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Adopting an image analysis method to study the influence of segregation on the compressive strength of lightweight aggregate concretes

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ABSTRACT

Aggregate segregation in concretes, especially in lightweight aggregate concretes (LWAC), is a pathology that can seriously impact on different material properties, both in terms of mechanical strength and durability. Some studies have already analysed the impact of this phenomenon in the compressive strength of LWAC , almost always adopting segregation quantification methods based on the comparison of variables such as weight or density measured in sections extracted from cylindrical samples. Although the methods used so far are simple and easy to apply, in certain circumstances they may not offer sufficient accuracy to measure the phenomenon. Moreover, the analysis of segregation in LWAC, which due to the lower density of aggregates in relation to the mortar matrix occurs in the opposite direction to the segregation of conventional concretes (from bottom to top), has not been widely studied so far. The analysis of the cross sections of cylindrical concrete samples through image analysis techniques has been increasingly used to estimate parameters related to the distribution of materials inside them. This study aims to measure the impact of segregation on the compressive strength of LWAC cylindrical specimens, employing an image analysis technique capable of quantifying the phenomenon with a more accurate segregation index. During the experimental campaign 22 scenarios were defined, combining different types of aggregate, vibration methods and vibration times, to achieve different levels of segregation. Among the main results it can be noted that the impact of the type of moulding (one layer vs. two layers) considerably affected the mechanical properties of concrete, with concretes vibrated in two layers showing a maximum reduction in compressive strength due to segregation of 9%, while concretes vibrated in only one layer showed reductions ranging from 63% to 118%. Analyzing the type of rupture of the samples, the study identifies the appearance of well-defined compression cones in samples where segregation is excessive, with 90% of the cases presenting this type of rupture and that the size of the compression cone increases as the effect of segregation is accentuated.

1. Introduction

Because of its advantageous properties, including low density, good thermal insulation and fire resistance, lightweight aggregate concrete (LWAC) has been extensively studied as both structural and non-structural construction material [1]. Sometimes lightweight aggregate concrete may be the most suitable solution for certain types of civil engineering constructions, as thanks to their reduced density (usually from 1500 to 2000 kg/cm^3 [2]), they may present better properties than conventional concrete and may be interesting in applications like long span bridges, high rise buildings, and special structures such as floating and offshore platforms [3]. Besides that, the reduction of concrete density provides a number of other benefits, such as high sound absorption [4] and improved hydration due to internal curing [5]. However, LWAC also presents the tendency to segregate either during compaction [6–8] or resulting from the longer mixing times [9].

Although good compaction of LWAC is crucial to eliminate the trapped air in the mixture and to ensure that the material will fill all the voids in the formworks, the compaction is also one of the biggest problems in fresh LWAC because the excessive time of vibration can easily produce the phenomenon of segregation. The ability of fresh concrete to remain homogeneous during consolidation is a critical issue in the design of the mixture [10]. Different studies show that LWACs are susceptible to present segregation of aggregates and different factors

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such as the difference in densities between the materials of the mixture [11,12], the type of compaction [7,13] or the consistency of the concrete [12] can affect more or less the phenomenon. Unlike conventional concrete, the aggregates used in LWAC usually have a density lower than the density of the mortar matrix where they are immersed in fresh state. This difference in densities between both materials associated with the regular shape that have many lightweight aggregates (especially expanded clay aggregates) facilitates their vertical upward movement within the structural elements during compaction [7,14,15].

Since, for design purposes, the distribution of materials in structural parts and samples is considered homogeneous, the segregation caused by the vertical movement of aggregates can lead to the formation of a multiphase material and has a dramatic negative impact on mechanical [16], transport [17] and microscopic properties [18,19] of hardened concrete. The segregation phenomenon induces anisotropy in the casting direction, causing variations in the w/c ratio and in the porosity between upper and lower parts of the concrete [20]. Moreover, the results of other works found that segregation weakens the interface between the cement paste and aggregate influencing the permeability, durability and resistance [21] of concrete. The separation of the aggregates from the rest of the mixture increases the risk of shrinkage and cracking [17,22] and the areas where segregation occurs are mainly the areas where the concrete failure begins [23].

Although several studies have been conducted analysing the impact of segregation in conventional concretes, very few studies have been conducted focusing on the study of the influence of segregation on the mechanical properties of LWAC. Tenza-Abril et al [24] has been analysing the influence of segregation on the mechanical properties of LWAC using ultrasonic wave measurements and statistical analysis. Artificial Neural Networks were also used to predict the compressive strength variation in segregated LWAC [25]. Solak et al [8] studied the impact of segregation on the mechanical properties of LWAC by performing compression tests on cylindrical cores, extracted from different heights of segregated samples.

Considering that segregation can impact drastically by destabilizing the volumetric fraction of aggregates in certain regions of structural elements and that the variation of the volumetric fraction of LWA is a factor that can affect the mechanical properties of LWAC [26], more studies analysing this impact need to be carried out. While most studies related to LWAC focus on analysing their dosages, materials and their impacts on their thermal, mechanical and durability properties, few studies focus on studying the impact caused by segregation on the mechanical properties of these concrete.

The aim of this study is to analyse the influence of segregation caused by excessive vibration on the compression strength of LWAC. Complementing previous studies, this document focuses on the execution of normalized compression strength tests, considering cylindrical samples of standard size. As a segregation indicator this study adopts the Solak Index [27], a quantification methodology through image analysis used to measure the phenomenon in LWAC in other studies [8].

2. Mixture design and material preparation

Considering the results of previous studies [8], some parameters related to concrete dosage that affect accentuating segregation were adopted, so that the phenomenon can be analysed also in cases of extreme segregation. To obtain different degrees of segregation, four mix proportions were considered, which also were vibrated considering five different vibration times and two compaction modes (in one and two layers).

White cement CEM I 52.5 R with an absolute density of 3176 kg/m^3 was used for all concretes. White cement was used, with the aim of analysing whether the image analysis method for quantifying segregation developed by Solak et al.[27] would be compatible with this type of material. The study adopted a water/cement ratio (w/c) of 0.6, resulting in 350 kg/m^3 of cement 210 kg/m^3 of water to produce 1 m^3 of concrete. This value is possibly a little high when compared to conventional concrete, however one of the objectives of this study was to cause excessive segregation and certainly a high water/cement ratio could greatly affect the phenomenon. In a real situation, a simple error in the dosage of concrete on site could easily increase the water/cement ratio and this study seeks to demonstrate one of the consequences that an error like this could cause in the compressive strength of the material.

The dosages were obtained using the method proposed by Fanjul [28], considering design densities of 1700 kg/m^3 and 1900 kg/m^3. Fanjul's method [28] was used because it is one of the few dosing methods that allows a “design density” to be established as an input parameter. Through this method, we could establish among the objectives the production of concrete with known densities, and the “design density” could, from the beginning, be considered as a variable to be studied.

Two types of Lightweight Expanded Clay Aggregates (LECA), whose commercial names are Arlita Leca M and Arlita Leca HS were used. Table 1 shows the dosages to produce 1 m^3 of concrete.

The bulk density of the LWAs was obtained according to the procedure described in the standard UNE EN 1097-3 [29]. Particle size of the aggregates was determined according to the UNE EN 933-1 [30]. In addition, the particle density and water absorption were determined by the methodology proposed by Fernández-Fanjul et al. in [31]. According to this method, the determination of the particle density was obtained using glycerine to avoid the surface absorption in the aggregates. According this method, the value of the water absorption obtained in the aggregates was more accurate than the values usually obtained according the UNE EN 1097-6 standard [32]. Natural fine limestone aggregate was used as fine aggregate. The physical characteristics of these aggregates are described in Table 2.

Considering that previous studies [8] indicate that the way the samples are vibrated can significantly affect the segregation of concrete, it was decided to analyse this factor, and the samples were vibrated with needle vibrators, in one and two layers. In total 20 different combinations were analysed (Table 3).

3. Methodology

Cylindrical LWAC samples of 150 mm in diameter and 300 mm in height were manufactured considering different dosages (LWAC1, LWAC 2, LWAC 3 and LWAC 4), manufacturing modes (one and two vibration layers) and different vibration times (0, 10, 20, 40 and 80 s per layer). The specimens were compacted using an electric needle vibrator with a frequency of 18000 rpm/min and a needle diameter 25 mm. Although the use of a vibrating table or other external compaction method could lead to segregation results that are easier to analyse, this study attempted to simulate the reality in many laboratories and chose a method to analyse segregation [27] that has been successfully applied to samples vibrated with a needle vibrator before. As was the initial objective, the combination of these three manufacturing parameters (dosages, type o casting and time of vibration) caused different degrees of segregation in the concrete series analysed.

For each combination six samples were produced. Considering that the tendency to aggregate fluctuation was high, resulting in a quick separation between aggregate and mortar in some circumstances even in

Table 1
Manufacturing characteristics and mix proportions to produce 1 m^3 of concrete.

Concrete identification	Type of LWA	Amount of fine aggregate in a cubic meter (kg/m^3)	Amount of LWA in a cubic meter (kg/m^3)
LWAC1	HS	723.9	416.2
LWAC2	HS	1046.0	294.0
LWAC3	M	991.1	148.9
LWAC4	M	1234.8	105.2

Table 2
Physical characteristics of the aggregates used in this study.

Property	Method	Arlita Leca M	Arlita Leca HS	Fine Aggregate
Apparent particle density (kg/ m^3)	According to [31]	482	1019	2688
Bulk density (kg/ m^3)	UNE EN 1097–3 [29]	269	610	1610
Water absorption (%)	According to [31]	36.6	12.2	0.12
Particle size (di/ Di)	UNE EN 933–1 [30]	6/10	4/10	0/4
Crushing strength (MPa)	According to the manufacturer	1.0	5.0	–

Table 3
20 different scenarios combining the variables analyzed in this study. For each combination 6 samples were frabricated.

Comb.	Concrete	Type of Vibration	Total Time of Vibration	LWA	Design Density (kg/ m^3)
1	LWAC1	2 layers	0 s	HS	1700
2	LWAC1	2 layers	20 s	HS	1700
3	LWAC1	2 layers	40 s	HS	1700
4	LWAC1	2 layers	80 s	HS	1700
5	LWAC1	2 layers	160 s	HS	1700
6	LWAC2	2 layers	0 s	HS	1900
7	LWAC2	2 layers	20 s	HS	1900
8	LWAC2	2 layers	40 s	HS	1900
9	LWAC2	2 layers	80 s	HS	1900
10	LWAC2	2 layers	160 s	HS	1900
11	LWAC3	1 layer	0 s	M	1700
12	LWAC3	1 layer	10 s	M	1700
13	LWAC3	1 layer	20 s	M	1700
14	LWAC3	1 layer	40 s	M	1700
15	LWAC3	1 layer	80 s	M	1700
16	LWAC4	1 layer	0 s	M	1900
17	LWAC4	1 layer	10 s	M	1900
18	LWAC4	1 layer	20 s	M	1900
19	LWAC4	1 layer	40 s	M	1900
20	LWAC4	1 layer	80 s	M	1900

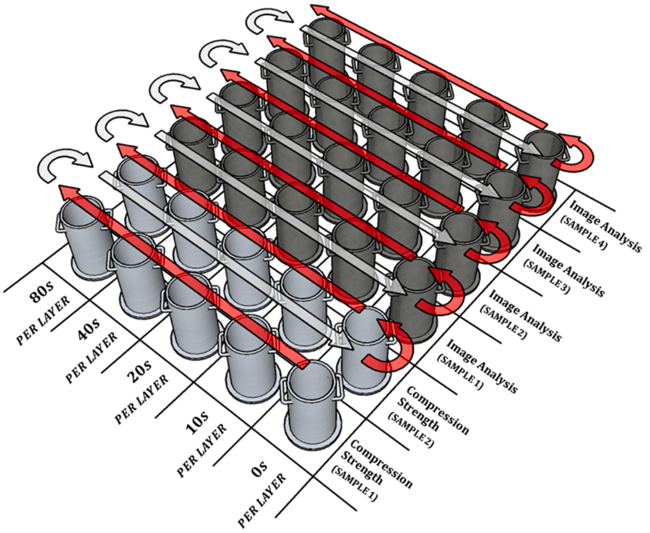

Fig. 1. Order in which the colindrical moulds were filled before the samples were vibrated. For each concrete, two series containing five samples each were prepared for compression strength tests and four series containing five samples to determine the segregation index by image analysis.

static state, it was decided to register the order of filling of the metallic moulds for eventual consult and justification. The metallic moulds were filled following the order shown in Fig. 1. Then all the moulds were vibrated following a transversal order to the one represented in Fig. 1, so that first all the samples of 10 s per layer were vibrated, then the samples of 20 s per layer and so on. This procedure was repeated four times (LWAC1, LWAC2, LWAC3 and LWAC4). Fig. 2 represents the methodology of this study.

After 28 days submerged in water at room temperature these samples were separated into two groups. Two samples of each combination had their upper and lower surfaces polished and then submitted to compression tests which were performed in accordance with the UNE EN 12390–3 standard. [33], a 3000-kN compression testing machine with the loading rate of 0.25 MPa/s was used. The average between the two results (fc_{avg}) was taken into consideration for the calculations (Fig. 3b).

The remaining samples of each combination (four in total) were vertically cut into two halves (Fig. 3a). These halves were cleaned, dried in for 72 h at 50°C and photographed to obtain their segregation indexes by image analysis following the methodology proposed by Solak et al [27]. Following the recommendations of Solak et al [27], before photographing them the surfaces were slightly moistened in order to enhance the aggregates and facilitate further analysis.

The image analysis method proposed by Solak et al [27] analyses the segregation of the aggregates of a sample based on their distribution, considering the volumetric proportion between aggregates and mortar, as well as the position of each of these phases within the sample. After some image treatments that include perspective correction and binarization of the photographs, the mortar portion is represented by white pixels and the aggregates are represented by black pixels. From this classification a binary “matrix of blacks and whites“ is generated, where the aggregate pixels (black) receive the numerical value of 1 and the mortar pixels (white) receive the numerical value of 0. The ”black and white matrix“ is then analysed and the aggregate volumetric fraction is calculated (GAI) (Fig. 4a). The matrix generated for each sample is then subdivided into 701 horizontal sections and for each of them the local aggregate volumetric fraction (LAI) is calculated (Fig. 4b). From the local volumetric fractions, the local absolute difference coefficients (LAD) for each row are calculated according to the Equation (1).

$$LAD_i = |LAI_i - GAI| \tag{1}$$

The average of LADs results in the Local Distribution Coefficient (LDC). As a result, and final indicator, Solak’s segregation index is calculated according to Equation (2).

$$SI(\%) = \frac{LDC}{2 \times GAI \times (1 - GAI)} \tag{2}$$

Each sample resulted in two halves that were photographed for the SI calculation. The average between the two values was adopted as the segregation indicator. The range of values of the SI varies from 0% (totally homogenous specimen) to 100% (totally segregated concrete where the aggregates are concentrated in the top of the specimen).

4. Results and discussion

Twenty combinations were analysed considering different types of LWAC, different vibration modes and different vibration times. For each combination ten results were obtained, eight of them coming from the image analysis performed on the cross sections of four samples and another two coming from the compression strength tests performed on two samples.

4.1. Image analysis results (Segregation Index)

In order to analyse the influence of segregation on the compressive strength of LWAC, it was first necessary to make sure that different

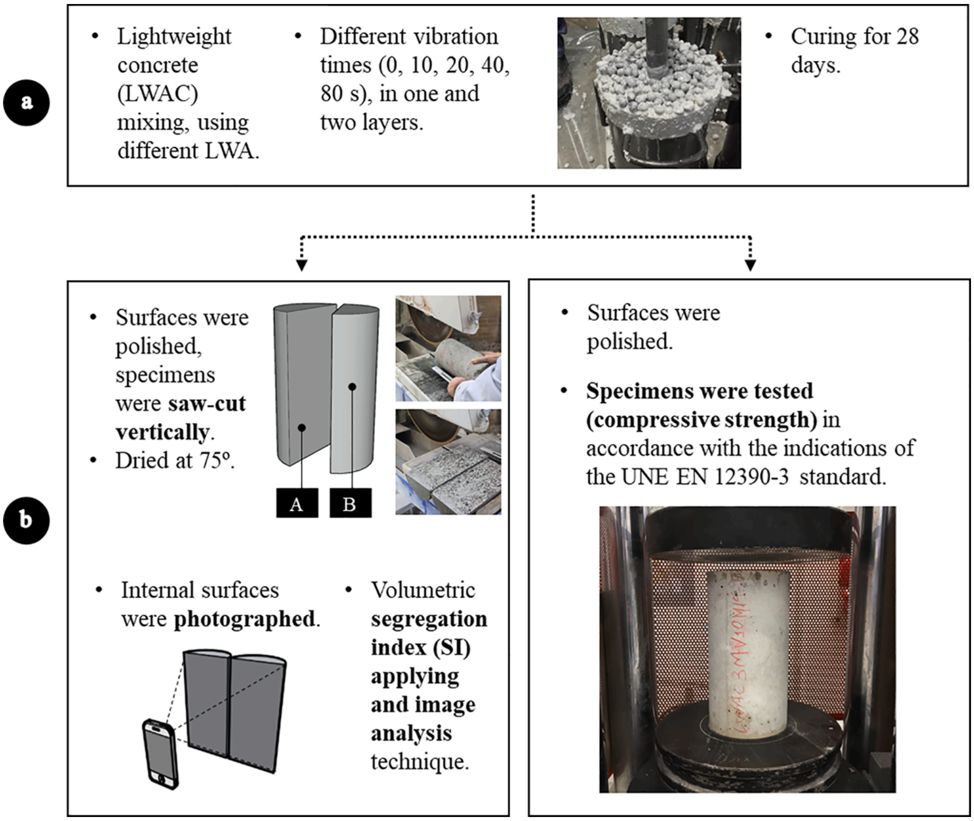

Fig. 2. Methodology adopted in this study. (a) Manufacture of the samples considering different scenarios. (b) Tests for segregation and compression strength analysis.

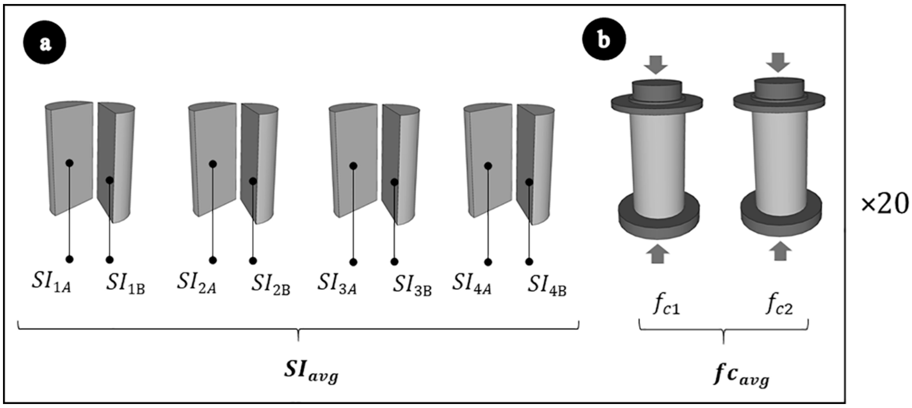

Fig. 3. For each combination, ten results were obtained. Eight of them were results referring to segregation (a), used to obtain the SI_{avg} and two of them, referring to compressive strength (b), used to calculate the fc_{avg}.

degrees of segregation were caused in the samples, only then to be able to study the effect of this phenomenon on the reduction of resistance.

The graphs in Fig. 5 contain the data of the eight values found for SI for each combination, arranged in ascending order of total vibration time and separated by type of LWAC. As we can expect and coinciding with the results of Solak et al [8] the segregation increases as the total vibration time increases. From the total of 160 values analysed, the results varied from 12.09% (most homogeneous sample) to 48.69% (sample with the highest segregation).

Comparing the results of LWAC1 and LWAC2 with the results of LWAC3 and LWAC4, a general increase in SI values can be observed, indicating that the concrete vibrated in two layers (LWAC1 and LWAC2) suffered less impact from the segregation phenomenon.

4.1.1. Variations in LWAC3 and LWAC4 due to manufacturing order

The results of LWAC3 and LWAC4 image analysis showed that the volumetric fraction of aggregates of the samples of series 3 and 4 were lower than the volumetric fractions of the samples of the series 1 and 2, for all vibration times. This parameter, from the theoretical point of view was constant, and therefore, from the experimental point of view, should present low variations. This variation is probably explained by the intense floatability phenomenon observed in aggregates of type Arlita Leca M during the manufacture of concrete. By adopting the order of concreting presented in Fig. 1, the moulds of the last rows (Image Analysis Sample 3 and Sample 4) were probably filled with concrete with a lower proportion of LWA, since the floatability of the aggregates in the container where the concrete was stored (Fig. 6a) induced a larger collection of aggregates to fill the first rows, resulting in fewer

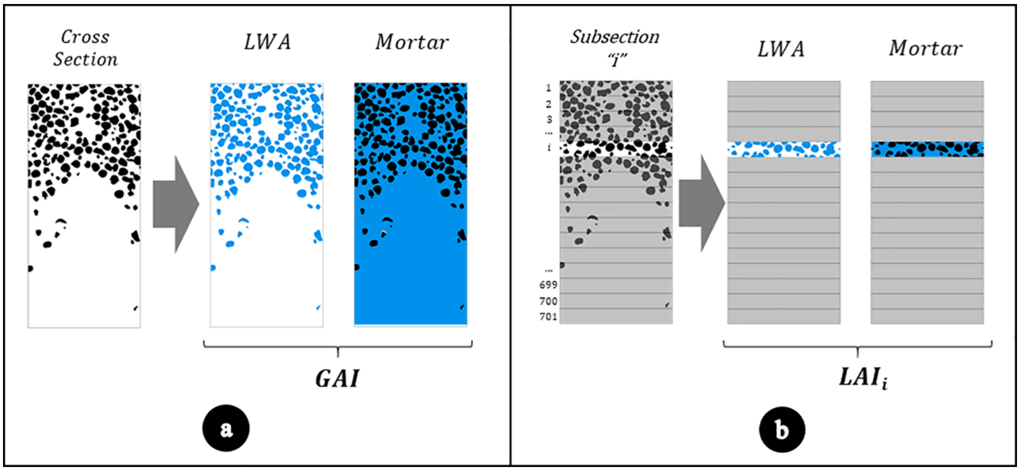

Fig. 4. (a) From the aggregate volume fraction found in the cross section of a sample we calculate the GAI. (b) The data matrix of a sample is then divided into 701 rows and for each row its respective aggregate volume fraction (LAIi) is calculated.

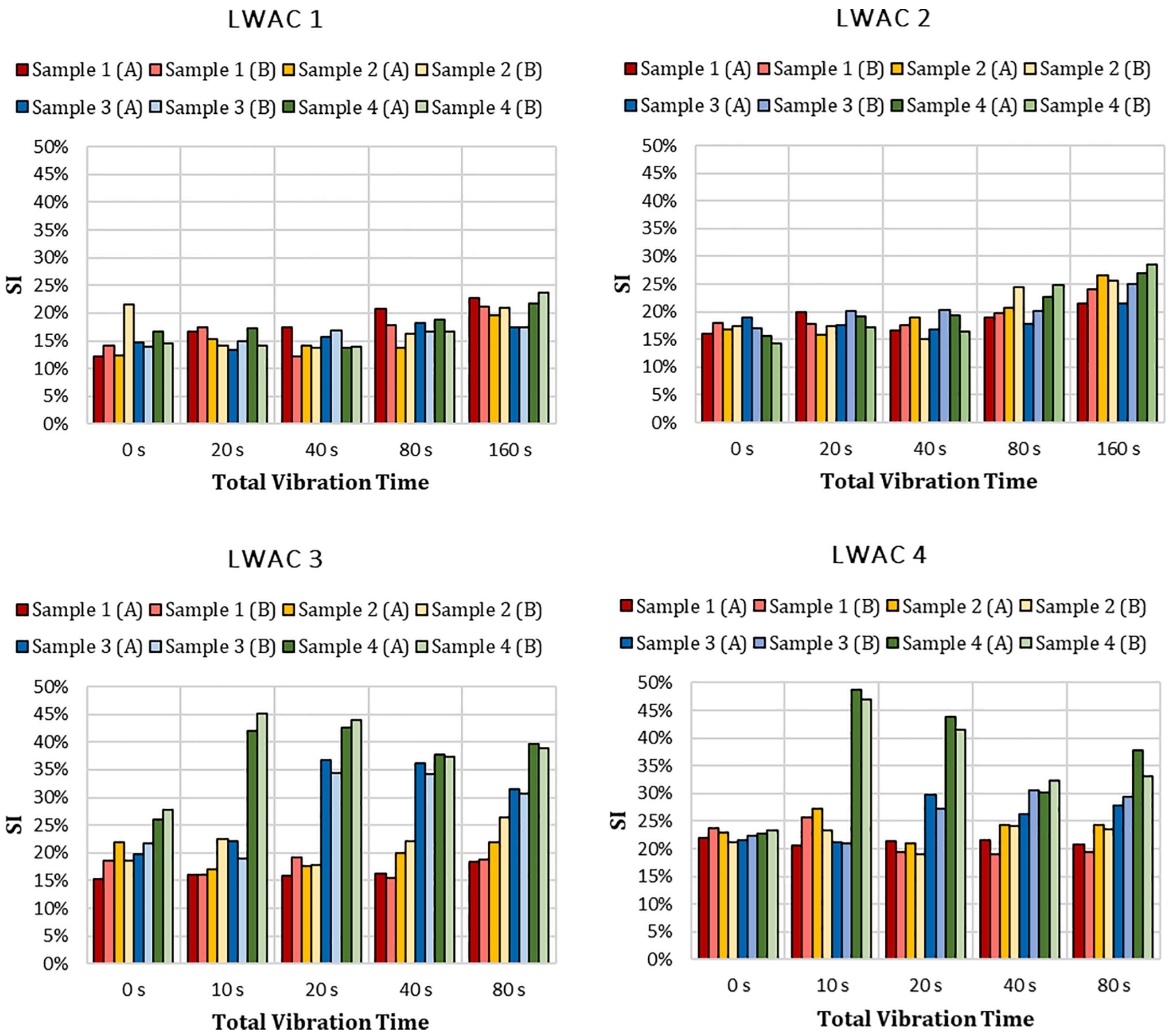

Fig. 5. Segregation index results for all sample halves, represented in ascending order according to total vibration time and separated by concrete type.

Fig. 6. a) Excessive fluctuation of lightweight aggregates in the mixer. It is observed that the aggregates on the surface are enveloped only by a thin layer of cement paste. b) Loss of lightweight aggregates during vibration (high vibration times).

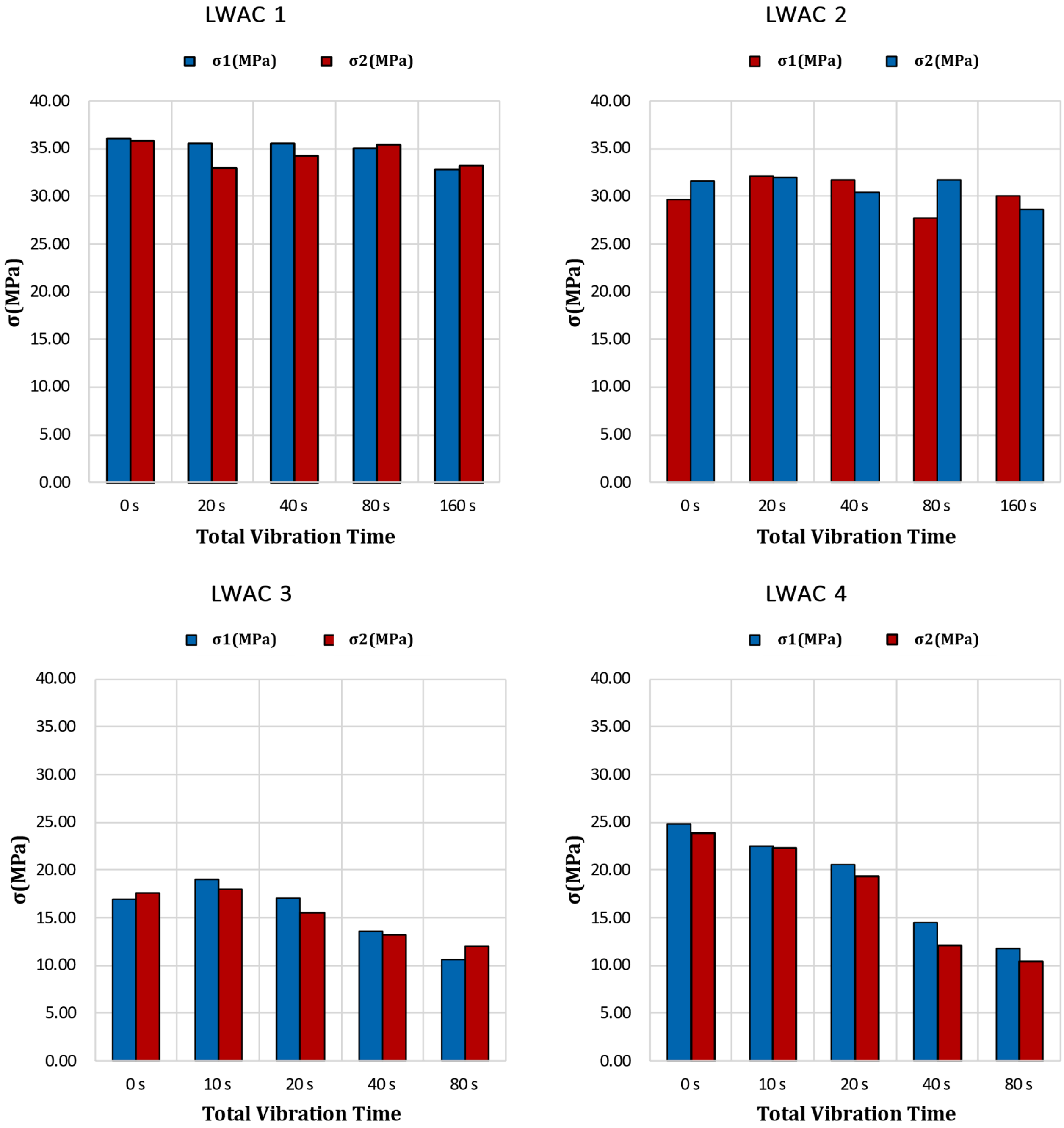

Fig. 7. Variation of the compression strength test results for each vibration time.

aggregates to fill the moulds of the last rows. These results reaffirm that, in certain cases, segregation can happen even without the use of vibrators.

Another phenomenon that possibly explains the variation in the volumetric fraction of aggregates is the excessive loss of aggregates that reached the mould surface during high vibration times, and were then expelled out of the moulds. This can be observed in Fig. 6b.

Considering that the volumetric fraction of aggregates in some samples was lower, by applying the same compaction energy, the segregation in these samples increased. This explains the higher values in graphs c and d of Fig. 5, represented in tones of green and blue.

4.2. Results of compression strength

In normal weight concrete, the aggregate strength is not a factor affecting concrete strength because the aggregate is much stronger than the matrix and the transition zone [34]. However, in LWAC, the constituent LWA may have a lower strength and elastic modulus than the mortar matrix, and thus the properties of the LWA are the most important determinants of the properties of the resulting concrete [35] and usually the failure of concrete then is controlled by aggregate fracture [36].

The results of this study indicate that concretes vibrated in one layer (LWAC1 and LWAC2) showed greater homogeneity in the distribution of the aggregates inside each sample and less variation in the compressive strengths when compared with concrete vibrated in two layers (LWAC3 and LWAC4). As shown in Fig. 7, in LWAC1 the highest resistance obtained was 35.9 MPa and the lowest resistance obtained was 33.0 MPa, resulting in a maximum loss of resistance due to the segregation of 9%. In LWAC2 the highest resistance obtained was 32.1 MPa and the lowest resistance obtained was 29.4 MPa, resulting in a maximum loss of resistance due to segregation also of 9%.

Analysing the results of the two-layer vibrated concrete (LWAC3 and LWAC4), we notice a significant decrease in the compression resistance of the samples with the increase of vibration times. It is likely that this decrease is related to the increase in segregation observed in these concretes and to the repositioning of aggregates in the upper zone of the cylindrical samples, generating areas with excess aggregates and lack of mortar. In LWAC3 the highest resistance obtained was 18.5 MPa and the lowest resistance obtained was 11.3 MPa, resulting in a maximum loss of resistance due to segregation of 63%. The most critical situation occurs in LWAC4 where the highest resistance obtained was 24.3 MPa and the lowest resistance obtained was 11.1 MPa, resulting in a maximum loss of resistance due to segregation of 118%.

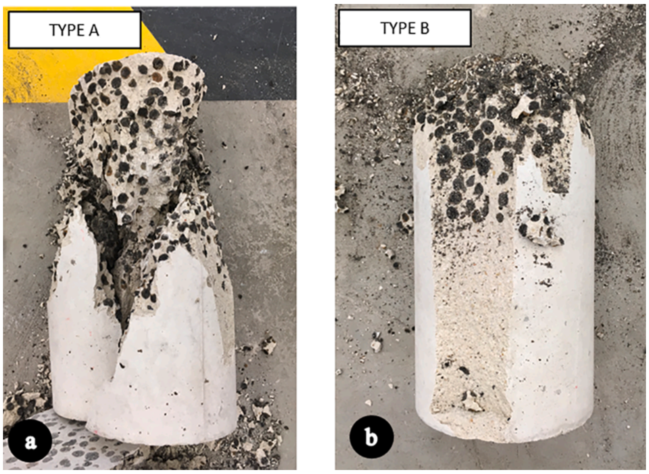

Fig. 8. Type of rupture of the specimens in this study during compressive strength tests. (a) Conical shape rupture (90% of the samples). (b) Rupture by crushing of the upper region (10% of the samples).

4.3. Position and type of rupture

The rupture of the cylindrical samples in the compressive strength tests happened in two ways which can be seen in Fig. 8 and are described below:

TYPE A: rupture of the samples was characterized by the formation of well-defined compression cones in the upper and middle regions of the cylinders. Most samples presented this behaviour (in 36 out of 40 samples). This type of rupture was found for all vibration times, both in samples vibrated in one and two layers. In the Table 4 they are tagged with a green coloured triangle. The Figs. 9, 10, 11 and 12 represent these cones, arranged head-on and ordered by type of concrete and in ascending order according to the vibration time applied to each sample.

TYPE B: rupture characterized by the crushing of the lightweight aggregates that have been displaced to the top of the sample, without the formation of compression triangles. Few samples showed this behaviour (in 4 out of 40 samples). This type of rupture was found only for high vibration times (40 and 80 s per layer), only in samples vibrated in a single layer. In the Table 4 they are tagged with a green coloured circle.

As can be seen on Figs. 9, 10, 11 and 12, the height of the compression cones (Ch) varies from sample to sample, with samples with less segregation having larger cones (rupture in the central part of the sample) and samples with more segregation having smaller cones (rupture closer to the top of the sample). The analysis of the shape of the ruptures makes clear that the concentration of aggregates at the top of the sample caused by segregation divides the sample into two regions where practically two new materials are placed side by side: on the one hand a denser region, formed by the mortar matrix, and on the other less dense, where the LWA are concentrated. The rupture, in general, happens at the close encounter of these two regions.

The size variation of the compression cones due to the segregation is more accentuated in the concrete vibrated in one layer (LWAC3 and LWAC4). In LWAC1 (two layers) the highest Ch obtained was 22.7 cm and the lowest Ch obtained was 8.7 cm, resulting in a maximum variation of Ch due to the segregation of 145%. In LWAC2 (two layers) the highest Ch obtained was 27.1 cm and the lowest Ch obtained was 9.9 cm, resulting in a maximum variation of Ch due to segregation also of 152In LWAC3 (two layers) the highest Ch obtained was 26.3 cm and the lowest Ch obtained was 6.9 cm, resulting in a maximum variation of Ch due to segregation also of 251%.

In the case of LWAC4 not all combinations showed ruptures with the formation of compression cones (see Table 4). For comparative purposes, the size of the fragments resulting from the crushing of the upper region of the samples were taken as reference in the analysis of this concrete. In LWAC4 (one layer) the highest Ch obtained was 18.9 cm and the lowest Ch obtained was 2.7 cm, resulting in a maximum variation of Ch due to the segregation of 575%.

4.4. Influence of segregation on compressive strength

The analysis of the results clearly shows that the greater the segregation of the concrete, the greater the loss of resistance of the material. The graph in Fig. 1 represents the average of the compressive strength of the samples of the same combination (σ_{avg}) versus the segregation index obtained by image analysis for each combination (SI_{avg}), with a R^2 of 0.7204, between the increase in segregation and the reduction in the compressive strength of the samples.

The size of the compression cones, in general, is also proportional to the maximum resistance obtained in the samples. Analysing different samples with the same dosage, the larger the compression cone, the greater the resistance obtained in the compression resistance test.

4.4.1. One-layer vibration versus two-layer vibration

The results obtained for LWAC1 showed different behaviours even for samples with the same manufacturing characteristics. When analysing LWAC1-Sample I we notice a descending behaviour in the size of

Table 4
Qualitative analysis of the type of rupture of the samples in the compressive strength test. Samples marked with a green triangle refers to rupture type A and samples marked with a red circle refers to rupture type B.

Type of Vibration	Density (kg/m^3)	Sample	Vibration time (per layer)				
			0s	10s	20s	40s	80 s
2 layers	1700	I	 ▼	 ▼	 ▼	 ▼	 ▼
		II	 ▼	 ▼	 ▼	 ▼	 ▼
	1900	I	 ▼	 ▼	 ▼	 ▼	 ▼
		II	 ▼	 ▼	 ▼	 ▼	 ▼
1 layer	1700	I	 ▼	 ▼	 ▼	 ▼	 ▼
		II	 ▼	 ▼	 ▼	 ▼	 ▼
	1900	I	 ▼	 ▼	 ▼	 ●	 ●
		II	 ▼	 ▼	 ▼	 ●	 ●

the compression cones, while when analysing LWAC1-Sample II we notice a variable behaviour in their size. Most probably the better homogenization of the mixture (vibration in two layers) prevented the formation of compression cones in certain situations and contributed to avoid the decrease in compression strength. In the graph of Fig. 13, this is statistically reflected when we find an R^2 of 0.46 when looking for a correlation between Ch and σ. In the case of LWAC2, also vibrated in two layers, the variations in compression cone size are more evident and present a descending behaviour for both samples. However, when statistically analysing this result, the correlation found between Ch and σ

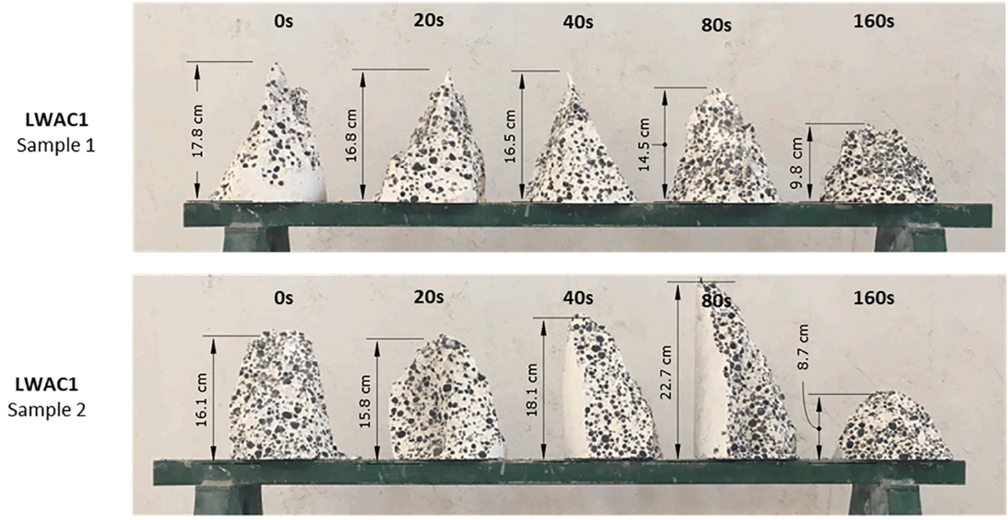

Fig. 9. Size of compression cones ordered by vibration time. Results of LWAC1, vibrated in two layers.

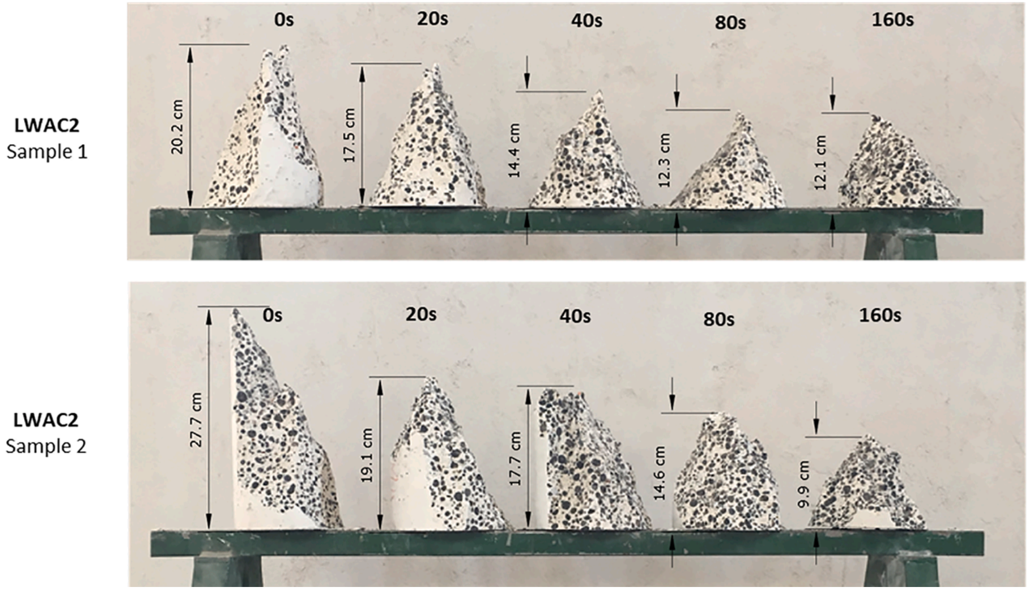

Fig. 10. Size of compression cones ordered by vibration time. Results of LWAC2, vibrated in two layers.

was 0.53.

The concrete vibrated in two layers (LWAC1 and LWAC2), even if submitted to double compaction energy, showed a better distribution of LWA inside the samples, so that the separation between LWA and mortar fractions is not always evident. When analysing the size of the compression cones, we verified that the variation in the sizes of the cones as a function of the vibration energy applied is more intense in the concrete vibrated in one layer (LWAC3 and LWAC4). In the graph of Fig. 14 we verify that the correlations found between Ch and σ are better, with LWAC3 presenting a value of R^2 of 0.76 and LWAC4 presenting a value of R^2 of 0.88.Fig. 15.

4.4.2. *Influence of LWA volume fraction on compressive strength results affected by segregation*

The volumetric fraction of LWA is certainly a design parameter that affects the compressive strength results obtained and, for concretes not susceptible to segregation, it can be a relatively easy parameter to consider when dosing the material. However, in concretes susceptible to segregation, whether caused by the characteristics of their materials or their manufacturing process, a combined effect between "volume fraction and segregation" can affect the strength of the material in a different way than normal.

Comparing two concretes that presented less variation in SI, (LWAC1 vs LWAC2), the only variable that differs between both materials is the design density and, consequently, the volumetric fraction of LWA present in the mixture. Although the compressive strength results of the lighter concrete (LWAC1) are slightly higher than the results of the heavier concrete (LWAC2), contrary to what is expected for this type of materials [37], in both cases the results are within the same order of magnitude (fc_{avg} between 29 and 35 MPa) and the maximum variation of fc_{avg} between the lowest and highest vibration times does not exceed 9%, indicating little influence of the combined effect between "segregation and volume fraction" on compressive strength.

On the other hand, when analysing the concretes that presented large variations in the SI (LWAC3 and LWAC4), and whose differences between them are also reduced only to the volumetric fraction (design density), it appears that the situation is reversed and, in this case, the heavier concrete presented much better results of compressive strength

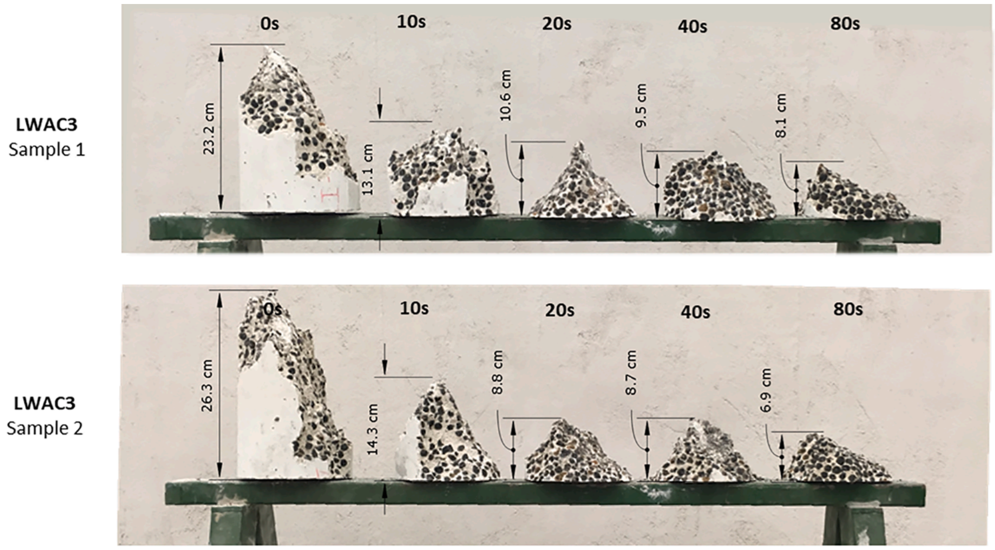

Fig. 11. Size of compression cones ordered by vibration time. Results of LWAC3, vibrated in one layer.

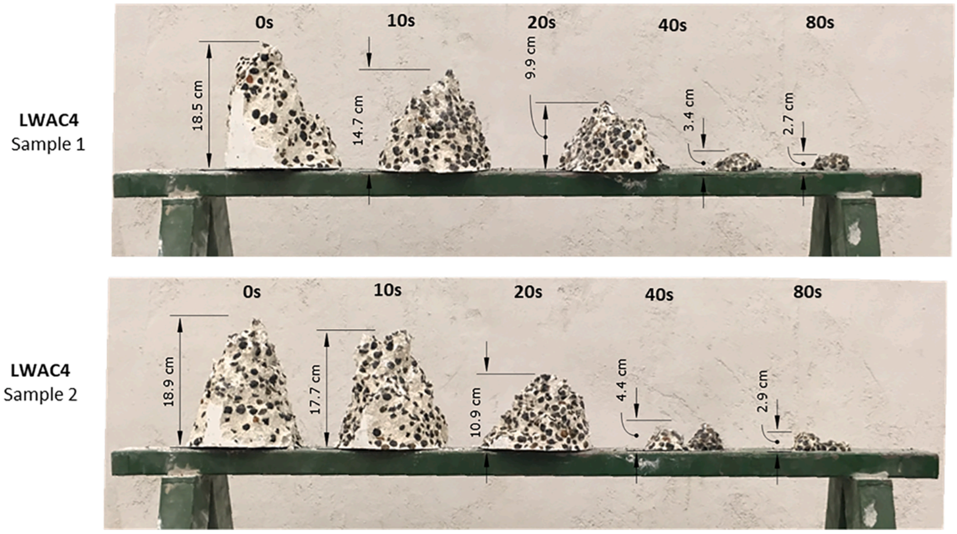

Fig. 12. Size of compression cones ordered by vibration time. Results of LWAC4, vibrated in one layer.

than the lighter concrete, especially for vibration times closer to those that are usually adopted in conventional laboratory procedures (10 and 20 s). These results could indicate that the mixtures with a higher percentage of aggregates had a greater impact on the results of compressive strength than the mixtures with a lower percentage of aggregates, for similar segregation indexes.

Analysing the cross-section images of LWAC3 and LWAC4 concretes, it was observed that, at high vibration times (40 and 60 s), the excessive segregation agglomerated the aggregates at the top of the samples generating excessively weak regions, practically composed of LWA and cement paste. For these vibration times it was observed that 100% of the aggregates were concentrated on the top of the samples, so that the rupture occurred mostly by crushing of these aggregates, without the formation of compression cones, since the aggregates did not present a good cohesion with the mortar matrix.

Considering that the lighter concrete (LWAC3) presented a higher volumetric proportion of LWA, its region of agglomerated aggregates on the top of the samples was larger (Fig. 16). However, this parameter did not necessarily contribute further to the reduction of compressive strength in these concretes, since the compressive strength results for high vibration times (40 and 80 s) are quite similar in both materials. For these vibration times the only variation found in the ruptures of the lighter concretes with respect to the heavier ones was in the position of the fractures, which happened closer to the top in the samples with lower aggregate concentration (LWAC4).

4.5. *Compression cone size as a possible indicator of segregation*

Considering that the type of rupture of the samples found in the study is quite homogeneous, presenting in 90% of the cases ruptures in conical format, which only varied in their size, during the results analysis it was hypothesized to seek a correction between the height of the compression cone and the segregation index to use the compression cone (Ch) as a possible indicator of the segregation phenomenon (SI).

By representing the data graphically, disregarding the samples without vibration (0 s), dividing the results by concrete type and adopting power trend lines, some results indicate a possible correlation between SI_{avg} and Ch_{avg}. In the graphs of Fig. 17 it can be noted the clear trend that "the higher the Segregation Index, the less the compression cone", for the three concretes that presented conical ruptures. The

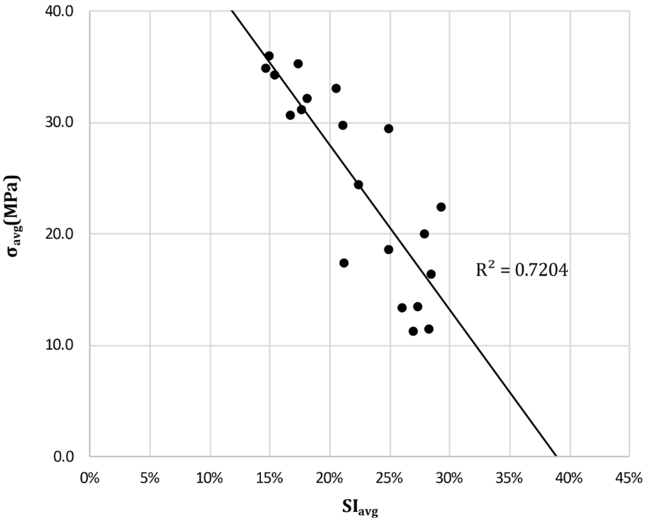

Fig. 13. Variation of the average compressive strength (σavg) as a function of the average segregation index (SIavg).

concrete LWAC4 was not included in the analysis since 50% of its specimens (between 10 and 80 s per layer) did not present conical shaped ruptures.

5. Conclusions

This study concludes that the static segregation that occurred during the mould filling process slightly affected the results by changing the proportions of the materials in different samples. This shows that even in a controlled environment and without even the use of vibration, segregation of the aggregates needs to be considered in the manufacturing phase of the samples in future studies.

Vibrating the samples in two layers can be a good practice to prevent segregation of the aggregates and ensure good compaction in lightweight aggregate concretes. In addition to that, the results obtained in this paper clearly indicate that segregation caused by excessive vibration of the concrete specimens directly affect the compressive strength of lightweight aggregate concretes.

The combined effect of the segregation phenomenon with the variation in the volume fraction of lightweight aggregates seems to impact the compressive strength results more at excessive vibration times (40 to 80 s per layer) than at conventional vibration times (10 and 20 s per layer).

Although this paper analyses few combinations and a small number of specimens, the results obtained indicate that possibly the size of the compression cone obtained in the compressive strength tests could be used as an indicator of the degree of segregation of excessively vibrated specimens.

CRediT authorship contribution statement

Afonso Miguel Solak: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Supervision, Validation, Methodology, Writing – original draft, Writing – review & editing. **Antonio José Tenza-Abril:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project administration, Supervision, Validation, Methodology, Writing – original draft. **Victoria Eugenia García-Vera:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Project

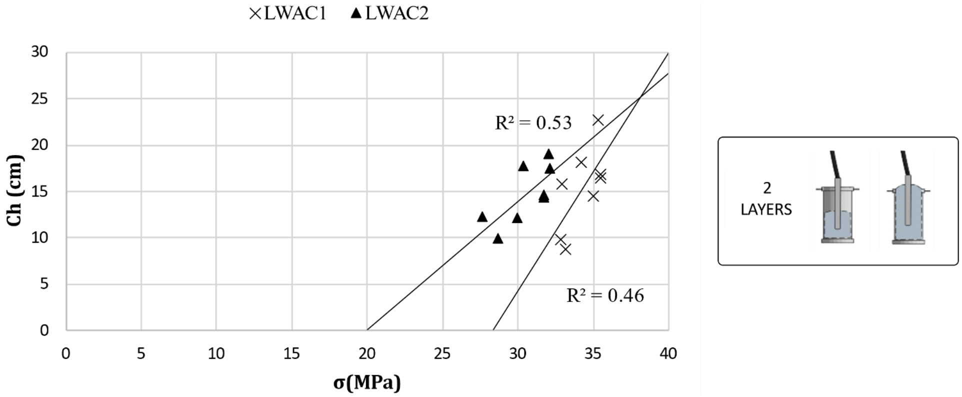

Fig. 14. Variation of the compression strength of the samples according to the compression cone size. Concrete vibrated in two layers.

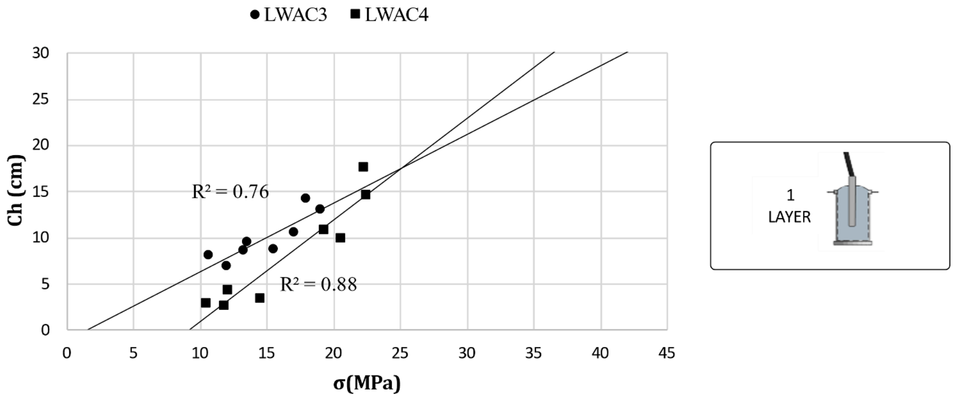

Fig. 15. Variation of the compression strength of the samples according to the compression cone size. Concrete vibrated in one layer.

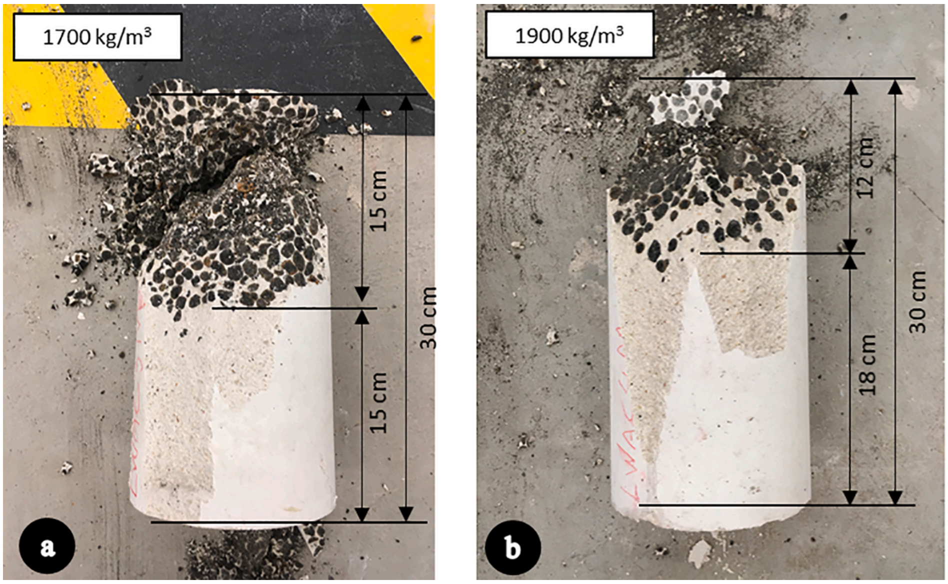

Fig. 16. Concentration of 100% of the aggregates on top of the samples (excessive vibration times). a) LWAC3 (1700 kg/m^3), with highest LWA volume fraction. b) LWAC4 (1900 kg/m^3), with lowest LWA volume fraction.

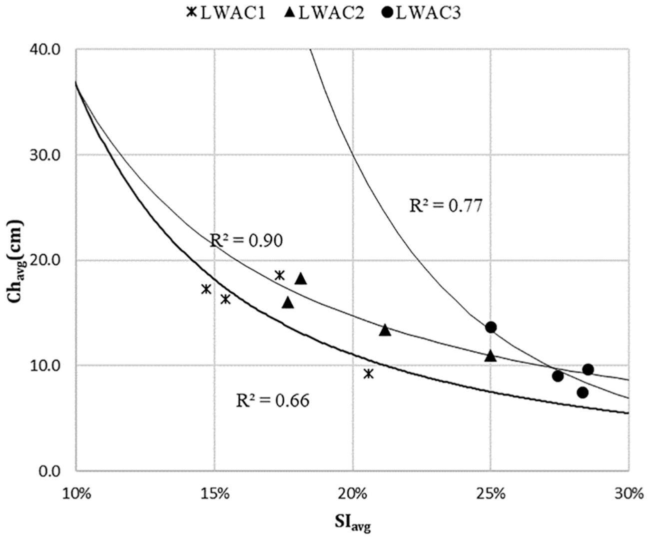

Fig. 17. Correlation between Segregation Index (SI$_{avg}$) and compression cone height (Ch$_{avg}$).

administration, Supervision, Validation, Methodology, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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