Spinning the Rocks - Basalt Fibres

D Saravanan, *Non-Member*

The nature is constantly providing various resources for making textile materials for variety of applications. Though many textile fibres in the nature are available in the fibrous form itself, nature also offers raw materials that can be modified and formed into a filament in a way similar to the melt and solution spinning of other textile fibres. More than 60 sample representing 25 different types of metallic and industrial minerals, aggregates and the three main rock groups namely igneous, sedimentary and metamorphic. Basalt is a natural material belonging to the family of igneous rocks, which has the capability of melting at certain temperature in a way similar to thermoplastic materials. Also basalt material is capable of withstanding high temperature and pressures, which can be used for high performance applications. This paper deals with the manufacturing of basalt fibres, their properties and the applications.

Keywords *:* Basalt continuous filaments; Magma; Composites; Melting; Crystallisation

INTRODUCTION

Basalt originates from volcanic magma and flood volcanoes, a very hot fluid or semifluid material under the earth's crust, solidified in the open air. Basalt is a common term used for a variety of volcanic rocks, which are gray, dark in colour, formed from the molten lava after solidification[1-4]. Basalt rock-beds with a thickness of as high as 200 m have been found in the East Asian countries.

Basalt Formation

The heavily thickened lavas contain olivine, clinopyroxene (salite), plagioclase and opaque metal oxides. Plagiocene and pyroxene make up 80% of many types of basalt. Narrow range of silicone dioxide, magnesium oxide and titanium dioxide have also been found to present along with the traces of elements like Zr, Y, Nb. These kind of basalt has been classified as alkali basalt[5]. When a portion of the earth mantle, which is close in composition to chondrite meteorites, melts to form a basaltic liquid, the light rare earths are more strongly concentrated in the basaltic melt. The mantle perioditite, which remains solid becomes depleted in light rare earth elements, while basaltic melts produced from it show both overall and light rare earth enrichment[6]. Elemental analysis shows the presence of elements like Fe, Ca, K, Na, Sc, Co, La, Ce, Sm, Eu, Yb, Hf, Ta, Th in the basalt rocks[7]. Table 1 shows the results of the chemical analysis of the basalt material. Evidences have also been found that basaltic rocks also exist in the planets other than earth[8]. Basalt makes up the crust beneath the oceans[6, 9-10].

Because of good hardness and thermal properties, basalt has been used for the construction of the roads as the surfacing and fillings, lining material in the pipes for transporting the hot fluids and as the floor tiles. Basalt is different from the granites in that it has a higher content of iron and magnesium. This can be considered as a major replacement to the asbestos, which poses health hazards by damaging respiratory systems.

D Saravanan is with the Department of Textile Technology, Bannari Amman Institute of Technology, Sathyamangalam, Tamilnadu 638 401.

This paper (modified) was received on July 8, 2005. Written comments on the paper will be received till May 31, 2006.

Table 1 Chemical composition of basalt rock

Chemical	%
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
P_2O_5	0.28
MnO	0.16
Cr_2O_3	0.06

Spinning of Basalt Fibre

Though basalt stones are available in different compositions, only certain compositions and characteristics can be used for making the continuous filaments with a dia range of 9 to 24 microns. Compounds present in the basalt rock may vary, especially the SiO_2 content depending on their nature and origin. Basalt rocks with SiO2 content about 46% (acid basalt) are suitable for fibre production. A French scientist in the US filed the first patent revealing the technique of producing the basalt fibre in the year 1923 and subsequently the research was started in Russia, Czech and Prague. After dismantling of USSR, the technology was made available to others.

Basalt continuous filaments (BCF) are made from the basalt rocks in a single step process melting and extrusion process[1, 2, 11, 12]. Technological process of manufacturing basalt filament consists of melt preparation, fibre drawing (extrusion), fibre formation, application of lubricants and finally winding. Basalt fibres are currently manufactured by heating the basalt and extruding the molten liquid through a die in the shape of the fibres (Figure 1). Crushed rock materials are charged into the bath-type melting furnace by a dozing charger, which is heated using air-gas mixture. Crushed rocks are converted into melt under temperature of 1430°C - 1450°C in furnace bath. Molten basalt flows from furnace through feeder channel and the feeder window communicates with recuperator. The feeder has a window with a flange connected with slot-type bushing and is heated by furnace waste gases. The melt flows through the platinum-rhodium bushing with 200 holes (500 is possible), which is heated

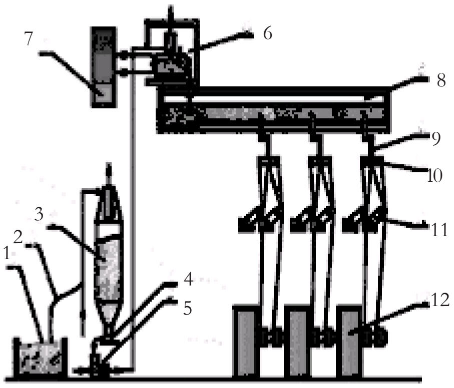


Figure 1 Schematic diagram of basalt fibre spinning[11]

electrically. The fibers are drawn from the melt under hydrostatic pressure and subsequently cooled to get hardened filaments.

A sizing liquid with components to impart strand integrity, lubricity, and resin compatibility is applied and then filaments are collected together to form a 'strand' and forwarded to the take up device to be wound on to a forming tube. The forming package is often referred to as 'forming cake'. The dried cakes are ready for further processing. Basalt twisted yarn is produced by twisting the basalt roving. Twist provides additional integrity to the yarn before it is subjected to weaving. Basalt Cut Fibre is produced from continuous basalt filament, chopped to a specific fiber length in a dry cutting process[12]. The moisture content of the final material lies in the range of less than 1% and with sizing add on levels ranging from 1.0% - 2.0%.

The very high melting temperature of basalt rocks makes the process more complicated than that is normally used in the case of glass. Molten basalt is non-homogeneous in nature, which leads to non-uniform temperature distribution during production stage. This requires a very precise temperature maintenance and control system at multiple stages.

The main problem that is frequently encountered during the manufacture of basalt fibres is the gradual crystallisation of various structural parts like plagioclase, magnetite, pyroxene. This arises mainly because of difference in the crystallisation temperature (T_c) of the different components, which varies from $720^{o}C$ - $1010^{o}C$ (magnetite T_c - $720^{o}C$, pyroxene T_c - $830^{o}C$ and plagioclase T_c - $1010^{o}C$). Fresh basalt fibres are practically amorphous when the rapidly quenched, due to the action high temperature these fibres develop the ability to crystallize partially[3]. A slow cooling of these fibres leads to more or complete crystallization to form an assembly of minerals.

Trivalent rare earth ions have same size as the divalent calcium ions. So the rare earth elements fit into the crystal lattices of calcium-bearing rock forming minerals[6] such as pyroxene ($CaMgSiO_3$) and plagioclase ($CaAl_2SiO_8$). Some times these minerals are also considered as the incompatible elements depending upon their charge quantity and thermodynamic equilibrium.

Research works are being carried out to develop the means to draw the as-spun, spun filaments between rollers to modify the physical properties and to apply the surface finishes to the filaments to suit the specific applications. The fibres may be used either as a filament

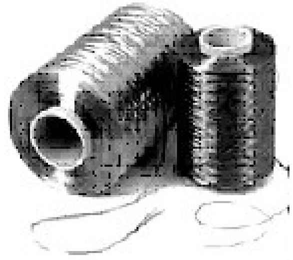


Figure 2 Basalt roving

or chopped into staple fibres as per the requirement. Basalt roving (Figure 2) is produced by assembling a bundle of strands into a single large strand. Manufactured basalt fibres have a fineness of 9μ - 22μ (chopped fibres 10μ - 17 μ) and 320 tex - 4800 tex for roving[14].

Possibility of the production of basalt and glass fabric for the electrical insulation and construction application has been demonstrated (Figure 3). The magnitude of specific volume electrical resistance was found one order higher than that of the glass cloth[15].

Properties

Properties of the basalt material are different from that of granite thought both are obtained from the similar raw material *ie*, rock. Table 2 gives the comparison of basalt with the granites interms of type, distinct characteristics, and composition.

Figure 3 Basalt fabric

Table 2 Comparison of basalt with granite

Character	Granite	Basalt
Rock Type	Igneous(intrusive/plutonic)	Igneous (extrusive/volcanic)
Environment	Granite is formed by 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 because it is less.
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

The density of the basalt, in the rock form, ranges from 2.8 g/cc to 2.9 g/cc, which is very much lower than metal and closer to carbon and glass fibres. However, basalt fibres have the advantage of being very low weight compared to that of steel.

Moisture regain and moisture content of basalt fibres exist in the range of less than 1%[16]. Basalt fibres have very good resistance against alkaline environment, with the capability to withstand pH up to 13 - 14 and relatively less stability in strong acids[17]. Basalt fibres can retain up to 92% of their properties in 2N NaOH and up to 75% of their properties in 2N HCl acid and results in weight loss of only 5.0% and 2.2% respectively but these conditions lead to severe damage in the case of glass fibres[18-19]. Basalt materials have strong resistance against the action of fungi and micro-organisms.

The poor bending property of the basalt results in easy damage of the fabrics immediately after weaving and, further, needs to be stabilized with some coating. Basalt material is extremely hard and has hardness values between 5 to 9 on Mohr's scale, which results in better abrasion properties. Even continuous abrasion of the basalt fibre-woven fabrics over the propeller type abraders do not result in the liberation of fine fibres or splitting of fibres by fracture and results only in breaking of individual fibres from the woven structure which eliminates possibility of causing hazards related to respiration[11].

The fractures in the fibre mainly occur due to the non-homogenities in the fibre volume, probably near the small crystallites of the minerals[20]. Basalt fibres exhibit catastrophic failures at specific places 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, which are evident from the fracture analysis using SEM[11].

Reheating at lower temperatures and weathering the crystallized basalt materials results in the formation of un-consolidated layers of substances (regolith) especially over the exterior surface, mainly because of the reduction reactions[3]. Heat treatment at 850°C for specified durations is also given to basalt fibres and fabrics depending on their end use. Basalt fibres have an excellent thermal properties compared to that of glass (E-type) and can easily withstand the temperature of 1100°C - 1200°C for hours continuously without any physical damage. Unstressed basalt fibres and fabrics can maintain their integrity even up to 1250°C, which makes them superior compared to glass and carbon fibres. Table 3 gives the various mechanical, thermal, electrical properties of the basalt fibres[2,19].

Applications

Basalt is ecologically pure material and attracts the attention from the various segments. Basalt fibres do not undergo any toxic reaction with water and do not pollute air also. Unlike asbestos fibres, which poses health hazards by affecting respiratory system, the basalt fibres do not cause any damage to the health since the filaments are spun with higher dia than 5 μ and also due to favourable biopersistence, it has been made label-free material in the US and Europe. Also, particles or fibrous fragments due to abrasion are too thick to be respirable but care in handling is recommended[20].

Table 3 Physical properties of basalt fibre

Property	Value
Density, g/cc	1.95 - 2.75
Tensile Strength, Mpa	1200 - 4840
Compressive Strength, Mpa	420
Bending Strength, Mpa	800
Elastic Modulus, Gpa	89
Elongation at Break, %	3.15
Moisture at 65% RH, %	< 0.1
Max Application Temperature, °C	982
Sustained Operating Temperature, °C	820
Min Operating Temperature, °C	-260
Melting Point, °C	1450
Thermal Conductivity, W/m K	0.031 - 0.038
Glow Loss, %	1.9 - 2.0
Sound Absorption Coefficient	0.9 - 0.99
Loss Angle Tangent Frequency, MHz	0.005
Specific Volume Resistance, Ωm	1×10^{12}
Relative Dielectric Permeability, MHz	2.2

Application of basalt fibres in composites, high performance end-uses have been discussed individually by many authors in the past[21-29]. Basalt is ecologically pure material and attracts the attention from various segments.

Basalt fabrics are produced for the structural, electro-technical purposes. Structural applications include electromagnetic shielding structures, various components of automobiles, aircraft, ships and household appliances. Fabrics of varying surface densities are made depending upon the application type and are in the range 160 g/m^2 to 1100 g/m^2 for the insulation type of applications. Basalt fibres reinforced in the glass matrix can be viably used for opto-mechanical applications[21].

Basalt fibres have better heat insulating properties, almost three times, than the asbestos. Basalt fabrics are used as the fire blocking materials in the public transport systems due to the inherent better thermal properties. Both woven as well as knitted fabrics are used for these applications. Basalt interliners in the mattresses prevent unexpected fire accidents that can happen by smoking cigarettes or by other means. A very high abrasion resistance property of basalt material is useful in making the cut resistance fabrics.

Geo-composites

Basalt materials do not absorb the radioactive radiations, which makes them to consider as the potential material in production and transformation of radioactive materials, in nuclear power plants. Protective cap using geo-composites in the waste disposal sites, incorporating basalt materials, can offer the best protection for the human health and environment against the radioactive wastes[30]. Many of these wastes need to be protected for centuries in an isolated way for harmless disposal. The major requirements of such capping system for the long term use include, ability to function in a semiarid to subhumid climate, limit the recharge of water table to near zero

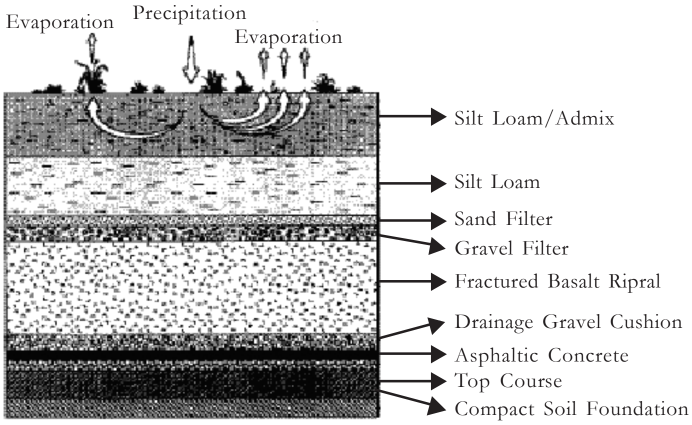


Figure 4 Isolated dumping system for radioactive wastes[30]

amount, maintenance free, resisting animal, human intrusion and limiting the release of noxious gases. Waste dumping pits are constructed with several layers, which include coarse material such as sands, gravels and basalt riprap (Figure 4).

Basalt geo-mesh[19] offers a number of advantages over glass or metals used for the pavement reinforcement. They are ecologically safe and can withstand very high temperature of molten asphalt. The basalt geo-meshes are chemically inert and lighter than metallic meshes. Basalt geo-mesh is also suitable for soil and embankment stabilization and environmental and ecological safety.

Geo-polymeric concretes reinforced with basalt fibres show better fracture toughness as shown by three point bending tests than the conventional cement structures[31].

Civil Construction and Concrete Reinforcements

Basalt, in civil construction, is mainly used in the form of crushed rock in construction, industrial and high way engineering[17]. Applicability of basalt fibres as a strengthening for concrete structural materials has been studied for durability, mechanical properties and flexural strength[28]. Requirements of the moderate strengthening in the civil structures and high fire resistance can be met with basalt fibres while FRP strengthening can be considered for pure strengthening.

Basalt filaments incorporated unidirectional rods are used as the reinforcement of concrete slabs in hydraulic engineering and construction in seismically hazardous regions. On the weight basis, one kilogram of basal reinforcement can replace 9.6 kg of steel in the concrete structure[23]. The basalt rebar, consisting of 80% basalt fibre with an epoxy binder offer better mechanical properties to the reinforced concrete and are, also, less expensive[24]. Rods made of basalt have same coefficient of thermal expansion (8ppm/^{o}C)[11, 16] as that of concrete, which also increases the compatibility and performance in adverse conditions[23]. Presence of alkali or alkaline treatment results in loss of the volume accompanied by the reduction in strength, significantly. In the accelerated weathering tests, basalt fibres show better results compared to glass fibres. Exposure to 600^{o}C for 2 h also results in almost retention of 90% of normal strength while carbon fibre and glass fibres loss their volumetric integrity[28]. Strengthening of concrete members were improved up to 27% depending upon the number of layers applied. The basalt fibres have the advantage of low weight compared to the steel and also have a similar co-efficient of thermal expansion as that of concrete. Basalt can also be used in the interiors, partitioning of the buildings, elevator shafts, and in sound insulations for the buildings.

Basalt Fibre Composites-Tissues, Plastics, Prepegs and Laminates

A very high Young's modulus, ultimate tensile strength and good wetting properties of basalt filaments can be utilized for making high performance composites.

Basalt fibre tissue is a non-woven material, composed of uniformly distributed basalt fibres, bound by organic additives like thermosetting resins[32]. Its porosity makes easy to impregnates and also possesses better resistance against atmospheric agents, UV rays, acids, and alkalis. Different binders like foro-phenolic, melamine, latex, urea formaldehyde or PVA can be used for making basalt tissues. Basalt tissues can be used as soft roofing and water proofing using bituminous coatings, geotextiles, anti-corrosion material, plastic foams with PU foam linings, tissue tapes for joining two boards, batter plate separators and etc.

Basalt plastics based on various thermosetting binders, phenolic polyesters through the laying out method, suitable for automobile, aircraft, ships and households appliances[23]. Basalt fibre reinforced plastics are more suitable for painting because of their better surface quality. This, also, can be electroplated without imparting any pretreatment to this material [22]. Silane coupling agents are used to improve the interaction between basalt fibres and polymeric matrix like polyester. But hydrolysis of silane, condensation, orientation on the basalt surface and chemical bonding on the surface are the factors that affect the flexural strength of the composites[29].

Prepegs suitable for transfer molding, die-casting, winding laying, direct pressing autoclaves, and vacuum molding can be manufactured using basalt fibres, both filaments and chopped fibres with modified polyester resins. These prepegs can be stored for a longer time, at least four years, under storage conditions of hermetical packing with a temperature of below 40^{o}C. The following Table 4 gives the comparison between basalt filament based prepegs and chopped fibre based prepegs.

Hybrid composites of basalt fibres can also be used in combination with other reinforcements *eg*, basalt/carbon[17]. Composite panels

Table 4 Comparison between basalt filament and chopped fibre prepegs[23,29]

Characteristics, MPa	**Basalt Filament Prepeg**	**Basalt Fibre Prepeg**
Ultimate bending strength	238.00	83.00
Bending modulus	19.50	8.00
Ultimate compressive strength	86.00	126.00
Compressive modulus	23.10	8.80
Ultimate tensile strength	302.00	23.00
Tensile modulus	21.00	8.00
Bending strength after heat treatment	75.00	–

Table 5 Properties of the basalt laminates[12]

Characteristics	Values
Width, mm	24.900
Thickness, mm	3.250
Failure load, kN	46.205
Ultimate strength, MPa	578.800
Elastic modulus, GPa	33.940
Poisson's ratio	0.193

fabricated by resin transfer moulding (RTM) using five plies of laminates of woven basalt fabrics show excellent properties. The laminates with a fibre volume fraction of 0.44 and laying configuration of [$0^o/90^o$] yield the following results. Basalt fibre laminates have been developed using the resins including phenols, epoxy, polyamides[33]. These laminates are mainly used for the production of printed circuit boards, electrical circuits and graph plotters.Table 5 shows the typical values of various properties achievable in the basalt fibre laminates.

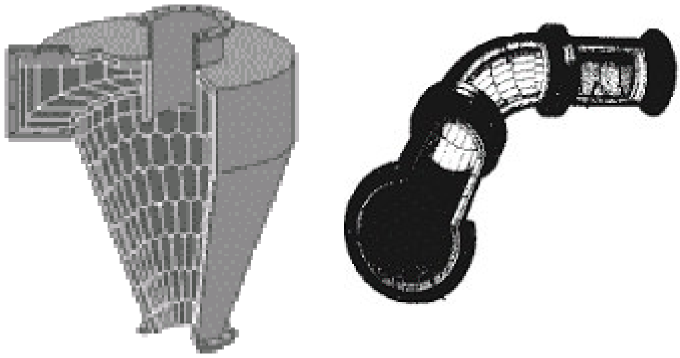
Abrasion Resistant Basalt Fibre Pipes, Castings

Installation of Basalt lined pipes started widely in 1980s and 1990s. These pipes have the hardness of 9 on Mohr scale so that they provide the highest level of abrasion and impact resistance[34]. Transporting slag is one of the most severe strain put on pipes and its components. High-pressure pipes can be manufactured using basalt-plastic combinations, which can withstand more 1000 atm, which is not possible with the metal pipes. Basalt fibre pipes are manufactured through filament winding, using fabrics and prepegs impregnated with a binder. These pipes are useful as the component parts of shaft linings, building components for transporting corrosive liquids and gases. Also, basalt-plastic pipes can be used for a longer service life *ie,* 60 years - 80 years, which is 2 or 3 times longer than the metallic pipes.

Basalt lined pipes carrying abrasive coal slurry can be used for decades without any assessable damages. In a typical cyclone boilers, a unique requirement is that the ash from these boilers must be melted and turned into liquid to the slag tank[35]. Situations, where low sulphur coals are used, the melting (fusion) temperature is very high and also they yield slag as brittle and hard, which has high abrasion.

Mining operations, also, involve separation of sodium chloride and potassium chloride by flotation technique. The transportation of these un-separated salts and tramp material takes place across large area. Abrasive and corrosive natures of these salt slurries cause premature wear in many of the pipes. Installation of basalt and ceramic lined pipes help to reduce the down time and increase the productivity[36]. Basalt lining incorporated pipes are used to overcome this wear problems (Figure 5). Pre-engineered linings are made by melting and casting the volcanic rock with final annealing treatment to impart required hardness. Due to low thermal conductivity of basalt, deposition of salt and paraffin inside the pipes is also reduced. Basalt fibre pipes can also be used in machine building because of their good frictional, heat and chemical resistance [17].

Table 6 shows the comparative properties of the basalt-plastic with the steel and glass-plastic composites.



(a) (b)

Figure 5 Transport pipes using basalt lining

Table 6 Comparison of physical properties of different pipe materials[17,23]

Property	Basalt-plastic	Steel	Glass-plastic
Ultimate tensile strength, Mpa	300	200	140
Tensile modulus, Gpa	70	210	56
Volume resistivity, Ω /m	4×10^{12}	Conductor	1×10^{10}
Density, g/cc	1.7	7.8	1.9

Good wetting property of basalt fibres helps to apply various chemicals through topical treatment to achieve various functional finishes like oil resistance, soil resistance, colouring the fabrics and the finishes to impart abrasion resistance. Because of very high resistance to the various chemicals, basalt pipes can be used for transporting hydrogen sulphide, acid, alkalies and etc, without any hazard.

The chief advantages of basalt pipes[23] include

- Pipes can withstand very high pressures like above1000 atm, which is not possible with steel pipes.
- Being insulators, basalt-plastic pipes are resistant to electrochemical corrosion, which results in the life expectancy of 60 - 80 years.
- Basalt fibres are resistant to the action of fungi and micro-organisms.
- High chemical resistance to aggressive media makes it possible to manufacture pipelines for transporting hydrogen sulphide, acids, alkalis and etc.
- Low thermal conductivity prevents deposition of salts and paraffin in pipelines.

Basalt Castings

The equipment used in the coal mines often suffer from high wear and tear problems, resulting frequent downtime and reduction in the productivity. These equipment are mainly used for transporting of coal, flyash, wet ash and lime. Linings of the equipment with basalt casting reduces friction induced abrasions. Basalt casting being corrosion resistant, creates smooth surface with good flow properties. In coal mines ash removing pipes (dia-10″ to 12″) are normally made of hardened cast iron, which normally gives a life of four years.

Granulated blast furnace slag are used in the production of slag cement which is an additive for Portland cement and transporting them through the pipes result in higher wear and tear since the slag composed of lime, silica, alumina and magnesia is extremely abrasive. Basalt pipes provide an ideal solution in this situation[34]. With basalt linings the life can be improved up to 8 years in the case of abrasives and up to 12 years in the case of conveying ash and sand. In a typical pipe, the basalt cast-linings are incorporated to the extent of 7/8" (22.22 mm) thickness and 11/8" (35 mm) at elbows[37].

Electro-technical Application

Basalt fabrics for electro-technical purposes are used as a base for the production of insulation materials. Preliminary metallization of the fabrics result in shielding properties of electromagnetic radiations. These materials have superior properties to conventional fibre glass materials. Basalt can be used over a wide temperature range from about -260°C/-200°C to 650°C/800°C compared to E-glass which can be used from - 6°C to 450°C/600°C[17].

The wide range of possible applications results from its wide range of good properties. It can replace asbestos in almost all applications because of its heat insulating properties. Because of its good insulating properties, it can replace glass materials. Table 7 shows the comparison between the composition of E-glass and basalt fibres.

Tapes made from the basalt material can be used in the electrical cables as the insulation material against fire hazards during power transmission. Even at very low temperatures, the basalt fibres attain their properties, which makes this material suitable for low temperature insulations.

Industrial Applications

Basalt fibres, as a sewing thread, attract major attention in the high temperature application,. Stitching of filter bags for hot media, filter bags intended for highly aggressive chemical environment[13, 26-27].

Incombustible basalt fabrics inserts in industrial ventilators increase their fire safety as well as fire resistance of ventilating systems and construction materials.

Automobile, aircraft, ship and household appliances using basalt are also made with incorporating thermosetting resins such as epoxy and phenolic resins in the form of prepegs, laying out. Lubricated, chopped fibres are used in car brakes etc. the ability to recycle the basalt fibres to different forms solves the problem of disposal of the scraps, and different degraded components obtained from various applications.

Table 7 Comparison of compositions between glass and basalt[17]

Compound	**E-glass,** Wt %	**Basalt,** Wt %
SiO_2	52 - 56	51.6 - 57.5
Al_2O_3	12 - 16	16.9 - 18.2
CaO	16 - 25	5.2 - 7.8
MgO	0 - 5	1.3 - 3.7
B_2O_3	5-10	---
Na_2O	0.8	2.5 - 6.4
K_2O	0.2 - 0.8	0.8 - 4.5
Fe_2O_3	$\leq$ 0.3	4.0 - 9.5

Basalt fibres reinforced cardboard with suitable binders like PVA can be used for cryogenic applications that are required for storing biological materials in liquid nitrogen atmosphere[25]. Epoxy sheets containing basalt fibres and intumescent nonwoven fibre mats as a fireproofing material to meet fire codes in concrete bridge and marine applications[14].

Basalt fibres have better sound proofing abilities and can act as a barrier in the frequency range up to 1800 Hz, to the extent of 80% - 95%[18].

Basalt fibres can also be used in the various agricultural applications like, land drainage pipes, pipes for irrigation and hosing, raising vegetable and seeding, and agricultural machine constructions[38].
At present, the cost of basalt fibres is almost three times higher than that of the glass fibres but this is likely to come down once the production volume goes up.

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