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COMPRESSIVE STRENGTH AND STRUCTURAL EFFICIENCY OF STRUCTURAL LIGHTWEIGHT AGGREGATE CONCRETE

Throughout a compressive strength biphasic behaviour

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***Abstract*—This paper aims to characterize the compressive behavior and structural efficiency of structural lightweight aggregate concrete (SLWAC) produced with different types of lightweight aggregates (LWA). To this end, a comprehensive experimental study was carried out on different concrete compositions with strength classes from LC12/13 to LC55/60 and density classes from D1.6 to D2.0, involving all possible failure modes. The mechanical behavior is characterized by means of the concepts of limit strength, ceiling strength and strength of the aggregate in concrete. High correlations are found between experimental and design values based on a biphasic model to estimate the strength of SLWAC. Covering the most common types of LWA, expressions are suggested to estimate the strength of the aggregate in the concrete.**

Keywords — Structural Lightweigh aggregate concrete, compressive strength, structural efficiency, limit strength

I. Introduction

Contrary to normal weight concrete (NWC), in which the compressive strength is mainly determined by the mortar quality, the mechanical behavior of structural lightweight aggregate concrete (SLWAC) is also controlled by the type and volume of aggregate and the strength level of concrete [1-4]. In the most common cases, in which the lightweight aggregate (LWA) possess a lower modulus of elasticity than that of the cement paste, cracks tend to propagate directly through the aggregate particles. However, there are cases, usually associated to low quality pastes or the use of less porous LWA, in which the behavior of SLWAC becomes similar to that of NWC, with cracks propagating through the interfacial transition zone (ITZ) and the cement paste [1,5]. The high quality of the ITZ of SLWAC makes this failure mode less likely to occur, especially in concretes produced with more porous LWA, in which the matrix-aggregate bond is more effective [6,7].

Chen et al.[5] proposed a method for the prediction of the concrete strength based on the concept of 'limit strength', f_L, corresponding to the concrete strength beyond which the modulus of elasticity of the LWA is lower than that of the surrounding mortar [8,9]. Below f_L, SLWAC behaves similarly to NWC. Above f_L, the concrete strength depends on the strength of the mortar, the LWA particles and the quality of the ITZ.

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Based on a biphasic model, Chandra and Berntsson [1] proposed the expression (1) to estimate the strength of SLWAC as a function of the volume and strength of the mortar and the LWA. However, the expression is only valid when the the concrete strength is affected by the LWA, i.e., above f_L. In expression (1), f_{cm} is the mean compressive strength of the concrete, f_{LWA} is the strength of the aggregate in concrete, f_m is the mean compressive strength of the mortar with the same composition as that of the concrete and υ_{LWA} and υ_m are the relative volumes of LWA and cement in the mix, respectively.

$$\log(f_{cm}) = \upsilon_{LWA}\log(f_{LWA}) + \upsilon_m\log(f_m) \qquad (1)$$

This paper aims to characterize the mechanical behavior of SLWAC and its structural efficiency, i.e., the quotient between the compressive strength and dry density. Expressions to estimate the strength of the aggregate in concrete are defined and a biphasic model to predict the compressive strength of SLWAC, regardless the type of aggregate, is assessed.

II. Experimental program

A. *Materials*

Four types of coarse lightweight aggregate were selected for the production of SLWAC specimens: two expanded clay aggregates from Portugal (Leca and Argex, which was supplied in two different fractions, namely Argex 2-4 and Argex 3-8F); one sintered fly ash aggregate from the UK (Lytag); one expanded slate aggregate from the USA (Stalite). For the production of NWC reference specimens, two crushed limestone aggregates of different grain sizes were used, namely fine and coarse gravel. In order to obtain the same grading curve as Leca, a proportion was established between the two fractions of crushed limestone (34% fine and 66% coarse gravel) and the two fractions of Argex (70% Argex 2-4 and 30% Argex 3-8F). Fine aggregates consisted of 70% coarse and 30% fine normal weight sand for all mixes. The main properties of these aggregates are listed in Table 1. All mixtures were produced with cement type I 42.5 R (CEM I). In concretes with low water/cement ratio (w/c), a polycarboxylate based superplasticizer (SP) was also adopted.

The LWAs were previously soaked for 24h to ensure a better control of the workability and the effective water content of concrete. For concretes produced with Argex, the aggregates were initially dry before mixing. In this case the mix water was corrected according to the method suggested by Bogas et al [10].

TABLE I. AGGREGATE PROPERTIES

Property	Stalite	Lytag	Leca	Argex 2-4	Argex 3-8F	Fine Gravel	Coarse Gravel	Fine Sand	Coarse Sand
Oven dry density, (kg/m^3)	1483	1338	1076	669	597	2646	2683	2605	2617
Loose bulk density, (kg/m^3)	760	750	624	377	330	1309	1346	1569	1708
Water absorption at 24h, (%)	3.57	17.92	15.81	21.38	19.28	0.7	0.4	0.19	0.26
Open porosity, (%)	14.9	39.8	40.7	55.5	58	-	-	-	-
Granulometric fraction, di/Di	8/16	4/11.2	4/11.2	4/8	4/11.2	0/8	4/11.2	0/1	0/4
Crushing strength, (MPa)	7.7	6.3	7.1	-	3.2	-	-	-	-

B. Mixture composition, specimen preparation and test methods

Taking into account different types of coarse aggregate and w/c ratios from 0.35 to 0.65 the concrete compositions indicated in Table 2, with different strength and density classes, were produced. In addition, mortars with the same composition of the concretes were also produced to determine the f_L (Table 2). The concretes were produced in a vertical shaft mixer with bottom discharge.

Seventeen 150 mm cubic specimens of each concrete mix were produced for compressive strength tests at 18h, 24h, 2, 3, 7, 28 and 56 days, according to EN 12390-3 [11]. The mortars were tested at the same ages in 150 mm cubic specimens. In addition, two 100 mm cubic specimens were cast to determine the dry density of concrete at 28 days, according to EN 12390-7 [12]. After demolding at 24h, the specimens were kept in water until testing.

III. Results and discussion

The average values of dry density, ρ_d, compressive strength, f_{cm}, and structural efficiency, (f_{cm}/ρ_d) are listed in Table 2. The most common range of SLWAC was covered, with strength classes from LC12/13 to LC55/60 and density classes from D1.6 to D2.0 [13]. Depending on the type of LWA and w/c ratio, the reduction of compressive strength on SLWAC compared to NWC of the same composition varied from 14% to 60% at 7 days and from 13% to 63% at 28 days. The reduction was more pronounced in SLWAC with lower w/c ratio and more porous LWA. SLWAC with denser aggregates (Stalite) presented similar or slightly lower compressive strength than that of NWC, leading to higher structural efficiency levels, regardless the w/c ratio (Table 2). SLWAC with aggregates of intermediate density (Leca and Lytag) presented similar structural efficiency levels to NWC for w/c ratios above 0.55. The structural efficiency of SLWAC with more porous aggregates (Argex) was 25% to 46% lower than that of NWC of the same composition and, therefore, Argex is considered to be more adequate for low-strength concrete or in situations where the reduction of density is a determining factor.

A. Compressive strength evolution and limit strength, f_L

From Figure 1a, it is shown that the compressive strength evolution of SLWAC with denser aggregates (Stalite) generally follows that of the mortar. Only at later ages, in SLWAC with low w/c (0.35-0.45), the influence of the LWA on the concrete strength seams relevant. The discrepancy between the strength of SLWAC produced with the other types of LWA and that of the mortars is clear from the earliest ages, indicating that f_L has been exceeded and the concrete strength is affected by the LWA. However, in SLWAC with w/c of 0.65 and aggregates of intermediate density (Leca and Lytag), the strength evolution is similar to that of the mortar, which suggests a close proximity to f_L (Figures 1b and 1c). In this case, the structural efficiency is highly improved, when compared to NWC of the same composition. In SLWAC with more porous aggregates (Argex) the strength evolution is negligible from the earliest days, especially for w/c ratios below 0.55 (Figure 1d). The concrete seems to reach its ‘ceiling strength’, i.e., the point beyond an improvement of the mortar quality does not affect much the concrete strength, confirming that Argex is not adequate for moderate to high-strength concrete.

To calculate the limit strength, f_L, the relation between the strength of SLWAC for a given type of aggregate and that of a mortar of the same composition tested under similar conditions is presented in Figure 2. The average values of f_L, resulting from the intersection of the two regression lines that best fit the strength values at different test ages of mixtures with w/c of 0.35-0.65, are indicated in Table 3.

For all test ages and w/c ratios, the strength of SLWAC with more porous aggregates was lower than that of the mortar (Figure 2d). Therefore, it is concluded that f_L, is lower than 10 MPa and that the concrete strength is always affected by the LWA. On the other hand, the strength of SLWAC with denser aggregates (Stalite) generally follows the straight line y=x (Figure 2a), indicating that the concrete strength is mainly affected by the mortar, which leads to high structural efficiency levels. It is not possible to accurately determine f_L, but based on the strength evolution of Figure 1 and on the mismatch between the straight line y=x and the evolution of the concrete strength above 60 MPa in Figure 2b, f_L should be 59-62 MPa. It is confirmed that Stalite is adequate for the production of high-strength concrete.

Bogas and Gomes [4] reported a f_L value of 26 MPa for SLWAC with a Leca type LWA similar to the one used in the present study, which is very close to the f_L determined in Table 3. Despite the considerably greater density of Lytag, it was found that its f_L was only slightly higher than that of Leca (Table 1). This suggests that the concrete strength is not only affected by the total porosity of the aggregate but also by its porous structure. In fact, contrary to the Lytag particles, produced by a sintering process without significant expansion, in the expanded clay aggregates, like Leca, a denser outer shell is formed, thereby improving their mechanical strength.

TABLE II. COMPOSITIONS, OVEN-DRY DENSITY, COMPRESSIVE STRENGTH AND STRUCTURAL EFFICIENCY

Type of coarse aggregate	Coarse aggregate (L/m^3)	CEM I (kg/m^3)	w/c	$\rho_{d,28d}$ (kg/m^3)	Compressive strength, f_{cm} (MPa) 3 days	7 days	28 days	56 days	$f_{cm}/\rho_{d\,(28d)}$ (x10^3 m)
Stalite	350	450	0.35	1893	51.1	59.0	63.8	65.7	3.4
		400	0.45	1794	34.4	41.8	49.4	52.0	2.8
		350	0.55	1771	27.2	34.4	41.5	46.9	2.3
		300	0.65	1760	17.4	22.6	31.9	35.2	1.8
Lytag	350	450	0.35	1791	44.1	44.0	47.8	47.9	2.7
		400	0.45	1733	32.2	34.6	40.9	43.3	2.4
		350	0.55	1723	26.1	31.0	36.2	39.3	2.1
		300	0.65	1712	19.0	24.4	30.6	32.3	1.9
Leca	350	450	0.35	1697	39.7	42.0	43.3	43.3	2.6
		400	0.45	1656	30.3	33.9	37.8	39.7	2.3
		350	0.55	1627	23.5	28.6	33.8	36.2	2.1
		300	0.65	1607	17.0	22.0	28.4	30.4	1.8
Argex	350	450	0.35	1602	27.4	28.0	28.5	28.5	1.8
		400	0.45	1523	21.7	24.0	26.1	29.4	1.7
		350	0.55	1518	17.0	20.1	23.6	23.7	1.6
		300	0.65	1491	12.8	15.7	19.8	20.5	1.3
NA	350	450	0.35	2299	-	70.7	76.3	-	3.3
		400	0.45	2220	-	49.5	57.7	-	2.6
		350	0.55	2199	-	39.8	47.8	-	2.2
		300	0.65	2137	-	19.4	37.0	-	1.8
Mortar	350	450	0.35	2121	55.7	58.9	65.7	72.3	3.2
		400	0.45	2039	36.7	42.3	52.0	57.4	2.6
		350	0.55	1997	27.6	33.4	42.9	46.1	2.1
		300	0.65	-	19.6	24.3	32.7	35.1	-

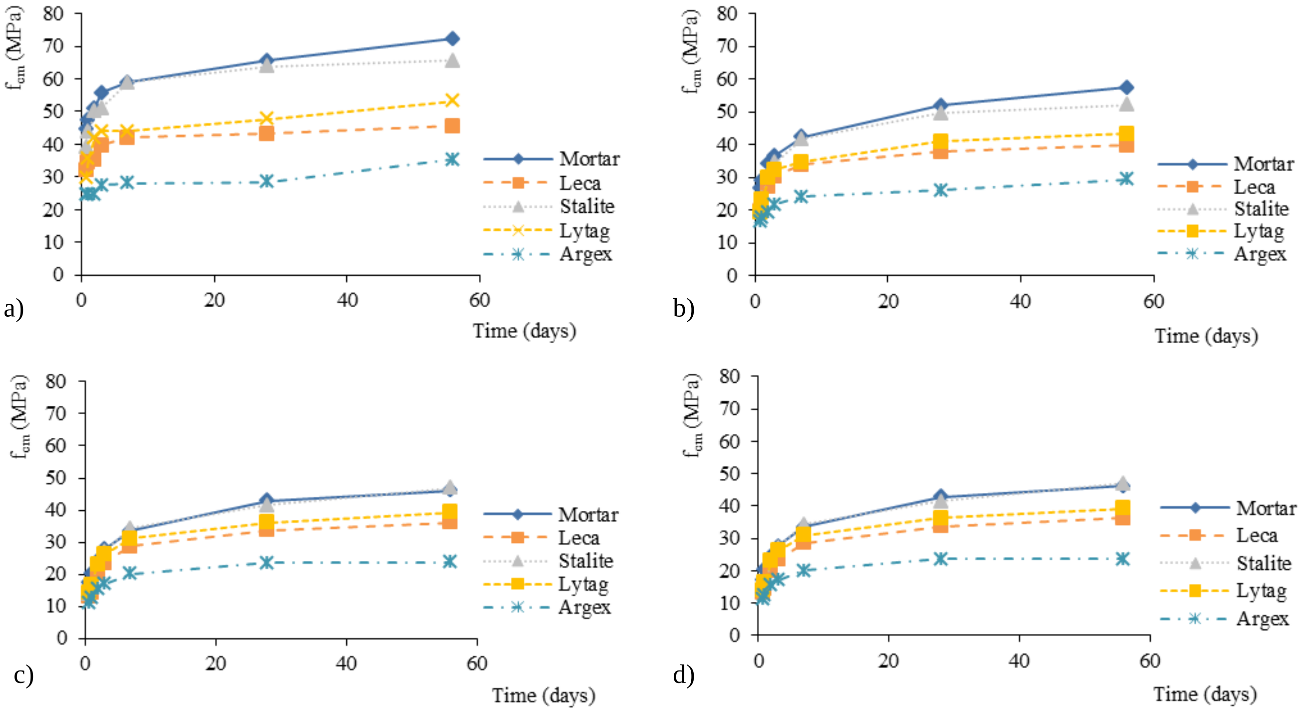

Figure 1. Strength evolution of SLWAC and mortar: w/c = 0.35 (a); w/c = 0.45 (b); w/c = 0.55 (c); w/c = 0.65 (d)

B. *Ceiling strength, f_{cs}*

Table 3 presents the estimated range for the ceiling strength, f_{cs}, of SLWAC produced with each type of LWA. This was estimated from f_{cm} results of SLWAC with w/c of 0.35. Although Figure 1 indicate that SLWAC with Leca, Lytag and Argex may have reached their ceiling strength, in SLWAC with Stalite the ceiling strength has not been identified, indicating that higher compressive strengths may be obtained. Based on this study, it is thus possible to define the range of strength and density classes of SLWAC, for each type of LWA (Table 3). These ranges were defined in order to avoid uneconomical concretes with low structural efficiency. Concerning only the expanded aggregates, it is possible to distinguish three main classes of LWA; $\rho < 1000$ kg/m^3, $\rho < 1400$ kg/m^3 and $\rho > 1400$ kg/m^3, which are related to low-strength, moderate-strength and high-strength concrete, respectively.

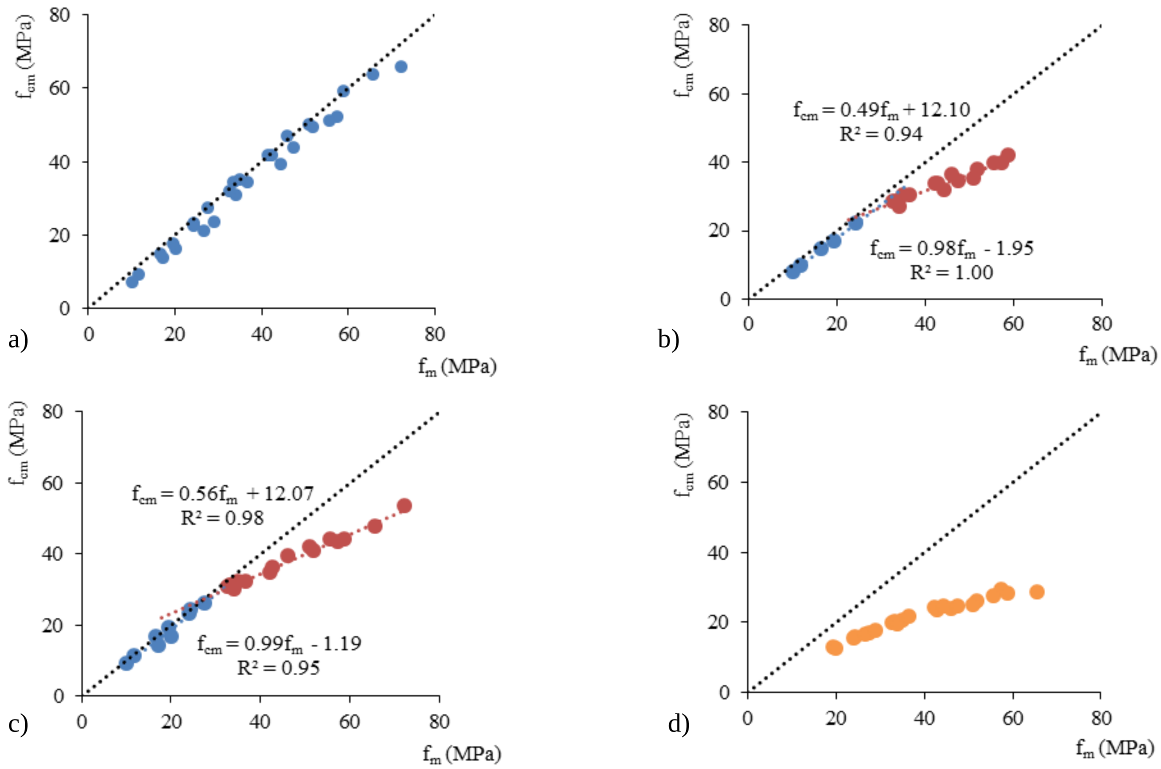

Figure 2. Relation between the strength of the mortar and that of SLWAC: Stalite (a); Leca (b); Lytag (c); Argex (d)

C. *Validation of a biphasic model to estimate the SLWAC strength*

The expression (2), based on expresion (1) of the biphasic model, can be used to estimate the strength of SLWAC. Note that this expression is only valid above f_L.

$$f_{cm} = 10^{(v_{LWA} \cdot \log(f_{LWA}) + v_m \log(f_m))} \tag{2}$$

The expression (2) requires prior knowledge of the strength of a mortar, f_m, of identical composition as that of concrete (Table 2), and the strength of the aggregate in the concrete, f_{LWA}. Based on expression (1), f_{LWA} can be easily estimated from expression (3). The estimated values of f_{LWA} for each type of LWA are indicated in Table 3. As expected, the values of f_{LWA} are of the same order of magnitude of f_L, although they have different meanings; f_L corresponds to the concrete strength for which the modulus of elasticity of the mortar is similar to that of the aggregate, while f_{LWA} corresponds to the strength of the LWA in concrete.

$$f_{LWA} = 10^{\left(\frac{\log(f_{cm}) - v_m \log(f_m)}{1 - v_m}\right)} \tag{3}$$

In general, a high correlation was found between the experimental, $f_{cm,experimental}$, and design values of the compressive strength of SLWAC determined by expression (2), $f_{cm,design}$ (Figure 3). The $f_{cm,design}$ values of SLWACs with Stalite could not be assessed, because, as mentioned, expression (2) is not valid above f_L. This confirms the good accuracy of the biphasic model for the estimate of the compressive strength of SLWAC, regardless the type of aggregate, cement content and w/c ratio.

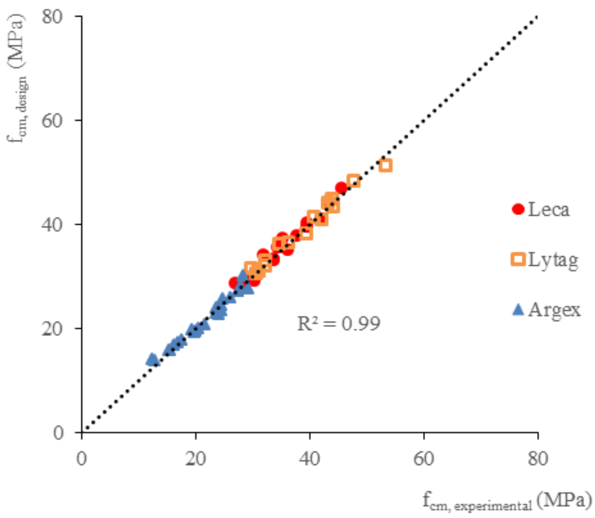

Figure 3. Experimental versus design compressive strength of SLWAC

TABLE III. LIMIT STRENGTH, F_L, CEILING STRENGTH, F_{CS}, STRENGTH OF THE AGGREGATE IN CONCRETE, F_{LWA}, AND STRENGTH AND DENSITY CLASSES

Type of LWA	f_L (MPa)	f_{cs} (MPa)	f_{LWA} (MPa)	Strength class	Density class
Stalite	59–62	65–70	60.3	LC40/44-LC55/60 LC25/28-LC40/44	D2.0 D1.8
Lytag	29.2	50–55	27.4	LC25/28-LC40/44 LC20/22-LC25/28	D1.8 D1.6
Leca	26.7	45–50	21	LC25/28-LC35/38 LC20/22-LC25/28	D1.8 D1.6
Argex	< 10	30–35	7.2	LC12/13-LC20/22	D1.6

D. Dry density of LWA versus f_{LWA}

Figure 4 presents the relationship between the dry density and strength of LWA, taking into account the results of this study and those reported by other authors [4,14]. Only when the artificial expanded aggregates with dense outer shells (DOS) and the aggregates without dense outer shells are considered in separate, high correlations are found between the two mentioned properties. This confirms that the strength of the aggregate in concrete is not only affected by its density or total porosity.

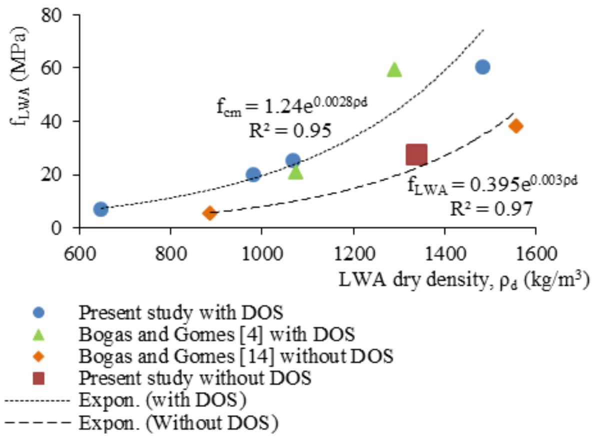

Figure 4. Dry density of LWA versus f_{LWA}, for LWA: with dense outer shell (DOS) - different types of artificial expanded LWA; without DOS - sintered fly ash (Lytag), pumice and slag aggregates

From Figure 4, expressions (4) and (5) are suggested to estimate f_{LWA}, for LWA with and without dense outer shell. Based on the estimated value of f_{LWA} and from expression (2), it is thus possible to estimate the compressive strength of the SLWAC commonly used for structural applications, regardless the type of coarse lightweight aggregate.

$$f_{LWA} = 1.24e^{0.0028\rho_d}\ [MPa] \quad (4)$$
(aggregates with dense outer shell)

$$f_{LWA} = 0.395e^{0.003\rho_d}\ [MPa] \quad (5)$$
(aggregates without dense outer shell)

IV. Conclusions

In this study, it was possible to characterise the compressive behaviour of the most common structural lightweight concrete, covering strength classes from LC12/13 to LC55/60 and density classes from D1.6 to D2.0. The following main conclusions have been drawn

- Different ranges of strength and density classes were defined for each type of LWA, based on the concepts of limit strength, f_L, ceiling strength, f_{cs}, and strength of the aggregate in concrete, f_{LWA}. It was shown that the mechanical behavior depends on the type of LWA and the strength of the surrounding mortar. It is thus not correct to specify the SLWAC strength according to its relative strength to NWC;
- Denser LWA ($\rho > 1400$ kg/m^3) have proven suitable for high-strength concrete, LWA of intermediate density (1000 kg/m^3 < ρ < 1400 kg/m^3) for moderate-strength concrete and more porous LWA ($\rho < 1000$ kg/m^3) for low-strength concrete;
- The biphasic model was adequate for estimating the compressive strength of SLWAC, within its validity domain ($f_{cm} > f_L$). High correlations between the design and experimental values were obtained;
- It is shown that the strength of the aggregate in concrete, f_{LWA}, is not only affected by the density of LWA. New relations are suggested to estimate f_{LWA}, for aggregates with and without dense outer shells.

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