Continuous Filament Basalt

A Unique Fiber Capable of Leadership in High Temperature Applications

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I Overview

This paper will focus on the applications for a very common material, basalt rock, in a relatively new form, continuous filament basalt (CFB). Basalt is the most common rock type in the earth's crust. During the past twenty years the technology was developed in the former Soviet Union to melt this once molten rock and form continuous fibers. The continuous strand of multiple filaments can then be twisted into a yarn, plied into a multi-strand roving or cut into chopped fiber. The CFB can be converted into woven or non-woven textiles or used to reinforce composite structures with techniques similar to those used with continuous filament fiberglass.

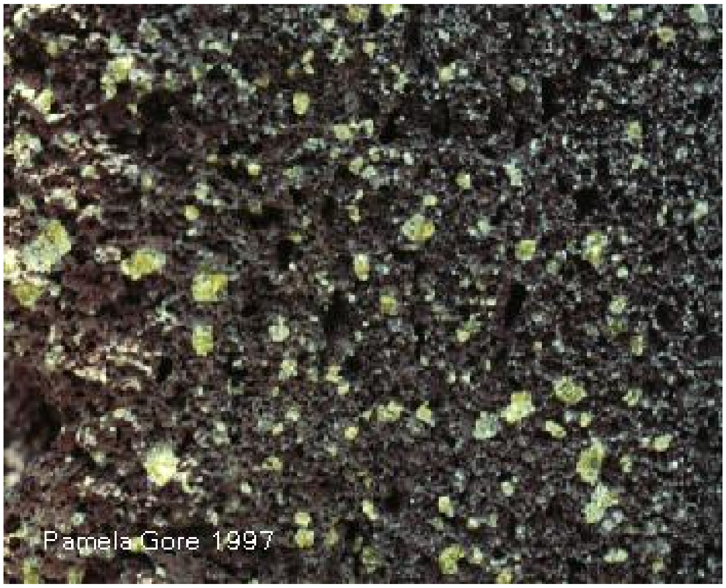
II What is Basalt?

Basalt is a hard, black volcanic rock with about 52% silica (SiO_2) by weight. Basalt rock is a mixture of minerals that has a fine grain and slight differences in chemical composition. Common minerals in basalt include olivine, pyroxene, and plagioclase. Each deposit has small deviations in chemistry but fall within the same general parameters. Some deposits are more favorable than others for the manufacture of fibers due to the presence or absence of trace elements.

Basalt lava (glowing rock) oozes over basalt lava flow (USGS photo)

According to the US Geologic Survey, because of basalt's low silica content of about 52%, it has a low viscosity. Therefore, basaltic lava can flow quickly and easily move >20 km from a volcanic vent. The low viscosity typically allows gases to escape without generating enormous eruption columns. Basaltic lava fountains and fissure eruptions, however, still form explosive fountains hundreds of meters tall. Common minerals in basalt include olivine, pyroxene, and plagioclase. Basalt is erupted at temperatures between 1100 to 1250° C.

Hawaiian basalt used as building stone



Close-up showing grains of mineral crystals present

- Basalt is the most common rock type in the Earth's crust (the outer 10 to 50 km). In fact, most of the ocean floor is made of basalt.

- Basaltic magma is commonly produced by direct melting of the Earth's mantle, the region of the Earth below the outer crust. On continents, the mantle begins at depths of 30 to 50 km.
- Shield volcanoes, such as those that make up the islands of Hawaii, are composed almost entirely of basalt. [1]
- Huge outpourings of lava called "flood basalts" are found on many continents. The Columbia River basalts cover most of southeastern Washington and regions of adjacent Oregon and Idaho.

II What is Continuous Filament Basalt (CFB)?

The direct melting of “flood basalts” has produced two major types of basalt fibers. The first and most known for many years is the wool type. Basalt wool fibers have properties similar to other types of mineral wools. This paper will focus, however, on the newer continuous filament basalt (CFB) technology. CFB is similar to special recipe fiberglass, silica and quartz fibers.

It is well known that the properties of all mineral fibers depend on their chemical composition, thermal history, manufacturing conditions, filament diameter and composition of the chemical sizing applied. Glass fibers are made from a blend of raw materials whose recipe depends on the exact properties desired, i.e. E (electrical) grade, C (chemical resistant) grade, S (high strength) grade.

Basalt fibers are made by melting a single material, basalt rock, with the properties determined by selection of the quarry from which the rock is obtained rather than a raw material recipe. Using a naturally occurring composition provides a high level of stability to basalt fiber.

Comparing the chemical composition of glass and basalt fibers reveals that natural basalt contains ingredients that are added to fiberglass to obtain special properties. Al_2O_3 is used to increase the viscosity and chemical resistance. Oxides of Calcium, Magnesium, and Titanium raise the water and corrosion resistance.

CFB meets the technical definition of a glass, however the presence of iron oxides gives basalt a golden brown color that doesn’t have the translucence of fiberglass:

“any of various amorphous materials formed from a melt by cooling to rigidity without crystallization as a usually transparent or translucent material consisting especially of a mixture of silicates “. [2]

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[1] http://volcanoes.usgs.gov/Products/Pglossary/basalt.html

[2] On-line version of Merriam-Webster dictionary

Chemical Comparison of Basalt and E-Glass (% by weight)[3]

Chemical	Formula	Basalt	Basalt =/+/-	E-Glass
Silicon Dioxide	SiO_2	48-59%	=	52-56%
Boron Oxide	B_2O	<1%	-	5-10%
Calcium Oxide	CaO	6-9%	-	21-24%
Titanium Dioxide	TiO_2	0.8-2.3%	+	0-1.5%
Iron Oxides	Fe_2O_3 + FeO	7-12%	+	<1%
Alumina	Al_2O_3	15-18%	+	12-14%
Magnesium Oxide	MgO	3-5%	+	0-5%
Sodium + Potassium Oxides	NaO + K_2O	4-5%	+	0-1%

III The CFB Manufacturing Process

CFB is formed in a similar way to continuous filament fiberglass. While a fiberglass and basalt furnaces look externally alike, the difference in the temperatures and viscosities of their respective molten material are different enough that the furnace and fiber forming equipment are not interchangeable between the two.

CFB manufacturing differs from fiberglass in that it does not require the material blending and air pollution control equipment needed for handling raw materials. CFB uses crushed and washed basalt stone directly from the quarry with only drying required before melting.

Melting natural basalt, then quickly solidifying it converts it from a partially crystalline material to an amorphous solid without any crystallinity. An amorphous solid behaves as a super-cooled liquid with extremely high viscosity. Over many years an amorphous solid, such as found in very old windowpanes, will change shape revealing its true liquid nature.

[3] Composite of published values for basalt from Russian and Ukrainian sources

Glass continuous fibers being drawn [4]

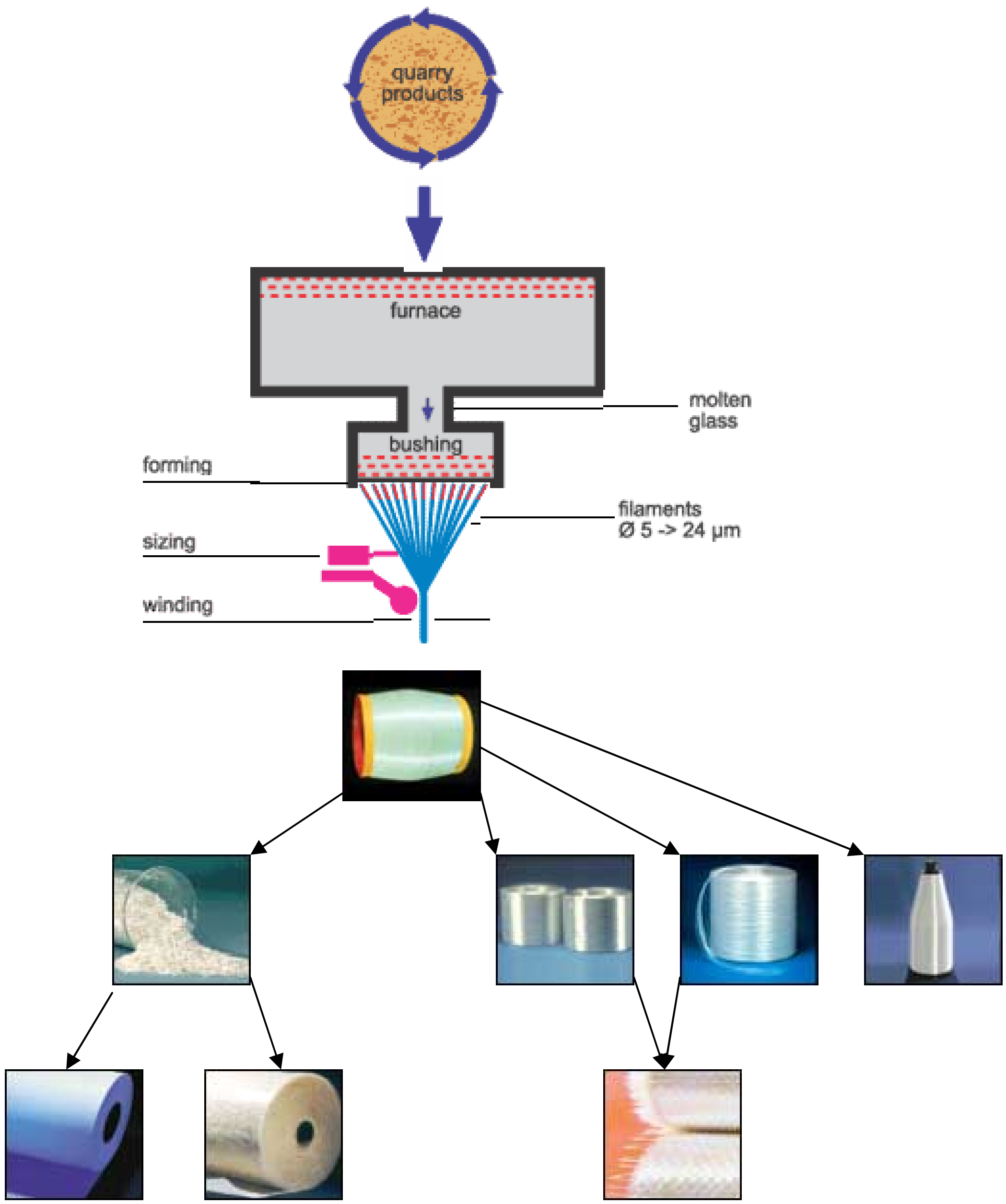
Basalt yarn after forming, twisting and plying[5]

The following diagram shows how continuous filament glass fiber (as opposed to glass wool) is made. A similar process replacing the batch house blending of raw material with a direct feed of crushed basalt rock to the furnace is used to produce basalt fiber.

[4] Courtesy PPG Industries

[5] Courtesy Basalt Fiber Company, Inc.

Continuous Filament Fiberglass Manufacturing[6]



[6] Courtesy of Saint Gobain/Vetrotex

An overview of the basalt fiber manufacturing process[7] is:

- A single-component basalt material is fed into a gas-fired furnace.
- The basalt is heated to about 1,450°C (2,650° 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-holes each make a filament that is gathered into a single strand of continuous-filament basalt fiber.
- The combination of micro-hole size and viscosity of the melt determine the diameter of the resulting filaments (7-17μ).
- The basalt filaments are quenched with a water-based sizing to solidify the strands and deposit a small quantity of lubricant/bonding agent on the filaments.
- The strands are wound onto a bobbin called a forming package at high speed.
- The strands can then be sold as an untwisted roving, twisted/plied into a yarn for weaving, or chopped to a fixed length for production of a non-woven mat.

Before and After the Furnace [8]

[7] Courtesy Basalt Fiber Company, Inc.

[8] Courtesy of Anthony Fanale

IV Properties of CFB

A direct comparison of properties of Basalt fiber with E-Glass and S-glass fiber is useful for understanding its potential applications.

Physical Property Comparison[9]

	Basalt	E-glass	S-glass
Operating Temp.[10]	820°C (1,500°F)	540°C (1,000°F)	690°C (1,275°F)
Max. Excursion Temp.	950°C (1,740°F)	620°C (1,150°F)	760°C (1,400°F)
Thermal Conductivity (W/mK)	0.11	0.11	0.11
Density (g/cm3)	2.8	2.6	2.5
Tensile strength (Mpa)	3450-4900	3100-3800	4590- 4830
Elastic Modulus (Gpa)	88-91	76-78	88-91
Elongation at break	3.2%	4.7%	5.6%
Coefficient of Thermal Expansion	8.0	5.4	2.9
Chemical Stability after 3 hr. boiling			
H_2O	1.6%	6.2%	-
2N NaOH	2.8%	6.0%	-
2N HCl	2.2%	38.9%	-
Spec. vol. electrical resist. (ohm M)	1×10^{12}	1×10^{11}	-

E-glass and CFB have similar silica content, while S-glass has about 20% more. S-glass's higher silica content gives it its higher temperature capability and lower density when compared with E-glass. The iron oxides in CFB give it a higher density and coefficient-of-thermal-expansion than E-glass or S-glass. Thermal conductivity is equivalent between the three fibers.

Basalt compares favorably with E-glass in these ways

- 280°C (500°F) higher operating temperature
- Better strength at elevated temperatures
- Higher elastic modulus

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[9] Data except temperatures from Sudogodskoye Steklovolokno using Russian basalt rock

[10] Temperature data from BGF Industries, Inc.

- Lower elongation at break
- Much more resistant to acid
- Less degradation by water and alkalis

One of the most significant differences between E-glass and CFB is how the tensile strength of each changes with increasing temperature. Under standard ambient temperature (23°C) test conditions, the tensile strength of E-glass and CFB are roughly equal. At 250 °C, E-glass loses up to 23% of its strength while CFB's tensile strength actually increases by up to 15%[11].

Based on this characterization, let's look at some of the product possibilities for continuous filament basalt.

V Thermal/Acoustic Insulation

There is a market opportunity for basalt needled insulation blankets for industrial use at operating temperatures above that of E-glass and below the temperatures where ceramic fibers are required. Except for operating temperature, E-glass and CFB blankets behave similarly:

- CFB, like E-glass, is vibration resistant and will not powder like ceramic fibers
- E-glass and CFB will conform to most complex shapes.
- CFB has fiber diameters of 9-17μ, which are not deeply respirable.
- E-glass and basalt have very low chloride content and meet NRC 1.36-C-3 for use in nuclear plants.

Approximate cost factors are:

- CFB = 2x E-glass
- Ceramic = 3x CFB

[11] M. Sokolinsky and A. Medvedev; "Strength Properties of Basalt Fibers", Science for the Glass Industry, vol. 10, 1991.

Truck Muffler formed from needled insulation[12]

Needled Basalt Insulation Blanket[13]

Thermal Insulation Blanket Comparison[14]

		E-glass	Basalt	Ceramic
Operating Temperature	°C	540°C (1000°F)	820°C (1,500°F)	1175°C (2150°F)
Maximum Temperature	°C	650°C (1200°F)	1050°C (1,920°F)	1260°C (2300°F)
Thermal Conductivity -*	W/mK	0.11	0.11	0.11

*- density of 96 Kg/m3 (6 lb/ft3), 500°C (932°F), 9µ fiber diameter

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[12] Courtesy of Mtuh GmbH

[13] Courtesy of BGF Industries

[14] BGF Industries, Inc.

VI Friction Materials

The facing reinforcements used in brakes and clutches until recent years were constructed of asbestos because of its temperature resistance, strength, high coefficient of friction and low rate of wear. However, the crystalline nature of asbestos causes very fine particles to be formed when the asbestos fibers are fractured. The respirability of these fine asbestos particles led to the removal of asbestos from friction materials.

Basalt fiber has replaced asbestos in friction materials in the former Soviet Union[15]. Asbestos was a functionally superior friction material, however when asbestos was replaced with basalt, part life was extended by a factor of 1.5-2x. The longer life is attributable to basalt's better properties. The following table shows basalt with a wear rate an order of magnitude lower than asbestos while having a higher coefficient of friction:

Asbestos and Basalt Properties for use in Friction Materials-*

	Asbestos	Basalt
Operating Temperature	420°C (790°F)	450°C (840°F)
Coefficient of Friction	0.37-0.42	0.42-0.50
Wear rate (g/m)	9.01×10^{-6}	0.87×10^{-6}
Breaking load for 500 tex yarn (N)		
20°C	12.0	145
400°C	1.4	75
500°C	0.5	12.2

* - Dry friction sliding speed: 1.37-5.5 m/s with a pressure applied of 3-8 Kg/cm^2

[15] Data and photo courtesy of Tsniism

VII FRP – Fiber Reinforced Plastics

Most of the composites development using continuous basalt fiber to date has been done in the former Soviet Union. Most of the development work there was done to replace metal with basalt reinforced plastic parts. That work was focused around these key facts:

- 1 Kg of BFRP could replace 9.6 Kg of steel
- BFRP are non-conductive, so no galvanic protection is required to prevent electrolysis when used in ground or electrolyte contact
- BFRP has much higher acid resistance than standard E-glass
- BFRP has the same CTE as concrete which makes it an ideal reinforcement
- Greater strength retention than E-glass at elevated temperatures – 30% more at 400°C (750°F)
- Basalt has a lower elongation at break, 3.2% versus 4.7% for E-glass with a much higher elastic modulus

The US market (excluding exports) for fiberglass is over 2 billion pounds per year. FRP accounts for the majority with about 56% of this consumption or about 1.2 billion pounds per year. In recent years the US fiberglass industry has been motivated by stricter environmental regulations to eliminate the boron and fluorine from E-glass recipes in order to avoid expensive air pollution control equipment to treat furnace exhaust gases and collect particulate. These new boron-free formulas have found their way into the composites market as E-CR glass.

E-CR (Corrosion Resistant) glass has similar properties to E-glass, but with a significant increase in corrosion resistance as shown in this data from Fiberex Glass Fibers of Canada with Basalt test data from a Russian source for comparison:

Properties	Unit	E-Glass	E-CR Glass	Basalt
Tensile strength @ 23°C	Mpa	3100-3500	3300-3800	3450-4900
Modulus of Elasticity	Gpa	76-78	80-81	87-91
Elongation at break	%	4.4 - 4.5%	4.5 - 4.9%	3.2%
Weight loss in 10% HCl After 24 hours	%	42.0%	5.4%	-
Weight loss in 2N HCl after 3 hours boiling	%	38.9%	-	2.2%

The corrosion resistant FRP market alone is over 120 million pounds/year in the US. Basalt fiber's greater acid resistance and higher strength retention at elevated temperatures should offer it a place in the US composites market, but more testing directly against the newer E-CR glass fiber is needed to be able to definitive comparisons as to usefulness in this market.

CFB's tensile strength is typically above E-glass and with certain sources of natural basalt, is comparable to S-glass. With CFB priced at roughly mid-way between E-CR glass and S-glass, basalt fiber should have a good future in applications requiring a high enough strength to weight ratio to use S-glass such aircraft cargo floors and other structural composites. Albarrie Canada Ltd. has tested the laminate properties of CFB and E-glass epoxy laminates. The data in this section is excerpted from their published test results:

Mechanical Properties[16]

Property	Unit	Basalt	E-Glass	S-Glass
Tensile Strength	MPa	4840	3450	4710
Elastic modulus	GPa	89	77	89
Elongation at Break	%	3.15	4.7	5.6

Basalt Fiber Laminates

The composite test panel was fabricated using resin transfer molding. The panel consisted of 5 plies of wide weave basalt fabric and the resulting composite was roughly equal to a [0º/90º] laminate. The resin used was Shell EPON-862 with curing agent W. The fiber volume in the composite was approximately 44%.

Characteristics of Basalt Laminate

Width	24.9 mm	0.979"
Thickness	3.25 mm	0.126"
Failure Load	46.205 kN	10.126 lb
Ultimate Strength	578.8 MPa	83.95 kP.S.I.
Elastic modulus	33.94 GPa	4.92 MP.S.I.
Poisson's Ratio	0.193	

[16] Courtesy of Albarrie Canada Ltd.

Comparative Characteristics of Basalt and E-Glass Laminates

Quasi-isotropic Composite	Basalt Laminate	E-Glass Laminate
Elastic modulus	34 GPa (4.9 MP.S.I.)	17.2 GPa (2.5 MP.S.I.)
Ultimate Strength	579 MPa (84 kP.S.I.)	207 MPa (30 kP.S.I.)

VIII Other Applications

The properties of continuous basalt could bring value in many other applications where extensive testing has not yet been done. For instance, E-glass is used extensively in hot gas filtration applications, but is lacking in acid and abrasion resistance. The inherent abrasion resistance which makes basalt a good friction material would be an improvement over E-glass in hot-gas filtration, particularly in pulsejet cleaned applications where the fabric is placed over a metal cage. Albarrie Canada Ltd has introduced basalt fabrics into the North American filtration market under their trademark Meteor™. Unfortunately, I have no additional data beyond the previously cited property comparisons between E-glass and CFB to data to substantiate the expected improvements in acid and abrasion resistance.

IX Summary

Continuous filament basalt is a fiber that brings value to several markets that currently use fiberglass, ceramic fibers or asbestos replacement materials. Basalt's mechanical and physical properties bring the possibility for upgrading the performance of thermal insulation blankets for use at 540-820°C (1,000-1,500°F), high temperature friction materials in clutches and brakes and structural composites requiring a high strength to weight ratio and /or chemical resistance. Continuous basalt is priced mid-way between standard E-glass and S-glass with properties that can exceed those of both.