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A Review of Experimental Studies on the Mechanical Properties of High-Temperature Mixed Fiber Lightweight Aggregate Concrete

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Abstract

As the economy continues to develop, the proliferation of large-span and multi-story buildings has led to an increasingly prominent issue of high-temperature fire hazards. This paper briefly summarizes the research findings on the changes in the mechanical properties of lightweight aggregate concrete after exposure to normal and high-temperature fires. By analyzing the effects of different temperatures and the addition of various fiber materials on the mechanical properties of lightweight aggregate concrete, the current state of research indicates: At normal temperatures, the addition of steel fibers can enhance the compressive strength of lightweight aggregate concrete; however, excessive amounts may lead to adverse effects; Polypropylene fibers can improve the high-temperature blast resistance of lightweight aggregate concrete and mitigate its brittle failure mode. When both types of fibers are mixed into the concrete, the synergistic effect of the mixed fibers can further enhance the mechanical properties of lightweight aggregate concrete after high-temperature exposure.

Keywords

Lightweight aggregate concrete, high temperature, mechanical properties.

1. Introduction

The growing demand for the construction of long-span bridges, high-rise buildings, and large-scale infrastructure has made the use of lightweight materials with specific performance characteristics an inevitable trend. Lightweight aggregate concrete is a typical example of such materials, composed of lightweight coarse aggregate, lightweight sand (or ordinary sand), cement, and water, with a dry bulk density not exceeding 1,950 kg/m^3. With its significant advantages such as low self-weight and excellent thermal insulation properties, lightweight aggregate concrete effectively addresses self-weight issues. However, it also has some unavoidable drawbacks, such as susceptibility to brittle failure and poor tensile performance.

Research by domestic and international scholars has shown that adding fibers to lightweight aggregate concrete can mitigate these defects. This paper aims to briefly summarize the improvements achieved by single or mixed fibers in lightweight aggregate concrete, while also investigating the effects of ambient and high temperatures on the mechanical properties of mixed-fiber lightweight aggregate concrete. Through in-depth research and analysis of the mechanical properties of mixed-fiber lightweight aggregate concrete after high-temperature exposure, this study provides a basis and reference for the practical application of mixed-fiber lightweight aggregate concrete in engineering projects.

2. Current State of Research

2.1. Current State of Research on Mixed Fiber Concrete at Room Temperature

Zhai Quan [1]investigated the effect of different dosages and incorporation methods of polypropylene fibers and basalt fibers on the compressive strength of lightweight aggregate concrete. For single-fiber incorporation, the compressive strength of lightweight aggregate concrete increased initially and then decreased with increasing dosage. The trend for lightweight aggregate concrete with a mixture of both fibers is similar to that of single-fiber addition. The compressive strength reaches its maximum value when the polypropylene fiber content is 0.6 kg/m^3 and the basalt fiber content is 0.5 kg/m^3. Calculations show that although the compressive strength of lightweight aggregate concrete with a mixture of fibers is higher than that of single-fiber addition, it reduces the ductility of the lightweight aggregate concrete.

Libre[2] conducted compressive strength tests on lightweight aggregate concrete with different volumes of steel fibers and polypropylene fibers, concluding that polypropylene fibers have no significant effect on concrete compressive strength. However, when the addition of steel fibers reaches 0.5% of the concrete volume, the compressive strength of the concrete increases by approximately 47%. However, further increases in compressive strength were not observed when more steel fibers were added, and the compressive strength increased by approximately 44% in this case. For steel fiber volume fractions greater than 0.5%, the effect of steel fibers on compressive strength appears to be insignificant and highly inconsistent.

Dong Xiping [3] et al. compared the compressive strength of lightweight aggregate concrete with single and mixed additions of glass fibers and polypropylene fibers. They found that the compressive strength trends for both types of fibers increased initially and then decreased with increasing addition levels, and both were higher than those of lightweight aggregate concrete without fibers. Comparing the two, it was found that the reinforcing effect of glass fibers was superior to that of polypropylene fibers. The compressive strength of lightweight aggregate concrete with mixed fibers is significantly higher than that of single-fiber concrete, but an optimal mix ratio is required to achieve the maximum compressive strength.

Eethar Dawood's [4] research further revealed the complex mechanism underlying the mechanical properties of carbon fiber-reinforced foam concrete. He found that there is a clear positive correlation between the volume content of carbon fibers and the flexural strength of foam concrete, attributed to the excellent stiffness and tensile strength characteristics of carbon fibers. At the microscopic level, carbon fibers bridge microcracks, inhibiting their further development, while at the macroscopic level, they directly enhance the concrete's crack resistance. Additionally, Eethar observed a significant strengthening effect of carbon-polypropylene hybrid fibers in foam concrete. This hybrid fiber system not only significantly improves the toughness of foam concrete but also leverages the respective advantages of carbon fibers and polypropylene fibers during the initial cracking and crack propagation stages: Carbon fibers primarily contribute to enhancing the initial fracture strength, while polypropylene fibers are more effective at improving the performance stability after cracks appear. The two complement each other, jointly optimizing the mechanical properties of foam concrete.

Fu Xueqing [5] conducted mechanical property tests on lightweight aggregate concrete by mixing steel fibers and polypropylene fibers. The test results indicated that as the fiber content increased, the slump value of the lightweight aggregate concrete decreased to varying degrees, with a reduction ranging from 12% to 40%. This change had an impact on the concrete's flowability and workability. Meanwhile, the dry apparent density of lightweight aggregate concrete slightly increased after fiber addition, but the increase was not significant, indicating that the addition of fibers has a limited impact on the overall density of the concrete. The addition of fibers significantly suppressed the expansion and development of cracks in the concrete during tensile and compressive loading, with the compressive strength, splitting tensile strength, and flexural strength of the concrete increasing by 26%, 116%, and 37%, respectively. These improvements in mechanical properties exhibit a similar trend, showing a significant increase initially followed by a gradual flattening or even slight decrease as the fiber content increases.

In summary, the improvement in the mechanical properties of lightweight aggregate concrete due to mixed fibers is not simply a result of the cumulative effect of fiber content, but rather depends on the interaction between the fibers. Excessive or insufficient fiber content is detrimental to the mechanical properties of lightweight aggregate concrete. Therefore, studying the interaction between mixed fibers and exploring the optimal mix ratio is particularly important for improving the mechanical properties of lightweight aggregate concrete.

2.2. Current Status of Research on Lightweight Aggregate Concrete with Mixed Fibers After High Temperature Exposure

Zhang Xiaohui [6] studied the effects of adding steel fibers and polypropylene fibers at volume fractions of 0.3% and 0.6% in lightweight aggregate concrete, and tested their high-temperature residual mechanical properties and apparent characteristics under different high-temperature conditions. The following conclusions were drawn: the addition of fibers slightly improves the compressive strength of concrete, but the strength gradually decreases as the temperature increases. The strength retention rate of steel fiber and mixed fiber concrete is relatively high. Although the peak load of steel fiber and mixed fiber concrete continues to decrease, the deflection and crack width growth are well controlled. In terms of fracture energy, steel fiber and mixed fiber concrete significantly outperform polypropylene fiber and pure concrete, with higher dosages yielding more pronounced effects. However, the gap narrows as temperature increases.

Wei Min [7] investigated the effects of different lightweight aggregates, different steel fiber types, and temperature on the physical and mechanical properties and toughness of concrete. Experimental results showed that the mass loss rate of lightweight aggregate concrete at high temperatures is influenced by the type of aggregate. The type of steel fiber significantly affects the splitting tensile strength and flexural strength of lightweight aggregate concrete, with end-hooked steel fibers yielding better results. Aggregate type primarily determines the change in compressive strength with temperature. In bending and splitting tensile tests, as temperature increases, both the bending test curve and the splitting tensile test curve become gradually flatter and smoother. Steel fibers significantly enhance the toughness of lightweight aggregate concrete, with end-hooked steel fibers being more effective.

Guo Jiadong [8] studied the mechanical properties of lightweight aggregate concrete at room temperature and high temperature under different fiber types and cooling methods. The results showed that the addition of polypropylene fibers significantly improves the high-temperature blast resistance of lightweight aggregate concrete and mitigates its brittle failure mode. Appropriate fiber content also enhances the compressive and splitting tensile strength of concrete at room temperature. However, as fiber content increases, strength gradually decreases. Under high-temperature conditions, concrete with an appropriate amount of fibers exhibits better strength performance, but spray cooling has a negative impact on strength at high temperatures. Additionally, high temperatures cause the decomposition of concrete hydration products; while spray cooling can promote their regeneration, it also exacerbates structural damage to the concrete.

Bo et al. [9] conducted a study to investigate the effects of polyvinyl alcohol fibers and polyacrylonitrile fibers on the mechanical properties of lightweight aggregate concrete (FLWAC) after freeze-thaw cycles and subsequent high-temperature treatment. The experimental design involved subjecting FLWAC specimens to 25 freeze-thaw cycles, followed by testing at room temperature, 200°C, 400°C, 600°C, and 800°C. The experimental results showed that when the temperature rose above 200°C, the cube compressive strength of FLWAC significantly increased; particularly within the temperature range from room temperature to 600°C, its splitting tensile strength also exhibited a noticeable improvement. Notably, when subjected to peak loads, the addition of fibers effectively mitigated the brittle fracture tendency of lightweight aggregate concrete caused by freeze-thaw cycles. However, although the addition of fibers may improve certain mechanical properties of the concrete, there was no significant improvement in mass loss after 25 freeze-thaw cycles.

In summary, fibers can improve the compressive, splitting tensile, and flexural strengths of lightweight aggregate concrete after high-temperature exposure. Although fiber addition enhances strength, strength decreases with increasing temperature. Mixed fiber concrete exhibits higher residual strength, significantly outperforming single-fiber-reinforced and plain concrete. Different fiber types exhibit varying effects. Polypropylene fibers enhance the high-temperature blast resistance of lightweight aggregate concrete and mitigate brittle failure modes; steel fibers comprehensively improve compressive strength, flexural strength, and other mechanical properties.

2.3. Current research on the effect of cooling methods after high-temperature treatment on the mechanical properties of fiber-reinforced concrete

Numerous scholars have conducted in - depth research on the impact of different cooling methods on the mechanical properties of fiber - reinforced concrete after exposure to high temperatures, and the obtained results have their own focuses.

Gai - Fei Peng et al. [10] explored the effect of thermal shock generated by different cooling methods on the residual mechanical properties of fiber - reinforced concrete at high temperatures ranging from 200°C to 800°C. The test showed that the thermal shock caused by water spraying cooling and water quenching would aggravate the deterioration of the mechanical properties of concrete, resulting in greater losses in compressive strength, splitting tensile strength and fracture energy compared with natural cooling. When the water spraying time exceeds 30 minutes, its thermal shock effect is similar to that of water quenching. Moreover, steel - polypropylene hybrid fibers can effectively improve the residual strength and fracture energy of concrete under the condition of high - temperature rapid cooling.

Li Xincong et al. [11] studied the influence of low - temperature treatment on the degradation law of mechanical properties of recycled concrete after high temperature. The results indicated that low - temperature action changed the failure characteristics of high - temperature recycled concrete. The compressive and tensile strengths of the specimens cooled naturally were better than those cooled by water spraying, and the weakening effect of the low - temperature environment on the cubic compressive strength of naturally cooled recycled concrete showed significant differences.

Jia Fuping et al. [12] adopted natural cooling and water - pouring cooling methods for concrete test blocks that had experienced high temperatures of 250°C, 450°C and 650°C to study the influence of standing time and cooling methods on the residual compressive strength of concrete after high temperature. It was found that with the increase of temperature, the concrete strength continued to decay, and the time taken for the residual strength to decrease gradually under natural cooling was longer than that under water - pouring cooling.

Guo Jiadong [13] studied the mechanical properties of lightweight aggregate concrete at normal temperature and after high temperature under different fibers and cooling methods. The results showed that polypropylene fibers could significantly inhibit high - temperature spalling and improve brittle failure, and also could increase the compressive strength and splitting tensile strength of concrete. However, with the increase of fiber content, the strength would decrease. When the temperature was too high, water spraying cooling would accelerate the reduction of the strength of lightweight aggregate concrete, and at this time, the residual strength of the specimens was lower than that under natural cooling.

Gao Fangfang [14] studied the influence of natural cooling, water immersion cooling and water spraying cooling on the mechanical properties of concrete after high temperature. The results showed that the compressive strength, energy absorption and impact toughness of the specimens cooled by water spraying were better than those of the groups cooled by water immersion and natural cooling, and the higher the temperature, the more significant the influence of cooling methods on performance differences.

Sun Chuanwu et al. [15] studied the influence of fiber content, fiber hybrid mode and fiber type on the mechanical properties of concrete after high temperature, and also explored the effect of different cooling methods on concrete strength. The test showed that under the same temperature and the same cooling method, the compressive strength and flexural strength of concrete mixed with glass fibers and polypropylene fibers were better than those of non - fiber concrete and concrete with single fiber. The compressive strength of each group of concrete showed a downward trend at 200℃, rebounded between 200℃ and 400℃, and decreased sharply after 400℃.

Pang Jianyong et al. [16] studied the influence of natural cooling and water spraying cooling on the performance degradation of basalt fiber - reinforced concrete after high temperature, and analyzed the changes in the mechanical properties of basalt fiber - reinforced concrete under different temperatures and cooling methods. The results showed that under the same temperature and different cooling methods, the peak strain of basalt fiber - reinforced concrete and non - fiber concrete under water spraying cooling was significantly greater than that of concrete under natural cooling, while the elastic modulus under natural cooling was higher than that under water spraying cooling.

In addition, studies have found that cooling methods have different effects on the mechanical properties of lightweight aggregate concrete after high temperature.

3. Conclusion and Outlook

In summary, domestic and international scholars have conducted numerous mechanical tests to study the mixing effects between different types of fibers and improve the mechanical properties of lightweight aggregate concrete. The findings are summarized as follows:

(1) The improvement in the mechanical properties of lightweight aggregate concrete due to the mixing of fibers is not simply the result of adding more fibers. The key lies in the mixing effects produced between the fibers. When the dosage of various types of fibers is either too high or too low, it can have an adverse effect on the mechanical properties of lightweight aggregate concrete.

(2) Different types of fibers exhibit significant differences in their effects on lightweight aggregate concrete. Specifically, polypropylene fibers demonstrate outstanding performance in enhancing the high-temperature blast resistance of lightweight aggregate concrete while effectively improving its brittle fracture morphology; steel fibers, on the other hand, offer greater advantages in enhancing mechanical properties, comprehensively strengthening key indicators such as compressive strength and flexural strength of lightweight aggregate concrete.

(3) The addition of fibers can effectively improve the mechanical properties of lightweight aggregate concrete after high-temperature exposure, including compressive strength, splitting tensile strength, and flexural strength. However, it is important to note that while fibers can enhance concrete strength, their strength still decreases with increasing temperature. Notably, mixed-fiber concrete exhibits relatively high residual strength after high-temperature exposure,

a performance that significantly outperforms single-fiber-reinforced concrete and plain concrete.

(4)The elastic modulus of lightweight aggregate concrete under natural cooling is higher than that under water spraying cooling, while the peak strain of concrete under water spraying cooling is higher than that of lightweight concrete under natural cooling.

Outlook: Currently, there are still some issues in the research on high-temperature performance testing of concrete. First, most tests use electric furnaces for heating, but electric furnace heating cannot effectively simulate the conditions encountered by actual structures or components during a fire. In actual fires, temperatures rise rapidly and remain elevated for an extended period. Additionally, when structures are exposed to fire, components are often subjected to fire on one or three sides, resulting in highly uneven temperature distributions within the concrete. In an electric furnace, the specimen is heated uniformly on all six sides, and the heating rate is often determined by the maximum power of the furnace. Second, during testing, the components are often in a state of free deformation without restrictions on their expansion deformation. However, in actual concrete structures or components exposed to fire, external loads still exist, meaning that loads and fire coexist. The presence of external loads restricts the expansion deformation of concrete under fire conditions. Domestic research needs to strengthen studies on the long-term performance of concrete under high-temperature conditions. Third, most studies focus on changes in concrete performance under short-term high-temperature conditions, while the effects of long-term high-temperature exposure on concrete are less explored. However, in actual engineering applications, concrete structures may need to withstand high-temperature environments for extended periods, making research on the bending performance of concrete under long-term high-temperature conditions of significant importance.

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