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Fiber Lightweight Aggregate Pipe Segment Fire Performance Study

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Abstract

The material characteristics of fiber lightweight aggregate concrete pipes were analyzed, along with the bending toughness of fiber lightweight aggregate concrete. A review was conducted on the bending resistance performance of fiber concrete beams and pipes at normal and high temperatures domestically and internationally. It was found that steel fibers and polypropylene fibers exhibit a positive synergistic effect when used together. They enhance toughness and ductility significantly, contributing greatly to bending toughness. Hybrid fibers can partially replace steel reinforcement, optimize the arrangement of reinforcement, and improve the residual load-carrying capacity of concrete pipes. They effectively address issues such as tight reinforcement spacing in shield tunneling pipes.

Keywords

Fiber; Lightweight Aggregate; Pipe Segment; Fire; Mechanical Performance.

1. Introduction

In recent years, there has been a strong national push to develop expressways, high-speed railways, and subway systems. An increasing number of underground tunnel and pipeline projects such as subways, submarine tunnels, gas pipelines, and heating pipelines have been developed and constructed [1–3], thereby promoting rapid tunnel development. In recent years, tunnel fires have occurred frequently both domestically and internationally. The rupture and collapse of tunnel segments and the reduction rate and magnitude of the ultimate bearing capacity of tunnel segments during fires directly affect the overall integrity of underground structures. Once a tunnel fire occurs, it poses serious threats to personal and property safety.

In tunnel construction, the most commonly used method is shield tunneling, and prefabricated reinforced concrete pipe segments are an indispensable part of shield tunnel systems. Traditional tunnel segments have dense reinforcement and heavy weight, requiring high demands on design, construction, and transportation. During segment production, insufficient compaction of concrete often occurs, causing surface defects such as roughness and air bubbles after hardening. Ordinary reinforced concrete segments are prone to internal surface cracking during fires, exposing the reinforcement to high temperatures. The tensile strength of reinforcement decreases linearly at high temperatures [4–7], leading to a sharp reduction in segment load-bearing capacity during fires.

Lightweight aggregate concrete has advantages such as lightweight, high strength, and good fire resistance. Polypropylene fibers have a low melting point and can prevent concrete from cracking during fires. Steel fibers can partially bear tensile forces after concrete cracking, thereby improving residual load-bearing capacity of the segments. Incorporating hybrid fibers into lightweight aggregate concrete instead of some steel reinforcement can enhance the mechanical performance of the segments. The application of hybrid fibers in tunnel segments

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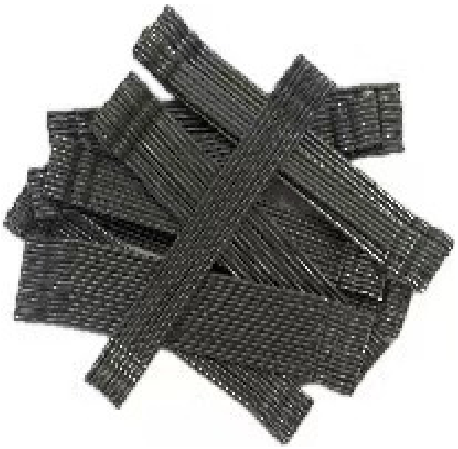
can prevent concrete collapse and cracking after fires, maintaining certain residual load-bearing capacity [8–11].

Currently, the commonly used experimental methods for shield tunnel segments both domestically and internationally include the rod arch method, the simply supported beam method with constant axial force, and the symmetrical inclined beam method. The symmetrical inclined beam method proposed by European scholars for simulating the stress state of tunnel segments has been adopted by domestic scholars for room temperature and high-temperature tests. Compared with traditional segment testing methods, the symmetrical inclined beam method has advantages such as simple fabrication, axial force varying with external forces, and the ability to reflect the stress states of segments with different curvatures by changing the beam end inclination angle. This method is more suitable for laboratory research.

2. Current Research Status on Fiber Lightweight Aggregate Concrete Materials Performance

In recent years, both domestic and international scholars have conducted extensive research on fiber lightweight aggregate concrete (FLAC). FLAC, a novel type of concrete material, is widely utilized in high-rise buildings and bridge engineering due to its advantages of high strength, lightweight, and environmental friendliness.



(a) steel fiber

(b) synthetic steel fiber

(c) polypropylene fiber

(d) fly ash lightweight aggregate

Fig 1. Appearance of the material

Zhao Shunbo [12] studied the uniaxial compressive stress-strain behavior of lightweight aggregate concrete with varying volumes of steel fibers. It was found that the cement strength grade influences the peak stress and corresponding strain of the stress-strain curve, with minimal impact on curve shape and specimen failure mode. The volume of steel fibers significantly affects the curve, increasing peak strain and reducing the slope of the descending segment. Failure modes transitioned from primary inclined cracks to lateral expansion and vertical crack failure, indicating reduced brittleness and increased ductility during failure.

Zhang Zhiyin [13] investigated the mechanical properties of high-strength lightweight aggregate concrete (HLAC) by incorporating different types and volumes of steel fibers. The study revealed that compressive strength, splitting tensile strength, and flexural strength increase with higher fiber volume, albeit with diminishing returns. Poor workability was observed at higher fiber volumes, suggesting optimal inclusion rates of 0.5%-1.0% for fine fibers and 1.0%-1.5% for large fibers. Steel fibers notably enhance HLAC's shear performance, with micro-fibers showing significant improvements in shear strength and toughness at lower volume rates (0.5%-1.0%).

Wu Tao [14] examined the workability, mechanical properties, and microstructure of self-compacting lightweight aggregate concrete blended with steel and polypropylene fibers. Results demonstrated synergistic crack resistance effects at different structural levels and loading stages, significantly enhancing splitting tensile strength and flexural strength. Despite increased compaction at the aggregate-matrix interface with prolonged curing periods, micro-pores persisted between fibers and the matrix, maintaining a relatively loose structure in the interface zone.

Wei Hui [15] investigated the stress-strain behavior of FLAC through prism tests under various concrete grades, fiber types, and volumes. Their systematic study revealed that fibers effectively inhibit crack propagation, enhancing crack resistance and toughness.

Li Qing et al. [16] conducted early-age compressive strength and elastic modulus tests to assess the impact of externally added steel fibers on early-stage concrete mechanical properties. Their findings indicated a moderate increase in early-stage elastic modulus due to steel fiber addition, with insignificant improvements in early-age compressive strength.

These studies collectively highlight the diverse applications and performance enhancements achievable through fiber lightweight aggregate concrete, contributing valuable insights for its practical implementation in construction engineering.

3. The Current Research Status of Bending Toughness of Fiber Lightweight Aggregate Concrete

Yanxia Ye [17] added different types of steel fibers to high-strength lightweight aggregate concrete, with volume fractions ranging from 0.5% to 2.0%. The study indicates that with increasing volume fraction of steel fibers, both the mechanical strength and toughness of high-strength lightweight aggregate concrete show an increasing trend. Among the steel fiber types, fine steel fibers exhibit the best enhancement in both strength and toughness. Hooked-end steel fibers show similar effects to fine steel fibers in improving flexural strength but are less effective in other aspects of mechanical strength and toughness enhancement. Crimped steel fibers show relatively poorer enhancement effects on high-strength lightweight aggregate concrete.

Zhiguo You [18] conducted four-point bending tests on 15 beams of fiber hybrid self-compacting concrete and found that the residual flexural strength of beams with PP fibers (length 45mm, aspect ratio 60) was higher compared to TF fibers (length 30mm, aspect ratio 45). Longer fibers with larger aspect ratios exhibit higher residual flexural strength.

Yining Ding [19] conducted experiments on the bending strength and shear toughness of steel fiber self-compacting concrete. The study indicates that steel fibers can increase the bending

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and shear strength of concrete and improve its bending and shear toughness, with enhancement effects increasing with fiber content.

Bywalski [20] performed three-point bending tests on notched beams of steel fiber concrete, analyzing bending strength, fracture energy, and bending toughness. The study shows that steel fibers with a length of 20mm and diameter of 0.3mm significantly affect the tensile strength of concrete, with a weaker impact on compressive strength. A 1.0% volume fraction of steel fibers increases tensile strength by 95.0%, while a 1.5% volume fraction increases it by 132.1%. Furthermore, the addition of steel fibers notably increases the toughness of concrete.

Ghasemi [21] conducted notched beam three-point bending tests under different water-cement ratios, maximum aggregate sizes, and varying steel fiber contents, analyzing fracture energy and bending toughness of concrete beams. The study demonstrates that hooked-end steel fibers with a length of 30mm and diameter of 0.6mm have a minimal effect in higher water-cement ratio concrete and a more significant effect in lower water-cement ratio concrete, effectively enhancing the bending toughness and fracture energy of concrete. Steel fiber contents in this study were 0.1%, 0.3%, and 0.5%.

4. The Current Research Status on the Flexural Performance of Fiber-Reinforced Concrete Beams and Pipe Sections at Normal and High Temperatures

Currently, research on the mechanical properties of shield tunnel segments primarily focuses on ordinary reinforced concrete segments under normal and high-temperature fire conditions, with limited studies on the high-temperature performance of fiber-reinforced concrete (FRC) segments. Particularly lacking are studies on the performance of hybrid fiber FRC segments under fire and high-temperature conditions.

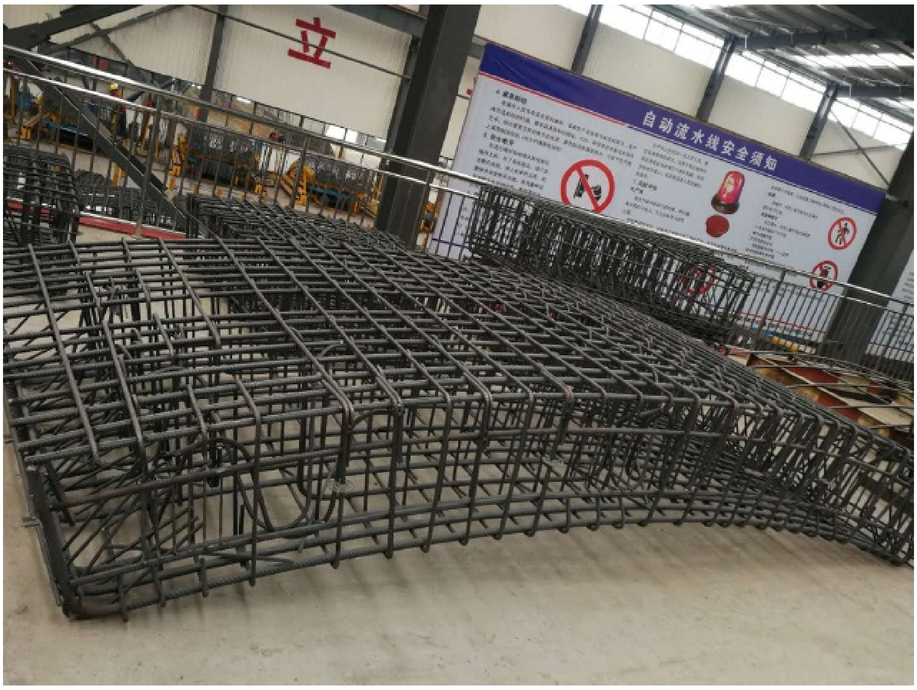

Fig 2. Traditional segment reinforcement

Zhang Cong [22] simplified the stress behavior of shield tunnel symmetric inclined beams to study the flexural performance, crack formation, and deflection changes of symmetric inclined beams reinforced with different fibers under normal and high-temperature conditions. The experiments indicated that fiber incorporation resulted in slower and more frequent crack propagation with smaller crack spacing post-cracking. Notably, steel fibers significantly reduced the average crack spacing compared to structural polypropylene fibers and controlled crack spacing better. Using steel fibers alone or in combination with structural polypropylene fibers increased the maximum load-bearing capacity and strength limit of the beams, albeit this improvement gradually diminished with increasing reinforcement ratios.

Jiang Jinbo [23] conducted bending tests on four steel fiber-reinforced concrete beams, showing enhanced crack loads, load-bearing capacity, and ductility after the addition of steel fibers. The average strain in the beam sections adhered to the assumption of plane sections after cracking.

Xie Xi [24] investigated the post-high-temperature performance of hybrid fiber cement mortar beams, where fiber incorporation altered the failure mode. Steel fibers suppressed crack propagation and exhibited good thermal conductivity. Fiber inclusion increased both crack initiation load and peak load, ensuring continued fiber functionality post-high temperatures.

Liang Yu [25] studied hybrid fiber self-compacting concrete beams and symmetric inclined beams under high temperatures, finding that steel fiber incorporation reduced internal temperature gradients within concrete. Polypropylene fibers melted at high temperatures, exacerbating internal temperature gradients but preventing concrete spalling and protecting exposed reinforcement. Mechanical performance changes in beams pre- and post-high temperatures were fiber combination-dependent; excessive polypropylene fiber content reduced post-high-temperature mechanical properties of hybrid fiber self-compacting concrete beams.

Gao Danying [26] substituted some cement with slag micropowder to study the bending performance of fiber slag micropowder concrete post-high temperatures. The bending ductility and flexural strength of fiber slag micropowder concrete decreased with increasing temperature, with optimal improvement in flexural performance observed at 40% slag micropowder content. Steel and polypropylene fibers enhanced the flexural strength of fiber slag micropowder concrete post-high temperatures.

Fan et al. [27] designed and manufactured 7 reinforced concrete short beams to study their performance under high temperatures. Their experiments showed that concrete spalling significantly affects the temperature distribution, deflection rate, and failure time of short beams. Generally, spalled specimens experience higher concrete temperatures, greater deflection rates, and shorter failure times.

Cong Zhang [28] created 12 fire-resistant self-compacting concrete (SCC) beams with added steel fibers, long polypropylene (PP) fibers, and micro PP fibers to evaluate the impact of mixed fibers on the bending performance of tunnel lining segments. The addition of fibers increased the ultimate load of the beams, with PP fiber-reinforced beams showing smaller and denser cracks. Steel fibers had a greater impact on the load-bearing capacity of fire-resistant self-compacting beams compared to long PP fibers, while micro PP fibers had no significant effect.

M. Shariq [29] experimentally investigated the bending response of high-strength reinforced concrete (RC) beams with and without steel fibers after exposure to high temperatures. The RC beams were tested under four-point loading. The study found that adding fibers to RC beams results in ductile failure and delays the onset of bending and shear cracks, both at room temperature and after high-temperature exposure. At 200°C, high-strength RC beams with steel fibers exhibited higher ultimate load capacity compared to those without.

Zainab M.R. Abdul Rasoul [30] studied the mechanical properties of reinforced concrete beams with different volumes of waste polypropylene fibers (WPPF) under normal and fire conditions. It was found that the mechanical properties of fiber-free reinforced concrete beams significantly deteriorated at 400°C, while the crack load was significantly improved with the addition of fibers.

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Srishti Banerji [31] conducted fire tests on five ultra-high-performance fiber-reinforced concrete (UHPFRC) beams and found that, compared to traditional high-strength concrete beams, UHPFRC beams experienced easier spalling in the compressive zone. Adding polypropylene fibers to the beams helped reduce the extent of spalling. Higher load levels facilitated the release of pore pressure through tensile cracking, thereby reducing the degree of spalling in UHPFRC beams.

5. Conclusion

The addition of steel fibers can significantly increase the compressive strength, splitting tensile strength, and flexural strength of concrete, with strength decreasing with increasing fiber content. Steel fibers and polypropylene fibers work synergistically, with polypropylene fibers having the greatest impact on compressive strength and steel fibers having the greatest impact on splitting tensile strength. The inclusion of fibers alters the failure mode under uniaxial compression and inhibits crack propagation. Polypropylene fibers have a crack-resistant effect at high temperatures. This provides a basis for fiber selection in this study, which will use a combination of steel fibers, polypropylene macro-synthetic fibers, and polypropylene short fibers. This combination can prevent concrete from spalling at high temperatures and improve the material properties of concrete.

Steel fibers and polypropylene fibers enhance toughness and contribute significantly to flexural toughness. Their combined action exhibits positive hybrid effects. This serves as a basis for fiber selection in this study, which will use a combination of steel fibers, polypropylene macro-synthetic fibers, and polypropylene short fibers. This combination can prevent concrete from spalling at high temperatures and improve the material properties of concrete.

Hybrid fibers can partially replace steel bars, optimize reinforcement configuration, enhance the residual load-carrying capacity of tunnel segments, and effectively address issues such as tight reinforcement spacing in shield tunnel segments. Polypropylene fibers also prevent concrete spalling under high-temperature conditions. Furthermore, the combined action of steel bars and fibers helps improve the fire resistance performance of concrete structures under high temperature.

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