*ECCM15 -16$^{TH}$ EUROPEAN CONFERENCE ON COMPOSITE MATERIALS, Seville, Spain, 22-26 June 2014*

# MECHANICAL CHARACTERIZATION OF UNIDIRECTIONAL BASALT FIBER EPOXY COMPOSITE

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**Keywords:** basalt fiber, polymer matrix, mechanical characterization, rail test, tensile test, elastic properties

## Abstract

Basalt fibers present more recent development compared to traditional fibers used in the manufacture of polymer composites, such as glass, aramid and carbon fiber. Some properties, such as strength and modulus, for instance, are located between those offered by E-glass and S-glass fibers. Also show higher working temperature, good chemical and impact resistance, and low outgassing in burning. In addition, their low price – may be lower than that of E-glass fibers–could be another attractive to increase their use. However, there are still few studies in the literature with this reinforcement if compared with glass fiber. To design new components with basalt fiber and also to performing numerical analysis, the input data required need to be well determined and among them there are the elastic properties. The aim of this work is to determine mechanical and elastic properties of basalt/epoxy composites following the ASTM standard. Tensile test was carried out at laminated specimens in longitudinal and transversal fiber directions and in-plane shear test. The panels were manufactured by a filament winding process and not only the fiber content was obtained for all panels but also the glass transition temperature of the epoxy matrix.

## 1. Introduction

Composite materials are produced to optimize the material properties, including mechanical, chemical and physical, as well as optical and acoustic, electrical and thermal properties. They are manufactured employing a fiber that exerts the structural function and a polymer matrix that performs the task of binding and protecting fibers, and also act as loading distribution element, leading it to the fibers.

Basalt is volcanic mineral, dark or black. Its rocks are heavy, tenacious and resilient. Its density is about 5% higher than the glass. It's the most abundant crustal rock and the seabed is predominantly composed of basalt. The chemical composition of the basalt is variable according to the mineral deposit. The weight percentage of the constituent oxides: SiO2, 48.8 to 51; Al2O3, 14 to 15.6, CaO, ≈ 10; MgO, 6.2 to 16; FeO + Fe2O3, 7.3 to 13 3, TiO 2, 0.9-1.6, MnO, 0.1 to 0.16; Na2O + K2O, 1.9-2.2 (2)

The use of basalt fiber (BF) as reinforcement in polymer matrix composites is relatively new compared to popular glass fibers (GF) and carbon fibers. The first trials to produce basalt fiber refer to the year 1923, when the French Paul Dhé was granted a U.S. patent. After World War II, researches were developed in the U.S., Europe and the Soviet Union to get the fibers extruded and, at this time, the first applications were studied in military and aerospace fields. Only after 1990/92, with the dissolution of Soviet Union, its production technology became public domain, and civilian research begun (3) (4).

The production of fibers was, however, only developed in recent decades. Current technology for producing BF is very similar to that used in E-glass fiber production, but requires less power to be produced (4). This fact, coupled with the high availability of raw material around the world, justifies the low price of BF compared to GF. The main difference between the BF and GF is the raw material used. GF are produced from various components, while BF is made with the fusion of basalt rock without other additives. The fact of being environmentally friendly makes BF use very attractive and unlike GF, BF does not require additives in their production. The replacement of GF by BF can reduce the risk of environmental pollution with and highly toxic metals and oxides, which are generated in the production of GF (5). Moreover, BF is an alternative to asbestos fibers, banned for being carcinogenics.

Furthermore, BF has high resistance to acids and solvents, overcoming E-glass fibers and many other mineral and synthetic fibers, nevertheless having less acid resistance than E-glass fibers. Its moisture absorption is less than 0.2% at room temperature and relative humidity of 65%. Have excellent wet ability for various binders, coatings and matrices. The goal of this work is to obtain mechanical properties of unidirectional laminates in fiber direction (0°) and transverse direction (90º), as well as composites volume fractions and polymer matrix glass transition temperature.

## 2. Materials and Method

### *2.1. Basalt Fiber-properties and application*

BF is highly competitive with FV, mainly in comparison to mechanical properties, besides to overcome them in certain properties - in particular as water resistance and chemical stability. In various forms of presentation, whether as twisted and non-twisted filaments, yarns, fabrics or mats, BF represent a promising alternative as a reinforcement element for composite materials. Furthermore, have been applied to the resolution of a number of specific problems, for example, for preparation of composites with project requirements that need different loads and deformations in many directions and orientations; in that case, producing a hybrid composite with GF (high resistance) and carbon fibers (high strength and high modulus) (Chikhradze et al. 2012).

The application of BF is possible in many areas thanks to its multiple and good properties. It exhibits excellent resistance to alkalis, similar to GF, at a much lower cost than carbon and aramid fibers. Its thermal properties make them excellent substitutes for high temperature resistant fibers (carbon fibers) and is commonly used in the manufacture of heat shields, heat insulating barriers and articles for fire protection – in addition to working temperature markedly higher than GF, from -260 °C to 700 °C, against -60 °C to 250 °C for glass (4).

The vibration damping of BF is much higher than of GF, which made them suitable for applications under high loads and acoustic vibrations, such as in structures where such conditions exist, for example, in the aerospace and marine industry (4). Its high water resistance also explains the wide application in the marine industry, as in production of boat hulls. For their good electrical insulation properties (10 times greater than glass) (4), BF are used in printed circuit boards, extra-thin insulation for electrical cables and underground pipelines. Regarding the mechanical properties of the BF in comparison of glass fiber and carbon fiber, as shown in Table 1, elastic modulus and tensile strength of BF exceeds the GF in around 11% (resistance) and 15% (modulus).

| | **Basalt fiber (6)** | **E-glass fiber (7)** | **Carbon fiber (7)** |
|---|---|---|---|
| **Tensile strength [MPa]** | 2800-4800 | 3450 | 3500 |
| **Elastic modulus [GPa]** | 89 | 72,4 | 240 |
| **Elongation at break [%]** | 3,1 | 4,7 | 1,25 |
| **Density [g/cm$^3$]** | 2,8 | 2,6 | 1,75 |

**Table 1.** Comparison of fibers properties.

One of the possible applications of BF is in manufacturing of compressed natural gas cylinders. Kamenny Vek performed tests in order to compare the mechanical properties of cylinders made of epoxy matrix composite reinforced with basalt fiber (FB), E-glass fiber (E-GF) or carbon fiber (CF), using the filament winding technique. A possible method of manufacturing these cylinders used as a metallic liner mold (mandrel) which is reinforced in its outer surface with winding the BF filament impregnated with epoxy resin, as illustrated in Figure 1 (6).

### *2.2. Filament Winding Technique*

The better use of fiber properties applied as continuous reinforcement occurs when they are requested in its longitudinal direction. Filament winding technique stands out as the manufacturing process that makes better use of this advantage. Components manufactured by this process aim to achieve one of the highest strength-to-weight ratios between materials used for structural applications. However, to ensure this result, it is necessary that the fiber direction is in the principal stresses direction, and at the same time to use matrix reinforcement fraction proportional to these stresses magnitude.

**Figure 1.** Compressed natural gas cylinder reinforced with epóxi/BF and BF roving (6).

Filament winding technique consists in deposition of continuous filaments impregnated with resin onto a mold or rotary cylinder, using a computer numerical control (CNC). The basalt filament bobins (rovings) are placed in a holder with tension control of filament. The filaments released from the system pass through a heated bath of matrix (resin-curing agent-accelerator) equipped with a temperature control. The mold remains in a horizontal position and rotates pulling the filament, while the car has longitudinal movement parallel to the mandrel axis. The winding parameters such as filament tension, die angular velocity and longitudinal velocity of the car are controlled by the CNC. The coordinate movement of these two axis establishes the fiber deposition angles over the mandrel. An illustration of a filament winding machine with two freedom degrees is shown in Figure 2. It is recommended that the production environment has controlled temperature and humidity.

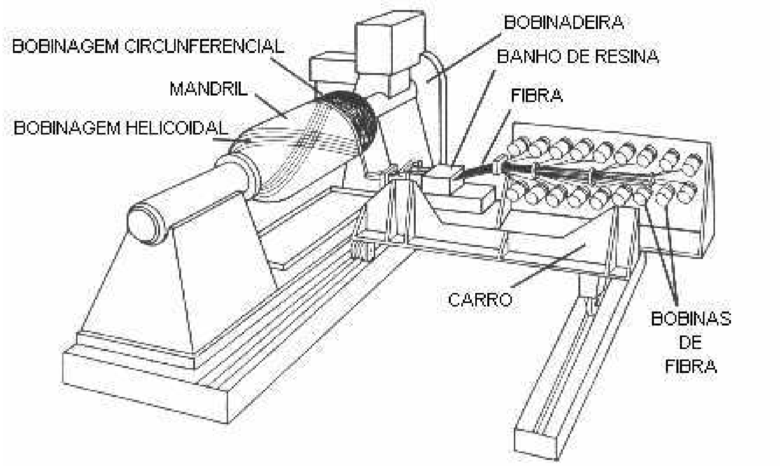

**Figure 2.** Filament winding machine (8).

Filament winding is one of the most efficient methods to manufacture cylindrical structures. Pipes, tanks, gas cylinders, cylinder shells, rockets and missiles are among structures fabricated by this process. Other highlighted features of the process are the possibility of obtaining high fiber volume fractions (60-75%), possibility of large parts fabrication, producing smooth inside structures and still to require little manual labor, with great possibility of automation. Some limitations of the process are associated with relatively high investment, shape limitation of parts (without dimples) and require skilled labor[9].

### 2.3 *Method*

A unidirectional basalt/epoxy composite was manufactured wound the fiber onto a spindle-shaped flat rectangular metallic mandrel with two working faces, that was internally heated up to 70ºC. The BF was supplied by Kammeny Vek in continuous filament with a linear density of 1200 tex, made from fibers of 13 μm diameter, with silane agent sizing compatible with epoxy and phenolic resins. The mandrel was coated with an impermeable adhesive film to ensure efficient composite demolding, as can be seen in figure 3.

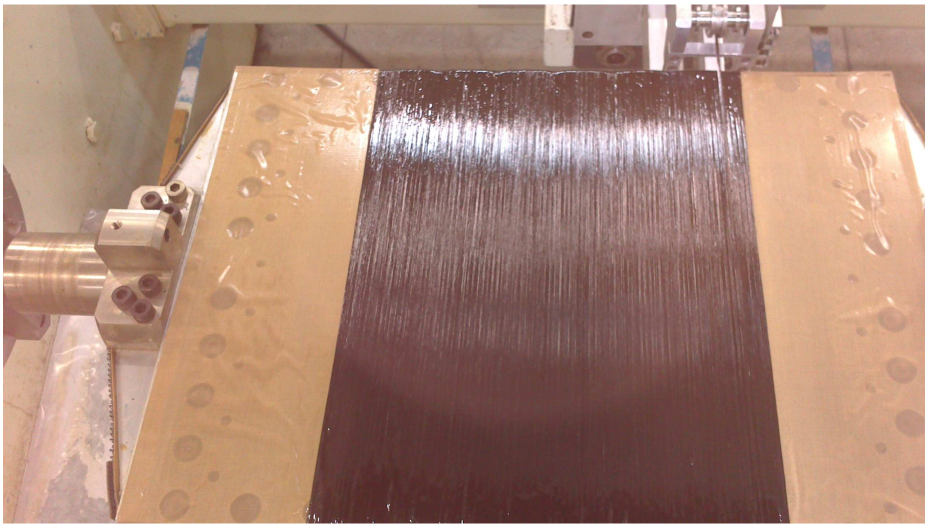

**Figure 3.** A basalt fiber panel manufactured by a filament winding technique.

After the process the mold is pressed in both sides with flat and polished steel plates (caul plates), as shown in Figure 4, provided with end stops fixed by bolts at their ends. In order to produce panels with the desired thickness, the end stops determine the thickness of the panels, which were produced with 1 and 2 mm in accordance ASTM 3039. The set mold-press panel was taken to oven for a curing cycle of 11h, reaching a maximum temperature of 130°C, with slow cooling in the air at oven.

The 1 mm thickness panels were laid with $[0_4]_T$, and the 2 mm ones $[90_8]_T$. The panels were thermal cured with the last step at 130ºC. Specimens were cut using a diamond saw and the final dimension were 250 x 15 x 1 mm for 0º and of 175 x 25 x 2 for 90º. A sketch, on Figure 5, shows the 90º specimens on the panel where they were cut off. Both, mandrel and resin bath were kept at the same temperature during the winding process

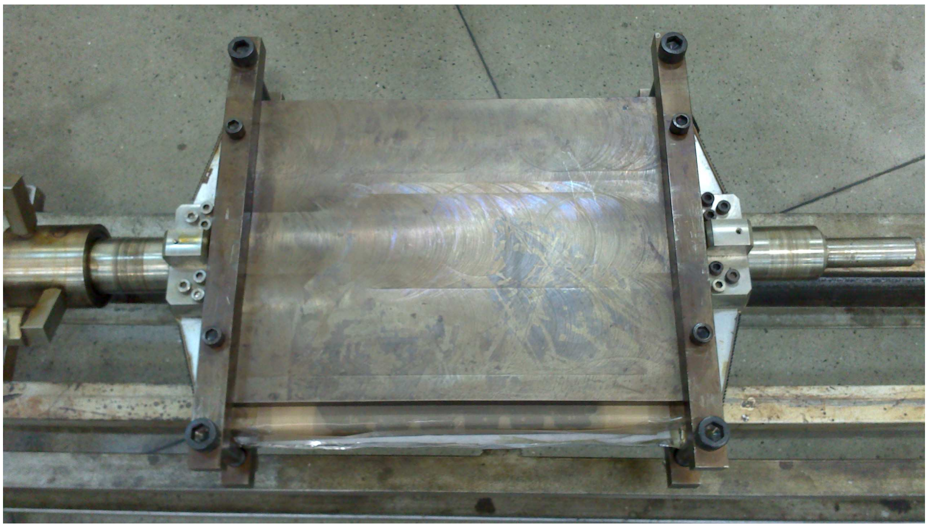

**Figure 4.** The set mold-press panels.

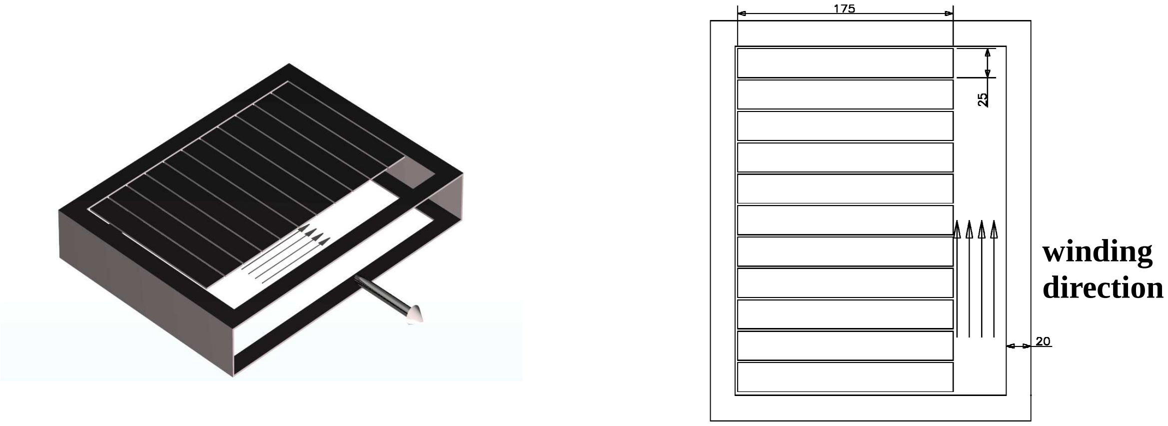

**Figure 5.** Basalt/epoxy panel sketch and transversal cutting direction of the specimens.

## 3. Results

To obtain the Poisson ratio for the specimens, the strains in the longitudinal and in the transversal directions were determined by means of an optical extensometer (specimens 1,2 and 3) and a bidirectional extensometer (specimens 4 and 5) for both longitudinal (0º) and transversal direction (90º).

| Specimen | Load (N) | Ultimate Tensile Stress (MPa) | Modulus of Elasticity (MPa) | Poisson Ratio (chord 0.10%-0.60%) | Strain (%) | Failure Mode |
|---|---|---|---|---|---|---|
| 01 | 24213 | 1663 | 50 | 0.222 | 3.48 | XGM |
| 02 | 23640 | 1640 | 48 | 0.209 | 3.36 | MGM |
| 03 | 21803 | 1518 | 48 | 0.173 | 3.07 | SGM |
| 04 | 22572 | 1568 | 50 | 0.293 | - | MGM |
| 05 | 22000 | 1546 | 52 | 0.290 | - | XGM |
|  | 22846 | 1587 | 50 | 0.237 |  | - |
|  | 1046 | 62 | 1.5 | 0.05 |  | - |

**Table 2.** Experimental properties of basalt/epoxy composites specimens in the longitudinal direction (0º).

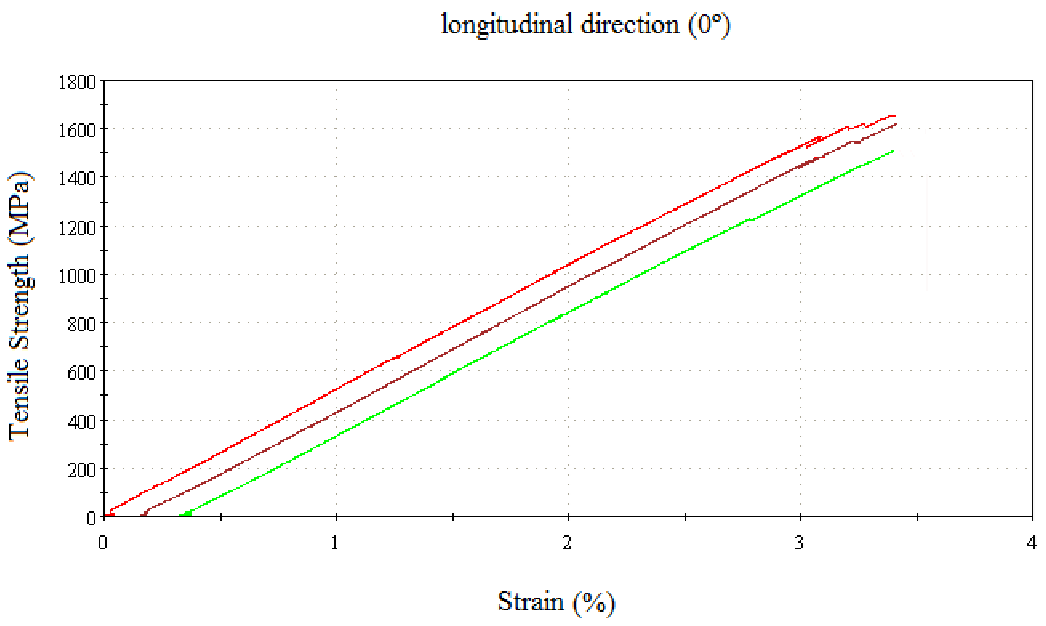

**Figure 5**. Tensile strength versus strain curve for basalt/epoxy composite specimens 1, 2 and 3 in the longitudinal direction (0°).

| Specimen | Load (N) | Ultimate Tensile Stress (MPa) | Modulus of Elasticity (MPa) | Poisson Ratio (chord 0.10%-0.25%) | Strain (%) | Failure Mode |
|---|---|---|---|---|---|---|
| 01 | 2137 | 45 | 23 | 0.447 | 0.31 | LAT |
| 02 | 2026 | 42 | 23 | 0.409 | 0.30 | LAT |
| 03 | 2106 | 44 | 27 | 0.736 | 0.26 | LAT |
| 04 | 2796 | 58 | 16 | - | 0.36 | LAT |
| 05 | 2636 | 55 | 15 | - | 0.35 | LAT |
|  | 2340 | 49 | 21 | - | 0.32 | - |
|  | 350 | 7 | 5 | - | 0.04 | - |

**Table 3.** Experimental properties of basalt/epoxy composites specimens in the transversal direction 90°).

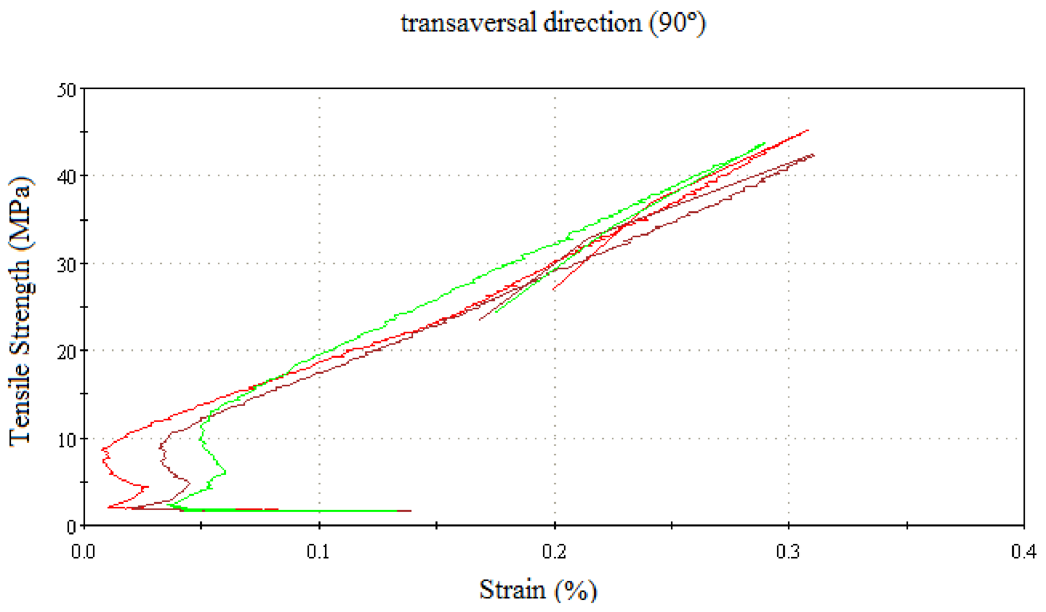

**Figure 6**. Tensile strength versus strain curve for basalt/epoxy composite specimens 1, 2 and 3 in the transversal direction (90°).

All tensile tests are performed following ASTM D3039/D3039M standard[10]. The tables 2 and 3 show the properties respectively in longitudinal and transversal directions, with the curves of these tests in figures 5 and 6. The terminology in the last column of the tables 2 and 3, in accordance ASTM 3039, defines de mode and location of failure of the specimen. For instance, XGM (specimen 1 of longitudinal direction test in Table 2) means e**X**plosive, **G**age, **M**iddle, representing that the failure was as a sorceress's broom and the failure happened in the gage length of the specimen, in the middle position.

## CONCLUSIONS

Comparing the average values of Tables 2 and 3 with those presented by Leitão, 2007[11], considering fiber glass-E, as shown in Table 4, the basalt/epoxy composite shows a tensile stress 15% higher than glass fiber-E/epoxy composite in the longitudinal direction (0º) and the same modulus of elasticity. In transversal direction, tensile stress of the basalt fiber/epoxy composite is 22% higher and the modulus of elasticity 23% also higher than fiberglass-E/epoxy composite.

| basalt/epoxy composites fiber fraction 60-65% | Ultimate Tensile Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|
| 0º | 1587±62 | 50±1.5 |
| 90º | 49±7 | 21±5 |

| glass fiber-E/epoxy composites fiber fraction 60-65% | Ultimate Tensile Stress (MPa) | Modulus of Elasticity (MPa) |
|---|---|---|
| 0º | 1369±35 | 50±1 |
| 90º | 40±3 | 17±1 |

**Table 4.** Experimental properties of basalt/epoxy composites compared with glass fiber-E/epoxy specimens.

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