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Basalt Fibre – Ancient Mineral Fibre for Green and Sustainable Development

Bazaltna vlakna – starodavna rudninska vlakna za zeleni in trajnostni razvoj

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Abstract
Basalt is a solid, compact igneous rock which is formed when volcanic lava cools adequately to solidify, covering many parts of the Globe. It is mainly used as a crushed rock in building and highway engineering. Both the staple and continuous type of fibres can be manufactured from basalt rocks. Basalt fibres have excellent mechanical, chemical and thermal properties. They are highly resistant to alkalis, acids, salt attack, oxidation and radiation. Basalt fibres are most suitable for concrete reinforcement, bridge and shoreline structures. Basalt-based composites offer better performance than steel and all known reinforced plastics (1 kg of basalt reinforcement equals 9.6 kg of steel). Basalt fibres are also fulfilling the concept of sustainable design and green building. In various applications, basalt fibres are replacing various high-performance fibres, e.g. asbestos, glass, aramid and carbon fibres. Recently, continuous basalt fibres have become attractive for electro-technical purposes as an insulation material and a natural flame retardant. An attempt has been made to provide a comprehensive review covering the basalt fibre manufacturing process, the eco-friendly building system, prime fibre properties, products and its ubiquitous application.
Keywords: basalt fibres, mineral fibres, hybrid composite, sustainable materials

Izvleček
Bazalt je trdna, kompaktna magmatska kamnina, ki nastane, ko se vulkanska lava dovolj ohladi, da se strdi, nahaja pa se na številnih predelih Zemlje. Večinoma jo uporabljajo kot zdrobljeno kamnino pri gradnji zgradb in avtocest. Iz bazaltnih kamnin izdelujejo tudi kratka in filamentna vlakna, ki imajo odlične mehanske, kemične in toplotne lastnosti. So visoko odporna na alkalije, kisline in soli, oksidacijo in sevanja. Bazaltna vlakna so primerna za ojačitev betona za gradnjo mostov in obalnih konstrukcij. Kompoziti, ojačeni z bazaltnimi vlakni, so zmogljivejši od jekla in vse znane ojačitve iz plastike (ojačitev z enim kilogramom bazaltnih vlaken ustreza ojačitvi z 9,6 kg jekla). Bazaltna vlakna ustrezajo konceptu trajnostnega oblikovanja in zelenih stavb. V različnih aplikacijah lahko zamenjajo številna visokozmogljiva vlakna, kot so azbestna, steklena, aramidna in ogljikova vlakna. V zadnjem desetletju so filamentna bazaltna vlakna pritegnila pozornost na področju elektrotehnike kot elektroizolacijski materiali in naravna ognjevarna vlakna. V članku je podan celovit pregled bazaltnih vlaken, od proizvodnega procesa, ekološko prijaznega sistema, lastnosti vlaken, izdelkov in široke uporabe.
Ključne besede: bazaltna vlakna, rudninska vlakna, hibridni kompoziti, trajnostni razvoj

1 Introduction

The industry is always motivated to locate new and better materials to manufacture new or improved products. With this in mind, the environment, strength, economy, risk and sustainability are important factors when a product is changed or a new product is developed. Sustainable building,

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sustainable design and green building are recent concepts that explain the efficiency of building in terms of the energy used to reduce the impact of the built environment onto human health and natural environment. According to the data recorded by the World Business Council for Sustainable Development, buildings are responsible for at least 40% of the energy use in most countries [1].

These days, a significant escalation has been observed in the production of composite materials. Intensively developed polymer composite materials (PCM) are used in different sectors of the industry and technology. One of the basic reinforcing elements of composite materials is the fibre. The glass fibre and carbon fibre are among the most effective and promising reinforcing fibres for manufacturing polymer composite materials used in the conditions of high loads. In the glass fibre production, a rare component, boron oxide (B_2O_3), is used, while the carbon fibre bears high manufacturing costs. Consequently, both fibres have no prospect for mass application. Currently, a lot of work is being executed on the development of a modern continuous fibre from basalt stones. With the industrial production of the basalt fibre on the basis of new technologies, the cost is equal or even less than the cost required for the production of glass fibres. Basalt fibres and materials on their basis have the most preferable parameter, the ratio of quality and price in comparison with glass and carbon, and other types of fibres [1]. Basalt originates from volcanic magma and flood volcanoes, a very hot fluid or semi fluid material below the Earth's crust, solidified in open air. Basalt is a common term used for a variety of volcanic rocks, which are dark grey in colour, formed from molten lava after solidification [2]. Basalt is a building material that could effectively find wider application, since it is abundant worldwide. Basalt fibres are more advanced than other fibres in terms of thermal stability, heat and sound insulation properties, vibration resistance and durability. They are used as a fibre reinforcement of resin, pipes and geocomposites.

Russia has unlimited basalt reserves. The bulk of Iceland's bedrock is basalt, which is widely used as a building material in the country. Basalt rock beds with the thickness of as much as 200 m have been found in the East Asian countries. Basalt is a building material that could due to its worldwide abundance effectively find wider application. One suggested use would be as a fibre reinforcement of resin.

2 Composition of basalt fibre

A basalt fibre is a material made from basalt rock which is composed of plagioclase, pyroxene and olivine minerals [2]. Plagioclase is an important series of minerals within the feldspar family. The name pyroxene comes from the Greek words for fire and stranger. Pyroxenes were named this way due to their presence in volcanic lavas, where they are sometimes seen as crystals embedded in volcanic glass; it was first assumed that they were impurities in the glass, hence the name "fire strangers". The pyroxenes are a group of important rock-forming inosilicate minerals discovered in several igneous and metamorphic rocks. Inosilicates, or chain silicates, have interlocking chains of silicate tetrahedral with either SiO_3, 1 : 3 ratio, for single chains or Si_4O_{11}, 4 : 11 ratio, for double chains. A pyrogenic rock is formed through the cooling and solidification of magma or lava. A metamorphic rock is a result of the transformation of an existing rock type [3]. A comparison of basalt with granite is shown in Table 1.

The mineral olivine is a magnesium iron silicate with the formula $(Mg, Fe)_2SiO_4$. It is a common mineral in the Earth's subsurface but weathers quickly on the surface.

The mineral level and chemical makeup of basalt formation depends on the geographical area. Moreover, the rate of cooling when the original flow reaches the Earth's surface influences the crystal structure. Basalt is mostly found on ocean floors, while granite represents the Earth's crust in all continents. Basalt is an extrusive, while granite is an invasive igneous rock. Basalt is darker, composed of magnesium and iron, whereas granite is lighter, and composed of feldspar and quartz. Basalt is called mafic, whereas granite is known as felsic. Basalt splits along columnar planes, while granite splits along horizontal planes [6].

Despite basalt stones being easily available with different compositions, only certain compositions are suitable for manufacturing a continuous filament with the diameter range 9–24 micrometres. A basalt fibre contains about 48.8–52.2% of silicon dioxide (SiO_2), about 14–17.5% of aluminium

Table 1: Comparison of basalt with granite [4, 5]

Character	Granite	Basalt
Rock type	Igneous (intrusive/plutonic)	Igneous (extrusive/volcanic)
Environment	Granite is formed from magma that cools very slowly into hard rock below or within the Earth's crust.	Basalt is solidified lava, like rhyolite. However, it flows much quicker as it is less viscous.
Distinguishing characteristics	Visible crystals of pink feldspar white or grey quartz, and black mica. There is no horizontal banding in granite.	Red-brown to black, frothy with small visible holes where gas escaped while the lava cooled.
Composition	Feldspar, quartz, mica, hornblende	Feldspar, olivine, pyroxene, amphibole

oxide (Al_2O_3), the rest of the components being shown in Table 2.

Table 2: Chemical composition of basalt rock [3, 5]

Chemical compound	Share in basalt rock [%]
Silicon dioxide (SiO_2)	48.8–52.8
Aluminium oxide (Al_2O_3)	14–17.5
Iron oxide ($FeO + Fe_2O_3$)	7.3–13.3
Magnesium oxide (MgO)	6.2–16
Calcium oxide (CaO)	8.59
Sodium oxide (Na_2O)	3.34
Potassium oxide (K_2O)	1.46
Titanium oxide (TiO_2)	0.9–1.6
Phosphorus pentoxide (P_2O_5)	0.28
Manganese (II) oxide (MnO)	0.1–0.16
Chromium (III) oxide (Cr_2O_3)	0.06

3 Manufacturing basalt fibre

Basalt fibres are divided into two large groups: continuous fibres and staple fibres. Staple fibres are also known as basalt fine fibres. The production process of discrete fibres has been well perfected over the last five decades, whereas the production technology for continuous basalt fibres is still in its initial stages. Fibre manufacturers, composite material manufacturers and consumers are interested in continuous basalt fibres for a number of reasons. A continuous basalt fibre has several advantages over a glass fibre. The raw material used to produce a continuous basalt fibre is widely available at low cost. The recent development in the continuous basalt fibre production technology and equipment has resulted in the low production costs similar to those of E-glass fibres.

Basalt fibres are mainly produced with the melt blowing (Junkers technology) and melt spinning technology [2, 7, 8].

3.1 Basalt fibre production with melt blowing (Junkers technology)

Basalt fibres are produced in a continuous process similar to that of glass fibres. A basalt rock is crushed, washed and loaded into a bin attached to feeders which further transfer the material into the melting baths in gas-heated furnaces. This process is made simpler due to the less complex composition of basalt fibres as compared to glass fibre processing. A glass fibre normally contains aluminium, silica, boron oxide and several other minerals that must be fed separately into the metering system before entering the furnace. This is not the case with basalt fibres as it does not consists of any such secondary materials and thus the process requires a single feed line to carry the crushed basalt rock into the melt furnace. As basalt stone is procured directly from the nature, this results in its manufacturers having less direct control over the purity and consistency of the raw basalt stone. When crushed, basalt enters the furnace, thereby liquefying the material at the temperature of 1500 °C (melting point of glass is 1400–1600 °C). It becomes difficult to uniformly heat the entire basalt mix with overhead gas burners used in conventional glass furnaces. The melting basalt must be held in a reservoir for extended periods, up to several hours to ensure a homogenous temperature under the overhead gas. Several strategies have been developed by basalt producers to promote uniform heating, which includes the immersion of electrodes in the bath. Finally, a two-stage heating scheme is employed, which features separate zones, furnished with controlled heating systems. The temperature control system in the furnace outlet zone feeding the extrusion bushings requires great precision; hence, a less sophisticated control system in the initial heating zone may be used. The blowing technology with centrifugal cylinders (e.g. Junkers method) is used for manufacturing cheap fibres with 60–100 mm in length and 8–20 µm in diameter, primarily used as insulating materials in the construction and automotive industries. The basalt melt is fed to a horizontal shaft fibre spinning machine after coming from the 1580 °C furnace, which consists of three centrifugal heads, one accelerating and two fibrillating cylinders [9, 10]. The fibres formed as a result of the centrifugal force are blown-off with high-pressure air as depicted in Figure 1.

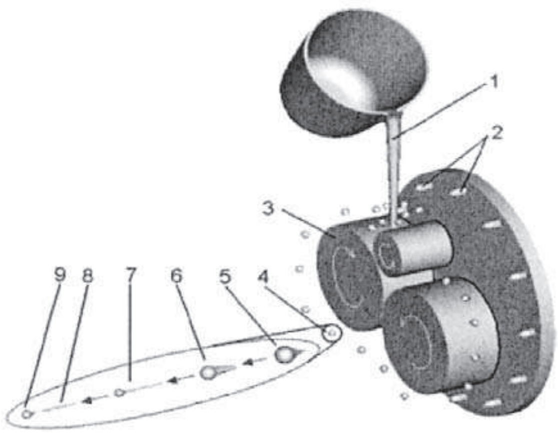


Figure 1: Scheme of Junkers type basalt fibre production with melt blowing: 1 – molten basalt rock, 2 – blowing valves, 3 – fibrillising cylinder, 4 – droplets, 5–7 – fibre formation, 8 – fibre, 9 – fibre head [2]

3.2 Basalt fibre production with melt spinning

The continuous fibre production consists of the following stages:

- preparation of basalt melts for basalt fibre production,
- forming basalt melt through a platinum alloy bushing assembly, and
- extraction of initial fibre, lubrication and winding on bobbins.

Basalt rocks are crushed (5–12 mm) for a continuous basalt fibre (CBF) production, the metal and magnetic contaminations are removed with the help of magnetic separation and screening, and small inclusions like dirt and dust are removed by washing. This is followed by drying, which is carried out either at natural air circulation or in a special dryer. The prepared raw material is periodically loaded into the hopper of the loader mounted above the smelting furnace [11].

The smelting furnace (Figure 2) represents a recuperative bath-type furnace of continuous operation with direct gas heating of the smelting zone. Basalt rocks melt at 1500 ± 50 °C as a result of the burning of air-natural gas mixture. The melt flows into the feeder due to gravity forces after the homogenisation. At the bottom of the feeder, electrically heated feeding tubes are located, through which the melt is supplied to electrically heated platinum-rhodium bushing. From the bushing, the melt is drawn in the form of a filament yarn [12].

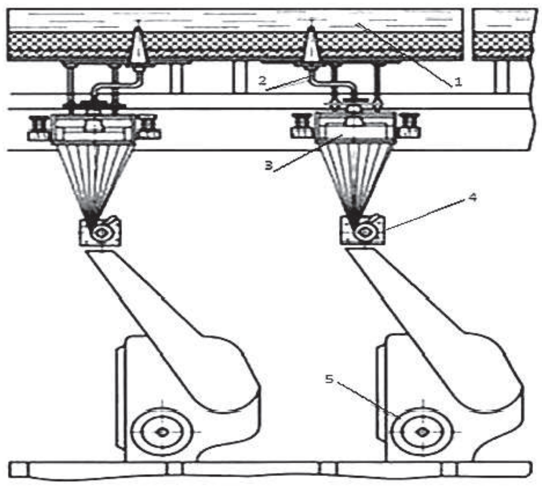


Figure 2: Smelting furnace: 1 – bath type furnace, 2 – feeding tube, 3 – bushing, 4 – gathering shoe, 5 – winder [13]

In the process of continuous filament, their surface is coated with a sizing agent which stops the growth of micro-cracks on the filament surface to avoid the decrease in fibre strength. Additionally, the sizing agent improves the adhesive properties of fibres. With the help of a gathering shoe, the filament yarn is wound on a spool.

The manufacturing of a high quality continuous filament requires a proper selection of the raw material, in addition to the melting and drawing technological parameters and properties. The manufactures of continuous filaments require materials with a low rate of crystallisation; basalt glass should have the drawing interval which is wide enough [14, 15].

The CBF manufacturing process is different to fibre glass in the following ways:

- Basalt is a natural raw material which is melted to the state of super fluent magma,
- Basalt fibre shows a different crystalline structure and chemical composition from glass fibre,
- Thermo-physical properties of the basalt melt differ from alumina silicate glass melts [12].

The process of basalt melting does not include the operations that are specific for glass melting, and clearing and cooling the glass melts, which results in the difference between the design of basalt melting furnaces and the design of glass melting furnaces.

The basalts obtained from different basalt deposits differ in their properties, affecting the parameters of the continuous basalt fibre production process.

The reduction in the diameter of the monofilament results in the increase of elasticity and thus proves useful in textile processing. The diameter of the monofilament depends on the temperature in the feeder and the speed of the filament drawing.

4 Properties of basalt fibre

4.1 Mechanical and physical properties of basalt fibre

Basalt, the density of which is between 2.8–2.9 g/cm^3, has a maximum contribution of iron and magnesium. Being extremely hard (from 5 to 9 on Mohs scale) gives basalt a superior abrasion resistance. Casted basalt is often used as a paving and building material. Continuous basalt fibres and fabrics are labelled as safe by the US and European occupational safety guidelines [7, 16].

A continuous filament of basalt with the diameter of more than 5 µm cannot split longitudinally and is thus characterised as non-respirable. The continuous basalt fibres (filaments) have the diameter between 9 and 13 µm, which is a suitable replacement for asbestos. Continuous fibres are highly water resistant (90.0–99.9%). The specific tenacity of continuous basalt fibres exceeds that of steel fibres by many times. Basalt is by roughly 5% denser than glass. The tensile modulus (E modulus, Young modulus) of continuous basalt fibres is higher than of E-glass fibres, making them attractive for the reinforcement of composites. A basalt textile exhibits sufficient flexibility, drape ability and good fatigue resistance. Yarn made from continuous basalt fibres shows low friction coefficients when compared to most reinforcement materials [7, 16–19].

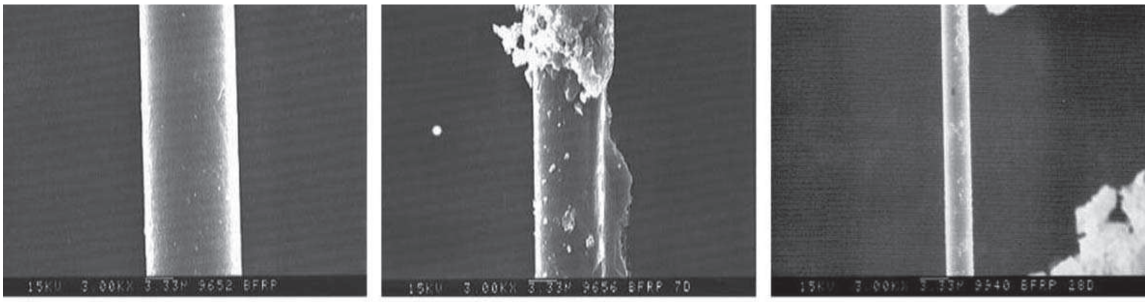
4.2 Chemical properties of basalt fibre

Continuous basalt fibres have good acid, alkaline and solvent resistances, surpassing those of E-glass fibres. The main advantage of basalt fibres is the resistance to an alkaline environment, as it can withstand the pH of up to 13–14. The fibre has good resistance to UV-light and biological contamination in addition to its anti-corrosion properties. In its pure form, it is free of odour and has low soiling sensitivity with the absorption of humidity less than 0.1% at 65% of relative air humidity at room temperature. Continuous basalt fibres show excellent wettability with natural adhesion to a broad range of binders, coating compounds and matrix materials in composite applications [20]. A comparison of chemical resistance of basalt and glass fibres is shown in Table 3.

Figures 3 and 4 show a comparison of the damage of basalt, carbon and glass fibres at alkaline conditions. Basalt materials have strong resistance against the action of fungi and microorganisms. However, after the weaving, basalt fabrics show easy damage due to their poor bending properties. This defect may be overcome with some coating and finishing.

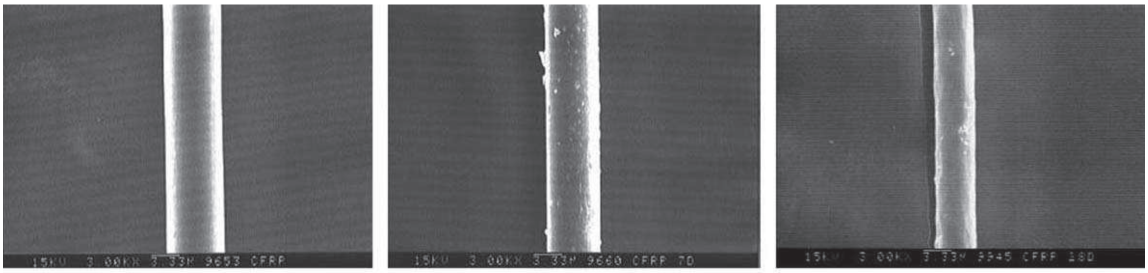
Table 3: Comparison of chemical resistance of basalt and E-glass [8, 18, 21]

Material	Chemical resistance in solution of [%]		
	0.5N NaOH	2.0N NaOH	2.0N HCI
Basalt	73–99	48–92	35–75 (90–92% after crystallisation)
E-glass	50	–	1.2



(a) Normal (b) 7 days (c) 28 days

Figure 3: Scanning electron microscope (SEM) images (3KX) of basalt fibres in NaOH solution [18, 21]



(a) Normal (b) 7 days (c) 28 days

Figure 4: Scanning electron microscope (SEM) images (3KX) of carbon fibre in NaOH solution [18, 21]

4.3 Thermal properties of basalt fibre

Basalt fibres have excellent thermal resistance. They can easily withstand the temperature of 1100–1200 °C for hours without enduring any physical damage. Unstressed basalt fibres can maintain their integrity even at up to 1250 °C, making them superior in comparison with E-glass and carbon fibres. The thermal properties of basalt fibres for composites are shown in Table 4 [19, 22].

4.4 Assessment of different high-performance fibres in comparison with basalt fibres

Basalt fibres have a higher or a comparable modulus of tensile strength and elasticity than E-glass fibres. Moreover, they have great chemical and thermal stability, and good electrical and sound insulating properties. The thermal insulating properties of basalt fibres are by three times higher than that of asbestos fibres. They show by 10 times better electrical insulating properties than E-glass. Table 5 describes the properties of basalt fibres compared with different high-performance fibres [23, 24].

Table 4: Operating temperatures of basalt fibres [22, 23]

Thermal properties of basalt fibres	Values
Maximum operating temperatures [°C]	982
Sustained operating temperatures [°C]	820
Minimum operating temperatures [°C]	–260

Table 5: Comparison of properties of basalt and other high-performance fibres [3, 16, 25, 26]

Property	Basalt	E-Glass	Asbestos	Silica	Stainless steel	Carbon	Aramid
Thermal limit of application [°C]	–260–700	–60–460	500	1,050	600	2,000	250
Glass transition temperature [°C]	1,050	600	700	1,300–1,670	–	–	280–300
Melting temperature [°C]	1,450	1,120	1,500	2,000	1,400–1,600	2,500	370–500
Glow loss [%]	1.91	0.32	13.5	–	–	–	–
Thermal conductivity [W/(m.K)]	0.031–0.038	0.85–1.3	–	1.4	20–100	5–185	0.04–0.13
Specific heat capacity [kJ/(kg.K)]	0.86	0.84	1.05–1.11	0.96	0.51	0.71	1.2–1.4
Linear expansion coefficient [$x10^{-7}$/K]	5.5	5	–	0.5	0.16	0.1–1.3	–0,35
Density [kg/dm^3]	2.60–2.80	2.52–2.63	2–2.6	2.00–2.73	7.90	1.67–2.52	1.38–1.44
E-modulus [GPa]	62.0 ± 3.6	57 ± 3	30–190	60–72	176–196	160–830	58–120
Moisture at 65% RH, [%]	< 0.1	< 0.1	1.6–1.9	0	0	0.01	3–7

5 Basalt fibre products

Basalt fibres offer the prospects of a completely new range of composite materials and products with their unique range of properties. Some basalt products are shown in Figure 5. A continuous basalt fibre is mainly used in the making of roving fabrics, thin fabrics, reinforcing nets for building and road constructions, chopped fibre mats and thin mats (basalt paper) [26–28].

Basalt scales

Basalt scales got their name due to the protective quality similarity with fish scales. Basalt scales are used exclusively for the production of protective, wear proof, anticorrosive and chemically proof coverings, reinforced composite materials, reinforced plastics, frictional materials (e.g. brake blocks and clutch plates) [29]. The wear resistance and chemical stability of lacquer coatings reinforced with basalt scales increases by several times. The durability

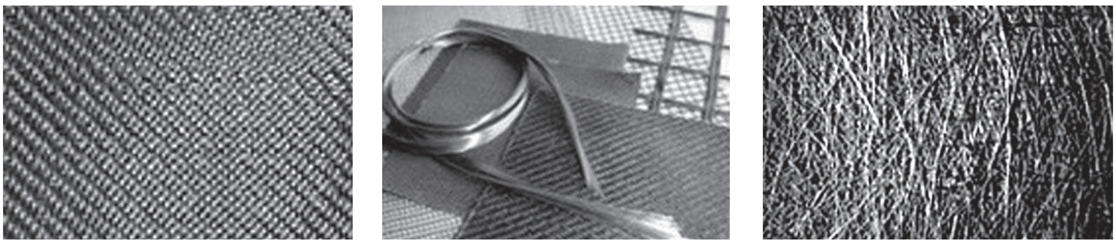


Figure 5: Products from continuous basalt fibres (CBF) [28]

of plastics reinforced with basalt scales increases by 2–3 times [30].

Basalt fibre bars

By utilizing basalt fibres and a resin epoxy binder, basalt composite bars are prepared. They are non-corrosive, with the tensile strength by three times higher than that of a steel bar normally used in the building construction. Nevertheless, these bars are costly and also not resistant to alkalis. The high mechanical performance/price ratio of basalt fibre composite bar, combined with the corrosion resistance to alkaline attack, advocates replacing steel in concrete with basalt fibre composite bars [27, 28, 31–34].

Basalt roving

Roving is a natural, inert and extremely strong material, which is resistant to aggressive environments, has long service life and excellent electric insulating properties. Basalt roving is a bundle of continuous mono-directional complex basalt fibres. Basalt roving is heat resistant; its long use temperature range is between 200–680 °C. Temporarily, it can withstand up to 900 °C. Its absolute hardness on the Mohs scale is graded 8–9 (for comparison, diamond equals 10). Its specific tensile strength is by 2.5 times higher than that of alloyed steel and by 1.3 times higher than that of E-glass [29, 34, 35].

Basalt fabrics

Basalt fabrics are produced for structural, electrotechnical, general and specialised purposes. Basalt fabrics are useful for producing structural basalt-plastics based on various thermosetting binders epoxy and phenolic polyesters (e.g. by laying out method) from which components for automobiles, aircrafts, ships and household appliances can be produced. The basalt-plastics acquire the shield properties against electromagnetic radiation in the case of preliminary metallisation. Basalt fabrics can also be used as basics when producing soft and rigid roofing [35]. Basalt fabrics are used for the electrotechnical purposes as a base for the production of insulation materials. These materials are employed in the production of substances for printed circuit boards for electronics and electrical engineering. The employment of incombustible basalt fabric inserts in industrial ventilators increases their fire safety as well as the fire resistance of ventilating systems. The cost of basalt fabrics is considerably lower than that of similar materials. Basalt woven materials are resistant to flames due to their non-combustible properties that make basalt tapes effective as extra resistant insulation for electrical cables and underground ducts. Basalt fabric hoses may be useful for reinforcing cables, as well as for repairing the interior and exterior of tubes and pipelines [36–38].

Basalt prepregs

Prepregs are pre-impregnated composite basalt fibres or fabrics into which a pre-catalysed polyester resin system has been impregnated by a machine. The resin systems in these materials react very slow at room temperature, allowing a long shelf life. They are cured by heating at the prescribed elevated temperature [39, 40]. Prepregs have a long life (at least 4 years) under storage conditions, hermetically packed at the temperature under 40 °C [41–43]. Prepregs are used for the production of various basalt plastic composites.

Basalt fibre pipes

Basalt fibre pipes are obtained by winding basalt threads impregnated with a binder. They are regarded as one of the most promising materials in the modern construction technology. They are much better than the materials used in the designs of piping hot water systems such as steel, asbestos and other traditional building components. They are chemically-resistant in aggressive environments and ecologically friendly. The enormous stock of basalt raw materials and the relatively low cost make its use very tempting, particularly in laying of the heating systems. The basalt fibre pipes may be useful as components for shaft linings, building components, for transporting corrosive liquids and gases in constructions, industrial, agricultural and public service sectors. Other possible areas of application for basalt pipes are masts, aerial frames, various pipes in constructions, communication etc. They can be applied in a pipeline construction with the working temperature of up to 115 °C and pressure of up to 1.5 MPa with the exploitation period of no less than 25 years. The basalt fibre insulated pipe is a new concept of energy efficient hot water and heating pipelines. These pipes have high corrosion resistance and do not require special electrochemical protection. They are resistant to the effects of fungi, groundwater and sewage, which increases the lifetime of basalt fibre pipes by up to 50 years and more [40, 42].

Subsequently, basalt fibre pipes also have a significant maintenance and mounting advantages compared to conventional steel pipes. Due to their greater hydraulic resistance, the capacity of basalt fibre pipes is much higher than that of a steel pipe. Moreover, they are by 3–4 times lighter than steel pipes. This makes the installation of basalt fibre pipes cheaper and more convenient. Another important advantage of basalt fibre pipes is their higher durability. The operation time of basalt fibre pipes is at least 20 years in comparison to the 5–7 years of steel pipes. Galvanised steel pipes are used to extend the operation time. However, the price of such pipes is by 75% higher than that of conventional steel. Thus, the operating costs (depreciation, maintenance) for basalt fibre pipes are significantly lower than for pipes made from steel [38].

Flame retardant protection product

Flame retardant fabrics are fabrics which are difficult to ignite, easy to self-extinguish, they burn slowly, have small burned area, reducing fire damage and the loss of property. Flame retardant fabrics play an important role in our daily life and production [44].

The performances of high-temperature resistant fibres are: (1) no size change at high temperature; (2) high softening and melting temperature; (3) high kindling and ignition point; (4) high thermal decomposition temperature; (5) having the general characteristics of fibres, e.g. flexibility, elasticity, workability, flame resistance or incombustibility; (6) maintaining general characteristics even after exposed for a long time to high temperature. Basalt fibres are characterised by all of the above. The application temperature of CBF is from –269 °C to up to about 650 °C (softening temperature is 960 °C). Furthermore, CBF has outstanding flame-resistance performance and can be developed in a flame-resistant protection field [44, 45].

Basalt fibres have excellent flame retardant properties. Fibre combustion is decided according to: 1) the composition and structure of a fibre, which directly affects its thermal decomposition temperature and formed speed of ·OH and ·H; 2) the oxygen supply circumstance, as the fibre combustion performance is judged by the limit oxygen index (LOI). The lower the LOI value, the easier is the fibre combustion. A fibre is inflammable when its LOI is less than 20%, it is flammable fibre when the LOI of a fibre reaches 20–26%, flame-retardant when LOI reaches 26–34% and non-combustible when the LOI of a fibre is above 35% [44].

6 Application of basalt fibre

Geocomposites

A protective cap using geocomposites in waste disposal sites, including. incorporated basalt materials, can put forward the best protection for human health and environment against radioactive waste. A lot of this waste needs to be protected for centuries in an isolated way for an inoffensive disposal [46, 47].

Such a capping system for a long-term use should include the ability to function in a semi-arid to subhumid climate, to limit the recharge of water table to near the zero amount, should be maintenance free, resist animals, human intrusion and limit the release of noxious gases. Waste dumping pits are constructed in several layers which include coarse material such as sands, gravels and basalt riprap [4]. Basalt geo-meshes are ecologically safe and can withstand very high temperatures of molten asphalt. Basalt geo-meshes are chemically inert and lighter than metallic meshes. They are also fit for soil and embankment stabilisation, and environmental and ecological safety. Geo-polymeric concretes reinforced with basalt fibres offer better fracture toughness than conventional cement structures (as shown by three-point bending tests) [48].

Civil construction

Basalt fibres are also used in building constructions and facing plastics such as reinforcing plaster grids, warmed panels for the construction of prefabricated houses, floors, dropped ceilings, fireproof walls, fire resistant doors, building plastics etc. [49].

The fibre reinforced polymer (FRP) composite bars and fabric sheets are currently used as internal or external reinforcement for concrete members in many structural systems. The use of corrosion resistant FRP reinforcement is beneficial in transportation structures particularly in those exposed to de-icing salts, and/or located in a highly corrosive environment. Glass, carbon and aramid fibres are commonly used in the manufacture of reinforcing bars for concrete applications. Recent developments in the fibre production technology allow the making of basalt fibre reinforced polymer (BFRP) bars. Nowadays, several BFRP products are made in the form of straight rods, loops, two-dimensional meshes and spirals. They show high strength, light weight, non-magnetic and non-corrosive properties, and good fatigue endurance properties. The high initial cost, low modulus, linear tensile stress-strain behaviour until failure, and durability issues are some limitations to the adoption of BFRP materials in the transportation infrastructure [50]. Based on various experimental studies performed by several researchers, the following outcomes can be drawn [50–52]:

- The compressive strength of specimens doubly wrapped with basalt fibres has shown an increase by about 25% over the compressive strength of conventional specimens.
- The tensile strength of specimens doubly wrapped with basalt fibres has shown an increase by about 100% over the split tensile strength of conventional specimens.
- The flexural strength of specimens doubly wrapped with basalt fibres has shown an increase by about 68% over the flexural strength of conventional specimens.

Automotive industry

Basalt chopped strands are good for use in friction materials. Brake pads based on basalt fibre have a better and more stable friction coefficient and higher endurance than those based on glass fibres. Basalt fibres are also used as fillers for car mufflers, showing great silencing virtue and good resistance to thermal cycling.

Higher strength and elastic modulus of basalt fibres (compared to conventional E-glass and carbon fibres) offer car makers the opportunity for a significant cost-reduction of SMC/BMC parts while retaining the high strength and stiffness. Basalt fibres are also used as a substitute of glass fibres in radars due to the same dielectric and transparency properties [53].

Electricity and electronics industry

Basalt fabrics are used for electro-technical purposes as a base material for the production of insulation materials. A preliminary metallisation of fabrics results in the shielding properties of electromagnetic radiations. Basalt can be used over a wide temperature range from about –200 to 800 °C, compared to E-glass, which can be used from –6 °C to 450–600 °C. It can substitute asbestos in almost all applications due to its heat insulating characteristics. The tapes made from basalt fibres may be used in electrical cables as the insulation material against fire hazards during power transmission. Basalt fibres can sustain their properties for low temperature insulations. In power industries, basalt fibres are also used for fire resistant cable construction components as fillers, braiding and tapes [35, 54].

Chemical and petrochemical industry

In the petrochemical industry, basalt fibres are used as chemical and wear-proof coverings of tanks, pipelines, oil pipelines, and as non-flammable coverings of fireproof composite materials. Traditionally used in oil collection systems and pumping water systems, carbon steel pipes have a very short period of lifetime due to their weak anti-corrosion resistance and affection by aggressive components, which are in varying degrees contained in hydrocarbons, as well as hydrogen sulphide, carbon disulphide, brine and corrosion products. Increasing the lifetime of pipelines is possible by making costly repairs, cathode protection and adding anticorrosive inhibitors. The more the pipeline is aging, the more the matter of anticorrosive preventions increases. In terms of economic efficiency, one of the most acceptable options to solve these problems is to use basalt fibre pipes [55]. Basalt is also used in the chemical industry for the production of chemically proof materials and products: pipes, tanks for aggressive liquids, acids, alkalis, chemical fertilisers, pesticides, poisonous substances etc. [56].

Municipal and home appliances services

Nowadays, the problem of enhancing the reliability of the functioning of housing and utilities infrastructure has become of great significance. The ground is saturated with technological communications, electrolytic mixtures and stray currents, which help in accelerating the corrosion of steel pipes. Moreover, high temperature can accelerate the chemical processes. From the point of view of economic efficiency, the most acceptable options for these problems are using basalt and glass fibre pipes. High physical-mechanical performance, as well as the resistance to corrosive environments has identified the broad use of these materials in various fields of industry, e.g. materials for cleaning installation filters for air and liquid environments, big pipes for water supply and sewage, municipal drains, cleaning installations etc. [4, 57].

Miscellaneous applications
Basalt fibres are used as the material for thermal equipment, furnaces, recuperators and pipelines. Basalt filters are best for the filtration of metals melt during moulding, for clearing waste gases from the dust at ore mining and processing plants, for sewage treatment etc.
Moreover, basalt fibre products are used in port constructions, sea platforms as reinforcing and construction materials made from basalt plastics, paint, varnish proof coverings of bridges, waterproof coverings for ferro-concrete installations, it can be used as thermo-insulation of furnaces and equipment during the production of ceramic and porcelain products. The field of agriculture is also not far from using basalt fibre products as grids for strengthening soil, material for hydroponics for the cultivation of bacterial cultures, tanks for storage and transportation of liquid chemical fertilisers and pesticides. Basalt materials do not absorb the radioactive radiation, which makes them candidates for the budding material in the production and transformation of radioactive materials, e.g. in nuclear power plants [58–61].

7 Conclusion

Most studies focus on the positive aspects of basalt fibres; nevertheless, the deficiencies or lacunas of the material before using it in any application is to be taken into consideration. A few deficiencies exist in the performance of basalt fibres, e.g. the instability in the basalt fibre properties, resulting from the volatile composition of the basalt material. Basalt fibres also show low stretch properties. The production process of basalt fibres may produce many defects in the end product, e.g. the heterogeneity of the basalt melt can affect the characteristics of the produced fibre. The basalt fibre may have higher specific gravity resulting from high iron content and it can affect its comb performance. In consequence, the modification of the material is important before putting it to end use. Furthermore, the cost of a basalt fibre is 3 times higher than that of an E-glass fibre, which is expected to fall with the increase in the production volume.

Despite the few shortcomings, the latter can be overlooked considering the weightage of the basalt fibre advantages in various applications. Basalt fibres can be of great interest for the building industry, since they now represent a popular choice for the replacement of carbon fibres and steel owing to their high tenacity and low elongation. Due to its non-corrosive nature and very good heat resistance power, basalt has the potential to replace E-glass. It is also an ecologically friendly material, since it has no toxic reaction with air, water and other chemicals. Basalt fibres can be used as a retrofitting material for concrete specimens. In conclusion, it can be stated that basalt fibres can be used in a wide range of applications in the construction and concrete industry.

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