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Mechanical response and spalling sensitivity of air entrained high-strength concrete at elevated temperatures

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HIGHLIGHTS

- Spalling and strength loss in high-strength concrete (HSC) are concerns in fire provisions.
- Low porosity in HSC is sensitive to elevated temperatures.
- Air entrainment provides intrinsic porosity in HSC to relieve pore pressure.
- Air entrained concrete can be suitable alternate to polypropylene fibers in HSC.
- Relative retention of mechanical properties is better in air entrained concrete.

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ABSTRACT

Polypropylene fibers are commonly used to increase the porosity in high-strength concrete (HSC) in high-temperature environments, to release the vapor pressure in the micropores. However, air entrained HSC can provide suitable alternative to polypropylene fiber reinforced HSC in structures under fire conditions, essentially due to intrinsic porosity. An experimental program was designed to obtain higher strength in air entrained concrete and study its performance at elevated temperatures in 23–800 °C range. In this study, mechanical and material properties of air entrained HSC at varying air volume of 4% and 8% were investigated and compared with conventional HSC in unstressed (hot) state. Compressive strength, splitting tensile strength, stress-strain response, elastic modulus, and spalling along with mass loss and cracking behavior under a higher heating rate of 10 °C per minute were studied. Results show better retention of mechanical properties in air entrained HSC at elevated temperature with improved spalling mitigation and physical properties.

1. Introduction

Use of high-strength concrete (HSC) in build infrastructure has increased many folds due to advancements in concrete technology and commercial availability of mix modification materials in concrete. Additionally, HSC performs better in mechanical and durability properties as compared to conventional normal strength concrete (NSC). However, reinforced concrete (RC) structures made of HSC exposed to fire are more temperature sensitive due to significant factor of fire induced spalling and rapidly deteriorating strength properties [1,2]. Spalling is a stochastic, abrupt, and non-deterministic process in HSC that occurs due to thermo-mechanical-hygral coupled processes which take place within its microstructure at elevated temperatures [1–3]. Fire induced spalling leads to loss of cross-section of already thin sections of HSC and with deteriorating mechanical properties at elevated temperatures, HSC structural members exhibit lower fire resistance compared to NSC [4]. Therefore, RC structures utilizing the superior properties of HSC remain threatened by a potential hazard of failure under fire conditions.

The understanding of fire behavior becomes important with recent advancements and evolution of concrete that allows selection of specific type of concrete depending on desired properties for a project. The production of a concrete type varies depending upon the choice of the material engineer to meet the project requirements. The high-temperature behavior of NSC and to quite an extent high-strength concrete (HSC) have been reasonably established with better predictability of its fire behavior [5–8]. Moreover, the spalling sensitivity of increasingly used high performing concretes such as self-consolidating concretes, whose fire

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induced spalling is close to that of HSC even at lower strength, because of their denser matrix can be fairly predicted [9]. However, as the use of HSC in built infrastructure is rising, its weaknesses under fire conditions need rigorous investigations to establish the reliability of its high-temperature properties. Data on fire behavior of HSC clearly indicates that its high-temperature performance is poorer than NSC [6,7,10]. The lower fire performance of HSC is attributed to rapid deterioration in mechanical properties at elevated temperatures, and susceptibility to fire induced spalling, latter being the major flaw associated with HSC [4,11,12].

Research and development have shown that there can be different solutions for fire resistance applications of HSC, namely restricted use in fire risk exposures, modification of mix design by incorporating different fibers, improvement in design of member dimensions, and provision of insulation [1]. Strategies adopted to overcome weaknesses of HSC in high-temperature applications are basically influenced by mechanical and material property modifications [1,4,8]. A more workable solution involves inducing permeability in concrete achieved by incorporation of polypropylene fibers in HSC, as these fibers melt in the temperature range of 160–170 °C depending on its material molecular structure. This porosity attained through melting of polypropylene fibers allows dissipation of high vapor pressure developing inside concrete due to temperature rise, thus helping in spalling mitigation [1,13]. However, polypropylene fibers need extra effort in uniform mixing in concrete and greatly reduce the slump flow [14] requiring more mechanical effort in placement, compaction and finishing especially in RC members with congested reinforcement. Steel fibers, on the other hand, have been found to be useful in mitigating fire induced spalling through enhanced tensile strength and ductility especially in the critical temperature range of 100–400 °C [8,15]. However, challenges in handling steel fiber reinforced concrete are similar to that of polypropylene fibers reinforced concrete in mixing, placing, and finishing, thus making it difficult for its practical application in the field.

As an alternative to fiber reinforced HSC for fire resistance applications, air entrained HSC can provide enhanced workability due to ball bearing effect in fresh state and much-needed porosity in hardened state due to deliberately entrained air in concrete [16]. However, attainment of higher strength in air entrained concrete is quite a challenge and needs careful design for such concrete mix as, incorporating air in HSC becomes difficult to handle in presence of superplasticizers [17,18]. Individual chemical compositions in air entraining agents and superplasticizers result in such products which cause incompatibility in fresh state of concrete and disturb the air void system in hardened state [17].

Air void system in concrete is measured with two factors, related to their properties, which are spacing factor ($\bar{L}$) and specific surface (α) of air voids. Spacing factor ($\bar{L}$) is defined as the maximum distance in cement paste from the periphery of an air void and specific surface (α) is defined as the surface area of air voids divided by their volume [19]. For maximum freeze-thaw durability of hardened concrete, the value of $\bar{L}$ should be less than 200 μm and α should be not more than 25 mm^{-1} [20], and these values are widely accepted among various authors [21–23]. The perturbations due to chemical incompatibility disturb both $\bar{L}$ and α parameters owing to contradictory results for different admixture combinations [21–23]. It is hard to recognize a particular air entraining agent (AEA) that is suitable in superplasticized concrete mix [17]. Few detailed studies are available covering all the possible factors which describe the air void system in fresh and hardened state of concrete in order to successfully incorporate air in the superplasticized mix [22,23]. Based on these studies, it is determined that the most stable chemical combination among various admixtures with varying alkali content in cement is synthetic detergent based AEA when used with naphthalene based superplasticizers. Although the usual parameters of spacing factor and specific surface are for optimization of freeze-thaw durability and not for fire endurance. It is evident that through adjustments in parameters of spacing factor and specific surface of air void system, the performance of air bubbles can be optimized to improve freeze-thaw durability. However, due to lack of research no specific range of these parameters is given for fire endurance. Therefore, it is postulated that air void system suitable for freeze-thaw durability should also be suitable for fire resistance. Hence, the usual values of these parameters for freeze-thaw durability are considered for fire endurance in this study.

In the absence of well-defined test standards for high-temperature tests on HSC or NSC, researchers employ various test procedures, a main reason for large variability in high-temperature properties of different concrete types. For high-temperature tests on HSC, usually, a heating rate for specimens is kept in 2–5 °C per minute for a cylinder size of 100 mm diameter and 200 mm height [6,24]. However, usually, a higher heating rate of 10 °C per minute is used when spalling behavior is to be studied in HSC [1,25]. Moreover, to evaluate the mechanical strength of concrete specimens at elevated temperatures, three test conditions based on the heating and loading scenarios namely stressed, unstressed, and residual test conditions are generally adopted [8,10,15]. Since the results of mechanical tests are largely dependent upon the test procedures adopted, therefore, characterization of properties under unstressed (hot) test conditions are considered as suitable representative of high-temperature material properties.

The fire performance of HSC, plain and with different fiber reinforcements has been evaluated to a reasonable extent and its weaknesses identified [8]. However, as an alternate to tackle fire induced spalling in HSC, air entrained HSC has never been identified as an option and its fire performance has never been investigated. The main focus of this research program, therefore, is to recognize better fire performance of HSC by air entrainment and identify improvements through intrinsic advantages offered by air entrained HSC with controlled air void system. Air entrainment can also be considered to provide thermal insulation and also be used in applications such as thermal reactors and furnaces where application of higher strength and reduction to microstructural damage is desired [26]. In this study, high-temperature mechanical, spalling, and cracking properties of air entrained HSC were evaluated and compared with that of conventional HSC. The mechanical properties namely compressive strength, splitting tensile strength, stress-strain response, elastic modulus, and spalling response under higher heating rate along with physical properties consisting of mass loss and cracking behavior were investigated.

2. Experimental program

To acquire test data on fire performance, high-temperature experiments under unstressed test conditions were carried out on 96 cylindrical specimens of conventional HSC and air entrained HSC with different air content.

2.1. Test materials

For the production of both control and air entrained high-strength concrete types, ordinary portland cement (OPC) Type-I conforming to ASTM C150/C150M-16e1 [27] was used. Natural fine aggregate having fineness modulus of 2.7 and limestone based coarse aggregate with maximum size of 9.5 mm were used in the mix. Potable water was used for mixing and curing of concrete. Two types of densified silica fume having percentage of reactive SiO_2 as 96.98% and 89.24% respectively were tested for this research. To achieve higher strength in air entrained concrete, the one with higher silica content of 96.98% and bulk specific gravity (BSG) of 2.241was selected as mineral admixture. Naphthalene based, second generation high range water reducer having BSG of 1.22 was used as superplasticizer. As appropriate chemical admixture to attain air entrainment, conforming to