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Comparative study of the mechanical and thermal properties of lightweight cementitious composites

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HIGHLIGHTS

- Mechanical and thermal properties of cementitious composites with lightweight fillers were studied.
- The effects of filler type, particle size, and shell properties were systematically investigated.
- Microstructures and failure mechanisms were examined.
- Analytical approach was proposed to calculate material thermophysical properties.

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ABSTRACT

Lightweight concrete and cementitious composites are increasingly studied by researchers due to their advantageous performance in reducing structural load and building's operational energy consumption. In this research, a comprehensive and thorough study was carried out to investigate the effects of different lightweight fillers on both the mechanical and thermal properties of lightweight cementitious composites, or LWCCs. Four different types of lightweight fillers (LWFs) including expanded polystyrene (EPS) beads, dry-expanded thermoplastic microspheres (ETM), hollow glass microspheres (HGM), and fly ash cenospheres (FACs) are studied in conjunction with various particle sizes, shell wall thickness, and proportions. Both mechanical and thermophysical properties were tested for these LWCCs after 28-day curing. The results indicated that the thermal property of LWCC is mostly governed by the volume fraction of LWFs and it can be accurately predicted by the Felske equation, whereas the mechanical properties are heavily affected by the type and property of LWF particles included. It was revealed that most fly ash cenospheres (FAC) and hollow glass microspheres (HGM) with higher density are suitable for producing LWCC materials that may be used for structural applications, whereas lower density HGMs and LWFs with soft polymer shell are more suitable for nonstructural thermal insulating components.

1. Introduction

The use of lightweight concretes (LWCs) in building structures brings twofold advantages: first, the use of LWC reduces structural weight and the dead load acting on the structures which would lead to smaller structural members and foundation size [1]; secondly, they have lower thermal conductivity than normal weight concrete which will in turn reduce building energy consumption and provide better fire resistance [2]. The reduction of a building's operational energy and the associated greenhouse gas emissions is critical for its life-time sustainability. Since energy consumed in space heating and cooling constitutes a major portion of a building's total energy consumption [3], construction materials with low thermal conductivity can effectively reduce the heat exchanged between a building's interior space and the outside environment.

Traditionally, lightweight concretes are produced by incorporating lightweight course aggregates (LWA) such as expanded perlite [4–6], shale [7–9], and expanded clay [10] into concrete. While the unit weight of these materials has been successfully achieved within the stipulated guidelines [11,12], traditional lightweight concrete and cementitious composites had lower mechanical strength and reduced performance such as impaired durability [10] and brittle failure [13]. In order to circumvent the drawbacks presented by traditional lightweight aggregate concrete, more recently, millimeter and micrometer size lightweight functional fillers (LWFs) including expanded polystyrene beads, expandable thermoplastic microspheres [14], hollow glass microspheres [15–17], and fly-ash cenospheres [18–21] have been exploited to

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produce high performance LWCC for structural application in buildings. Some of the emerging LWFs are introduced herein.

1.1. LW cement mortar with EPS beads and plastic microspheres

Expanded polystyrene (EPS) beads are artificial ultra-lightweight aggregate (typical density < 30 kg/m^3 [22]) with rounded shape and smooth surface. Earlier research on expanded polystyrene (EPS) concrete incorporates millimeter-size EPS spheres into mortar or cement paste to reduce density and thermal conductivity [22]. In comparison to regular lightweight aggregate concrete (LWAC), EPS concrete has shown better workability and volume stability [23]. It has been used for the fabrication of lightweight concrete bricks [24] and even load-bearing structural components [25]. Structural elements made from EPS concrete can be fabricated at the construction site. This provides advantages over other materials such as autoclaved cellular concrete whose fabrication process has to be performed in a well-controlled environment at a prefabrication plant. On the other hand, the drawbacks of EPS concrete are also well documented including low thermal resistance (i.e., EPS combust and release toxic gas at temperature above its ignition point) and because of its very low density, EPS aggregates are prone to segregation during mixing [24]. Mechanically, EPS concrete has shown low mechanical strength and brittle failure [22].

In addition, Aglan et al. [14] incorporated micro-size hollow expandable thermoplastic microspheres (ETM) with average particle size around 35–55 μm into cement paste. Their study showed improvements in tensile strength and fracture toughness for cement pastes having 0.1–0.4 wt% of ETM.

1.2. Hollow glass microsphere (HGM) bubbles

Due to its higher crush strength, light weight, and thermally insulating features, hollow glass microsphere (HGM) bubbles have been explored as an lightweight micro-filler in cementitious binders [16]. In comparison with polymer-based lightweight aggregate such as EPS beads and ETM, glass microspheres offer advantages including high crush strength, good thermal resistance (with typical softening temperature around 650 °C), and the cement mortars containing HGMs have more predictable mechanical and thermal properties [15]. In addition, the spherical shape and smooth surface of HGM can be utilized to alter the rheological property of fresh cement mortar, which has led to their applications in oil well cement slurry [26]. However, since the chemical properties of most HGM resemble those of a soda-lime borosilicate glass, cement mortar containing HGM particles may experience some degree of alkali-silica reaction [27]. In addition, due to its smooth surface and weak bonding to cement paste binder, HGM modified cementitious materials typically exhibit lower strength and brittle failures [17].

1.3. Fly-ash cenospheres (FAC)

Fly-ash cenospheres, or FAC, are an alumino-silicate based by-product of coal combustion at thermal power plants [28]. The coal burning process in the thermal power plants produces fly ash in both solid and hollow (cenosphere) particulate forms. Most cenosphere particles have spherical shape and hollow interior covered by a thin shell with typical shell thickness of about 5–15% of its diameter. Due to its hollow structure, FAC have low particle density (400–900 kg/m^3) and low thermal conductivity. It has been used for making ultra-lightweight concrete and cementitious composite (e.g., ULCC) in recent years [18–21]. The composition of FAC is mostly compatible with cementitious binders. Due to its partial pozzolanic reactivity, together with the rougher surface of FAC, it provides good interfacial bonding within the mortar system.

Although individual researches have been conducted for each type of the aforementioned lightweight aggregates/ filler materials, there still lacks a comprehensive investigation on the mechanical and thermal performance of cementitious composites containing these emerging LWFs. Unlike most lightweight coarse aggregates with irregular shape and porous surfaces (e.g., expanded shale clay), the lightweight particulate aggregates/ fillers discussed in this paper have much smaller particle size and are mostly spherical in shape (or have a core-shell configuration). This will allow the fine-tuning of material properties by varying material parameters such as particle size, shell thickness (stiffness), and volume fraction. For this purpose, an accurate knowledge of relationships between the composition, aggregate property, and the equivalent properties of the cementitious composites is required.

In this research, a comparative study is conducted on the properties of lightweight cementitious composites (LWCCs) mixed with four types of lightweight aggregates/filler particles – i.e., EPS beads, dry-expanded plastic microspheres, hollow glass microspheres, and fly ash cenospheres. The materials' thermophysical (e.g., density, thermal conductivity) and mechanical (compressive strength) properties are investigated with respect to the particle type, size distribution, as well as their volume concentration. Key parameters governing the material thermal and mechanical properties are discussed, and the composition-property relationships are deduced from both experiment results and predictive models. The results will provide valuable insights into the quantitative design of concrete and cementitious composites containing micrometer and millimeter size lightweight particle fillers.

2. Experimental program

2.1. Material preparation and mix design

The constituent materials used for preparing the lightweight and ultra-lightweight cementitious composites in this study include ASTM Type I-II Portland cement, silica sand (*US silica*), water, superplasticizer (*Sika Corp.*), and lightweight fillers (LWF). The water to cement ratio (w/c) was selected at 0.43 for all mixtures. The mass of cement, sand, and water used for each cubic meter of the reference mortar (without LWF) are 530.64 kg/m^3, 1367.67 kg/m^3, and 228.18 kg/m^3, respectively. The LWF used in this research include expanded polystyrene (EPS) beads, expanded thermoplastic microspheres (ETM), hollow glass microspheres (HGM), and fly ash cenospheres (FAC). For each type of LWF, different particle properties (i.e., size, density, crushing strength, and volume fraction etc.) were studied with respect to their influences on the mechanical and thermophysical properties of LWCC. For each group of LWF tested herein, four LWF volume fractions (v_f) – i.e., namely 7%, 14%, 21%, and 28% of the total volume were tested and for each volume fraction the equivalent volume of regular fine aggregate (i.e., silica sand) was deducted from the mix (i.e., the amount of silica sand used for v_f = 7%, 14%, 21%, and 28% are 1138.37 kg/m^3, 937.38 kg/m^3, 715.83 kg/m^3, and 533.71 kg/m^3, respectively). The air content of fresh cement mortar was measured at 2–5% according to ASTM C185 – 15a, which does not account for the air contained within the LWF. The properties of lightweight micro-fillers (LWF) used in this research are listed in Table 1 and are briefly introduced as follows.

EPS beads and ETM

Two types of EPS beads with average particle size of 2.5 mm (noted as "medium") and 1 mm (noted as "small") are used in this