Basalt: structural insight as a construction material

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Abstract. The need for the development of novel and innovative materials is instrumental at every stage of societal improvements, leading to the overall development of a country. One such material of abundant source is basalt. The use of basalt in different forms like fibre, rod, grid and laminates has captured the interest of society from the 20th century onwards. Lately, basalt fibre has attracted attention as a possible construction material due to its properties such as high modulus of elasticity, high elastic strength, corrosion resistance, high-temperature resistance, extended operating temperature range and ease of handling. This paper explores the state of the art of basalt used in the construction industry with the overall layout of different subcategories of historical background starting from fibre development and different chemical and mechanical fibre properties to its applications in the field. Comparative studies have also been reported with respect to other high-strength fibre like glass, steel and carbon fibre based on different physical, chemical and mechanical properties. Along with these, a review has been done on the usage of different basalt products like aggregate, rod, fibre, mesh, etc. in structural applications. The review also tends to identify critical constraints that restrain the implementation of basalt as a global construction material, thereby opening avenues of needed research. An insight on inconsistency reported in the literature with respect to the behaviour of basalt-fibre-reinforced composites is also expressed in this paper. The overall idea is to gain information and identify and prioritize research areas of the possible applications of basalt towards sustainable construction.

Keywords. Basalt; fibre; structural application; aggregate; reinforcement.

1. Introduction

Paul Dhe [1] extruded fibre from basalt in the year 1927; since then the developments in basalt fibre continued after World War II by researchers in the USA, Europe and the Soviet Union mainly for military and aerospace applications [2–4]. From the 20th century onwards, the use of composite materials is growing at a very fast rate and is successfully replacing traditional construction materials in many areas [5]. Basalt is one such material, which finds multi-faced application in various industries [6–10]. From the year 1995 onwards, basalt has been used in a wider range of civil applications [11, 12]. Basalt is advantageous over various other materials with respect to melting points as well [13]. Broadly speaking, the composite materials being used in the construction industry consist of reinforcing elements embedded in a hardened matrix; the reinforcing element is chosen to have thermal strain

compatibility and to exhibit non-reactive nature with the hardened matrix [14]. The functionality of the reinforcing element is to impart high strength; on the other hand, the matrix provides strength to the system and also stability to the reinforcing element to enable it to perform to its intended limits. One of the most widely used reinforcing elements in a composite is ‘fibre’. In the present scenario, extensive research is going on to develop basalt fibre and to improvise it as more sustainable among all available fibres. Recently, application of “basalt” as reinforcement in the different fields of civil and structural applications is being explored [12, 14–16]. As of today, it is the only inorganic fibre that melts at a very high temperature of 1004°C [17]. Basalt as such is known to fulfill the aforementioned requirements as a possible reinforcing material in the fibre form. Figure 1 shows the tensile stress–strain comparison of the basalt fibre with the commercially available fibres.

From figure 1, it can be seen that basalt fibre possesses better stiffness and strength compared with E-glass fibre and

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Figure 1. Tensile stress vs. strain of different fibres compared with basalt fibre [22].

has more ductility in comparison with carbon fibre, making it a suitable reinforcing material on par with carbon and glass fibre, where its advantages over the other fibres are sought for. The world is working towards wider use of fibre-reinforced concrete for increasing strength and quality of building construction. The use of basalt in different forms like fibre, rod, grid, laminates, etc. captured the interest of the civil engineering community due to their favorable properties such as high performance in terms of strength [18, 19], corrosion resistance [20], high temperature resistance [21] and fire resistance [12], as well as the lower potential cost with respect to other fibre-reinforced polymer (FRP) materials. Basalt-fibre-reinforced polymer (BFRP) products have been used in various infrastructures where the structure requirement is more towards durability, light weight and quick recovery of construction after a disaster like an earthquake and blast [22]. They have proven their merits for high-performance applications. Basalt fibres are being used for flexural strengthening, confinement purpose, shear strengthening and internal reinforcement [12]. They are used as reinforcements in bridges and tunnels [22]. In roofing materials also, they are being used in the form of a non-combustible material. The following sections of the paper discuss various aspects starting from the availability, mineral and chemical composition resulting in different physical, chemical and mechanical properties, manufacturing process, a relative comparison of basalt fibre with steel, carbon and glass fibres and its final usage in relevance to various properties listed out in the paper.

2. Availability of basalt

Basalt rocks are formed by solidification of volcanic lava. Generally, basalt rocks melt in the range of 1500–1700°C. Because of its volcanic nature of origin, there is an abundant source of basalt rock on the earth [23]. A world map is shown in figure 2, which gives an idea of the availability of basalt rock all around the globe.

Figure 2. Availability of basalt across the earth [23].

In India, the Deccan trap exposed in western and central part is assumed to be covered by basalt rock. Based on different structural applications, various types of basalt products [22] have been developed over the recent years. The basalt products are available in different forms such as laminates, bars, profile sheets, steel fibre composite, fibre steel wire plate, etc. [22].

3. Atomic properties of basalt

Basalt mineralogy is governed by atomic properties of basalt. Yoder and Tilley have devised a scheme for classifying basaltic rocks by their CIPW norms, using a “basalt tetrahedron” as shown in figure 3 [24].

The basalt tetrahedron is simply the quaternary system of forsterite (Fo), diopside (Di), nepheline (Ne) and quartz (Qz). Each corner represents the minerals that constitute basalt. Forsterite represents olivine, quartz represents quartz, nepheline represents feldspathoid and diopside represents pyroxene. The amount of silica present in the basalt is marked by two planes, a critical plane of silica undersaturation, marked by forsterite–diopside–albite and a plane of silica saturation, marked by diopside–albite–enstatite (En). Albite represents a plagioclase mineral.

4. Basalt mineralogy

Basalt mineralogy plays an important role in assessing the nature of the fibre, as evident in the fibre manufacturing process, which will be discussed in the later sections of the paper. Plagioclase and pyroxene are the two essential minerals that make up to nearly 80% mineral composition of basalts obtained from different origins. Plagioclase is an intermediate member of the An-Ab series. It imparts resistance to isomorphic substitution [13]. But pyroxene is chiefly calcic and is a very critical mineral in basalt classification. Its presence signifies tholeiitic basalt and its absence usually implies alkali basalt. Olivine is another critical mineral that substitutes for pyroxene in alkali basalt.

Figure 3. The fundamental tetrahedron of Yoder and Tilley [24].

Olivine imparts magnetic properties of basalt [25]. Other minerals that occur in basalts and that play an important role in its classification are quartz and nepheline. Rocks that carry quartz are oversaturated with silica and rocks that carry pyroxene instead of quartz could be described as silica-saturated rocks. The presence of nepheline signifies a state of silica undersaturation [26]. Basalt rocks having higher quartz content exhibit a better acid stability and temperature stability, the temperature stability being relatively 50–200°C higher compared with basalt with lesser quartz [13].

5. Chemical composition

The chemical composition of the average basalt consists of 50% SiO₂ followed by 15% Al₂O₃ and similar quantities of CaO, MgO and FeO averaging a little less than 10% each. The sum of the other oxides is almost always below the 5% level. Table 1 gives the chemical composition of the average basalt, as estimated from the data of Chayes and Lipman [27].

Since basalt is formed from cooling of volcanic lava, it tends to contain lots of compounds, both acidic and basic in nature, in the form of oxides. Hence, basalt fibres can be characterized based on their acidity modulus (Ms), which is a ratio of acidic oxides to the basic oxides. If Ms < 1.2, the fibre is called slag wool, indicating that the base material is cinder. These fibres are very brittle and possess very poor chemical resistance. If Ms is in the range of 1.2–1.5, the fibre is considered to be a mineral wool whose base materials are volcanic rock and cinder. These fibres are brittle with

Table 1. Chemical composition of Cenozoic basalt [27].

SiO ₂	47.65
Al ₂ O ₃	15.28
Fe ₂ O ₃	3.57
FeO	7.54
MgO	7.52
CaO	9.91
Na ₂ O	2.98
K ₂ O	1.23
TiO ₂	2.14
P ₂ O ₅	0.44
H ₂ O	1.51
Total	99.77

The figures represent the average of 2413 individual chemical analyses.

acceptable insulation properties. If Ms > 1.5, the fibre is called rock wool and its base material is basalt; this fibre has several excellent properties as reported earlier in this paper [28]. The mechanical attributes exhibited by basalt can be related to the chemical compounds present in it as listed below.

Silicon dioxide imparts both strength and hardenability to the material. Apart from this, it also imparts the ability to withstand high temperature without undergoing many transitions. It also helps the material to be in its original form even in high acidic and alkaline environments. The large quantity of silicon dioxide can be seen as a reason for light weight and low thermal conductivity of basalt. The crystalline nature of silicon dioxide can be thought of as a cause for the brittleness of basalt.

Aluminum oxide imparts hardness, wear resistance, ability to resist strong acid and alkali attack at elevated temperatures, good thermal stability and high strength and stiffness.

Iron oxide helps basalt in having strength and higher heat resistance and does not allow it to undergo corrosion. The presence of iron oxide imparts golden brown colour to basalt [29].

Calcium oxide imparts both strength and the bonding nature to basalt.

Magnesium oxide imparts physical and chemical stability to basalt at high temperatures. It also imbibes the characteristics of fire resistance, moisture resistance and mold and mildew resistance and helps in strength improvement.

6. Chemical resistance

The basalt fibres, when subjected to the acidic and alkaline environment at room temperature or elevated temperatures, were reported to exhibit controversial behaviour. Ramachandran *et al* [30] concluded in their study that the basalt fibres have excellent resistance to alkaline attack at both room temperature and at elevated temperatures but they do not have good resistance against acids. They also concluded in their study that the acid attack on basalt was

marginal at room temperature and very severe at elevated temperatures. Caiyun [31] concluded in their study that basalt fibre has outstanding acid and alkali resistance and stable chemical property. They further concluded that acid resistance of basalt fibre is better than alkali resistance, indicating that basalt performance is more stable in an acidic environment. This controversial behaviour exhibited by basalt is explained by Ying *et al*.

Ying and Zhou [32] explained the controversial behaviour of both strength increase and decrease in acidic environment, by dividing the reaction process of basalt into two stages. The first stage was attributed to hydration in the acid solution, resulting in formation of hydration products on the fibre surface. This increased the thickness of the fibre, depicting improved acid resistance and increased strength of basalt fibres. However, in the later stage, due to excess formation of H^+ ions on the surface, the effect of H^+ ions became obvious, resulting in erosion of the fibre surface, which in turn resulted in reduced thickness and fibre strength. Hence, he concluded that the extent of exposure and the composition of basalt can result in both strength increase and decrease in acidic environment.

Lipatov *et al* [33] conducted studies on improving the alkali resistance of basalt fibre in concrete environment by doping the basalt glass fibres with zirconia compound. As a part of their study, they found that the alkali resistance of basalt fibres is primarily due to insoluble compounds of Fe^{3+} , Ca^{2+} , Mg^{2+} and Ti^{4+} that are present in basalt. The solubility product constants of $Ca(OH)_2$, $Fe(OH)_3$ and $Mg(OH)_2$ are 5.5×10^{-6} , 6.3×10^{-38} and 6×10^{-10} , respectively. Since the alkali resistance of the material is inversely proportional to the solubility product constants, it can be said the alkali resistance of the basalt is dependent on the concentration of the aforementioned compounds. Based on the chemical composition, basalt from various sources has varied alkali resistance.

7. Mechanical properties

7.1 Density of basalt

The density of basalt is in the range of $2.5\text{--}2.9 \text{ g cm}^{-3}$ [28, 29, 34], which is much lower than that of steel but closer to those of carbon or glass fibres. However, basalt is far less expensive than carbon fibre and has higher strength than that of glass fibre; it has a good chance of being an ideal candidate for low-weight, less expensive and tough composite material.

7.2 Abrasion properties

Basalt material is extremely hard and has hardness values between 5 and 9 on Mohr's scale, which results in better abrasion properties. The Brinell hardness of basalt is 420 MPa [35]. The basalt fibres provided reductions

between 2% and 18% in abrasive wear of concretes. The increase in fibre content and fibre length also contributed to resistance to abrasion [36]. Even continuous abrasion of the basalt-fibre-woven fabrics over the propeller-type abraders does not generate fine fibres or splitting of fibres by fracture and results only in breaking of individual fibres from the woven structure, which eliminates the possibility of causing hazards related to respiration.

7.3 Fracture properties

The fractures in the basalt fibres occur mainly due to the heterogeneity of the material composition of the basalt. Also, the process of uneven cooling of the molten lava would create residual stress in the system and inherent thermal differential cracks. Basalt fibres exhibit catastrophic failures at specific planes where the defects of formation, temperature and material are evident depending upon the critical defect size present in the fibres. Since the defects are present randomly in the fibres, this also leads to mutually independent multiple failures [28].

7.4 Thermal properties

Basalt fibres have excellent thermal properties and it can easily withstand the temperature of $1100\text{--}1200^\circ\text{C}$ [37] for hours continuously without any physical damage. Unstressed basalt fibres and fabrics can maintain their integrity even up to 1250°C [17], which makes them superior compared with glass and carbon fibres. The thermal conductivity of basalt is in the range of $0.034\text{--}0.04 \text{ W/(m K)}$ [17] and the thermal coefficient of expansion is $8 \times 10^{-6} (1/K)$ [37]. The good insulation property of basalt was recognized earlier, making it a widespread insulation material in the construction industry, processed in the form of Rockwool.

7.5 Magnetic properties

Basalt with olivine mineral is found to be more magnetic compared with basalt that does not contain olivine [25]. Generally, basalt tends to exhibit non-magnetic properties compared to other materials such as steel.

7.6 Acoustic properties

In addition to its high elasticity modulus and excellent heat resistance, its fibres have a significant capability of heat and acoustic damping and are outstanding vibration isolators [38]. The sound absorption coefficient of basalt fibre is in the range of $0.95\text{--}0.99$ compared with $0.8\text{--}0.92$ of glass fibre [39].

8. Basalt fibre manufacturing process

The basalt fibre roving and unidirectional sheets were first developed and widely used. The fibres that are drawn from molten basalt rocks under hydrostatic pressure are subsequently cooled to get hardened filaments. Filament strands are collected together and forwarded to the wound on take-up device. Twisted basalt yarn is produced by twisting the basalt roving. Continuous basalt filaments are chopped to a specific fibre length in a dry cutting process to get staple fibre [28]. The various basalt fibre products are basalt fibre roving, unidirectional sheet and grids [22]. The most common technique to make basalt fibre is Junkers Technology, Toplan Ltd., Tapolca, Hungary [28]. The process of fibre production by Junkers Technology is shown in figure 4.

The basalt produced by Junkers technology, which is one of the melt blowing technologies, results in inexpensive, short basalt fibres, which have relatively poor and uneven mechanical properties. Continuous basalt fibres are made by the spinneret method. Broken basalt stone is melted in a rhodium–platinum pot, lead to a spinneret made from the same material and spun gravitationally through holes in the spinneret bottom at 1350–1420°C [29]. The basalt fibre does not contain any other additives in a single production process, which gives an additional advantage in terms of capital [13].

8.1 Shortcomings in making of fibre

Fibres are manufactured from natural basalt stone without adding any other secondary material. Hence, manufacturing techniques have less direct control over the purity and consistency of raw basalt stone and finally on its product fibre. This will result in a similar composition of fibre as that of the parent material. Other than this the main problem in the manufacturing of fibre is the gradual

Figure 4. Scheme of the Junkers-type basalt fibre production by melt blowing: 1 – molten basalt rock, 2 – blowing valves, 3 – fibrillizing cylinder, 4 – droplets, 5–7 fibre formation, 8 – fibre, 9 – fibre head [28].

crystallization of various structural parts like plagioclase, magnetite and pyroxene. Each mineral has a different crystallization temperature T_c , which varies from 720 to 1010°C (magnetite T_c – 720°C, pyroxene T_c – 830°C and plagioclase T_c – 1010°C). Through good heat strategy, this disadvantage can be overcome [28].

9. Comparison of basalt fibre with steel, carbon and glass fibre

Basalt fibre application has recently been developed and found to be good compared with other high-modulus fibre like glass and carbon. In terms of making of fibre-like glass and carbon, manufacturing of basalt fibre is more environment-friendly and also less expensive in cost. In order to enhance the mechanical property of basalt fibre, it is not necessary to add any extra additive, unlike glass and carbon. Energy absorption capacity of basalt fibre is more than that of carbon and glass; hence for the ductile mode of failure, basalt fibre is preferable over carbon and glass. A comparative study of basalt with carbon and glass is reported in table 2.

10. Studies on basalt as construction material

Due to the aforementioned properties, basalt was sought as a constructional material for different structural applications. The structural usage envisaged based on basalt properties are listed below under their respective property heads.

10.1 Mechanical properties

Ramakrishnan *et al* [19] conducted parametric studies for compressive and flexural strength of basalt fibre with different volume fractions. There was little or no variation in compressive strength also with respect to normal concrete. Fibre failure was found to be pullout-type failure, imparting ductility and large energy absorption capacity. Studies were also carried out separately on basalt-fibre-reinforced bar by Ramakrishna *et al* [19] Subramanian [40] and Bi and Wang [41].

It was concluded that increasing the bonding length and diameter of basalt-fibre-reinforced polymer bar resulted in decreasing average bond strength. The good effect of bonding strength was optimized for 0.2% basalt fibre [41]. Basalt composite rebar was found to be an alternative to steel bars [40]. The stress–strain behaviour of BFRP is shown in figure 5.

Raj *et al* [42] conducted characterization studies on basalt-fibre-reinforced composite using different volumes of basalt fibre fractions. It was found that addition of basalt into the high-strength mix did not improve failure

Table 2. Comparative studies of basalt with glass steel and carbon fibre.

Properties	Glass fibre	Carbon fibre	Basalt fibre	Steel fibre
Fibre production	For making glass fibre, mainly 50% silica in combination with oxides of boron, alumina and/or several other minerals are independently mixed in the metring system before introducing into the furnace	The raw materials of carbon fibres are polyacrylonitrile (PAN), cellulose (rayon) and pitch. Fibres are made from these materials in three steps: stabilization at 400°C, carbonization at 1200°C and graphitization at 1000–3000°C	For making basalt fibre, quarried basalt rock is put into the furnace in crushed form. No secondary materials are mixed before introducing into the furnace. This process requires only a single feed line to carry crushed basalt rock into the furnace	Steel fibres are obtained by mechanical cutting of drawn steel wires from steel billets in the appropriate size
Density (g cm ⁻³)	~2.6 [59]	1.4–1.6 [60]	2.5–2.9 [28, 29, 34]	7.85 [61]
Tensile strength (MPa)	1798.3 [12]	3528.1 [12]	992.4 [12]	250 [61]
Stiffness (GPa)	70–86 [60]	280–530 [60]	76 [12]	200 [61]
Alkali immersion test	50% strength reduction (7 days) [12] 80% strength reduction (28 days) [12]	5% strength reduction (7 days) [12] 13% strength reduction (28 days) [12]	50% strength reduction (7 days) [12] 80% strength reduction (28 days) [12]	
Thermal stability at 600°C	45% strength loss [12]	40% strength loss [12]	5% strength loss [12]	30% strength loss [62]
Thermal conductivity (W/(m K))	0.031–0.038 [17]	80–270 [63]	0.034–0.04 [37]	33.6 [64]
Specific heat capacity (kJ g ⁻¹ K ⁻¹)	840–860 [17]	520–710 [66]	840–860 J g ⁻¹ K ⁻¹ [17]	490 [66]
Coefficient of thermal expansion (1/K)	5.4×10^{-6} [37]	8×10^{-7} [65]	8×10^{-6} [37]	12×10^{-6} [61]
Acoustic absorption coefficient	0.8–0.93 [13]		0.9–0.99 [13]	
Brittleness	It is less brittle compared with basalt fibre	It is more brittle compared with basalt fibre	Strengthening and toughening significant than those of carbon fibre for OPC concrete [40]	Ductile in nature
Moisture	Glass fibre absorbs moisture	Carbon fibre absorbs moisture. It needs an extra coupling agent like silane in order to increase adhesion with the matrix	Basalt fibres do not absorb and transfer moisture, but regain. The moisture content of basalt fibre is less than 1%	Does not absorb moisture

mechanism of the high-strength mix. Liu *et al* [43] conducted studies for dynamic compressive strength, deformation and energy absorption capacity of basalt fibre in geopolymer concrete. It was found that the addition of basalt fibre can significantly improve deformation and energy absorption capacities of geopolymeric concrete

while no notable improvement was found for dynamic compressive strength.

Sim and Park [12] carried out studies for characterizing basalt fibre as the strengthening material. Liu *et al* [43] reported that when polymer composites are reinforced with basalt and glass fabric, there were no significant differences

in Young's modulus and tensile, flexural, shear and compression strength observed between basalt and glass composites. BFRP-ALC sandwich panel (basalt-fibre-reinforced polymer-aerated lightweight concrete) was proposed by Zhishen *et al* [22]. This type of sandwich panel was intended for its use in the civil defense field, bridge engineering, civil construction, etc. Basalt fibre and mesh were used in the development of basalt-fibre-reinforced composite (BFRC) sandwich panel [44], where contribution of fibre and mesh has been reported in carrying the load even after the first crack load of the panel. Using basalt as strengthening material in the form of BRM (basalt-reinforced mortar) was also carried out by Di *et al* [45]. Bi-directional basalt laminates pre-impregnated with epoxy resin bonded with cement-based mortar were used as wrapping material and the results were compared with strengthening by uniaxial GFRP (glass-fibre-reinforced Polymer) laminates. The results showed that the BRM confining system could be a more suitable strengthening material. Zhishen *et al* [22] reported that basalt carbon fibre composite cable can be an alternative to traditional steel cable due to excellent static and dynamic performance like CFRP cable, but the price is only about 68% of that of carbon FRP cable and the aerodynamic stability performance of the hybrid basalt-carbon FRP cable is superior to that of CFRP cable. Lopresto *et al* [34] conducted mechanical tests carried out on equivalent basalt and E-glass-fibre-reinforced plastic laminates. Basalt composite showed a 35–42% higher Young's modulus as well as a better compressive strength and flexural behaviour, whereas a higher tensile strength was found in the glass material. Experimental work was carried out on basalt bars and laminates and compared to glass [46]. Results showed that tensile strength and modulus of elasticity of basalt laminates were 10% and 38% higher, respectively, than those of glass laminates. It was also found experimentally that

confinement with BFRP was 14% more effective than that with GFRP in terms of compressive strength.

A type of concrete was produced in which 20%, 40% and 60% natural sand was replaced by recycled glass and basalt fibre having different volume fractions of 0.1%, 0.3% and 0.5% [47]. The result showed an enhancement in compressive and split tensile strength by 4.23% and 15%, respectively.

Towards finding the applicability of basalt fibre as reinforcement for composites, studies were carried out on basalt fibre roving and compared to E-glass by Van *et al* [48]. The tensile strength of glass fibre/roving was found to be more than that of basalt fibre roving. Effect of temperature on fibre strength was also taken into consideration and the residual relative strength was more for basalt in comparison with glass.

10.2 Corrosion properties

Studies were carried out for concrete reinforced with basalt fibre composite rebars. Basalt fibre composite rebars have the potential to replace steel in reinforced concrete structures, wherever a corrosion problem exists like salt water, ocean climate, etc. Experimental results showed that basalt bar has a very high tensile strength and the failure of basalt bar alone was sudden and explosive but in the concrete beam, basalt bar exhibited ductile behaviour.

Patnaik [20] suggested the use of basalt fibre reinforced in transportation infrastructure since transportation structures are exposed to deicing salts and highly corrosive environment. A similar kind of study was carried out to evaluate the performance characteristics of the modified basalt-reinforced concrete beam [49]. In the study, Brik [49] found that basalt-reinforced bars and cables had a good bond with the concrete. Failure was observed due to the tensile failure of rebars and cables, not due to bond slip. Wei *et al* [50] conducted a test on epoxy-resin-reinforced basalt and glass fibres by treating them with a seawater solution for different periods of time. It was observed that the mass gain change of the BFRP and GFRP composites after being immersed in seawater is a combination of two effects: water absorption and soluble material extraction. The chemical stability of BFRP and GFRP in seawater was nearly the same. It was also suggested that an effective lowering of the Fe^{2+} content in the basalt fibre could lead to a higher stability of BFRP in the seawater environment. Basalt fibre composite rebars, which typically consist of 80% fibre and 20% resin binder, may potentially replace steel, wherever a corrosion problem exists such as exposure to salt water, alkaline attack and marine environment [51].

Figure 5. Stress-strain behaviour of basalt compared with Fe-415 steel.

10.3 Fracture studies

Kabay [36] conducted studies on RCC beams with basalt fibre. In his study, he concluded that fracture energy increased remarkably with the use of basalt fibres to the

order of 126% and 140% compared with the reference concretes. Dias and Thaumaturgo [52] conducted studies to investigate the influence of the volumetric fraction of the fibres on the fracture toughness of geopolymeric cement concretes reinforced with basalt fibres. The basalt fibres were more efficient in strengthening and toughening geopolymer cement concrete than Portland cement concretes only for higher fibre concentrations. Czigány [38] conducted studies on basalt-fibre-reinforced polypropylene composites. Fracture mechanical tests were conducted and it was proved that treatment of the matrix and the reinforcing fibres increased the strength of interfacial adhesion. The fracture behaviour of polysiloxane-based basalt-fibre-reinforced composites was studied by Glogar *et al* [53]. Brittle fracture was observed and composite properties got worsened after treatment in air at an elevated temperature of 650–750°C.

10.4 Thermal properties

Ultimate tensile properties of basalt fibres were investigated at temperatures of 50, 100, 200 and 300°C by Militký *et al* [21]. It was determined that only 300°C treatment led to a statistically significant drop of strength and dynamic acoustical modulus. Probably, the changes of these properties are based on the changes in the crystalline structure of the fibres. Effect of elevated temperature on concrete compressive strength using basalt aggregate was studied [54]. The study showed that the compressive strength of basalt aggregate concrete decreases when exposed to high temperature. The residual compressive strength varied in large ranges of 62–81% around 900°C.

10.5 Chemical resistivity

Wei *et al* [55] conducted tests on basalt and glass fibres treated with sodium hydroxide (NaOH) and hydrochloric acid (HCL) solutions for different time period. The basalt fibres are much more resistant to acid corrosion as compared with the glass fibres. For the basalt fibres, the acid resistance is much better than the alkali resistance. For improving the alkali resistance of basalt, different approaches such as altering the material composition and apply coatings have been tried. One of process found to be very productive is adding of zirconia compound as a part of the fibre or as a coating, [33, 56–58] which had shown to improve the alkali resistance of the basalt fibre.

11. Applications

Basalt as a crushed aggregate is used in construction projects (Shanghai Zenith Mining and Construction Machinery Co., Ltd, China) [22]. It is used as reinforcement in bridges

and tunnels [22]. It was used as an admixture in the ballastless track slab and passenger dedicated line from Wuhan to Guangzhou [22]. In 2007, for Seismostation's non-magnetic requirements, the Lanzhou seismological bureau used BFRP bars instead of steel bars in the construction of the Seismostation [22]. In May 2008, BFRP bars were used as continuous reinforcement for the Xingtang bridge (work carried out by Southeast University, Zhejiang GBF Basalt Fibre Co. Ltd. and Zhang Shi Shijiazhuang highway management) [22]. Hangjinq Highway K143+512 ~ K144+141 section incorporated basalt fibres manufactured by Zhejiang GBF Basalt Fibre Co. to strengthen AC-13 modified asphalt concrete [22].

12. Summary

As basalt is obtained from volcanic lava, it tends to have varied properties depending on the chemical constitution of lava and the materials imbibed in it during cooling at the surface. Based on the acidity modulus, rock wool basalt chosen tends to have excellent mechanical, chemical, thermal, acoustic and non-magnetic properties. This type of basalt is a very promising construction material. The basalt is environment friendly, since its production does not create any harmful gasses like CO₂ or any kind of environmental waste and also less expensive compared with other fibres like glass and carbon. Further, a basalt fibre does not involve any other additive during its production. Based on the review of literature discussed in this paper, it can be concluded that basalt fibre has excellent bonding capability and can be used in a different kind of composite like concrete, geopolymer concrete, polymers, polypropylene composites, polysiloxane-based matrices, epoxy composites, etc. From the characterization studies conducted on basalt-fibre-reinforced composite for optimum volume fraction, it can be seen there is a need for research.

Regarding basalt, it is claimed that coefficient of thermal expansion is very low compared with concrete, although in literature it was reported that coefficient of thermal expansion of BFRP bar is comparable to that of concrete. Other FRP bars like glass are also in use, but their performance degrades in an extreme environment, but BFRP bars are found to have good durability characteristics.

Further, it is observed that basalt performs better than glass in civil engineering applications because of its corrosion resistance in acid and alkaline medium. Variations in the results were found regarding chemical resistivity of basalt in comparison with glass fibre. Some studies report that basalt fibre has stronger alkali resistance than acid resistance while some studies report it vice versa. Differences in results are also noted for comparing performance between the chemical resistance of basalt and glass fibre.

Basalt is found to have high tensile strength in the elastic range, but the ductility of the material is not so pronounced,

leading to categorizing the material as brittle in nature. Basalt bars can be thought of as a substitute over a steel bar in the case where high elastic strength is the governing factor rather than ductility. Basalt is making its presence in various structural applications, even though glass, carbon and steel have already been in use for a very long time. There are furthermore horizons to be explored to utilize the potential of basalt for civil engineering applications as it has high tensile strength, good thermal and sound insulating property, high vibration resistance, chemical resistance, etc. In a nutshell, it can be concluded that extensive research is still required for exploring basalt for civil engineering applications.

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