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Ultra-lightweight concrete: Conceptual design and performance evaluation

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ABSTRACT

The present study presents a methodology to design ultra-lightweight concrete that could be potentially applied in monolithic concrete structures, performing as both load bearing element and thermal insulator. A particle grading model is employed to secure a densely packed matrix, composed of a binder and lightweight aggregates produced from recycled glass.

The developed ultra-lightweight concrete, with a dry density of about 650–700 kg/m^3, shows excellent thermal properties, with a thermal conductivity of about 0.12 W/(m K); and moderate mechanical properties, with a 28-day compressive strength of about 10–12 N/mm^2. Furthermore, the developed concrete exhibits excellent resistance against water penetration.

1. Introduction

The history of lightweight concrete (LWC) dates back to over 3000 years ago [1]. There are several LWC structures in the Mediterranean region, of which the most notable structures like the Port of Cosa and the Pantheon Dome were built during the early Roman Empire [2]. Because of its many advantages such as low density, good thermal insulation and fire resistance, LWC has been widely studied as both structural and nonstructural material. Among various types of lightweight aggregates (LWA) used nowadays, synthetic LWAs such as Leca (Denmark), Liapor (Germany) Liaver (Germany) and Poraver (Germany), produced in special industrial processes, are widely used in LWC because of their properties (e.g. low density, low water absorption, high strength) [3].

Lightweight aggregates concrete (LWAC) has been extensively investigated. Many applications of LWAC can be found in structures such as long span bridges, high rise buildings, buildings where foundation conditions are poor, or highly specialized applications such as floating and offshore structures. Loudon [4] summarized the thermal properties of lightweight concrete, and reported that density and moisture content are the main factors affecting the thermal conductivity, while the mineralogical properties of aggregate material can affect the thermal conductivity of LWC up to 25% under a similar density condition. Zhang and Gjørv [5] reported that the cement paste penetrates into lightweight aggregates during the mixing, but the amount highly depends on the microstructure of the surface layer of the aggregate, particle size distribution of cement and viscosity of the cement paste. Wasserman and Bentur [6] found that both physical and chemical characteristics of LWA affect the strength of LWAC due to the processes taking place at the interfacial transition zone. Alduaij et al. [7] researched lightweight concrete in hot coastal areas applying expanded clay as LWA. They reported a compressive strength increase from 15.5 N/mm^2 to 29.0 N/mm^2 when increasing the cement content from 250 to 350 kg/m^3, while keeping similar densities of about 1500 kg/m^3. Demirboğa and Gül [8] investigated the thermal conductivity and compressive strength of expanded perlite aggregate concrete with mineral admixtures. They reported that silica fume and fly ash used as cement replacement can decrease the thermal conductivity up to 15%, while the density and compressive strength of the concrete is also reduced, up to 30%. Ünal et al. [9] developed a lightweight concrete block applying diatomite as LWA with a 28-day compressive strength of 3.5–6.0 N/mm^2 and densities of 950–1200 kg/m^3. A linear relation between the cement content and thermal conductivity of the LWAC was derived as the thermal conductivity increased from 0.22 to 0.30 W/(m K) with the increase of cement content from 250 to 400 kg/m^3. Liu et al. [10] developed a lightweight aggregates concrete with high resistance against water and chloride-ion

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penetration. With the cement content of 500 kg/m^3 and unit density of 1400 kg/m^3, applying expanded clay and expanded glass as lightweight aggregates, the 28-day compressive strength of the LWAC reached 24 N/mm^2. Wang and Tsai [11] investigated lightweight aggregate concrete using dredged silt as LWA with different particle densities between 800 and 1500 kg/m^3 and applying different binder contents of 364, 452 and 516 kg/m^3. A 28-day compressive strength of 18–42 N/mm^2 with a thermal conductivity of 0.5–0.7 W/(m K) was obtained. Results show that the LWA density significantly affects the compressive strength of concrete with the same water and cement dosages, while the thermal conductivity is more complexly influenced by factors such as water content, cement content and LWA (type and content). Ling and Teo [12] researched lightweight concrete bricks applying expanded polystyrene (EPS) and rice husk ash (RHA) as lightweight aggregates. An optimal cement replacement by RHA of 10 wt.% was found and water curing was suggested to be the most effective curing method. Karakurt et al. [13] studied the effect of zeolite addition on the properties of autoclaved concrete using aluminum as a pore-forming agent. Zeolite was used as the quartz aggregates replacement with a total content of 535 kg/m^3. A maximum compressive strength of 3.2 N/mm^2 was achieved with a 50% replacement, with a thermal conductivity of 0.19 W/(m K). Wongkeo et al. [14] studied the properties of autoclaved concrete using bottom ash as partial cement replacement and with aluminum powder as a pore-forming agent. With a bulk density of about 1400 kg/m^3, an increase in compressive strength from about 9 N/mm^2 to 11.6 N/mm^2 is seen when the bottom ash content is increased from 0 to 30%, but the thermal conductivity also slightly increases, from 0.5 to 0.61 W/(m K). Akçaözoglu et al. [15] studied lightweight concrete applying waste PET as LWA. A thermal conductivity between 0.4 and 0.6 W/(m K) was achieved with the unit dry density between 1530 and 1930 kg/m^3, with the corresponding compressive strength at 28 days of 9.5 to 25.3 N/mm^2.

It can be summarized that the literature reviewed above shows a significant variation regarding both mechanical and thermal properties, indicating both the effect of the used materials and applied mix design methods. Although some mix design methods have been investigated [1,16,17], no systematic mix design methodology of ULWC has been addressed to the best knowledge of the authors, especially considering a balance between mechanical properties and thermal properties. Most research focused either only on obtaining a LWC suitable for structural purposes (e.g. with high strength) or as nonstructural material with low thermal conductivity, and therefore additional insulation materials or load bearing elements are often needed when applying LWC in buildings. Moreover, currently great attention is paid to sustainability in concrete research, for instance by applying low cement content and partially replacing cement by secondary cementitious materials (SCM). This is economically and ecologically attractive since cement is a highly energy-intensive material and great amounts of CO_2 are emitted during its production process, while about 90% cumulative energy needed for concrete production is spent in the production of cement [18].

The present research aims at the development of an ultra-lightweight concrete (ULWC) with a good balance between the mechanical and thermal properties, i.e. concrete with excellent thermal properties (e.g. a very low thermal conductivity) while retaining a reasonable strength. The developed ULWC could be a suitable material for novel monolithic building concept with the following advantages: (1) cost saving, due to the exemption of extra insulation installations; (2) more flexibility for architects and structural engineers for the building design; (3) sustainability, since monolithic structure will ensure a relatively easy maintenance requirement and it is easier to recycle. The effect of different types of cements produced by incorporating different SCMs such as fly ash or granulated blast furnace slag is investigated. A lightweight material produced from recycled glass is used as LWA in the present study. This type of LWA has a particle density ranging from 300 to 800 kg/m^3 (depending on the size fraction), with a crushing resistance of up to 6 N/mm^2 [2], which indicates that concrete produced using this aggregates can be potentially used for structural purposes [19,20].

2. Mix design

2.1. Materials

The four types of cement used in this study are CEM I 52.5 N, CEM II/B-V 42.5 N, CEM III/A 52.5 N and CEM V/A (S-V) 42.5 N [21] provided by ENCI HeidelbergCement (The Netherlands), and the detailed information is listed in Table 1. The lightweight aggregates used here are commercially available product manufactured from recycled glass in Germany. These LWA contain a number of air pores (cellular structure) encapsulated in rather closed and impermeable outer shells, as can be seen in Fig. 1. The LWA have very low particle densities, which provide a great freedom for the design of lightweight concrete with desired low density, as can be seen in Table 2. Limestone powder, with the density of 2710 kg/m^3, is used as filler to adjust the powder amount. A nano-silica (AkzoNobel), with a solid content of 50%, density of 1.4 kg/l and a BET surface area of the silica particles of 50 m^2/g, is used here to investigate its effect. A polycarboxylic ether-based superplasticizer (BASF) is used to adjust the workability. An air-entraining agent (Cugla), with a density of 1.05 kg/l and resin acid soaps as active agent, is applied here to adjust the density of the lightweight concrete.

2.2. Design methodology

For the design of the LWAC, a mix design methodology previously used for normal density mortars and concretes was considered [20]. This mix design tool is based on the insight that superior properties of a granular mix are achieved when a so-called geometric grading curve is designed and obtained, i.e. the ratios of particle sizes and the ratios of pertaining quantities are constants. In the case of continuous distributions, the cumulative finer fraction of the entire mix is determined from the modified Andreasen and Andersen model [22], reads:

$$P(D) = \frac{D^q - D^q_{min}}{D^q_{max} - D^q_{min}} \quad (1)$$

where $P(D)$ is a fraction of the particles being smaller than size D, D is the particle size (μm), D_{max} and D_{min} are the largest and smallest particle size (μm), respectively, in the mix, and q is the distribution modulus.

This particle packing principle insight has been transformed into a numerical mix design, in which all the solid mixture ingredients, which all have their own particle size distributions

Table 1
Properties of the used cement.

Cement	Density (kg/m^3)	Clinker content (%)	Fly ash content (%)	Slag content (%)
CEM I 52.5 N	3180	95–100	0	0
CEM II/B-V 42.5 N	2980	73	25	0
CEM III/A 52.5 N	3000	48	0	52
CEM V/A (S-V) 42.5 N	2870	55	23	22