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Influence of microstructure on fluid transport and mechanical properties in structural concrete produced with lightweight clay aggregates

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HIGHLIGHTS

- Lightweight aggregates do not affect the fluid transport properties of concrete.
- An increase of lightweight aggregates volume affects the mechanical properties.
- Fluid transport in lightweight concrete is regulated by the mortar matrix properties.
- Lightweight particles are isolated by an external denser shell.

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ABSTRACT

The use of lightweight aggregates (LWA) in concrete is an interesting alternative to simultaneously reduce the total structure weight and provide both appropriate resistance and concrete's performance. This paper studies the influence of LWA on concrete, comparing the changes in the mechanical properties, pore structure and fluid transport related to the increase of LWA content. Results reveal that although LWA reduces the mechanical properties of the studied samples does not significantly affect the fluid transport properties. Total porosity rises with LWA content whereas open porosity remains nearly invariable. LWA pores do not totally participate in the fluid transport through the concrete and, consequently, fluid transport through lightweight concrete is limited by the continuity and accessibility of the LWA pores and is dominated by the properties of the mortar matrix.

1. Introduction

Durability and mechanical resistance are considered key properties in the election of concrete as a construction material. Normally, both durability and mechanical resistance can be enhanced using highly dense concretes. However, this solution implies the use of part of the structure strength to support its own weight. Alternatively, the concrete industry has introduced different materials and additions to improve concrete features and performance with low density concretes.

Among these alternatives, the replacement of normal aggregates by lightweight aggregates (LWA) has proved advantages such as the improvement of thermo-insulation properties and the reduction of concrete density [1]. Nevertheless, LWA are generally more porous than the concrete matrix and durability might be negatively affected. As a consequence, the research focused in lightweight concrete (LWC) has experienced an extensive growth, mainly related to concrete deterioration and fluids migration through the porous system.

The main deterioration processes of concrete are triggered by the movement of fluids or aggressive substances from the environment where the structure is built to inside the structure by capillary absorption, permeability of gases and liquids or diffusion [2–5]. In particular, capillary absorption predominates when the porous medium is not saturated, while permeability is the principal mechanism when concrete is completely saturated with the fluid. Despite the higher porosity of LWA, an increase of pore connectivity in LWC might not be associated with the increase of LWA in the concrete mixture, as it has been previously observed by [6] or [7]. Moreover, previous studies [8,9] reported that the interaction of the lightweight aggregate and the mortar matrix is related to excellent durability performance in some LWC. Although might be only restricted to some types of LWA, in some cases, chemical

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reactions between the aggregate and the matrix can create an interface surrounding the LWA particles. This interface contributes to slightly improve both, strength [8] and fluids migration resistance, since mechanical properties depend on the aggregate strength and the mortar matrix, as well as the bonding structure of the aggregate/matrix interfacial zone [10,11].

Nowadays, LWC can be produced in a wide range of densities and strengths according to the requirements of the final use [12]. Lightweight expanded clay aggregates are one of the most common LWA employed in the construction industry due to its low production cost and excellent chemical stability and require a special attention from the research community.

In this paper, a comparative study between different lightweight concrete and normal weight concrete has been performed with the aim of determining the changes in the mechanical properties, pore structure and fluid transport with the addition of lightweight expanded clay aggregates. In particular, the influence of LWA and mortar matrix on mechanical and durability properties of concrete is evaluated and the role of microstructure on fluids movement through the samples is determined. An ANOVA analysis is carried out on results in order to identify significant variations of the concrete properties with the increase of LWA. Results from this study show that high-performance concrete can be obtained using lightweight expanded clay aggregates with low densities and no significant impact on durability properties.

2. Materials and methods

2.1. Materials

The different lightweight concretes (LWC) included coarse and fine limestone aggregates (CLA and FLA, respectively), lightweight aggregates (LWA) from Saint-Gobain Company (Arlita Leca HS) and cement (CEM I 52.5 SR) with an absolute density of 3176 kg/m^3. The main properties of the aggregates are collected in Table 1.

The aggregate fraction was determined according to standard [13]. For LWA, FLA and CLA, determination of loose bulk density and voids and particle densities was conducted following [14]. Water absorption at 24 h was performed using pre-dried lightweight particles immersed in water according to [15]. Finally, the water absorption and weight ratio were measured in both total and fractured particles and lasted from 1.5 min up to 28 days (Fig. 1). Fractured particles were measured following a specific methodology based on the standard 933.5 [16]. The fractured particles constitute 3.1% of LWA fraction.

Four different types of concrete were produced, according to a final target density of 1700, 1900 and 2200 kg/m^3 for the LWC (samples LWC-1, LWC-2 and LWC-3 respectively) and an additional normal weight concrete (NWC) fabricated to compare results (with density higher than 2200 kg/m^3). All four concrete types had the same w/c ratio (0.6), cement content (350 kg/m^3), water (210 kg/m^3) and FLA (750 kg/m^3). Concrete dosage was accomplished by following the Fanjul method [17]. Different amounts of CLA and LWA were used to achieve the required densities (Table 2). Thus, the mortar remained the same for all concretes (water, cement and fine limestone aggregate) and the coarse aggregate was the component that changed among the four concrete types (LWA and CLA).

The w/c ratio informs about the effective water available for cement hydration and it is directly related to the concrete workability. Due to the high water absorption capacity of LWA, previous measurement of superficial and internal water content in LWA was required. This measurement implied the submersion of pre-soaked LWA in water during 7 days; after that, LWA were extended in a mesh for 20 min to reduce the superficial water content and placed into hermetic plastic bags to prevent water losses before the mixing process. Afterwards, a LWA sample with superficial and internal water was weighed, placed in a sieve covered by a paper filter sheet and vibrated during 15 s to remove the superficial water content. Later, this LWA sample without superficial water was weighed and oven dried until constant mass to obtain the internal water content. Superficial water content was subtracted from total mixing water to keep constant the w/c ratio.

All initial materials were mixed in a vertical shaft mixer. The mixing methodology for all concretes consisted of one-minute mixing cement and fine aggregate, two-minutes mixing after the addition of the total calculated water, two-minutes mixing after the addition of the coarse aggregate. The specimens were demolded after 24 h and exposed to underwater curing for 28 days.

Table 1
Physical characteristics of the aggregates (Lightweight aggregates, LWA; fine limestone aggregates, FLA; coarse limestone aggregates; CLA).

Property	LWA	FLA	CLA
Granulometric fraction (d_i/D_i)*	4/10	0/4	6/12
Loose bulk density (kg/m^3)	610	1610	1376
Voids (%)	38.6	40.3	48.8
Apparent particle density (kg/m^3)	1221	2716	2714
Oven dry particle density (kg/m^3)	962	2708	2669
Saturated surface dry particle density (kg/m^3)	1173	2710	2685
24 h water absorption (%)	16.7	0.12	0.62

* d_i: minor diameter (mm); D_i: mayor diameter (mm).

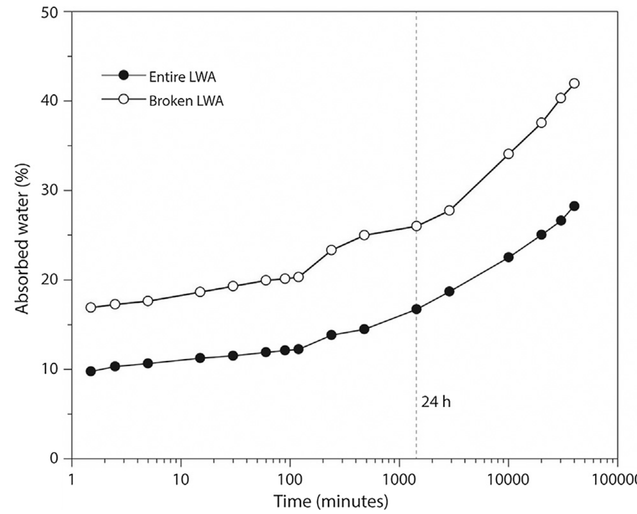

Fig. 1. Water absorption test in LWA (entire and broken particles) according to UNE-EN 1097-6.

Table 2
Mix proportions (kg/m^3).

Code	CLA	LWA
LWC-1	1	389
LWC-2	315	275
LWC-3	787	104
NWC	1042	–

2.2. Microstructural analysis

The microstructural study was mainly based on mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM). MIP determined the porosity and pore size distribution of the LWA and the mortar matrix, and SEM described the LWC microstructure, including porosity of LWA and mortar, the changes in the interfacial transition zone, the cracks around the coarse limestone aggregates, etc. MIP was measured with an Autopore IV 9500 Micromeritics. The employed surface tension and contact angle of mercury were 480 mN/m and 130°, respectively.

The concrete specimens were cut in regular samples of approximately 1 cm^3 and observed using scanning electron microscopy at voltage of 5–30 keV in low- and high-vacuum modes with a Hitachi S3000N. Uncover samples were employed to develop some visual inspections and EDX (energy dispersive X-ray) was applied to obtain basic chemical analysis of the elements associated with the SEM images. SEM images under high-vacuum mode were captured after EDX analysis, by coating the samples with a thin film of gold.

2.3. Porosity and density

For each concrete type, Ø30 × 50 mm samples were extracted from Ø150 × 300 specimens for the porosity and density tests. The ratio between bulk and grain densities determined total porosity. Bulk density was calculated through direct measurement of dried weights and dimensions of samples. The ratio of the mass to the solid volume of a material defines its grain or real density, which was obtained with an AccuPyc 1330 Helium pycnometer. The vacuum water saturation test [18] was employed to obtain the open porosity, i.e., the ratio of the volume of connected voids to the total sample volume.