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A Review on Basalt Fiber and Basalt Fiber Reinforced Polymer Composites: Advancement and Industrial Applications

Gajanan S. Mundhe[1], Prakash A. Mahanwar[2], Jayesh R. Patil[3], Elamaran S[4]
[1, 2, 3, 4]*Departnment of Polymer and Surface Engineering, Institute of Chemical Technology, Mumbai, Maharashtra, India*

Abstract: Basalt fiber is a type of mineral fiber that is derived from basalt rock. It has excellent mechanical properties, high resistance to chemicals, superior thermal stability, and good resistance to moisture. Additionally, it is environmentally friendly as it can be easily recycled. All these properties are better when compared to E-glass, which uses many industries for structural applications. The use of basalt fiber reinforced composites (FRC) in industries is still limited because there isn't enough information available about them and their production is not yet at a large scale. This makes them more expensive to produce, which reduces their adoption in industrial applications. This paper critically evaluates the current knowledge and understanding of basalt FRC and highlights the growing interest in researching and publishing articles related to basalt composites. In addition to reviewing the current state of knowledge on basalt fiber reinforced composites, this paper also shares information about the physical, chemical, and mechanical properties of basalt fibers. It also includes some data on the environmental impact of producing basalt fiber reinforced composites and reviews the typical industrial applications where they can be used.
Keywords: Fiber reinforced composites (FRC), Basalt fiber (BF), Glass fiber (GF), Mechanical properties, Industrial applications.

I. INTRODUCTION

Fiber-reinforced composites (FRC) refer to a type of material that is created by blending reinforcing fibers with a matrix material. These fibers can be made from various materials, such as glass, carbon, or aramid, and are embedded within a matrix material like a polymer, metal, or ceramic. Fiber-Reinforced Composite materials have many uses that extend across various industries, such as aerospace, automotive, energy, construction, marine engineering, electronics, chemical packaging, and medical equipment[1], [2]. These materials are employed for an array of purposes, from producing components for aerospace to creating automotive products and packaging for chemicals to fabricating medical equipments. FRC materials are being utilized in several sectors as a substitute for metal components, particularly in settings prone to corrosion. By replacing metallic materials with FRC alternatives, industrial applications can benefit from a more sustainable solution. This is because FRC offers a more well-rounded balance of technical, economic, environmental, social, and governance factors, compared to its metallic counterparts[3].

Fiber Reinforced Composites utilize reinforcement fibers with diverse fabric configurations, including unidirectional, woven, knitted, non-crimp, and multiaxial, each having a distinct orientation. The fibers act as the primary reinforcing component, and they are incorporated into a polymeric matrix composed typically of either a thermosetting or thermoplastic material[4]. In industrial applications, the most widely utilized fiber reinforcements for FRCs are made of petroleum-based carbon, glass, or aramid fibers. Incorporating FRC materials in industrial settings can offer notable advantages over metallic materials, resulting in enhanced structural, mechanical, and tribological characteristics of the final FRC products[1]–[3], [5]. While there are several advantages of using FRC materials, the recycling of thermoset materials remains a significant challenge once they reach the end of their lifespan. Several methods of composite recycling have been developed to manage the considerable volume of composite waste generated each year. The techniques used for recycling include pyrolysis for thermal recycling, solvolysis for chemical recycling, and high voltage fragmentation[4]. However, many of these recycling methods have limitations, such as high energy costs for operation. Additionally, preserving the mechanical and volumetric stability of the recycled fibers continues to be a significant challenge[5]. As a result, the disposal of composite waste in landfills is currently the most practical solution[4], [5]. The recycling of fibers remains a crucial issue. Burning waste fibers at high temperatures, known as thermal incineration, is not a good way to recycle them because the fibers are not able to withstand the heat. This causes the recycled fibers to become much weaker. The disposal of composite waste in landfills, made from fiber reinforcements, has negative impacts on the environment.

Over the past few years, there has been an increasing awareness of environmental concerns and the need for composite materials to be recycled. As a result, sustainable composites for industrial use have become more popular. These composites incorporate natural fibers such as jute, flax, hemp, kenaf, and wood, as well as animal fibers like silk or wool, as reinforcing agents[6]–[8]. The majority of natural fibers are hydrophilic, which implies that they possess a propensity to absorb water. This characteristic can impact the performance of composites reinforced with these fibers, resulting in lower performance compared to composites reinforced with synthetic fibers[9], [10]. One option for a sustainable alternative could be basalt fiber, which is derived directly from volcanic basalt rocks and does not contain any secondary additives. In contrast to synthetic fibers such as E-glass, basalt fibers exhibit better physical, chemical, and mechanical characteristics. Basalt fibers exhibit exceptional thermal stability at elevated temperatures, are highly resistant to moisture and chemicals, provide effective insulation for both heat and sound, and are simple to work with during processing. Basalt fiber production is more cost-effective compared to glass fiber production as it involves using lower amounts of energy and does not require the addition of extra materials. Basalt fiber is an eco-friendly alternative as it is non-toxic when exposed to air and water, and is also non-combustible and resistant to explosions. This makes it a safer option for the environment compared to other fibers[6]–[8]. Research studies called Life Cycle Assessments (LCAs) have found that using basalt fibers to strengthen building materials is better for the environment than using steel rebars, which are commonly used in construction[9], [10]. Despite its broad range of industrial applications, from aerospace and automotive to marine and energy, basalt fiber reinforced composites are not yet widely adopted due to a lack of cost-effectiveness compared to traditional synthetic FRCs and a lack of readily available data[11].

This paper aims to provide a thorough assessment of the present knowledge regarding basalt fiber reinforced composite materials, as documented in publicly accessible literature. The main focus is on the increasing research and publications in the field of basalt composites. This study looks at what we currently know about basalt fiber reinforced composites. It focuses on research and information that is available to the public. It covers aspects such as the physical and chemical properties of basalt fibers and their mechanical behaviour. Moreover, the research also explores the diverse industrial uses of basalt fiber reinforced composite materials, and emphasizes the progress made in comprehending their physical, mechanical, and chemical properties.

II. BASALT

Basalt is the most commonly occurring igneous rock showed in figure 1, with over 90% of all volcanic rocks being composed of this dark-coloured mafic extrusive rock. When molten lava cools at a slow rate, the atomic arrangement in basalt exhibits a mainly regular pattern. On the other hand, if the solidification process happens rapidly, an amorphous or uncrystallized structure is formed in the basalt. Basalt is made up of three different types of silicate minerals, which are plagioclase, pyroxene, and olivine[12]. Basalt's major chemical constituent is silicon dioxide (SiO_2). Other metal oxides, such as Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, and TiO_2, are also present in basalt fibers. The geographical position of the basalt rocks has a significant impact on the proportion of various metal oxides in basalt fibers. Basalt rocks are widely distributed throughout the world and are typically categorised based on their SiO_2 content. These basalts can be classified as alkaline (having a SiO_2 content of less than 42%), mildly acidic (having a SiO_2 content between 43 and 46%), or acidic (having a SiO_2 content greater than 46%)[13]. Due to their increased SiO_2 concentration, which aids in giving basalt fibers exceptional mechanical and chemical durability, only acidic basalts are thought to be appropriate for use in the creation of basalt fiber[14].The existence of other oxides like Al_2O_3 helps in providing good chemical stability. Basalt fibers have strong moisture and corrosion resistance due to the presence of CaO, MgO, and TiO_2, they also have good thermal stability due to the presence of Fe_2O_3[15].

Fig. 1 Basalt rock

For many years, basalt has been employed in casting techniques, including the production of slabs and tiles for use in architecture. Paul Dhè discovered basalt fibers from molten rocks in early 1920s[16]. Afterword in the 1960s, the Soviet Union began to develop production methods to make continuous basalt fibers while simultaneously researching the uses of basalt for military and aeronautical equipment[17]. In 1979, the United States granted a patent for a production technique that improves the properties of basalt fibers. To improve the performance of fibers, researchers proposed the use of silane coupling agents and hydrate zirconia coatings as additives to enhance the fiber sizing[18].

In India in 1981, Ramachandran BE et al.[19] conducted the first study on the chemical resistivity of Basalt fibers (BFs) [19]. Soviet researchers created a practical manufacturing method to create continuous basalt fibers in 1985[20]. In 2005, scientists investigated how well an adhesive called epoxy (EP) could be used with basalt fibers. This was to determine whether the combination was strong and effective for certain applications.

They then utilized this EP matrix to produce a composite material by incorporating BFs into it. When the properties of composites made with basalt fibers and epoxy were compared to those made with S-2 glass fibers and epoxy, it was found that basalt fibers could be used as a replacement for some of the glass fibers in composite materials. Scientists conducted a study to investigate how well a basalt fiber and its composites would hold up under mechanical stress and exposure to chemicals. To do this, they looked at the condition and chemical makeup of the surface of the fibers, which were sourced locally. When basalt fiber composites were exposed to acidic environments, their ability to bend and their stiffness both decreased.

In alkaline environments, their stiffness remained relatively the same, but their ability to bend decreased. In 2007, scientists conducted a test to see how well composites reinforced with continuous basalt fibers (CBFs) would hold up under different conditions. They looked at how strong the composites were, whether they could withstand high temperatures, and how resistant they were to chemical corrosion. They also studied how well the basalt fibers were bonded to the rest of the composite material. The scientists also took a close look at the chemical composition, structure, surface properties, and density of a particular type of continuous basalt fiber that was sourced locally[21].

Kim H[22] In 2012, an inquiry was conducted to explore the feasibility of utilizing short BFs in South Korea to create a thermally-resistant composite material through the implementation of a bicomponent resin system. Scientists in Spain used microwave technology to create composites made from furan and reinforced with basalt fibers. They found that composites that were cured using microwaves had better interlaminar shear strength, could withstand more force before delaminating, and were stronger overall compared to those cured conventionally. They also observed that the composites had a higher threshold for penetration. Numerous studies have been conducted to create procedures and protocols for making basalt fibers. These studies have been aimed at improving the manufacturing process for basalt fibers[23].

Experts predict that the worldwide market for basalt fibers will increase from 286 million USD to 517 million USD by 2027. This represents a compound annual growth rate of 12.5% between 2022 and 2027. Due to the substantial basalt deposits in the aforementioned locations, Russia and Ukraine currently produce the majority of the world's basalt fibers[24]. In order to meet the increasing demand, several new producers of basalt fibers are emerging in various countries, including Japan, China, Germany, Ireland, Belgium, and the United States of America (USA) [24]. The primary regions for consumers are North America, Asia, and Europe.

III. SIGNIFICANCE OF REINFORCEMENT

Reinforcements refer to the components incorporated into a composite's polymeric matrix, which play a crucial role in enhancing various properties, such as strength, rigidity, interaction with the matrix, conductivity, resistance to heat, and protection against physical and chemical corrosion. Different reinforcements are used depending upon the desire applications. While single strands or bundles of fibers can be used in filament winding processes, they are usually woven into sheets or fabrics to make them easier to handle.

The specific arrangement and orientation of fibers within a fabric can significantly impact the resulting mechanical properties of the composite.

Therefore, variations in the assembly and alignment of fibers can lead to distinctive changes in the material's mechanical characteristics. In essence, these fibers function as crucial load-bearing elements in the composite.

Composites that contain reinforcing fibers have much better mechanical properties than non-reinforced resin-based composites. The characteristics of fiber/resin-based composites are contingent upon the essential role played by the fibers, as they produce a synergistic effect that bolsters and reinforces the composite material. Several key factors determine the significance of fibers in composites including:

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1) The fiber's inherent mechanical properties
2) The amount of fiber that is added to the composite
3) Recyclability of the composite material
4) The interaction that occurs between the fiber and resin at the interface is primarily of a physico-chemical nature.
5) Orientation, position and fiber layout in the composites.

When the factors mentioned above are fulfilled, the reinforcement works effectively by improving the composite matrix's strength and rigidity to a great extent, surpassing that of the original matrix. In other words, the composite material becomes much more durable and less prone to bending or deformation, leading to an overall improvement in its mechanical properties. The improved strength and stiffness of a composite matrix also helps to prevent deformation and can even change or delay how the material fails. As a result, the composite material becomes more resilient, and it can endure more stress and strain without breaking down or losing its structural integrity, ultimately leading to an increase in its lifespan and reliability.

IV. MANUFACTURING METHODS FOR THE PRODUCTION OF BASALT FIBER

Plagioclase, magnetite, and pyroxene's slow crystallisation into structural elements and the melt's non homogeneity are the two main difficulties in the production of basalt fibers[25]. Technologies for continuous spinning can assist in overcoming the difficulties involved in producing basalt fibers appropriate for producing basalt textiles for structural composites. Basalt fibers are produced using the Spinneret and Junkers technologies, respectively[26], [27].

A. Spinneret Technology

The manufacturing process used to create continuous basalt fibers using Spinneret technology is similar to that used to create glass fibers (Figure 2 shows Spinneret technology). However, a single raw material feed procedure for the manufacture of basalt fiber does not require any extra additions in the intermediate steps (unlike glass fiber manufacturing process). Crushed and then cleaned basalt rock is used to make basalt fiber. Then, using either a gaseous mixture or electricity, the shattered rock pieces are put into the furnace and heated to between 1200 and 1500°C. Some electrodes are immersed in the melting fluid to guarantee uniform heating and to reach thermal equilibrium as quickly as feasible. To produce basalt fibers, molten basalt is extruded through heated bushings made of platinum-rhodium, which results in the formation of fine basalt threads. Once the basalt fiber filaments have undergone the cooling process, they are collected into strands and lubricated to maintain their chemical stability and structural integrity. Basalt fiber diameter is managed during production by adjusting the melting temperature and drawing speed[26]. These continues fibers can converted into fabric form as shown in figure 3.

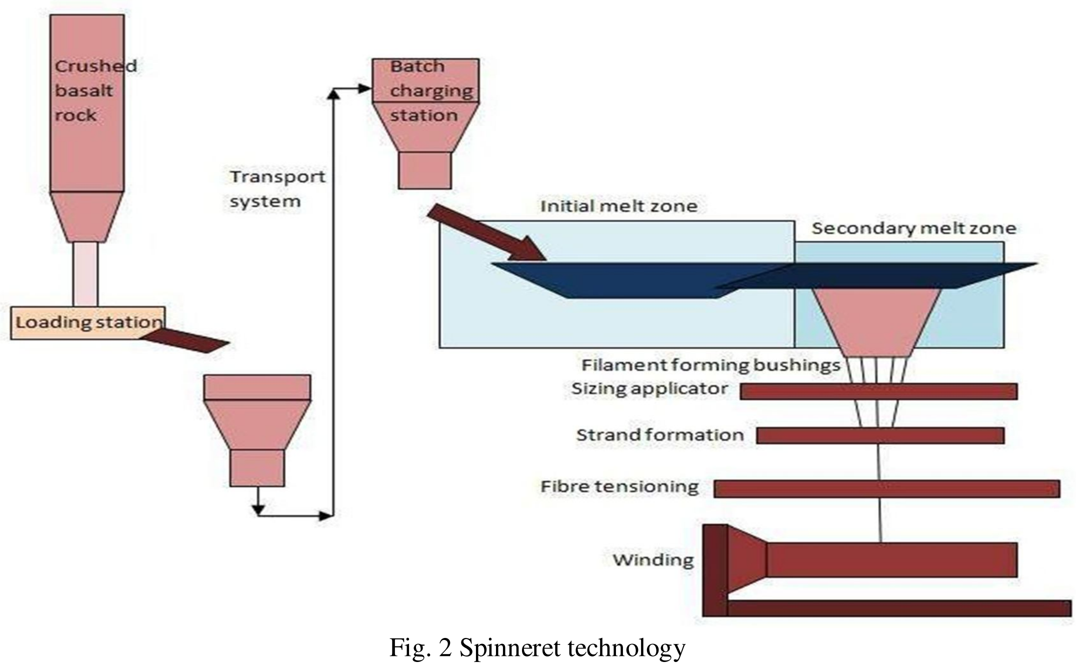

Fig. 2 Spinneret technology

B. Juncker's technology

Fig. 3 Basalt fibers in woven form

Melt-blowing is a method utilised by Junckers technology showed in figure 4, which is generally used to produce short-basalt fibers. In this method, the process involves pouring molten basalt onto a top-loading rotating cylinder, which is then transferred to the two cylinders underneath using tangential force. When high centrifugal forces are applied to molten basalt, it separates into small droplets, which then turn into thin, cylindrical forms when compressed air jets are released from nozzles positioned behind the fibrillation shafts. When the basalt cools, this process results in the development of short basalt fibers[27]. Figure 5 shows short basalt fibers.

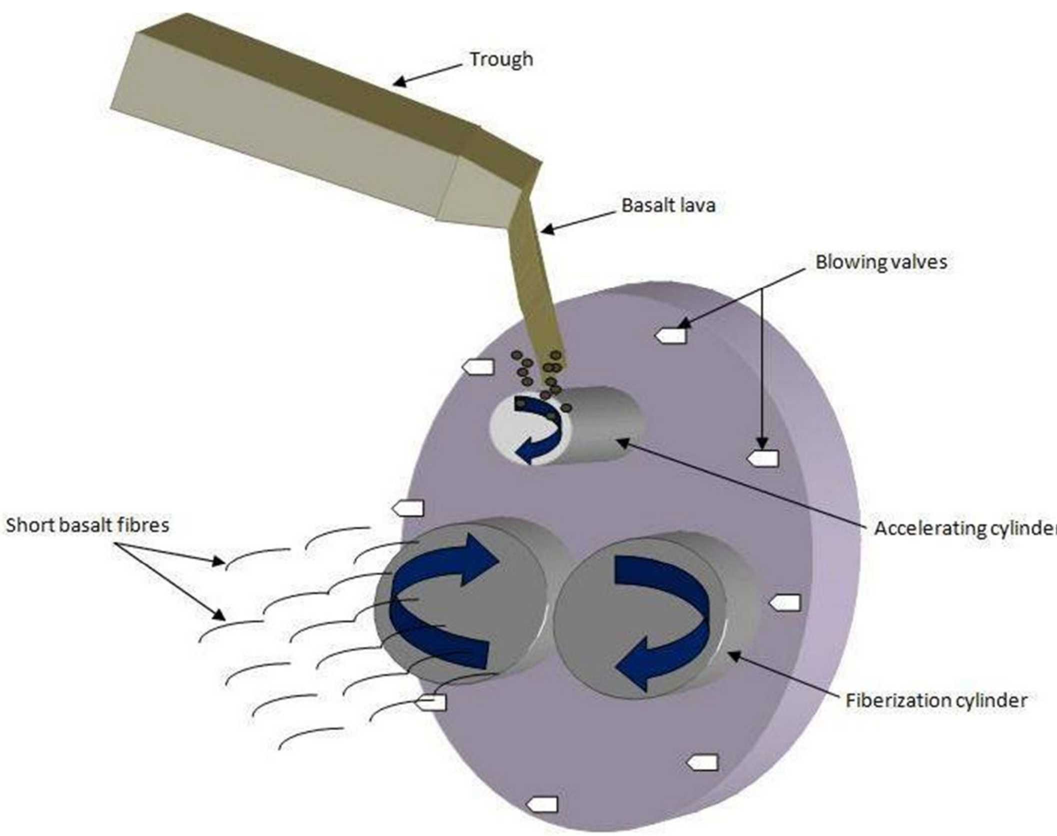

Fig. 4 Junckers technology

Fig. 5 Short basalt fibers

V. PROPERTIES OF BASALT FIBERS

A. *Mechanical Properties of Basalt Fiber*

Under stress, basalt fibers typically behave linearly elastically until brittle failure. Greco et al.[28] looked into the effects of geometrical characteristics and chemical composition, taking SiO_2 and Al_2O_3 concentration into account, on the tensile strength of basalt fibers from various producers. Deak et al.[29] looked into the impact of a higher Al_2O_3 concentration on the tensile strength of basalt fiber. Both investigations showed that basalt fiber tensile strength rose from 1.7 GPa to 2.5 GPa with an increase in Al_2O_3 concentration from 10% to 24%. Possible manufacturing flaws have little effect on the stiffness of the fiber but significantly affect its tensile strength. Table 1 provides a summary of the characteristics of several fibers frequently utilised in composite materials for industrial purposes. Due to supply issues brought on by the present political upheaval throughout the world, basalt fiber prices might increase but yet remain within reach of the average person's budget[30].

TABLE 1: A COMPARISON OF CHARACTERISTICS AMONG COMMONLY USED FIBERS IN FIBER-REINFORCED POLYMER COMPOSITES

Various Fiber	Density (g/cm^3)	Diameter of fiber (µm)	Strain at Break (%)	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Cost (USD/kg)
E-glass	2.5–2.6	9–13	4.7	72.5–75.5	3100–3800	0.75–1.2
Aramid	1.44	5–18	2.8–3.6	70–112	2900–3400	25
S-glass	2.46–2.5	9–13	5.6	88–91	4590–4830	5–7
Carbon	1.75–1.9	4–7.5	1.5–2.0	230–600	3500–6000	30
Basalt	2.8–3.0	9–23	3.1	79.3–93.1	3000–4840	2.5–3.5

Greco et al.[28] suggested that basalt fibers' mechanical properties might be improved by adjusting the fiber sizing (coupling agents) used throughout their production process in order to minimise the impact of manufacturing technique and surface imperfections. When compared to unsized basalt fibers, sized basalt fibers showed a noticeable improvement in mechanical characteristics. Basalt fibers treated with silane coupling agents have a smooth surface. Basalt fibers that have been treated with sizing agents have been found to have better adhesion to polymer matrices compared to similarly treated glass fibers. The adhesion of the sized basalt fibers to the polymer matrix is comparable to that of sized carbon fibers with the same resin[28]. Figure 6,7 shows the optical microscopic image of short basalt fibers and woven basalt fibers.

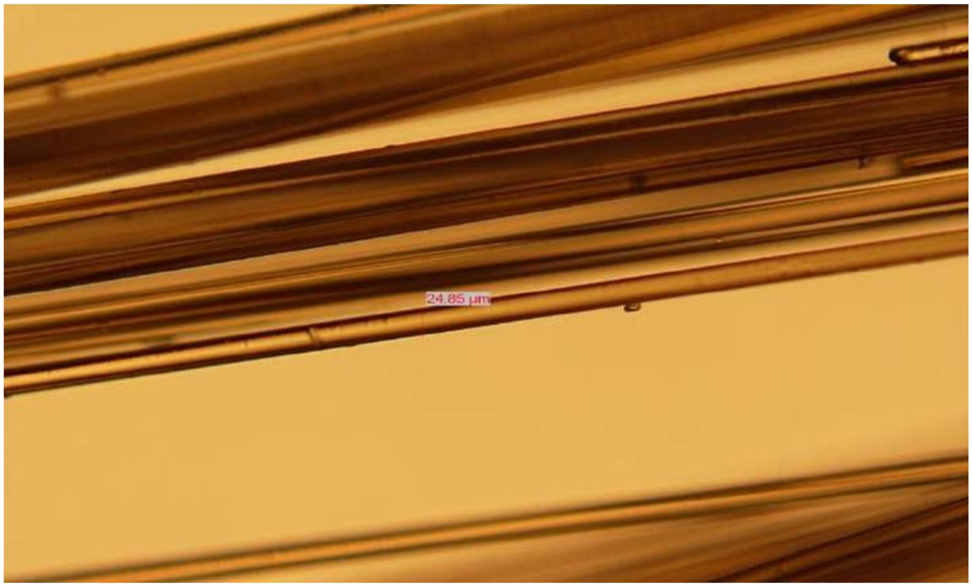

Fig. 6 Optical microscopic image of short basalt fibers

B. Chemical Properties of Basalt Fibers

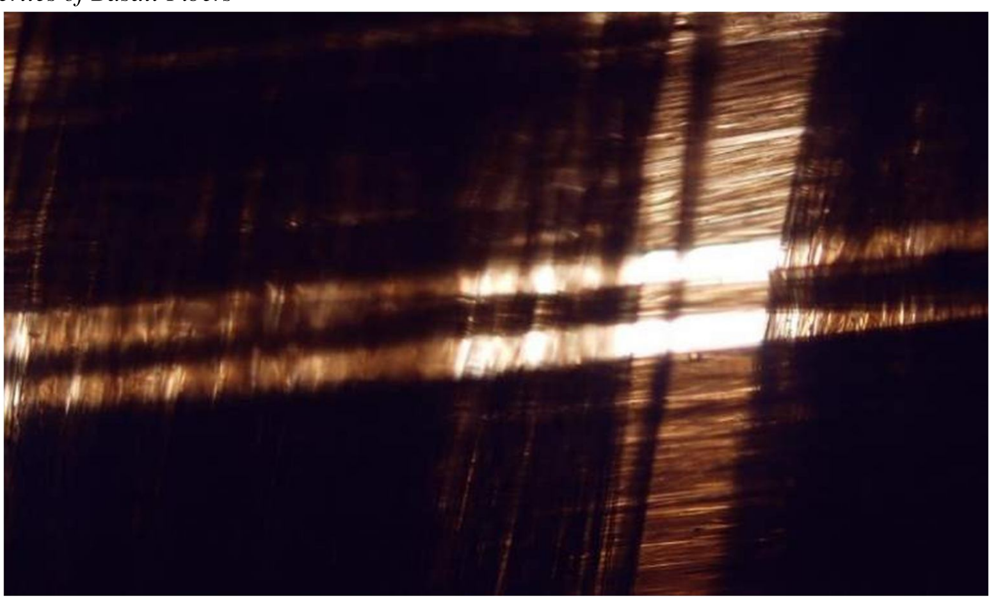
Fig. 7 Optical microscopic image of woven basalt fibers

Basalt fibers exhibit non-combustibility and demonstrate excellent resistance to acidic and alkaline environments, also demonstrate good resistance to chemical deterioration and moisture absorption[31]. Basalt fibers surpass glass fibers in corrosive conditions in terms of mechanical qualities[32]. Table 2 presents a comparative analysis of the chemical composition of basalt and E-glass fibers. Basalt and E-glass vary significantly in that basalt contains a comparatively high amount of ferric oxide (Fe_2O_3), a natural nucleating agent that gives basalt great thermal stability and contributes in maintaining its crystalline structure[33]. Basalt fibers are commonly paired with epoxy resin as the preferred matrix material. However, they can also be compatible with other types of resin systems, such as phenolic, polyester, and vinyl ester[33]. Ralph et al.[34] showed that basalt fibers' mechanical and chemical bonding with a polymer matrix are significantly influenced by the size of the fibers (especially for polypropylene) and they compared the chemical, mechanical, and geometrical characteristics of basalt fibers with those of E- glass fibers. The findings indicate that the elemental compositions of basalt and E-glass fibers are similar, yet basalt fibers possess greater tensile strength than E-glass.

Table 2: Comparison Of Chemical Composition Between Basalt And E-Glass Fibers

Oxides Content (wt. %)	SiO2	Al2O3	Fe2O3	CaO	MgO	B2O3	TiO2	Na2O + K2O	ZrO2	MnO
Basalt	47.5–53.0	13.3–18.0	7.0–14.0	8.0–11.0	3.5–5.0	0.8	0.2–3.5	2.5–6.0	0.0	0.17–0.22
E-Glass	53.4	14.3	0.28	19.0	3.3	10.3	0.14	0.29	0.8	N/A

Numerous investigations examined the basalt fibers' acidic and alkaline resilience. The research showed that basalt fibers were more resistant to acid when submerged in HCl solution as opposed to being exposed to an alkaline environment (NaOH solution)[35]. In an alkaline medium, basalt fibers experienced an 8% mass loss, which was twice that observed in acidic media. Moreover, the tensile strength of basalt fibers deteriorated by approximately 35%, while a decline of about 20% was observed in acidic media. Comparative analysis between the chemical stability of basalt and glass fibers indicated that basalt fibers demonstrate superior resistance to acids compared to glass fibers (30% reduction in both tensile strength and mass loss of the fibers). Basalt fibers' alkaline resistance varied with exposure period. As the exposure duration increased from 7 to 28 days, there was a corresponding increase in basalt fiber mass loss from 20% to 70%, and the decrease in tensile strength ranged from 50% to 80%[36], [37]. It has been studied how basalt fibers degrade after being submerged in alkaline cement solutions. Following immersion in cement solution, basalt fiber mass loss was not seen to be significantly reduced[37].

C. Heat-related Characteristics of Basalt Fibers

Basalt fibers are more stable and retain their properties better than other fibers like glass and carbon at high temperatures[38]– [41]. Table 3 provides comparison between thermal resistance of Basalt, E-glass, S-glass, and Carbon fibers. Basalt fibers offer exceptional thermal stability over a broad spectrum of temperatures ranging from -260°C to 700°C. At approximately 960°C, basalt fibers undergo a softening process that occurs at a temperature around 15% higher than that of E-glass[42].

Table 3: Comparison Between Thermal Resistance Of Different Types Of Fibers.

Fiber	Basalt	E-glass	S-glass	Carbon
Working Temperature Range (ΔT) [°C]	−260 to 700	−50 to 380	−50 to 300	−50 to 700
Thermal Conductivity ($W{\cdot}m^{-1}{\cdot}K^{-1}$)	0.031–0.038	0.034–0.040	0.034–0.040	5–185 (axial only)
Thermal Expansion Co-Efficient ($10^{-6.}\ ^{\circ}C^{-1}$)	8.00	5.40	29.00	0.05 (axial only)

Based on the available literature, it has been observed that basalt fibers possess notable resistance to high temperatures, with their thermal stability remaining intact up to approximately 200°C, even after exposure for an hour. This is further supported by the fact that such elevated temperatures do not seem to have any significant detrimental effects on the fibers' tensile strength[39]. Basalt fibers lose tensile strength less quickly than other fibers like glass and carbon over 200°C. In contrast to glass and carbon fibers, basalt fibers have been found to exhibit greater robustness when subjected to temperatures ranging from 600°C to 1200°C[43]. Studies have indicated that the degradation of basalt fibers begins at approximately 200°C. Between the temperature range of 200°C to 800°C, the mass loss is relatively low, estimated at around 0.74%. In comparison, during the temperature range of 160°C to 850°C, glass fibers experience a mass loss of approximately 1.8%, which is higher than that of basalt fibers[40].

VI. MECHANICAL PROPERTIES OF BASALT FIBER REINFORCED COMPOSITES

As mentioned previously, the incorporation of reinforcements into the matrix leads to an enhancement in the composite'smechanical properties. In this section, we'll talk about the strength and toughness of composites made with basalt fibers, as described in various written works. Basically, we'll explore what people have found out about how strong and durable these composites are.

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Different types of thermoset resins, like epoxy, polyester, as well as thermoplastic resins, can be utilized in conjunction with basalt fibers in the production of FRC materials. "In order to increase the mechanical responsiveness of basalt FRC, several investigations in the research papers have concentrated on enhancing the fiber/matrix adhesion qualities to strengthen the fiber/matrix interfacial connection, incorporating silica nanoparticles, colloidal silica, sol/gel techniques, silanized and acid- treated multi-walled carbon nanotubes, and plasma treatment are some of the techniques used to increase mechanical interlocking on the surface of basalt fibers" [44]–[54].

Wei et al.[48] showed that basalt FRC's tensile strength was raised by 30% and its ILSS (interlaminar shear strength) by 15% when SiO_2 nanoparticles were applied using a sol-gel process. According to Kim et al.[47], the use of silanized and acid treatment improved the fracture toughness and flexural characteristics of carbon nanotubes filled basalt epoxy composites. According to Wei et al.[49], basalt fibers' tensile strength was dramatically increased by silica nanoparticle-epoxy coating as compared to pure epoxy coating. Basalt FRC coated with silica nanoparticles and epoxy also showed noticeably better interfacial characteristics. Interlaminar fracture toughness significantly increased after basalt/epoxy composites were treated with low-temperature oxygen plasma, according to Kim et al.[50]. In comparison to untreated specimens, SEM micrographs of plasma treated basalt/epoxy specimens showed excellent resin and fiber adhesion.

Kurniawan et al.[55] studied how plasma treatment affected the basalt fibers when combined with polylactic acid to make a composite material. They exposed the basalt fibers to plasma for different amounts of time, from zero to six minutes, and then analysed how this affected the different properties of the composite. The results indicated that the composite material's characteristics, such as its strength and stiffness, were significantly better than those of untreated composites. Specifically, the strength was 45% greater, and the stiffness was 18% higher. They discovered that the ideal duration for plasma treatment was 4.5 minutes to achieve the most significant improvement in composite properties. However, when the irradiation time was less than minutes, the composite's properties worsened. This could be because the treatment caused the silane bonds to break, rather than forming the desired polymeric bonds, resulting in reduced composite properties. This composite material is susceptible to damage even with short exposure to plasma because the Si-C bonds within the fiber have a lower bond dissociation energy than the C=C polymer bonds. In simpler terms, the plasma treatment can break the weaker Si-C bonds, leading to damage to the composite. The strength of a composite is not determined solely by the curvature of its fibers; the material chosen for the composite's matrix also plays a critical role. In other words, both the fiber's shape and the matrix material contribute to the composite's strength[56]–[58].

The following is an overview and discussion of the mechanical characteristics of basalt FRC materials [59]–[63] Comparing basalt FRC materials to glass FRC materials utilising the same polymeric resin and equivalent fiber volume fractions, basalt FRC materials exhibit mechanical qualities that are relatively greater (or comparable). Epoxy served as the main resin matrix in each study, although Carmisciano et al.[62] employed vinyl ester resin.

Plain woven (PW) basalt FRC materials had their tensile characteristics assessed by Dorigato & Pegoretti[59], they were contrasted with a counterpart made of glass. When compared to glass FRCs with identical fiber volume percent of around 60%, Basalt FRCs exhibited 17% higher tensile strength and 20% greater elastic modulus. Contrarily, basalt FRC had a tensile strength that was approximately 14% lower than that of carbon equivalents with a comparable fiber volume percentage. Comparatively higher failure strain was seen in unidirectional (UD) basalt FRC materials than in carbon (30% lower) or UD glass (5% lower)[59]. Carmisciano et al.[62] found that basalt FRC reinforced with PW fabric exhibited more than 20% and 40% greater tensile and compressive strengths, respectively, than glass fabric reinforced FRC. Additionally, the flexural strength and modulus of basalt FRC reinforced with PW fabric were approximately 20% higher than those of glass FRC[62].

Cerny et al.[64] evaluated how the matrix parameters affected the mechanical characteristics of basalt FRC. When compared to basalt FRC with a vinyl ester resin matrix, those with an epoxy resin matrix exhibited superior mechanical properties. Specifically, the basalt FRC with an epoxy showed 20% more tensile strength and 15% higher modulus, as well as approximately 45% greater compressive strength[64]. Numerous researchers have examined the properties of fiber-reinforced composite (FRC) materials, specifically the interlaminar shear strength (ILSS), flexural strength, and modulus, when reinforced with pultruded-woven (PW) fabric. These properties were evaluated under 3-point bending stress. [65]–[72]. As per the results all properties varied significantly depending on the production process, including hand lamination, vacuum assisted resin infusion (VARI), and resin transfer moulding, in addition to the material system. In investigations, VaRTM (vacuum assisted resin transfer moulding) was used to create PW basalt/epoxy composites[67], [68], [72]. "Previous studies involved the creation of PW basalt/epoxy composites through manual lamination, which employed an impregnation roller technique, and subsequently applying either a hot mould press or resin transfer-moulding with a fixed cavity mould" [69], [71].

Basalt FRC's flexural strength values ranged from more than 220 MPa, according to Subagia et al.[67], to around 500 MPa, according to Lopresto et al.[63]. Flexural strength was reported to range from more than 4.5 GPa by Bulut[73] to more than 20 GPa by Lopresto et al.[63]. ILSS was calculated by many scholars. As reported by Lopresto et al.[63], ILSS values ranged from around 18 MPa for PW basalt FRC created by VARI using hand roller method to around 40 MPa for basalt FRC manufactured using VaRTM technology to more than 55 MPa for bi-directional woven basalt/epoxy composite[61], [63], [65], [72]. The fabrication of laminates involved utilizing positive pressure infusion of 1 MPa, followed by a curing process under both pressure and vacuum conditions. The curing process lasted for 2 hours at 50°C, followed by an additional 2 hours at 80°C. Utilizing VaRTM, PW basalt/epoxy composites and PW E-glass have been compared. According to Lopresto et al.[63] and Chairman et al.[61], the basalt/epoxy composite had flexural strength and ILSS that were up to 55% and 50% greater, respectively.

Sfarra et al.[74] used impact tests to compare the damage aspects of glass fiber reinforced epoxy composites with basalt. The scientists discovered that basalt composites exhibited more anisotropic impact damage behaviour than glass fiber composites, this could restrict the capacity to predict the mechanical properties of composites made with basalt fibers. Shishevan et al.[75] analysed the impact properties of epoxy composites reinforced with basalt fibers that were woven in a twill weave pattern. They also conducted a comparison of these impact properties with those of composites reinforced with carbon fibers. For each kind of composite, a fiber volume fraction of 60% was reached using the VaRTM process to construct composite laminates. Compared to carbon/epoxy composites, basalt/epoxy composites showed superior low velocity impact performance. Fu et al.[76] looked into the impact characteristics of plain-woven and unidirectional basalt epoxy composites. To describe the impact characteristics of both types of composites, different tests were carried out. Unidirectional basalt/epoxy composites showed greater impact resistance in low-velocity impact tests with a hemispherical impactor than woven basalt/epoxy composites, but they responded to impacts from sharp impactors less quickly than woven basalt/epoxy composites. In ballistic testing, unidirectional basalt/epoxy composites had better ballistic properties than braided basalt/epoxy ones. Sanchez-Galvez et al.[77] conducted high-speed impact experiments to assess the performance of vinyl ester composites made with plain basalt, hybrid glass/basalt, and hybrid carbon/basalt, by comparing their ballistic limitations. The findings revealed that the hybrid glass/basalt vinyl ester composite exhibited the highest ballistic limit at 480 m/s and outperformed the other composites.

Dhakal et al.[78] examined the properties of flax/basalt hybrid vinyl ester composite in a different investigation. The results of the tests revealed that using both flax and basalt fibers in composite materials produced better outcomes than using only flax fibers and vinyl ester. The hybridization process could be a promising method for enhancing the toughness of composites reinforced with natural fibers, as hybrid flax/basalt composites had higher impact energy and peak load. In investigation of the effects of basalt fiber hybridization on the mechanical performance and ageing parameters of sisal-reinforced bio composites, Zuccarello et al.[79] Through experimental analysis of bio composites reinforced with a combination of sisal and basalt fibers, it was demonstrated that an increase in the volume fraction of basalt fibers resulted in improved mechanical performance and a significant reduction in the aging effects on the mechanical characteristics of the composite. Saleem et al.[80] studied hybrid bast/basalt polymer composites, where the inclusion of basalt fibers increased the composite's mechanical characteristics and energy absorption capacity, these factors are very important in the automobile industry.

De La Rosa Garca et al.[81] studied the bending behaviour of wood beams with composite reinforcements. Strength and stiffness of timber beam with UD (Unidirectional) basalt composite was more than carbon-based reinforcement. Basalt FRC's mechanical characteristics when reinforced with non-crimp fabric (NCF) have been documented in the research papers. VaRTM method was used to create laminates. According to Davies et al.[82], The NCF basalt/epoxy composites were observed to have a flexural strength of about 690 MPa and a modulus of 39 GPa and the ILSS value was measured to be 44 MPa. Regarding flexural strength, NCF basalt/epoxy composites exhibited superiority over NCF E-glass/epoxy composites, with a margin of approximately 15%.

Epoxy has not been the only polymeric resin matrix utilised to embed basalt fiber composites; vinyl ester and polyester resin have also been employed. PW basalt and E-glass FRC's post-impact performance was compared by De Rosa et al.[83] Impact damage tolerance was comparable across basalt and glass-fiber composites, while basalt composites had better post-impact residual characteristics. Gideon et al.[84] examined the impact behaviour of composites made of unsaturated polyester resin and basalt fiber by carrying out low velocity impact tests and static 3-point bending tests. Basalt composites made of PW, cross-ply, and UD were created using a manual lay-up and hot pressing under pressure procedures. The mechanical properties of UD basalt composites were found to be impressive when tested under static loading. However, woven and cross-ply laminates showed better performance under dynamic loading conditions. The research also revealed that the mechanical characteristics of basalt composites were influenced by various factors such as fabric architecture, fiber lay-up, and testing conditions. Thus, it is important to consider these factors while designing and testing basalt composites for various applications[84].

The investigation of the mechanical characteristics of thermoplastic polymer matrix composites reinforced with basalt fibers has also received considerable attention in the literature. The recyclability and weldability of thermoplastic composites make them an attractive option for circular economy applications. In addition, they can be used to form large composite structures in a shorter amount of time[85]–[87]. Although thermoplastic composites have significant advantages, they are still not as well-established as thermoset composites due to several challenges. These challenges include difficulties with achieving good fiber-matrix compatibility, the requirement of high processing temperatures, and complex processing procedures[85]–[87].

Most of the research on basalt fiber reinforced thermoplastics (BFRTP) has focused on composites with short basalt fibers and thermoplastic matrices. The thermoplastic matrices used in these studies include polypropylene (PP), polypropylene/poly (butylene terephthalate), and poly (vinylidene fluoride)/poly (methyl methacrylate) blends. These composites have been investigated mainly for their suitability in injection molding manufacturing processes[6], [8], [88].

Incorporating basalt fiber reinforcement in thermoplastic matrix composites has been shown to enhance various properties, such as strength, mechanical characteristics, frictional behaviour, injection moulding shrinkage, tensile and flexural properties, and even nanoparticle dispersion[89]–[92]. Xinying Deng et al.[93] studied Polycarbonate and Polypropylene with basalt fiber (both short and continues fibers). To improve the adhesion between the basalt fiber and the polypropylene (PP) matrix in composites, polypropylene-graft-maleic anhydride (MAPP) pellets were added, leading to increased tensile strength. When a compatibilizer was not used, the tensile and impact properties of the basalt fiber reinforced PP short-fiber composites showed no improvement beyond a fiber loading of 30 wt%. However, when a compatibilizer was used, these properties continued to improve at a fiber loading of 40 wt%. The Young's modulus values of the basalt fiber reinforced PP and PC composites were measured, and they were at least 69% and 81% of their respective theoretical values, indicating that stress transfer was more effective in the PC composites, which performed better than the PP composites. Overall, these results suggest that using a compatibilizer can enhance the performance of basalt fiber reinforced thermoplastic composites.

Anna Kufel et al.[88] manufactured hybrid composites made by basalt and glass fibers with polypropylene and studied various parameters, after the specimens broke, they were looked at closely with a scanning electron microscope to see how well the fibers and matrix stuck together and spread out. The outcomes demonstrate that it is possible to successfully produce a composite made of glass and basalt fibers in a polypropylene matrix using maleic anhydride-grafted polypropylene. For a composition containing 20% by weight of fibers, the inclusion of the two types of fibers raised the tensile strength by 306% and the tensile modulus by 333%.

Different architectural designs of fabrics are frequently employed in the production of basalt fiber reinforced composites (FRC). These include unidirectional (UD), bidirectional, plain weave (PW), non-crimp fabric (NCF), and short discontinuous fiber reinforcement.

The failure mechanisms displayed by fiber reinforced composites (FRC) tend to vary based on the imposed load conditions[94]–[96]. The failure behaviour of fiber reinforced composites (FRC) can be impacted by a range of factors, including the anisotropic properties of each layer, the layer's orientation, the fiber architecture, the strength of the bond between the fibers and the matrix[97]. The various factors that contribute to the overall behaviour of the composite structure operate at the level of individual layers. As a result, the composite structure can exhibit a wide range of failure modes when subjected to different load conditions. These factors interact with each other in complex ways, making it difficult to predict exactly how the structure will behave. Damage mechanisms commonly seen in unidirectional (UD) basalt fiber reinforced composites (FRC) include:

1) Fiber breakage along the tensile axis during tensile loading[98].
2) Buckling of fibers under compressive loading[99].
3) Under shear loading, the fiber/matrix interface in a unidirectional basalt fiber reinforced composite may fail, leading to matrix cracking that usually occurs parallel to the fiber's tensile axis. This type of failure is caused by the shearing forces acting between the fiber and matrix, which can weaken and break the bond between them. As a consequence, the composite's load-carrying capacity is further reduced due to the resulting matrix cracking [99].

Distinct failure modes can be observed in a composite when the fibers are arranged perpendicular to the loading direction, including:

a) Tensile loading causes failure at the fiber/matrix contact, which spreads across the thickness as the stress rises and results in fracture perpendicular to the loading direction[100].
b) Under compressive force, shear failure occurs at an angle of about 45° to the loading direction[100].
c) Under shear stress, the matrix deforms in the direction perpendicular to the fibers, causing a crack to develop at the fiber/matrix interface and subsequently within the ply at a 45-degree angle to the tensile axis[100].

For PW basalt fiber reinforced composites under bending loads, the most frequently observed failure modes are fiber pull-outon the tension side, debonding between fibers and matrix[73], [101], In composites where the fibers are perpendicular to the loading direction, the compression side of the fibers may experience buckling while the tension side may undergo fiber breakage[102]. Additionally, kink bands may also be observed on the compression side[73], [103].

VII. BASALT FIBER REINFORCED POLYMER COMPOSITES FILLED WITH NANO FILLERS

Understanding how nano fillers affect the mechanical, thermal, and tribological characteristics of basalt fiber reinforced polymer composites is crucial since their high surface energy may significantly improve the properties of composites. Despite sharing a similar chemical structure with glass fibers, basalt fibers demonstrate better compatibility with a range of polymers, such as epoxy, vinyl ester, and polyester resins. Additionally, basalt fibers possess exceptional mechanical strength, thermal stability, and chemical resistance, making them a suitable alternative to glass fibers in various applications[29], [104]–[106]. Basalt fiber has a low surface energy, is chemically inert, and may have its interfacial contact with the matrix improved by applying surface treatments or using small amounts of fillers like micro fillers and nanofillers in the matrix. Due to their higher density as compared to low density matrix, micro fillers are needed in significant quantities to improve mechanical qualities, which will also result in an increase in the weight of the composites. Nanoparticles are commonly employed for fabricating nanocomposites, with some of the most frequently used ones being Graphene, Graphene Oxide, Graphite, Carbon Nanotubes (CNT), Nano-clay, Nano-alumina, Nano-iron oxides, Nano-tungsten carbide, and Nano-silica etc. These nanoparticles are incorporated into the matrix material to improve the composite's properties and performance, such as its mechanical strength, thermal stability, and electrical conductivity. [107]–[115]. Adding conductive nanoparticles to FRP composites can also improve the material's mechanical and dielectric characteristics. In comparison to other natural fibers and glass fibers, basalt fiber can be a better option for reinforcing of composites. Basalt fiber with different polymer matrix showed very enhanced properties after adding some fillers as shown in table 4.

Table 4: Results From Different Studies On Basalt Fibers Reinforced Polymer Composites Reinforced With Nano Fillers With Results.

Material system	Nano filler content	Thermal, tribological and electrical properties.	Mechanical properties	TEM/SEM result	Refere nce
Graphene nano fillers, epoxy, Basalt fabric	0, 0.1,0.2,0.3 wt. %		Tensile modulus and strength was enhanced by more than 18% and 10% respectively, The addition of 0.1 wt% GnPs to the composites resulted in a significant improvement in their flexural modulus and strength by 69% and 30% respectively. Furthermore, the impact strength of the composites was increased by more than 11%.	Due to the insertion of more than 0.1 weight percent of GnPs into composites, there are more interfacial fiber raptures and fiber pull-outs, which leads to poor interfacial bonding.	[116]
Tourmaline powder (900 nm-8 µm), Epoxy, woven Basalt fiber	0.5, 1, 1.5, 2 wt%		Flexural modulus and strength rise as filler content increases; with a filler loading of 2 wt%, maximum flexural strength was 16% and maximum flexural modulus was 153% greater than BFRP composites.	Good matrix- fiber bonding and dispersion of TM particles gives to strong interfacial adhesion.	[101]
Alpha-Nano alumina, Epoxy, Basalt fiber woven mat.	0, 0.2, 0.4, 0.6, 1.2, 1.8, 2.4, 3 wt%	The composites thermal stability was only slightly impacted by the addition of fillers.	Composites' tensile strength deteriorate when fillers are added.	The homogenous distribution of the fillers in the matrix was the cause of the improved characteristics for the samples with low filler percentages.	[117]

MWCNT fillers, Epoxy resin and Basalt fiber.	0, 0.5, 1, 1.5 vol%	Glass transition temperature (Tg) rises with MWCNT content up to 1.5 vol% and is observed to fall with increasing MWCNT concentration.	Increase in elastic modulus and strength. Because of aggregation and CNT waviness, experimental results fell short of theoretical expectations. Composites using CNT reinforcement significantly improve the effectiveness of the	Covalent bonding and nanoparticle dispersion boost stress transmission across interface when CNT surfaces are modified. Crack deflection and fracture	[45]
			reinforcement in the fiber direction.	propagation pinning are two toughening mechanisms that are activated by the addition of CNT. MWCNT, when added in modest amounts to epoxy, lowers agglomeration and debonding.	
Nano SiO_2, Graphite powder (<1lm), Basalt fabrics, Phenolic resin.	BFC/Gr/SiO_2 BFC/Gr BFC/SiO_2 BFC		BFC/ Gr/SiO_2 composites have a 58.5% higher friction coefficient than BFC composites, and fillers significantly reduce wear rate at higher loads.	Pure BFC exhibits fiber pull-out and debonding between the fiber and matrix, whereas the inclusion of fillers results in little fiber breakage and minimal fiber pull-out.	[118]
GnPs, epoxy, and unidirectional basalt fiber fabric.	GnPs/Epoxy composites: 0.1 to 2 wt% GnPs/Basalt/epoxy composites: 0.07, to 0.41 wt%.	GnPs/Epoxy composites: With increasing filler loading, AC conductivity, dielectric permittivity, and dielectric loss all rise.	The use of fillers improves the composites' mechanical characteristics. The optimal strength and modulus values are obtained when the filler content is 0.07% by weight.	When up to 1 weight percent of GnPs were added to Epoxy composites, they were uniformly distributed within the matrix. However, the addition of fillers led to their clustering, forming conductive pathways within the material. GnPs may evenly scatter in a matrix at low filler loadings, but when filler loading reaches 0.24 weight percent, agglomeration starts to occur.	[116]
Epoxy glue and MWCNTs- coated plain-weave basalt fiber was used to create this.	Coating cycle from 1 to 10%	Due to a reduction in resistance with an increase in CNT concentration, electrical conductivity for a two-cycle	Flexural strength and modulus both rise with the number of dip cycles; for two dip	MWCNTs were discovered to be firmly coated through	[119]

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		coating dramatically increased from 3.25 10 9 to 3.47 10 3 S/cm, whereas it was only 1.44 10 1 S/cm for a ten-cycle dip coating.	cycles, a 25% increase in flexural strength and a 6% increase in flexural modulus were seen. accumulating MWCNTs causes a reduction in characteristics and inadequate load transmission from matrix to fiber.	hydrophobic contact and particular bonding. Due to the presence of MWCNT on basalt fiber, a rough surface can be seen, and the amount of MWCNT surface coverage grows as the number of dip-dry coating cycles rises.	
CNTs, woven basalt fiber, Epoxy.	Unmodified, Oxidised, silanised CNTs.	Silanized composites had a storage modulus that was 48% greater than untreated composites. Strong interfacial bonds and homogeneous dispersion minimise the mobility of the matrix around the CNTs, increasing their thermal stability.	In comparison to composites without modification, the silanized CNT/basalt/epoxy composites showed a 60% increase in Young's modulus and a 34% increase in tensile strength due to a strong cross-linking network., excellent dispersion, and interfacial contact between the matrix and CNTs.	For oxidised composites, the fracture surface was rather clean and the amount of fiber pull-out was reduced. CNTs were evenly distributed and heavily matrix-impregnated in silanized composites, with minimal fiber pull-out.	[120]
Na-montmorillonite (Na- Mt), 3-GPTS (3-glycidoxypropyltrimethoxysil) nano clay, basalt fiber, and epoxy	0, 1, 3 and 5 wt%.		Adding 5% nano clay to a composite increased its tensile strength by 11% and modulus by 23%. The composite also showed a 28% improvement in flexural strength and modulus. Additionally, compressive strength and modulus increased by 43% and 34%, respectively.	Fiber-epoxy debonding is seen in BF/epoxy composites that are not filled. A composite containing 5 weight percent nano clay shows improved interfacial bonding strength and fracture deflection.	[121]
Basalt fibers, TiC nanoparticles, coconut fiber microparticles, and bio epoxy.	Epoxy, Epoxy/Coir/basalt, Epoxy/Coir/Basalt/TiC, Bio-epoxy, Bio- epoxy/coir/basalt, and Epoxy.	In comparison to other samples, epoxy/Coir/basalt/TiC composites and bio-epoxy/Coir/basalt/TiC demonstrate greater thermal stability.	Maximum Tensile strength 112 MPa and impact strength 27.67 kJ/m2 obtained for Epoxy/Coir/	Epoxy/Coir/Bas alt composites showed stronger interfacial adhesion, and the rough surface of the composites was caused by the	[122]
			Basalt composites.	inclusion of TiC nanoparticles. Failure of composite samples was caused by a tiny gap and uneven distribution of fibers and fillers.	

Unmodified nano clay, surface-modified nano clay, 0.5 mm-thick aluminium sheet, basalt fiber, and epoxy.	Unmodified nano clay, surface modified nano clay: 0, 1, 3, 5 wt%.		Flexural strength rises as nano clay concentration rises, and maximum flexural strength and impact strength for 3 wt% of modified nano clay composites were 52% and 10% higher, respectively, than for control sample. The mechanical characteristics of composites filled with modified nano clay were superior than those of composites filled with unmodified nano clay.	Agglomerations were more common in unmodified nano clay composites than in modified nano clay samples, which makes the region more brittle and fragile.	[122]

VIII. THE LONGEVITY OF COMPOSITES REINFORCED WITH BASALT FIBERS

The capacity of a material to withstand harmful elements including high temperatures, dampness, ultraviolet rays, exposure to corrosive chemicals, and stress cycles is what determines how long it will last. The durability of a material is evaluated by analysing its properties such as strength and modulus, both prior to and following exposure to various destructive factors over a specified time frame, under well-defined conditions.

A. *Durability in moist condition*

During their operational lifetime, structural composites frequently face exposure to moisture in the environment. Typically, moisture absorption in fiber-reinforced composites occurs via three distinct mechanisms.

1) moisture content diffusion through tiny spaces (free volume) between polymer chains.
2) Capillary action driving the movement of water into the micro-spaces.
3) By penetrating defects at the boundary between the fiber and matrix [123]–[125].

The aging process due to moisture exposure can cause morphological alterations in fiber-reinforced polymer composites in various manners. Initially, matrix expansion due to swelling can result in internal stresses and the formation of micro-cracks. This changes the paths for moisture diffusion and absorption in the composite. Secondly, the plasticizing effect on the matrix can result in a higher strain-to-failure and a decrease in the glass transition temperature (T_g) of the composite. Smith & Schmitz's research indicates that a mere 2% of moisture absorption can lead to a decrease of 20% in the glass transition temperature of a typical polyester resin[126]. Exposure to moisture can affect the chemical bonds between the fiber and matrix interface, causing alterations in the strength and stiffness of the composite[127]. Wright [125] compiled data from five published papers on epoxy resins and plotted the decline in glass transition temperature (T_g) against moisture content. He found a general trend that for every 1% increase in water uptake, there was a drop of approximately 20°C in T_g, based on data up to 7% moisture content. He stated this as a rough generalization. The T_g was 20°C lower for saturated PMMA at 1.92% water pick-up. T_g for PLA microspheres decreased from 52°C (0.3% H_2O) to 37°C (3.5% H_2O), indicating that PLA matrix composites must be carefully designed if they are to be employed in humid tropical conditions [127].

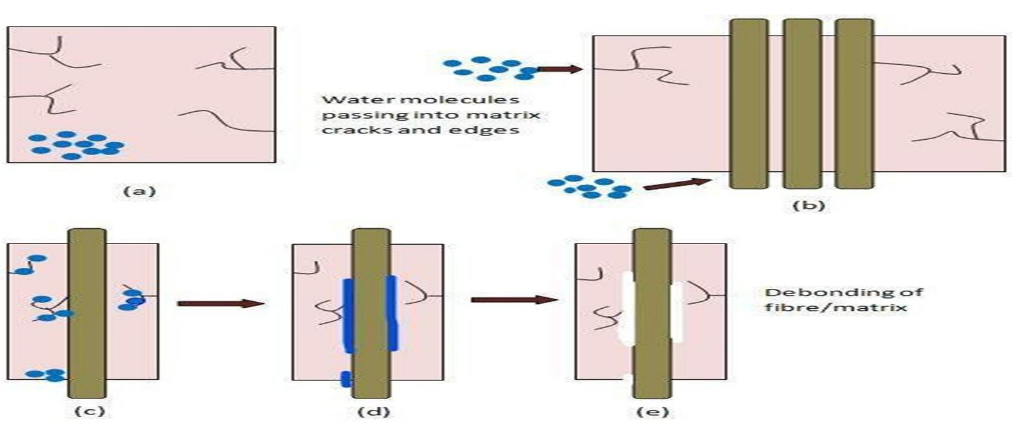

Fig. 8 moisture absorption

To evaluate the expansion of materials due to moisture, the Coefficient of Hygroscopic Expansion (CHE) is utilized, which measures the strain resulting from a 1% variation in moisture content and is also referred to as the swelling- or moisture-expansion coefficients. Natural fibers only have a longitudinal (axial) and transverse (radial) CHE, whereas anisotropic materials will have distinct CHE in each direction.

By utilizing the moisture absorption capacity (M) and the diffusion coefficient (D), it is possible to determine the amount of moisture a material can absorb. The assessment of D and M is commonly conducted at temperatures that are at least 20°C lower than the glass transition point of the material[128], [129]. The rate of moisture absorption, which is evaluated through the measurement of D and is based on Fickian diffusion theory, can be influenced by temperature. Typically, an increase in temperature results in an elevation of D [130].

Several studies have been conducted to investigate the weight gain behaviour (M^{∞}) of basalt-epoxy composites as related to moisture absorption[131]–[134]. In a 200-day seawater immersion test at 40°C, Basalt-epoxy composites created via VaRTM with non-crimp fabric displayed a weight gain of 1.5%. In comparison, E-glass-epoxy composites demonstrated a weight increase of 1.25% under the same conditions[82]. After being subjected to normal water and seawater for 24 hours, composites produced from basalt and polyester through compression molding exhibited a comparable weight gain of roughly 2%[131]. Composites made of basalt and epoxy using Vacuum-Assisted Resin Transfer Molding (VaRTM) showed a weight gain of approximately 3.5% after being immersed in distilled water at 80°C for 100 days[132]. Under identical conditions, E-glass/epoxy composites displayed a weight gain of roughly 6%, whereas VaRTM-manufactured unidirectional (UD) basalt/epoxy composites exhibited a weight gain of 0.8% after being immersed in distilled water at 40°C for 45 days[133]. A test was conducted where pultruded UD basalt/epoxy composites and pultruded UD E-glass/epoxy composites were put in seawater for 84 days at 40°C. After the test, it was observed that the weight of the basalt/epoxy composites increased by around 3%, while the E-glass/epoxy composites showed a weight gain of about 0.3%[134].

The differences in moisture absorption capacity of the composites can be attributed to the variations in the epoxy matrix, fiber architecture, manufacturing process, and exposure conditions used in each of the studies. Table 5 shows the different fiber with various manufacturing techniques shows different moisture absorption capacity. Exposure of composites to hygrothermal conditions allows moisture to permeate the matrix, leading to swelling of the matrix and a local rise in fluid pressure. This can cause distortion or separation of the layers, known as delamination[135].

TABLE 5: AN OVERVIEW OF HOW THE MOISTURE ABSORPTION CAPACITY, M, VARIES DEPENDING ON THE TYPE OF REINFORCEMENT USED, THE EPOXY RESIN USED, THE MANUFACTURING PROCESS, AND THE CONDITIONING ENVIRONMENT (PW: PLAIN-WOVEN, NCF: NON-CRIMP FABRIC, UD: UNIDIRECTIONAL).

Fiber	Plain- woven Basalt	Non-crimp fabric E-Glass	Non-crimp fabric Basalt	Plain-woven Basalt	Plain- woven E- Glass	Unidirectiona l Basalt	Unidirectio nal Basalt	Unidirectional E-Glass
Epoxy resin type	Epoxy RIM 135/137	Araldite 1564 LY	Araldite 1564 LY	Polyester	Epoxy RIM	Epoxy Bisphenol-A	Epoxy JN-C3P	Epoxy Bisphenol-A
Manufacturing technique	VaRTM	VaRTM	VaRTM	Compression moulding	VaRTM	Pultrusion	VaRTM	Pultrusion
Temperature	80°C	40°C	40°C	Ambient	80°C	40°C	40°C	40°C
Period	100 days	200 days	200 days	24 hrs	100 days	84 days	45 days	84 days
Medium	Distilled water	Seawater	seawater	Seawater	Distilled water	Seawater	Distilled water	Seawater
Moisture absorption capacity	3.5	1.25	1.5	2	6	3	0.8	0.3
references	[51]	[82]	[82]	[131]	[51]	[134]	[133]	[134]

B. Thermal Stability

In industrial settings where the risk of fire is a constant concern, it is imperative to ensure the thermal stability of industrial composites in order to minimize injury and harm to property. The ability of a material to maintain its structural integrity and physical characteristics during combustion is referred to as its thermal stability. The stability of the material can be assessed using different metrics, such as mass loss, carbonization, smoke production, heat release rate, and limiting oxygen index (LOI).

According to Tang et al.[136], basalt fiber-reinforced polypropylene composites showed a lower limiting oxygen index (measured at 18.6) compared to pure polypropylene (19.1). Basalt fiber-reinforced polypropylene composites burned slower than pure polypropylene when subjected to the same concentration of oxygen and displayed improved anti-melt dripping properties. Thermogravimetric analysis results indicated that the inclusion of basalt fiber in polypropylene resulted in a reduction of the maximum thermal degradation rate and an increase in the temperature at which this degradation occurs. A study using a cone calorimeter test revealed that a composite material made of basalt fiber reinforced polypropylene had lower heat release rate, total heat release, rate of smoke release, and total smoke release compared to polypropylene alone. In conclusion, adding basalt fiber to polypropylene led to a composite with improved ability to withstand high temperatures and burn more slowly compared to pure polypropylene[136]. Cerny et al.[64] studied how well FRC with continuous basalt fibers could withstand high temperatures after some of the polysiloxane matrix had been burned away. Wet-winding was used to create the composites, which were then further pyrolyzed between 650 and 750°C in nitrogen environment. It was shown that the temperature effects depended more on the elastic characteristics of the matrix, such as the shear modulus, than on the composite's Youngs modulus, which is dominated by reinforcing fibers[64]. Comparing basalt-based FRC to glass- and carbon-based FRC, basalt-based FRC showed improved thermal stability with higher rates of mechanical property preservation.

C. Chemical Durability

Exposure to corrosive substances can shorten the service life of composite materials. The mechanical behaviour of composite materials can significantly deteriorate when exposed to corrosive environments. Mingchao et al.[137] examined how well basalt fiber reinforced concrete could resist different types of chemicals by putting it in various chemical solutions. The durability of basalt fiber reinforced concrete against chemical deterioration was tested by exposing it to different chemical substances like sulfuric acid, hydrochloric acid, nitric acid, sodium hydroxide, sodium carbonate, ammonia, acetone, and water. The study found that the FRC was more durable and resistant to corrosion when it was exposed to alkaline solutions[137].

The stress-corrosion performance of basalt-based fiber reinforced concrete was studied through immersion in a corrosive solution composed of 5% sulfuric acid. Experiments with interruptions were conducted at stress levels of 30%, 50%, and 70% of the maximum strength. The study found that the degradation of basalt fiber reinforced concrete was influenced by time and was more severe when stress levels exceeded 50% of the maximum strength. Analysis of the composite samples using a scanning electron microscope (SEM) showed a significant effect of matrix plasticization[138].

IX. INDUSTRIAL APPLICATIONS

The versatility of basalt fiber-reinforced composites (FRC) opens up numerous possibilities for industrial use. These materials are sought after for their ability to resist corrosion in the chemical industry[139], and to offer wear and friction resistance in the automotive sector[140]. Basalt FRCs are also suitable for use as primary components in low-impact applications[141]. Other industries that can benefit from the use of basalt FRCs include construction, energy[142], and sports[142]. They can be used for high-temperature insulation in automotive catalysts and electrical appliances, and as a means of fire protection [143].

A. Automotive sector

Car manufacturers in the automotive industry often use basalt fiber-reinforced composites to make headliners due to their excellent recyclability. This gives basalt composites a clear advantage over other materials when it comes to manufacturing car headliners. Car headliner composite laminates consist of a core material with an adhesive layer on either side, with basalt fiber-reinforced composites (FRC) being placed adjacent to each of these adhesive layers[140], [142]. Basalt fiber composites are used not only in car headliners but also in making brake pads and clutch facings for automobiles. The use of basalt fiber-reinforced composites (FRC) in the automotive sector brings several benefits as compared to composites made from other fibers, such as glass. Basalt fiber-reinforced composites offer several advantages such as extended service life due to their increased durability, enhanced resistance to wear and friction, superior shock resistance, ability to withstand high operating temperatures, improved resistance to chemicals and moisture, and being environmentally friendly[140], [142].

B. Construction Industry

The construction industry also utilizes basalt fibers in a variety of applications. One of the most common uses is the production of basalt composite rebar for reinforcing concrete, offering numerous advantages over steel and glass fiber rebar. Basalt rebars offer a number of advantages over other materials, including superior fracture toughness, lightweight, improved resistance to chemicals and moisture, exceptional thermal stability, ease of processing, and good electrical conductivity[144]. Basalt rebars are often considered a preferable alternative to conventional materials in the marine and chemical industries due to their exceptional corrosion resistance. This advantage makes them particularly useful for construction projects in these sectors[144].

Basalt fiber-reinforced concrete has many benefits in the construction industry, including increased strength and durability, better resistance to moisture and impacts, and improved shock resistance. Compared to other types of fiber-reinforced concrete, such as those reinforced with polypropylene or polyacrylonitrile fibers, basalt fiber-reinforced concrete offers superior volumetric stability, thermal resistance, crack and impact resistance, and is also cost-effective. The construction sector demands panels that can withstand high temperatures and possess remarkable fire resistance to create room partitions, hallways, and elevator shafts. The outstanding fire resistance and thermal stability of basalt fibers make them a potential reinforcement material for the production of panels used to divide the interior into rooms, elevator shafts, and hallways in the building industry[144].

In road engineering Incorporating short basalt fibers in asphalt concrete can significantly enhance the performance, providing improved tensile strength, fracture toughness, and resistive to deformation[142], [144].

C. Energy Industry

Basalt fiber-reinforced composite materials offer a viable alternative to the commonly used E-glass fiber-reinforced composites in the manufacture of various components of wind turbine blades, such as the main spar and wing shell sections[145], [146]. Companies that make wind turbine blades use both carbon fiber and glass fiber composites together to make hybrid layers for the spar cap section of the main box spar. The aim is to achieve maximum bending stiffness. This leads to the production of longer and lighter blades, resulting in increased energy generation. By incorporating basalt fiber-reinforced composites, wind turbine blades can greatly improve their performance, recyclability, and overall eco-friendliness due to the exceptional material properties of basalt. This can result in a significant cost-to-quality ratio improvement for blade manufacturers. For offshore wind energy installations, floating steel structures such as towers and platforms are utilized, however, they are susceptible to corrosion and moisture degradation[142], [145], [146]. The outstanding mechanical properties and superior moisture and corrosion resistance of basalt fiber-reinforced polymer materials make them a promising alternative to steel floating structures for offshore wind turbine installations.

D. Geocomposites

Basalt fiber are effective for the transportation and storage of radioactive nuclear materials due to their non-absorption of any form of nuclear radiation. The usage of basalt-based geo-composites is widespread in the production of protective caps that are resistant to radiation, for the purpose of nuclear waste disposal sites. The protective caps offer long-lasting shielding that extends for multiple centuries, guarding the environment and public health from the potential hazards of nuclear underground waste leakage or release. Nuclear landfill sites are frequently located in arid or sub-humid regions that have little to no underground water and are typically barren of any biological activity. These sites must be impermeable, free of maintenance requirements, and ensure zero leakage[147].

E. Sports equipment

Basalt fiber reinforced polymers have found extensive use in sporting gear due to their exceptional resistance to moisture and corrosion. Their suitability for water sports equipment, including kayaks, canoes, paddles, and water skis, makes them an excellent choice. Beyond that, basalt FRC materials are also used in a variety of other sports gear, including the outer rings of bicycles, tennis rackets, skis, and snowboards[148].

F. Other Applications

An alternative to S-glass fiber-reinforced composite materials in ballistic applications could be basalt fiber-reinforced composites. In the petrochemical sector, filament winding is utilized in the production of pipes and compressed gas cylinders. The use of basalt fibers in the fabrication process has the advantage of outstanding wet-out, providing filament winders a cost-saving opportunity while producing components that have superior material properties[149], [150]. In the power sector, carbon fiber-reinforced composite cores have been introduced as a replacement for metal cores in high- voltage power transmission wires for distribution lines.

The power industry has embraced carbon fiber-reinforced composite cores as an alternative to metal cores for high-voltage distribution lines' power transmission wires. In power transmission lines, glass fiber-reinforced composites are utilized as a substitute for steel cross-arms in the form of composite cross-arms. When creating composite cross-arms, we can swap out materials made with glass fibers for materials made with basalt fibers. The basalt fibers are a better option because they can insulate better, resist rust better, and are much stronger. The poles used for distributing electricity are typically constructed from standard materials like wood, metal, and cement. As a result of their exceptional mechanical and chemical characteristics, composite poles made from GFRC are being developed as an alternative to traditional material poles. BFRC poles can replace GFRC poles because they have better mechanical properties, can resist rust and moisture better, and have good thermal stability and electrical conductivity. Basalt FRC can also be used in the aviation industry to insulate the engine and the body of the aircraft from heat. In the railway industry, basalt fiber reinforced composites can be employed for electro-insulation as well as insulation against heat and sound in train carriages.

X. CONCLUSIONS

This review article aims to give a detailed summary of the latest developments in basalt fibers and how they are used in basalt fiber reinforced composites. In simpler terms, the paper will explain what basalt fibers are, how they are used to make stronger materials, and the new ways researchers are using them. Furthermore, the practical uses of basalt fiber composites in various industries are examined. The main goal of this study is to see if basalt fibers, which come from rocks called basalt, can be a better and cheaper option for making strong materials used in factories. Researchers want to know if they can replace the old fibers that are not as good for the environment with basalt fibers that are more sustainable. Basalt fibers have been found to have superior mechanical properties, excellent thermal stability, a high degree of resistance to chemicals and moisture, good sound insulation properties, and are easily processed, making them a desirable material in a wide range of applications. Additionally, basalt fibers are recyclable, further adding to their sustainability credentials. Research has shown that materials made with basalt fibers are stronger, more heat-resistant, and more resistant to moisture than materials made with glass fibers. In simpler terms, when we use basalt fibers instead of glass fibers to make things, the final product is stronger, can withstand higher temperatures, and is less likely to get damaged by moisture. This is attributed to the strong fiber/matrix interface and compatibility with a broad range of polymeric resin matrices.

Our review paper explains that when we add small amounts of nano fillers to materials made with basalt fibers, the resulting composites become much stronger in many different ways. This includes their ability to bend, resist being crushed, withstand sudden impacts, resist heat and friction, conduct electricity, and resist breaking. These improvements are similar to the ones seen in materials made with glass fibers that also have nano fillers added to them. Because of agglomeration and decreased flowability of the resin matrix during production, an increase in the proportion of nano fillers degrades the mechanical qualities. The characteristics of composites can be improved by altering the surface of nanofillers to reduce agglomeration, improve adhesion, and create a homogeneous matrix. The application of basalt fiber reinforced composite materials across various industries offers a cost-effective solution for manufacturers as it enables them to reduce production costs without sacrificing the material's mechanical performance. The cost-to-quality ratio of basalt FRC materials is highly favourable. The current paper showcases the substantial progress made in the research of basalt fiber reinforced composite materials and their various industrial applications. Based on the literature review, previous studies concur that basalt fiber reinforced composites have great potential as a reinforcing material in industrial structural composites. If we want to use basalt fibers more often in building strong materials in various industries, we need to make a lot more of them to keep up with the demand. This would also help make them cheaper than the usual materials like E-glass that we use to strengthen things.

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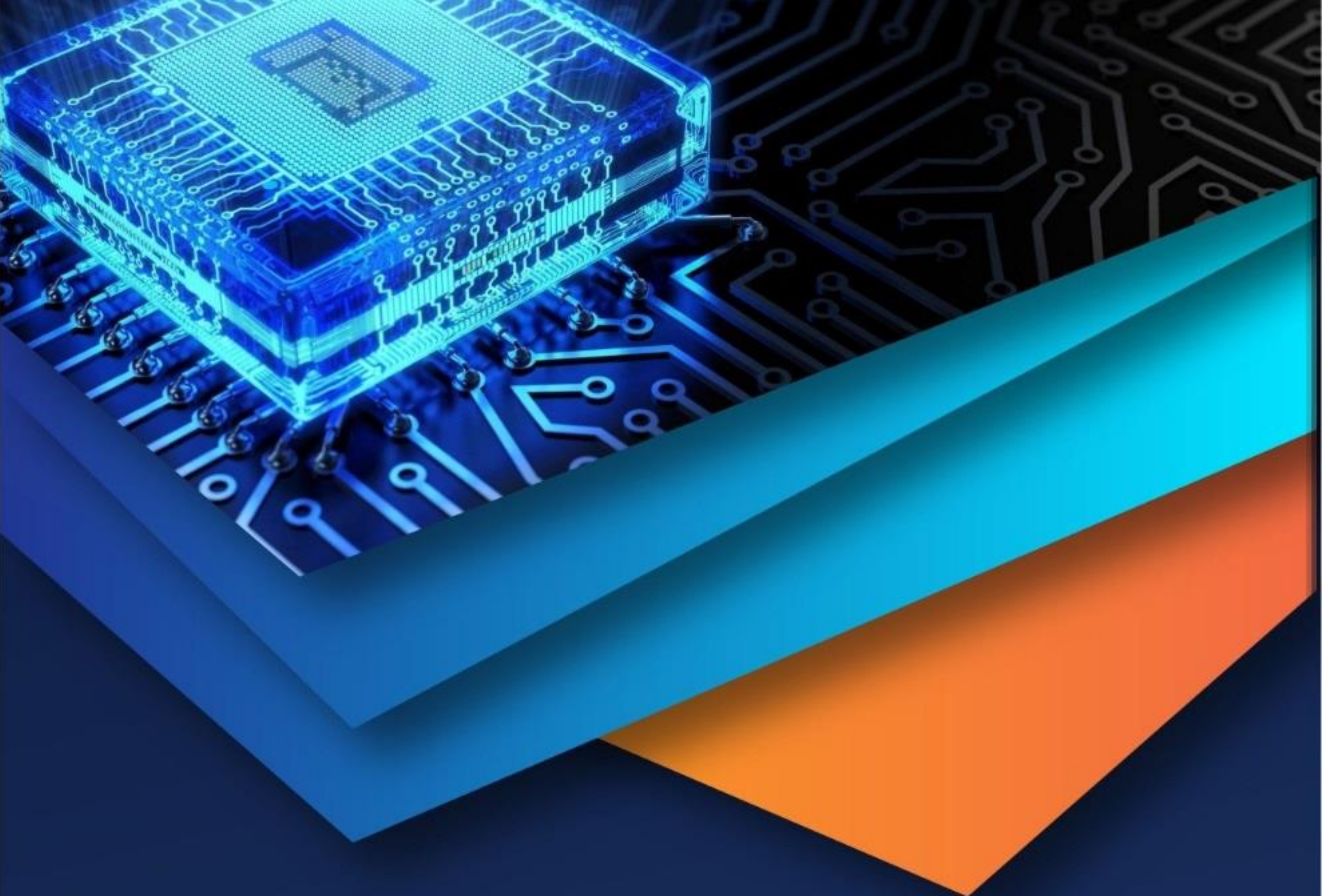

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