OXYGEN PERMEABILITY OF STRUCTURAL CONCRETES PRODUCED WITH VARIOUS TYPES OF LIGHTWEIGHT AGGREGATES AND CEMENTITIOUS MATERIALS

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Extended Abstract

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Abstract

The purpose of this paper is to evaluate the oxygen permeability of structural lightweight concretes (LWAC) produced with 4 types of lightweight aggregates, one type of normal weight aggregate for production of the reference concrete, 3 water/binder ratios (0,35; 0,45; 0,55) and 9 types of binders (CEMI; CEMII/A-V; CEMII/B-V; CEMII/A-D(1); CEMII/A-D(2); CEMII/A-L; CEMII/B-L; CEMIV/A; CEMIV/B). Therefore, a vast experimental campaign was conducted, involving mechanical testing (compressive strength) and durability testing (capillary absorption and oxygen permeability).

It was found that the reduction of compressive strength in LWAC, when compared to normal weight concrete (NWAC) of equal composition, increases as the w/b ratio decreases and the lightweight aggregate density decreases. NWAC produced with denser aggregates can achieve similar results to NWAC, or even better results for superior w/b ratios.

Capillary absorption is primarily influenced by the paste characteristics (w/b ratio and type of addition), independently of the aggregate type. In general, low w/b ratio mixtures with silica fume addition obtain the lower absorption coefficients.

Oxygen permeability depends on various factors as the water/binder ratio, the type of cement and the age of the concrete. It also presents relevant variability related to modifications in the pore structure and the degree of saturation. Generally, the best permeability coefficients were obtained in LWAC with denser aggregates, lower w/b ratios and silica fume addition at 364 days of age. Then again, higher density aggregate LWAC's are the ones who achieve closer behaviors to NWAC, while lower density LWAC present higher permeability coefficients and, therefore, inferior durability performance.

Keywords: Concrete durability; Oxygen permeability; Structural lightweight aggregate concretes

1. Introduction

Nowadays, concrete is the construction material of excellence due to its good mechanical properties and known durability. However, resources scarcity and environmental consciousness have created an urge to use innovative and sustainable materials.

Structural lightweight aggregate concrete (SLWAC) is a material which density is lower than that of normal weight aggregate concrete (NWAC) in about a third. The advantages of SLWAC also include being energetically efficient and the possibility of being produced with aggregates made with industrial waste. According to NP EN 206-1 [1], lightweight aggregate concretes (LWAC) have densities from 800 kg/m^3 to 2000 kg/m^3 and their compressive resistance classes vary from LC 8/9 to LC 80/88, with classes over LC55/60 being already considered as high resistance concretes.

In opposition to general knowledge, until the middle of 20th century, concrete was subjected to severe degradation mechanisms which drastically reduced its structural efficiency. One of those mechanisms is concrete carbonation that leads to steel corrosion.

The evaluation of oxygen permeability arises as a good way of determining concretes behavior to the ingress of gases (especially CO_2) since oxygen generally does not create major reactions in the concrete pore structure and O_2 ingression is a necessary factor for steel corrosion (Cembureau Recommendation, 1989) [2].

The amount of water in the pore structure is fundamental for gas permeability due to the fact that there is only flow through the empty pores. Several authors concluded that gas permeability increases for reductions of relative humidity until 65-75%, with few alterations for reductions until 40% [3, 4].

Garboczi (1995) [5] states that, considering the high volume of aggregates in concrete, there is a strong probability that paste/aggregate transition zones get connected and allow easy continuous passages for substance transportation. However, lightweight aggregates (LWA), due to their previous saturation, work as small water reservoirs inside concrete during the curing process and, consequently, lead to the creation of high quality and high compactness transition zones, better than the ones observed in NWAC. Many authors relate the importance of SLWAC's better transition zones to its durability, [6-8].

However, in Gesoğlu et al. (2014) [9], SLWAC with fly ash LWA present values of oxygen permeability around 50% higher than NWAC. In addition, water permeability results for concretes with partial replacements of NWA for fly ash LWA in various percentages are higher than NWAC in the study carried out in Gesoğlu et al. (2013) [10].

Nevertheless, in Güneysi et al. (2015) [11] relatively low values of oxygen permeability were observed in self-compacting concretes with fly ash LWA, with decreases for higher ages of the concrete, as well as silica fume (SF)and fly ash (FA) additions.

The use of additions in cement replacement is also a very important factor in oxygen permeability, in Güneysi et al. (2012) [12] mixtures with SF had permeabilities 40% lower than CEM I mixtures for a water/cement (w/c) ratio of 0.35. Other authors [4, 13], referred permeabilities lower than CEM I mixtures in concretes with FA addition at 90 and 28 days of age, respectively.

In gas permeability testing there is an important phenomenon called Klinkenberg effect [14] which consists in the apparent gas permeability coefficient varying with the applied gas pressure (Eq. 1). When the mean pressure tends towards infinity the apparent permeability coefficient equals to the intrinsic permeability coefficient.

$$K_{ap} = K_i \left(1 + \frac{\beta}{p}\right) \tag{1}$$

Where K_{ap} is the apparent permeability coefficient (m^2), K_i is the intrinsic permeability coefficient (m^2), β is the Klinkenberg slippage coefficient (Pa) and p is the pore pressure (Pa).

The main objective of this paper was to evaluate the oxygen permeability of structural lightweight concretes produced with different types of aggregates and various types of binder.

2. Experimental program

2.1. Materials

Several compositions were used in order to achieve different strength and density classes. Based on a comprehensive experimental work, various concretes with normal weight sand and four types of coarse LWA were produced and tested. The production of the concretes was carried out with 3 different water/binder (w/b) ratios (0.35–0.55) and 9 different types of binder, according to NP EN 197-1 [15], which included different percentages, in weight, of silica fume (SF), fly ash (FA) and lime filler (LF), thus: CEM I 42.5R; CEM II/A-D (6% and 9% SF); CEM II/A-V (15% FA); CEM II/B-V (30% FA); CEM II/A-L (15% FL); CEM II/B-L (30% FL); CEM IV/A (10% SF and 20% FA); CEM IV/B (10% SF and 40% FA).

Cement properties consisted in 38.6% residue on the 45 mm sieve for LF, class F fly ash with 13.8% residue on the 45 mm sieve and a reactivity index of 84.4%, SF with 94.3% of SiO_2 and cement type I 42.5 R (CEM I). A polycarboxylate based superplasticizer (SP) was used in concretes with low w/c ratio.

Four coarse lightweight aggregates were selected: two expanded clay aggregates from Portugal (Leca and Argex); one sintered fly ash aggregate from the UK (Lytag); and one expanded slate aggregate from USA (Stalite). Their major characteristics (which include very distinct porosities) were listed in Table 1.

Fine and coarse normal weight aggregates (NA) were also used to produce reference concretes and comprise two crushed limestone aggregates of different sizes, specifically, fine and coarse gravel (Table 1). NA and Argex volume fractions were combined according to the grading curve of Leca. Fine aggregates consisted of 70% coarse and 30% fine sand. The main properties of fine aggregates were also listed in Table 1.

Table 1 - Properties of the aggregates

Property	Lightweight Aggregates					Normal weight Aggregates			
	Leca	**Stalite**	**Lytag**	**Argex 2-4**	**Argex 3-8F**	**Fine Sand**	**Coarse Sand**	**Coarse Gravel**	**Fine Gravel**
Absorption at 24h (%)	15.81	3.57	17.92	21.38	19.28	0.19	0.26	0.35	0.73
Dry density (kg/m^3)	1076	1483	1338	669	597	2605	2617	2683	2646
Dry bulk density (kg/m^3)	624	760	750	377	330	1569	1708	1346	1309
Granulometric fraction (di/Di)	4/11.2	8/16	4/11.2	4/8	4/11.2	0/1	0/4	0/8	4/11.2
Open porosity (%)[a]	40.7	14.9	39.8	55.5	58.0	-	-	-	-

[a] The open porosity was defined as the 24 h water absorption of aggregates in vacuum.

2.2. Mixture composition and production

The compositions considered in this study corresponded to the usual mixtures present in the concrete industry, resulting in 92 different compositions, as indicated in Table A1 in Appendix. The w/b ratio relates to the effective water available for cement hydration. The volume of coarse aggregate was fixed in 350 L/m^3 to allow a better comparison and interpretation of the results.

All the LWA, except for Argex, were initially soaked for 24 h in order to minimize the water exchanges during the mixture and, therefore, have a better control of the workability and the effective water content of the concrete. Afterwards, the aggregates were surface dried using absorbent towels and then placed in a vertical shaft mixer (with bottom discharge) with sand and 50% of the total water.

The materials were mixed for two minutes and then the mixture would rest for one minute before the binder and a fraction of the water were added. When SP was used, its addition was made slowly with 10% of the water, after another minute. If the compositions had SF it was added along with the SP. The total mixing time was about 7 minutes. Argex aggregate was initially dry before mixing due to the difficulty of achieving the saturated condition with dry surface in this aggregate. For this particular case, a previous estimative of the absorption of the LWA in the mix was made to take into account the correction of the total mix water, based on the method suggested by Bogas et al. [16].

2.3. Specimen preparation and test methods

2.3.1. Compressive strength and density

The compressive strength and density tests were conducted at 28 days of age according to EN 12390-3 [17] and EN 12390-7 [18]. For both tests, the curing procedure consisted on demolding after 24h and keeping the specimens in water until they were tested.

2.3.2. Oxygen permeability

The oxygen permeability tests were conducted according to the specification E 392 (1993) [19], based on the Cembureau method. The equipment consisted in three permeability cells (where specimens were placed and subjected to lateral pressure), an oxygen supply cylinder, a permeameter from *Testing* company and a stop-watch (Figure 1).

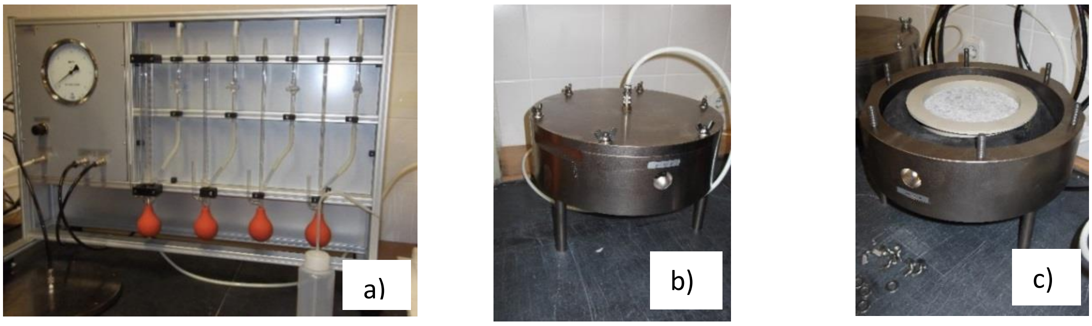

Figure 1 – Gas permeability measuring system: a) control unit; b) measuring cell; c) specimen in measuring cell

The coefficient of permeability was obtained using Equation (2) of Hagen-Poiseuille at constant pressure for compressible fluids.

$$K_g = \eta \frac{Q\, l}{t\, A} \frac{2\, p}{(p_1^2 - p_2^2)} \qquad (2)$$

Where K_g was the permeability coefficient (m^2); η was the coefficient of viscosity of the gas (N.s/m^2); Q was the gas flow (m^3); l was the thickness of the specimen (m); A was the cross-sectional area (m^2); p was the atmospheric pressure (N/m^2); p_1 was the input pressure (N/m^2); p_2 was the output pressure (N/m^2); and t was the time (s).

As for the curing procedure, the specimens were kept in water for 7 days, then placed in a controlled chamber at 22 ± 2 °C and 50 ± 5% relative humidity (RH) for 70 or 344 days (for the tests at the ages of 90 or 364 days, respectively) and then oven dried for 3 days at 40 °C, followed by 10 days at 40 °C and 1 day at 20 °C without moisture exchange. After this procedure, the 3 cylindrical specimens (ϕ150x50 mm) were laterally sealed with aluminum tape in order to guarantee the uniaxial flow of the gas.

The actual test procedure consisted in sealing the permeability cells and imposing a pressure gradient between the upper and lower surfaces of the specimen. The flux had to stabilize and then the time needed for a bubble to complete one of the graduated tubes that compose the permeameter was measured using the stop-watch.

2.3.3. Capillary absorption

The absorption tests were carried out at 90 days according to E393 [20] and TC116-PCD [21]. This test consisted fundamentally on determining the water absorption rate (sorptivity) of concrete by measuring the increase in the mass of a specimen due to absorption of water as a function of time, as only one surface of the specimen was exposed to water.

The exposed surface of the specimen was immersed in 5 ± 1 mm of water and the mass of the specimen was registered at 10, 20, 30, 60 min and 3 and 6 h after the initial contact with water. The absorption coefficient was defined as equivalent to the slope of the linear regression line from $\sqrt{20}min$ to $\sqrt{6}h$.

The absorption tests were conducted on the same specimens used for the oxygen permeability test, after those were completed.

3. Results and discussion

The average values of dry density, ρ_s, compressive strength, f_{cm}, capillary absorption coefficient, C_{abs}, and oxygen permeability coefficient at 90 and 365 days, K_{O2}, are presented in Table A1, in the Appendix, for each composition.

3.1. Compressive strength and density

The values obtained for the compressive strength of SLWAC varied between 16.9 and 66.8 MPa and the dry density from 1430 to 1893 kg/m^3, covering the most usual SLWAC for strength classes LC12/13-LC 60/66 and density classes D1.6-D2.0.

In general, concretes produced with denser LWA (Stalite) could achieve high resistance concretes, whereas moderate resistances were obtained with Leca and Lytag and, finally, concretes produced with Argex had very low resistance (Table A1). The higher values of compressive strength were observed for NWAC and SLWAC with denser aggregates (Stalite), independently of the types of binder and w/b ratio. In fact, for w/b ratios above 0.35, the mixtures with Stalite tended to structural efficiencies higher than NWAC. As expected, there was a clear reduction of the structural efficiency as the w/b ratio increased.

3.2. Capillary absorption

The capillary absorption tests resulted in coefficients that varied from 0.0155 to 0.2036 mm/min$^{0.5}$, corresponding to reduced to high quality concretes according to Browne [22]. The increase or decrease of the w/b ratio revealed itself as the most conditioning factor in this mechanism and was responsible for most of the differences between compositions sorptivities. On top of that, the type of aggregate only affected absorption for higher values of the w/b ratio and, therefore, pastes with lower compactness.

In general, for a given type of binder and w/b ratio, the absorption coefficient did not depend on the type of aggregate used to produce the concrete. However, concretes using LWA with more accessible porosity (Lytag and Argex) verified higher values of sorptivity than the other concretes. SLWAC with Lytag clearly presented the higher absorption rates, which is most likely related to the production process of this aggregate. In addition, SLWAC with Stalite achieved lower sorptivity than NWAC for lower w/b ratios due to the better paste/aggregate transition zones and the internal curing effect characteristic of LWA.

In most cases, the partial cement replacement with FA resulted in the increase of the absorption coefficient, as at the age of 90 days this addition essentially contributes as filling material due to its low pozolanic activity (Figure 2).

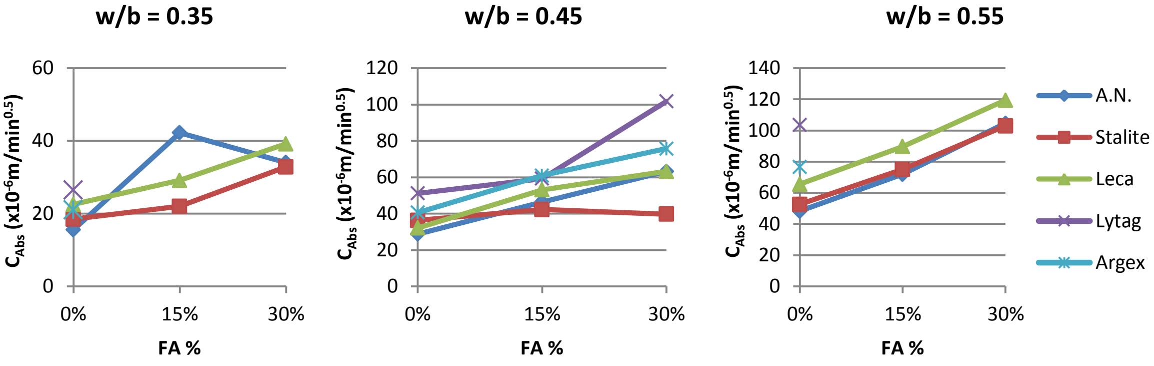

Figure 2 – Absorption coefficients *versus* percentage of cement replacement with fly ash for the 3 w/b ratios

In addition, the cement replacement with SF only led to lower sorpitivity in a few cases and it could be concluded that this addition's efficiency in refining SLWAC microstructure was rather limited (Figure 3), except for SLWAC with denser aggregates (Stalite). However, silica fume dispersion became more difficult for higher w/b ratios and the actual improvement in the transition zones was indeed lower in LWAC than in NWAC for, the same composition.

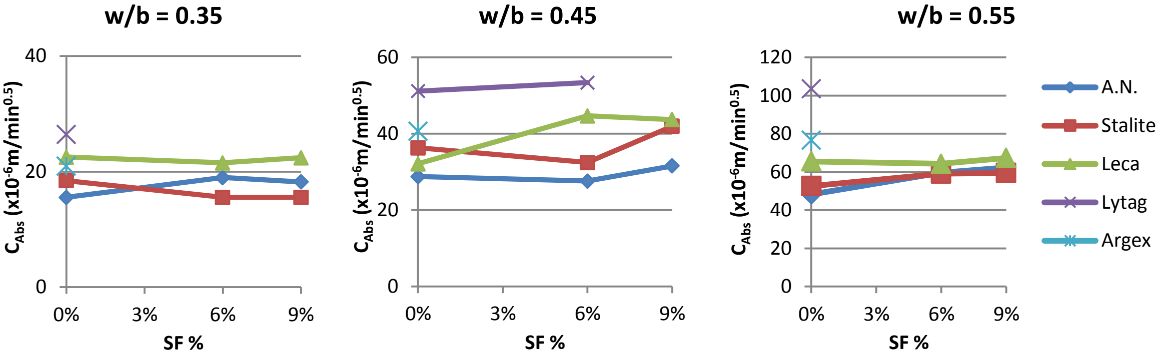

Figure 3 - Absorption coefficient *versus* percentage of cement replacement with silica fume for the 3 w/b ratios

3.3. Oxygen permeability

The oxygen permeability of a vast set of mixtures was tested and the average permeability coefficient varied in two orders of magnitude (Table A1), depending on several factors such as the w/b ratio, the type of binder, the type of aggregate and the age of the concrete. High values of variability were observed (Table A1), since the oxygen permeability test is very sensitive to small differences in the specimens pore structure which are related to the concrete composition and production conditions, as well as its saturation degree. It was clear that O_2 permeability coefficients increased with the w/b ratio (Figure 4), since there is an increment on the pore structure connectivity for less compact pastes.

3.3.1. Influence of the type of aggregate

In general, permeability was influenced by the type of aggregate (Figure 4). As expected, the permeability was higher in SLWAC that contained aggregates with higher open porosity and a less dense cracked surface (Argex, Lytag). On the other hand, SLWAC with denser aggregates (Stalite) achieved better permeabilities (Figure 4). In addition, it could also be concluded that the type of aggregate assumed a greater influence in mixtures with higher w/b ratio, due to the fact that these concretes are associated to pastes with increased connectivity which allows an easier access of fluids and greater participation of LWA in the transport phenomenon. However, alike the capillarity tests, SLWAC with denser aggregates could achieve coefficients very similar to NWAC's, especially for lower w/b ratios.

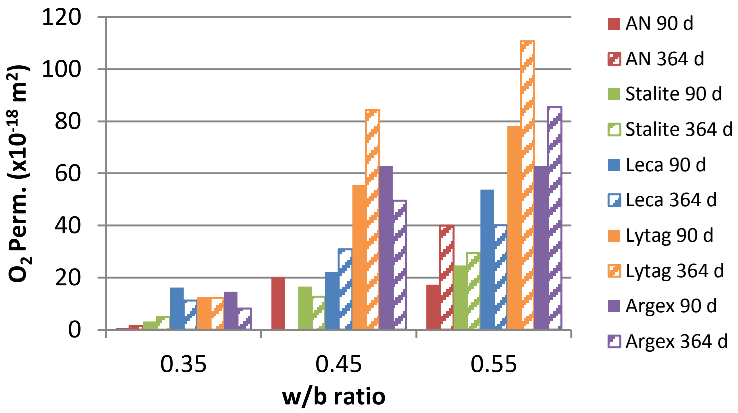

Figure 4 - Oxygen permeability coefficients in CEM I mixtures for the age of 90 days and 364 days

SLWAC produced with Lytag presented the higher permeability coefficients (Figure 4), due to this aggregate's high internal porosity and its non-existent compact superficial layer. Similar results were obtained in [9] where SLWAC produced with FA aggregates achieved results of O_2 permeability approximately 50% higher than NWAC, for similar compositions.

When compared with capillary absorption, in oxygen permeability the type of aggregate had a greater influence, especially for high w/b ratio mixtures. This is related to the fact that the two transport properties are associated to very distinct mechanisms. While permeability evolves proportionally to the dimension and interconnectivity of the pores, the capillary absorption is also conditioned by the form of development of the porous structure.

3.3.2. Influence of the type of binder

The SLWAC with addition of SF obtained permeability coefficients similar to the ones of reference mixtures with type I cement (Figure 5), due to its limited efficiency in refining the pore structure, as it was referred for the capillary absorption. Additionally, it did not seem to exist a clear correlation between the effectiveness of SF and the w/b ratio, in opposition to capillary absorption.

Nonetheless, although there was not a great effectiveness in the partial replacement of cement by SF (especially for low w/b ratios), there was a slight refinement of the pore structure in SLWAC.

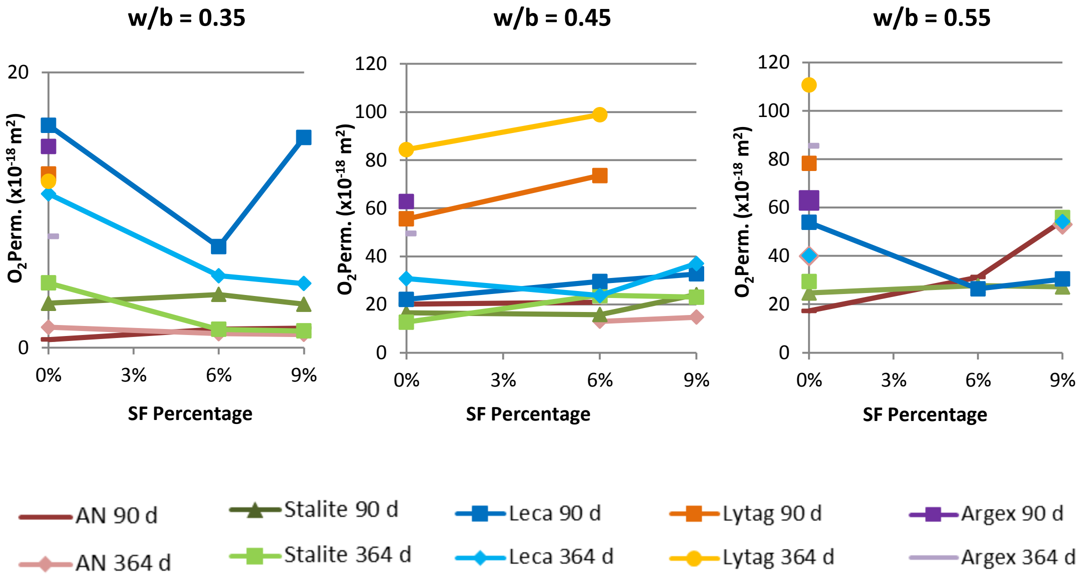

Figure 5 - Oxygen permeability versus cement replacement with silica fume for the 3 w/b ratios

Considering the partial replacement of cement with FA, the permeability coefficient tended to increase with the percentage of replacement, which can be related to the early age of testing (90 days) and the limited activity index of the FA (Figure 6). The contrary was referred in [13] where concretes with 5% SF presented permeabilities 40% lower than CEM I concretes, for the same ratio w/b=0.35. On another perspective, there was an increment of permeability with the increase of the cement replacement and bigger w/b ratios, as K_{O2} tended to be superior for SLWAC with more porous aggregates (Lytag, Argex).

The compositions produced with different percentages of lime filler presented similar results to the mixtures with the same cement replacement with FA at the age of 90 days. As for the ternary mixtures, very high values of the permeability coefficient were achieved, possibly due to the fact that, in high percentage addition mixtures, the quantity of hydration products might not be enough for all the reactions to take place. On the other hand, it can also be a consequence of the great equivalent w/c ratios that go as high as w/c=1.1 for w/b=0.55 mixtures, which lead to higher matrix interconnectivity.

However, analyzing the mixtures for the effective quantity of cement, it was possible to conclude that, in general, the incorporation of additions did not contribute to a relevant improvement in their performance, as can be observed in Figure 7 for NWAC.

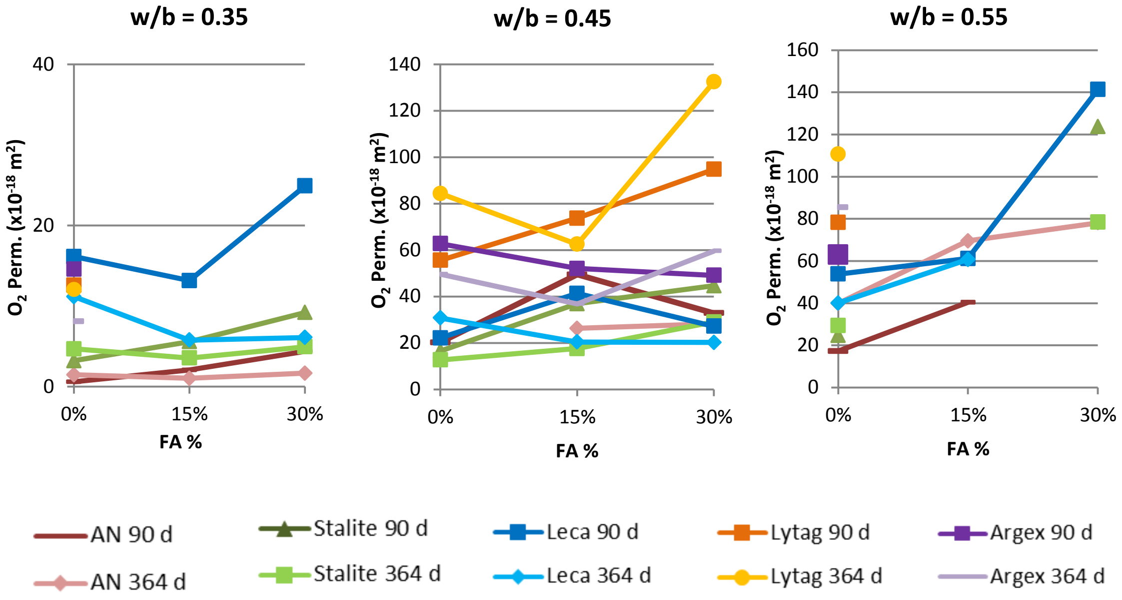

Figure 6 - Oxygen permeability versus cement replacement with fly ash for the 3 w/b ratios

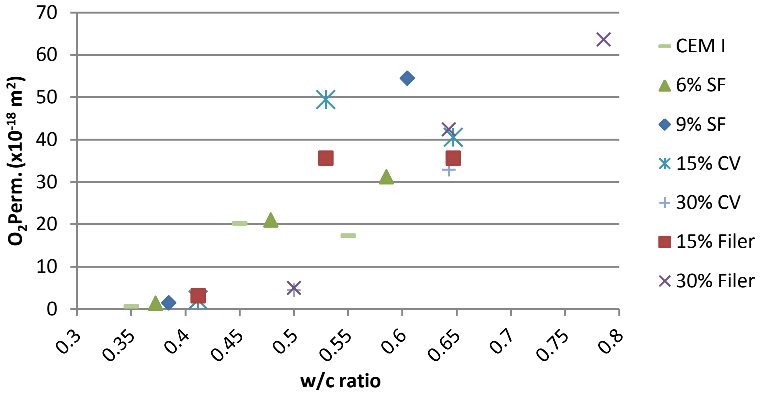

Figure 7 – Oxygen permeability coefficient *vs* w/c ratio for different percentages of additions (90 days) in NWAC

3.3.3. Influence of the age of concrete

As expected, the age of the specimens influenced O_2 permeability, as the mixtures containing SF had lower coefficients in long term (364 days), especially for lower w/b ratios. As for mixtures with addition of FA, there was a clear reduction of permeability for the same age. The better performance of these additions can be justified by new reactions of C-S-H formation that contribute to refine the pore structure and tend to be more relevant at higher ages.

3.3.4. Correlation between tests

In Figure 8, high values of correlation could be observed between oxygen permeability and compressive strength, since both properties are affected by pore structure, for each type of aggregate analysed separately. The same conclusion could not be reached considering all types of aggregate simultaneously.

Regarding the correlation between oxygen permeability and capillary absorption, the aggregates' role was different in the two transport mechanisms. However, there was a reasonable correlation between the two coefficients (Figure 9) which relates to the paste's relevant influence on concrete penetrability, particularly in mixtures with higher compactness (lower w/b ratios).

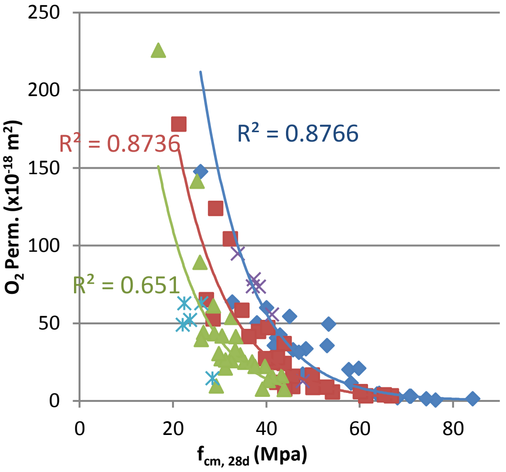

Figure 8 - Relation between oxygen permeability and compressive strength

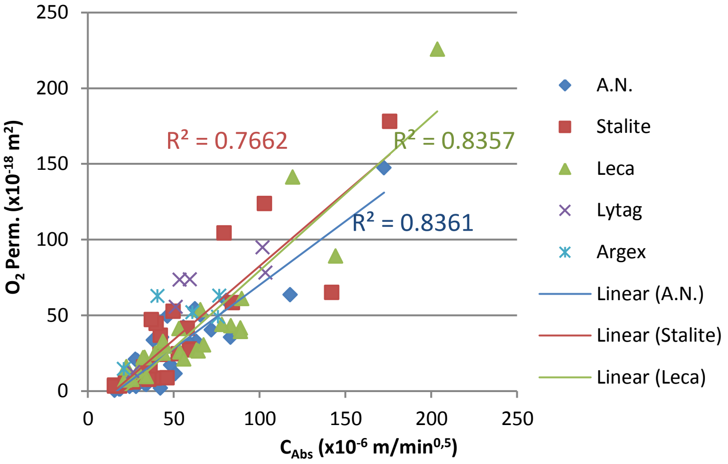

Figure 9 - Relation between oxygen permeability and capillary absorption

3.3.5. Influence of the Klinkenberg effect

The Klinkenberg effect was clear, since in most cases there was a reduction of the permeability coefficient with the increase of the applied pressure of the gas (Figure 10), as referred in Abbas et. al [14]. However, there were some cases that did not present this effect which can be explained by the pore structure alterations due to high pressures or modifications in flow properties for high pressures.

3.3.6. Variation of oxygen permeability with relative humidity and saturation degree – complementary study

Finally, a complementary study was made for the variation of oxygen permeability with relative humidity (RH) and saturation degree (SD) in CEM I mixtures with 3 of the aggregates studied (NA, Stalite, Leca).

This study allowed concluding about the importance of water presence and also the influence of the type of aggregate on permeability for various values of relative humidity. For a given saturation degree, SLWAC were associated to higher relative humidities and that tendency seemed to be proportional to the lightweight aggregates increase porosity (Figure 11). In addition, for relative humidities of at least 40%, LWAC with Stalite had slightly lower permeabilities than NWAC (Figure 12).

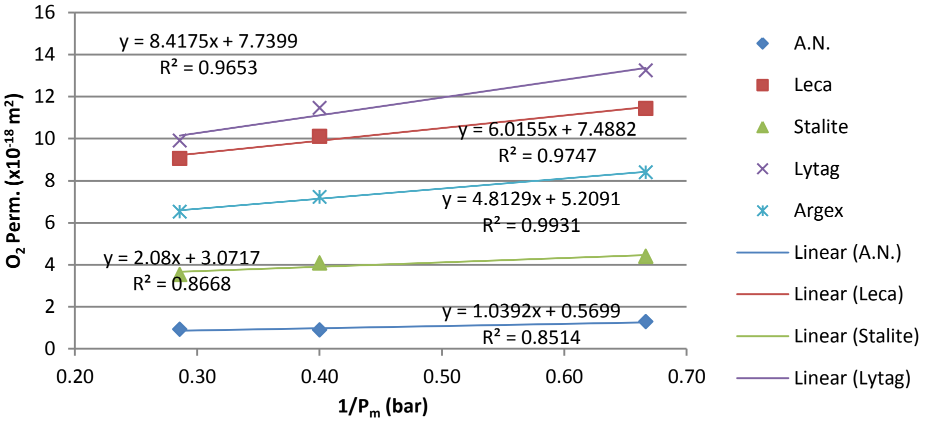

Figure 10 - O_2 permeability *versus* inverse of the applied pressure for CEM I mixtures (w/b=0.35)

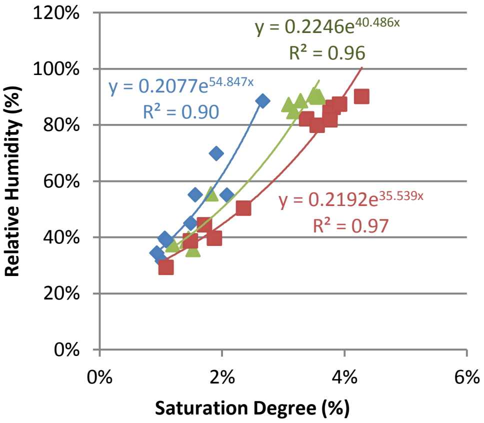

Figure 11 - Relative humidity *versus* saturation degree

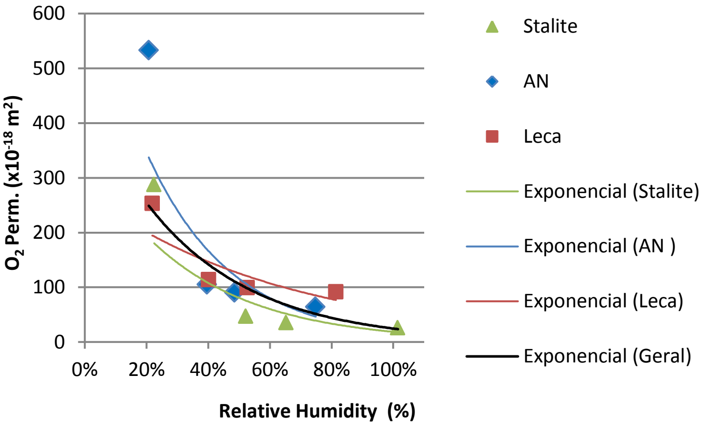

Figure 12 - Oxygen permeability *versus* relative humidity

4. Conclusions

The present study characterized the oxygen permeability of SLWAC produced with different types of aggregate and binder. The main conclusions drawn were:

- SLWAC characterized by strength classes LC12/13-LC 60/66 and density classes D1.6-D2.0 were produced. The SLWAC produced with denser aggregates (Stalite) achieved similar or better results than NWAC.
- Capillary absorption values varied from 0.0155 to 0.2036 mm/min$^{0.5}$, corresponding to low to high quality concretes. Capillarity was mainly influenced by w/b ratio and the type of aggregate only affected absorption for higher values of the w/b ratio. Also, SLWAC with Stalite obtained lower sorptivity than NWAC for lower w/b ratios. The addition of FA and SF did not improve capillary absorption significantly at 90 days age.

- The average permeability coefficient varied in two orders of magnitude and was influenced by several factors such as the w/b ratio, the type of binder, the type of aggregate and the age of the concrete. The O_2 permeability coefficient increased with the w/b ratio and was influenced by the type of aggregate.
- Permeability values were higher in SLWAC that contained aggregates with higher open porosity and a less dense cracked surface (Argex, Lytag). On the other hand, SLWAC with denser aggregates (Stalite) achieved better permeabilities.
- The incorporation of additions did not allow the production of mixtures with significant increment in the performance. SLWAC with SF addition obtained similar permeability coefficients to the ones of reference mixtures with type I cement. However, permeability coefficients of SLWAC with FA addition tended to increase with the percentage of cement replacement.
- Oxygen permeability was influenced by the age of concrete and both SF and FA cement replacement had better results at 364 days of age.
- Both compressive strength and capillary absorption had reasonable correlation with oxygen permeability.
- The present study was able to verify the influence of the Klinkenberg effect.
- The conducted complementary study allowed obtaining knowledge of the relation between oxygen permeability, RH and SD. For a fixed saturation degree, SLWAC had higher relative humidities in proportion with the aggregates porosity. Also, SLWAC with Stalite presented slightly lower permeabilities than NWAC, for relative humidities of at least 40%.

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Annex: Table A1 – Mixture composition and test results

Aggregate	Mixture	w/b	w/c	M_{cement} (kg/m3)	V_{sand} (l/m3)	ρ_s (kg/m3)	f_{cm28d} (Mpa)	C_{abs} ($x10^{-6}m/min^{0.5}$)	CV (%)	K_{O2} 90 d ($x10^{-18}m2$)	CV (%)	K_{O2} 364 d ($x10^{-18}m2$)	CV (%)
NA	CEM I	0.35	0.35	450	314	2299	76.3	15.5	8%	0.59	10	1.48	15
	CEM II/A-D(1)		0.37	450	311	2241	74.3	19.0	6%	1.35	16	1.02	5
	CEM II/A-D(2)		0.38	450	309	2259	84.2	18.2	4%	1.43	12	0.96	20
	CEM II/A-V		0.41	450	307	2228	68.1	42.2	5%	2.07	29	1.04	4
	CEM II/B-V		0.50	450	300	2234	63.7	34.0	3%	4.40	14	1.67	8
	CEM II/A-L		0.41	450	310	-	71.0	24.3	13%	3.06	13	2.73	27
	CEM II/B-L		0.50	450	306	-	64.2	33.1	15%	4.94	13	-	-
	CEM IV/A		0.50	450	299	2226	70.7	28.1	5%	3.10	16	1.45	7
	CEM IV/B		0.70	450	290	2211	58.2	50.8	2%	11.44	1	19.98	11
	CEM I	0.45	0.45	400	310	2220	57.7	28.8	1%	20.16	14	-	-
	CEM II/A-D(1)		0.48	400	307	2175	59.8	27.6	12%	20.97	6	13.04	15
	CEM II/A-D(2)		0.49	400	305	2163	58.8	31.6	5%	-	-	14.76	23
	CEM II/A-V		0.53	400	304	2189	53.4	46.4	6%	49.41	0	26.23	5
	CEM II/B-V		0.64	400	297	2203	45.7	63.2	4%	32.84	0	28.25	31
	CEM II/A-L		0.53	400	306	-	53.0	42.9	7%	35.55	8	18.48	44
	CEM II/B-L		0.64	400	302	-	42.9	55.7	1%	42.32	1	18.86	14
	CEM IV/A		0.64	400	296	2146	48.5	38.2	1%	33.56	5	20.12	34
	CEM IV/B		0.90	400	288	2127	38.0	65.5	5%	50.28	3	40.18	3
	CEM I	0.55	0.55	350	315	2199	47.8	48.2	3%	17.24	0	39.88	30
	CEM II/A-D(1)		0.59	350	312	2187	47.0	59.5	5%	31.17	0	-	-
	CEM II/A-D(2)		0.60	350	310	2166	45.0	62.4	3%	54.42	0	52.95	20
	CEM II/A-V		0.65	350	309	2219	42.2	71.9	3%	40.44	39	69.51	1
	CEM II/B-V		0.79	350	304	2203	36.0	104.6	7%	-	-	78.09	28
	CEM II/A-L		0.65	350	311	-	41.7	83.1	6%	35.52	16	77.29	16
	CEM II/B-L		0.79	350	308	-	32.7	117.9	7%	63.58	28	-	-
	CEM IV/A		0.79	350	303	2179	40.1	80.7	8%	59.82	14	75.58	0
	CEM IV/B		1.10	350	295	2135	25.9	172.5	3%	147.49	26	163.10	5
Stalite	CEM I	0.35	0.35	450	314	1893	66.8	18.5	14%	3.22	15	4.70	13
	CEM II/A-D(1)		0.37	450	311	1869	65.3	15.6	1%	3.86	14	1.33	6
	CEM II/A-D(2)		0.38	450	309	1831	61.3	15.6	1%	3.16	14	1.22	25
	CEM II/A-V		0.41	450	307	1831	54.2	22.0	7%	5.60	3	3.57	6
	CEM II/B-V		0.50	450	300	1824	45.7	32.8	26%	9.22	11	4.95	23
	CEM II/A-L		0.41	450	310	-	60.2	26.2	14%	5.97	26	7.19	13
	CEM II/B-L		0.50	450	306	-	50.0	39.0	12%	8.61	8	-	-
	CEM IV/A		0.50	450	299	1785	52.9	46.1	0%	8.82	8	4.36	34
	CEM IV/B		0.70	450	290	1762	42.3	32.5	20%	11.94	9	23.37	13
	CEM I	0.45	0.45	400	310	1794	49.9	36.3	5%	16.55	41	12.68	0
	CEM II/A-D(1)		0.48	400	307	1764	45.7	32.5	23%	15.82	17	23.88	0
	CEM II/A-D(2)		0.49	400	305	1750	43.8	42.0	11%	24.12	10	23.06	11
	CEM II/A-V		0.53	400	304	1790	43.8	42.3	10%	36.85	8	17.57	40
	CEM II/B-V		0.64	400	297	1795	38.4	39.7	2%	44.59	76	28.99	115
	CEM II/A-L		0.53	400	306	-	44.0	35.6	2%	7.65	11	17.42	13
	CEM II/B-L		0.64	400	302	-	36.3	58.0	4%	41.46	18	55.51	23
	CEM IV/A		0.64	400	296	1712	40.4	37.0	2%	47.12	0	23.71	36
	CEM IV/B		0.90	400	288	1674	28.6	49.7	1%	52.66	18	56.79	2
	CEM I	0.55	0.55	350	315	1832	41.5	52.6	6%	24.65	33	29.40	16
	CEM II/A-D(1)		0.59	350	312	1758	42.4	59.1	7%	27.67	33	-	-
	CEM II/A-D(2)		0.60	350	310	1744	39.9	59.5	7%	27.15	19	55.91	27
	CEM II/A-V		0.65	350	309	1803	36.7	75.0	8%	-	-	-	-
	CEM II/B-V		0.79	350	304	1772	29.2	102.9	6%	123.74	34	78.42	31
	CEM II/A-L		0.65	350	311	-	34.8	84.3	1%	58.29	32	-	-
	CEM II/B-L		0.79	350	308	-	27.2	142.0	3%	65.14	7	-	-
	CEM IV/A		0.79	350	303	1777	32.3	79.3	9%	104.32	49	75.43	0
	CEM IV/B		1.10	350	295	1733	21.3	175.9	6%	178.06	4	266.73	18

Leca	CEM I	0.35	0.35	450	314	1697	43.3	22.5	0%	16.16	0	11.18	12
	CEM II/A-D(1)		0.37	450	311	1717	43.9	21.5	3%	7.34	35	5.23	51
	CEM II/A-D(2)		0.38	450	309	1652	41.4	22.4	4%	15.27	91	4.66	54
	CEM II/A-V		0.41	450	307	1667	40.4	29.1	6%	13.16	35	5.80	0
	CEM II/B-V		0.50	450	300	1617	35.4	39.2	1%	24.92	90	6.10	32
	CEM II/A-L		0.41	450	310	-	39.8	33.1	0%	22.26	62	9.76	20
	CEM II/B-L		0.50	450	306	-	37.0	44.0	4%	25.00	10	-	-
	CEM IV/A		0.50	450	299	1628	39.2	25.7	3%	7.59	8	5.64	68
	CEM IV/B		0.70	450	290	1582	29.3	34.0	2%	9.62	0	7.65	19
	CEM I	0.45	0.45	400	310	1656	37.6	32.1	12%	22.14	6	30.75	19
	CEM II/A-D(1)		0.48	400	307	1601	34.4	44.7	6%	29.58	16	23.72	22
	CEM II/A-D(2)		0.49	400	305	1581	33.3	43.7	9%	32.73	26	37.04	30
	CEM II/A-V		0.53	400	304	1594	33.5	53.1	4%	41.28	1	20.43	20
	CEM II/B-V		0.64	400	297	1600	30.3	63.3	5%	27.15	0	20.17	4
	CEM II/A-L		0.53	400	306	-	32.5	53.7	1%	25.87	12	31.04	18
	CEM II/B-L		0.64	400	302	-	28.9	83.3	21%	43.15	33	61.20	16
	CEM IV/A		0.64	400	296	1560	31.2	55.8	1%	21.25	0	36.12	0
	CEM IV/B		0.90	400	288	1551	26.6	78.0	0%	44.05	0	47.87	13
	CEM I	0.55	0.55	350	315	1627	32.6	65.5	4%	53.81	47	40.05	25
	CEM II/A-D(1)		0.59	350	312	1595	31.3	64.3	7%	26.39	1	-	-
	CEM II/A-D(2)		0.60	350	310	1574	29.8	67.4	4%	30.43	1	54.12	5
	CEM II/A-V		0.65	350	309	1621	28.7	89.7	4%	61.15	33	60.73	25
	CEM II/B-V		0.79	350	304	1593	25.2	119.4	5%	141.28	15	-	-
	CEM II/A-L		0.65	350	311	-	30.6	88.8	4%	41.71	7	56.12	3
	CEM II/B-L		0.79	350	308	-	25.8	144.3	5%	89.11	6	-	-
	CEM IV/A		0.79	350	303	1571	26.1	88.9	9%	39.43	4	68.30	15
	CEM IV/B		1.10	350	295	1564	16.9	203.6	6%	225.72	6	303.40	9
Lytag	CEM I	0.35	0.35	450	314	1791	47.8	26.4	2%	12.61	0	12.09	7
	CEM I	0.45	0.45	400	310	1733	41.2	51.2	3%	55.57	7	84.37	11
	CEM II/A-D(1)		0.48	400	307	1690	38.5	53.4	8%	73.60	0	98.88	63
	CEM II/A-V		0.53	400	304	1676	37.1	59.3	4%	73.71	33	62.50	19
	CEM II/B-V		0.64	400	297	1700	33.9	101.7	4%	94.78	19	132.44	8
	CEM I	0.55	0.55	350	315	1746	37.3	103.5	6%	78.23	12	110.68	17
Argex	CEM I	0.35	0.35	450	314	1602	28.5	21.0	14%	14.61	67	8.09	15
	CEM I	0.45	0.45	400	310	1523	26.1	40.6	1%	62.79	7	49.54	14
	CEM II/A-V		0.53	400	304	1430	23.7	60.9	8%	52.07	0	36.79	25
	CEM II/B-V		0.64	400	297	1485	22.1	75.8	2%	49.06	1	59.56	13
	CEM I	0.55	0.55	350	315	1518	22.5	76.6	0%	62.90	16	85.47	54