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ORIGINAL ARTICLE

Effect of fibre content and specimen shape on residual strength of polypropylene fibre self-compacting concrete exposed to elevated temperatures

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Abstract This experimental study investigates the effect of specimen shape on residual mechanical properties of polypropylene (PP) fibre self-compacting concrete (SCC) exposed to elevated temperatures from 200 to 600 °C. Various shaping regimes were used including cylindrical and cubical shapes for a series of durations of 2 and 4 h, and air cooling to the room temperature before testing. The temperature determination results prove that the shaping regimes caused an action of "thermal shock" to SCC under elevated temperatures, characterized by a high temperature at fixed time of exposure. The experimental results indicate that, compared cylindrical specimen with cubical one, thermal shock induced by cylindrical shape air cooling caused more severe damage to concrete in terms of greater losses in compressive strength than those with cubical shapes. The fact that the impact of shapes on mechanical properties indicates that shaping could cause thermal shock to specimens, which is in good agreement with the results of the temperature determination. PP fibre can enhance residual strength and fracture energy of concrete subjected to thermal shock induced by air cooling from high temperatures up to 600 °C to room temperature.

1. Introduction

Concrete has inherent fire resistance and it is a material ideally suited for providing fire safe construction. However, recent well-publicized fires in tunnels and the collapse of the World Trade Center in New York on September 11, 2001 have focused attention on the performance of all construction materials in fire. In addition, concrete design Euro code (EN 1992: 1–2) includes a design methodology that can lead to a more efficient concrete design. Guth (1998) has pointed out that the occurrence of spalling in reinforced concrete (RC) structures using high-strength concrete must be prevented. It is well known that spalling is prone to occur under certain conditions such as; low water to cement ratios, high moisture content and exposure to abrupt increase in temperatures. Liu et al. (2008), in their paper, define spalling as a phenomenon in which the surface of the concrete scales falls off from the structure along with an explosion at elevated temperatures.

Hertz and Sørensen (2005) devised a test method for determining the suffering of the actual concrete due to explosive

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spalling at a specified moisture level, taking into account the effect of stresses from progressive thermal expansion at the surface exposed to the fire. The study used cylinder shapes for testing, with different variations of concrete. The study concluded that the sufficient quantities of polypropylene fibres with suitable characteristics may prevent spalling of a concrete sample even when thermal expansion is showing restraint. Thus the material can be used in Self-Compacted Concrete (SCC) to prevent spalling when it is exposed to elevated temperatures, taking into consideration the characteristics of the SCC, and the different percentages of PP fibres under different conditions and elevated temperatures.

Fares et al. (2009, 2010) studied the performance of SCC subjected to high temperatures. Two mixtures of SCC and one vibrated concrete were used. Specimens were heated at different temperatures (150, 300, 450, and 600 °C) with 1 h time of exposure. They measured the mixtures' mechanical (compressive strength, flexural strength, and modulus of elasticity) and physical (water loss, density, porosity, and permeability) properties. They conclude that spalling happens at 315 °C. Moreover, compressive strength, flexural strength, and modulus of elasticity decrease with an increase in temperature. Between 20 and 150 °C, a small strength with no sensible degradation of the microstructure was observed just departure of bound water contained in C–S–H, and of free water contained in the concrete. From 150 to 300 °C, an increase in compressive strength, due to hydration of anhydrous cement and water movement, and cracks in the concrete within the paste for SCC were observed. In temperature beyond 300 °C, the mechanical and physical properties decreased quickly. At 600 °C the mixture became very weak in mechanical properties, and microstructure of concrete deteriorated quickly, with some chemical transformation such as, the crystal change of the Brucite and the decomposition of the portlandite which produce more cracks resulting in an increase in porosity of about 7%.

Overall, if concrete has been well prepared for inhibiting explosive spalling, then the main damage to concrete caused by fire accident should be the loss in mechanical properties. Experimental results (Chan et al., 1999; Khoury, 1992) confirmed that compressive strength can be broadly maintained within a range of temperatures from 20 to 400 °C. Considerable loss in compressive strength occurs between 400 and 600 °C, and most of the original compressive strength before heating may be lost from 600 to 800 °C. Compared with compressive strength, tensile splitting strength suffers a more severe loss under an identical temperature, as the latter is more sensitive to thermally induced cracking (Chan et al., 1999). Therefore, the effect of cooling regimes on mechanical properties of concrete is of great concern, especially after a fire case was reported (Anonymous, 2003; Chen, 2004), which happened in the city of Hengyang, Hunan Province, China, November 3rd, 2003. In this case, an 8-storey reinforced concrete building collapsed catastrophically during fire extinguishing and twenty fire fighters died from the building collapse. Furthermore, apart from these reports on the effect of cooling on plain concrete with no fibre (Khoury, 1992; Luo et al., 2000; Anonymous, 2003; Chen, 2004) there is little literature on properties of fibre concrete moulded in various shape regimes.

Nowadays in construction, self-compacting concrete is widely used and there is a need to understand its behaviour when subjected to elevated temperatures. As it has been found in a preceding investigation by Peng et al. (2006) that using hybrid fibre (steel fibre and polypropylene fibre) is an optimum approach for enhancing fire resistance of HPC this study presents an investigation on the effect of specimen shape for a duration from 2 to 4 h, and air cooling to room temperature, on residual mechanical properties of SCC incorporating PP fibre after exposure to elevated temperatures at 200, 400, and 600 °C.

Banthia and Sheng illustrated that the interfacial bond between PP fibres and cement paste is weak due to their smooth fibre surface. They explained that there is no strength enhancement with PP fibres even at a volume fraction of 5%. Nevertheless, PP is chemically inert and hydrophobic, thus removing the potential for chemical bonding. Therefore, the fibrillation (the quality of being made up of fibrils) has a considerable effect on the bonding. Bentur et al., (1989) and Bentur, (1991) suggested that the interfacial adhesion and mechanical anchoring are the two main factors that affect the fibre–matrix interaction.

Moreover, the compressive strengths of M0.15 (0.15% of PP fibres by volume of SCC mixture) concretes were slightly decreased. This may be ascribed to the formation of a multifilament structure due to the insufficient diffusion of this amount of PP fibres in the mixture (Lankard et al., 1971). The enhancement in residual compressive strength for all four concretes at 200 °C is attributed to the increase in surface forces between gel particles (Van der Waals) due to the removal of water content (Sarshar and Ga, 1993).

Kalifa et al. (2001) showed that the compressive strength gain may be attributed to the rehydration of the gel, the hydration of un-hydrated cement grains, and the carbonation of calcium oxide. The strength loss generally is attributed to rehydration of lime accompanied by a 44% increase in volume. Furthermore, PP fibres turn into vapour at 341 °C. The decomposition products of PP fibres have been reported to be a variety of hydrocarbons, with the major components being propylene, pentene, and heptene. The strength recovery of concretes containing PP fibres was different from those of SCC without fibres. The improvement at 200 °C is attributed to the amount of water vapour that escapes freely through the pathways formed by the melting of the PP fibres between 170 and 175 °C and getting out the of surface of the concrete through the pores. The permeability of a concrete mixture containing 10% silica fume and 0.91 g/cm^3 of PP fibres were close to that of Ordinary Portland Cement concrete at 200 °C. Kalifa et al. suggested that the cement matrix is able to absorb the melted PP, despite the large size of the molecules compared to diameter of paste pores.

Pore pressure thus, depends on the porosity of concrete. Since the PP fibres melt before reaching 200 °C, the porosity of the concrete is increased and more escape routes are added to reduce the water vapour pressure. Furthermore, the decomposition of the PP fibres may reduce the results of thermal incompatibility between aggregates and cement paste due to the provision of more free space which acts as a thermal shock absorber. After exposure to 600 °C, the relative residual compressive strengths dropped a little for all concretes. In terms of water vapour pressure, as indicated previously, the behaviour of fibre concretes was better than that of the M0.0 concretes. In terms of lime, some post-cooling behavioural changes were reported in the form of strength gain and loss in the concrete mixtures (Petzold and Rohrs, 1970; Ozawa, 1989).