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Mechanical properties and microstructure of ultra-lightweight cement composites with fly ash cenospheres after exposure to high temperatures

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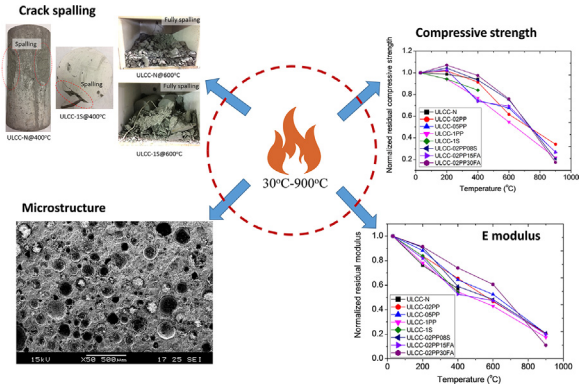
HIGHLIGHTS

- Examine mechanical behaviour and microstructure of ULCC after elevated temperature.
- Residual behaviour of ULCC at different temperatures with fibres and fly ash revealed.
- 0.2%–0.5% PP fibres eliminates explosive spalling and improves fire resistance.
- Hybrid fibres shows fire resistance and ductility after elevated temperature exposure.
- Mixes with fly ash show enhanced strength up to 200 °C before decreasing beyond 200 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper investigates the mechanical behaviour and micro-structure of a new type of ultra-lightweight cement composite (ULCC) using cenospheres as lightweight aggregates exposed to high temperature up to 900 °C. This type of ULCC material has a density less than 1400 kg/m^3 and compressive strength up to 60 MPa and thus it has high compressive strength to weight ratio compared to other types of concrete materials. To prevent the spalling of ULCC material when exposed to high temperature, synthetic fibres are needed. In this paper, ULCC materials comprising eight different mixtures considering different contents of polypropylene (PP) fibres, steel fibres, hybrid fibres and fly ash replacement for cement are examined. The effect of fibre content, fibre types, fly ash replacement for cement are quantified in terms of their compressive strength, flexural strength, elastic modulus after exposed to elevated temperature. In addition, weight loss, failure modes, load-deflection and stress–strain curves are reported. Macro scale examination of the specimens was carried out to investigate the modification in the physical behaviour i.e. color changes, cracking and spalling of ULCC at various temperatures. Microstructural characterization of specimens was examined before and after exposure to temperature deterioration by using scanning electron microscopy (SEM). Results indicates that ULCC containing small amount of PP fibre can improve the fire resistance of ULCC and eliminate the explosive spalling behaviour of ULCC for temperature up to 900 °C. Hybrid fibres improves both fire resistance and ductility after elevated temperature

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exposure. Finally, recommendations are made in terms of the use of fibre mixes and fly ash replacement amount to achieve the desired structural performance of ULCC materials when exposed to fire.

1. Introduction

Lightweight concrete is being considered for prefabricated pre-finished volumetric construction (3D modular) as the lifting weight can be reduced compared to normal weight concrete construction, thus easing the assembly of free-standing modular units. The main advantage of using lightweight concrete is the reduction of self-weight of structural members and overall structures, allowing smaller sizes of structural members and less reinforcing materials. Thus, requirements for foundations and transportation cost can be reduced significantly. In addition, it allows for easy and rapid installation at construction sites due to its lower self-weight, thereby saving time and improving productivity in construction. With the industry's consistent pursuit for lighter construction material, ultra-lightweight concrete emerges as a promising solution.

Ingredient materials used for lightweight concrete are often similar to those for normal weight concrete. There are generally three types of lightweight concretes: (1) lightweight aggregate concrete (voids are mainly introduced in aggregates) [1], (2) cellular concrete and foam concrete (voids are in cement paste or mortar) [2], and (3) no fines concrete (sand is eliminated and voids are between coarse aggregate particles). There are various materials which can be used as lightweight aggregates to reduce unit weight of concrete with good mechanical and functional properties, e.g. pumice [3], expanded clay/shale [4], perlite [5], and high-volume fly ash [6]. In recent years, ultra-lightweight cement composites (ULCCs) incorporating cenospheres from thermal power plants with very low densities of less than 1000 kg/m^3 and compressive strength higher than 30 MPa have been developed with higher specific compressive strengths compared to conventional lightweight aggregate concretes [1,7–9]. Cenospheres are hollow spheres extracted from residue of coal combustion at thermal power plants, and considered as industrial by-product. Their low densities of about 400–900 kg/m^3 provide them great buoyancy. Due to their many desirable properties such as, lightweight and low thermal conductivity, they can be used for various applications, for example, building insulation material, cementing, paints and fire proofing layer etc.

Fire is one of the major risks to reinforced concrete structures which can cause mechanical deterioration and explosive spalling of concrete although concrete material is recognized as a good fire-resistant material in building construction compared to metals. Mechanical properties and chemical composition of concrete may be affected significantly when exposed to fire as high temperatures could cause spalling in concrete and reduction in strength and modulus of concrete. Numerous studies have been conducted on the behaviour of normal weight concrete exposed to fires. Xiao and König [10] and Ma et al. [11] explained the deterioration mechanisms of concrete when exposed to fires at different temperatures. Several methods were proposed to alleviate the risk of concrete spalling at high temperature exposure, among which the inclusion of polypropylene (PP) fibre and air entraining admixture (AEA) were found to be economical and effective [12].

Othuman and Wang [2,13] reported an experimental and analytical study to quantify the thermal properties of lightweight foamed concrete (LFC) at high temperatures. Similar findings by Chen and Liu [14] reported low thermal conductivity (0.07 W/mk) of expanded polystyrene (EPS) foamed concrete. However, the low compressive strength of the material makes it unsuitable for structural applications. Steel fibre addition is found to improve the mechanical properties (e.g., residual strength, ductility and fracture energy) for normal and high strength concrete and its behaviour under elevated temperature has been investigated [15–17]. Other investigations focused on improving the sustainability of lightweight concrete by incorporation of fly ash. Tanyildizi and Coskun [18] explored the effect of high temperature on fire performance of lightweight concrete incorporating high volume fly ash. The test results showed that fly ash was identified as a good supplementary material to prevent the decrease of concrete strength at high temperatures [19].

Most of the past research focused on fire resistances of normal weight concrete, high strength concrete, low strength lightweight aggregate concrete and other recycled aggregate concrete [20]. Recently, some research has been done on cenosphere-based ultra-lightweight cement composite (ULCC) to investigate the mechanical properties, namely, density optimization, compressive strength/flexural strength/elastic modulus [21,22], thermal properties [23], shrinkage and creep [24], durability-related issues [25] and later structural flexural/shear/punching and impact performance of reinforced concrete, steel-concrete composite structures in building and offshore structure at ambient temperature [26–33]. There are limited studies on the fire resistant behaviour of ULCC material and their structural applications [34]. The fire resistance information such as concrete spalling resistance and flexural stiffness is essential to promote the use of such material in building construction. This indicates the need for a comprehensive investigation encompassing not only the morphological change and mechanical properties but also the fire performance of ULCC structural members at or after elevated temperature exposure.

In this paper, the effect of elevated temperature on mechanical properties and microstructure of ULCC with fly ash cenospheres exposed to elevated temperatures (up to 900 °C). ULCC materials with different types and amount of fibres incorporating of different amounts of fly ash will be investigated. The influences of polypropylene (PP) fibre and fly ash were analyzed in terms of physical and mechanical properties, microstructure and fibre-matrix interactions as a function of heat treatment by using surface characterization, weight loss measurement, stress-strain measurement and SEM observations. Based on the test results, recommendations are made in term on the use of fibre mixes and fly ash replacement amount to achieve the desired structural performance of ULCC materials when exposed to fire.

2. Experimental investigation

2.1. Materials and mix proportions

Ultra-Lightweight Cement Composites with different types and dosages of fibres together with 15% and 30% replacement of cement by weight are used in this investigation, details of which are given in Table 1. ASTM Type I Portland cement, fly ash cenosphere having a particle density of 870 kg/m^3 and sizes from 10 to 300 μm in diameter, silica fume, Class F fly ash requirements, monofilament polypropylene fibres/straight steel fibres. The chemical composition of the cement, silica fume and fly ash are reported in Table 2. Fig. 1(a) and (b) shows the SEM micrograph and pho-