Advances in Basalt Fiber Reinforced Cement-Based Composites: Mechanical Properties and Durability Insights

Abstract: Basalt fiber cement-based composite materials represent a novel category of building materials that have garnered significant attention in recent years, finding extensive application in water conservancy projects and infrastructure construction. This review examines the development status of basalt fiber both domestically and internationally, as well as the advancements in its mechanical properties and durability. The findings indicate that incorporating an optimal amount of basalt fiber can lead to a maximum increase in compressive strength and splitting tensile strength of approximately 7%. Furthermore, the 7-day strength can achieve 55% to 64% of the 28-day strength. The addition of basalt fiber not only enhances the tensile strength, impact resistance, and durability of composite materials but also reduces the cracking sensitivity of concrete, thereby extending the service life of structures. These characteristics render basalt fiber cement-based composites particularly advantageous in extreme environments, such as bridges, tunnels, high-rise buildings, and ocean engineering. Future research directions should prioritize investigating the reaction mechanisms and technological advancements associated with basalt fiber in concrete.

Key words: basalt fiber, cement-based, mechanical properties, durability

1. Introduction

Since the 20th century, cement-based materials have rapidly developed and become the most widely used engineering materials globally[1]. These materials dominate the construction industry. However, due to variations in component performance, numerous cracks of varying sizes can form both internally and on the surface of the components. The presence of these cracks significantly reduces the tensile, compressive, and bending mechanical properties of concrete, which is a primary factor contributing to its brittle failure. Fiber concrete, a cement-based composite material, utilizes concrete as the base and incorporates discontinuous short fibers or continuous long fibers as reinforcement materials[2-3]. By integrating fibers characterized by high tensile strength, considerable elongation, and excellent corrosion resistance into the concrete matrix, the performance of the concrete material can be markedly improved, particularly regarding crack resistance. This enhancement effectively delays crack propagation within the matrix. Since its introduction, fiber concrete has found widespread application in the engineering field.

Several types of fiber-reinforced concrete are currently in common use, including basalt fiber concrete, steel fiber concrete, carbon fiber concrete, glass fiber concrete, and synthetic fiber concrete, which span various fields of civil engineering. The incorporation of fiber composites has significantly enhanced the mechanical properties and durability of concrete materials. However, the diversity of fiber types presents varying toughening properties and economic implications. Basalt fiber, in particular, demonstrates excellent natural compatibility with cement-based materials and has been widely adopted in engineering applications. The practical application technology for basalt fiber has been continuously optimized and expanded within the industry standards[4] of our country. A judicious incorporation of basalt fiber into concrete can improve the performance of concrete materials, while also offering notable economic advantages.

Basalt fiber (BF), along with carbon fiber, aramid fiber, and ultra-high molecular polyethylene fiber, is classified as one of the four high-performance fibers. These fibers are derived from volcanic rock, which is melted at temperatures between 1450℃ and 1500℃ and subsequently drawn through a casing. Typically, basalt fiber appears brown, with some variations exhibiting a golden hue. This fiber is characterized by its heat insulation and fire protection properties; its composite fireproof materials demonstrate excellent high-temperature resistance, making them suitable for applications in fire protection, metallurgy, petrochemicals, and other industries. Additionally, basalt fiber exhibits remarkable thermal stability, high strength, sound absorption and insulation capabilities, as well as a consistent friction coefficient. Its applications extend to the automotive and construction sectors, serving as reinforcement materials for automotive friction components, high-temperature filter media, and various indoor materials. In recent years, both domestic and international researchers have extensively explored the crack resistance mechanisms, mechanical properties, and engineering applications of basalt fiber reinforced cement-based composite materials. This article aims to review the advancements in research concerning basalt fiber and its reinforcement of cement-based composite materials.

2. Research background and significance

Fiber cement composites (FCMC) are composite materials that utilize cement slurry, cement mortar, or concrete as the base material, with discontinuous short fibers or continuous long fibers serving as reinforcement. The use of such materials dates back over 1,000 years; for instance, the ancient Romans mixed horse hair with lime to create statues. In the early 20th century, Austria pioneered the invention of asbestos cement board and established the world's first factory for asbestos cement products. Between the 1960s and 1970s, steel fibers and fiberglass were employed to reinforce cement-based materials. With the advent of high-performance fibers and advancements in the properties of cement-based materials, fiber-reinforced cement-based composite materials have entered a new era. Notably, in 1954, the former Soviet Union successfully developed basalt fiber as a novel material for the first time. Prior to 2002, basalt fiber was primarily utilized in the military sector. Subsequently, researchers worldwide conducted extensive studies on this material, leading to its designation as an 863 high-tech project by the government in 2002. By 2005, basalt fiber was successfully developed for broader applications. This fiber exhibits excellent physical and mechanical properties, including a high elastic modulus, strong corrosion resistance, elevated tensile strength, good chemical stability, and favorable natural compatibility. The judicious incorporation of basalt fiber into concrete can significantly enhance the compressive strength, flexural strength, and splitting strength of concrete materials, as well as improve their resistance to seepage and dry shrinkage deformation.

Current research on basalt is ongoing, highlighting its potential in construction. In our country, the majority of existing buildings are concrete structures, with data indicating that at least 50% of these have been in use for 20 years. Due to technical issues and inadequate management during the design and construction phases, the reinforcement, repair, and maintenance of these structures will become focal points in the future of the construction industry[5]. As civil buildings and various structures evolve towards super-high-rise and long-span designs, the demands for material performance continue to increase. Research findings demonstrate that the high-strength characteristics of basalt fiber concrete can effectively meet these evolving requirements. Furthermore, varying dosages of basalt fiber yield different impacts on its strength[6].

3. Research on basalt fiber reinforced concrete

In 2016, Luigifenu, Danieleforni et al.[7] investigated the dynamic properties of basalt fiber cement mortar. The findings indicate that the incorporation of basalt fibers significantly enhances the static flexural strength of the mortar, while the increase in dynamic tensile strength is minimal. Furthermore, the post-peak properties of basalt fiber mortar exhibit improvements under dynamic loading conditions.

Dias[8] examined the mechanical properties of basalt fiber concrete and concluded that its crack resistance surpasses that of other fiber-reinforced concretes, with basalt fiber markedly enhancing its toughness. This aligns with the findings of Sim[9] and other researchers regarding the crack resistance of basalt fiber concrete, indicating consistency across studies.

Experimental research conducted by Militky et al.[10] demonstrates that basalt fiber retains an aesthetically pleasing appearance and exhibits substantial mechanical strength at temperatures of 600°C. Continuous basalt fiber (CBF) can perform effectively at 860°C without significant shrinkage following pretreatment at 780-820°C. In contrast, even mineral wool, known for its excellent temperature resistance, can only retain 50% to 60% of its strength under similar conditions, while glass wool is completely compromised. Additionally, carbon fiber emits harmful gases such as CO and CO_2 at elevated temperatures. These findings highlight the superior temperature resistance of CBF compared to other fiber materials.

4. Study on mechanical properties of basalt fiber cement-based materials

Arslan[11] conducted a comparative study on the fracture behavior of basalt fiber reinforced concrete (BFRC) and glass fiber reinforced concrete (GFRC). To achieve this, three-point bending tests were performed on notched beams made from BFRC and GFRC with fiber contents of 0.5, 1, 2, and 3 kg/m^3 to assess the fracture energy. Utilizing the RILEM proposal, the fracture energy of the notched beam specimens was calculated by analyzing the load versus crack mouth opening displacement (CMOD) curve. The average compressive strength of the control (Ref), BFRC, and GFRC, derived from cylindrical specimens, is illustrated in Figure 1. The figure indicates that the different types of fibers (basalt and glass) and fiber contents (0.5, 1, 2, and 3 kg/m^3) do not significantly affect the compressive strength. However, the compressive strength of all specimens increased compared to the Ref specimen, with the exception of the GFRC-24-3 mixture. Notably, the BFRC-24-3 exhibited a maximum increase of 7% relative to the Ref specimen. After conducting SEM observation and analysis, it was determined that while the BF surface was smooth, it was partially covered by cement slurry. Although it cannot be stated that perfect bonding was achieved due to the BF slipping off the cement paste, the presence of the cement paste coating on the BF surface suggests a bond exists between the two materials. Additionally, the observed increase in flexural and splitting tensile strength further indicates that the BF contributes positively to the bond strength.

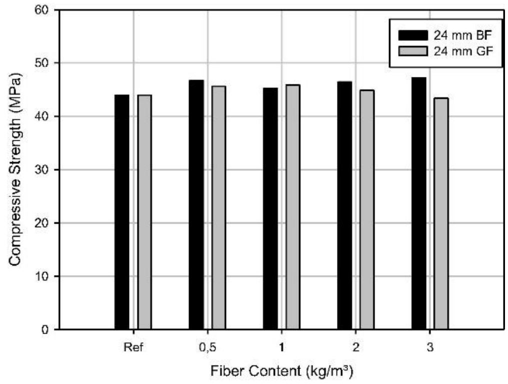

Fig. 1. Compressive strengths of the mixtures.

Meyyappan[12] investigated the incorporation of basalt fibers into M30 grade concrete at volume fractions of 0.5%, 1%, 1.5%, 2%, 2.5%, and 3%. As illustrated in Figure 2, the experimental results indicate that the compressive strength and splitting tensile strength of the concrete, with basalt fiber content ranging from 0% to 3%, show that the 7-day compressive strength is approximately 55% to 64% of the 28-day compressive strength. A similar trend was observed for the splitting tensile strength of basalt fiber-reinforced concrete. The findings reveal that the strength performance of the reinforced concrete is optimal at a basalt fiber volume fraction of 1%, with a significant decline in strength observed as the volume fraction is increased beyond this point.

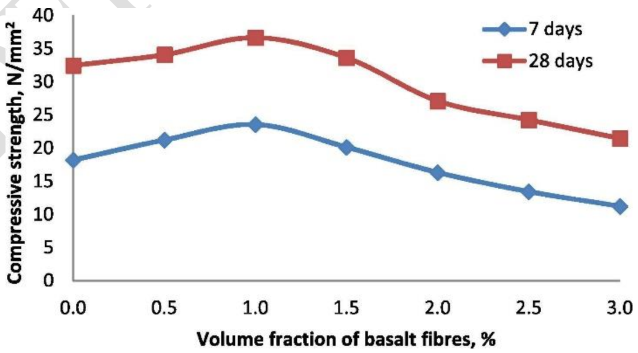

Fig. 2. Compressive strength Vs Volume of Basalt fibre.

5. Study on durability of basalt fiber reinforced concrete

5.1 Frost resistance

Yihong Guo[13] investigated the impact of basalt fiber (BF) on the frost resistance of concrete under various curing conditions and analyzed the underlying mechanisms of this frost resistance. Three types of curing conditions were employed: conventional curing, short-term curing, and seawater curing, with concrete mixtures designed to incorporate different BF dosages. Freeze-thaw tests were conducted on basalt fiber-reinforced concrete (BFRC) using the rapid freezing method. Additionally, the mass loss rate (MLR), changes in relative dynamic elastic modulus (RDME), and the reduction in compressive strength of the specimens during freeze-thaw cycles were evaluated. When the BF content was set at 0.15%, the residual compressive strength of BFRC, under ordinary curing, short-term curing, and seawater curing conditions, increased by 5.4%, 28.1%, and 30.9%, respectively, compared to ordinary concrete after freeze-thaw cycles (FTCs). The incorporation of BF into concrete effectively delays the development of microcracks and mitigates the damage incurred during FTCs.

5.2 Corrosion resistance

Seawater can induce cracks in the concrete of BFRC bridges and lead to the corrosion of the steel reinforcement within the concrete. Yunfeng Li[14] investigated an efficient method for preparing BFRC superhydrophobic surfaces to enhance its durability. BFRC exhibits a high surface density, and sodium stearate serves as an effective modifier. Through orthogonal experiments, superhydrophobic BFRC was synthesized, and the effects of three primary factors (temperature, time, and concentration) on the wettability of BFRC were examined. Soaking time and solution concentration were found to have the most significant impact. Compared to standard BFRC, the capillary water absorption rate of superhydrophobic BFRC is notably reduced. Furthermore, through equivalent circuit analysis, it was determined that the soaking method can enhance the corrosion resistance of BFRC. Overall, the soaking method is effective in improving the durability of BFRC.

5.3 chloride ion erosion

The research conducted by Hesong Jin[15] investigates the relationship between rainfall intensity and chloride ion distribution in concrete, particularly under varying initial water saturation conditions. By simulating rainfall environments and measuring potential differences, it was observed that as rainfall intensity increases, the concentration of chloride ions at the surface decreases significantly, while the binding capacity of chloride ions weakens. This trend is particularly pronounced under low saturation conditions. Another study by Viet Quoc Dang[16] explored the potential application of non-desalted sea sand (NSS) in concrete production. The findings indicate that chloride ions present in NSS have minimal impact on the slump loss and air content of fresh concrete, while also promoting the early pozzolanic reactions of fly ash (FA) and the early hydration of blast furnace slag powder (BFS). Furthermore, the presence of chloride ions enhances the later mechanical properties and durability of concrete, contributing to increases in permeability and adsorption rates. Collectively, these studies not only elucidate the influence of environmental factors on the behavior of chloride ions in concrete but also assess the effective utilization of non-desalted sea sand containing chloride ions, thereby providing a scientific foundation for optimizing concrete performance.

6. Conclusions

This study comprehensively explores the performance and potential of basalt fiber concrete (BFRC) concerning its mechanical properties, frost resistance, corrosion resistance, and chloride ion erosion. Through a comparative analysis of the fracture behavior of BFRC and glass fiber concrete (GFRC), it was found that when BFRC is mixed with an appropriate amount of fiber, there is no significant difference in compressive strength compared to GFRC. However, the maximum compressive strength of BFRC is higher than that of GFRC without fiber, demonstrating an improvement in concrete performance with a maximum increase of 7%. Additionally, the bond strength of BFRC contributes positively to structural safety and maintenance. Building on the optimization of mechanical properties, the investigation into the frost resistance of BFRC revealed that, under various curing conditions—particularly short-term curing and seawater curing—the residual compressive strength can be effectively enhanced by incorporating an appropriate amount of fiber. This indicates that BFRC has significant potential for application in extreme environmental conditions. Furthermore, research on corrosion resistance showed a substantial reduction in capillary water absorption, thereby enhancing the durability of concrete through the development of superhydrophobic BFRC surfaces. This provides a scientific basis for the extensive application of BFRC in corrosive environments such as marine settings. Additionally, the study on chloride ion attack not only examined the relationship between rainfall intensity and chloride ion distribution in concrete but also assessed the feasibility of using non-desalted sea sand in concrete production. This research highlights the complex effects of chloride ions on concrete properties, which may both promote early hydration reactions and enhance subsequent mechanical properties and durability. Collectively, these findings offer a robust theoretical framework and scientific foundation for the performance optimization and widespread application of BFRC.

7. Discussion and outlook

Basalt fiber exhibits exceptional properties, including high temperature resistance, tensile strength, chemical stability, thermal shock stability, and resistance to both acids and alkalis. My country possesses independent intellectual property rights, advanced manufacturing technology, and competitive costs. Although significant research results have been achieved regarding the application of basalt fiber in reinforcing cement-based materials, numerous challenges remain to be addressed. Microscopic methods were employed to investigate the microcrack orientations in fiber-reinforced cement-based materials under load, and the varying outcomes were analyzed through a combination of theoretical and experimental perspectives.

The emergence of new alternative materials is exerting pressure on the basalt fiber concrete market. Regarding technical challenges, key factors that continue to restrict its development include the need to further reduce production costs, stabilize product performance, and enhance the industry standard system. Future research directions should prioritize the application mechanisms and technologies of basalt fiber in concrete. Specifically, it is essential to intensify research on the effects of basalt fiber on the durability of concrete structures, particularly its inhibitory effects on steel corrosion and alkali-aggregate reactions. Additionally, exploring more effective ways to utilize basalt fiber to enhance the mechanical properties, durability, and crack resistance of concrete is crucial to meet the increasing demands for environmental protection and performance. Concurrently, in-depth investigations into the stability of production costs and product performance are necessary to promote the sustainable development of the basalt fiber concrete industry.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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