IMAGE ANALYSIS APPLICATIONS FOR THE STUDY OF SEGREGATION IN LIGHTWEIGHT CONCRETES

AFONSO M. SOLAK, ANTONIO J. TENZA-ABRIL & FRANCISCO BAEZA-BROTONS
Department of Civil Engineering, University of Alicante, Spain.

ABSTRACT

The use of lightweight concrete allows great flexibility and cost savings when it is used in building construction having a positive impact on the energy consumption of buildings due to its good thermal characteristics. However, it is also known that the differences between the densities of the materials used to produce these concretes make it highly susceptible to the segregation phenomenon. The main objective of the present work is to present a method to quantify this phenomenon using techniques of image analysis. In this work, a lightweight concrete produced was molded in cylindrical molds using different times of internal vibration and causing different degrees of segregation. The samples were cured, vertically saw-cut in two pieces (halves) and the sections were photographed. Subsequently, the halves were saw-cut horizontally in four equal parts and posteriorly their densities were determined experimentally. The densities obtained were used to calculate the segregation index of each sample (experimental method). Furthermore, the photographed sections were processed using image analysis software in order to determine the volumetric proportions of aggregates in each sample (noise reduction, threshold adjustment, binarization and fill holes). The processed images were used to calculate the densities and segregation index of the lightweight concrete produced through image analysis. In addition, using the photographed sections, a vertical density profile was programmed to analyze the distribution of the lightweight concrete components (mortar and aggregate). Finally, the results obtained experimentally and through image analysis were compared. This study demonstrates that the image analysis allows a deeper knowledge of the behavior of segregated concrete

Keywords: density, image analysis, lightweight concrete, segregation index, segregation

1 INTRODUCTION

The use of lightweight concrete allows great flexibility in design and cost savings due to the decrease in dead loads, lowering of foundation costs, etc [1–3]. In addition, the reduction of the density of the concrete produces an increase in the thermal resistance, improving the energy efficiency of the buildings constructed with this type of material.

Lightweight concretes usually used for structural applications are concretes with lightweight aggregates (LWAC), in general obtained by the total or partial substitution of conventional aggregates by lightweight aggregates and characterized by having densities lower than 2000 kg/m^3 [4].

The vibration is an industrial practice to compact fresh concrete into formwork and around reinforcement. During the vibration process, the yield stress of concrete is reduced or removed so the concrete flows by its weight [5] for releasing air bubbles and producing concrete of the highest density, strength and durability [6]. Usually, a concrete that has been vibrated carefully may contain 1 to 2% of entrapped air [7].

A homogeneous and randomly oriented aggregate distribution can improve the mechanical properties, durability, stability and impermeability of concrete [8]. The ability of fresh concrete to remain uniform during consolidation is a critical issue in the mixture design [9]. During the mixing of lightweight aggregate concrete (LWAC), due to the low density of the aggregates used and the longer mixing times [10], LWAC is susceptible to segregation of the aggregates as a result of the differences between the densities of their components [11]. In fact, during the vibration of the concrete, lightweight aggregates tend to float.

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As the mechanical strength of the mortar is considerably higher than the strength of lightweight aggregates [12–14], a non-uniform distribution of the aggregates in the concrete mixture can strongly affect the overall characteristics, which are commonly considered as homogeneous values for design purposes.

All aspects presented above justify the experimental evaluation of segregation in concrete using indexes for it quantification [15].

What follows are some methods to quantify the phenomenon of segregation proposed by other authors.

1.1 Method proposed by Ke *et al.*

Ke proposes a method for determining the segregation index (I_s) [16, 17], dividing the specimens into four equal sections and using the densities obtained from the upper (ρ_{top}) and lower (ρ_{botton}) slices of a cylinder. A possible segregation tends to reduce the density in the upper section because the lightweight aggregates tend to float in the mortar matrix.

The index is calculated according to the eqn. (1).

$$I_s = \frac{\rho_{top}}{\rho_{botton}} \tag{1}$$

If I_s=1, it can be considered that the sample shows perfect uniformity. An index of less than 0.95 indicates a start of segregation [17]. However, experimental results indicate that this segregation index does not always reflect the real conditions of the specimen. Another fact is the difficulty in locating concentrations of aggregates, which could demand the weighing and the comparison of many specimens [18].

1.2 Method proposed by Lopez – Navarrete – Esmaeilkhanian

Using a particular case of the method proposed by Esmaeilkhanian *et al.* [19] and using an unbiased stereology technique based on count pointing [20, 21], Navarrete-Lopez have calculated a segregation index based on the volumetric fraction of aggregates at different heights of a specimen [9]. Each specimen was divided into three equals sections (top, middle and bottom). For the top and bottom sections, the volume of coarse aggregate was calculated using the eqn. (2),

$$V_{ai} = \frac{P_{ai}}{P_{refi}}.100\% \tag{2}$$

where P_{ai} is the sum of the points intersecting the aggregate in section i; P_{refi} is the sum of the points intersecting section i and V_{ai} is the aggregate volume fraction of section i. To evaluate segregation, the volumetric index (VI), proposed by Esmaeilkhanian *et al.* [19] was calculated:

$$VI\left(\%\right) = 2 * \frac{\left|V_{at} - V_{ab}\right|}{V_{at} + V_{AB}} * 100\% \tag{3}$$

where V_{at} and V_{ab} are the coarse aggregate volume fraction of the top and bottom sections, respectively.

The results of the studies of Kwasny *et al.* [20] suggest that lightweight concrete may be considered as non-segregated when VI values are below 20%. Esmaeilkhanian *et al.* [22]

Table 1: VI range of segregation levels Navarrete-Lopez [11].

Segregation level	VI range (%)
None to slight	0–40
Moderate	40–80
Severe	80–120
Slightly stratified	120–160
Highly stratified	160–200

have studied the dynamic segregation of self-compacting concrete and have proposed the value of VI = 25% as the limit for segregation. Navarrete-Lopez proposes a scale with five degrees of segregation to classify the results obtained (Table 1).

1.3 The use of 2D images to represent 3D phenomenon

When the distribution and location of the aggregates is evaluated based on a 2D image (cross-section of the specimen), it is important to understand its representation in the three-dimensional (3D). According to the Cavalieri Principle, the percentage of an area in the cross-section of a specimen can be considered equivalent to the percentage of its volume in a 3D representation [23]. In the study of concrete, it is easier to use 2D images than 3D, in order to represent information. Jianguo Han used the technique of 2D image analysis to study the characteristics and distribution of aggregates in concrete[8]. The research carried out by Masad *et al*. demonstrated the usefulness of this technique to obtain the percentage of holes in bituminous mixtures using 2D images of X-ray tomographies and contrasting it with the volumetric tests usually used in this type of materials [24]. Scrivener, in one of his investigations, discussed the limitations of the use of 2D images and affirmed that these images correspond to a fraction of total area, directly equivalent to the fraction of volumen [25].

2 MATERIALS

The experimental campaign involved the production of a concrete made with coarse lightweight aggregate using the Fanjul method [26], in order to produce LWAC with a target density of 1700 kg/m^3. This method allows the maximum control in the design of concretes with a pre-set density. Table 2 includes the mix proportions.

CEM I 52.5 R cement with an absolute density of 3176 kg/m^3 was used; expanded clay was used as lightweight aggregate (Arlita Leca produced by Weber, commercially referred as M). Limestone sand was also used as fine aggregate. Prior to mixing lightweight aggregates were presaturated. At the time of mixing, the water content of the lightweight aggregates (54%) and the surface water content (3.7%) were determined in order to make the necessary corrections and maintain a constant effective w/c ratio of 0.6.

Table 2: Mix proportions to produce 1 m^3 of concrete.

	Cement	**Water**	**Fine aggregate**	**LWA**
Wheight (kg)	350	210	991	149
Volume (m^3)	0.110	0.210	0.369	0.309

Table 3: Characteristics of aggregates and the methods/standard used for testing.

Property	Method	Fine Coarse	LWA
Dry particle density (kg/ m^3)	Fernández-Fanjul el al [27]	2708	482
Bulk density (kg/ m^3)	UNE EN 1097-3	1605	269
24 h Water absortion (%)	UNE EN 1097-6	0.12	36.9
Granulometric fraction (di/Di)	UNE EN 933-1	0/4	6/16

Table 4: Mortar characterization

Age (days)	Density (kg/m^3)	Absortion (%)	Porosity (%)
7	2039	11.25	22.98
28	2049	10.78	22.25
90	2060	10.92	22.52

The main characteristics of aggregates and the methods/standard used for testing are presented in Table 3.

In order to know the physical properties of the mortar that forms part of the lightweight concrete, and knowing its dosage, prismatic mortar probes of 40x40x160 mm (according to UNE EN 196-1) were manufactured to characterize its density, porosity and absorption. The curing of the specimens was in water at a temperature of 20 ± 1°C; their values determined at 7, 28 and 90 days of age (Table 4).

3 METHODOLOGY

In order to achieve the objectives set forth in the previous section, the methodology described below and represented in the diagram of Fig. 1 was adopted.

3.1 Manufacturing and preparation of the concrete specimens

The concrete was manufactured considering the following variables when making the specimens (cylindrical of 150 mm of φ and 300 mm of height): the compaction has been performed using an electric needle vibrator of 18000 rpm/min and a needle diameter of φ25 mm. The specimens were vibrated with six different times (5–10–20–40–80–160 seconds) in a single layer.

After being made and cured in the water at a temperature of 20 ± 1°C, the specimens were saw-cut through its longitudinal axis, their bulk densities were determined by the hydrostatic balance method. Subsequently, their sections were photographed for the subsequent image analysis.

3.2 Experimental phase

The specimen’s halves were then saw-cut into four equal parts, resulting in octaves, which had their bulk densities determined. Using the density values of the upper and lower sections, the segregation index was obtained according to the methodology indicated by Ke [10].

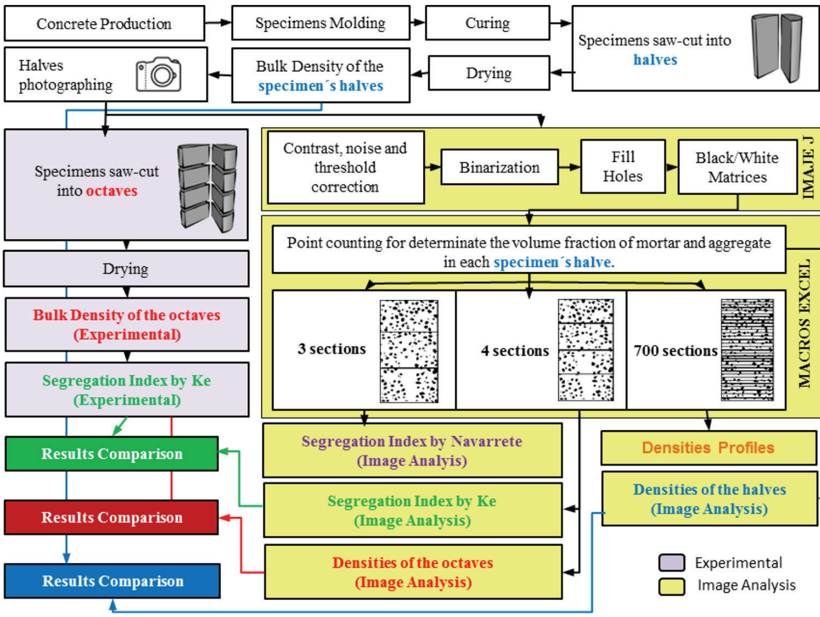

Figure 1: Methodology diagram.

3.2.1 Image processing

The same treatment was performed for all the samples: from the original image the perspective was corrected, seeking to eliminate any errors caused by the unevenness of the camera or the surface where the specimens were located. Once the perspective correction was done, the contrast and threshold were adjusted, the noise was reduced, the image was binarized and the internal voids of the aggregates were filled using ImageJ (Fig. 2).

3.2.2 Binarization

With the binarization what is tried is to classify each pixel of the image, differentiating between the lightweight aggregate and the mortar. A binary code is established where the

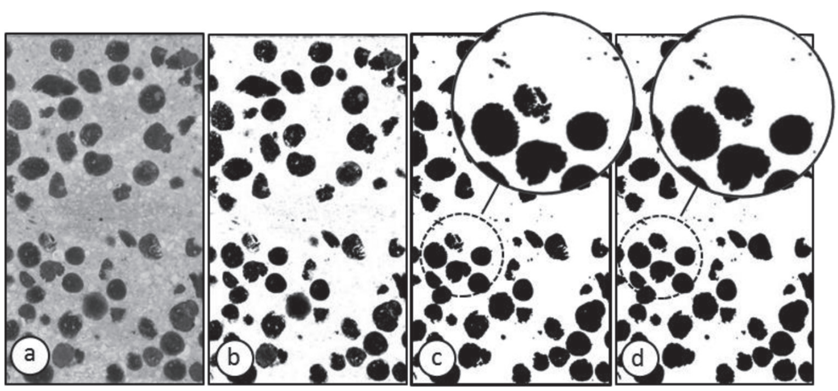

Figure 2: a) Original image. b) Contrast, threshold and noise adjustments. c) Binarization. d) Fill holes.

black color, representing the lightweight aggregate, have a numerical value of 1 and the white colour, representing the mortar matrix, have a numerical value of 0.

3.2.3 Black and White matrices data processing

The black and white matrices, which represent each half of the specimen, were horizontally separated into four parts, which represent an eighth of each of the specimens. In this way, the densities of the upper and lower octaves of each specimen were obtained by image analysis. From the densities obtained for these octaves, using image analysis, the Segregation Index proposed by Ke [8] was calculated.

In addition to the study, the same procedure has been applied separating the sample halves into three equal parts, from where the values for the volumetric fraction of aggregates of the respective regions were determined and used to calculate the Segregation Index proposed by Navarrete *et al*. [9].

To obtain the densities by image analysis, the percentage of each material in each zone was quantified as described above and, since we know the densities of the mortar matrix and of the lightweight aggregates, it is possible to determine the density of the section analyzed by means of the Eq. 4, where N_{mortar} is the percentage of mortar pixels present in the analyzed area, N_{LWA} is the percentage of lightweight aggregate pixels present in the analyzed area, ρ_{mortar} is the bulk density of mortar at 28 days of age (Table 4) and ρ_{LWA} is the dry density of the lightweight aggregates (Table 3).

$$\rho_{secci\ n} = \frac{N_{mortar} * \rho_{mortar} + N_{LWA} * \rho_{LWA}}{N_{mortar} + N_{LWA}} \tag{4}$$

Microsoft Excel was used for processing the data from the Black and White Matrices. Each concrete sample generated one file containing one Spreadsheet arranged in 701 rows and 326 columns, equivalent to the 700x325 pixels of each image and it reference axes. In order to facilitate the processing of the data and for obtaining more reliable results, Macros have been programmed in Visual Basic to speed up the process.

The first step is unifying all the Spreadsheets from each concrete section into a single file using the file *UNIR.xlsm*. All samples must be placed in the same directory before running the first Macro pressing the button '*Combine data in a single file*'. This Macro generates a new file called '*AI_Serie_Matrices.xlsx*' in the same directory of the other samples (Fig. 3).

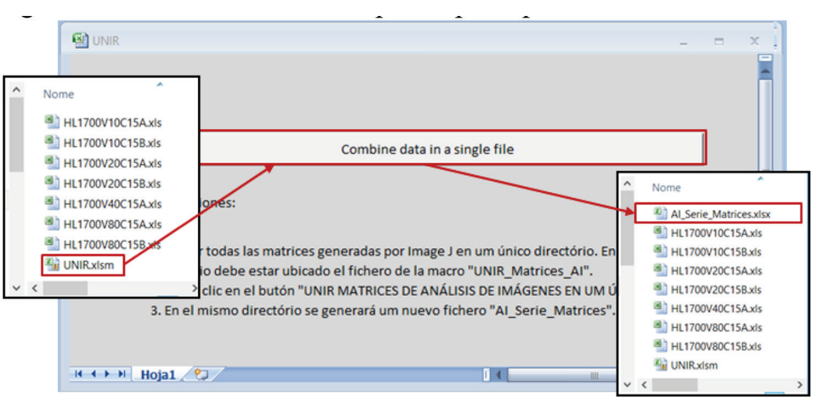

Figure 3: UNIR.xlsm is the tool to unify the samples in a single file (AI_Serie_Matrices.xlsx).

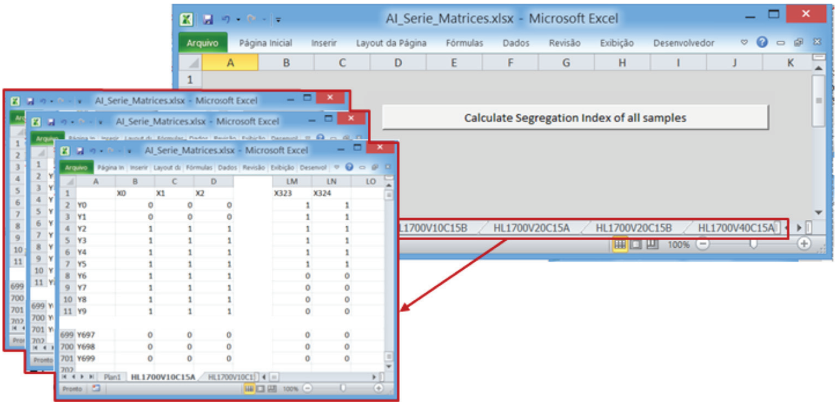

Figure 4: AI_Serie_Matrices.xlsx is the file to run the second Macro by pressing '*Calculate Segregation Index of all samples*'. All the samples are united in this file, one sample in each Spreadsheet.

Opening the file '*AI_Serie_Matrices.xlsx*' and keeping the file '*UNIR.xslm*' running in the background, the second Macro is executed by pressing *'Calculate Segregation Index of all samples'*. Internally, the Macro runs a process to count the points of each region, and based on the input data (densities of mortar and aggregates), combines this information to calculate the densities of each region (Fig. 4), the segregation indexes of Ke *et al*., Navarrete *et al*. and traces the densities profile. The process is automatically repeated for each sample.

4 RESULTS AND DISCUSSION

4.1 Validation of the image analysis methodology

4.1.1 Density: experimental and image analysis methodology.

Once described the methodology used in the research, this section shows the results obtained experimentally and through the methodology of image analysis. Figure 5, on the left, shows

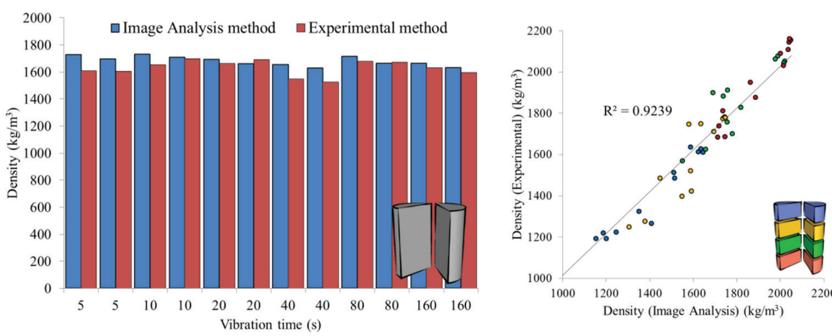

Figure 5: On the left, comparison of the dry densities of concrete specimens compacted with different vibration times and obtained through and by image analysis. On the right, experimental densities, vs image analysis of the eighth eight concrete specimen sections.

the dry density results of the concrete saw-cut halves vibrated with different times. As can be seen, the results obtained by image analysis are slightly higher than those obtained with the experimental procedure described in the previous section. This difference is higher in those with a few seconds of vibration because, during the compaction process, a high percentage of entrained air remains inside the specimen [7] and causes a decrease in the density of the concrete. However, through image analysis, voids are considered as a mortar, which is denser than the aggregate, and therefore the result is a higher density.

In Fig. 5, on the right, the comparison between the densities obtained in the octaves of the concrete specimens is shown. As can be observed, there is a high coincidence between the values of dry concrete density obtained through experimental procedure and the values obtained by image analysis. The coefficient of determination (R^2) is related to the straight line 1:1 and its R^2 value is 0.9239, which, according to the Evans scale [27], shows a very strong correlation between both results.

These results demonstrate that concrete density can be obtained using photographed section (provided component densities are known) allowing for more in-depth concrete section analysis.

As an example, Fig. 6 shows the evolution of the density of the four concrete sections subjected to different compaction times. As can be seen in Fig. 6, the density of the concrete of the upper section (ρ_{top}) decreases with the increase of the vibration time when the entire concrete specimen is saw-cut into four sections. In addition, the density of the concrete of the lower section (ρ_{bottom}) rises by the increase in the time of vibration. All this will lead, as will be seen in the following section, to an increase in the segregation of the concrete with the time of vibration.

Thus, demonstrate and verify that density of the concrete can be obtained by image analysis. Next step is to obtain the segregation indexes proposed by Ke according to eqn. (1) and by López-Navarrete according to eqn. (3).

4.1.2 Segregation index according to Ke: experimental procedure vs image analysis.

As in the previous section, this section aims to verify the possibility of obtaining the segregation index according to eqn. (3) by means of the image analysis of each concrete section comparing them with the results obtained experimentally.

In Fig. 7 shows a very strong correlation ($R^2 = 0.967$) between the I_s values obtained by experimental and by image analysis method. Thus, the results showed the possibility to determine the segregation index according to Ke methodology with the photographed concrete section and without the need to perform experimentally the determination of the densities.

As an example, the evolution of the concretes segregation index has been represented in Fig. 8. As can be seen, the increase in the vibration time increased the segregation index of

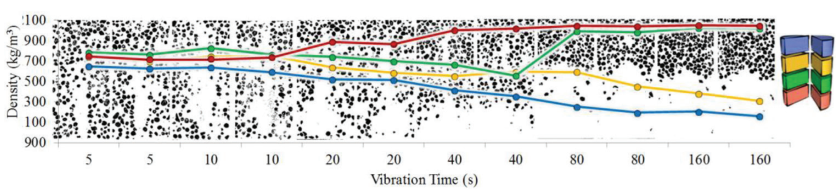

Figure 6: Evolution of the four concrete density sections increasing the vibration time obtained through image analysis.

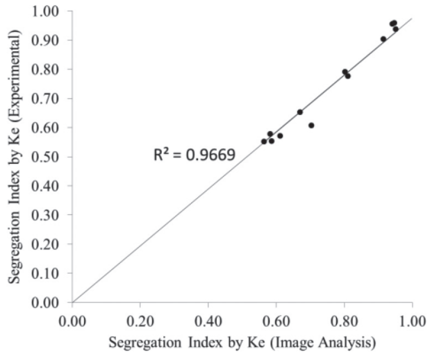

Figure 7: Comparison between segregation indexes (according to Ke) obtained by experimental and image analysis method.

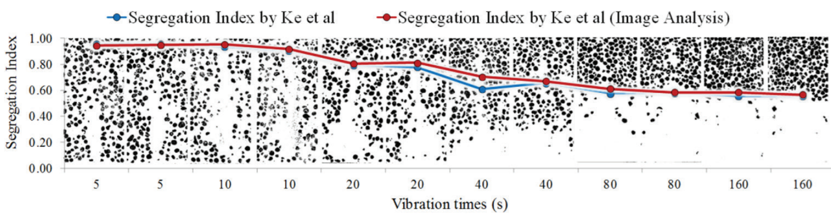

Figure 8: Segregation Indexes (I_s) evolution (Image Analysis).

the concrete. Homogeneous concrete were manufactured with reduced vibration times (5–10 s) because values of I_s obtained were approximately 1. However, as the compaction times increased, segregation became evident. The maximum values of I_s obviously, were presented with 80–160 seconds of vibration, where all the lightweight aggregate was located in the upper zone of the concrete specimens (Fig. 8).

4.2 Other results obtained

4.2.1 Density profile

As demonstrated in the results, the image analysis tool obtains very closely the density values of the concretes studied. Thus, it allows to study in detail the mechanisms of the segregation in concrete.

For that reason, using Visual Basic, an application in Microsoft Excel was developed to obtain the density profile of the concretes. Figure 9 shows the segregation sheets that can be obtained using the application programmed in Visual Basic. In red, the part related to the mortar is plotted and in blue the part related to the lightweight aggregate. Therefore, image analysis based applications can be used to study with a greater degree of detail the segregation of concrete that is impossible or very difficult to carry out experimentally.

4.2.2 Segregation index according to Navarrete *et al*.

In the last section, since the use of the images to determine the density has been demonstrated, the authors wanted to compare the segregation indexes obtained according to Ke and those obtained according to Navarrete *et al*.

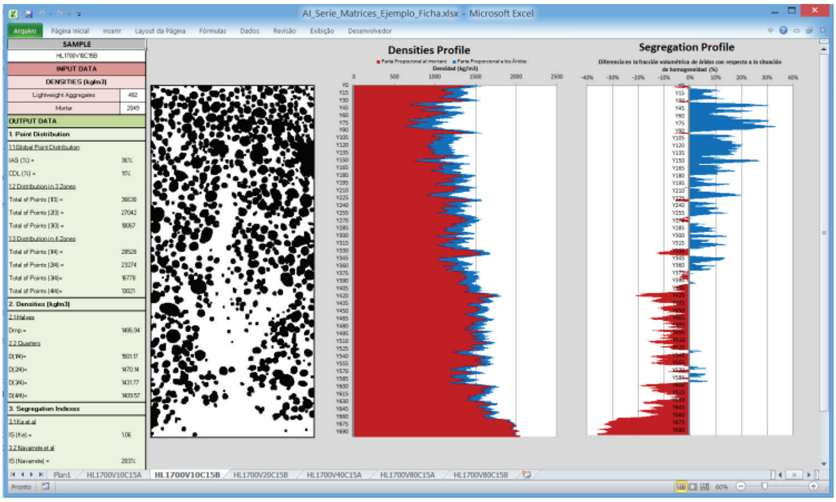

Figure 9: Result sheets. Density profile of the specimen related to lightweight aggregate and mortar parts in each section.

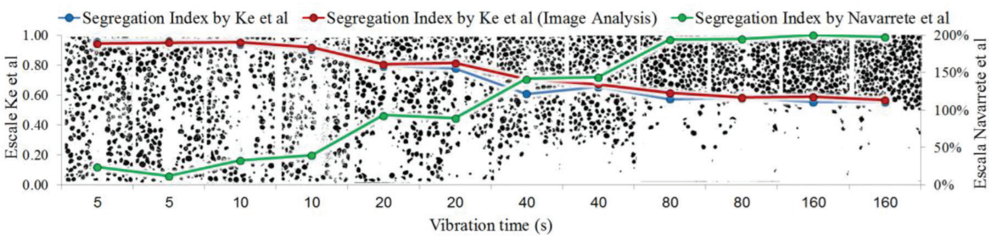

Figure 10: Segregation index (I_s) according to Ke and VI index according to Navarrete.

The scales in both methods are different since a value of 1 or 0% means homogeneous concrete according to Ke or Navarrete method, respectively. In contrast, a value of 0 or 200% means a totally segregated concrete.

Plotted in Fig. 10, there was a similar trend in both methods. It was found homogeneous values with the shorter vibration times (5–10 s) and the maximum segregation with vibration time of 160 s.

5 CONCLUSIONS

In this paper, the main objective has been to determine the density of segregated lightweight concrete using image analysis software and to compare with experimental results.

- The results showed that the concrete density could be obtained using a photographed section (as long as the densities of the constituents are known).
- Segregation indexes of lightweight concretes can be obtained through the photograph of the section. The method allows replacing the experimental method for determining the density of each section using images of the concrete specimens.
- By means of the image analysis, the density profile was obtained using a tool developed in Visual Basic. This tool let to perform a deeper analysis of the segregation phenomenon.

Therefore, this study demonstrates that the image analysis allows a deeper knowledge of the behavior of segregated concrete opening new possibilities for engineers to understand and analyze the mechanisms of segregation in lightweight concrete.

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