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Evaluation of compressive behavior of ultra-lightweight cement composite after elevated temperature exposure

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HIGHLIGHTS

- Residual mechanical properties of novel ULCC are reported.
- New test data for ULCC after elevated temperature exposure to 1000 °C are reported.
- No spalling of ULCC has been found after exposure to high temperature of 1000 °C.
- ULCC with small amount PVA fiber exhibits promising fire resistance.

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ABSTRACT

This paper investigates the mechanical behavior of a new type of ultra-lightweight cement composite (ULCC) with density less than 1400 kg/m^3 and strength up to 60 MPa after exposing to elevated temperature up to 1000 °C. The residual compressive strength, elastic modulus, weight loss, failure modes and stress-strain curve behavior are studied experimentally. The heated specimens are explored both at macro and micro scales to investigate the physical behavior deterioration, color changes, cracking and spalling of ULCC at various temperatures. Chemical deterioration behavior is analyzed through XRD analysis and interfacial zone changes in ULCC matrix is examined by SEM observations. It is found that the ULCC containing high volume cenospheres and small amount of PVA fiber (0.2% and 0.5% in volume) exhibits promising thermal resistance compared to normal lightweight aggregate concrete and normal concrete of similar strength. The strength reduction rate and level of ULCC at elevated temperatures is smaller. Based on the test data, this paper proposes empirical equations to calculate the residual compressive strength and elastic modulus. Knowledge extracted from the experimental findings in this paper provides better understanding of the fundamental mechanical behavior of novel ultra-lightweight cement composite material after exposure to elevated temperature, which is helpful to develop design guide for fire resistance design of lightweight cement composite structures in the future.

1. Introduction

Building constructions around the world have become increasingly interested in using lightweight concrete. Lightweight concrete which is similar to normal weight concrete, is a mixture of water, ordinary Portland cement (OPC) and lightweight aggregates. It is classified as structural and non-structural concrete depending on strength, generally determined by the types of lightweight aggregate materials. There are generally three types of lightweight concretes: (1) lightweight aggregate concrete (voids are mainly in aggregates) [1], (2) cellular concrete and foam concrete (voids are in cement paste) [2], and (3) no fines concrete (sand is eliminated and voids are between coarse aggregate particles). The main advantage of using lightweight concrete is self-weight reduction of the structure, allowing smaller member size and fewer reinforcing materials. Thus, transportation and foundation cost can be reduced significantly. However, the application of structural lightweight concrete in today's practical construction is rare. One of the major reasons that inhibits the adoption of lightweight concrete is owing to its brittleness, low strength or requirement for special curing [3].

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Fire is known as 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 constructions compared to metal materials. Concrete may severely change in its physical properties and chemical composition when exposed to elevated temperatures. Mechanical properties of concrete after such exposures are of great importance in terms of the safety and serviceability of building [4]. Extensive research have been performed to investigate the thermal properties of normal concrete [4–7], lightweight aggregate concrete [8–12] and high strength concrete [13–19]. Othuman and Wang [2] reported an experimental and analytical study to quantify the thermal properties of lightweight foamed concrete (LFC) at high temperatures. Two methods namely direct measurement using hot guarded plate (HGP) and analytical solution were proposed. Later on, they [11] presented a comprehensive study on mechanical properties including compressive strength, flexural strength, modulus of elasticity, compressive stress-strain relationship, strain at peak compressive stress and porosity. However, the mechanical properties were expected to be lower than normal concrete for construction purpose (*i.e.*, <16 MPa) which may be only suitable for low-rise residential constructions. Chen and Liu [12] investigated the mechanical properties and thermal conductivity of EPS foamed concrete. Compressive test showed the EPS foamed concrete was ductile and had a high energy absorption capacity. But again the strength is its drawback and compressive strength of less than 11 MPa has been obtained although it has impressively low thermal conductivity of 0.07 W/mk. A number of methods have been proposed to alleviate the adverse effect of high temperature exposure on concrete. For example, the inclusion of polypropylene (PP) fiber, steel fiber can improve the mechanical properties (*e.g.*, residual strength, fracture energy and spalling resistance, *etc.*) for normal and high strength concrete [10,16–19]. Akca and Zihnioğlu [10] used PP fiber and air entraining admixture (AEA) to improve the fire performance of high performance concrete (HPC) and they found that it was an effective method to decrease the risk of spalling. Behavior of HPC was different than normal concrete under high temperatures due to very dense microstructure of HPC. Tanyildizi and Coskun [8] 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 against high temperature. Al-Sibahy and Edwards [9] reported an experimental investigation on a new type of lightweight concrete made with by-product materials including recycled glass and metakaolin. Their fundamental mechanical properties were first measured at ambient and high temperatures.

Numerous studies were conducted in the past on fire behavior of normal strength concrete. Those studies, reviewed by Xiao and König [5] and Ma et al. [20] have provided a comprehensive understanding of the main physical and chemical deterioration mechanics underwent by concrete and its main components at different temperatures. However, all the research work are focused on the normal concrete, high strength concrete, low strength lightweight concrete and some other recycled aggregate concrete [21]. The physical and chemical deterioration behavior has not been well investigated on high strength structural lightweight concrete.

This paper extends the research work on the development of ultra-lightweight cement composite (ULCC) incorporating high volume fly ash-based cenospheres which is a novel type of composites characterized by combinations of low density less than 1400 kg/m^3 and high compressive strengths up to 60 MPa with specific strength (strength-to-density ratio) of up to 43 kPa/kgm^3 [22]. It is comparable to that of normal weight concrete with a compressive strength of about 110 MPa. This lightweight composite employs high dosage of fly ash-based cenospheres obtained from coal-fired power station. Fly ash is thought to be a good fire-resistant material since the main chemical composition is refractory silicon dioxides [23]. Beyond that, the fine aggregates is lightweight, inert, hollow sphere and filled with air or inert gas, and typically has very low thermal conductivity (0.08 W/mK) and water absorption. Also, ASTM C227 and C1260 test results indicated that the cenospheres used for ULCC were not potentially deleterious due to alkali silica reaction [24]. The ULCC would have a great potential for wide range of uses due to its high strength-to-density ratio and stable properties. Previous studies showed that ULCC exhibited good mechanical and physical properties and were filled in steel-concrete-steel (SCS) sandwich composite structures for offshore applications [25–30]. Nevertheless, little information on the thermal resistance behavior of ULCC is known [31]. The thermal resistance information is quit useful for researchers and engineers to understand the fundamental behavior to promote this material for structural fire application. Before it can be considered for use as a load bearing material in the building industry especially where fire situation is critical, it is necessary to acquire reliable information on mechanical properties of ULCC at ambient and elevated temperatures to quantify its fire resistance performance. Thus, the main objective of this work is to investigate the fire behavior of ULCC experimentally and analytically. The results presented in this paper, also compared with that of normal lightweight concrete, will be valuable for achieving a better understanding of the fire performance of ULCC. Abovementioned information is helpful to improve the behavior of ULCC, expand its application and lead to a safer design in building structures.

2. Experimental programme

2.1. Material and mix proportions

ULCC is made of water, ASTM Type I Portland cement, fly ash-based cenosphere fine aggregate, silica fume, PVA fibers and chemical admixtures. Table 1 shows the chemical composition of cement and silica fume used. The cenospheres in use had a particle density of 870 kg/m^3 and most of the particles had sizes from 10 to 300 μm. Fig. 1 shows the basic components of fly ash-based cenosphere while Fig. 2 shows the particle size distribution of cenospheres. Shrinkage reducing admixture (SRA) was used to reduce the air void content and shrinkage of mixture. A polycarboxylate based superplasticizer was used to achieve required flow around 200 mm according to flow table test [32]. PVA fibers were monofilament fibers with a length of 12 mm, an aspect ratio of 308 and a high tensile strength up to 1600 MPa which were added at a dosage of 0.2% and 0.5% by volume to prevent the earlier shrinkage cracking and spalling. Table 2 shows the material properties of PVA fibers.

Table 1
Chemical composition of cement and silica fume.

Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	K_2O	Na_2O	SO_3	C_3S	C_2S	C_3A	C_4AF
Cement	63.45	19.42	4.81	2.77	1.30	0.35	0.17	1.93	68.98	3.63	8.05	8.44
Silica fume	0.2	96.0	0.3	0.3	0.4	0.6	0.05	0.2	N.A.	N.A.	N.A.	N.A.