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A review on basalt fibre and its composites

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ABSTRACT

In recent years, both industrial and academic world are focussing their attention toward the development of sustainable composites, reinforced with natural fibres. In particular, among the natural fibres (i.e. animal, vegetable or mineral) that can be used as reinforcement, the basalt ones represent the most interesting for their properties. The aim of this review is to illustrate the results of research on this topical subject. In the introduction, mechanical, thermal and chemical properties of basalt fibre have been reviewed. Moreover, its main manufacturing technologies have been described. Then, the effect of using this mineral fibre as reinforcement of different matrices as polymer (both thermoplastic and thermoset), metal and concrete has been presented. Furthermore, an overview on the application of this fibre in biodegradable matrix composites and in hybrid composites has been provided. Finally, the studies on the industrial applications of basalt fibre reinforced composites have been reviewed.

1. Introduction

Basalt is a natural material that is found in volcanic rocks originated from frozen lava, with a melting temperature comprised between 1500° and 1700 °C [1,2]. Its state is strongly influenced by the temperature rate of quenching process that leads to more or less complete crystallization.

Perhaps 80% of basalts are made up by two essential minerals; i.e. plagiocene and pyroxene.

Analyzing the chemical composition it is possible to observe that SiO_2 is the main constituent and Al_2O_3 is the second one [1,3,4]. In Table 1 is reported the typical composition, as identified by Militky et al. [1] and Deák et al. [3].

Basalt fibre, which was developed by Moscow Research Institute of Glass and Plastic in 1953–1954, is a high-tech fibre invented by the former Soviet Union after 30 years of research and development, and its first industrial production furnace that adopted 200 nozzles drain board combination oven bushing process was completed in 1985 at Ukraine fibre laboratory [5].

The base cost of basalt fibres varies in dependence of the quality and type of raw material, production process and characteristics of the final product. As the cost, the chemical and mechanical properties depend from the composition of the raw material. Differences in terms of composition and elements concentration give difference in thermal and chemical stability and more or less good mechanical and physical properties [6].

Overall, the manufacturing process of this kind of fibre is similar to that of glass fibre, but with less energy consumed and no additives, which makes it cheaper than glass or carbon fibres. Using a natural volcanic basalt rock as raw material, basalt fibre is produced by putting raw material into furnace where it is melted at 1450–1500 °C. After this, the molten material is forced through a platinum/rhodium crucible bushings to create fibres. This technology, named continuous spinning, can offer the reinforcement material in the form of chopped fibres or continuous fibres, that can be used in the textile field manufacturing process and have a great potential application to composite materials. In addition to the ability to be easily processed using conventional processes and equipments, the basalt fibres do not contain any other additives in a single producing process, which makes additional advantage in cost [7].

Blowing melt technologies are proposed for the production of short and cheap basalt fibres characterized by poor mechanical properties [3]. Continuous basalt fibres are produced by spinneret method (see Fig. 1) similarly to glass fibres. Recently, Kim et al. [8] proposed melt-spinning method based on dielectric heating in order to produce fibres on laboratory scale.

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Table 1
Typical composition of basal fibres (as reported by different authors [1,3]).

Constituent	Content [wt%]	
	[1]	[3]
SiO_2	43.3–47	42.43–55.69
Al_2O_3	11–13	14.21–17.97
Fe_2O_3	<5	10.80–11.68
CaO	10–12	7.43–8.88
MgO	8–11	4.06–9.45
Na_2O	<5	2.38–3.79
TiO_2	<5	1.10–2.55
K_2O	<5	1.06–2.33

The increasing application of basalt fibre raised the question whether basalt fibre is harmful to health.

Even if asbestos and basalt fibres present similar composition, basalt seems to be safe, because of different morphology and surface properties avoid any carcinogenic or toxicity effects, which are presented by asbestos instead [9,10]. In particular, Kogan et al. [11] made rats inhale air containing asbestos and basalt fibres for 6 months. In the case of asbestos fibres at a dose of 1.7 g kg^{-1} (referred to the body weight of the rat), one third of the animals died, while a dose of 2.7 g kg^{-1} killed all the rats. In the case of the basalt fibre, all the animals survived even when the dose reached the 10 g kg^{-1} concentration. Similar investigations were conducted by McConnell et al. [12] and they also concluded that basalt fibres pose no risk to human beings.

It is know that the fibrous fragments with diameter (d) of 1.5 μm or less and length (l) of 8 μm or greater should be handled and disposed of using the widely accepted procedures for asbestos. Fibres falling within the following three criteria are of concern [13]:

- fibres with diameters lower than 1.5 μm (some say <3.5 μm) remain airborne and are respirable;
- fibres with an l/d aspect ratio higher than 3 do not seem to cause the serious problems associated with asbestos;
- fibres durable in the lungs do not cause problems if they are decomposed in the lungs.

Since most of nonpolymeric fibres have diameter significantly higher than 3.5 μm but break into long thin pieces, emission of particles, including fibres, occurs during handling. For simulation of these phenomena, the abrasion of basalt weaves was made by Militký et al. [1]. The experimental results showed that, because the mean value of fibre fragment diameter is the same as diameter of fibres, no splitting of fibres during fracture occurs. The aspect ratio l/d of basalt fibre fragments is equal to 20.8, higher than the critical value.

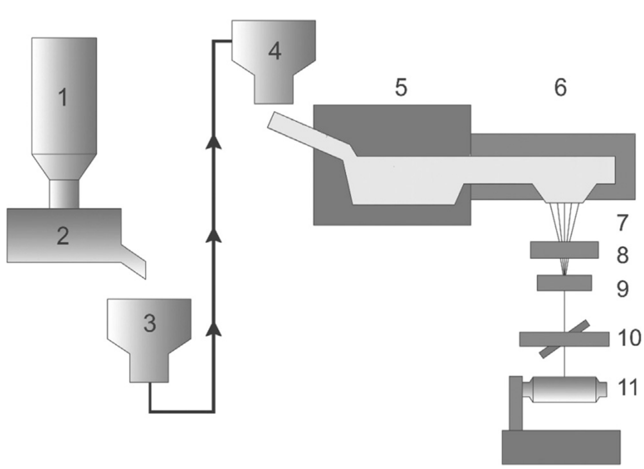

Fig. 1. A simplified scheme of a basalt fiberization processing line: 1) crushed stone silo; 2) loading station; 3) transport system; 4) batch charging station; 5) initial melt zone; 6) secondary heat zone with precise temperature control; 7) filament forming bushings; 8) sizing applicator; 9) strand formation station; 10) fibre tensioning station; 11) automated winding station (reproduced with permission from [3]).

Overall basalt fibres show several advantages, which make them a good alternative to glass fibres as reinforcing material in composites used in several fields such as marine, automotive, sporting equipment, civil, etc. In particular, basalt fibres have mechanical properties similar to those of glass ones (see Table 2).

Moreover, basalt fibres are non-combustible, they have high chemical stability [4,15], and good resistance to weather, alkaline and acids exposure. Moreover, basalt fibres can be used from very low temperatures (i.e. about −200 °C) up to the comparative high temperatures (i.e. in the range 600–800 °C) [3,7,16–18].

The thermal stability that depend from the composition of the raw material and the presence of a large amount of micro-pores that prevent convection and thermal radiation of the air are reasons to think to use basalt fibres fabrics in thermal insulation and passive fire protection applications [6,19,20].

In particular, the thermal gravimetric analysis performed by Hao and Yu [20] shows that the mass loss occurs in the temperature range of 200–350 °C for both basalt and glass fibres (Fig. 2). However, the basalt fibre has better thermal stability than glass fibre. In Table 3 the parameters of thermal decomposition of the fibres from analysis of TG curves are reported (T_o the onset temperature of the decomposition, T_i the temperature at which the mass loss is maximal, T_t the terminal temperature of the decomposition).

The main factor determining the heat temperature stability of basalt fibres is their crystallization behaviour. Crystallization ability primarily depends on fibre chemical composition as well as heat treatment conditions. In particular, due to its high content of iron oxides, crystallization in basalt fibre begins with oxidation of ferrous cations and formation of spinel structure phase on the fibre surface: i.e. divalent cations (Ca^{2+}, Mg^{2+}, Fe^{2+}) diffuse from the interior to the surface where they react with environmental oxygen forming nanocrystalline layers CaO, MgO, $(Mg,Fe)_3O_4$. Moreover, with increasing temperature the crystallization of pyroxene phases takes place on the spinel crystals, which act as nucleation sites. The crystallization of continuous basalt fibre during heat treatment was studied in details [21,22]. It is worth nothing that the crystallization ability of basalt fibre can be selectively controlled by doping with other elements: for instance, the effect of zirconium oxide on the crystallization and thermal stability of basalt fibres was analyzed by Lipatov et al. [23].

For the first time, the chemical durability of basalt fibre was studied by Ramachandran et al. as early as 1981 [24]. The authors stated that this fibre has excellent resistance to alkaline attack, but it has poor resistance to acids. The better mechanical behaviour of the basalt fibres than glass ones after corrosion treatments was then shown by Nasir et al. [25]. Even if the corrosion mechanism is

Table 2
E-Glass and basalt fibres properties compared (reproduced with permission from [14]).

	E-glass	Basalt
Density (g/cm^3)	2.56	2.8
Elastic modulus (GPa)	76	89
Tensile strength (GPa)	1.4–2.5	2.8
Elongation to fracture (%)	1.8–3.2	3.15
Specific E modulus (GPa per g/cm^3)	30	31.78
Specific tensile strength (GPa per g/cm^3)	0.5–1	1