ISSN: 1813-4890

Discussion on hybrid fiber lightweight aggregate concrete after fire

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Abstract

Tunnel fires can reduce the mechanical performance and durability of tunnel lining concrete structures, severely affecting the later use of tunnel segments. Lightweight aggregate concrete has advantages in applicability, durability, workability, and economy. There are types of lightweight aggregates such as natural aggregates, artificial lightweight aggregates, and industrial waste lightweight aggregates, with the main use being ceramic foam aggregates, which have high cylindrical compressive strength, high porosity, and corrosion resistance. Under high temperatures of fire, steel fibers can effectively enhance the flexural strength and toughness of lightweight aggregate concrete, while polypropylene fibers have a low melting point to prevent concrete from bursting. The combined action of these two types of fibers, with clear division of labor, can reduce the loss of fire tunnels.

Keywords

Fiber concrete, tunnel fires, lightweight aggregate concrete, steel fibers, polypropylene fibers.

1. Research Background and Significance

The impact of fire on concrete structures is multifaceted, involving the reduction of material performance and the threat to structural safety. Under the action of high temperatures, the mechanical properties of concrete will change significantly, including the reduction of compressive strength, flexural strength, and splitting tensile strength. Studies have shown that when the temperature rises to 800°C, the compressive strength of concrete may drop to 50%-75% of that at room temperature [1]. In addition, fires can also cause cracks and spalling inside the concrete, affecting the integrity and durability of the structure.

Hybrid fiber lightweight aggregate concrete, due to its excellent mechanical properties and lightweight characteristics, has a broad application prospect in modern construction engineering. The addition of hybrid fibers, especially steel and polypropylene fibers, can effectively enhance the compressive strength and crack resistance of concrete, thereby enhancing its toughness and stability under extreme conditions such as fire. The use of lightweight aggregates reduces the self-weight of the structure, improves heat insulation and sound insulation effects, and is suitable for high-rise buildings and bridge construction. With the construction industry's emphasis on sustainable development and energy efficiency, the environmental and energy-saving advantages of hybrid fiber lightweight aggregate concrete are also increasingly valued.

2. Literature Review

2.1. Domestic and International Research Status

As a new type of structural material, hybrid fiber lightweight aggregate concrete has attracted extensive attention and research in recent years. Internationally, several research teams are committed to exploring the application effects of hybrid fibers in lightweight aggregate concrete, especially in improving the mechanical properties of the material.

Taotao Cui et al. [2] studied the bending fatigue behavior of hybrid fiber reinforced high-strength lightweight aggregate concrete under different stress levels, including fatigue life and crack propagation process. The results show that under a constant stress level, the failure life of hybrid fiber reinforced high-strength lightweight aggregate concrete is the longest. As the stress level increases, the impact of hybrid fibers on failure life is more significant. With the increase of loading cycles, the addition of fibers extends the duration of the stable development stage, thereby extending the fatigue life of high-strength lightweight aggregate concrete. Compared with single-fiber reinforced high-strength lightweight aggregate concrete, hybrid fiber reinforced high-strength lightweight aggregate concrete shows the longest stable development duration. Hybrid fibers can minimize the crack propagation rate of high-strength lightweight aggregate concrete.

Gilbert Sebastiano Gondokusumo et al. [3] studied the residual flexural strength of ordinary and lightweight concrete beams with different fiber contents, heated in a furnace at temperatures ranging from 200°C to 800°C, and then subjected the specimens to three-point bending loading to assess the residual flexural strength at high temperatures. The results show that steel fiber reinforced concrete can maintain ductility even at high temperatures up to 800°C. During the test, no specimen was completely broken. All specimens can maintain hardening behavior. The residual flexural strength of steel fiber reinforced concrete decreases with the increase of temperature. The content of steel fibers and the type of concrete have no significant effect on the deterioration of the flexural strength of steel fiber reinforced concrete specimens at high temperatures.

Fatih Altun and Bekir Aktas [4] made lightweight concrete and reinforced concrete beam specimens by adding steel fibers of different strengths and proportions. The specimens were tested by four-point loading experiments, and their practicality for building components was studied. The results show that the addition of steel fibers improves the toughness and ductility of prismatic concrete beams. Steel fibers also improve the bearing capacity and ductility of reinforced concrete beams. Through this experimental study, the addition of steel fibers improves the performance of reinforced concrete beams. It is also concluded that in the design of reinforced concrete beams, it is possible to consider adding lightweight concrete to reduce static loads.

Jingjun Li et al. [5] proposed a new method for designing steel fiber reinforced self-compacting lightweight aggregate concrete mixtures, and studied the impact of steel fiber content on the workability and mechanical properties (including compressive strength, splitting tensile strength, and flexural toughness) of self-compacting lightweight aggregate concrete. The results show that the new mixing method can quantitatively determine the content of raw materials. The addition of fibers reduces the filling ability and passing ability of self-compacting lightweight aggregate concrete, but improves the anti-segregation of self-compacting lightweight aggregate concrete. The improvement effect of micro steel fibers on the mechanical properties such as compressive strength, splitting tensile strength, and bending toughness of self-compacting lightweight aggregate concrete is significantly better than that of long steel fibers.

P.V. Ramana [6] studied the impact of single-length (12 mm) polypropylene fibers on the mechanical, microstructural, and thermal behavior of standard strength concrete. The results show that fibers effectively improve the flexural and compressive strength of concrete, while reducing the tensile strength and wear resistance of concrete; the ability of fibers to bear loads outside the matrix cracking is greater than that of concrete; fibers effectively improve the compressive strength and flexural strength of concrete, while reducing the fracture stress and wear of concrete.

Chen Bo'an et al. [7] studied the fracture energy of fiber lightweight aggregate concrete before and after changes at 25, 200, 400, and 600°C through three-point bending fracture tests. The results show that steel fibers improve the toughness of lightweight aggregate concrete and improve the brittleness of lightweight aggregate concrete; on the one hand, high temperature reduces the bearing capacity of lightweight aggregate concrete, but on the other hand, it improves the deformation ability of lightweight aggregate concrete.

Yang Nan [8] conducted experimental studies on the workability and mechanical properties of high-alkali-resistant glass fiber and hybrid fiber high-performance concrete. The results show that polypropylene fibers and glass fibers are not much different in resisting the free shrinkage of concrete in the early age, and both have an impact on the energy absorption before concrete beams crack, ultimate bearing capacity, flexural strength, and toughness after the beams crack.

Thomas Gernay et al. [9] discussed the use of concrete models in the performance-based structural fire engineering framework, and introduced several examples of numerical simulation based on the nonlinear finite element method, focusing on practical applications with high requirements for material models. The results show that a new high-temperature concrete model has been developed based on the plastic damage formula. The concrete model has been used for numerical simulation carried out by finite element software specifically for the analysis of building structures in fires. The purpose is to demonstrate the functionality of the concrete model in a performance-based framework and to show that it can be used for practical applications in fire engineering.

Gaole Zhang et al. [10] developed a finite element model to evaluate the fire resistance of composite lining segments by simulating the thermo-mechanical behavior under fire conditions. A finite element model of a single composite segment, segment-to-segment joint, and full segment lining was established in ABAQUS. The model was verified and compared with the results of three experiments. Based on the calibrated finite element model, the carrying capacity of the three models at normal temperature and after fire was first studied. Then the temperature distribution and deformation mode were studied. The results show that under the action of fire load, the carrying capacity and flexibility of the composite segment joints may be significantly reduced; concrete damage is mainly caused by the rise in temperature during the fire process and the corresponding deformation of the entire lining ring as different components expand. The covering of steel plates enhances the fire resistance of the composite segment. The proposed finite element model can be used to simulate the thermo-mechanical behavior of other types of composite structures with reasonable material properties.

Sam Fragomeni et al. [11] summarized the research progress of large-scale fire tests on concrete tunnel linings in recent years, focusing on the methods, problems, and challenges of large-scale fire tests on tunnel lining concrete, as well as the current design guidelines. The results show that it is important to apply vertical loads through a rocking saddle mechanism to eliminate inaccurate bending and axial stresses on the tunnel lining segments. Current design standards need to be updated to reflect the need to address structural cracking of specimens during the heating process in the design process.

2.2. Research Gaps and Problem Statement

Despite certain progress, research on the mechanical properties of hybrid fiber lightweight aggregate concrete under extreme conditions, such as after fire, is still insufficient. Fire, as a common disaster, poses a serious threat to the safety of building structures. Therefore, understanding the mechanical properties of hybrid fiber lightweight aggregate concrete after fire is crucial for assessing its potential for application in practical engineering.

At present, research on the mechanical properties of hybrid fiber lightweight aggregate concrete after fire is still in a blank state. Experimental research is needed to explore the impact of fire on the mechanical properties of hybrid fiber lightweight aggregate concrete, including compressive strength, flexural strength, and splitting tensile strength.

In addition, changes in the internal structure of concrete after fire, such as the expansion of microcracks and changes in the bond performance between fibers and the matrix, are also issues that need in-depth study. This will help to reveal the synergistic reinforcement mechanism of hybrid fibers under fire conditions and provide a theoretical basis for improving the post-fire performance of lightweight aggregate concrete.

3. Heoretical Model Construction of the Mechanical Properties of Hybrid Fiber Lightweight Aggregate Concrete After Fire

When constructing the theoretical model of the mechanical properties of hybrid fiber lightweight aggregate concrete after fire, we first need to clarify several key assumptions, which will provide the basis for the establishment and subsequent analysis of the model.

Assumption 1: Material Continuity It is assumed that under the action of fire, the basic physical and chemical properties of hybrid fiber lightweight aggregate concrete maintain continuity, that is, the composition and structure of the material do not undergo abrupt changes macroscopically.

Assumption 2: Uniformity of Temperature Distribution During the fire process, the temperature distribution inside the concrete can be considered relatively uniform, or an effective temperature field model can be used to approximate its distribution characteristics.

Assumption 3: Bonding Action of Fibers and Matrix The bonding action between hybrid fibers and the lightweight aggregate concrete matrix remains consistent before and after the fire, that is, the bond strength will not change significantly due to the increase in temperature.

Assumption 4: Recoverability of Mechanical Properties After the fire, some mechanical properties of concrete (such as compressive strength, tensile strength, etc.) have a certain recoverability under certain conditions, which may be achieved through subsequent curing or repair measures.

Assumption 5: Locality of Damage The damage caused by fire is mainly limited to the surface or near-surface area, with the internal structure relatively intact, providing a basis for the post-fire structural performance assessment and repair.

Assumption 6: Independence of Load Action The action of fire and the subsequent mechanical load can be considered as independent processes, that is, the impact of fire on concrete performance will not produce a coupling effect with mechanical loads.

Assumption 7: Material Performance Degradation Model Establish a mathematical model that describes the performance degradation of hybrid fiber lightweight aggregate concrete under the action of high temperature, which can reflect the specific impact of different temperature levels on material performance.

Assumption 8: Validity of Test Data The theoretical model based on existing test data can accurately predict the mechanical properties of hybrid fiber lightweight aggregate concrete after the fire, including but not limited to compressive strength, flexural strength, elastic modulus, etc.

Through these assumptions, we can construct a theoretical model that will comprehensively consider the impact of fire on the microstructure and macro performance of hybrid fiber lightweight aggregate concrete, and then predict the mechanical behavior of the material after the fire. The establishment of the model will provide a theoretical basis for the safety assessment and repair of structures after the fire.

4. Engineering Application and Suggestions for Hybrid Fiber Lightweight Aggregate Concrete After Fire

4.1. Structural Repair and Reinforcement Suggestions

Post-fire structural repair and reinforcement of hybrid fiber lightweight aggregate concrete are important measures to ensure engineering safety and extend the service life of structures. Based on existing research and engineering practice, the following are some specific suggestions:

Conduct a comprehensive damage assessment of the structure after the fire, including tests on the mechanical properties such as compressive strength and elastic modulus of concrete, as well as assessments of the bond performance between steel reinforcement and concrete.

Develop targeted repair plans based on the results of the damage assessment. For slightly damaged structures, surface treatment and local reinforcement methods can be used; for moderately damaged structures, partial replacement of damaged components may be necessary; and for severely damaged structures, overall reinforcement or reconstruction of the structure may be required.

Use high-performance repair materials, such as polymer-modified cement mortar, fiber-reinforced composite materials, etc., to improve the performance and durability of the repaired structure.

Considering the characteristics of hybrid fiber lightweight aggregate concrete, the reinforcing effect of fibers should be fully utilized in the repair process. By reasonably designing the type, volume ratio, and distribution of fibers, the crack resistance and toughness of the repaired structure can be improved.

4.2. Fire Protection Design and Material Selection

Fire protection design is the first line of defense to prevent fire damage to structures. The following are some suggestions in terms of fire protection design and material selection:

Consider the fire protection requirements of the structure in the design phase and choose appropriate fire protection materials and construction measures, such as setting up fire walls, using components with high fire resistance, etc.

Hybrid fiber lightweight aggregate concrete, due to its lightweight, high strength, and good fire resistance, can be the preferred material for fire protection design. When selecting materials, the fire resistance of fiber types and lightweight aggregates, as well as their impact on the fire resistance of concrete, should be considered.

For structures that may be exposed to fire, fire resistance performance test research should be carried out to assess the structural response and damage patterns under different fire scenarios.

In fire protection design, the repair and reinforcement of structures after a fire should also be considered. Choose materials and construction plans that are easy to repair and reinforce to reduce the difficulty and cost of post-fire repair.

Through the above measures, the fire safety and post-fire repair efficiency of hybrid fiber lightweight aggregate concrete structures can be effectively improved.

5. Conclusion and Prospects

For the mechanical properties of hybrid fiber lightweight aggregate concrete after fire, future research can be carried out in the following aspects:

Further optimize the types, ratios, and surface treatment methods of hybrid fibers to achieve better mechanical and fire resistance properties.

Explore the matching of different types of lightweight aggregates with hybrid fibers, and study how to improve the overall performance of concrete through the physical and chemical properties of lightweight aggregates.

Strengthen research on the damage mechanism of concrete after fire, and analyze in depth the impact of hybrid fibers on the internal structure and performance of concrete.

Carry out long-term durability research to evaluate the service life and maintenance needs of hybrid fiber lightweight aggregate concrete in practical engineering.

Expand the research scope and consider the impact of different environmental factors such as humidity and temperature on the performance of hybrid fiber lightweight aggregate concrete.

References

[1] Hao Shaoju, Ma Jing. Hybrid fiber synergistic reinforcement of the mechanical properties of lightweight aggregate concrete[J]. China Measurement & Test, 2022, 48(6): 128-133.

[2] Cui T, Ning B, Shi X, et al. Flexural fatigue behavior of hybrid steel-polypropylene fiber reinforced high-strength lightweight aggregate concrete[J]. Construction and Building Materials, 2023, 377: 131079.

[3] Gondokusumo G S, Venkateshwaran A, Li S, et al. Residual flexural tensile strength of normal-weight and lightweight steel fibre-reinforced concrete at elevated temperatures[J]. Construction and Building Materials, 2023, 367: 130221.

[4] Altun F, Aktaş B. Investigation of reinforced concrete beams behavior of steel fiber added lightweight concrete[J]. Construction and Building Materials, 2013, 38: 575-581.

[5] Li J, Zhao E, Niu J, et al. Study on mixture design method and mechanical properties of steel fiber reinforced self-compacting lightweight aggregate concrete[J]. Construction and Building Materials, 2021, 267: 121019.

[6] Ramana P V. Temperature effect and microstructural enactment on recycled fiber concrete[J]. Materials Today: Proceedings, 2022, 66: 2626-2635.

[7] WANG Huailiang, Chen Baian, Xie Bao. Study on fracture energy of steel fiber lightweight aggregate concrete before and after high temperature [J]. Concrete,2020,(06):11-14. Harmathy TZ. Effect of moisture on the fire endurance of building elements[J]. Astm Special Technical Publication, 1965, 385: 74-95.

[8] Yang Nan. Experimental study on glass fiber and hybrid fiber high performance concrete [D]. Dalian University of Technology,2006.

[9] Gernay T, Franssen J M. A plastic-damage model for concrete in fire: Applications in structural fire engineering[J]. Fire Safety Journal, 2015, 71: 268-278.

[10] Peng G F, Bian S H, Guo Z Q, et al. Effect of thermal shock due to rapid cooling on residual mechanical properties of fiber concrete exposed to high temperatures[J]. Construction and Building Materials, 2008, 22(5): 948-955.

[11] Lee W M, Fragomeni S, Monckton H, et al. A review of test Methods, issues and challenges of Large-Scale fire testing of concrete tunnel linings[J]. Construction and Building Materials, 2023, 392: 131901.