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Non-steady-state accelerated chloride penetration resistance of structural lightweight aggregate concrete

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ABSTRACT

This study aims to characterise the chloride penetration resistance of structural lightweight aggregate concrete (LWAC) produced with different types, volumes and initial wetting conditions of lightweight aggregates (LWA), types of cement and contents of fly ash and silica fume, *w*/*c* ratios and curing conditions. A comprehensive experimental study was carried out involving three types of non-steady-state tests, which simulate different exposure conditions and penetration mechanisms. It is shown that the chloride penetration resistance is mainly affected by the cementitious paste and that high performance LWAC of 30–70 MPa can be produced. Regardless of the type of aggregate, we propose exponential relations to estimate the diffusion coefficient of chlorides. The volume and initial wetting condition of LWA had little influence on the chloride resistance. A long-term higher reduction of the diffusion coefficient was found in less dense LWAC. Reasonable correlations between the non-steady-state tests were obtained. Contrary to what is suggested in some European standards, the concrete strength cannot properly predict the durability behaviour of LWAC.

1. Introduction

Although knowledge of the durability behaviour of lightweight aggregate concrete (LWAC) is limited, there are several examples of its good performance in existing structures. The Port of Cosa on the west coast of Italy and the dome of the Pantheon in Rome are two examples of two-thousand-year-old structures built with volcanic lightweight aggregates (LWA) which have survived until today with no major signs of deterioration [1,2]. The durability of LWAC has also been shown in some Norwegian maritime structures, particularly in large-span bridges and offshore structures [3,4].

Chloride induced corrosion is one of the most frequent and serious causes of concrete deterioration [5,6]. Chloride penetration in concrete depends on the diffusion coefficients of the paste, aggregate and interfacial transition zone (ITZ). Compared with normal weight concrete (NWC), the diffusivity of lightweight aggregates is usually higher than that of the surrounding paste [7,8]. In fact, LWA tends to have a cellular three-dimensional interconnected structure with an average pore size 10–10,000 times larger than that of cement paste [1,9]. Zhang and Gjørv [10] found comparable diffusivity in cut particles of different types of lightweight aggregates and in cementitious pastes with a *w*/*c* ratio of 0.9.

However, the influence of the aggregate-paste composite system on the permeability of concrete should be analysed as a whole rather than as the sum of the separate contributions of each phase. Therefore, since the LWA particles are usually surrounded by a high quality paste, the permeability of LWAC can be quite low [8,11].

The Japanese [12], Norwegian [3,4,13] and North American [1,14] experiences with existing structures suggest that the chloride penetration resistance of LWAC is generally at least as high as that of NWC. The higher quality of the interfacial aggregate-paste transition zone, the internal curing provided by LWA and the better elastic compatibility between the aggregate and the surrounding mortar contribute to the good performance of LWAC [1,11]. In addition, LWAC is often associated with lower *w*/*c* ratios and a smaller volume of aggregates than NWC of the same compressive strength, which means higher quality pastes and a lower percentage of ITZs in concrete.

Based on the less appropriate rapid chloride permeability test set out in ASTM C1202 [15] and on immersion tests, Thomas [16] reports a reduction of the diffusion coefficient with the incorporation of LWA and the progressive replacement of cement by fly ash. However, Chia and Zhang [17], using the same ASTM test on concretes with *w*/*c* ratios of 0.35 and 0.55, found similar performances

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in LWAC and NWC of the same composition. The authors also found that the LWA particles did not show any signs of chloride penetration and concluded that the paste quality is the main factor in chloride penetration in concrete. Several authors [18–21] also emphasise that aggregates are less relevant to the chloride penetration resistance of concrete with high quality pastes.

However, Osborne [22] reports slightly higher chloride penetration in LWAC produced with scoria or fly ash LWA than in NWC of the same composition. Based on the ASTM C1202 [15] test, Vieira [23] also found higher chloride permeability in LWAC than in NWC of the same composition, especially when a more porous type of LWA was used. This was attributed to the prior vacuum saturation of the specimens that facilitated the participation of the aggregates in the diffusion process. Gjørv et al. [24] report small differences in the diffusion coefficient of LWA produced with different lightweight aggregates that were submerged in saltwater for three years.

Using concrete produced with expanded clay LWA and $w/c = 0.38$, Liu et al [21] found that although the durability behaviour of LWAC did not differ significantly from that of NWC, the chloride resistance decreased with the further incorporation of lightweight sand (LWS) in the mixtures. In another study, Gesoglu et al. [25] also found that, regardless of the curing method (steam or water curing), the rapid chloride permeability (ASTM C1202 [15]) of concrete produced with fly ash LWA and $w/c = 0.35$ increased with the incorporation of LWS.

According to Guneyisi et al. [26] the incorporation of 10% silica fume in LWAC produced with sintered fly ash aggregate reduced the total charge passed in the ASTM C1202 [15] test by about 38%. ForLWAC specimens submerged for 3 years in saltwater, Gjørv et al. [24] found diffusion coefficients that were five times lower when 9% of silica fume was incorporated.

Assuming identical compressive strength classes, the chloride penetration is usually lower in LWAC than in NWC with a weaker mortar [18,21,27]. However, Al-Khaiat and Haque [28] found slightly higher chloride penetration in LWAC with coarse and fine fly ash LWA than in NWC of equal strength, for specimens exposed to a maritime atmosphere for 9 months.

In brief, chloride penetration in LWAC is not yet properly understood. The type of test and the test setup, the curing conditions, the type of aggregate, the paste quality, the water content of the concrete and the penetration mechanism involved are some of the factors that explain the different results reported in the literature. A more comprehensive study involving different types of LWAC is thus necessary.

To better understand the chloride penetration behaviour of LWAC, concretes of different compositions and strength and density classes were analysed in this study. The non-steady-state tests used were rapid chloride migration (RCM), immersion and salt-fog tests. In brief, the work used accelerated laboratory tests to characterise the chloride penetration resistance of LWAC, it included different types, volumes and initial wetting conditions of lightweight aggregates, different w/c ratios and types and contents of binders, the partial replacement of natural sand with lightweight fines and different curing conditions. Lightweight concretes with strength classes ranging from LC20/22 to LC55/60 were studied, making it possible to cover the commonest LWACs.

2. Experimental programme

2.1. Materials

Three Iberian expanded clay lightweight aggregates were analysed: Leca and Argex from Portugal and Arlita from Spain. Their total porosity, P_T, particle density, ρ_p, bulk density, ρ_b, and 24 h water absorption, $w_{abs,24\,h}$, are indicated in Table 1. Before the burning process in a rotary kiln, the particles of Arlita were pelletised by rolling and those of Argex were moulded by extrusion. Leca was pre-moulded inside the kiln by a complex system of chains. The three aggregates therefore differ in terms of porosity, bulk density and geometry. A more detailed microstructural characterisation of these aggregates is presented elsewhere [9,29]. In terms of their specific properties, the selected LWA are categorised as types A (Arlita), B (Leca) and C (Argex), which represent LWA of low, moderate and high porosity (Table 1).

Normal density coarse and fine aggregates were also used. For the reference NWC, two crushed limestone aggregates of different sizes were combined so as to have the same grading curve as Leca (20% fine and 80% coarse gravel). Fine aggregates consisted of 2/3 coarse and 1/3 fine sand. Their main properties are listed in Table 1. The two fractions of type C LWA were also combined to have the same grading curve as type B LWA (35% type C 4–8 and 65 % type C 6–12, Table 1). Fly ash (FA) from the Pego thermoelectric power plant in Portugal, silica fume (SF) from Spain and cement types I 52.5 R and I 42.5 R according to EN 197-1 [30] were used. Their main physical and mechanical properties are listed in Table 2. For low water/binder (w/b) ratios, a polycarboxylate based superplasticizer (SP) was also used.

2.2. Mixture proportions, concrete mixing and tests

The concretes were produced in a vertical shaft mixer with bottom discharge. Except for initially dry or pre-wetted aggregates, the LWA was pre-soaked for 24 h to better control the workability and effective water content of the concrete. The aggregates were then surface dried with absorbent towels and placed in the mixer with sand and 50% of the total water. After 2 min. of mixing, the cementitious materials and 40% of the water were added. The SP was added slowly with 10% of the water. The total mixing time was 7 min.

Thirty-one different compositions were designed according to Bogas and Gomes [29,31]. The compositions and their respective slump, fresh, ρ_f, and dry density, ρ_d, are listed in Table 3. The w/b ratio relates to the effective water available for binder hydration. The SP/c is the percentage of superplasticizer by cement weight. The denominations 'NWC', 'A', 'B' and 'C' represent the mixes with normal weight aggregate (NA) and type A, type B and type C

Table 1
Aggregate properties.

Property	Normal weight aggregates				Lightweight aggregates				
	Fine sand	Coarse sand	Fine gravel	Coarse gravel	Type A	Type B 0–3	Type B 4-12	Type C 4-8	Type C 6-12
Particle dry density, ρ_p (kg/m^3)	2620	2610	2631	2612	1290	1060	1068	865	705
Loose bulk density, ρ_b (kg/m^3)	1416	1530	1343	1377	738	562	613	423	397
24 h water absorption, $w_{abs,24\,h}$ (%)	0.2	0.5	1.4	1.1	12.1	–	12.3	22.9	23.3
Total porosity, $P_{T\,(\%)}$	–	–	–	–	52	59	60	67	73
Granulometric fraction (d_i/D_i)	0/2	0/4	4/6.3	6.3/12.5	3/10	0.5/3	4/11.2	4/8	6.3/12.5
Los Angeles coefficient (%)	–	–	33.3	30.5	–	–	–	–	–