibre. They concluded that corrosion of fibres was due to diffusion of corrosive agents.Nasir et al. [71]studied the formation of crack and corrosion of BF in H_2SO_4. They concluded that strength of BF was high as compared to glass fiber.

V. APPLICATIONS:

BFRC is preferred over conventional materials because of its resistance to chemicals & corrosive environment and low weight. BFRP also has significant physical, geometrical, and thermal properties when compared to other SFRC and NFRC. The proportion of basalt fibre in the BFRC has a major effect on the properties of the composites. Basalt fibre has a wide range of applications in manufacturing, automobile, architecture, insulation, and fire safety applications.

Basalt fibres are non-hazardous since they are spun with a diameter greater than 6 micrometre, unlike traditional asbestos/glass fibres that might cause health hazards. Basalt fibres are three times more heat insulating than asbestos fibres.[72] Basalt abrasion produces only thick fibre fragments that are not harmful to the human body. Basalt fibre does not react with water and does not pollute the air.[73] Basalt fibres are mostly used in structural and electro-technical applications, including as electromagnetic shielding structures, vehicle, aeroplane,[45] and ship components, and domestic appliance components. Basalt fibres, both woven and knitted, are utilised to make fire-blocking fabrics for public transportation systems due to their inherent thermal properties. Mattresses with basalt inter-liners are often used to prevent fires. In opto-mechanical applications, glass reinforced with basalt fibres is used.

Over the past decade, Basalt Fibres are used in the construction of CNC cylinders because of its impact resistance and light weight properties. It also used in electro technical applications insulation for underground cables, ducts because of its insulation properties. BFRC composites can be used in construction of boats [74] because of its corrosion resistance and resistant to alkaline environment.[21], [75], [76]It is used in the construction of roads and other reinforcement applications. [8]

Basalt fibres are gradually being utilized in disc brake pads and clutch facing applications in automobiles. Basalt may be utilised in a variety of construction projects. It may be used to make extrusion profiles as well as rebar for concrete reinforcement. Basalt serves as a substitute for steel and fibreglass in construction application.Basalt fibre chopped strand has a reinforcing role in asphalt concrete in highway construction. It may significantly increase the tensile strength, toughness, and rutting deformation resistance of pavement. Basalt fibre composites can be utilised to make wind turbine blades in the energy infrastructure.[77]–[79]

Basalt fibres are used in Toyato's Car mufflers. Basalt PP Composites have Low CTE, better acoustic properties and good ductility. So, BF/PP is used in sunshades, CNG Cylinders & Head Liners. [80]Basalt is used to make tubes, bars, plumbing fittings, and sound insulation for flooring[81], walls, framework walls, tanks, chimneys, boiler shells and fire protection construction. Some other significant applications include Waterproofing for concrete structures, wear-resistant paints for bridges, railway tunnels, and other essential structures and facilities. BFs are excellent for fire prevention [82]and soundproofing.

Basalt woven tapes have been used for the construction of fire-proof electricity supply cables due to their good thermal conductivity, as well as their enhanced electrical resistivity and exceptional fire resistance.[83] BFs are also used in pcb, resulting in components with better overall features than typical fibre glass component. Due to its resistance to corrosion, it can be used as lamp posts.

BFRC are used in wear and chemical resistance protection in pipelines, chemical tanks. [84], [85] Because of its low thermal conductivity, deposition is minimized. Wind blades with Basalt Fibres gives better mechanical strength compared to GFRC. Corrosion resistance of BFRC prevents the blades from different weather and climatic changes. In Sports, BFRC are used in skate boards, Snow boards, skis, yachts, tennis racket and hockey sticks.[86]

Basalt geo-mesh[84]has unique characteristics such as resistance to chemicals, good thermal endurance against molten bitumen, and lightweight than metallic meshes.Pipes conveying limestone, sand, alumina, and gypsum containing granulated ash and slag generate considerable wear due to high abrasiveness in the manufacturing of slag cement. This problem can be overcome by employing casted pipelines with a basalt liner. [87]

VI. CONCLUSION

In this review paper, the research trends for basalt fibre as a reinforcing material for composite have been highlighted, from its discovery through current developments employing BFRC. Basalt was identified to offer better properties than asbestos and glass fibres. Basalt fibres are currently nearly as good as carbon fibres, but they have an advantage since they are environmentally safe.Basalt fibres are considered non-hazardous and ecologically beneficial materials. It is not a novel material, but its applications in various industrial and economic domains, from architecture to energy conservation, from automobiles to aeronautics, are unquestionably innovative, owing to its excellent mechanical, chemical, and thermal properties. As a result, basalt fibre is gaining popularity as a reinforcement material, particularly when compared to conventional fibre.

Researchers have investigated the tailoring of matrix and fibre interface by treating surface of fifibres with silane coupling agents resulting in an outstanding improvement in mechanical and physical properties. Alkali attack is the most destructive of all compounds, and numerous attempts to avoid fibre corrosion are still being done, but there is a still far to go to reach this objective. Furthermore, the use of basalt in industrial uses may reduce prices in the future, enhancing research in the area of basalt material properties and composites.

Most of the researchers focused on investigating basalt fibre synthesis, processing and properties and but only few of the researchers studied mechanics and science behind the physical, thermal, chemical and mechanical properties of the BFRC. So the authors of this review decided to concentrate on advancement in the properties of BFRC with different resins and hybridize with different light weight and superior fibres and study the different properties and their effects in different fields of applications like marine, infrastructure, automobile, aircrafts, insulation, electrical and other industrial applications.

Figure Catalogue:
Fig 1. Classification of Fibers [88]
Fig 2. Different Forms of Basalt
Fig 3. Chemical Composition of Basalt Fibre

Table Catalogue:
Table 1 Comparison on Mechanical properties of different fibres
Table 2 Comparison on Chemical properties of different fibres
Table 3 Comparison on Thermal properties of different fibres
Table 4Literature Review on Basalt Fibres with different matrix in composites.

Fig 1.

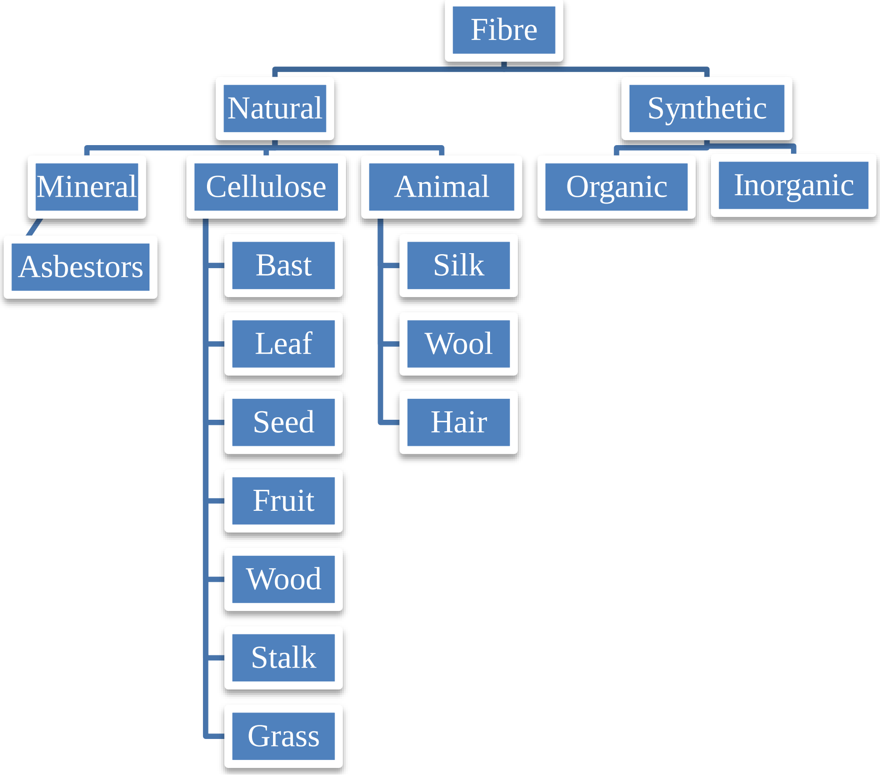

Fig 2.

Fig 3.

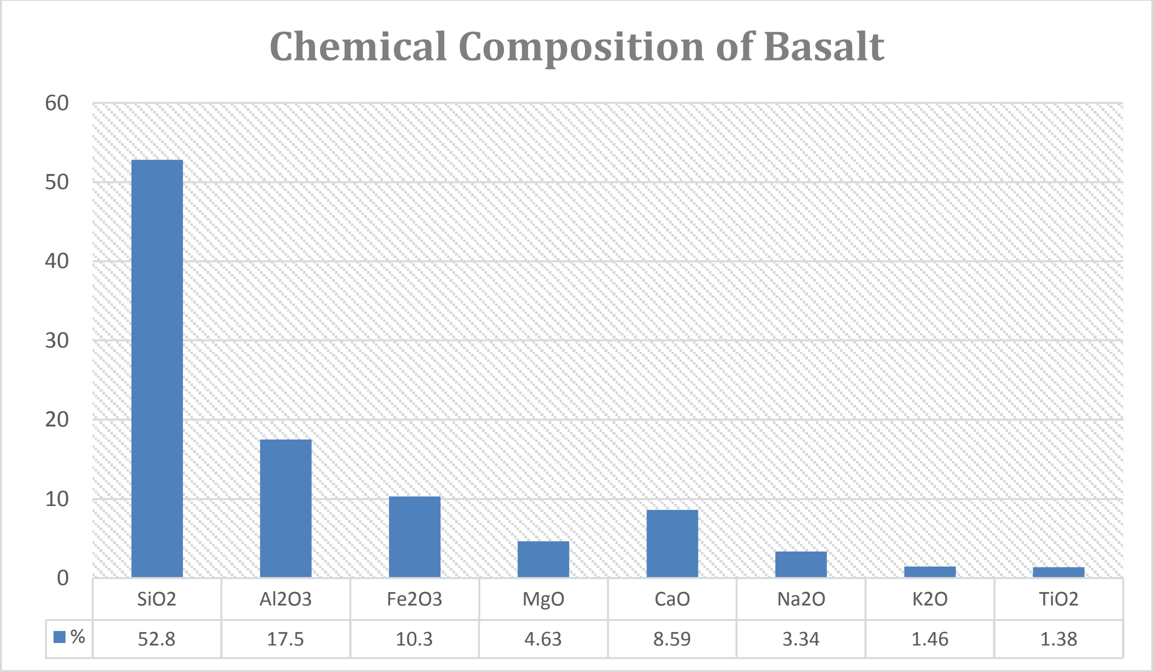

Table 1

Fiber	**Density (kg/m3)**	**Youngs Modulus (GPa)**	**Tensile (MPa)**	**Elongation (%)**	**Ref.**
Aramid	1.4	63-67	3000	3.3-3.7	[89]
Banana	1.3	29-32	750	2.0-4.0	[30]
Basalt	**2.7**	**89**	**4840**	**3.15**	[81]
Carbon	1.4	230-240	4000	1.4-1.8	[90]
Coir	1.2	4.0-6.0	175	30	[32]
Cotton	1.5	5.5-12.6	287-597	7.0-8.0	[91]

E-Glass	2.5	70	2800	2.5	[92]
Flax	1.5	27.6	345-1035	2.7-3.5	[3]
Hemp	-	-	690	1.6	[13]
Jute	1.3	26.5	393-773	1.5-1.8	[3]
Kevlar	1.45	124	2800	2	[93]
Oil Palm	1.55	26.5	100-400	-	[94]
Pineapple	1.56	62	172	-	[95]
Ramie	-	61.1-128	400-938	3.6-3.8	[17]
S-Glass	2.5	86	4570	2.8	[35]
Sisal	1.5	9.2-22	511-635	4.0-6.0	[3]
Soft woodcraft	1.5	40	1000	-	[3]

Table 2

Properties	**Basalt**	**E-Glass**	**S-Glass**
% wt. loss after 3 h, boiling in H_2O	1.6	6.2	5
% wt. loss after 3 h, boiling in HCl	2.2	38.9	15.7
% wt. loss after 3 h, boiling in NaOH	2.75	6	5

Table 3

Thermal Property	**Unit**	**Basalt**	**S-Glass**	**E-Glass**
Maximum application temperature	K	1255	1640-2070	923
Melting temperature	K	1720	2070	1390
Minimum operating temperature	K	15	100	210
Sustained operating temperature	K	1093	1470	753
Thermal conductivity	W/Mk	0.031-0.038	0.035-0.04	0.034-0.04
Thermal expansion coefficient	1/K	$8.0 * 10^{-6}$	$5 * 10^{-8}$	$5.4* 10^{-6}$

Table 4

Sl. No.	**Reinforcement**	**Matrix**	**Wf / Vf (%)**	**Process**	**Inference**	**Ref.**
1	Basalt, Glass	Epoxy	33	RTM	GFRC have highest load peak & Hybrid performed better than BFRC	[46]
2	Basalt, Glass	Epoxy	60	HLU	Treated GF and BF shows better stability in acid but BF shows instability in alkaline. HCl-treated fibersshows the highest tensile strength&	[96]

					Surface Hardness	
3	Basalt, Flax	Vinyl Ester	34	VARI	In comparison to non-hybrid composites, hybrid composites absorb less moisture and have a lower diffusion coefficient.	[97]
4	Basalt, Flax, Hemp, Glass	Epoxy	20, 24, 28	VARTM	Flexural performance GFB > FHB > GHB. Impact Energy is good for FHB	[98]
5	Basalt, Kevlar, Glass	Epoxy	75	VARTM	Kevlar/E-GF have higher impact strength, Kevlar fiber has better coordination with E-Glass fiber than basalt fiber. Electrical conductivity of Kevlar /E-Glass laminate samples showed the highest.	[99]
6	Basalt, Glass	UPR		Compression	(4B/8G) shows maximum Impact strength 12B shows high flexural strength and flexural modulus. 8B/4G shows highest tensile.	[100]
7	Basalt, Glass	UPR	30	HLU	B 22.5 / G 7.5 exhibits high Tensile Strength, Modulus &flexural properties; GF composite exhibits higher EB%;	[101]
8	Basalt, Jute	Epoxy	30	VARI	The salt-fog exposure harmed the laminates' microstructural	[102]

					integrity, resulting in severe degradation to the jute/epoxy matrix interface. Sandwich-like structure (Jute/BF) laminates offer the best mechanical properties.	
9	Basalt	UPR	20	Compression	BF+ KH550 gives 20.3% increase in impact strength.	[103]
10	Basalt	PBS	15	IM, Extrusion	By increasing the fibre content in the composites, the flexural and tensile properties of the PBS matrix resin are improved.	[104]
11	Basalt, Glass	Epoxy	51	VARI	Basalt composite had a 35–42 percent higher Young's modulus, greater compressive strength, and flexural behaviour, but GFRC had a higher tensile strength.	[105]
12	Basalt, Glass	Epoxy	30-50	VARI	Hybrid BF/GF with two external layers of basalt shows increases in mechanical properties compared to GFRP laminates.	[106]
13	Basalt	UPR		HLU	BF/UPR have superior mechanical props than BF/Epoxy, Acid Treated Basalt	[75]

					fibre have superior properties than normal	
14	Basalt, Glass	Epoxy		Prepreg	In seawater, the chemical stability of BFRP and GFRP is essentially same. A significant reduction in Fe2+ content in basalt could improve BFRP stability in a marine environment.	[107]
15	Basalt, Glass, Carbon			Concrete beams	Basalt fibre retained its volumetric integrity and 90% of its strength when exposed to a high temperature of over 600°C.	[108]
16	Basalt, Glass	UPR	57	VARI	The tensile fire resistance of a BFRC is lower than that of an equal GFRC	[109]
17	Basalt, Aramid	Epoxy	33	RTM	When compared to aramid laminates, basalt laminates had a tolerance capability and damage resistance	[110]
18	Basalt	UPR	25	Compression	Optimum fibre weight percentage of 68 % of fibre and optimum length of the fibre of 10 mm were exhibited better properties than others.	[111]
19	Basalt, Kevlar	Epoxy	48	HLU	Compared with Kevlar and hybrid samples, basalt fibres	[112]

					reinforced epoxy showed the better damage tolerance.	
20	Basalt, Glass, Carbon, Hemp	PP	15	Prepreg	In the case of hemp fibre composites, fibre hybridization resulted in just a minor improvement in mechanical properties, but carbon fibre and glass fibre composites have seen a massive upgrade.	[113]
21	Basalt, Hemp	UPR	27	HLU, Compression	Hemp fibre composites lost 46% and 34% of their strength and stiffness, respectively, when compared to roughly 23% of hybrid composites.	[114]
22	Basalt, Carbon	Epoxy	62	VARTM	The flexural strength and modulus of carbon fibres in the outermost layers were higher than those in the innermost layer.	[115]
23	Basalt, Jute	Epoxy	30	VARI	Due to barrier effect of the exterior basalt layers, which shield the jute internal layers from degradation problems, hybrid composites with sandwich-like sequences showed improved ageing resistance to the	[116]

					physical conditions.	
24	Glass, Basalt	Concrete	60, 5	Mixing	In all proportions, concrete with sand glass aggregate can provide good thermal and mechanical qualities. To improve the properties of this concrete, basalt fibre in its ideal volume fraction is suggested.	[117]
25	Basalt	Vinyl Ester	50,75	Pultrusion	The fibre volume fraction is dependent to the creep rupture stress and the ratio of strain rate to onset strain.	[118]
26	Basalt	Vinyl Ester, Epoxy			BFR-Epoxy composites exhibited superior mechanical qualities than vinyl ester composites in tension and compression behaviour, as well as a more compact mode of failure.	[119]
27	Basalt, CNF	Epoxy	3 (CNF)	HLU	CNF grafted Composites exhibits better properties	[120]
28	Basalt	PP		Extrusion	The filament length has a significant impact on tensile strength. Basalt fibres were shown to have better adhesive characteristics than glass and carbon fibres.	[121]

29	Basalt	PE	40	IM	Composites using basalt fibres improved Young's modulus and tensile. Low water absorption was observed in both unmodified polymer and composites with basalt fibres.	[122]
30	Basalt	PEEK	25	Extrusion	The surface roughness of composites rises as the BF content increases, whereas the cof steadily decreases. Good maximum tensile strength and EB percent were attained.	[123]
31	Basalt	PA6	20	Extrusion	IFSS and tensile strength increases 50.3 and 32.5% than untreated BF.	[124]
32	Basalt	PC	50	IM, Extrusion	The addition of BF increased tensile properties while lowering impact strength. Tg stayed the same.	[125]
33	Basalt	ABS	15	IM	When compared to pure ABS, the ultimate tensile strength improves by 40.52 percent. With increasing amounts of additives, Young's modulus steadily rises. The energy of the unnotched impact is reduced.	[126]
34	Basalt	PET	30	IM, Extrusion	Increased interfacial filler-matrix adhesion	[127]

					was validated by higher complicated viscosity and storage modulus values. The 20 percent and 30 percent loading with basalt fibres considerably improved the utility qualities of PET.	
35	Basalt, Nano Clay, TiO2	Epoxy		Compression	T+CL-BE filled composite showed better abrasion resistance.	[128]

DECLARATION OF INTERESTS

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES:

[1] L. Mohammed, M. N. M. Ansari, G. Pua, M. Jawaid, and M. S. Islam, “A Review on Natural Fiber Reinforced Polymer Composite and Its Applications,” Int. J. Polym. Sci., vol. 2015, 2015.

[2] S. N. A. Safri, M. T. H. Sultan, M. Jawaid, and K. Jayakrishna, “Impact behaviour of hybrid composites for structural applications: A review,” Compos. Part B Eng., vol. 133, pp. 112–121, 2018.

[3] C. Dong, “Review of natural fibre-reinforced hybrid composites,” J. Reinf. Plast. Compos., vol. 37, no. 5, pp. 331–348, 2018.

[4] “Hybrid Fiber Composites,” Hybrid Fiber Compos., Oct. 2020.

[5] I. Daniel, O. Ishai, I. Daniel, and I. Daniel, Engineering mechanics of composite materials. 2006.

[6] R. F. Gibson, “A review of recent research on mechanics of multifunctional composite materials and structures,” Compos. Struct., vol. 92, no. 12, pp. 2793–2810, 2010.

[7] Sudirman, M. Anggaravidya, E. Budianto, and I. Gunawan, “Synthesis and Characterization of Polyester-Based Nanocomposite,” Procedia Chem., vol. 4, pp. 107–113, 2012.

[8] A. P. Mouritz, E. Gellert, P. Burchill, and K. Challis, “Review of advanced composite structures for naval ships and submarines,” Compos. Struct., vol. 53, no. 1, pp. 21–42, 2001.

[9] Y. Swolfs, L. Gorbatikh, and I. Verpoest, “Fibre hybridisation in polymer composites: A review,” Compos. Part A Appl. Sci. Manuf., vol. 67, pp. 181–200, 2014.

[10] G. Cacciapaglia, C. Pica, and F. Sannino, “Fundamental composite dynamics: A review,” Phys. Rep., vol. 877, pp. 1–70, 2020.

[11] G. Santosh Gangappa and S. Sripad Kulkarni, “Experimentation and validation of basalt & jute fiber reinforced in polymer matrix hybrid composites,” Mater. Today Proc., vol. 38, pp. 2372–2379, 2020.

[12] N. P. J. Dissanayake, J. Summerscales, S. M. Grove, and M. M. Singh, “Life Cycle Impact Assessment of flax fibre for the reinforcement of composites,” J. Biobased Mater. Bioenergy, vol. 3, no. 3, pp. 245–248, Sep. 2009.

[13] A. Shahzad, “Hemp fiber and its composites - A review,” J. Compos. Mater., vol. 46, no. 8, pp. 973–986, 2012.

[14] C. Sergi, J. Tirillò, M. C. Seghini, F. Sarasini, V. Fiore, and T. Scalici, “Durability of basalt/hemp hybrid thermoplastic composites,” Polymers (Basel)., vol. 11, no. 4, pp. 1–17, 2019.

[15] A. Shahzad and R. S. Choudhry, “Design and manufacturing of natural fiber/synthetic fiber reinforced polymer hybrid composites,” Handb. Compos. from Renew. Mater., vol. 1–8, pp. 411–447, Jan. 2017.

[16] R. Prasanna Venkatesh, K. Ramanathan, and V. Srinivasa Raman, “Tensile, flexual, impact and water absorption properties of natural fibre reinforced polyester hybrid composites,” Fibres Text. East. Eur., vol. 24, no. 3, pp. 90–94, 2016.
[17] S. N. Monteiro et al., “Selection of high strength natural fibers,” Rev. Mater., vol. 15, no. 4, pp. 488–505, 2010.
[18] V. S. Srinivasan, S. Rajendra Boopathy, D. Sangeetha, and B. Vijaya Ramnath, “Evaluation of mechanical and thermal properties of banana–flax based natural fibre composite,” Mater. Des., vol. 60, pp. 620–627, Aug. 2014.
[19] G. Di Bella, V. Fiore, G. Galtieri, C. Borsellino, and A. Valenza, “Effects of natural fibres reinforcement in lime plasters (kenaf and sisal vs. Polypropylene),” Constr. Build. Mater., vol. 58, pp. 159–165, May 2014.
[20] M. Najafi, S. M. R. Khalili, and R. E. Farsani, “Accelerated heat aging study of phenolic/basalt fiber reinforced composites,” Mech. Adv. Compos. Mater., vol. 3, no. 1, pp. 1–7, 2016.
[21] F. Rubino, A. Nisticò, F. Tucci, and P. Carlone, “Marine application of fiber reinforced composites: A review,” J. Mar. Sci. Eng., vol. 8, no. 1, 2020.
[22] Y. Swolfs, I. Verpoest, and L. Gorbatikh, “Recent advances in fibre-hybrid composites: materials selection, opportunities and applications,” Int. Mater. Rev., vol. 64, no. 4, pp. 181–215, 2019.
[23] K. Pareek and P. Saha, “Basalt Fiber and Its Composites: An Overview Sustainable Material View project benchmark cable stayed bridge View project Basalt Fiber and Its Composites: An Overview,” no. March, 2019.
[24] H. yan Cheung, M. po Ho, K. tak Lau, F. Cardona, and D. Hui, “Natural fibre-reinforced composites for bioengineering and environmental engineering applications,” Compos. Part B Eng., vol. 40, no. 7, pp. 655–663, 2009.
[25] P. Mallick, Fiber-reinforced composites: materials, manufacturing, and design. 2007.
[26] B. Raton, L. New, Y. Washington, and S. K. Mazumdar, Composites manufacturing: materials, product, and process engineering. 2001.
[27] P. Navaneethakrishnan, S. Shankar, R. Rajasekar, and N. Rajini, “Characterization of natural fiber and composites − A review,” J. Reinf. Plast. Compos., pp. 1457–1476, 2013.
[28] A. O’Donnell, M. A. Dweib, and R. P. Wool, “Natural fiber composites with plant oil-based resin,” Compos. Sci. Technol., vol. 64, no. 9, pp. 1135–1145, Jul. 2004.
[29] S. I. Hossain, M. Hasan, M. N. Hasan, and A. Hassan, “Effect of chemical treatment on physical, mechanical and thermal properties of ladies finger natural fiber,” Adv. Mater. Sci. Eng., vol. 2013, 2013.
[30] L. A. Pothan, C. N. George, M. Jacob, and S. Thomas, “Effect of chemical modification on the mechanical and electrical properties of banana fiber polyester composites,” J. Compos. Mater., vol. 41, no. 19, pp. 2371–2386, 2007.
[31] O. Faruk, A. K. Bledzki, H. P. Fink, and M. Sain, “Progress report on natural fiber reinforced composites,” Macromol. Mater. Eng., vol. 299, no. 1, pp. 9–26, Jan. 2014.
[32] A. G. Adeniyi, D. V. Onifade, J. O. Ighalo, and A. S. Adeoye, “A review of coir fiber reinforced polymer composites,” Compos. Part B, vol. 176, no. June, p. 107305, 2019.
[33] M. Rokbi, H. Osmani, A. Imad, and N. Benseddiq, “Effect of chemical treatment on flexure properties of natural fiber-reinforced polyester composite,” Procedia Eng., vol. 10, pp. 2092–2097, 2011.
[34] T. Scalici, G. Pitarresi, D. Badagliacco, V. Fiore, and A. Valenza, “Mechanical properties of basalt fiber reinforced composites manufactured with different vacuum assisted impregnation techniques,” Compos. Part B Eng., vol. 104, pp. 35–43, 2016.
[35] T. P. Sathishkumar, S. Satheeshkumar, and J. Naveen, “Glass fiber-reinforced polymer composites - A review,” J. Reinf. Plast. Compos., vol. 33, no. 13, pp. 1258–1275, 2014.
[36] H. Jamshaid and R. Mishra, “A green material from rock: basalt fiber – a review,” J. Text. Inst., vol. 107, no. 7, pp. 923–937, 2016.
[37] L. Yan et al., “Review of research on basalt fibers and basalt fiber-reinforced composites in China (I): Physicochemical and mechanical properties,” Polym. Polym. Compos., vol. 29, no. 9, pp. 1612–1624, 2021.
[38] E. Monaldo, F. Nerilli, and G. Vairo, “Basalt-based fiber-reinforced materials and structural applications in civil engineering,” Compos. Struct., vol. 214, pp. 246–263,

2019.
[39] K. Pareek and P. Saha, "Basalt Fiber and Its Composites: An Overview Sustainable Material View project benchmark cable stayed bridge View project Basalt Fiber and Its Composites: An Overview," no. February, 2019.
[40] "Kamenny, V. (2015). Advanced basalt fiber, Basfiber - Google Scholar." [Online]. Available: https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Kamenny%2C+V.+%282015%29.+Advanced+basalt+fiber%2C+Basfiber&btnG=. [Accessed: 01-Dec-2021].
[41] S. M. Sapuan et al., "Mechanical properties of longitudinal basalt/woven-glass-fiber-reinforced unsaturated polyester-resin hybrid composites," Polymers (Basel)., vol. 12, no. 10, pp. 1–14, Oct. 2020.
[42] M. A. Ruzian, S. M. Sapuan, and R. A. Ilyas, "Thermal Properties on Basalt Fiber Reinforced Polymer : A Review," Researchgate, no. January, 2021.
[43] A. Paul, K. Joseph, and S. Thomas, "Effect of surface treatments on the electrical properties of low-density polyethylene composites reinforced with short sisal fibers," Compos. Sci. Technol., vol. 57, no. 1, pp. 67–79, 1997.
[44] B. Şimşek and T. Uygunoğlu, "Thermal, electrical, mechanical and fluidity properties of polyester-reinforced concrete composites," Sadhana - Acad. Proc. Eng. Sci., vol. 43, no. 4, pp. 1–10, 2018.
[45] C. Buratti, E. Moretti, E. Belloni, and F. Agosti, "Thermal and acoustic performance evaluation of new basalt fiber insulation panels for buildings," Energy Procedia, vol. 78, pp. 303–308, 2015.
[46] F. Sarasini et al., "Effect of basalt fiber hybridization on the impact behavior under low impact velocity of glass/basalt woven fabric/epoxy resin composites," Compos. Part A Appl. Sci. Manuf., vol. 47, no. 1, pp. 109–123, 2013.
[47] I. Subagia, L. Tijing, Y. Kim, … C. K.-C. P. B., and undefined 2014, "Mechanical performance of multiscale basalt fiber–epoxy laminates containing tourmaline micro/nano particles," Elsevier.
[48] X. Wang, Z. Wu, G. Wu, H. Zhu, F. Z.-C. P. B. Engineering, and undefined 2013, "Enhancement of basalt FRP by hybridization for long-span cable-stayed bridge," Elsevier.
[49] F. Sarasini, J. Tirillò, L. Ferrante, … M. V.-C. P. B., and undefined 2014, "Drop-weight impact behaviour of woven hybrid basalt–carbon/epoxy composites," Elsevier.
[50] Y. Zhang et al., "Mechanical and thermal properties of basalt fiber reinforced poly(butylene succinate) composites," Mater. Chem. Phys., vol. 133, no. 2–3, pp. 845–849, 2012.
[51] D. Kurniawan, B. S. Kim, H. Y. Lee, and J. Y. Lim, "Effect of Silane Treatment on Mechanical Properties of Basalt Fiber/Polylactic Acid Ecofriendly Composites," Polym. - Plast. Technol. Eng., vol. 52, no. 1, pp. 97–100, Jan. 2013.
[52] W. Chen et al., "Quasi-static and dynamic tensile properties of basalt fibre reinforced polymer," Compos. Part B Eng., vol. 125, pp. 123–133, Sep. 2017.
[53] M. T. Kim, M. H. Kim, K. Y. Rhee, and S. J. Park, "Study on an oxygen plasma treatment of a basalt fiber and its effect on the interlaminar fracture property of basalt/epoxy woven composites," Compos. Part B Eng., vol. 42, no. 3, pp. 499–504, Apr. 2011.
[54] X. Xu, P. Rawat, Y. Shi, and D. Zhu, "Tensile mechanical properties of basalt fiber reinforced polymer tendons at low to intermediate strain rates," Compos. Part B Eng., vol. 177, Nov. 2019.
[55] M. Botev, H. Betchev, D. Bikiaris, and C. Panayiotou, "Mechanical properties and viscoelastic behavior of basalt fiber-reinforced polypropylene," J. Appl. Polym. Sci., vol. 74, no. 3, pp. 523–531, 1999.
[56] P. I. Bashtannik, A. I. Kabak, and Y. Y. Yakovchuk, "The effect of adhesion interaction on the mechanical properties of thermoplastic basalt plastics," Mech. Compos. Mater., vol. 39, no. 1, pp. 85–88, Jan. 2003.
[57] T. Czigány, K. Pölöskei, and J. Karger-Kocsis, "Fracture and failure behavior of basalt fiber mat-reinforced vinylester/epoxy hybrid resins as a function of resin composition and fiber surface treatment," J. Mater. Sci. 2005 4021, vol. 40, no. 21, pp. 5609–5618, Aug. 2005.
[58] S. H. Kim, Y. J. Heo, M. Park, B. G. Min, K. Y. Rhee, and S. J. Park, "Effect of hydrophilic graphite flake on thermal conductivity and fracture toughness of basalt fibers/epoxy composites," Compos. Part B Eng., vol. 153, pp. 9–16, Nov. 2018.
[59] J. H. Lee, K. Y. Rhee, and S. J. Park, "The tensile and thermal properties of modified

CNT-reinforced basalt/epoxy composites," Mater. Sci. Eng. A, vol. 527, no. 26, pp. 6838–6843, Oct. 2010.

[60] H. Zhang, Y. Yao, D. Zhu, B. Mobasher, and L. Huang, "Tensile mechanical properties of basalt fiber reinforced polymer composite under varying strain rates and temperatures," Polym. Test., vol. 51, pp. 29–39, May 2016.

[61] C. R. Mahesha, Shivarudraiah, N. Mohan, and M. Rajesh, "Role of Nanofillers on Mechanical and Dry sliding Wear Behavior of Basalt- Epoxy Nanocomposites," Mater. Today Proc., vol. 4, no. 8, pp. 8192–8199, Jan. 2017.

[62] T. Bhat, D. Fortomaris, E. Kandare, and A. P. Mouritz, "Properties of thermally recycled basalt fibres and basalt fibre composites," J. Mater. Sci., vol. 53, no. 3, pp. 1933–1944, Feb. 2018.

[63] G. Landucci, F. Rossi, C. Nicolella, and S. Zanelli, "Design and testing of innovative materials for passive fire protection," Fire Saf. J., vol. 44, no. 8, pp. 1103–1109, Nov. 2009.

[64] T. Czigány, "Special manufacturing and characteristics of basalt fiber reinforced hybrid polypropylene composites: Mechanical properties and acoustic emission study," Compos. Sci. Technol., vol. 66, no. 16, pp. 3210–3220, Dec. 2006.

[65] J. Militký, V. Kovačič, and J. Rubnerová, "Influence of thermal treatment on tensile failure of basalt fibers," Eng. Fract. Mech., vol. 69, no. 9, pp. 1025–1033, Jun. 2002.

[66] B. Öztürk, F. Arslan, and S. Öztürk, "Hot wear properties of ceramic and basalt fiber reinforced hybrid friction materials," Tribol. Int., vol. 40, no. 1, pp. 37–48, Jan. 2007.

[67] O. Medvedyev and Y. Tsybulya, "Basalt use in hot gas filtration," Filtr. Sep., vol. 42, no. 1, pp. 34–37, Jan. 2005.

[68] G. J. Wang, Y. W. Liu, Y. J. Guo, Z. X. Zhang, M. X. Xu, and Z. X. Yang, "Surface modification and characterizations of basalt fibers with non-thermal plasma," Surf. Coatings Technol., vol. 201, no. 15, pp. 6565–6568, Apr. 2007.

[69] G. Mittal and K. Y. Rhee, "Chemical vapor deposition-based grafting of CNTs onto basalt fabric and their reinforcement in epoxy-based composites," Compos. Sci. Technol., vol. 165, pp. 84–94, Sep. 2018.

[70] V. Manikandan, J. T. Winowlin Jappes, S. M. Suresh Kumar, and P. Amuthakkannan, "Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites," Compos. Part B Eng., vol. 43, no. 2, pp. 812–818, Mar. 2012.

[71] V. Nasir, H. Karimipour, F. Taheri-Behrooz, and M. M. Shokrieh, "Corrosion behaviour and crack formation mechanism of basalt fibre in sulphuric acid," Corros. Sci., vol. 64, pp. 1–7, Nov. 2012.

[72] B. Wei, H. Cao, and S. Song, "Environmental resistance and mechanical performance of basalt and glass fibers," Mater. Sci. Eng. A, vol. 527, no. 18–19, pp. 4708–4715, 2010.

[73] R. Fangueiro, F. E. M. Cunha, G. Vasconcelos, and S. Abreu, "A brief overview on the retrofitting possibilities of masonry infill walls," 2011.

[74] G. Palomba, G. Epasto, and V. Crupi, "Lightweight sandwich structures for marine applications: a review," Mech. Adv. Mater. Struct., vol. 0, no. 0, pp. 1–26, 2021.

[75] V. Fiore, G. Di Bella, and A. Valenza, "Glass-basalt/epoxy hybrid composites for marine applications," Mater. Des., vol. 32, no. 4, pp. 2091–2099, 2011.

[76] H. B. Kaybal, H. Ulus, and A. Avcı, "Seawater Aged Basalt/Epoxy Composites: Improved Bearing Performance with Halloysite Nanotube Reinforcement," Fibers Polym., vol. 22, no. 6, pp. 1643–1652, 2021.

[77] M. Afroz, I. Patnaikuni, and S. Venkatesan, "Chemical durability and performance of modified basalt fiber in concrete medium," Constr. Build. Mater., vol. 154, pp. 191–203, Nov. 2017.

[78] G. Pravin Jaysing and D. A. Joshi, "Review on Application of Basalt Fiber in Civil Engineering," Ijl Temas, vol. II, no. XII, pp. 54–58, 2013.

[79] R. Ralegaonkar, H. Gavali, P. Aswath, and S. Abolmaali, "Application of chopped basalt fibers in reinforced mortar: A review," Constr. Build. Mater., vol. 164, pp. 589–602, 2018.

[80] "Performance and interfacial stresses in the polymer... - Google Scholar." .

[81] V. Lopresto, C. Leone, and I. De Iorio, "Mechanical characterisation of basalt fibre reinforced plastic," Compos. Part B Eng., vol. 42, no. 4, pp. 717–723, 2011.

[82] S. B. Milman, M. G. Velikanova, and L. E. Kotov, "Development and study of load-bearing heat insulation," Cryogenics (Guildf)., vol. 36, no. 2, pp. 127–130, Jan. 1996.

[83] L. C. Hao and W. D. Yu, “Evaluation of thermal protective performance of basalt fiber nonwoven fabrics,” J. Therm. Anal. Calorim., vol. 100, no. 2, pp. 551–555, May 2010.

[84] R. Subramanian, H. A.-I. J. of A. and, and undefined 1980, “Silane coupling agents in basalt-reinforced polyester composites,” Elsevier.

[85] B. Wei, H. Cao, S. S.-M. & Design, and undefined 2010, “Tensile behavior contrast of basalt and glass fibers after chemical treatment,” Elsevier.

[86] V. Sergeev, Y. Chuvashov, O. G.-P. M. and, and undefined 1995, “Basalt fibers-a reinforcing filler for composites,” osti.gov.

[87] J. S. WANG, J. Do KIM, and H. J. YOON, “Mechanical characteristics of fused cast basalt tube encased in steel pipe for protecting steel surface,” Trans. Nonferrous Met. Soc. China, vol. 19, no. 4, pp. 935–940, Aug. 2009.

[88] J. Naveen and S. Satheeshkumar, “Hybrid fiber reinforced polymer composites − a review,” J. Reinf. Plast. Compos., vol. 33, no. 5, pp. 454–471, 2014.

[89] P. Bazan, P. Nosal, A. Wierzbicka-Miernik, and S. Kuciel, “A novel hybrid composites based on biopolyamide 10.10 with basalt/aramid fibers: Mechanical and thermal investigation,” Compos. Part B Eng., vol. 223, no. January, 2021.

[90] V. Fiore, L. Calabrese, E. Proverbio, R. Passari, and A. Valenza, “Salt spray fog ageing of hybrid composite/metal rivet joints for automotive applications,” Compos. Part B Eng., vol. 108, pp. 65–74, 2017.

[91] N. Saba, M. T. Paridah, and M. Jawaid, “Mechanical properties of kenaf fibre reinforced polymer composite: A review,” Constr. Build. Mater., vol. 76, pp. 87–96, 2015.

[92] S. Y. Nayak and S. S. Heckadka, “Tensile and Penetration Behaviour of Glass Fibre Reinforced Tensile and Penetration Behaviour of Glass Fibre,” no. July 2016, 2015.

[93] M. J. Suriani, H. Z. Rapi, R. A. Ilyas, M. Petrů, and S. M. Sapuan, “Delamination and manufacturing defects in natural fiber-reinforced hybrid composite: A review,” Polymers (Basel)., vol. 13, no. 8, pp. 1–24, 2021.

[94] S. H. Shuit, K. T. Tan, K. T. Lee, and A. H. Kamaruddin, “Oil palm biomass as a sustainable energy source: A Malaysian case study,” Energy, vol. 34, no. 9, pp. 1225–1235, 2009.

[95] M. H. Zin, K. Abdan, N. Mazlan, E. S. Zainudin, K. E. Liew, and M. N. Norizan, “Automated spray up process for Pineapple Leaf Fibre hybrid biocomposites,” Compos. Part B Eng., vol. 177, p. 107306, Nov. 2019.

[96] C. R. Raajeshkrishna, P. Chandramohan, and D. Saravanan, “Effect of surface treatment and stacking sequence on mechanical properties of basalt/glass epoxy composites,” Polym. Polym. Compos., vol. 27, no. 4, pp. 201–214, 2019.

[97] F. A. Almansour, H. N. Dhakal, and Z. Y. Zhang, “Effect of water absorption on Mode I interlaminar fracture toughness of flax/basalt reinforced vinyl ester hybrid composites,” Compos. Struct., vol. 168, pp. 813–825, 2017.

[98] L. Boccarusso, L. Carrino, M. Durante, A. Formisano, A. Langella, and F. Memola Capece Minutolo, “Hemp fabric/epoxy composites manufactured by infusion process: Improvement of fire properties promoted by ammonium polyphosphate,” Compos. Part B Eng., vol. 89, pp. 117–126, 2016.

[99] M. S. Santhosh, R. Sasikumar, L. Natrayan, M. Senthil Kumar, V. Elango, and M. Vanmathi, “Investigation of mechanical and electrical properties of kevlar/E-glass and basalt/E-glass reinforced hybrid composites,” Int. J. Mech. Prod. Eng. Res. Dev., vol. 8, no. 3, pp. 591–598, 2018.

[100] P. Amuthakkannan, V. Manikandan, and M. Uthayakumar, “Mechanical properties of basalt and glass fiber reinforced polymer hybrid composites,” J. Adv. Microsc. Res., vol. 9, no. 1, pp. 44–49, 2014.

[101] S. M. Sapuan et al., “Mechanical properties of longitudinal basalt/woven-glass-fiber-reinforced unsaturated polyester-resin hybrid composites,” Polymers (Basel)., vol. 12, no. 10, pp. 1–14, 2020.

[102] V. Fiore, T. Scalici, F. Sarasini, J. Tirilló, and L. Calabrese, “Salt-fog spray aging of jute-basalt reinforced hybrid structures: Flexural and low velocity impact response,” Compos. Part B Eng., vol. 116, pp. 99–112, 2017.

[103] G. Y. Gong, J. C. Liang, and K. F. Yu, “Study on surface modified basalt fiber reinforced unsaturated polyester resin with silica-carbon black,” IOP Conf. Ser. Mater. Sci. Eng., vol. 479, no. 1, 2019.

[104] Y. H. Feng, Y. J. Li, B. P. Xu, D. W. Zhang,

J. P. Qu, and H. Z. He, “Effect of fiber morphology on rheological properties of plant fiber reinforced poly(butylene succinate) composites,” Compos. Part B Eng., vol. 44, no. 1, pp. 193–199, 2013.

[105] V. Lopresto, C. Leone, and I. De Iorio, “Mechanical characterisation of basalt fibre reinforced plastic,” Compos. Part B Eng., vol. 42, no. 4, pp. 717–723, Jun. 2011.

[106] V. Manikandan, J. T. Winowlin Jappes, S. M. Suresh Kumar, and P. Amuthakkannan, “Investigation of the effect of surface modifications on the mechanical properties of basalt fibre reinforced polymer composites,” Compos. Part B Eng., vol. 43, no. 2, pp. 812–818, 2012.

[107] B. Wei, H. Cao, and S. Song, “Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater,” Corros. Sci., vol. 53, no. 1, pp. 426–431, 2011.

[108] J. Sim, C. Park, and D. Y. Moon, “Characteristics of basalt fiber as a strengthening material for concrete structures,” Compos. Part B Eng., vol. 36, no. 6–7, pp. 504–512, 2005.

[109] T. Bhat, V. Chevali, X. Liu, S. Feih, and A. P. Mouritz, “Fire structural resistance of basalt fibre composite,” Compos. Part A Appl. Sci. Manuf., vol. 71, pp. 107–115, 2015.

[110] F. Sarasini et al., “Hybrid composites based on aramid and basalt woven fabrics: Impact damage modes and residual flexural properties,” Mater. Des., vol. 49, pp. 290–302, 2013.

[111] P. Amuthakkannan, V. Manikandan, J. T. Winowlin Jappes, and M. Uthayakumar, “Effect of fibre length and fibre content on mechanical properties of short basalt fibre reinforced polymer matrix composites,” Mater. Phys. Mech., vol. 16, no. 2, pp. 107–117, 2013.

[112] M. Khazaie, R. Eslami-Farsani, and A. Saeedi, “Evaluation of repeated high velocity impact on polymer-based composites reinforced with basalt and Kevlar fibers,” Mater. Today Commun., vol. 17, no. July, pp. 76–81, 2018.

[113] T. Czigány, “Special manufacturing and characteristics of basalt fiber reinforced hybrid polypropylene composites: Mechanical properties and acoustic emission study,” Compos. Sci. Technol., vol. 66, no. 16, pp. 3210–3220, 2006.

[114] H. Ku, H. Wang, N. Pattarachaiyakoop, and M. Trada, “A review on the tensile properties of natural fiber reinforced polymer composites,” Compos. Part B Eng., vol. 42, no. 4, pp. 856–873, 2011.

[115] H. N. Dhakal, F. Sarasini, C. Santulli, J. Tirillò, Z. Zhang, and V. Arumugam, “Effect of basalt fibre hybridisation on post-impact mechanical behaviour of hemp fibre reinforced composites,” Compos. Part A Appl. Sci. Manuf., vol. 75, pp. 54–67, 2015.

[116] V. Fiore, T. Scalici, D. Badagliacco, D. Enea, G. Alaimo, and A. Valenza, “Aging resistance of bio-epoxy jute-basalt hybrid composites as novel multilayer structures for cladding,” Compos. Struct., vol. 160, pp. 1319–1328, 2017.

[117] T. M. Borhan, “Properties of glass concrete reinforced with short basalt fibre,” Mater. Des., vol. 42, pp. 265–271, 2012.

[118] H. Sokairge, F. Elgabbas, A. Rashad, and H. Elshafie, “Long-term creep behavior of basalt fiber reinforced polymer bars,” Constr. Build. Mater., vol. 260, p. 120437, 2020.

[119] “Berozashvili: Continuous reinforcing fibers are being... - Google Scholar.” [Online]. Available: https://scholar.google.com/scholar?q=related:E0jm4DtMneEJ:scholar.google.com/&scioq=6.%09Berozashvili,+M.+2001,+“Continuous+reinforcing+fibers+are+being+offered+for+construction”,+civil+engineering+and+other+composites+applications.+Adv+Mater+Com+News+Compos+Worldwide,+21(6):5–6+Stephen+Cater.+2002.+‘Editorial’,+International+Comp&hl=en&as_sdt=0,5. [Accessed: 30-Nov-2021].

[120] Y. Wang, Y. Wang, B. Wan, B. Han, G. Cai, and R. Chang, “Strain and damage self-sensing of basalt fiber reinforced polymer laminates fabricated with carbon nanofibers/epoxy composites under tension,” Compos. Part A Appl. Sci. Manuf., vol. 113, no. July, pp. 40–52, 2018.

[121] A. Greco, A. Maffezzoli, G. Casciaro, and F. Caretto, “Mechanical properties of basalt fibers and their adhesion to polypropylene matrices,” Compos. Part B Eng., vol. 67, pp. 233–238, 2014.

[122] K. Mazur, P. Jakubowska, P. Romańska, and S. Kuciel, “Green high density polyethylene (HDPE) reinforced with basalt fiber and agricultural fillers for technical applications,” Compos. Part B Eng., vol. 202, no. August, 2020.

[123] B. Wang, S. Yu, J. Mao, Y. Wang, M. Li, and X. Li, “Effect of basalt fiber on

tribological and mechanical properties of polyether-ether-ketone (PEEK) composites," Compos. Struct., vol. 266, no. March, p. 113847, 2021.

[124] S. Yu, K. H. Oh, and S. H. Hong, "Enhancement of the mechanical properties of basalt fiber-reinforced polyamide 6,6 composites by improving interfacial bonding strength through plasma-polymerization," Compos. Sci. Technol., vol. 182, no. May, p. 107756, 2019.

[125] K. S. Jang, "Mechanics and rheology of basalt fiber-reinforced polycarbonate composites," Polymer (Guildf)., vol. 147, pp. 133–141, 2018.

[126] A. M. M. Abdelhaleem, M. Y. Abdellah, H. I. Fathi, and M. Dewidar, "Mechanical Properties of ABS Embedded with Basalt Fiber Fillers," J. Manuf. Sci. Prod., vol. 16, no. 2, pp. 69–74, 2016.

[127] M. Kráčalík et al., "Recycled poly(ethylene terephthalate) reinforced with basalt fibres: Rheology, structure, and utility properties," Polym. Compos., vol. 29, no. 4, pp. 437–442, 2008.

[128] C. R. Mahesha, Shivarudraiah, N. Mohan, and R. Suprabha, "Three Body Abrasive Wear Studies on Nanoclay/NanoTiO2 filled Basalt-Epoxy Composites," Mater. Today Proc., vol. 4, no. 2, pp. 3979–3986, 2017.