Construction and Building Materials 87 (2015) 100–112

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Development of ultra-lightweight cement composites with low thermal conductivity and high specific strength for energy efficient buildings

Yunpeng Wu [a], Jun-Yan Wang [b], Paulo J.M. Monteiro [c], Min-Hong Zhang [a,*]

[a] Department of Civil & Environmental Engineering, National University of Singapore, 1 Engineering Drive 2, Singapore 117576, Singapore
[b] Key Laboratory of Advanced Civil Engineering Materials, Tongji University, Ministry of Education, Shanghai 201804, China
[c] Department of Civil & Environmental Engineering, University of California, Berkeley, 725 Davis Hall, Berkeley, CA 94720, USA

HIGHLIGHTS

- Ultra-lightweight cement composites (ULCCs) are developed for energy efficiency.
- ULCCs with densities <1471 kg/m^3 are developed using hollow cenospheres.
- ULCC has specific compressive strength similar to that of concrete of 110 MPa.
- ULCC has 80% lower thermal conductivity than concrete of similar 28-day strength.
- Thermal conductivity of ULCCs may be estimated using Hashin–Shtrikman lower bound.

ARTICLE INFO

Article history:
Received 3 March 2015
Received in revised form 2 April 2015
Accepted 7 April 2015
Available online 20 April 2015

Keywords:
Cement composite
Cenospheres
Lightweight
Mechanical property
Thermal conductivity

ABSTRACT

Energy efficient building is defined as achieving satisfactory internal environment and service with minimum energy consumption. One of the most important parameters that affect the heat transfer through the building envelope is thermal conductivity. The thermal conductivity of lightweight concrete is generally lower than that of normal-weight concrete due to the lower thermal conductivity of air. Although introducing voids in concrete reduces its thermal conductivity and increases its insulation capacity, the mechanical properties are generally compromised.

This study focuses on the development of ultra-lightweight cement composites (ULCCs) with low thermal conductivity but high specific strength so that they can be used for structural applications. The lightweight is achieved by incorporating hollow cenospheres from fly ash generated in thermal power plants. The ULCCs had 1-day densities ranged from 1154 to 1471 kg/m^3 and 28-day compressive strengths ranged from 33.0 to 69.4 MPa. The properties of the ULCCs were compared with those of cement pastes with comparable water/binder and those of a concrete with 28-day compressive strength of 67.6 MPa.

Results indicate that the compressive strength, flexural tensile strength, and elastic modulus of the ULCCs were reduced with the decrease in density. However, compressive and flexural tensile strength of 69.4 and 7.3 MPa were achieved for the ULCC, respectively, similar to the cement paste with w/b of 0.35 and concrete. With similar 28-day compressive strength, the thermal conductivity of the ULCC was 54% and 80% lower than that of the cement paste and concrete, respectively. The low thermal conductivity of the ULCC is due to the incorporation of hollow cenospheres as micro-aggregate which effectively introduce voids and decrease density of the ULCC. The high specific strength of the ULCC may be attributed to (1) the presence of hard and stiff shell in the cenospheres, (2) the "control" of void sizes in the cenospheres, and (3) the creation of strong cement paste matrices that provide "three dimensional" confinement to the cenospheres.

1. Introduction

Energy consumption is growing rapidly due to economic development and population growth [1]. While over 40% of the total primary energy consumption in the world is for building sector [2], a significant part of that energy is consumed when buildings are in use through heating, ventilation, and air conditioning (HVAC) systems. In developed countries, 20% of the total energy consumption is by HVAC systems [1]. An energy efficient building is defined as achieving satisfactory internal environment and

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.conbuildmat.2015.04.004
0950-0618/

service with minimum energy consumption [3]. The energy required to achieve satisfactory indoor temperatures correlates mainly with the heat transfer through building envelope, heat convection on building surface, and heat generated by indoor equipment and human activities.

One of the most important parameters that determine the heat transfer through building envelope is the thermal conductivity. It is a measure of the rate at which heat is transferred through a material, and is defined as the ratio of heat flux to temperature gradient. Concrete has low thermal conductivity compared with other building materials, and can be further reduced by introducing air voids to resist heat flow between indoor and outdoor environment. There are several ways to introduce air voids into concrete: (1) voids in aggregates of various sizes, (2) voids in cement paste, (3) elimination of sand in the concrete mixture leading to voids in between the coarse aggregate, and (4) combinations of the above. Among them, the first one is typically used to achieve higher specific strength and low permeability.

Thermal conductivity of concrete is affected primarily by the thermal conductivity of the raw materials used, mixture proportion, void content, and moisture condition of the concrete. The thermal conductivity of most natural rock aggregates is much higher than that of the cement pastes, and it varies depending on the rock type. In general, rocks with crystalline structure show higher thermal conductivity than amorphous and vitreous rocks of the same composition [4,5]. The thermal conductivity of cement pastes increases with the reduction of water/binder (*w*/*b*) and capillary porosity. Due to the lower thermal conductivity of air (in the order of 0.03 W/m K), the thermal conductivity of lightweight concrete (LWC) is generally lower than that of normal weight concrete. For a given type of lightweight aggregate (LWA), the reduction in the concrete density results in a decrease in the thermal conductivity. Moisture content is another major factor that influences the thermal conductivity of concrete because the thermal conductivity of water (0.5 W/m K) is higher than that of air.

In recent years, structural concrete mixtures with low thermal conductivities have been developed using aggregates other than some commonly used manufactured LWA or industrial by-product such as expanded clay, expanded shale, or foamed slag etc. Examples of the LWAs include pumice [6,7], perlite [8,9], cenospheres [10,11], polyurethane foam [12], diatomite [7], expanded glass [13], aerogel [14], and high-impact polystyrene [15]. A summary of the density, compressive strength, thermal conductivity, and raw materials used for such lightweight-aggregate concretes (LWAC) reported in literature are presented in Table 1. A summary of the thermal conductivity data of the LWAC made with the traditional LWAs such as expanded clay and shale among others, can be found in the FIP manual of lightweight-aggregate concrete [16]. However, no information is available on their corresponding strengths. Thus, they are not included in Table 1.

Although introducing voids in concrete reduces its thermal conductivity and increases its insulation capacity, the mechanical properties, such as compressive strength and elastic modulus, are generally compromised. This study focuses on the development of structural materials which have low thermal conductivity for energy efficiency purpose but sufficient strength to be used for structural applications.

In this study, cenospheres were used to introduce voids into the ultra-lightweight cement composites (ULCCs). Cenospheres are hollow spheres typically produced as a byproduct of coal combustion at thermal power plants [17,18] (Fig. 1). The process of burning coal in thermal power plants produces fly ash which includes mainly solid particles and a small amount of hollow particles (cenospheres). Cenosphere particles have spherical shapes with sizes typically ranging from 10 to 400 μm [19]. They generally have a hollow interior that is covered by a thin shell with thicknesses in the order of 5–10% of its diameter [20]. Due to its hollow structure, cenospheres have low particle densities typically ranging from 400 to 900 kg/m^3. Because of their low particle densities, cenospheres have been used for making ultra-lightweight cement composites in recent years [10,11,21–26]. Ultra-lightweight cement composites with a density of 1430 kg/m^3 and 28-day compressive strength of about 60 MPa was developed and reported by Chia et al. [23].

The objectives of this study are to investigate the thermal conductivity of ULCCs in comparison to that of cement pastes with comparable water/binder ratios (*w*/*b*) of 0.35 and 0.45 and a

Table 1
Summary of relevant information in literature.

References	Aggregate information type/maximum size	*w*/*b*	Wet density (kg/m^3)	Oven dry density (kg/m^3)	Compressive strength (MPa)	Moisture condition at which TC was determined	Thermal conductivity (W/m K)
Blanco et al. [10]	Cenosphere/4 mm	0.3	1090–1415	1050–1350*	5.0–30.1	Moist cured Dried at 100 °C	0.46–0.60 0.36–0.46
Uysal et al. [6]	Pumice/16 mm	NA	2270–1329	NA	NA	0%	1.46–0.78
Gül et al. [8]	Perlite/16 mm	0.7	1773–1984	1590–1800*	11.3–25.1	NA	0.82–1.23
Topçu et al. [7]	Diatomite/4 mm Pumice/4 mm	0.2	NA	900 1500	6 9	0%	0.13 0.44
Mounanga et al. [12]	Polyurethane foam waste/ 10 mm	0.6–0.7	1261–2165	900–1980*	23.0–3.2	NA Saturated	1.44–0.31 2.34–0.68
Tandiroglu [9]	Perlite/15 mm	0.4–0.65	NA	1798–1883	60–80	0%	1.47–1.76**
Sengul. et al. [52]	Expanded perlite/2–4 mm	0.55	392–1937	354–1833	0.1–28.8	0%	0.6–0.13
Kim et al. [54]	Fine bottom ash/0.6 mm & expanded shale/19 mm	0.47	1800–1553	1500–1210**	22–8	0%	0.54–0.36
Wang & Meyer [15]	High impact polystyrene/ 2.36 mm	0.55	NA	1980–1560	37–19	NA	0.61–0.27
Huang et al. [11]	Cenosphere/600 μm & Iron ore tailings/300 μm	0.26	1649–2001	1483–1890***	44.3–48.1	NA	0.29–0.37
Yu et al. [13]	Expanded glass/4.0 mm	0.38–0.59	1280–1460	1100–1380*	23–30	0%	0.49–0.85
Yun et al. [53]	Glass Bubble/(Median diameter: 65 μm)	0.55	2011–2370	1900–2260*	43.9–24.6	NA	2.25–1.41
Gao et al. [14]	Aerogel/4 mm	0.38–0.39	1000–2050	900–1950*	8.3–60**	NA	0.26–1.9**

NA – not available.

* estimated based on ASTM C567 [51] where mix proportions are available.

** obtained from figures in literature.

*** air dry density was used here because it's lower than estimated oven dry density using ASTM C 567 [51].