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A review of the high-temperature properties and mechanism of fiber high-performance concrete

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Abstract

The mechanical properties of fiber-reinforced concrete are superior to those of ordinary concrete, and it has garnered increasing attention in recent years. In practical applications, the high-temperature resistance of fiber-reinforced concrete is of particular concern. This paper analyzes and summarizes the research findings on the high-temperature performance of fiber-reinforced concrete, reviews the research on the mechanism of concrete spalling, and elaborates on four types of spalling mechanisms: pore water pressure, steam pressure cracking, thermal stress, and thermal cracking. It also reviews the relevant literature on polypropylene fiber, basalt fiber, and steel fiber concrete, and provides a systematic summary of the current state of research on fiber-reinforced concrete in high-temperature environments. Current research indicates that under high-temperature conditions, the addition of polypropylene fibers, basalt fibers, and steel fibers all significantly enhance the compressive strength of fiber-reinforced concrete, with the reinforcing effect of steel fibers being superior to that of polypropylene fibers and basalt fibers. The use of polypropylene fibers and steel fibers, either singly or in combination, can effectively improve the high-temperature performance of concrete.

Keywords

Fiber concrete, fires, steel fibers, polypropylene fibers.

1. Introduction

Fiber concrete, as an innovative material, exhibits significant advantages over traditional reinforced concrete in many aspects. It not only has higher initial cracking strength, but also has significant improvements in compressive and tensile strength, which makes it excel in bearing heavy loads or complex stress conditions. In addition, the fracture toughness and impact resistance of fiber concrete are also outstanding, which makes it increasingly used in modern construction engineering. However, the performance of fiber concrete may be severely affected by extreme conditions such as fire. Fire not only destroys the integrity of the structure, but also may cause physical and chemical changes due to high temperature, which lead to a decrease in material performance. In the case of fire, the thermal stability and heat resistance of the cementitious material become particularly important because they directly affect the durability and safety of the concrete structure. [1]

In order to improve the stability and safety of fiber concrete in high-temperature environments such as fires, it has become particularly critical to conduct in-depth research on its mechanical properties at high temperatures. This not only involves the material's thermal stability, but also its stress-strain behavior, crack development patterns, and overall structural load-bearing capacity at high temperatures. Through these studies, theoretical basis and technical support can be provided for the application of fiber concrete in extreme conditions, thereby enabling the design of safer and more reliable engineering structures.

The performance of fiber concrete is greatly influenced by the type of fiber used, especially in high-temperature environments. Different fibers have significant effects on the residual properties of concrete due to their chemical and physical characteristics. At present, steel fibers and polypropylene fibers are the two most widely studied fiber types. Their application in fiber concrete not only improves its resistance to cracking and toughness, but also provides additional protection in fire conditions. [2-4]

In addition to steel fibers and polypropylene fibers, other types of fibers such as copper-plated fibers, glass fibers, polymer fibers, basalt fibers, and natural plant fibers are also used to enhance the performance of concrete. These fibers can be divided into two categories based on their role in fire protection: one is the fiber with good thermal stability, such as steel fibers, carbon fibers, and basalt fibers, which can maintain their strength at high temperatures and bridge cracks through the bridge effect; the other is the low-melting-point fiber, such as polypropylene fibers, PVA fibers, and PE fibers, which will melt when heated and provide channels for the release of water vapor, thereby reducing internal steam pressure and protecting the microstructure of concrete. [5]

In this paper, the influence of the composition of different fiber concrete mixtures on their mechanical behavior at high temperature is discussed. Through the analysis of different heating methods used in material testing, the law of material properties of fiber reinforced concrete changing with temperature is revealed. In addition, this paper also classifies and summarizes the existing research results, aiming to provide valuable reference and guidance for the application of fiber reinforced concrete in high temperature environment.

2. High temperature performance of fiber concrete

2.1. Polypropylene fiber

Due to its low melting point, polypropylene fiber has significant advantages in improving the high temperature performance and anti-burst ability of concrete. According to the research of Gao Danying [6], the sensitivity of plain concrete to temperature change is higher than that of polypropylene fiber concrete. At 150 ° C, the appearance of both types of concrete did not change significantly, but when the temperature rose to 800 ° C, the plain concrete surface appeared a large number of cracks and shed phenomenon, while the polypropylene fiber concrete only a small number of micro cracks, the appearance remained intact. Arabi[7] pointed out that when the content of polypropylene fiber is 0.5%, the residual performance of concrete after high temperature is the best. In addition, he found that the cube specimens had higher residual properties than the cylinder specimens. The research of Jin Zuquan et al. [8] shows that at 200℃, the compressive strength of ordinary concrete and polypropylene fiber concrete decreases by 8% and 16% respectively, but at 400℃, the compressive strength of both kinds of concrete recovers somewhat. At 800℃, the residual compressive strength of ordinary concrete is reduced to 30%, while the residual compressive strength of polypropylene fiber concrete is maintained at 67%. Polypropylene fiber has little effect on the linear expansion coefficient of concrete. In the process of increasing the temperature from 400 ° C to 800 ° C, although the porosity of the concrete is reduced, the pore of the polypropylene fiber concrete can still maintain 74% of the original diameter, which helps to maintain the structural integrity of the concrete.

2.2. Steel Fiber

Steel fiber plays an important role in improving the high temperature performance of concrete because of its excellent thermal conductivity and the ability to increase the adhesion of matrix. They can improve the concrete's ability to resist damage caused by temperature stress, thereby improving the overall performance of the material in high temperature environments.

Zhao Jun [9] pointed out that neither plain concrete nor steel fiber concrete would burst before 400℃. However, when the temperature rises to 400 ° C to 600 ° C, only plain concrete will burst. Further increase to more than 600 ° C, even steel fiber concrete, there will be a burst. This indicates that although steel fiber can improve the high temperature cracking resistance of concrete, it can not completely avoid the occurrence of cracking. High [10] further reveals that after 600℃, the reactive bending strength of steel fiber concrete remains at 81%, while that of plain concrete decreases to 59%. This shows that the flexural performance of steel fiber reinforced concrete is obviously better than plain concrete under high temperature conditions. However, when the temperature rises to 800 ° C, the bending strength of the two types of concrete will be significantly reduced. The research of Zhang Yanchun [11] shows that the loss of shear strength of steel fiber reinforced concrete is very small when it experiences high temperature of 500℃. Even at the extreme temperature of 900℃, steel fiber concrete can still maintain 40% of the residual shear strength. This further confirms the effectiveness of steel fiber in improving the high temperature performance of concrete.

2.3. Hybrid Fibers

Polypropylene fiber and steel fiber have different reactions to high temperature in concrete due to their different physical and chemical properties. When these two kinds of fibers act on concrete together, they can play a more excellent performance.

The test results of Kang Yirong [12] show that the addition of polypropylene fiber has little effect on the residual fracture energy of steel fiber concrete after high temperature, but the addition of steel fiber can effectively improve the residual fracture energy of polypropylene fiber concrete after high temperature. This shows that steel fiber plays a key role in improving the high temperature performance of concrete. Li Haiyan [13] pointed out that the volume ratio of polypropylene fiber needs to reach at least 0.3% to effectively prevent the occurrence of explosion, and when combined with steel fiber, its explosion suppression effect is better. It shows that the mixed use of polypropylene fiber and steel fiber can significantly improve the high temperature burst resistance of concrete. Bangi R M et al. [14] further confirmed that the addition of polypropylene fiber in high-strength concrete (HSC) can effectively alleviate the problems of internal spalling and pore pressure accumulation during heating, especially in the process of rapid heating, the addition of steel fiber helps to reduce the pore pressure in the deeper area of concrete. Ju Liyan et al. [15] studied the effect of the mixture of polypropylene fiber and steel fiber on the high temperature performance of HPC. The test results show that the residual flexural strength, residual compressive strength and residual splitting compressive strength of HPC with hybrid fiber are increased at 800℃, indicating that the addition of fiber significantly improves the burst resistance of concrete.

2.4. Hybrid Fibers

Cheng Bo's research[16] shows that the elastic modulus of polyacrylonitrile fiber concrete declines gently below 400℃, and the decline rate is slower than that of ordinary concrete. When the temperature exceeds 800℃, the elastic modulus of polyacrylonitrile fiber concrete is still higher than that of ordinary concrete, which indicates that polyacrylonitrile fiber can effectively improve the elastic modulus of concrete at high temperature, thereby enhancing its structural stability. Fan Linfei [17] pointed out that even at a low content of 0.1%, carbon fiber can significantly improve the high temperature dynamic mechanical properties of concrete. Under the joint action of impact load and high temperature, concrete may appear four typical failure modes, such as edge shedding, core failure, fragmentation failure and crushing failure. This shows that the addition of carbon fiber can improve the toughness and impact resistance of concrete under extreme conditions. Sun Changzheng [18] found that even if the high temperature of 1000℃ lasted for 30 minutes, the addition of 0.3% carbon fiber can still have a positive improvement effect on the performance of mortar. This shows that carbon fiber can still maintain its strengthening effect under extreme high temperature conditions, which helps to improve the high temperature stability of mortar. According to the study of Harun[19], adding 10% silicon powder and 0.5% carbon fiber can improve the compressive strength of mortar at room temperature. The addition of 10% silicon powder and 1% carbon fiber is more beneficial to the bending strength. In addition, the addition of carbon fiber with a high elastic modulus helps to alleviate temperature stress and concrete volume shrinkage due to temperature changes, thereby improving the overall performance of the concrete.

3. Mechanism of high temperature rupture of concrete

High-strength and high-performance concrete may burst and fail under the action of high temperature, but no unified theoretical framework has been formed for the understanding and explanation of its failure mechanism at present. Domestic and foreign scholars have proposed four main theoretical explanations for this phenomenon [20-25] : pore water pressure theory, steam pressure cracking theory, thermal stress theory and hot cracking theory.

3.1. Theory of pore water pressure

HARMATHYTZ[26] believed that pore water pressure caused by high water content and low permeability was the main cause of concrete cracking, and on this basis proposed the pore water pressure theory. At high temperature, the composition and physical properties of concrete will change, which may lead to permanent damage inside the structure, affect the performance and safety of concrete, and even lead to the collapse of the structure in severe cases [28]. CHENGM et al. [29] showed that the accumulation of steam pressure and thermal stress in the pores of concrete played a crucial role in the mechanism of fire accident intensity degradation and explosion spalling, which greatly affected the mechanical properties of concrete. During fire or high temperatures, the fibers in the concrete help to reduce the water vapor pressure in the pores of the concrete and ease the temperature gradient by facilitating the absorption of heat into the concrete, reducing the risk of explosive spalling and cracking, thereby improving the high temperature resistance of the concrete.

3.2. Vapor pressure cracking theory[30]

1)Evaporation of water: When the concrete is heated, the water inside it begins to evaporate into water vapor. This is a physical process caused by rising temperatures.

2)Steam loss and migration: Due to the thermal inertness of concrete, part of the water vapor will be lost to the air through the pore structure of the concrete, while the other part will move to the low temperature area inside the concrete. Condensation and saturation formation: Water vapor that migrates to cold regions condenses into liquid water there, causing the water content in the region to increase to saturation.

3)Formation of dry zone and saturated zone: With the migration and condensation of water to the low temperature zone, the surface of the concrete may form a dry zone, while the interior of the concrete forms a saturated zone. This uneven distribution of moisture creates a distinct dry and saturated interface within the concrete.

4)Pressure accumulation: In the saturated zone, because water cannot penetrate the saturated interface formed by the dry zone, the internal steam and air are limited in the saturated zone, and the pressure of these steam and air will gradually increase with the further rise of temperature.

5)Bursting occurs: When the internal pressure exceeds the cracking strength of the concrete matrix, the concrete will burst because it cannot withstand this pressure.

According to the "percolation theory", Bentz[23] believed that at high temperature, the compactness of the material would be reduced due to pore coarsening at the aggregate interface. Polypropylene fiber due to its low melting point (about 160 ° C), the small channel left after melting evaporation provides space for steam expansion, because many channels run through each other, so as to form a connected space with the outside world, steam pressure can be evaporated from the channel. The longer the fiber, the easier it is to form a connected channel, and the more prominent the resistance to bursting. Niu Xujing [24] believed that when coarse and fine fibers acted together, the melting of coarse fibers served as the trunk road and the fine fibers served as the branch road, and the improvement effect was better when mixed. The initial stress inhibits the development of damage inside the concrete and also inhibits the release of steam. Too fast a heating rate can cause concrete to have higher pore pressure at deeper depths. According to the steam pressure theory, low-permeability concrete is more prone to burst, so when the fiber content is lower than a certain water level, it will still burst.

3.3. Thermal stress theory

The thermal stress theory was proposed by BAZANTZP[27], who believed that the temperature inside the concrete led to multi-directional thermal stress in the concrete, and when the thermal stress increased to the tensile strength limit of the concrete itself with the temperature, the concrete burst. Thermal stress is the main factor that causes concrete cracks to expand and burst gradually, and pore water pressure is only the fuse.

With the increase of temperature, the surface of fiber reinforced concrete will undergo thermal expansion. However, due to the gradient of internal and external surface temperature caused by thermal inertia of concrete, the thermal expansion of the specimen surface will be constrained by the internal concrete and adjacent structures, resulting in higher stress. When this stress exceeds the tensile strength limit of concrete, cracks appear on the surface of the specimen, and stress concentration and further expansion occur at the crack end, causing the specimen to burst at high temperatures.

3.4. Thermal cracking theory

At high temperatures, the internal structure of concrete becomes weak due to a number of factors, including the decomposition of hydration products and the mismatch of thermal expansion between different materials.

1) Chemical decomposition: High temperature causes the hydration products inside the concrete to decompose, and this chemical change weakens the internal bonding force of the concrete, resulting in a reduction in its overall strength.

2) Thermal expansion difference: the coefficient of thermal expansion of aggregate and cement stone does not match, and when the temperature rises, this difference leads to uneven internal stress, which promotes the formation of cracks.

3) The effect of rapid warming: when the temperature rises rapidly, the cracks inside the concrete increase rapidly and expand. These cracks provide a path for water vapor in the pores to escape, helping to release internal pressure and reducing the risk of bursting due to pressure buildup.

4) The effect of slow warming: On the contrary, if the temperature rises slowly, the cracks inside the concrete develop slowly, and the accumulation of water vapor in the pores may cause the internal pressure to gradually increase, increasing the risk of bursting.

5) Strength reduction and pressure increase: with the decomposition of hydration products, the compressive strength of concrete decreases. In the case of increasing steam pressure in the pores, when this pressure exceeds the residual compressive strength of the concrete, the concrete specimen may burst.

6) The occurrence of bursting: Eventually, if the combined action of steam pressure and thermal stress in the pores exceeds the endurance limit of the concrete, the concrete specimen will not be able to maintain its integrity, resulting in bursting.

3.5. High temperature action mechanism of fiber concrete

When the content is 1.0kg/m^3, the permeability coefficient of the fiber increases significantly after melting and evaporation at high temperature. Literature [33] shows that: concrete with permeability coefficient greater than 5×10-15m^2 has a very low probability of bursting after high temperature. After high temperature, the porosity of polypropylene fiber concrete is significantly increased than that of ordinary concrete, which is the reason for the more serious attenuation of high-performance concrete at high temperature. In addition, when the concrete sintering phenomenon occurs, the influence of porosity on the strength will be greatly reduced. When water quenching [31] or water jet cooling [32] is used, the temperature stress of the specimen is generated due to the rapid cooling, which will further weaken the residual performance of the specimen.

Under the condition of high temperature, the steel fiber added into the concrete matrix shows a significant bridging effect, which effectively inhibits the non-uniform change of the matrix volume and slows down the expansion trend of micro-cracks, thus alleviating the deterioration process of concrete. The three-dimensional random distribution of steel fiber and its high thermal conductivity help to achieve the thermal balance between the interior and the surface of concrete, and reduce the stress damage caused by temperature difference. However, due to the difference of thermal expansion coefficient between the steel fiber and the concrete matrix, micro-cracks are easy to form around the steel fiber in the process of temperature rise. When the temperature drops to normal temperature, this difference results in the decrease of the bonding property between steel fiber and concrete matrix.

Although steel fiber can improve the high temperature resistance of concrete, its release of pore pressure is not ideal, resulting in the risk of cracking of concrete at high temperatures. In contrast, the composite use of polypropylene fiber and steel fiber, through their own unique modification effects complement each other, synergistic effect, significantly improve the damage repair ability of concrete after high temperature, compared with a single fiber or fiber free concrete, showing better damage repair effect after high temperature.

4. Conclusion and Prospects

1) The damage change of fiber reinforced concrete under high temperature environment can be divided into three stages: within 200℃, the damage is relatively small; When the temperature is between 200℃ and 400℃, the damage degree is reduced, and even recovery or performance improvement may occur; After 400℃, the damage will increase significantly and become irreversible.

2) Moisture content, porosity, heating method and rate, cooling method, etc. have an effect on the formation and diffusion of steam pressure in concrete, and the addition of polypropylene fiber is conducive to the release of steam pressure.

3) Single or multiple mixtures of polypropylene fiber and steel fiber can effectively improve the high temperature performance of concrete.

4) Different cooling methods have a great impact on the damage of concrete after high temperature, so the appropriate cooling rescue method can reduce secondary damage during fire site rescue.

5) Current studies on the high temperature performance of fiber reinforced concrete mostly focus on single factor, which is quite different from the fold coupling effect of actual buildings in complex environments. Scholars simulate high temperature heating methods mostly for box-type resistance furnace heating, and this heating method is different from the rapid heating at the fire site or the instant high temperature caused by explosion. Concrete is a composite material, and its high temperature damage involves physical and chemical changes. It is

necessary to use instruments and equipment to study the microstructure evolution law during and after high temperature.

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