ORIGINAL ARTICLE

INTERNATIONAL JOURNAL OF ARTIFICIAL INTELLIGENCE

ISSN: 2692-5206, Impact Factor: 12,23

American Academic publishers, volume 05, issue 10,2025

Journal: https://www.academicpublishers.org/journals/index.php/ijai

CHEMICAL COMPOSITION AND PRODUCTION TECHNOLOGY OF BASALT FIBERS

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Abstract. Basalt fibers are high-performance inorganic materials obtained from naturally occurring volcanic rocks. Due to their excellent combination of mechanical strength, thermal stability, and chemical resistance, basalt fibers have become one of the most promising reinforcements for polymer and metal matrix composites in the automotive, aerospace, construction, and energy industries. This paper investigates the chemical composition and production technology of continuous basalt fibers, emphasizing their dependence on the mineralogical composition of raw basalt and the processing conditions. The study applies X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM) to determine the chemical and structural parameters of basalt melts. The melting and fiber-drawing processes are discussed with respect to viscosity, temperature control, and crystallization behavior. Results demonstrate that basalt fibers typically contain 45–55% SiO_2, 14–18% Al_2O_3, 8–12% Fe_2O_3, 5–10% CaO, 3–5% MgO, and minor alkali oxides ($Na_2O + K_2O$ up to 5%). The optimal melting range of basalt glass is 1350–1500°C, with a viscosity window of 35–55 Pa·s enabling stable filament formation. The study concludes that by adjusting the chemical ratios and controlling crystallization kinetics, it is possible to produce fibers with tensile strength of 3.5–4.8 GPa and elasticity modulus of 85–95 GPa, suitable for advanced automotive composite structures.

Keywords: basalt fibers, chemical composition, production technology, viscosity, silicate melt, composite materials, automotive industry.

1. Introduction

The increasing demand for lightweight, durable, and environmentally sustainable materials in modern engineering has accelerated the research into inorganic fiber reinforcements, particularly those derived from natural minerals. Among these, basalt fibers have gained significant attention over the past two decades due to their outstanding thermal and mechanical properties, combined with the abundance and low cost of their raw material — basalt rock, a volcanic silicate material rich in iron, magnesium, and calcium oxides.

Basalt fibers are produced directly from molten basalt, without the need for additional chemical additives. This feature distinguishes them from glass fibers, which require precise batching and melting of multiple minerals (silica sand, alumina, limestone, boron oxide, etc.). The production simplicity and eco-friendliness make basalt fibers an environmentally responsible alternative to glass and carbon fibers, especially for structural applications in the automotive industry.

Chemically, basalt is a natural mixture of silicates with a high content of SiO_2 (silica), typically ranging from 45 to 55 wt.%, which serves as the main glass-forming oxide. Al_2O_3 (alumina) acts as a network stabilizer, improving the viscosity and durability of the melt. The presence of Fe_2O_3 (iron oxide) contributes to thermal conductivity and coloration, while CaO and MgO increase crystallization resistance and mechanical strength. Small quantities of Na_2O, K_2O, and TiO_2 enhance fiber flexibility and resistance to thermal shock.

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The advantages of basalt fibers over other fibers are remarkable. They exhibit a tensile strength of 3000–4800 MPa, an elastic modulus of 85–95 GPa, a density of 2.65–2.8 g/cm³, and a working temperature limit of up to 800–900°C. Furthermore, their corrosion resistance, non-flammability, and excellent insulation properties make them ideal for use in automotive body panels, heat shields, and brake components, where both lightweight and durability are crucial.

Despite these advantages, the large-scale industrial production of basalt fibers remains limited compared to traditional glass fibers. This is primarily due to the complexity of controlling melt viscosity, the variability of raw basalt composition, and the need for specialized platinum-rhodium drawing bushings that withstand high temperatures and chemical aggressiveness of the melt. Therefore, a detailed understanding of chemical composition–property relationships and optimized production parameters is essential for the reliable and cost-effective manufacture of basalt fibers.

The objective of this study is to analyze the chemical composition and production technology of basalt fibers, determine the optimal processing conditions for stable fiber formation, and highlight the influence of raw material composition on the physical and mechanical properties of the resulting fibers.

2. Materials and Methods

2.1. Raw Materials

The basalt used in this research was obtained from Andijan (Uzbekistan) volcanic deposits, characterized by a high content of silicate minerals. Chemical analysis revealed the following average composition (wt.%):

SiO_2 — 49.8, Al_2O_3 — 15.6, Fe_2O_3 — 10.2, CaO — 8.3, MgO — 4.1, $Na_2O + K_2O$ — 3.7, TiO_2 — 1.3, and minor impurities <0.5%.

These values correspond to calc-alkaline basalts suitable for fiber production due to their low crystallization tendency and balanced viscosity-temperature profile.

The raw material was crushed and screened into 5–10 mm particles for uniform melting.

2.2. Fiber Production Process

The production of basalt fibers involves five main stages:

Crushed basalt is melted in an electric resistance furnace at 1400–1500°C until a fully homogeneous melt is achieved. The viscosity of the melt is continuously monitored; the optimal range for fiber drawing is 40–55 Pa·s at 1350°C.

Gas inclusions and unmelted particles are removed through settling and filtration in a platinum-rhodium crucible.

The molten basalt passes through platinum bushings with nozzle diameters of 0.8–1.2 mm, forming continuous filaments of 9–17 µm diameter.

The filaments are air-cooled at 200–300°C and wound onto spools at a linear speed of 1–2 km/min.

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The fibers are coated with a silane-based coupling agent (typically 1–2 wt.%) to improve adhesion with polymer matrices.

2.3. Analytical Methods

X-ray Fluorescence (XRF) was used to determine the oxide composition using a Spectro XEPOS spectrometer.

X-ray Diffraction (XRD) analysis was performed on a Rigaku Ultima IV diffractometer (CuKα radiation, $2\theta = 20–80°$) to identify crystalline and amorphous phases.

Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) were carried out using a NETZSCH STA 449F3 to study melting and crystallization behavior up to 1000°C.

Scanning Electron Microscopy (SEM) was conducted on a JEOL JSM-7001F microscope to examine surface morphology and fiber diameter uniformity.

Viscosity Measurements were taken using a Rotational High-Temperature Viscometer at 1250–1500°C to define the optimal fiber-drawing window.

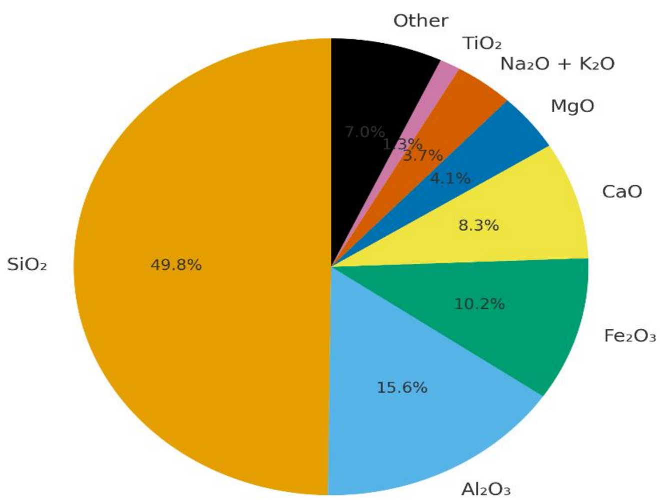
3. Results and Discussion

3.1. Chemical Composition and Phase Structure

The XRF results confirmed that the studied basalt samples fall within the typical compositional range suitable for fiber production. The dominance of SiO_2 and Al_2O_3 ensures good glass-forming ability, while the moderate content of Fe_2O_3 and CaO provides sufficient fluidity.

XRD patterns revealed a predominantly amorphous halo between 25–35° 2θ, indicating glassy structure formation, with minor crystalline phases of plagioclase $(Na,Ca)(Si,Al)_4O_8$ and pyroxene $(Mg,Fe)SiO_3$.

Fig. 1. Average chemical composition of basalt fibers



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The chemical composition thus ensures a balanced melt viscosity, minimizing premature crystallization during fiber drawing. The minor presence of TiO_2 and alkalis further enhances melt stability.

3.2. Melting and Fiber Formation Parameters

The basalt melt displayed stable behavior within the temperature range of 1350–1450°C. Below 1300°C, viscosity exceeded 70 Pa·s, preventing smooth filament formation. Above 1500°C, excessive fluidity ($\eta < 30$ Pa·s) caused filament breakage. The optimal working viscosity window was determined at 40–50 Pa·s.

Continuous fiber formation was achieved with drawing rates of 800–1200 m/min, producing fibers of 9–13 µm average diameter. SEM images (Figure 2) confirmed the absence of microvoids or inclusions, with smooth surfaces favorable for matrix adhesion.

3.3. Thermal Behavior

DSC curves revealed two main endothermic peaks:

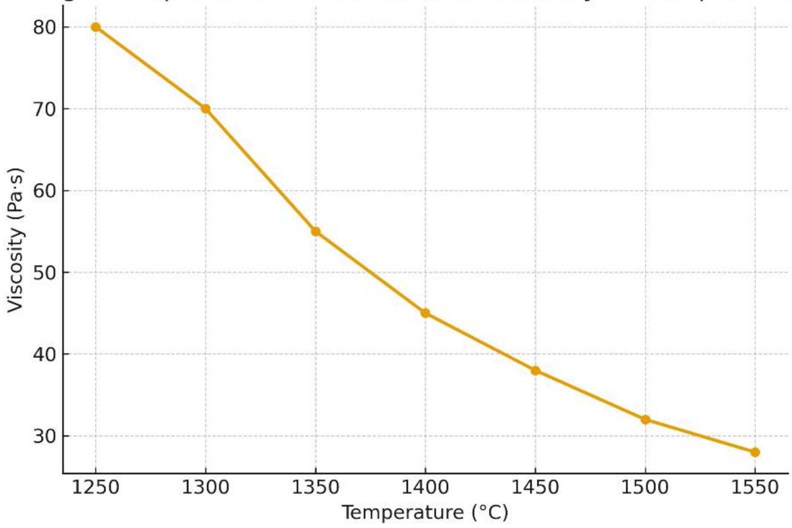
First at 720–750°C, corresponding to glass transition and onset of viscous flow;

Second at 1350–1380°C, corresponding to complete melting.

No significant exothermic crystallization peaks were observed up to 950°C, confirming high thermal stability and low devitrification tendency.

The coefficient of thermal expansion (CTE) measured at $(7.5 \pm 0.2) \times 10^{-6}$ K^{-1} and thermal conductivity ranged between 1.2–1.4 W/m·K, indicating suitability for thermal insulation and high-temperature applications.

Fig. 2. Dependence of basalt melt viscosity on temperature



3.4. Mechanical Properties

The tensile strength of single basalt filaments averaged 4100 MPa, with an elastic modulus of 91 GPa and elongation at break of 3.1%. These values surpass those of E-glass fibers (3500 MPa, 75 GPa) while maintaining similar density.

The mechanical properties correlate strongly with the SiO_2/Al_2O_3 ratio and cooling rate — faster cooling yields higher amorphous content and improved strength due to the suppression of crystalline defects.

3.5. Technological Considerations

The successful production of high-quality basalt fibers depends on:

Uniform raw basalt composition to prevent viscosity fluctuations;

Controlled cooling and drawing rates to maintain filament uniformity;

Proper surface sizing to enhance compatibility with resins and prevent static charge accumulation during winding.

The melting furnace design plays a crucial role: electric furnaces offer better control and lower contamination compared to gas-fired ones, though at higher operational cost.

Recycling of waste fibers into chopped mats or hybrid composites contributes to the environmental sustainability of the technology.

4. Conclusion

Basalt fibers are produced directly from natural basalt rock containing 45–55% SiO_2, 14–18% Al_2O_3, 8–12% Fe_2O_3, and minor CaO, MgO, and alkali oxides.

The optimal melting temperature for fiber formation is 1350–1450°C, where melt viscosity remains within 40–55 Pa·s, allowing continuous filament drawing.

The resulting fibers exhibit high tensile strength (3.5–4.8 GPa), modulus (85–95 GPa), and thermal resistance up to 900°C.

Proper control of raw material homogeneity, melting conditions, and cooling rate ensures minimal crystallization and excellent surface morphology.

The combination of thermal stability, chemical durability, and mechanical strength makes basalt fibers ideal for automotive composite materials, particularly in lightweight structural components.

Further optimization of surface treatment and melt filtration can enhance fiber uniformity and adhesion with polymer matrices, paving the way for large-scale industrial adoption.

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