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Research Article

A Study on the Thermal Performance of Eco-Friendly Flame-Retardant Building Materials Using Bamboo Charcoal Composites

Keunhoo Park

Independent Researcher, Seoul Innovation Research Institute, South Korea
Email: keunhoopark07@gmail.com

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Abstract
Environmental friendliness and fire safety have emerged as essential factors in selecting building materials. As sustainable development and carbon neutrality goals grow more important, the demand for eco-friendly materials increases. Among such materials, charcoal has received attention due to its low thermal conductivity, high porosity, and ability to suppress flames [1]. In this study, over 50 composite samples were fabricated using three types of charcoal (activated carbon, bamboo charcoal, oak charcoal) combined with four different additives: vermiculite, perlite, salt, and a mixed additive (V.S.P). Among the tested samples, the bamboo charcoal with 4g of vermiculite showed the best thermal performance, maintaining an average temperature of 185.6°C and a mass loss rate of only 6.6%. These results indicate competitive performance compared to conventional gypsum board [4]. The charcoal composites, being low-cost and environmentally sustainable, offer promising potential for future application as flame-retardant building materials.
Keywords: Bamboo Charcoal Composites, Flame-Retardant Building Materials, Thermal Insulation Performance, Eco-Friendly Construction Materials, Vermiculite-Based Additives.

1. Introduction

Recently, energy conservation and eco-friendly building practices have become a major focus globally. The direction of building material development is shifting toward sustainability and environmental responsibility. Interior finishing materials directly affect building performance, including air quality, fire resistance, and insulation efficiency [2]. While traditional gypsum and cement boards are affordable and easy to manufacture, they often emit toxic gases during fires, have low heat resistance, and are not environmentally ideal [3]. Charcoal, a natural material with high porosity and low thermal conductivity, is drawing attention as a potential alternative [1]. Especially, bamboo and oak charcoal are relatively inexpensive, biodegradable, and compatible with various inorganic additives [6]. This study aims to evaluate the flame retardancy and thermal insulation performance of charcoal-inorganic composites for practical use in building applications.

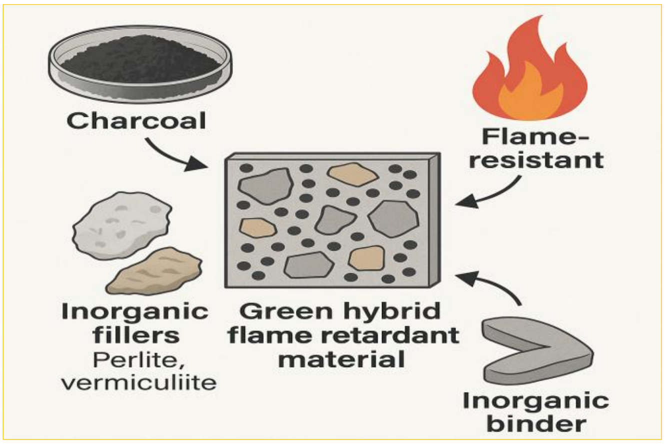

Figure 1. Conceptual diagram of eco-friendly flame-retardant charcoal composite materials and their application in building finishes.

2. Theoretical Background

Charcoal is a carbon-based substance created through high-temperature carbonization, characterized by a large surface area and microporous structure. These features help trap air, reduce heat transfer, and provide thermal protection. Activated carbon is known for high adsorption ability but has weaker mechanical strength. Bamboo charcoal is affordable and highly renewable, while oak charcoal offers greater structural stability. Inorganic additives such as vermiculite, perlite, and salt expand when heated and form thermal barriers, enhancing flame resistance. Previous research has shown that charcoal-mineral composites can offer some insulation and fire resistance, but few studies have quantitatively compared the effects of different charcoal types and additive ratios. This study addresses that gap with systematic experimental testing [2].

3. Methodology

Three types of charcoal-activated carbon, bamboo charcoal, and oak charcoal-were combined with four additives: vermiculite, perlite, salt, and V.S.P. Based on 20g of charcoal per sample, additives were mixed in ratios ranging from 1g to 4g. The mixtures were poured into silicone molds (40×40×20mm) and dried under ambient conditions for 24 hours, followed by 48 hours in a 60°C oven. A total of more than 50 samples were produced.

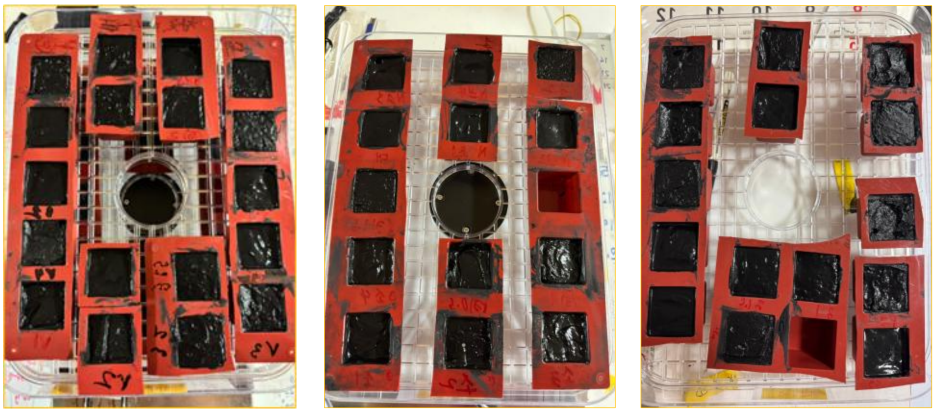

Figure 2. Sample fabrication process including material mixing, molding, and drying.

Each sample was placed on a heated plate for 5 minutes, with surface temperatures recorded every minute using an IR thermometer. Mass loss before and after heating was measured. Additional observations were made regarding surface cracks, visible flame, and fragmentation. All tests were repeated twice under identical conditions and analyzed based on average values.

4. Results and Discussion

The type of charcoal and the additive composition had a significant impact on thermal performance. Activated carbon-based samples had an average mass loss rate of 30.4% and maintained an average temperature of 121.3°C. In contrast, bamboo charcoal (17.6%, 182.6°C) and oak charcoal (16.3%, 175.5°C) showed better flame resistance and heat retention. The sample containing bamboo charcoal with 4g of vermiculite showed the best performance, with only 6.6% mass loss and a temperature of 185.6°C, exceeding typical gypsum board performance (10–15% mass loss, ~150°C) [4]. Salt-based samples temporarily reached 204.5°C but showed poor physical stability due to flame and swelling during heating [3]. These findings confirm that charcoal type influences combustion resistance, while additives enhance heat shielding and structural integrity [5].

The type of charcoal and the additive composition had a significant impact on the thermal performance of the composite samples. Activated carbon-based samples showed the weakest results, with an average mass loss rate of 30.4% and an average surface temperature of only 121.3°C during the 5-minute test. In contrast, bamboo charcoal (17.6%, 182.6°C) and oak charcoal (16.3%, 175.5°C) composites demonstrated significantly better flame resistance and heat retention. Among all samples, the one containing bamboo charcoal with 4g of vermiculite (Sample S1) exhibited the most balanced and outstanding performance, recording a mass loss of only 6.6% and an average surface temperature of 185.6°C. These values exceed the thermal performance of standard gypsum boards, which typically show 10–15% mass loss and surface temperatures around 150°C [4]. Figure 3 illustrates the surface temperature profiles of selected samples (S1–S6) recorded at one-minute intervals over 5 minutes of heating. The samples based on bamboo charcoal

(S1, S5, S6) consistently maintained higher temperatures than those based on activated carbon (S3, S4), demonstrating better thermal insulation characteristics.

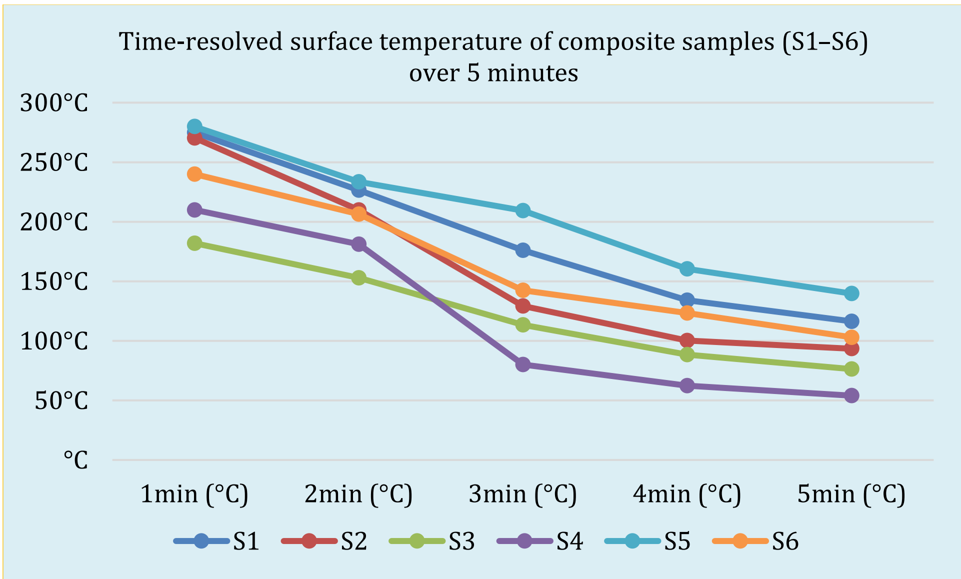

Figure 3. Time-resolved surface temperature profiles of six selected composite samples (S1–S6).
[S1: Bamboo charcoal + vermiculite 4g, S2: Oak charcoal + perlite 2g, S3: Activated carbon + perlite 2g, S4: Activated carbon + salt 1g, S5: Bamboo charcoal + salt 1g, S6: Bamboo charcoal + V.S.P. 2g over a 5-minute heating period. Bamboo charcoal-based composites (S1, S5, S6) showed better thermal retention compared to activated carbon and oak charcoal-based samples].

To better visualize both thermal performance and structural integrity, Figure 4 compares the average surface temperature and mass loss rate of six representative samples. Notably, samples S1 and S6 (bamboo charcoal + V.S.P.) achieved high temperature retention with minimal mass loss, making them strong candidates for flame-retardant applications.

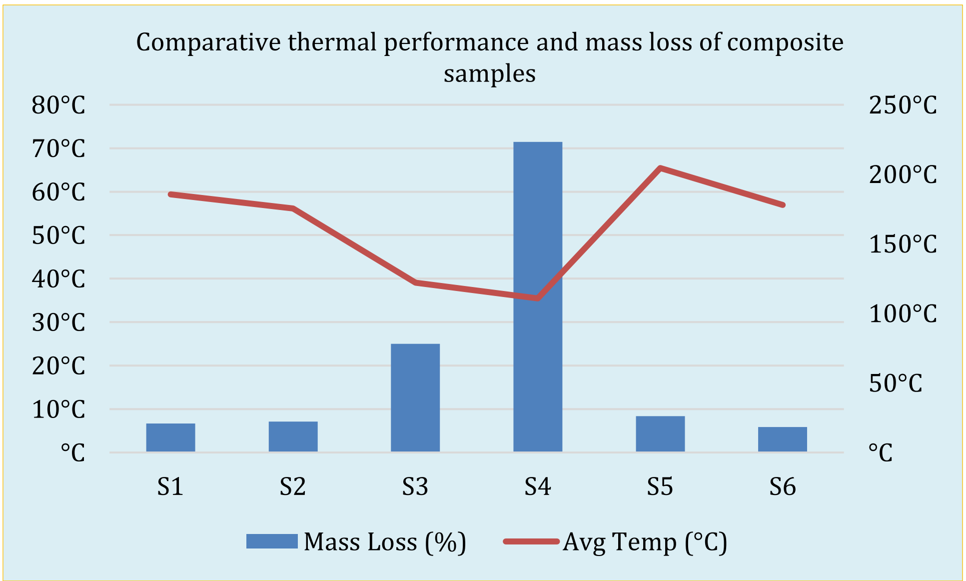

Figure 4. Comparison of mass loss percentage (bars) and average surface temperature (line) for selected composite samples.
[S1 (Bamboo charcoal + vermiculite) and S6 (Bamboo charcoal + V.S.P.) showed the best balance of flame retardancy and heat insulation].

These findings confirm that charcoal type directly influences combustion resistance, while inorganic additives such as vermiculite and V.S.P. contribute to heat shielding and mechanical stability [5]. In particular, vermiculite's expansion under heat appears to help form a thermal barrier layer, protecting the core material. Oak charcoal composites also performed well overall, but their slightly higher mass loss suggests they may require additional reinforcement for long-term application.

5. Conclusion

This study successfully analyzed the thermal performance and flame retardancy of charcoal-based composites with various inorganic additives. Bamboo charcoal combined with vermiculite showed the best results, highlighting its potential as a safe, eco-friendly, and affordable finishing material. Compared to conventional products, these composites demonstrated equal or superior performance. Future research should investigate other factors such as long-term durability, moisture resistance, and mechanical strength for real-world application.

Declarations

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