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BASALT FIBER - BASIC (PRIMARY) CONCEPTS

Jurabek Abdiev
Physical-technical Institute SPA "Physics-Sun" of the
Academy of Sciences of the Republic of Uzbekistan;

Omadjon Safarov
Department of Solid State Physics,
Faculty of Physics, Samarkand State University

Abstract

Although basalt fiber is a green fiber with high performance, it has not been widely used yet. One of the major concerns is that the defect generation and elimination mechanism of basalt fiber in the process of filament drawing is unclear. It is urgent to clarify the mechanism during fiber manufacturing and develop basalt fibers with high mechanical strength. Meanwhile, the current fibrous filters seem not to be robust enough to cope with the challenges such as high temperatures.

Given this, we aim to develop high-performance basalt fibers and evaluate their filtering efficiency in natural gas purification, which can also improve the added value of local basalt rock. By implementation of the project, we plan to fabricate high-performance fibrous filters based on basalt ore resources in Xinjiang. Using local basalt ore as raw material, through the study of the melting and spinning of basalt ore, the generation and repairing mechanism of the fiber defect is expected to be revealed. Further studies will be carried out on the performance of basalt fiber in the gas-solid separation process and the mechanism of interaction between solid particles. Also, simulations such as computational fluid dynamics (CFD) will be introduced to predict the gas filtering behaviors through fibrous filters. Thus, it would lay a theoretical foundation for the low value-added products to high-end filters. The hypothesis of the project includes the optimization of the basalt ore melting and spinning process, analysis of the defect cause and elimination mechanism, development of high-performance basalt fiber, and the application in natural gas purification. Nature is continually providing varied resources for creating textile materials for various applications. Although many textile fibers in nature are provided with the fibrous kind itself it additionally offers raw materials that may be changed and formed into a filament in a way similar to the melt and solution spinning of other textile fibers. Basalt is an igneous rock, which is solidified volcanic lava. In recent years, basalt received attention as a replacement for asbestos fibers. Basalt has emerged as a contender in the fiber reinforcement of composites. Basalt fiber (BF) is capable to withstand very high temperatures and can be used in high-performance applications. This paper is a review of state of art of knowledge of BF, the production methods, properties, and its applications.

Keywords: basalt; basaltic rock; basalt fiber; composites; fire blocking element

Introduction

The fast pace of technological advancement has always pushed engineering materials to their limits but in the last century, the development of new materials is so fast as requirements for structures, automobiles, etc. are changing rapidly. In the quest for ever more performance from existing materials engineers have developed arrangements of different materials that in combination have characteristics superior to that of their constituents. Many of our modern technologies require a material with an unusual combination of properties that cannot be met by conventional metal, ceramics, and polymeric materials. This is especially true for materials that are needed for construction and transportation applications. Composites are emerging as realistic alternatives to metal alloys in many applications like construction automobiles, marine, aerospace applications, sports goods, etc. Composites can be defined as the combination of dissimilar materials to perform a task that neither of the constituent materials can perform alone, since hardly any material is used in its pure form today, and have all-rounder properties. Composite materials have a long history of usage. The history of composites is as old as the history of mankind itself. The human body can be considered a composite made of bones and flash (Chaphalkar & Kelkar, 2001). Their beginnings are unknown, but all recorded history contains references to some form of composite material. Perhaps the very first composite was the adobe bricks made by man. Which grass or straw was used as a Preform and mud as Matrix.

The textile composites are composed of two materials i.e. a textile skeleton for reinforcement (called preform) and a binding adhesive (called the matrix) material to keep the skeleton integrated into a specific shape. The output and the scope of application for reinforced fibers within polymeric composites have been gradually expanding all over the world. In comparison with conventional materials, fiber composites boast several advantages - corrosion resistance, chemical inertness, a low factor of heat conductivity, high specific mechanical properties, small specific weight, high operating temperature, long-wearing life, and low cost of design installation. Fiber reinforcements in composite materials are generally used to improve mechanical properties. The most common fiber reinforcement in resin is glass fiber.

There are other types of fibers for reinforcement such as carbon fiber, and other plastic fibers.

Glass and carbon fiber are widely used for making composites. Glass fibers have good strength properties and good interfacial adhesion to the matrix. Carbon fibers are usually used in advanced applications like space technology, and the aircraft industry, however, their production cost is higher than glass fiber, and adhesion between the matrix and carbon fiber is difficult to achieve. Environment-friendly and cost-effective composites have recently been received considerable attention from scientists. The use of glass and carbon as reinforcements in composites is currently thought of as attributable to environmental concerns though they have possessed excellent mechanical and thermal properties and durability. These properties make it difficult to carry out suitable disposal processing. For example, the incineration of discarding glass fiber-based composite generates a lot of black smoke and bad odors and often creates damage to the incinerator by the fusion of glass fibers. Reclamation processing generates also a large environmental load; since synthetic fibers are not decomposed easily.

Basalt is an environment – friendly natural material. Basalt is used for basalt fibers (BFs) production. BF was one type of high-performance inorganic fiber which were made from natural basalt. BF is known as a green industrial material. BF is colloquially known as the “twenty-first-century nonpolluting green material”. Safe and abundant, basalt rock has long been known for its thermal properties, strength, and durability. BFs are environmentally friendly as recycling is much more efficient than glass fibers. Growing environmental awareness throughout the world has triggered a paradigm shift towards designing materials compatible with the environment. BF can be classified as a sustainable material because BFs are made of natural material and during its production, no chemical additives as well as any solvents, pigments, or other hazardous materials are added. When the BFs in resin are recycled the same material is obtained again as natural basalt powder as its melting point is quite high i.e. 1400° C, this means that composite containing basalt is incinerated, the only product left in an un-molten basalt that can be used again (Kamenny, 2015). BFs are 100% natural and inert. Basalt products have no toxic reaction with air or water and are non-combustible and explosion-proof. When in contact with other chemicals they produce no chemical reactions that may damage health or the environment. They have been tested and proven to be non-carcinogenic and non-toxic. Manmade fibers with a diameter of 5 microns or less are considered an inhalant hazard. BF is a new type of fiber prepared by drawing a natural ore, melted at a high temperature, through a platinum-rhodium alloy (Czigany, Vad, &

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Poloskei, 2005). It has numerous raw material sources. It is inexpensive (Sim, Park, & Moon, 2005), it has excellent properties such as corrosion resistance, minimal moisture absorption, and the ability to withstand high temperatures, provide thermal insulation, and absorb sound (Matko et al., 2006; Wang, Zhang, & Li, 2008). It is also a cost-effective and high-strength material (Botev, Betchev, Bikiaris, & Panayiotou, 1999; Dalinkevich, Gumargalieva, Marakhovsky, & Soukhanov, 2009; Liu, Shaw, Parnas, & McDonnell, 2006; Militky, Kovacic, & Rubnerova, 2002) that has been widely used in road construction (Palmieri, Matthys, Tierens, & Pikakoutas, 2009), buildings and other applications that require reinforcement (Ross, 2014).

By producing glass fiber scarce components are used as boric oxide (B_2O_3) and its recycling is not easy.

Carbon fibers have a high cost. BF is cheaper than carbon fibers and exhibits higher strength than glass ones (Fazio, 2014; Kamenny, 2015; Sim et al., 2005). Basalt base composites can replace steel (1 kg of basalt reinforces equals 9.6 kg of steel) with lightweight concrete, which has comparable mechanical properties. As a result, a lighter building is possible by using a BF rebar instead of steel reinforcing bars. It also leads to energy saving in terms of production of BF which is quite less compared to steel. Reducing energy demand leads to lower emissions of CO_2 in the atmosphere (Anade, Katkar, & Raybagi, 2012).

History of Basalt

Basalt applications are well known from the Roman age when this material was used in its natural form as a paving and building stone. The French Paul Dhe was the first with the idea to extrude fiber from basalt and he received a US patent in 1923.

Around 1960, both the US and the Soviet Union (USSR) began to investigate BF applications, particularly in the military field. In the northwestern USA, where large basalt formations are concentrated, Prof. R.V. Subramanian of Washington State University (Pullman, Washington) did a lot of research about its composition. He conducted research that correlated the chemical composition of basalt with the conditions for extrudability and Physico-chemical characteristics of the resulting fiber. The first BF samples were received in 1959-1961 by the Ukraine scientific research institute in the former Soviet Union. The first continuous BFs of satisfactory quality were produced with laboratory equipment in 1963. It was in 1963 when the first publication about BCF appeared in “The glass and ceramics” magazine.

Around 1970 USA glass companies imposed a research strategy that favored glass fiber over BF. The result was a better glass fiber including the successful development of S-2 glass fiber by Owens Corning. During the same time, the research in Eastern

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Europe research was carried out by independent groups in Moscow, Prague, and other locales and was nationalized by the USSR's Defense Ministry and concentrated in Kyiv (Ukraine), where technology was subsequently developed in closed institutes and factories. After the breakup of the Soviet Union in 1991, the results of Soviet research were declassified and made available for civilian applications. By 1985, the first industrial installation for CBF production was designed and commissioned in a factory near Kyiv. The basalt plants were Built-in USSR in the late 1980s in Sudogda, Ukraine, and Georgia. In recent times several works is executed on the development of modern continuous fibers from basalt stones. By industrial production of BFs based on new technologies, their cost is equal to and even less than the cost of glass fiber. The production processes and processing equipment for BF production are protected by many patents.

Today, BF research, production, and most marketing efforts are principally based in some of the countries once part of the Soviet Union (Georgia, Ukraine, same Russia) and China (Ross, 2014; Sim et al., 2005). In 2000 the joint Ukraine-Japanese enterprise of BCF production was established. In addition to Japan, South Korea, China, Austria, and the USA are working on BCF technology. The EU and some other countries have BF research programs.

BF is obtained from a natural material called Basalt which is dark-colored, fine-grained solidified volcanic rock. Basalt is a common term used for a variety of volcanic rocks. A hard, dense, inert rock found worldwide, basalt is an igneous rock i.e. it melts when heated like thermoplastic materials, which is solidified volcanic lava. Basalt originates from volcanic magma and flood volcanoes, very hot fluid or semi fluid material under the earth's crust, solidified in the open air. Basalt flows cover about 70% of the earth's surface in which SiO_2 accounts for the main part, followed by Al_2O_3, then Fe_2O_3, FeO, CaO, and MgO. For this reason, basalt rocks are classified according to the SiO_2 content as alkaline (up to 42% SiO_2), mildly acidic (43-46% SiO_2), and acidic basalts (over 46% SiO_2). Only acidic type basalts satisfy the conditions for fiber preparation. High silica contents are required to get a glass network. Figure 1 shows a typical basalt rock.

The chemical composition of BF is given in Table 1.

As regards chemical composition basalt and E glass fibers are alike but for some components a bit different, for example, it doesn't have B_2O_3 (which is added as a flux for processing) (Militky & Kovacic, 1996). A detailed comparison is shown in Table 2.

A qualitative elemental analysis of BF determined by EDS is shown in Figure 2. From a chemical composition point of view, SiO_2 and Al_2O are the dominant compounds. The content of FeO and Fe_2O_3 plays a very important role in determining many physicomechanical properties of BFs, such as density, color (from brown to dull green, depending on the FeO content), lower heat conduction, and better temperature stability compared to E-glass fibers (Chantladze, 2015; Wang et al., 2008).

Figure 1. Basalt rock (Kunalsingha, 2012). Re-used with permission.

Table 1. Chemical composition of BF (Militky & Kovacic, 1996).

Chemical composition basalt rocks	%
SiO_2	52.8
Al_2O_3	17.5
Fe_2O_3	10.3
MgO	4.63
CaO	8.59
Na_2O	3.34
K_2O	1.46
TiO_2	1.38

The chemical composition of basalt rocks influences the properties of resulting fibers. Basalt rock beds with a thickness of as high as 200 m have been found in East Asian countries. Russia has unlimited basalt reserves. There are large deposits of these rocks in the Ural, Kamchatka, Far East, Sakhalin, Kola Peninsula, Northwest Siberia, and Transcaucasia. Basalt formations in Ukraine are particularly well suited to fiber processing.

In BF production, no additives are added to the melt. This is in contrast with glass fiber production. Basalt products are 100% natural. BFs have no toxic reaction with air or water and are non-combustible and explosion-proof. There are also reports that being a product of the volcanic activity, the fiberization process is more environmentally safe than that of glass fiber. Basalt is, however, more abrasive than glass (Deshmukh, 2007).

Basalt can be suited for fire protection applications and so it can replace almost all applications of Asbestos, which poses health hazards by damaging respiratory systems as fiber should have a diameter above 5 µm and have sufficient length. Mineral wool also does not satisfies this condition (diameter, 1-3 µm) (Fangueiro, 2011).

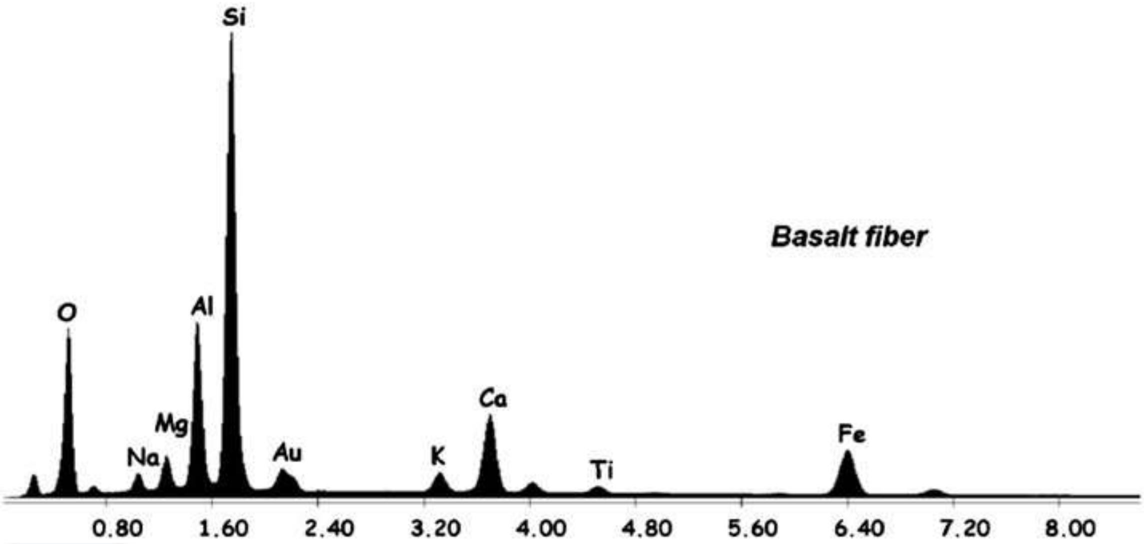

Figure 2. Elemental analysis of BFs (Murray, 2015). Re-used with permission.

BFs & fabrics are labeled as safe according to both the USA and the European occupational safety guidelines. Its particles or fibrous fragments due to abrasion are too thick to be inhaled and deposited in the lungs, but care in handling is recommended (Fazio, 2014).

Production process for BF

Basalt is an attractive raw material for fiber-forming because of its relatively homogeneous chemical structure, its large-scale availability throughout the world, its freedom from impurities, and, of course, its ability to form fibers in the molten state. BFs are divided into two big groups: Discrete fiber (mineral insulating wool, staple fiber) also known as basalt fine fiber, and continuous fiber (BCF). BCF production technology is young enough and is being improved further. Short-length BFs can be produced directly from crushed basalt stones and the technology is very simple so the fibers are very cheap, but they have relatively poor and uneven mechanical properties. There are three main manufacturing techniques, which are centrifugal-blowing, centrifugal-multirole, and melt blowing (Saravanan, 2006).

The BFs used as insulating materials in the construction and automotive industries are produced by so-called blowing technology with centrifugal cylinders (e.g. Junkers method).

It is used for manufacturing cheap fibers with 60-100 mm length and 6-10 μm diameter. The continuous process is used for the production of BF just like glass. Quarried basalt rock is crushed, washed, and loaded into a bin attached to feeders that transfer the material into melting baths in gas-heated furnaces. As BF is less complex so its processing is much easier than glass fiber. Glass is typically 50% silica and consists of boron oxide, aluminum, and several other minerals materials that must be fed independently into a metering system before entering the furnace. Unlike glass, BFs feature no secondary materials. The process requires a single feed line to carry crushed basalt rock into the melting furnace.

The essence of the method is that the basalt rock melt at 1450 °C coming from the gas-heated furnace is transmitted to a horizontal shaft fiber spinning machine that has three centrifugal heads and consists of one accelerating and two fibrillating cylinders as shown in Figure 3.

The lava adhered to the heads flies off due to the centrifugal force and as a result of blowing 60-100 mm long fibers of 6-10 μm diameter are formed from the viscous liquid (Bender, Hadley, Hellerstein, & Hohman, 2011; Czighny, 2003; Nolf, 2003). It is shown in Figure 4.

Another technology used for the production of fibers for insulating purposes is the centrifugal-multirole system, comprising several high-speed rotating wheels. The stream of basalt rock melt coming from the gas-heated furnace flows vertically down onto the surface of the first wheel, where it is thrown sideways by the wheel motion. Further, strategically placed wheels continue the process until finally fibers, with a typical diameter of approximately 10 microns, are produced (Basaltex, 2015).

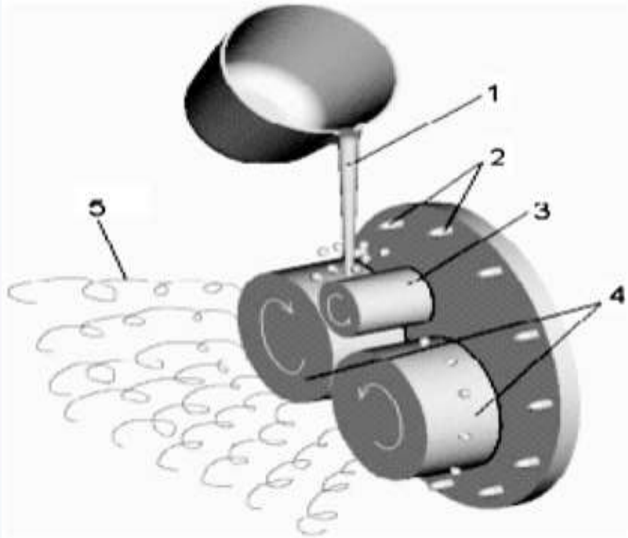

Figure 3. Junkers type basalt production. Notes: (1) basalt lava, (2) blowing valves, (3) accelerating cylinder, (4) fiberization cylinder, (5) basalt fibers (Bender et al., 2011; Czighny, 2003; Nolf, 2003). Re-used with permission.

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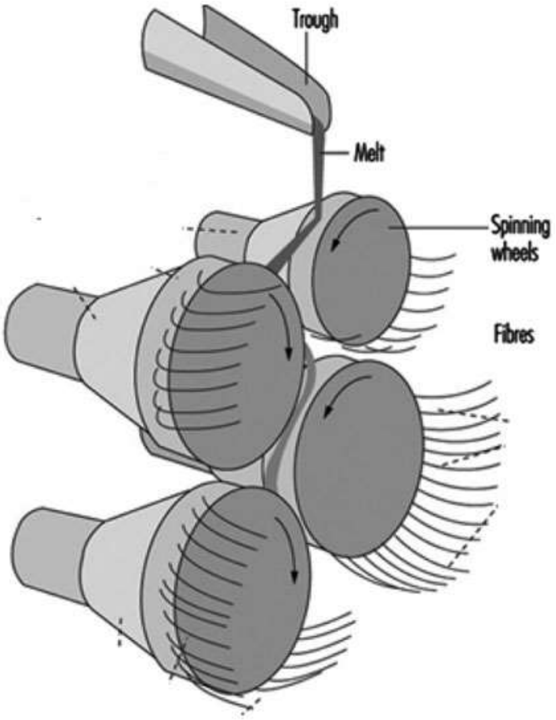

Figure 4. Centrifugal-multiroll system (Basaltex, 2015). Re-used with permission.

For more demanding applications continuous fibers, which can be processed by textile technologies, are prepared by spinneret technology from the melt spinning, similarly to traditional glass fiber production.

Glass and Basalt have different manufacturing processes even though both are organic. Glass fibers are produced from melted charge (composed of quartz sand, soda, limestone, fluxing agents, etc.) to obtain the glass, needed to create the desired chemical and physical properties of the final product, from which fibers are obtained by a blow with steam, air or at centrifugal. Additional steps and ingredients will always increase production costs. No flux like boric oxide is added for processing. BF is obtained, from melted basalt rocks without any additives.

At present, there are several methods for fabrication of continuous BF that differ from each other in furnace and feeder designs, cooling and winding mechanisms, etc. At present time in the world, there are two main variants of technologies and equipment for BCF production. There are big melting furnaces with a long feeder (feeding installation and technological lines consisting of modular units). But in principle manufacturing process of all producers includes the following key operations: (Gilewicz, Dominiak, Cichocka, & Frydrych, 2013; Manins, Kukle, Strazds, & Bernava, 2011).

• Raw material preparation;
• Rocks melting;
• Melt homogenization and delivery to bushings;

• Melt drawing through bushing units;

• Drawing of elementary filaments, application of sizing agent, and winding on bobbins.

Raw material preparation for basalt is much easier than glass fiber preparation. Raw material can be stored in the open air without packing. Basalt rocks for BCF manufacture are prepared peculiarly – crushing to fractions of 5-40 mm, separation of metal and magnetic impurities by the method of magnetic separation, screening, and washing out small inclusions (dust, etc.) then drying 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. The manufacture of BF requires the melting of the quarried basalt rock at about 1450 °C. The molten rock is then extruded through small nozzles to produce continuous filaments of BF.

These operations are quite simple, especially if we consider that primary fusion, homogenization, and enrichment of basalt initial raw material was made by ancient volcanoes, i.e. by nature. BFs are produced from basalt rock using a single component raw material by drawing and winding fibers from the melt. There are certain things about basalt that make it attractive and economically comparable with the production of glass fibers, like S-2.

The production of BF on a commercial scale is not easy as for glass fiber As basalt stone is of natural origin, BF manufacturers have less direct control over the purity and consistency of the raw basalt stone, as mineral level and chemical composition can differ from one location to other. Basalt and glass are both silicates, molten glass, when cooled, forms a non-crystalline solid. Basalt, however, has a crystalline structure that varies based on the specific conditions during the lava flow at each geographical location. Moreover, the rate of cooling, when the original flow reached the earth's surface, also influenced the crystal structure (Milman, Velikanova, & Kotov, 1996).

Crushed basalt enters the furnace, the material is liquefied at a temperature of 1450 °C (glass melt point varies between 1400 and 1600 °C). Opaque basalt absorbs rather than transmits infrared radiation, unlike molten glass which is more or less transparent to Infrared radiation, which allows heating from the top (gas burners) while obtaining a sufficiently homogeneous temperature in the melt, molten basalt is black. Heating molten basalt from the top results in a non-homogeneous temperature in the melt with a negative temperature gradient of about 80 °C per inch from the bath's surface down. The use of overhead gas burners in conventional glass furnaces is more difficult to uniformly heat the entire basalt mix. With overhead gas, the melting basalt must be held in the reservoir for extended periods - up to several hours - To ensure a homogenous temperature.

Basalt producers have employed several strategies to promote uniform heating, including the immersion of electrodes in the bath with high currents running between them. The Joule effect ensures the needed additional heating of the melt. Finally, a two-stage heating scheme is employed, featuring separate zones equipped with independently controlled heating systems. Only the temperature control system in the furnace outlet zone, which feeds the extrusion bushings, requires great precision, so a less sophisticated control system may be used in the initial heating zone (Subramanian & Austin, 1980; Wei, Cao, & Song, 2010).

The next stage is the filament stretching and winding, with automatic speed control, to get the filament down to its precise diameter. A schematic is shown in Figure 5.

A single-component basalt material is fed into a gas-fired furnace. The basalt is heated to about 1450 °C (2650° F) and melted. From the furnace, the molten material flows into a fore-hearth where the temperature of the molten material is more precisely controlled and distributed to each strand-making position. The molten material is gravity-fed from the fore-hearth at each forming position into a platinum alloy "bushing". Electricity is passed through the bushing to provide a final stage of resistance heating and precise adjustment of the viscosity of the molten mixture. Each bushing has hundreds of micro-orifice each making a filament that is gathered into a single strand of continuous-filament BF. The no. of the orifice (holes) and the diameter of the spinnerets are determined by the end-use of the fiber. The combination of micro-hole size and viscosity of the melt determine the diameter of the resulting filaments. Silane-based sizing liquid is applied to them to impart strand lubricity, integrity, and resin compatibility These Filaments strands are collected together and forwarded to take up the device for winding.

The continuous strand of multiple filaments can then be twisted into a yarn, plied into a multi-strand roving, or cut into the chopped fiber. The BCF can be converted into woven or nonwoven textiles or used to reinforce composite structures with techniques similar to those used with continuous filament fiberglass as shown in Figure 6 (Czigany, 2007; Swink, 2002; Wei et al., 2010).

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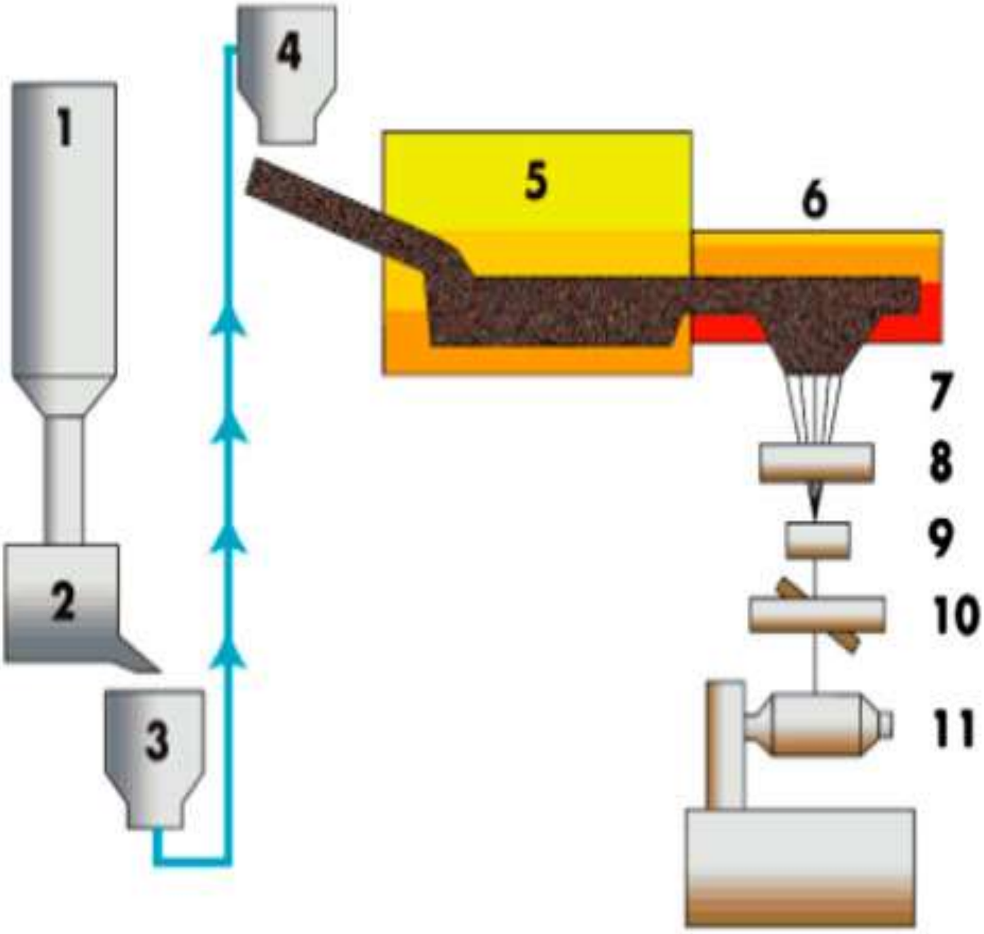

Figure 5. BF spinning (Wei et al., 2010). Copyright (2010), with permission from Elsevier. Notes: (1) Crushed stone Silos (raw material supply), (2) weighing, dosing, and mixing station, (3) Transporting system, (4) batch charging station, (5) Initial melt zone, (6) Secondary controlled heat zone(fore-hearth), (7) Bushings (BCF formation), (8) Sizing applicator, (9) Strand formation, (10) Traversing, (11) Winding.

BF is produced mainly in continuous filament forms as it is easy to use the fiber as yarn with a large number of filaments along its length and thus reducing the need for spinning. Due to fiber production problems of gradual crystallization of some parts and non-homogeneous melting, continuous BF was rarely used until the technology of continuous spinning overcame these problems (Dias & Thaumaturgo, 2005; Dorigato & Pegoretti, 2012; Hansen, 2005). Some basalt products are shown in Figure 7.

In the production process of BF, temperature levels in the furnace are of real importance as the final mechanical properties of basalt fibrous materials have relevance to it.

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Figure 6. Technological process of BCF Manufacturing. Re-used with permission.

In fact, it has been reliably determined that low variations in the chemical composition of basalt rocks have a minor effect on the level of mechanical properties of continuous BFs while the greatest effect comes from direct molding conditions of the fibers (drawing temperature and the period of melt homogenization). For example, for the same basalt chemical composition, a fiber drawing temperature increase of 160 °C (from 1220 to 1380 °C) increased their strength from 1.3 to 2.23 GPa and modulus of elasticity from 78 to 90 GPa. Great importance on final properties has also the fiber dimension: as the filament diameter increases by 3-4 μm, the strength value decreases from 2.8 to 1.8 GPa (Novitskii & Sudakov, 2004).

Properties of basalt

Although it is difficult to process its properties are good, BFs have attracted the attention of their users due to their properties. BFs have good physical and chemical properties, as well as good adhesion to metals, epoxies, and glues.

The BFs in comparison with glass, carbon, and other fibers have very good properties and compatible prices. BF from a performance point of view stands in between carbon fiber and glass fiber. The BFs have better tensile strength than E-glass fibers, greater failure strain than carbon fibers as well as good resistance to chemical attack, impact load, and fire with less poisonous fumes. The superior properties of BF are:

• Good range of thermal performance,

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- Significant Capability of heat and acoustic damping and outstanding vibration isolation,
- High Tensile strength,
- High resistance to alkalis and acids,
- Good electromagnetic properties,
- Resistance to corrosion,
- Resistance to radiation and UV light and
- Ecologically clean easy to handle and non-toxic to the end-user (Sezemanas, Keriene, Sinica, Lankaitis, & Mikulskis, 2005; Toropina et al., 1995).

Table 3 gives a detailed analysis of various properties between different types of fibers vis-a-vis BF.

Basalt has a low density like 2.6-2.8 g/cc, which is much lower than metal (steel) and closer to carbon and glass fibers though cheaper than carbon fiber and high strength than glass fiber.

Basalt material is extremely hard and has hardness values between 5 and 9 on Mohr's scale (for comparison diamond =10) resulting in better abrasion properties. Even continuous abrasion of the BF-woven fabrics over the propeller type abraders does not generate fine fibers or splitting of fibers by fracture and results only in the breaking of individual fibers from the woven structure which eliminates the possibility of causing hazards related to respiration.

Figure 7. Some BF products (Novitskii & Sudakov, 2004) source HG GBF. With kind permission from Springer Science and Business Media.

Table 3. Physical and mechanical properties (Landucci, Rossi, Nicolella, & Zanelli, 2009; Liu et al., 2006).

Properties	Basalt	E-glass	S2-glass	Aramid	Carbon
Density (g/cm3)	2.63-2.8	2.54-2.57	2.54	1.45	1.78
Filament diameter (p.m)	6-21	6-21	6-21	5-15	5-15
Tensile strength of single	3000-4840	3100-3800	4020-4650	2900-3450	3500-6000
Elastic modulus (GPa)	93-110	72.5-75.5	83-97	70-140	230-600
Elongation at break (%)	3.1-6	4.7	5.3	2.8-3.6	1.5-2.0
Specific gravity	2.65-2.8	2.5-2.62	2.46	1.44	1.75-1.95
Sound absorption coefficient	0.95-0.99	0.8-0.93			

Its specific strength is 2.5 times higher than alloy steels. BF has better sound insulation properties than glass fibers. Hence, with an interior based on BF, you will feel more comfortable. Sound proofing for 400-1800 Hz: 80-95% (Haeberle, Senne, Lesko, & Cousins, 2000; Olafsson & torhallsson, 2009; Sergeev, Chuvashov, Galushchak, Pervak, & Fatikova, 1994). Table 4 shows the thermal properties of various fibers.

Recent research showed that they have a good thermal/ heat resistance and humid absorption, moisture absorption of BF for 24 h is less than 0.02% while for glass it is 1.7%. Moisture regains of BFs is 1%. Producing industrial glass fiber, especially in a neutral composition can absorb significant amounts of moisture in humid air. This affects their physical and technical properties and durability and eventually leads to the destruction of fibers. BFs are low and are not changing over time hygroscopicity (0.2-0.3%), due to their chemical composition. Slow is not increased over time hygroscopicity BFs provide thermal stability characteristics in the long run. They are resistant to the influence of high temperature for a short time period up to 750 °C, whereas during longer work the working temperature is in the range from 260 to 700 °C; the single impact of temperatures up to 1000 °C. After exposure under 400, ° C BF loses their initial strength by only 20-25% while the strength of E glass under the same conditions drop more than 40-45%. The dependence of strength on temperature is shown in Figure 8 (Czigany, 2007; Swink, 2002; Wei et al., 2010)

Table 4. Thermal properties (Sergeev et al., 1994; Haeberle et al., 2000; Olafsson & torhallsson, 2009).

Properties	Basalt	E-glass S2-glass	Aramid	Carbon
Temperature °C to withstand Max application temperature, °C Melting temperature, °C Thermal conductivity at 25+/-5	-260/-200... +600/800 Approx. 700-720 1450 0.031-0.038 W/mK 8.0 ppm/°C	-50.+450 50.+300 Approx. 380 Approx. 500 1120 1550 0.034- 0.04 W/m K 5.4 ppm/°C	+205 Approx. 250 NA 0.04 W/mK	-5.+700 Approx. 400 NA

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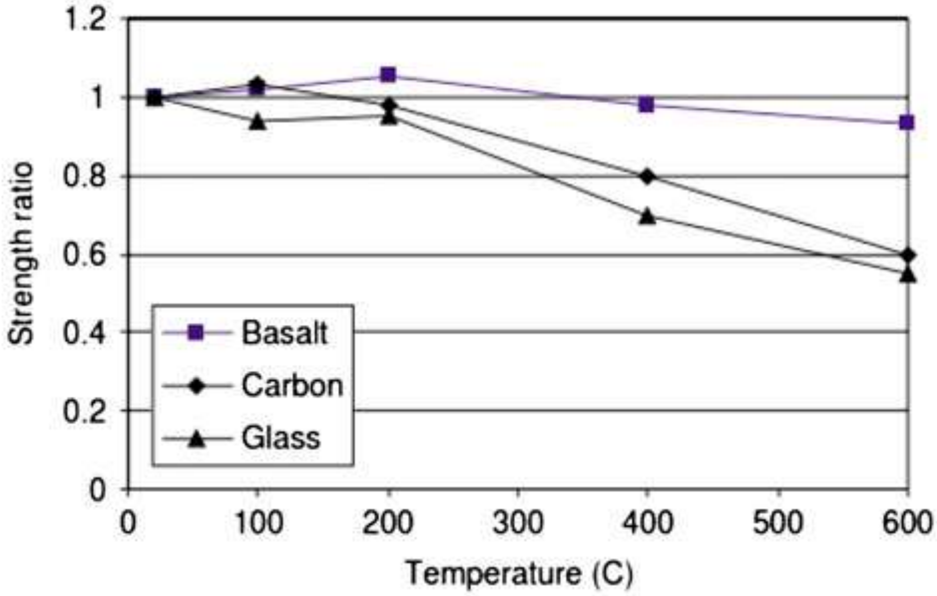

Figure 8. Strength variation w.r.t temperature.

The electrical properties of various fibers are compared in Table 5.
These fibers do not conduct electricity, and no fields are induced when exposed to RF radiation. Dielectric properties of basalt, in particular, volume resistance of BF are almost equal to ones of glass fibers. So, switching from glass to basalt does not change the radar transparency of construction. The chemical properties between glass and basalt are shown in Table 6.
BFs have high chemical resistance and belong to the first hydrolytic class, and on acid and alkali, steam resistance is far superior to glass fiber. Like metal, BF is not affected by corrosion. BF possesses high corrosion and chemical durability qualities towards corrosive mediums, such as salts and acids solutions and, especially, alkalis. Among various properties and characteristics, the high resistance of basalt to alkali and acids is of wider importance. In particular, BF has high acid resistance, which is greater than the resistance of E-glass and S-glass fibers but is somewhat less than the resistance of specific chemically resistant zirconium glasses. Basalts are slightly less stable in strong acids as compared to their behavior against alkalis which is very stable when exposed to strong alkali; rather it can withstand alkaline medium as strong as pH of 13-14. They can retain up to 92% of their properties in NaOH and up to 75% of their properties in HCl acid and resulting in weight loss of only 2.75 and 2.2% respectively as shown in Figure 9. During short-term exposure to strong mineral acid solutions, no fiber strength was observed while a long-term (more than 100 h) impact of hydrochloric acid solutions can cause strength reductions of 15-20% as shown in Figure 10. This reduction proceeds more slowly for basalt roving with a smaller filament diameter than for glass roving. When basalt is boiled with water, alkali, or

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acid, its weight loss is significantly low which is why it is common in use in concrete reinforcement materials in the form of bars. BFs are biologically inert as well as environmentally friendly so they can be used in aggressive environments. BFs are naturally resistant to ultraviolet (UV) and high-energy electromagnetic radiation and maintain their properties in cold temperatures. Basalt can be used as low weight cheap but tough composite material. Moisture regains and the moisture content of BFs is less than 1%. Basalt materials have strong resistance against the action of fungi and microorganisms.

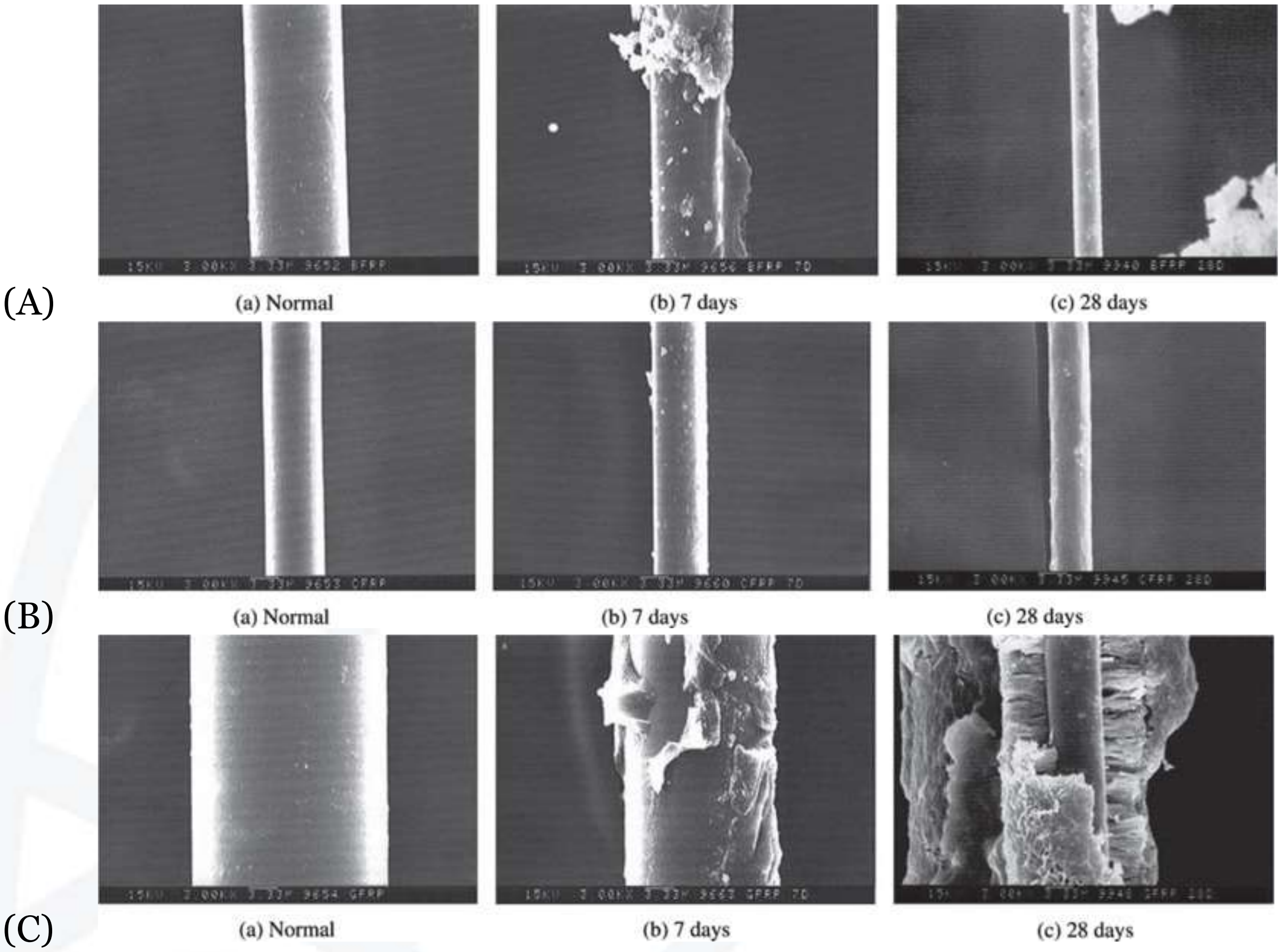
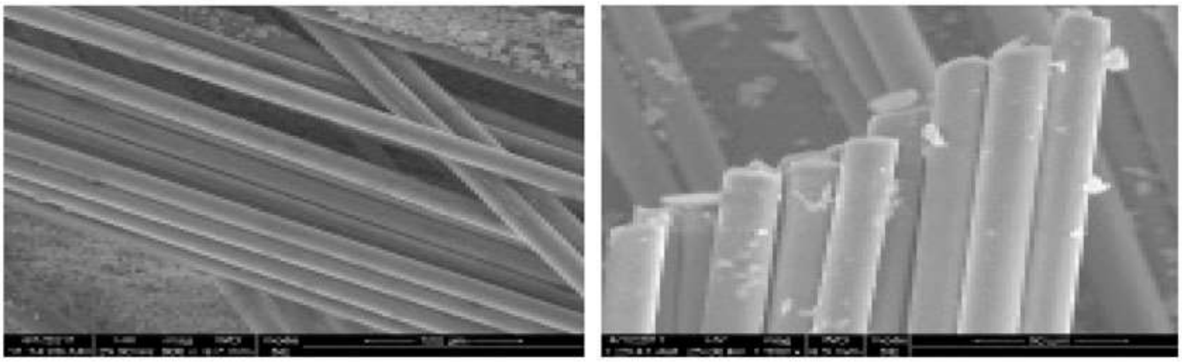


Figure 9. Comparison of damage under alkaline condition. (A) SEM images (3KX) of BFs under NaOH solution, (B) SEM images (3KX) of Carbon fibers under NaOH solution, and (C) SEM images (3KX) of Glass fibers under NaOH solution.



(A) (B)

Figure 10. SEM images of basalt and glass fiber. (A) BF under 2nHCL at 20 °C after 32 days and (B) Glass fiber under 2nHCL at 20 °C after 32 days.

Applications of BF

A wide range of possible applications results from its wide range of good properties. Manufacturers of fiber and composite materials have already shown an interest in BF. Development of technology and equipment for BCF production during recent years allowed achieving the cost of production as low as the cost of production of E-fiber glass (Dorigato & Pegoretti, 2012; Swink, 2002).

Basalt has good thermal, electrical, and sound insulating properties. BF is a possible polymer reinforcing material and can be applied in polymer matrix composites instead of glass fiber for many applications. The good mechanical properties of fibers, the easy wetting of the filament surface, and their recyclability make them particularly suitable for composites application. The UV resistance, the better acid resistance, the somewhat better alkaline resistance, and the very low water absorption of fibers ensure excellent weather ability to outdoors BF reinforced Composites. This intrinsic property of BF is very important for different applications including corrosive media storage and transfer systems, waste gas filters, pavement reinforcement, concrete rebars, and so on. The investigation of the fatigue behavior confirmed the better performances of BF laminates concerning the corresponding glass-fiber composites, with higher stiffness retention at low fatigue loads and better damping properties. It was therefore highlighted the potential of BF as a replacement for traditional glass fiber for the production of structural composites combining good mechanical performances and interesting energy dissipation capabilities (Dias & Thaumaturgo, 2005). The good mechanical properties of Basalt (strength & rigidity), the easy wetting of the filament surface and their recyclability make them particularly suitable for composites application. When used as (continuous) fibers, basalt can reinforce a new range of (plastic and concrete matrix) composites. Because of these properties, BFs and basalt-based composites resulted to be attractive for several technological applications, such as geo polymeric concretes, pressure pipes, fibrous insulators for residential and industrial buildings, protective clothes, bulletproof vests, automotive parts, and fire-blocking material. It has a great advantage even among other fibers; it is well-compatible with carbon fiber. The consequence is that high efficient hybrid materials can be manufactured by adding a small (pre-determined) amount of carbon fibers to BFs (e.g. basalt/carbon). The obtained thread will have a small content of carbon fiber, which is expensive, so it will be cost-effective. It will demonstrate considerably better elastic properties compared with BF.

Areas of application of BF

Automotive industry

In the 1990s first time, the Japanese automobile industry came in contact with the Kyiv industry for making the new exhaust system. The engines of the new models had a higher temperature of exhaustion, under which fiberglass, traditionally used for those purposes, was destroyed. Heat-resistant fibers, Basalt was used in Toyota's car mufflers.

In the automotive industry, the production of BF offers an alternative to carbon and glass in the filament winding of compressed natural gas cylinders. Noise-absorbing basalt stuffing mufflers are of propulsion-absorption type and use a heat-resistant BF as one of the main noise-damping components. The world-renowned car producer Toyota currently uses continuous BF as sub- muffler's stuffing for their cars. Other uses include, non-asbestos organic composite friction materials including BF are increasingly used in automotive brake disc pads and clutch facing applications, Car headliners (Winning the Environmental award was the headliner of the 2007 Honda Accura MDX), and other parts for interior applications. The industry's main requirements are high mechanical properties and outstanding recyclability. Basalt is corrosion-resistant, impact-resistant, and wear-resistant. In the automotive industry, Azdel Inc. (Southfield, MI), a 50/50 joint venture of GE Advanced Materials (Pittsfield, MA) and glass-fiber producer PPG Industries (Pittsburgh, PA), developed VolcaLite^{R}, a thermoplastic composite that combines thermoplastic resin polypropylene (PP) and long chopped BF. The company claims that the basalt/PP system offers acoustic absorption properties, a low coefficient of thermal expansion (CTE), and a high strength-to-weight ratio, providing good ductility. It can be used for headliners, CNG cylinders, mufflers, sunshades, trunk trims, etc. as shown in Figure 11 (Haeberle et al., 2000).

Civil and industrial construction

In this sector, good hardness, high mechanical properties, corrosion resistance, extended temperature range, and very good insulation properties are very important. Basalt can have various applications as construction materials like tubes, bars, pipes fittings, internal heat and sound insulation of floors, walls, frame walls, boiler shells, tanks, chimneys, fire protection structures, etc. wear-resistant paint coatings for bridges, tunnels, and other critical structures and facilities, waterproof coatings for reinforced concrete structures. BFs are ideal for fire protection and insulation applications. BF does not melt nor shrink in the flame and, when not mechanically stressed, keeps its geometric integrity Because of its thermal insulating properties it is already used as fire protection in the form of fabrics or tapes like fire curtains for hall partitioning and external emergency house protection in case of wild-fire, fire-blocking inter liners for mass transportation seat covers. When coming to heat resistance, basalt is exceptionally suited to block fire. Basalt products resist the open flame. Basalt melts at 1450 °C. A fabric made of basalt, with a Bunsen burner pointed at it (1100-1200 °C) becomes red hot as a metal fabric would. This can last for hours. For reference, an E-glass fabric of the same surface density gets pierced by the same flame in a few seconds. The good insulation property of basalt was recognized earlier, that is why it is a widespread insulation material in the construction industry, processed in the form of rock wool.

Concrete is widely used in structural engineering with its high compressive strength, low cost, and abundant raw material. But common concrete has some shortcomings, for example, shrinkage and cracking, low tensile and flexural strength, poor toughness, high brittleness, low shock resistance, and so on, that restrict its applications. To overcome these deficiencies, additional materials are added to improve the performance of concrete. Fiber-reinforced concrete is a cement-based a composite material that has been developed in recent years. BF is a new material that has been increasingly used in recent years. Therefore, BF reinforced concrete serves the functions of reinforcement, and crack resistance, for bridges and buildings. Due to the elasticity of micro-and macrostructure, BFs are vibration-resistant compared to similar products. This property is of particular importance in mechanical construction and civil engineering. For example, when buildings are erected near highways, railways, and underground, whereas under vibration cushions of mineral and glass fibers experience damage and finally disintegrate, basalt slabs are vibration-resistant and, hence, more durable. A wide range of products is also available for concrete reinforcement, pultruded load-bearing parts and concrete-reinforcing bars, geogrids for road and land reinforcement, and stucco nets for wall reinforcing and

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renovation. Rebar made with BFs ensured good durability to the reinforced concrete because they do not react in alkaline environments and with corrosive elements. Sudaglass (Houston, TX) produces several products from BF, including concrete reinforcement rods. Pultruded from unidirectional BF, the rods are reportedly 89% lighter than steel reinforcement rods, have the same CTE as concrete, and are less susceptible to degradation in an alkaline environment. The company claims that 1 ton of basalt rods can provide reinforcement equal to 9.4 tons of steel rods (Sergeev et al., 1994). For the construction of port structures, oil and gas offshore platforms, unlike glass fibers, is highly resistant to alkaline, acidic, and salt attack making them a good candidate for concrete, bridge, and shoreline structures. Some examples are shown in Figure 12.

Power engineering

The good thermal conductivity of basalt, combined with its equally high electrical resistivity and unique resistance to fire, has allowed basalt woven tapes to be selected for the construction of fire-proof electrical power cables. BFs are also incorporated into printed circuit boards, resulting in superior overall properties compared to conventional components made of fiberglass. It is also used in other electrotechnical applications such as extra fine resistant insulation for electrical cables and underground ducts.

It can be used as lamp posts because of its corrosion-resistant properties. In combination with its high specific strength (9.6 times as high as steel), high resistance to aggressive media, and high electrical insulating properties, this results in specialty products such as insulators for high voltage power lines.

Figure 11. CNG cylinder, muffler and headliners (Sergeev et al., 1994). With kind permission from Springer Science and Business Media.

Figure 12. Rebars and geo grids.

Is well known, that steel tends to corrode if not protected adequately. There are many ways to limit the oxidation, using stainless steel or a more expensive solution than simple steel - or bars obtained from glass fiber pultrusion. However, this last solution is limited because of the lower resistance of the glass fiber in the alkaline environment associated with concrete. Using pultruded bars made with BFs may be the right solution for this problem, given that BFs are more resistant than glass fibers in the alkaline environment and, moreover, cannot corrode (Sergeev et al., 1994).

Chemical & petrochemical industry

Basalt products can be used for chemical and wear-resistant protective coating for tanks, pipelines, and oil pipelines. Basalt composite pipes can transport petroleum and petroleum products, gases, aggressive liquids, loose materials, hot and cold water supply, etc. Due to basalt's low thermal conductivity, the deposition of salts and paraffin's inside the pipes is also reduced (Subramanian & Austin, 1980; Wei et al., 2010).

Wind mill blades

At the moment, wind energy is by far the most widely used form of renewable energy and it has gained a certain momentum. New wind-turbine production units are built every year, and increasingly longer blades are developed and launched into production to increase the amount of energy generated by the turbines.

A wind turbine is composed of several composite parts; but the blades, made of fiber-reinforced epoxy or unsaturated polyester, represent the largest use of material. E-glass is by far the most used reinforcement, while more costly carbon fiber is employed on a limited basis for greater stiffness and reduced weight in longer blades. To increase the energy output of existing turbines, the wind industry is constantly seeking cheap, easily available materials with higher mechanical properties.

High-quality BF shows 15-20% higher tensile strength and modulus, thus approaching and sometimes outperforming high-strength glass and other special fibers. Compared to standard E-glass, the superior mechanical characteristics of BF make it possible to produce longer blades with the same amount of fiber, i.e. to increase energy output. Here, the high corrosion resistance and high mechanical properties of basalt play the main role (Subramanian & Austin, 1980; Wei et al., 2010).

Sports industry

Due to their high mechanical properties, basalt products are highly suitable for the production of different sporting goods, including hockey sticks, tennis rackets, skis, snowboards, arrows, etc. Mervin Manufacturing was one of the manufacturers who are dealing in basalt-based composites for the snowboard. The board was on exhibit first time in the Basaltex booth at the 2005 JEC Composites Show (Sergeev et al., 1994).

The fields of applications of BF products are extremely broad. Basalt can be used in the Aviation industry for heat and sound insulation quilt, covered with waterproofing fabric for insulation propulsion and airframe. BF articles serve as effective vibration resistant and sound-insulator, which are not broken themselves under the effect of acoustic vibrations so used as insulation in aircraft. Basalt can be used for the heat insulation of gas turbines, including in nuclear plant locations, as basalt is known to resist degradation caused by radiation, unlike glasses. It is also functional in very low-temperature useful applications are insulation of liquid nitrogen tanks and pipes. It can be used for the industrial filter. Meteor™ is a filter medium comprised of an extremely stable scrim constructed of mineral BFs and yarns (Wei et al., 2010). BFs can also be used in machine building because of their good frictional, heat, and chemical resistance.

Conclusions

As a result of its characteristics and properties, BF can be considered the material of our future for green and sustainable development. Basalt comes from the unlimited green resource. BF is known as the green industrial material of the century and combines ecological safety, natural longevity, and many other characteristics. Further, basalt is 100% inert, that is, it has no toxic reaction with air or water, and is noncombustible and explosion-proof. If we consider the environmental impact of the whole complex of technological processes on obtaining exploitation of BFs, it is much lower than that of glass, carbon, or mineral fiber material in general. The BF is now being a popular choice for the material scientist for the replacement of steel and carbon fiber due to its high rigidity and low elongation or extension at the break. Its supreme tenacity value makes it a useful reinforcement material in the present and also for the future era to come. The majority of CBF manufacturers have been actively improving their equipment and, according to experts, the perfection of the CBF manufacturing process happens faster than the development of fiberglass production technology.

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