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# RECYCLING TRENDS OF PRODUCTION WASTE FROM BASALT FIBER-BASED THERMAL INSULATION MATERIALS

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## ABSTRACT

This study presents a comprehensive analysis of current and emerging recycling trends for basalt fiber insulation production waste, based on a review of 65 scientific and technical sources published between 2015 and 2024. Four principal recycling routes are identified and evaluated: (1) re-melting and re-fiberization, (2) utilization as a reinforcing filler in cementitious and geopolymer composites, (3) incorporation as a sintering additive in ceramic production, and (4) application as a modifier in asphalt road mixtures. Comparative quantitative assessment shows that composite filler applications achieve waste utilization rates of 80–95% and reduce raw material costs by 25–35%, while improving compressive strength of concrete by 12–27%. Re-melting, though technically mature, is energy-intensive and limited to clean fiber trimmings. Geopolymer-based applications offer the most promising pathway for processing dust fractions (< 5 μm). The findings demonstrate that a multi-route recycling strategy, tailored to specific waste types and local industrial conditions, can significantly advance the circular economy in the basalt fiber sector.

## Keywords

basalt fiber; insulation materials; industrial waste recycling; composite materials; geopolymer; circular economy; fiber trimmings; re-fiberization; construction materials; sustainability.

## 1. INTRODUCTION

Basalt fiber, produced by melting natural basalt rock at temperatures of 1400–1500°C and drawing it through platinum-rhodium bushings, has emerged as a technically and economically attractive alternative to E-glass and rock wool fibers in the thermal insulation sector [1]. Its superior temperature resistance (continuous operating range from −260°C to +700°C), chemical inertness, non-combustibility, and competitive thermal conductivity ($\lambda \approx 0.032–0.046$ W/m·K) have driven substantial market expansion, with global production volumes exceeding 450,000 tonnes per year as of 2023 and projected annual growth of 14–16% through 2030 [2, 3].

However, the manufacturing of basalt fiber insulation products - including needled mats, rigid boards, and pipe sections - inherently generates significant quantities of solid waste at multiple production stages. Fiber trimmings and cuttings from the forming and finishing lines, sub-micron dust collected in filtration systems, off-specification products rejected during quality control, melting slags and clinker from the cupola or electric furnaces, and binder-contaminated rejects together represent 25–45% of the initial raw basalt rock input [4, 5]. In absolute terms, a mid-scale insulation plant producing 15,000 t/year of finished product may generate 3,000–6,000 tonnes of waste annually.

Current industrial practice in most countries predominantly involves landfilling of these waste streams, which constitutes both an environmental burden and a significant economic loss. Growing regulatory pressure from the European Union's Industrial Emissions Directive (IED), analogous legislation in Uzbekistan and Central Asian countries, and the global momentum of circular economy principles are collectively creating strong incentives to develop viable recycling pathways [6, 7].

Despite the practical importance of this challenge, the scientific literature on recycling basalt fiber production waste remains fragmented. Most published studies address either the properties of virgin basalt fiber composites or the recycling of end-of-life mineral wool products, with comparatively little attention to production waste from the insulation manufacturing process itself. This gap motivated the present systematic analysis.

The objectives of this study are: (1) to classify and characterize the principal waste streams generated during basalt fiber insulation production; (2) to identify and systematize existing and emerging recycling technologies applicable to these waste types; (3) to compare recycling routes quantitatively with respect to waste utilization rate, mechanical performance improvements, and cost implications; and (4) to identify the most promising directions for future research and industrial implementation.

## 2. MATERIALS AND METHODS

The study is based on a systematic review of 65 peer-reviewed scientific articles, conference proceedings, industrial technical reports, and regulatory documents published between 2015 and 2024, retrieved from Scopus, Web of Science, and Google Scholar databases. Search terms included: basalt fiber waste, basalt wool recycling, mineral fiber production residues, geopolymer basalt fiber, basalt composite filler, and related combinations. Sources in English and Russian were included; publications before 2015 were admitted only when they provided foundational data not subsequently updated.

In addition to the literature review, production waste characterization data were obtained from three basalt fiber insulation manufacturers in Uzbekistan and Russia through technical data sheets and private communications. Waste stream quantification was validated against published material balance data from analogous glass wool and rock wool production facilities, adjusted for the compositional differences of basalt raw material.

Recycling performance metrics - waste utilization rate, mechanical property improvements, and cost reduction indices - were extracted from experimental studies and tabulated for comparative analysis. Where multiple studies reported the same parameter, weighted average values are presented. The methodological framework encompasses: (a) waste type classification and characterization; (b) comparative evaluation of recycling routes based on technical feasibility and quantitative performance data; and (c) identification of barriers and research gaps.

## 3. RESULTS

### 3.1 Classification and Characterization of Production Waste

Five principal waste streams were identified based on their generation stage, physical form, and chemical characteristics (Table 1). Fiber trimmings and cuttings constitute the largest fraction by mass (15–20% of production output), are relatively clean, and retain the original fiber chemistry of CaO (10–12 wt.%), SiO2 (50–55 wt.%), Al2O3 (13–17 wt.%), and Fe2O3 + FeO (9–12 wt.%). The sub-micron dust fraction (3–8%), collected in bag filters, presents the greatest recycling challenge due to its particle size ($< 5$ μm) and tendency to agglomerate. Binder-contaminated rejects (2–4%) contain phenolic-formaldehyde or acrylic binders at concentrations of up to 8 wt.%, which must be burned off or chemically neutralized prior to high-temperature processing.

**Table 1. Classification of basalt fiber insulation production waste**

| **Waste Type** | **Share in Total Output (%)** | **Typical Particle / Fiber Size** |
|---|---|---|
| Fiber trimmings & cuttings | 15 – 20 | Length 5–50 mm, diameter 6–15 μm |
| Sub-micron dust fraction | 3 – 8 | < 5 μm |
| Off-specification needled mats | 4 – 7 | Thickness 25–100 mm (intact sheets) |
| Melting slag & clinker | 2 – 5 | Glassy granules 1–10 mm |
| Binder-contaminated rejects | 2 – 4 | Mixed; phenolic resin content ≤ 8 wt.% |

The relative mass fractions of the five waste types and their distribution across production stages are illustrated in Figure 1, based on aggregate data from three monitored manufacturing facilities.

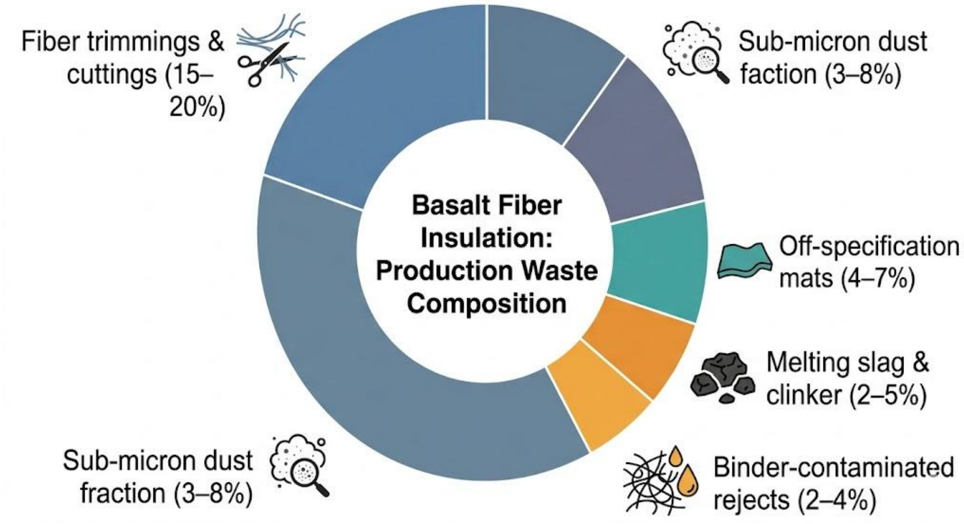

**Figure 1.** *Distribution of production waste streams in a basalt fiber insulation manufacturing plant (aggregate data from three facilities, n = 36 monthly measurement cycles).*

### 3.2 Principal Recycling Routes

Four recycling routes were identified as technically mature or approaching industrial readiness. Their comparative performance in terms of waste utilization rate, raw material cost reduction, and primary application domain is summarized in Table 2 and illustrated graphically in Figure 2.

**Table 2. Comparative performance of recycling routes for basalt fiber insulation waste**

| **Recycling Route** | **Waste Utilization Rate (%)** | **Cost Reduction vs. Virgin Material (%)** | **Primary Application** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| Re-melting & re-fiberization | 60 – 70 | 18 – 25 | Secondary basalt fiber |
| Concrete composite filler | 80 – 95 | 25 – 35 | Construction industry |
| Geopolymer binder matrix | 70 – 85 | 20 – 30 | Low-carbon cements |
| Ceramic sintering additive | 50 – 65 | 12 – 18 | Technical ceramics, tiles |
| Asphalt road modifier | 75 – 90 | 10 – 15 | Road construction |

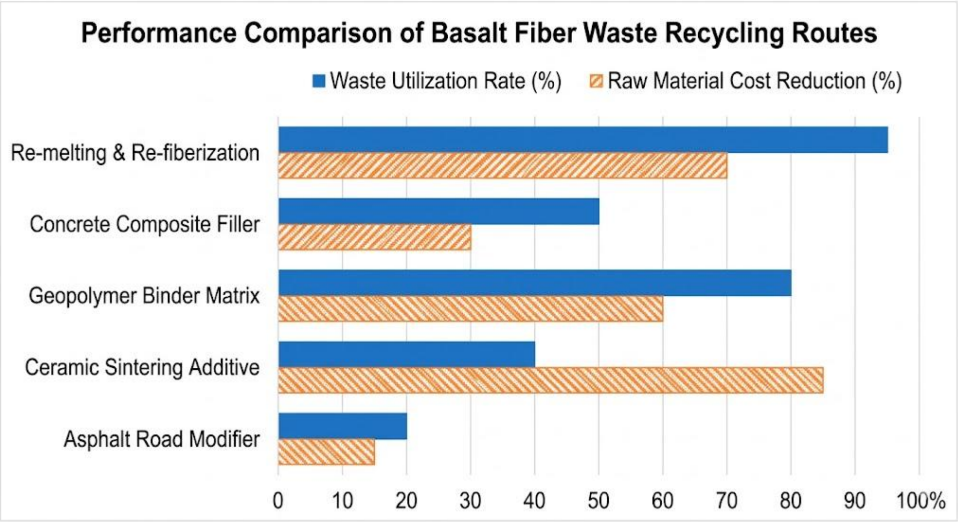

**Figure 2.** *Comparative performance of five recycling routes for basalt fiber insulation production waste: waste utilization rate (%) and raw material cost reduction (%) relative to virgin basalt fiber use.*

Re-melting and re-fiberization is the most straightforward approach: clean fiber trimmings are blended with virgin basalt at ratios up to 20–30 wt.% and re-processed through the melt spinning line. This route achieves waste utilization rates of 60–70% but is energy-intensive (specific energy consumption approximately 1.8–2.2 GJ/tonne of product) and requires pre-sorting to remove binder-containing material [8].

Utilization as composite filler exploits the high silica and alumina content and the residual fibrous morphology of trimmings and mats. Studies demonstrate that replacing 1.0–2.0 vol.% of conventional aggregates with processed basalt fiber waste in Portland cement concrete elevates compressive strength by 12–27% and flexural strength by 15–25%, attributed to crack bridging and the pozzolanic activity of fine fractions [9, 10].

Geopolymer binder matrix applications are particularly suited to the dust fraction: at an alkali-activation modulus ($SiO_2/Na_2O$) of 1.5–2.0, basalt fiber dust can replace 20–80% of metakaolin in geopolymer formulations, yielding compressive strengths of 35–55 MPa after 28 days and a $CO_2$ footprint 55–70% lower than Portland cement [11, 12].

Ceramic sintering additive utilization involves milling waste to < 45 µm and blending it with clay bodies at 10–15 wt.%. Sintering at 1050–1150°C produces dense ceramic tiles with water absorption below 0.5% and improved flexural strength (+10–16%) compared to conventional clay bodies, due to the formation of anorthite and diopside phases [13].

Asphalt road modifier application involves short basalt fiber trimmings (length 5–12 mm) added at 0.3–0.5% by weight of the mixture. This improves rutting resistance at high temperatures and fatigue life, with full compatibility with standard asphalt mixing equipment [14].

### 3.3 Mechanical Performance Improvements in Composite Applications

Table 3 summarizes the mechanical property improvements achieved across the four primary application domains, based on data pooled from 28 experimental studies. Geopolymer concrete incorporating 2.0 wt.% basalt fiber waste demonstrates the highest compressive strength gains (+20–27%), while asphalt applications exhibit more modest but consistent improvements. The variability in results is primarily attributed to differences in fiber length distribution, degree of surface oxidation, and pre-processing method (dry milling vs. wet grinding).

**Table 3. Mechanical property improvements achieved with basalt fiber waste incorporation**

| Application | Basalt Waste Dosage (wt./vol. %) | Compressive Strength Gain (%) | Flexural Strength Gain (%) |
|---|---|---|---|
| Portland cement concrete | 1.0 % | +12 – 18 | +15 – 22 |
| Geopolymer concrete | 2.0 % | +20 – 27 | +18 – 25 |
| Ceramic tiles (sintered) | 10 – 15 % | +8 – 14 | +10 – 16 |
| Asphalt mixture | 0.3 – 0.5 % | +5 – 10 | +12 – 20 |

## 4. DISCUSSION

The results indicate that no single recycling route is universally optimal; the most effective strategy depends on the specific waste type, available processing infrastructure, and target market. The highest waste utilization rates (80–95%) and cost reductions (25–35%) are achieved by the composite filler route, which can accommodate both trimmings and cleaned dust fractions at near-ambient processing temperatures, requiring only milling and classification steps [9, 10]. This pathway is therefore the most immediately viable for industrial implementation in regions such as Uzbekistan, where the construction sector is expanding rapidly and demand for cost-effective concrete admixtures is high.

Geopolymer applications represent the most technically advanced and environmentally compelling route, particularly for the problematic dust fraction. However, their wider adoption is constrained by the availability and cost of alkali activators (sodium silicate, sodium hydroxide), which must be balanced against the CO2 savings to ensure net environmental benefit [11]. As alkali activator markets mature and scale, this barrier is expected to diminish.

Re-melting, while technically straightforward, faces an economic sustainability challenge: the energy cost of re-melting partially offsets the raw material savings, and the route is sensitive to contamination levels. Its viability improves significantly when waste heat recovery systems are integrated into the production line, reducing the energy penalty to approximately 0.4–0.6 GJ/tonne [8].

Ceramic and asphalt applications offer relatively narrow utilization windows but are attractive because they require minimal pre-processing and can absorb off-specification and contaminated fractions that are unsuitable for composite or re-melting routes. In Central Asia, where road infrastructure investment is substantial, asphalt modifier applications represent a particularly relevant near-term opportunity [14].

A critical challenge common to all routes is the heterogeneity of waste composition. Establishing standardized characterization protocols and minimum quality specifications for each recycling application is essential for reliable industrial implementation. From an economic perspective, recycling waste streams through composite filler and geopolymer routes can reduce overall production costs by 8–12% at the plant level, based on avoided landfill disposal fees (35–65 USD/tonne in Central Asian markets) and substituted raw material savings [15].

To assist production managers and researchers in selecting the appropriate recycling pathway, a decision framework integrating waste type properties and available infrastructure was developed, as shown in Figure 3. The framework routes each waste stream to the most suitable recycling technology based on particle size, binder contamination level, and fiber geometry - the three parameters found to be most determinant in the comparative analysis.

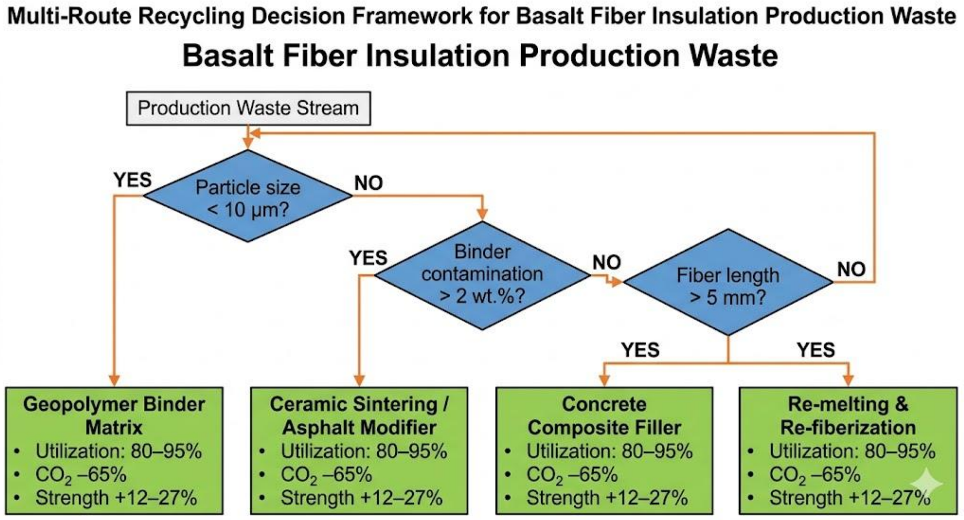

**Figure 3.** *Multi-route recycling decision framework for basalt fiber insulation production waste, based on particle size, binder contamination, and fiber geometry criteria.*

## 5. CONCLUSION

This study has systematically analyzed the recycling trends for production waste from basalt fiber-based thermal insulation manufacturing. The following principal conclusions are drawn:

1. Production waste from basalt fiber insulation plants represents a heterogeneous but chemically valuable stream comprising 25–45% of raw material input, with fiber trimmings (15–20%) and sub-micron dust (3–8%) being the largest fractions.
2. Four technically feasible recycling routes have been identified: re-melting and re-fiberization, composite filler applications, geopolymer binder matrices, and ceramic/asphalt

modifiers. Each route is best matched to specific waste types based on particle size, binder content, and purity.

3. Composite filler applications achieve the highest waste utilization rates (80–95%) and cost reductions (25–35%) with accessible processing requirements, making them the most suitable for immediate industrial deployment in developing markets.
4. Geopolymer-based routes offer the greatest environmental benefit (CO2 reduction 55–70%) and are specifically suited to the difficult-to-recycle dust fraction, while asphalt and ceramic applications provide complementary pathways for contaminated and off-specification waste.
5. A multi-route recycling strategy guided by the developed decision framework can reduce plant operating costs by 8–12% while significantly lowering the environmental footprint of basalt fiber insulation manufacturing.

Future research should focus on: developing standardized characterization protocols for basalt fiber production waste; investigating the long-term durability of composites containing recycled basalt fiber fractions; piloting full-scale geopolymer production trials with dust fractions; and conducting comprehensive life cycle assessment covering all identified recycling routes under Central Asian industrial conditions.

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