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Oxygen permeability of structural lightweight aggregate concrete

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HIGHLIGHTS

- The oxygen permeability of structural lightweight concrete is characterized.
- The influence of different parameters on the oxygen permeability is analysed.
- Structural lightweight concrete could have as low permeability as common concrete.

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ABSTRACT

This paper characterizes the oxygen permeability of structural lightweight aggregate concrete (SLWAC). The influence of different parameters is analysed, namely water/binder (w/b) ratio, type of binder and aggregate, relative humidity, water content and concrete age. The correlation between this and other properties is investigated. The oxygen permeability varied over a broad range. Nevertheless, the oxygen permeability of SLWAC with denser aggregates could be as low as that of normal weight concrete. The influence of the type of aggregate tended to increase with w/b ratio, aggregate porosity and percentage of additions. Small differences between mixtures were masked by the high variability of the test.

1. Introduction

In the last decades, durability has become a major concern and, consequently, a domain of research, due to the precocious degradation of many reinforced concrete structures in aggressive environments. The potential durability of structural lightweight aggregate concrete (SLWAC) can be witnessed by its performance in structures built centuries ago that have lasted until now with no relevant signs of deterioration [1–6]. However, the perfect knowledge of the durability behaviour of SLWAC is still limited, namely regarding the main mechanisms governing its deterioration.

The degradation of concrete usually involves the transportation of external aggressive agents into concrete, which takes place through the pore structure and micro-cracks in the cement matrix. Therefore, it is relevant to characterize the main transport mechanisms in concrete, essentially permeability, capillary absorption and diffusion, which may act simultaneously in the ingress of deleterious material into concrete [7–9].

The mechanism of diffusion in SLWAC has been essentially studied regarding the mechanisms of carbonation and chloride attack in concrete, in which Fick's laws are usually applied to model the penetration of these substances [10–12].

Capillary absorption has a relevant role, especially in non-saturated concrete. Despite some contradictory results reported in literature [13,14], various authors documented, at least, similar capillary absorptions in SLWAC and normal weight concrete (NWC). For different drying degrees and water/cement (w/c) ratios, Bogas et al. [15] found identical absorption coefficients in NWC and SLWAC produced with denser lightweight aggregates (LWA). This was attributed to the high quality of the aggregate-paste interface in SLWAC and the lower capillary action of the LWA with a coarser porosity than the surrounding paste.

In general, for both capillary absorption and chloride diffusion, the opinion seems to converge to a similar behaviour between

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Abbreviations: FA, fly ash; ITZ, interfacial transition zone; LF, lime filler; LWA, lightweight aggregate; NA, normal weight aggregate; NWC, normal weight concrete; RH, relative humidity; SF, silica fume; SFAA, sintered fly ash aggregate; SP, superplasticizer; SLWAC, structural lightweight concrete; w/b, water/binder; w/c, water/cement; WC, water content.

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SLWAC and NWC, being mainly governed by the quality of the paste [15–17].

In this paper, only the phenomenon of permeability in SLWAC is analysed, more specifically the oxygen permeability.

Permeability describes the rate of flow of a fluid through a porous solid caused by a pressure head. Permeability has been pointed out, in literature [18–20], as a means to indirectly study the potential durability of concrete.

Nowadays, the most common types of concrete have a low w/c ratio, usually lower than 0.5–0.6. According to Powers et al. [21], for such low w/c ratios, the water permeability of mature concretes can be as low as 10^{-13} m/s, which is not easily measured in usual stationary tests. In fact, the porous structure is sufficiently closed for the permeability to be lower than the limit detected by these tests [19,22–24]. Therefore, water permeability is now a less relevant property in common low w/c concretes.

The gas permeability coefficient can be obtained through the Hagen-Poiseulle equation, assuming a laminar flow in the pore system. However, this does not necessarily occur in concrete, due to the wide range of pore diameters of the hydrated cement paste [8].

In contrast to liquids, gas must be considered as compressible, which means that the permeability coefficient is affected by the pressure head.

The flow of gas through porous media was studied by Klinkenberg [25], who introduced the concept of the well-known slippage effect, characterized by a non-zero pore wall velocity. This effect is only relevant at low pressure and small pores, where the mean free path, i.e., the average distance between collisions for a gas molecule is of the same order of magnitude of the pore size [19]. As a result, part of the flow will have a non-viscous behaviour, known as molecular flow. The relevance of the molecular flow increases with the reduction of pressure and pore diameter, increasing the difference between the gas flow rate and the viscous liquid flow. If the pressure is high and/or the pore diameter is much higher than the mean free path, the amount of collisions is significant and the wall-pore slip velocity is not relevant.

Klinkenberg [25] suggested Eq. (1) to take into account this effect, as well as, the permeability dependence of the percolated gas and its mean pressure, P. In fact, at higher pressures, the gas molecules are closer together and more friction drag occurs at the pore walls, which reduces the gas permeability. K_{int} is the intrinsic permeability coefficient or equivalent liquid permeability, which is independent of the mean pressure, β is a constant that depends on the porous solid and the percolating gas and K_{app} is the apparent permeability, i.e., the measured permeability for a given pressure. Therefore, the gas permeability tends to be higher than that of liquid and its permeability coefficient varies with the applied gas pressure. At low pressure, if the pore diameter is rather small, the mean free path can be much greater than the pore size and a non-viscous flow takes place by diffusivity, known as Knudsen diffusion.

$$K_{app} = K_{int}\left(1 + \frac{\beta}{P}\right) \tag{1}$$

Concrete permeability is affected by the open porosity and the way its interconnectivity is established (size and pore geometry). According to Mehta and Monteiro [26], pores greater than 50 nm have a greater influence on porosity. Therefore, permeability depends on the porosity of cement paste (affected by the w/c ratio, the hydration degree and the type of binder), aggregate and interfacial transition zone (ITZ) [27,28], as well as other defects such as cracks and voids. The permeability is also affected by non-intrinsic material properties, namely relative humidity (RH) [8,18,24,27,29] and less significantly, temperature [8,27].

Contrary to normal weight aggregates (NAs), LWA exhibit a highly porous internal microstructure typically composed of interconnected pores ranging 1–300 µm wide [2,15,30], about 2–3 orders of magnitude higher than those of the cement paste.

It is therefore expected that LWA, due to their greater porosity, have higher permeability than cement paste [31–34]. In fact, Zhang and Gjørv [31] found that the average diffusivity of different types of LWA is comparable to that of cement pastes with a w/c ratio of about 0.9. However, SLWAC permeability cannot be analysed as the separate contribution of each phase. It is important to consider the whole pore structure of the composite material, namely the way pores are connected to each other. Usually, LWA particles are isolated and dispersed throughout concrete, surrounded by cement paste with low pore connectivity, and hence, SLWAC do not necessarily exhibit high permeability.

The ITZ can greatly affect concrete permeability, since, for the usual volume of aggregates in concrete, ITZ are intersected and continuous passages are established [35]. In SLWAC, the ITZ tends to be of better quality than in NWC, due to the usually greater mechanical bond and elastic compatibility between the porous LWA and the surrounding mortar [3,30,36–39]. According to FIP [40], this is the main reason for SLWAC presenting similar to lower permeability than NWC. In addition, SLWAC usually presents lower w/c ratios and lower volume of aggregates than NWC of equal strength, which results in denser cement matrixes and lower percentage of ITZ. SLWAC is also benefited by the internal curing promoted by LWA, which can contribute to the improvement of the hydration of the surrounding paste, as well as the increment of the water content (WC) in concrete, reducing the gas percolation through the porous structure [15,41].

According to Bogas et al. [15], capillary absorption and permeability are influenced by aggregate porosity in different ways. For example, the abrupt transition between the paste porosity and the 2–3 orders of magnitude higher pores of LWA leads to a sharp drop of the capillary action, but to greater permeability.

According to EuroLightConR2 [34], for hydrated cement pastes with w/c ratio lower than 0.5, LWA are sufficiently isolated and do not significantly participate in concrete permeability. However, if the cement matrix possesses an open enough porous structure and the high porosity of LWA becomes available, SLWAC permeability tends to be higher than that of NWC of the same composition. Higher carbonation and chloride penetration has been documented in non-structural lightweight aggregate concrete, in which the higher porosity of the cement matrix increased aggregate accessibility [3].

Several authors have found that the water permeability of SLWAC was similar or even lower than that of NWC [22,42–44].

Zhang and Gjorv [22] found very low permeability in SLWAC produced with w/c ratios of 0.28–0.44, being more dependent on the porosity of the cement matrix than on LWA's. At very low w/b ratios, between 0.3 and 0.4, Hammer [44] also concluded that aggregate porosity did not significantly affect SLWAC permeability. However, the relative importance of the aggregate increases when it does not possess a dense outer shell or the surrounding paste is less dense. Hossain and Lachemi [45], using volcanic pumice aggregates, reported higher permeability in SLWAC than in NWC of equal composition. Based on several investigations carried out in Romania, Ionescu and Ispas [46] referred that, for high strength levels, SLWAC permeability is similar to that of NWC and, for low strength levels, SLWAC permeability is higher than that of NWC.

Published studies concerning the gas permeability of SLWAC are more controversial and scarce Vaysburd [42], Sugiyama et al. [47] and Ben-Othman and Buenfeld [48] reported lower gas permeability in SLWAC than in NWC of the same composition. However, contrary results were reported by Lydon [33] and Lydon and Mahawish [49].