High-Temperature Properties of Concrete for Fire Resistance Modeling of Structures

Tulika Barman[1], Sanjukta Roy[2], Souvik Datta[3], Sourav Kumar Maity[4], Prof. Souvik Sharma[5], Prof. (Dr.) Biman Mukherjee[6]

[1234,]M. Tech Student of Narula Institute of Technology, West Bengal, India
[5]Assistant Professor, Dept. of Civil Engineering, Narula Institute of Technology, West Bengal, India
[6]Professor & Former HOD, Dept. of Civil Engineering, Narula Institute of Technology, West Bengal, India

ABSTRACT

Fire resistance is a critical property of construction materials, particularly in high-risk environments and structural applications. Concrete, known for its inherent fire-resistant qualities, continues to be optimized through various material enhancements to improve its performance under high temperatures. This review explores the current advancements in fire-resistant concrete, including the incorporation of supplementary cementitious materials, fibers, and phase-change materials. The mechanisms of thermal degradation, spalling, and structural integrity loss under fire exposure are discussed, alongside evaluation techniques such as thermal analysis and mechanical testing. Emphasis is placed on high-performance concrete types such as geopolymer and fiber-reinforced concretes, which demonstrate superior behavior under thermal stress. The review also highlights the challenges and gaps in research, including long-term durability after fire exposure and the standardization of testing protocols. This comprehensive overview provides insights into the development of concrete with enhanced fire resistance for safer, more resilient infrastructure.

INTRODUCTION

Concrete is one of the most widely used construction materials globally due to its versatility, strength, and durability. However, its performance under high temperatures, such as those encountered during a fire, is a critical concern in structural safety. Fire resistance in concrete refers to its ability to withstand elevated temperatures without significant loss of structural integrity or functionality. This property is crucial for ensuring the safety of buildings and infrastructure during fire events, minimizing damage, and allowing sufficient time for evacuation and firefighting operations.

Recent advancements in material science and engineering have led to the development of fire-resistant concrete mixes through the incorporation of specialized aggregates, fibers, and admixtures. These innovations aim to enhance thermal stability, reduce spalling, and improve the residual strength of concrete after exposure to fire. This review explores the current state of fire-resistant concrete technologies, examining material compositions, performance characteristics, testing methods, and their practical applications in construction. By understanding these developments, engineers and researchers can better design structures that offer improved fire protection and resilience.

KEY HIGH-TEMPERATURE PROPERTIES OF CONCRETE

Thermal Properties

a. Thermal Conductivity

- **Trend**: Decreases with temperature due to the breakdown of solid phases and increased porosity.
- **Typical Range**: 1.4–3.6 W/m·K at room temp → drops to 0.2–1.0 W/m·K above 800°C.
- **Influencing Factors**: Moisture content, density, aggregate type.

b. Specific Heat Capacity

- **Trend**: Increases with temperature, peaking around 100°C due to water evaporation.
- **Range**: 0.75–1.0 kJ/kg·K.
- **Importance**: Affects heat storage and transfer within the concrete during fire exposure.

c. Thermal Expansion

- **Behavior**: Concrete expands up to 600–700°C; then may contract due to microcracking and chemical degradation.
- **Coefficient**: ~10 × 10^{-6} /°C (can vary with aggregates and temperature range).

MECHANICAL PROPERTIES

Compressive Strength

- **Reduction**: Drastically decreases beyond 300°C. At 600°C, ~30–50% residual strength; nearly zero near 1000°C.
- **Mechanisms**: Microcracking, dehydration of cement paste, loss of bond between matrix and aggregates.

Tensile and Flexural Strength

- **Trend**: More sensitive than compressive strength; may drop to 10–20% of original value at 600°C.
- **Impact**: Key for fire-induced spalling and cracking prediction.

Modulus of Elasticity

- **Behavior**: Reduces significantly (up to 70–90%) by 600°C.
- **Consequences**: Increased deformation under load; essential for thermal strain calculations.

Chemical and Physical Changes in Concrete at High Temperatures

- **100–200°C**: Free water evaporation.
- **300–600°C**: Dehydration of C-S-H gel and decomposition of CH (portlandite).
- **600–900°C**: Breakdown of aggregates (quartz inversion at ~573°C).
- **>1000°C**: Complete disintegration; melting of components.

Spalling Phenomenon

- **Definition**: Sudden ejection of concrete surface layers.
- **Causes**: Thermal stresses, pore pressure from steam, restrained thermal expansion.
- **Modeling Needs**: Accurate moisture transport models and thermal-mechanical coupling.

FIRE RESISTANCE MODELING APPROACHES

Prescriptive vs. Performance-Based Design

- **Prescriptive**: Uses standardized fire ratings.
- **Performance-Based**: Requires advanced numerical simulations using real material data.

Modeling Tools

- **Software**: ABAQUS, SAFIR, ANSYS, OpenSees.
- **Methods**: Finite Element Method (FEM), Finite Difference Method (FDM).

Input Parameters Required

- Temperature-dependent material properties.
- Boundary conditions (fire exposure, load).
- Structural constraints and failure criteria.

Material Enhancements for Fire Resistance

- **High-performance concrete (HPC)**: Lower porosity but more prone to spalling.
- **Polypropylene fibers**: Help reduce spalling by creating pressure-relief channels.
- **Lightweight aggregates**: Better thermal insulation but reduced strength.

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SUMMARY AND RESEARCH GAPS

Summary

- Fire modeling requires multi-physics data: thermal, mechanical, and hygral.
- High variability in concrete properties under fire necessitates accurate, experimental-based models.

Research Gaps

- Need for standardized databases for temperature-dependent properties.
- Improved spalling prediction models.
- Coupled hygro-thermo-mechanical models with validated experimental data.

CONCLUSION

Understanding and modeling the behavior of concrete at high temperatures is vital for ensuring fire safety in structures. While significant progress has been made, further research into the complex interactions of heat, moisture, and mechanical loading in concrete is essential to develop more accurate fire resistance models.

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