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Method to determine mixture proportions of workable ultra lightweight cement composites to achieve target unit weights

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ABSTRACT

Ultra lightweight cement composite (ULCC) is a type of composite characterized by low unit weights <1500 kg/m^3 and high compressive strengths of up to about 65 MPa. The low unit weight is achieved by incorporating cenospheres as micro-lightweight aggregates in cement paste. As the cenospheres are by-products from coal burning power plants, their properties may vary greatly. This results in great difficulty in determining the mixture proportions of the ULCC. In this research, a new design method is developed and proposed that can be used to effectively determine the mixture proportions of workable ULCC to achieve a desired target unit weight with minimal laboratory trials. The relationship between the spacing among spherical cenospheres and the water-to-cementitious materials ratio (*w/cm*) needed to achieve the target workability is the basis of this design method. For a given cenosphere sample, if its particle size distribution and particle density are determined, it is possible to design a mixture of ULCC using this method.

1. Introduction

Ultra lightweight cement composite (ULCC) is a type of cement composite characterized by combinations of low unit weight <1500 kg/m^3 and high compressive strengths of up to about 65 MPa and specific strengths (strength-to-density ratio) of up to 47 kPa/(kg/m^3) [1,2]. For example, in terms of specific strengths, a ULCC with the unit weight of 1425 kg/m^3 and compressive strength of 65 MPa is equivalent to a high-strength concrete with the unit weight of 2400 kg/m^3 and compressive strength of about 110 MPa. Although 65 MPa is not considered as high strength for normal weight concrete today, such a strength level can be considered as high strength for lightweight composites with unit weight <1500 kg/m^3. According to the definition in EN206-1 (3.1.10), lightweight concrete with a compressive strength of above 50 MPa is regarded as high strength concrete [3]. Besides the higher specific strength, the ULCC also has other properties such as lower water permeability [4], as compared to typical lightweight aggregate concrete. The ULCC was originally designed as the core material for steel–concrete–steel sandwich composites [5,6]. It may be used in other composite structures and energy efficient buildings due to its porous nature.

The low unit weight of the ULCC is achieved by incorporating cenospheres as micro-lightweight aggregates in a cement paste matrix (Fig. 1). The cenospheres are hollow spheres with typical particle sizes varying from about 10 μm to 300 μm [7] obtained from fly ash in coal-burning power plants [8–10]. The thin shell of the cenospheres has a thickness of about 2.5–10.5% of the corresponding cenosphere diameter [11]. Due to their hollow structure, cenospheres have low particle densities typically ranging from 600 kg/m^3 to 900 kg/m^3. Cenospheres with thicker shells generally have higher particle densities. The ULCC, therefore, is a type of cement composite without coarse aggregate and sand.

As the cenospheres are by-products from coal burning power plants, their properties such as particle size distribution (PSD), specific surface area, and particle density may vary greatly depending on the sources and processing methods. These properties may affect the workability (including flowability and stability against segregation) and unit weight of the ULCC substantially. This results in great difficulty in determining the proper mixture proportions of the ULCC, and usual practice is mainly based on experimental trials.

The objective of this research is to develop a method based on the concept of spacing among cenospheres to effectively determine the mixture proportions to achieve workable ULCC with specified unit weights for various applications using commercially available cenospheres. The method developed is focused on the workability and unit weight of the ULCC.

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Nomenclature

Acronyms

- CPT: average thickness of cement paste surrounding cenosphere particles (μm)
- CPV: volume fraction of cement paste in the ULCC (%)
- LPDM: de Larrard's linear packing density model
- MPD: maximum packing density
- MPD_t: maximum packing density of the (*cenosphere* + *coating*) complexes with CPT equal to t
- PSD: particle size distribution
- SRA: shrinkage-reducing admixture
- ULCC: ultra lightweight cement composite
- w/cm: water to cementitious materials ratio (water = total water including the water in the admixtures; cementitious materials = cement and silica fume)

Notations

- D_{10}, D_{50}, D_{90}: the 10th, 50th and 90th percentile passing size (μm)
- $\overline{D}$: representative average size of the cenospheres (μm)
- d_i: average diameter of the cenospheres in the dominant class I (μm)
- d_j: average diameter of the cenospheres in a non-dominant class j (μm)
- d_{lower}: lower class boundary (minimum possible size) of a cenosphere class (μm)
- d_{upper}: upper class boundary (maximum possible size) of a cenosphere class (μm)
- $V_{ceno,j}$: volume of cenospheres in class j in 1 m^3 of a cement composite mixture (m^3)
- $V_{ceno+coating,j}$: volume of (*cenosphere* + *coating*) complexes in class j in 1 m^3 of a cement composite mixture (m^3)
- y_j: volume fraction of the j_{th} class with respect to the total cenospheres (%)
- y_{lower}: lower boundary of the cumulative percentage passing (%)
- y_{upper}: upper boundary of the cumulative percentage passing (%)
- β_i: maximum packing density of the cenospheres in the i_{th} class (dominant class)
- β_j: maximum packing density of the cenospheres in the j_{th} class (non-dominant class)
- γ_i: calculated maximum packing density of all the cenospheres, with class i as the dominant class
- ζ: total volume of cenospheres in 1 m^3 of a cement composite mixture (m^3)

The new design method developed and proposed in this research can be used to effectively determine the mixture proportions of workable ULCC with minimal lab trials. In addition, this design method is able to facilitate the quality control of the ULCC (especially the unit weight) using cenospheres from different sources. This is particularly useful in floating structures where controlling the self-weight of the structures is critical.

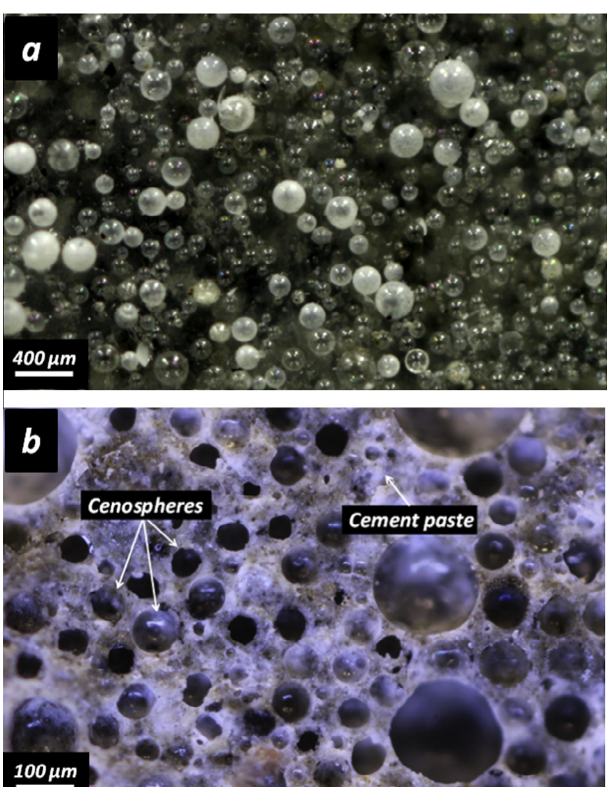

Fig. 1. (a) Image of cenospheres as received. (b) Image of ultra lightweight cement composite with cenospheres.

The new method can determine the spacing among polydispersed cenosphere particles in the cement paste matrix which is a critical parameter for properties of the composites such as workability, unit weight, strength, and thermal conductivity. As the cenospheres have also been used as fillers for other lightweight and high performance composites such as aluminum metal based composites for automobile and aerospace engineering [12–14] and polymer based composites [15], the method may also be applicable to the development of these composites.

2. Introduction of the proposed design method of ULCC

As shown in Fig. 1(b), the ULCC consists of two main components: (1) cenospheres and (2) cement paste. The discrete cenospheres are embedded in continuous cement paste matrix. The cement paste includes water, cement, silica fume, high range water reducer (HRWRA) and air. The relation between the volume fraction of the cenospheres and volume fraction of the cement paste (CPV) is given in Eq. (1), neglecting any entrained or entrapped air:

$$\text{Volume fraction of cenospheres} = 1 - \text{CPV} \tag{1}$$

The workability and unit weight of the ULCC are affected by the properties of the cenospheres and cement paste, as well as their relative proportions in a mixture. For the cenospheres, particle size distribution (PSD) and particle density are primary parameters which influence the workability and unit weight of the composites. For the cement paste, however, water to cementitious materials ratio (w/cm) and HRWRA dosage are critical parameters. For the relative proportion between the cenospheres and cement paste, since the density of the cenospheres (600–900 kg/m^3) is substantially lower than that of cement paste (1670–2320 kg/m^3 corresponding to w/c of 0.7–0.2) commonly used in concrete, the reduction in the volume fraction of cement paste (CPV) reduces the unit weight of the ULCC. On the other hand, a sufficient volume of the cement paste is essential to obtain workable ULCC with adequate strength development.

The workability of fresh ULCC is generally characterized by the flow value tested according to BS EN 1015-3 [16]. The cone based on this standard has a height of 60 mm ± 0.5 mm and internal