



Biphasic carbonation behaviour of structural lightweight aggregate concrete produced with different types of binder



J. Alexandre Bogas^{*}, Sofia Real, Beatriz Ferrer

DECivil/CeRis-ICIST, Instituto Superior Técnico, University of Lisbon, Av. Rovisco Pais, 1049-001 Lisbon, Portugal

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ABSTRACT

This study aims to characterise the carbonation behaviour of structural lightweight aggregate concrete (SLWAC) produced with different types of aggregate, w/c ratios and types and content of mineral admixtures (silica fume, fly ash, lime filler) by means of accelerated carbonation tests. A new biphasic model to describe the carbonation behaviour of SLWAC is suggested. Based on this model, the carbonation coefficient of SLWAC is estimated as a function of the w/c ratio, for different density classes of lightweight aggregates. It is concluded that the carbonation resistance of SLWAC cannot be properly predicted by its compressive strength and that the carbonation rate is little affected by the type of binder, being appropriate to neglect the contribution of mineral admixtures in carbonation resistance of SLWAC. It is also concluded that even with pastes of moderate quality, the carbonation mechanism should not be relevant to the durability of SLWAC.

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1. Introduction

Concrete structures are designed to meet safety, serviceability, durability and aesthetics requirements throughout their service life and therefore both mechanical and durability performances of concrete are of major importance for its success as a construction material. With the increasing use of structural lightweight aggregate concrete (SLWAC) in multi-storey building frames and floors, long span bridges, offshore oil platforms, prestressed and precast modules in high rise buildings and rehabilitation works, research on this material has intensified in recent decades [1–5]. Nonetheless, there is still lack of knowledge on SLWAC behaviour, especially regarding durability and the main mechanisms governing the deterioration of concrete. The potential durability of SLWAC is borne out by its excellent performance in structures built over 2000 years ago which have survived until today with no major signs of deterioration [1,6]. In recent years, SLWAC has been used in several structural applications under aggressive environments, which testifies to its structural capability and adequate durability [7–9].

Corrosion of the reinforcement, which occurs after depassivation of the steel surface through carbonation of the surrounding

concrete, penetration of chloride ions, or a combination of both, has been recognised as a leading cause of concrete structures deterioration [2,10]. This paper focuses on the carbonation behaviour of SLWAC.

Extensive data on the carbonation performance of normal weight concrete (NWC) is available, but only a few studies have been carried out on the carbonation behaviour of SLWAC, especially taking into account different concrete compositions and types of aggregate [11–13]. Nevertheless, research studies have been published on the effect of several parameters, such as the type of aggregate, w/c ratio and type and content of mineral admixtures, on the carbonation of SLWAC.

Contrary to NWC, the porous microstructure of SLWAC depends not only on the composition of the cement paste, but also on the type of lightweight aggregate (LWA) [1,14]. LWAs have less resistance to gas diffusion than normal weight aggregates (NAs), due to their greater porosity, which favours carbon dioxide diffusion through concrete [8,15–17]. In fact, according to Zhang and Gjorv [17], even when high quality LWAs are used, the aggregate permeability is as high as that of a cement paste with a w/c ratio of 0.9. Schulze and Günzler [11] analysed the shape of the carbonation front in SLWAC and confirmed a more rapid carbon dioxide diffusion through the aggregate particles. The relevance of this effect depended on the porosity of the aggregate, highlighting the importance of an effective dispersion and involvement of the

^{*} Corresponding author.

E-mail address: abogas@civil.ist.utl.pt (J.A. Bogas).

particles by high quality paste. If this effective dispersion and involvement of the aggregate particles by high quality paste does not exist and the establishment of diffusion bridges between the concrete surface and the steel reinforcement through the aggregate particles occurs, there might be an increased risk of corrosion [8,15]. Vaysburd [18] pointed out that the risk of establishment of diffusion bridges is less relevant in case aggregates with densities greater than 1500 kg/m^3 are used, due to their closed cell structure. For aggregates with density less than 1300 kg/m^3 , the concrete cover should be at least twice as high as the maximum aggregate particle size. These recommendations can be too conservative and should depend on the paste quality. According to Newman [15] the carbonation rate in SLWAC and NWC can be similar as long as the LWA particles are properly coated with high quality paste.

Considering concretes of the same strength level, the cement matrix is generally denser in SLWAC than in NWC, because of the lower w/c ratio, which decreases permeability. According to Vaysburd [19], the higher cement content and lower w/c ratio of SLWAC mean that both the amount of carbonatable substances and the protective capacity of the paste tend to be higher than in NWC of the same strength level, thereby contributing to lower carbonation depths. Bremner et al. [12] measured the carbonation performance of several SLWAC and NWC at various strength levels, concluding that the carbonation depths were lower in SLWAC than in NWC of the same strength. For both types of concrete, the high quality cement matrix was a primary factor for a good carbonation performance. Al-Khaiat and Haque [13] found slightly higher carbonation depths in SLWAC with coarse and fine fly ash aggregates than in NWC of the same strength level. However, for curing periods of more than 7 days, associated with more hydrated and denser pastes, the carbonation resistance in both types of concrete was similar. Haque et al. [20] reported comparable carbonation depths in SLWAC with coarse fly ash aggregates and in NWC of the same strength level.

The influence of the water content on the carbon dioxide diffusion through SLWAC manifests in two ways. First, since SLWAC is usually associated with high initial water content and high quality cement paste, its drying period is longer. Therefore, a higher resistance to carbon dioxide diffusion through the paste is expected, at least during the initial period before hygral equilibrium is established between the concrete and the environment. Second, as soon as the relative humidity of concrete is reduced, the water initially stored in the aggregate particles migrates to the paste, allowing them to participate in gas diffusion [21,22]. The higher quality of the matrix–aggregate interfacial transition zone in SLWAC compared to that of NWC [2,23] can also play a role in gas permeability.

The above mentioned factors explain why the carbonation behaviour of SLWAC is more complex than that of NWC, hence the different trends reported in literature. The high diversity of LWAs available allows the production of concretes in a wide range of structural and density classes, making a systematic characterization of the carbonation behaviour of SLWAC against the different environmental conditions to which it may be exposed extremely difficult.

The relative behaviour of NWC and SLWAC seems to depend on the type of aggregate and w/c ratio. For a given w/b ratio, Swamy and Jiang [24] reported greater carbonation depths in concretes with higher total pore volume. Brown and Beeby [25] found average carbonation depths about 90% higher in SLWAC with fly ash LWA than in NWC of the same composition. Gündüz and Uğur [26] reported lower carbonation rates in SLWAC with pumice LWA for lower aggregate-to-cement ratios. Vieira [27] also found higher carbonation depths in SLWAC produced with expanded clay LWA than in NWC of the same composition. However, in SLWAC with

less porous LWA, the carbonation depth was similar to that of NWC.

Mays and Barnes [28] reported carbonation depths between 6 and 25 mm after 20 years of exposure in specimens obtained from SLWAC produced in the United Kingdom. Although the carbonation depth in SLWAC was slightly higher than that of NWC of the same strength level, the authors found that the differences were not significant. Mircea et al. [29] analysed the durability and long-term performance of 260 beams with compressive strength between 30 and 50 MPa. The reinforced or prestressed beams were subjected to bending and exposed to laboratory, urban, marine and industrial environments for 10–12 years. The authors concluded that for cement content of more than 400 kg/m^3 the carbonation depth in expanded clay SLWAC beams was similar to that in NWC beams. However, for lower cement content, the carbonation depth in SLWAC beams was 10–30% higher than in their normal weight counterparts.

Lo et al. [30] performed accelerated carbonation tests in a closed chamber at relative humidity of 70–80% on SLWAC and NWC with w/b ratio between 0.3 and 0.7. The authors observed that SLWAC had higher carbonation resistance than NWC of the same strength. This was attributed to the usual lower w/b ratio and higher cement content of SLWAC with the same strength grade of NWC. However, it was confirmed that the carbonation of SLWAC was slightly higher than that of NWC of same composition and that there was a greater influence and participation of the aggregates in pastes with open pore structure. Bogas [22] analysed the carbonation resistance of SLWAC with different types of expanded clay aggregates, different types and content of binder and w/c ratios between 0.35 and 0.65, concluding that, for w/c ratios below 0.4, the carbonation depths in SLWAC and NWC were negligible and the two types of concrete had similar carbonation performances, except when fine LWA were used, which led to an increase in the carbonation depth of SLWAC. For concretes with higher w/c ratios, the carbonation depth was not negligible and the carbonation resistance of SLWAC was lower than that of NWC. In another study, Bogas and Gomes [31] found that the high porosity and absence of a dense outer shell of natural scoria aggregates contributed to a higher carbon dioxide diffusion through concrete. However, the authors claim that this mechanism only becomes relevant when the carbonation front reaches the aggregate particles, which may take a long time in concretes with low w/c ratio.

These works demonstrate that cement pastes with open pore structure make the participation of the aggregates in the carbonation mechanism more effective. These studies also emphasise the relevance of the paste quality to the carbonation resistance of SLWAC. In fact, according to Swamy and Jiang [24] and Bilodeau et al. [32], SLWAC with high carbonation resistance can be attained with pastes of low w/c ratio. A long time ago, Schulze and Günzler [11] stated that in dry air conditions the carbonation in SLWAC with w/c ratio below 0.65 would take more than 50 years to reach 30 mm. Investigations conducted by Holm [33], Holm et al. [34] and Ohuchi et al. [35] on SLWAC in ships, bridges and viaducts with 15 to more than 50 years of exposure demonstrated its excellent carbonation resistance in varying field conditions.

There are only a few studies on the influence of different types of mineral admixtures on the carbonation resistance of SLWAC, and they focus on specific compositions produced with a given type of LWA. Lo et al. [30] studied the accelerated carbonation behaviour of one type of expanded clay SLWAC produced with 25% of fly ash and 0%, 5% or 10% of silica fume. The authors concluded that in both NWC and SLWAC the increase of carbonation in mixes with 25% fly ash was marginal compared with concrete without mineral admixtures. However, further incorporation of silica fume in ternary mixtures led to higher carbonation rates, meaning that the reduction in the carbonatable constituents was more significant than the

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