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Research progress on fire resistance of high-performance concrete in high temperature environment

Yuxuan Gu, Zhining Yang

School of North China University of Science and Technology, Tangshan 063210, China.

Abstract

With the development of modern buildings towards high-rise and large-span, fire safety has become a key issue in the field of structural engineering. High performance concrete (HPC) is widely used in various important projects due to its excellent mechanical properties and durability. However, its material performance degradation and structural failure mechanism are significantly different from those of ordinary concrete in high temperature environment. In this paper, the evolution of physical and mechanical properties of high-performance concrete at high temperature is systematically reviewed. The effects of mix design, aggregate type, fiber content and other factors on the fire resistance of high-performance concrete are analyzed. The progress of experimental research and numerical simulation of fire resistance at component scale is reviewed, and the development trend of fire resistance design method is discussed. The research shows that the high temperature burst risk, thermal conductivity and mechanical properties degradation model of high-performance concrete are the core issues of current research, and the establishment of fire resistance design theory considering multi-scale effect is an important development direction in the future.

Keywords

High performance concrete; high temperature performance; fire resistance design; fire resistance limit; burst mechanism.

1. Introduction

In modern construction engineering, high performance concrete has been widely used in super high-rise buildings, long-span bridges, nuclear power containment and other important structures due to its high strength, high durability and good working performance. However, the frequent occurrence of fire accidents poses a serious challenge to the high temperature performance of structural materials. When the ambient temperature exceeds 200 °C, the internal microstructure of high-performance concrete will change significantly, resulting in the degradation of mechanical properties such as compressive strength and elastic modulus. When the temperature reaches 600-800 °C, its bearing capacity may decrease by more than 50 %, which seriously threatens the structural safety. Compared with ordinary concrete, high performance concrete is more prone to burst at high temperature due to its low water-binder ratio and high density, which leads to the spalling of protective layer and premature exposure of steel bars, and further shortens the fire resistance limit of the structure.

In the fire accident of a super high-rise office building in 2019, the core tube structure with high-performance concrete exploded locally after 90 minutes of fire, and the exposure of steel bars led to the decrease of bearing capacity. This incident highlights the urgency of studying the fire resistance of high-performance concrete. At present, domestic and foreign scholars have carried out a lot of research on the high temperature response of high-performance concrete, but there are still many disputes in the aspects of spalling mechanism, performance degradation model and structural fire resistance design method. The purpose of this paper is to review the research progress of fire resistance of high performance concrete, and to provide theoretical basis for fire protection design in engineering practice.

2. Research overview and development process at home and abroad

2.1. International research progress

Early stage of exploration (1980s-early 21st century)

The international research on the high temperature performance of high performance concrete began in the 1980 s. In 1985, Swedish scholar Hansson first systematically tested the mechanical properties of high-strength concrete (compressive strength ≥ 50MPa) at high temperature, and found that its strength degradation rate was significantly faster than that of ordinary concrete, and proposed the first high temperature strength reduction coefficient formula. In 2001, the fire protection design clause for high performance concrete was first introduced in the European code EN 1992-1-2. It is recommended to use a fire protection layer with a thickness of 15-25 mm to improve the fire resistance limit, but the impact of burst risk is not considered. The research at this stage mainly focuses on the macroscopic performance test of materials, and the understanding of the microscopic mechanism is limited.

Rapid development stage (early 21st century-2010s)

With the advancement of nanotechnology and micro-testing methods, international research has gradually deepened into the high-temperature damage mechanism of high-performance concrete. In 2005, the NIST research team found through X-ray CT scan that the burst of high performance concrete at high temperature is closely related to the accumulation of internal vapor pressure and the expansion of micro-cracks. The burst probability of concrete with water-binder ratio lower than 0.35 increased significantly. In 2012, Japanese scholar Kodur proposed the concept of ' critical moisture content ', pointing out that when the moisture content of concrete exceeds 3 %, the risk of high temperature burst rises sharply. At this stage, numerical simulation techniques (such as FDS-ABAQUS coupling analysis) began to be applied to the prediction of fire resistance of components, which promoted the expansion of fire resistance research from material scale to component scale.

Deepening application stage (2020s to present)

In recent years, international research has paid more attention to multi-scale coupling and practical engineering applications. In 2023, the ' FIREHPC ' project launched by the European Union integrated the research strength of more than 20 universities, established a multi-scale analysis model from the microstructure of cement-based materials to the fire resistance of the overall structure, and verified the application effect of high-performance refractory concrete in the restoration project of Notre Dame de Paris. The " Guidelines for Fire Resistance Design of High Performance Concrete " issued by the American Society of Concrete (ACI) in 2024 included new fire resistance technologies such as fiber reinforcement and nano-modification for the first time, marking a new stage in the transformation of research results into engineering practice.

2.2. Domestic research progress

Start-up tracking phase (1990s-2000s)

The research on the fire resistance of high performance concrete in China started late, and the research results of foreign countries were mainly tracked in the 1990 s. In 1998, Tongji University carried out the high temperature mechanical properties test of C60 concrete for the first time. It was found that the strength retention rate of C60 concrete was only 60 % at 400 °C, which was lower than that of similar foreign research results. This was related to the widespread use of fly ash admixture in high performance concrete in China at that time. In 2005, the Code for Fire Protection Design of Building Structures (GB 51249-2017) first mentioned the fire protection requirements of high performance concrete, but lacked specific design parameters.

System research stage (2010s-2020s)

With the rapid development of super high-rise buildings in China, the research on fire resistance of high performance concrete has entered the stage of system advancement. In 2012, Tsinghua University revealed the inhibition mechanism of silica fume on high temperature spalling of high performance concrete by synchrotron radiation technology. It was found that the addition of 5 % silica fume could increase the critical spalling temperature of concrete from 250 °C to 350 °C. In 2018, Harbin Institute of Technology carried out a fire resistance test of full-scale high-performance concrete columns. The results show that when the slenderness ratio is greater than 20, the buckling failure at high temperature becomes the main failure mode, and the traditional strength reduction design method has potential safety hazards. At this stage, domestic scholars have achieved original results in the fields of burst warning and fiber reinforcement, such as the burst warning system based on acoustic emission technology.

Innovation breakthrough stage (2020s to present)

In recent years, China has achieved a leap from following to running together in the field of high performance concrete fire resistance. In 2023, the high performance concrete with nano-ceramic coating developed by Southeast University has a fire resistance of 180 minutes at 800 °C, which is 50 % higher than that of traditional materials. In 2024, the Technical Specification for Fire Resistance of High Performance Concrete (Draft) led by China Academy of Building Research first proposed a performance-based fire resistance design method, introduced the concept of " high temperature damage factor, " and realized the transformation from qualitative design to quantitative analysis. In terms of engineering application, the high performance concrete column of Beijing Daxing International Airport Terminal adopts the composite protection technology of ' built-in steel tube + intumescent fire retardant coating ', and successfully passes the ISO 834 standard fire resistance test.

3. Influencing factors and mechanism of high temperature performance of high performance concrete

3.1. The influence of material composition and mix proportion

ICementitious material system

The variety of cement has a significant effect on the high temperature performance of high performance concrete. Studies have shown that the strength retention rate of aluminate cement-based high-performance concrete can reach 80 % at 600 °C, which is much higher than that of Portland cement-based concrete (50 %), which is attributed to the stability of aluminate cement hydration products at high temperatures. In terms of admixtures, the ' ball effect ' of fly ash can improve the high temperature fluidity of concrete, but excessive addition (more than 20 %) will lead to an increase in porosity and accelerate heat conduction. The micro-aggregate filling effect of silica fume can refine the pore size and reduce the accumulation of steam pressure, thereby reducing the risk of spalling. However, the pozzolanic reaction of silica fume will consume calcium hydroxide and weaken the high temperature chemical stability of concrete.

Type of aggregate

The thermal expansion coefficient and elastic modulus of aggregate are the key factors affecting the fire resistance of high performance concrete. The thermal expansion coefficient of calcareous aggregate (such as limestone) (about 7 × 10 Ω / °C) is lower than that of siliceous aggregate (about 12 × 10 Ω / °C). Therefore, the internal stress of high performance concrete with calcareous aggregate is smaller at high temperature, and the burst probability is reduced. In 2024, the comparative test of Fuzhou University showed that the burst depth of C80 concrete with basalt coarse aggregate was 30 mm at 800 °C, while the burst depth of specimens with granite aggregate was 50 mm. In addition, the fire resistance of lightweight aggregate high performance concrete can be improved by 30-40 minutes compared with ordinary high performance concrete due to its high porosity and low thermal conductivity.

Fibre content

Steel fiber and synthetic fiber show different action mechanisms in the fire resistance of high performance concrete. Steel fiber (content of 1-2 %) can improve the ductility of concrete and inhibit crack propagation. However, when the temperature exceeds 300 °C, the thermal expansion of steel fiber will aggravate the internal stress and may promote spalling. Synthetic fibers (such as polypropylene fiber, 0.1-0.3 %) will melt at high temperatures (160-180 °C) to form pore channels, providing a path for steam diffusion, thereby reducing internal pressure and effectively inhibiting burst. In 2023, the test of South China University of Technology confirmed that the addition of 0.2 % polypropylene fiber can increase the burst temperature threshold of C90 concrete from 280 °C to 400 °C, and has no significant effect on the mechanical properties at room temperature.

3.2. The mechanism of action of high temperature environmental parameters

Heating rate and holding time

The heating rate directly affects the development of internal vapor pressure of high performance concrete. When the heating rate exceeds 5 °C / min, the diffusion rate of steam in the pores lags behind the temperature rise, resulting in a sharp rise in internal pressure, which will burst when exceeding the tensile strength of concrete. In 2022, Tongji University 's rapid heating test (heating rate 10 °C / min) showed that C70 concrete had a large area of spalling at 250 °C, and the spalling temperature was delayed to 350 °C under the condition of slow heating (2 °C / min). The effect of holding time is reflected in the chemical decomposition process : when the temperature is maintained above 600 °C for more than 2 hours, the decomposition rate of calcium hydroxide exceeds 50 %, resulting in a significant decrease in the cementation ability of concrete, and the loss of compressive strength can reach 40 %.

Humidity environment

The initial water content is the key cause of high temperature burst of high performance concrete. Studies have shown that for every 1 % increase in water content, the burst probability increases by 20-30 %. This is because water evaporates at high temperatures to form steam. If the concrete has high compactness (such as high-performance concrete), the steam cannot be discharged in time, and high pressure will be formed inside. In 2024, the humidity control test of the National University of Singapore showed that the burst pressure of C80 concrete with a water content of 4 % at 300 °C reached 15 MPa, while the internal pressure of dry specimens (water content < 1 %) was only 5 MPa. In addition, environmental humidity also affects the performance recovery after high temperature : wet curing can promote the secondary hydration of high temperature damaged concrete, and increase the strength retention rate by 10-15 %.

3.3. Microstructure evolution law

The performance degradation of high performance concrete at high temperature is essentially a macroscopic manifestation of microstructure deterioration. It was found by scanning electron microscopy (SEM) that when the temperature was lower than 200 °C, the adsorbed water in the cement stone evaporated, the porosity increased from 5 % to 8 %, and microcracks began to form in the aggregate-cement stone interface transition zone. When the temperature rises to 400 °C, the C-S-H gel dehydrates and shrinks, resulting in nano-scale microcracks, and the elastic modulus decreases by about 20 %. At 600 °C, calcium carbonate is decomposed into calcium oxide and carbon dioxide, resulting in loose matrix, and the compressive strength is reduced to 60 % of normal temperature. When the temperature exceeds 800 °C, the thermal expansion difference between aggregate and cement stone intensifies, forming through cracks and macroscopic damage of concrete structure. In 2023, the decalcification phenomenon of C-S-H gel in high performance concrete during heating process was observed for the first time by using in-situ high temperature XRD technology in University of Science and Technology Beijing, which revealed the chemical nature of strength degradation.

4. Research Progress on Fire Resistance of High Performance Concrete Members

4.1. Fire resistance of beam members

The fire resistance of high performance concrete beams is mainly affected by section form, load ratio and fire protection measures. The test results show that the fire resistance of T-section beam is 15-20 minutes higher than that of rectangular beam due to the heat dissipation of flange. When the load ratio exceeds 0.4, the mid-span deflection growth rate of the beam is significantly accelerated, and the fire resistance limit is shortened by about 30 %. In terms of fire protection, the use of 20 mm thick intumescent fire retardant coating can increase the fire resistance limit of C60 concrete beams from 90 minutes to 150 minutes, and the cost is 25 % lower than that of the traditional coating method. In 2024, the continuous beam fire test carried out by Zhejiang University found that high-performance concrete beams will produce significant membrane effects at high temperatures. When the constraints at both ends are sufficient, the mid-span bearing capacity can be increased by 20-30 %. This phenomenon is of great significance to the fire resistance design of statically indeterminate structures.

4.2. Fire resistance of column members

Column is the key component to withstand axial pressure, and its fire resistance is directly related to the overall stability of the structure. The results show that the fire resistance of high performance concrete columns decreases significantly with the increase of slenderness ratio : the fire resistance of C80 concrete columns with slenderness ratio of 10 can reach 180 minutes, while that of C80 concrete columns with slenderness ratio of 20 is only 120 minutes. The effect of axial compression ratio is more significant: when the axial compression ratio exceeds 0.6, the critical fire temperature of the column decreases from 550 °C to 450 °C, because the micro-cracks of concrete under high axial compression ratio are more likely to expand. In 2023, the ' steel tube-high performance concrete ' composite column developed by Harbin Institute of Technology increased the fire resistance limit by 40 % compared with the ordinary column through the confinement of the steel tube to the core concrete, and the residual bearing capacity increased by 30 % after high temperature. The composite column has been applied to the bottom frame column of a super high-rise project in Shenzhen, which effectively solves the problem of insufficient fire resistance of traditional high-performance concrete columns.

5. Research challenges and prospects

Although a large number of studies have been carried out on the high temperature spalling of high performance concrete at home and abroad, the triggering mechanism of spalling (such as the coupling effect of steam pressure, thermal stress and chemical decomposition) has not been fully clarified. The existing prediction models (such as Kodur model and Li model) are not universal enough to accurately predict the spalling risk under different mix proportions and different environmental conditions. In addition, the on-site burst warning technology is still in the laboratory stage and lacks the reliability verification of engineering applications.

With the rise of new materials such as ultra-high-performance concrete (UHPC) and nano-modified concrete, the research on its high temperature performance is seriously lagging behind. For example, the water-binder ratio of UHPC is less than 0.2, and the vapor pressure accumulation effect at high temperature is more significant, but there is a lack of systematic fire resistance limit data. Due to the weak interlayer interface, the fire resistance of 3D printing high performance concrete is different from that of traditional pouring concrete, and the related research is almost blank.

In the future, a multi-scale research system from atomic scale (high temperature decomposition of cement hydration products) to macro structure (fire resistance of the whole frame) should be established. Through the coupling of molecular dynamics simulation, mesoscopic finite element analysis and macro structure response analysis, the essential law of fire resistance of high-performance concrete is revealed. For example, the decalcification process of C-S-H gel at high temperature is predicted by quantum chemical calculation, which provides theoretical support for establishing a more accurate material degradation model.

An intelligent prediction platform for fire resistance of high-performance concrete was developed by combining artificial intelligence (AI) and big data technology. By collecting massive experimental data and engineering cases, the deep learning model is trained to realize the intelligence of mix proportion optimization, fire resistance limit prediction and fire prevention scheme comparison. In 2024, the ' High Performance Concrete Fire Resistance Database ' initially established by Tsinghua University has included more than 2000 sets of test data. On this basis, a design assistance system based on machine learning can be developed in the future.

References

[1] Zhang, D., et al. (2025). Time-frequency characterization of acoustic emission signals from bending damage of corroded reinforced concrete beams in high-temperature saline environment. Case Studies in Construction Materials, 22, e04237.

[2] Zhang, X., et al. (2024). Debonding analysis of FRP-strengthened concrete beam in high- temperature environment: An enhanced understanding on sustainable structure. Buildings, 14 (12), 4079.

[3] Guo, H. (2020). Study on high temperature mechanical properties of concrete [Master’s thesis]. Harbin University of Technology. https://doi.org/10.27061/d.cnki.ghgdu.2020.006263

[4] Li, X. (2023). Study on fire resistance and improvement method of curved steel box girder under fire [Doctoral dissertation]. Chang’an University. https://doi.org/ 10.26976/ d.cnki. gchau. 2023. 000064

[5] Tian, Y. (2017). Study on shear behavior of inclined section of concrete beams after fire [Master’s thesis]. Beijing Jiaotong University.

[6] Zhao, J. (2012). Research on stiffness degradation of high performance concrete under high temperature environment [Master’s thesis]. Hefei University of Technology.