NUMERICAL MODEL FOR DESCRIBING THE SEGREGATION PHENOMENON IN LIGHTWEIGHT CONCRETE USING DENSITY SECTIONS

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ABSTRACT

In this work, numerical models were obtained for describing the segregation phenomenon in lightweight aggregate concrete. To that end, a numerical methodology based on the generation of geometric models of finite elements has been applied, selecting those that describe better this phenomenon. The use of lightweight aggregate concretes (LWC) allows greater design flexibility and substantial cost savings. It is also well known that it contributes to a positive impact on the energy consumption of a building due to the high-thermal resistance values. However, lightweight concretes are susceptible to present aggregate segregation due to density differences between its components during concrete vibration. Segregation in concrete may strongly affect the concrete global properties. This fact justifies the needs for the identification and quantification of this phenomenon, in order to estimate the concrete segregation experimentally, a LWC was mixed in laboratory conditions. Controlled segregation was caused applying different times of internal vibration in a cylinder specimen. The specimens were horizontally sectioned in order to obtain the density in each section because the segregation index can be estimated obtaining a relation by comparing the densities of the upper and lower parts. Firstly, ANOVA test was performed to determine the statistical significance ($p<0.05$) of the differences in the density of the different sections, differences in the aggregate type and differences in the time of concrete vibration. Results show that there is a significant difference of each section and there is no significant difference of each lightweight aggregate used to mix the concrete in spite of their different density. In order to model the segregation in the LWC, at first, linear models were considered and rejected because for not explaining the phenomenon. However, the application of numerical models shows good results to describe the phenomenon of segregation in LWC.
Keywords: ANOVA, compactation, lightweight concrete, prediction models, segregation, vibration.

1 INTRODUCTION

The history of lightweight concrete dates back to over 3000 years ago [1, 2]. Structural LWC has been widely used following advances in production technology for lightweight aggregates (LWA). Several advantages of LWC can be achieved, to reduce dead load for structures [3], the reduction of the density produce an increase in the thermal resistance of the concrete and increase the energy efficiency of buildings with this kind of material. But this kind of concrete tends to segregate due to the low density of the aggregates of the mixture.

After concrete placement, concrete can contain up to 20% of entrapped air. This percentage varies according to the type of the concrete. The vibration of the concrete can improve the compressive strength about 3–5% for each percent of entrapped air removed. Vibration produce a settled concrete and entrapped air is forced to the surface and allow the concrete to move into formwork and eliminate the bigger voids.

A homogeneous and randomly oriented aggregate distribution can improve the mechanical properties, durability, stability and impermeability of concrete [4]. Eurolightcon [5] emphasizes the importance of homogeneity among the constituents of lightweight concrete. During the mixing of LWC, due to the low density of the aggregates used and the longer mixing times

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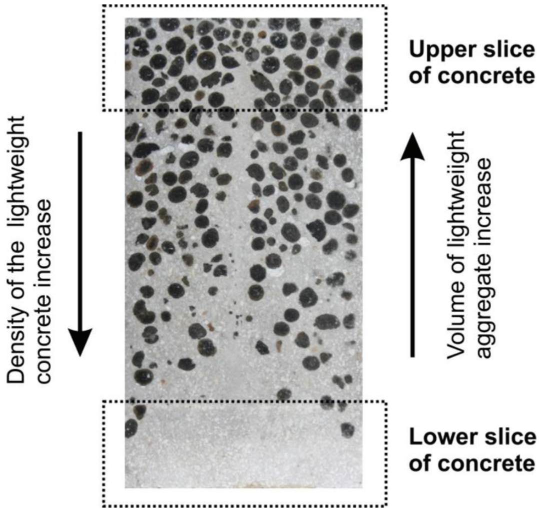

Figure 1: Segregation of concrete. Upper and lower slice in concrete specimen.

[6], the LWC is susceptible to the segregation of the aggregates as a result of the differences between the densities of their components. In fact, during the vibration of the concrete, lightweight aggregates tend to float.

According to Panesar and Shindman [7], segregated concretes are susceptible to an increased risk of cracking by cause of the separation of the aggregates from the rest of the mixture. To quantify the phenomenon of segregation, Ke and Beaucour propose several methods to determine segregation index [6]. In one of the methods to determine segregation index, the densities obtained from the upper and lower slices of a cylinder can be used. This segregation index can be calculated by Equation (1), as can be seen in Fig. 1.

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

where I_s is the segregation index, ρ_{top} is the density of the upper slice of the cylinder of concrete and ρ_{bottom} is the density of the lower slice of the cylinder of concrete.

The main objective of this study was to evaluate the possibility of using linear models or numerical models, based on experimental data, to determine the density of different sections of a segregated lightweight concrete in order to evaluate the segregation index knowing the vibration time of the concrete and the type of aggregate used in the mixture.

2 MATERIALS

Four different types of lightweight aggregates (LWA) of expanded clay having different densities as a coarse aggregate (M, LTM, HS and LTHS) and natural fine limestone aggregate were used to make several LWCs. Their main properties are listed in Table 1. Bulk density was determined by UNE EN 1097-3 [8]; dry particle density and 24 h absorption were determined by UNE EN 1097-6 [9] (pre-dried particles immersed in still water); absolute density was determined with Helio pycnometer; and the fraction of the aggregates was determined by UNE EN 933-1 [10].

Table 1: Geometrical and physical characteristics of aggregates used.

Aggregate type	Bulk density (kg/m^3)	Absolute density (kg/m^3)	Particle density (kg/ m^3)	24 h water absorption (%)	Granulometric fraction (d_i/D_i)
M	269	2573	482	36.60	6/10
LTM	276	2656	613	29.55	4/12
HS	610	2674	1019	12.20	4/10
LTHS	676	2667	1118	11.05	4/10
Limestone	1610	2661	2708	0.12	0/4

Table 2: Mix proportions of the different LWCs.

Concrete type	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3)	LWA (kg/m^3)
LW-M	350	210	991.1	148.9
LW-LTM	350	210	938.6	201.4
LW-HS	350	210	723.9	416.2
LW-LTHS	350	210	662.0	473.0

The experimental campaign involved the characterisation of concrete made with coarse LWA. Four types of concretes (with each LWA) with the same w/c ratio, cement content (CEM I 52.5 SR with an absolute density of 3176 kg/m^3) and fine aggregate were produced (Table 2) using the Fanjul method [11] in order to produce LWC with a target density of 1700 kg/m^3.

The w/c ratio relates to the effective water available for cement hydration. Due to the high absorption of the expanded clay, the LWA pre-soaked for 7 days in order to control the workability and effective w/c ratio of concrete [12]. For better control of the water content in the LWA, a day prior to mix the concrete, LWA were extended in a mesh for 20 min to reduce the superficial water content and placed into hermetic plastic bags to prevent water loss. Afterwards, a LWA sample with superficial and internal water is weighed and placed in a sieve covered by a paper filter sheet and vibrated for 15 s in order to remove the superficial water content. The LWA sample was then weighed without superficial water and immediately after that the sample was dried in an oven until a constant mass in order to obtain the internal water content.

3 METHODOLOGY

3.1 Experimental procedure

The procedure is summarised in Fig. 2. The concretes were mixed in a vertical shaft mixer (see Fig. 2, step 1). The mixing methodology for the concretes production consisted of: 1-min mixing cement and fine aggregate, addition of the total calculated water followed by 2-min mixing, addition of the coarse aggregate followed by 2-min mixing.

The concrete was vibrated using internal vibratory needle. Six 150x300 mm cylinders were cast for each mixture and were vibrated with six different times in one layer. Mixture samples were vibrated for 5, 10, 20, 40, 80 and 160 s (see Fig. 2, step 2).

After demoulding at 24 h, the specimens were kept in water until testing. After 28 days, each concrete specimen was saw-cut in horizontal slices in order to determine the density of all of them (see Fig. 2, step 4).

As mentioned above, the specimens manufactured were sectioned into seven slices of 40 mm thickness, as shown in Fig. 2, step 4. Subsequently, the density of each of these sections was determined by Equation (2).

$$\rho_i = \frac{m_{di}}{(m_{ssd} - m_{sub})} \tag{2}$$

where ρ_i is the section density, m_{di} is the dry mass of the concrete section, m_{ssd} is the saturated mass surface-dry of the concrete section and m_{sub} is the submerged mass of the concrete section.

3.2 Statistical analysis and numerical model approach

On the one hand, with the data obtained from the dry density of each section, type of aggregate, time of vibration and number of section, differences in the density of the sections of LWC in relation to the subpopulations defined in each of the other variable were analysed considering them as factors. On the other hand, mathematical models have been generated to obtain relationships between density of the LWC and factors, which will allow a better

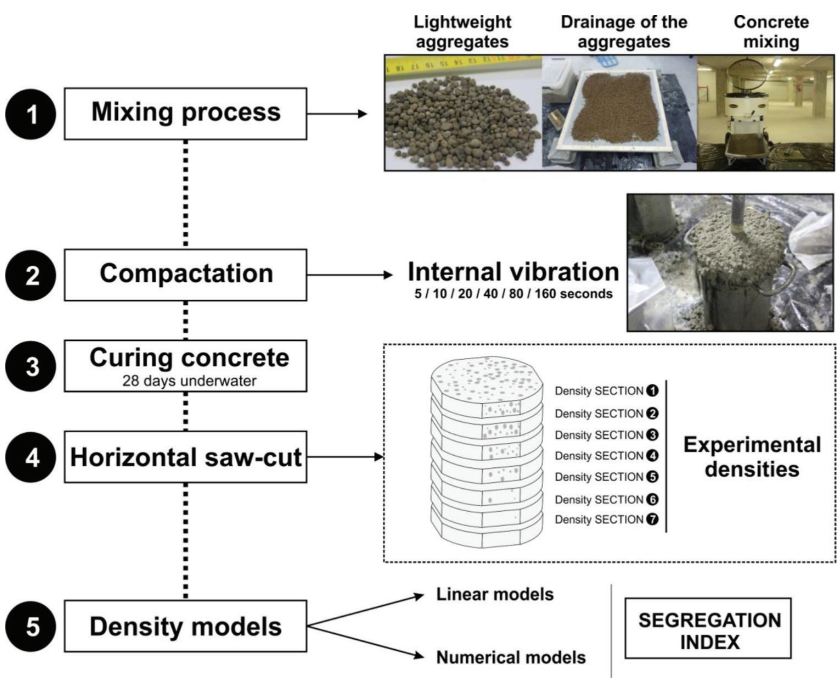

Figure 2: Summary of the process carried out in the research.

understanding of the phenomenon and make predictions. Generally, in the study and modelling of systems, it is necessary to analyse and determine the relationship between the variables defined by the Equation (3).

$$z = (x_1, x_2, \ldots, x_n) \tag{3}$$

and of which only the experimental data are known as Equation (4) shows.

$$\left\{ z_i, x_i^1, x_i^2, x_1^3, \ldots, x_i^n \right\}_{i=1,2,\ldots,p} \tag{4}$$

There are different methodologies to obtain models from the experimental data and they can be analytically (mathematical equations) or numerically defined. The linear models did not fit well to the experimental data, so it has been necessary to generated numerical models in which the function is defined by its value at a finite set of points which allows the calculation of the function value at any other point. The numerical models have been generated applying the methodology presented by Villacampa *et al.* [13] and by Navarro-González and Villacampa [14].

3.2.1 Variance analysis

An analysis of the variance (one-way ANOVA) has been performed to determine if there are significant differences in the densities regarding the following factors: type of aggregate, time of vibration and section. SPPS software was used for the analysis.

For the study of the analysis of the variance, it is necessary that the dependent variable be normally distributed in each group; that the homogeneity of the variances be fulfilled, i.e., the variances must be equal in each group; and that the observations be independent. The test of Levene uses the level of significance set *a priori* for the ANOVA ($\alpha = .05$) to test the assumption of homogeneity of variance for any factor. The results for the factor '*section*' can be seen in Table 3.

Since the assumption of equality of variances does not have statistically significant difference, the statistics of Welch and Brown-Forsythe have been determined for each of the factors. They indicate that there are only significant differences for the '*section*' factor, as observed in Table 4.

In order to obtain information on the sections that present significant differences between them, the equality of variances between the subpopulations (or groups) is not verified.

Table 3: Levene's test for equality of variances.

Dry density LWC (kg/m^3)			Section
Levene	df1	df2	Sig.
4409	6	161	,000

Table 4: Robustness testing of the means equality (section factor).

Dry density LWC (kg/m^3) / section	Statistics	df1	df2	Sig.
Welch	11,417	6	70,868	,000
Brown-Forsythe	14,158	6	134,426	,000

The statistic of Games-Howell has been determined, and it has been used an *a priori* alpha level of significance of 0.05. This test allows to state that the difference of means is significant in the 0.05 level between the following sections:

- The density of the section 1 has significant differences with the densities of the sections 4, 5, 6 and 7.
- The density of the section 2 has significant differences with the densities of the sections 5, 6 and 7.
- The density of the section 3 has significant differences with the densities of the sections 5, 6 and 7.
- The density of the section 4 has significant differences with the density of the section 7.

This difference makes the segregation in concrete visible. Taking into account that the first section is the upper section and the seventh section is the lower section in the LWC cylinder specimen, significant differences can be obtained between the upper and the lower slices.

3.2.2 Linear models

Linear regression models are mathematical models used to approximate a relationship between a dependent variable, a set of independent or explanatory variables, and a random error or perturbation term, as can be seen in Equation (5).

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots + \beta_n x_n + \varepsilon \tag{5}$$

In a linear regression model, the following assumptions must be fulfilled on the errors:

i) the mean of the error must be zero
ii) the variance of the error must be constant (homoscedasticity)
iii) the errors follow a normal distribution of zero mean and deviation σ
iv) the errors associated with the values Y are independent.

An adjustment measure is the coefficient of determination R^2 equal to the square of the correlation coefficient.

3.2.3 Numerical models

The numerical methodology developed by Villacampa *et al.* [14] generates n-dimensional representation models. The methodology is based on the definition and generation of a geometric model of finite elements described by González-Navarro and Villacampa [13]. The representation model is determined in the nodes, allowing the calculation at any point by using interpolation functions. The number of finite elements and nodes is determined by a number c called complexity of the model (Comp). For each value of complexity, a derived numerical model exists. So the methodology starts with the generation of a geometric model of finite elements defined in a hyper-cube. The meshing process generates a set of points called nodes, where the model is determined. To do this, each interval is divided into c sub-intervals, where c is called the *complexity of the model*.

The number of elements and nodes is determined by the value of c. Each model allows the estimation of relationship values at the experimental points and the correspondent sum of squared errors and determination coefficients can be calculated.

With the above-mentioned experimental data and the methodology, numerical models have been determined for different complexities. These models are models of representation of the relationship showed in Equation (6).

$$Density = f(x_1, x_2, x_3) \tag{6}$$

where x_1 x_2 y x_3 is the LWC section, time of vibration and aggregate type, respectively.

The following parameters have been compared in order to select the better models: the coefficient of determination that measures the goodness of the fit is defined by the Equation (7) and the absolute percentage error (MAPE) according to the Equation (8).

Numerical models have been generated for the complexities c = 10, 15, 20, 25, 30, 35, 40, 45 and 50.

$$R^2 = \frac{\sum_{i=1}^{n}\left(\overset{\approx}{y}_i - \bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2} \tag{7}$$

$$MAPE = \frac{\sum_{i=1}^{n}\left|\frac{y_i - \overset{\approx}{y}_i}{y_i}\right|}{n} \tag{8}$$

4 RESULTS AND DISCUSSION

4.1 One-way ANOVA

All the linear regression models between the density and the different variables were determined (section, time of vibration and type of aggregate) by applying the regression method backward that determines a model in which all the variables participate and after removing one by one all the variables. The backward method was used to generate three linear models that only explain a maximum of 34.6% of the data and in which the error is not normally distributed (it does not follow a normal distribution). The linear models are presented in Equations (9–11) and also can be seen in Fig. 3.

$$Density = 1428{,}586 + 56{,}923x_1 + 0.216x_2 - 12{,}244x_3 \tag{9}$$

$$Density = 1439{,}926 + 56{,}923x_1 - 12.244x_3 \tag{10}$$

$$Density = 1409{,}316 + 56{,}923x_1 \tag{11}$$

where x_1 is the section number, x_2 is the vibration time and x_3 is the aggregate type.

As can be observed, linear models to predict the density of the LWC in the different sections studied and each type of aggregate were not useful due to the low coefficient of determination (from 0.338 to 0.346) and do not describe the segregation phenomenon.

4.2 Numerical models

As mentioned above, the different complexity models up to 50 were studied in order to find the better explanation of the density of the LWC in the different sections. As can be seen in

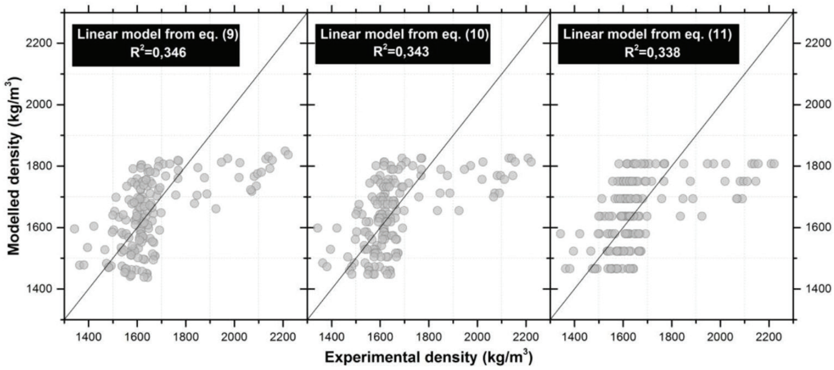

Figure 3: Linear models from Equations (9–11).

Fig. 4, the higher the complexity model the higher the coefficient of determination (R^2) and the lower the absolute percentage error (MAPE). For models higher than 30 slightly growth was observed, and probably, more noise is reproduced.

All models have a good fit because their coefficient of determination is between 0.88 and 0.99. Figure 5 shows the different models and the experimental density data.

The main goal in this research was to find a model capable of predicting the density knowing the vibration time and the type of the aggregate. It can predict the density of the LWC from the top to the bottom of the concrete specimen (seven different sections) so that the segregation index can be determined according to Equation (1), of the whole specimen (knowing the time of vibration and type of the aggregate). This makes it easier for engineers to know the state of the LWC placed without drill core.

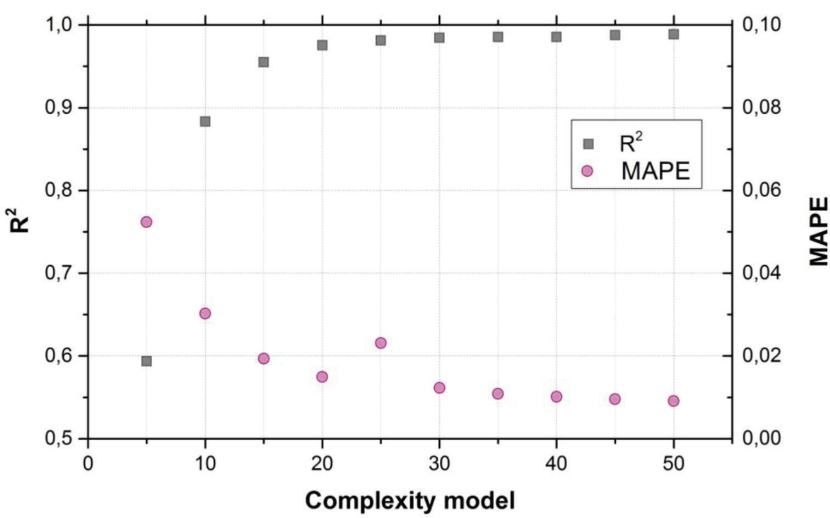

Figure 4: Evolution of MAPE and R^2 when the complexity model is increased.

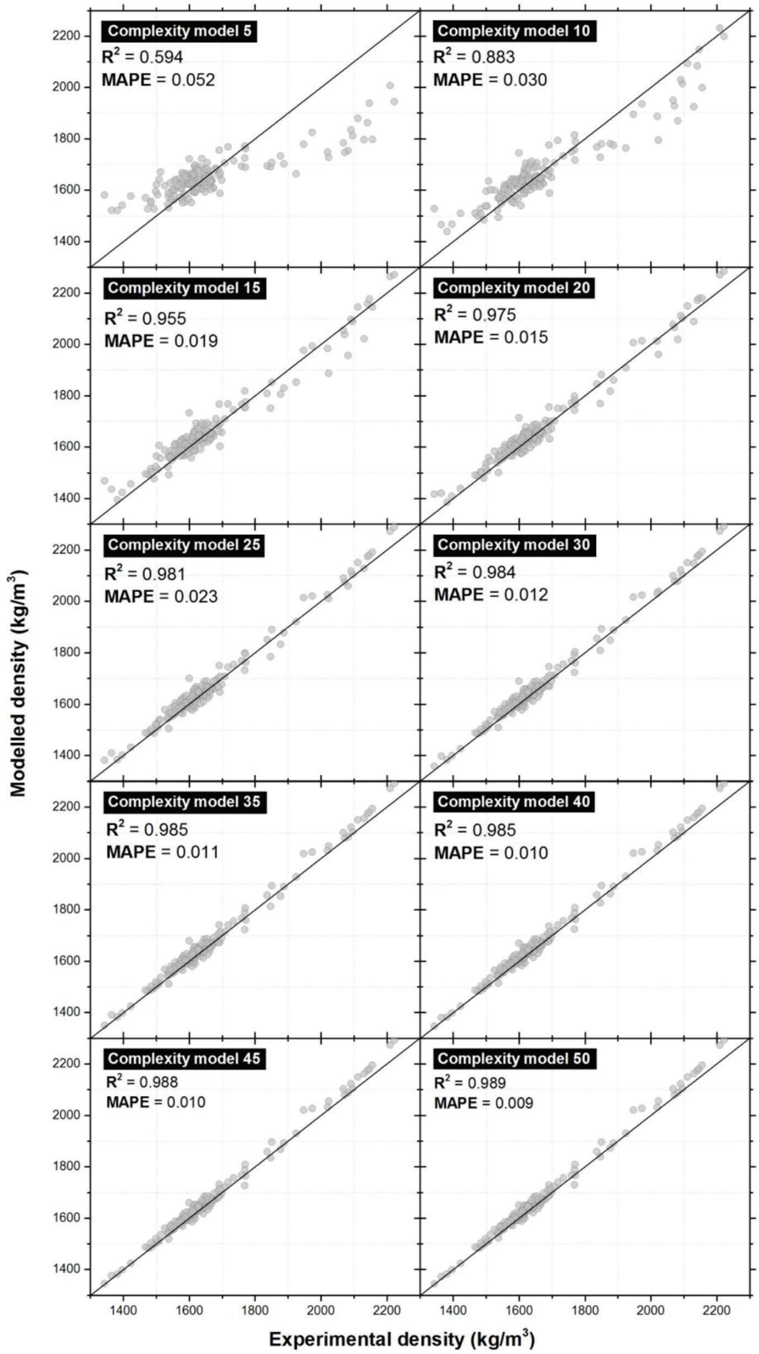

Figure 5: Experimental density vs. Modelled density with different complexity models.

5 CONCLUSIONS

In this research, linear models and numerical models were studied in order to predict the density of segregated lightweight concretes. Four types of lightweight aggregates, six different vibration time in the LWC and seven sections were studied in order to predict the density of the LWC in the different sections (from upper to lower). The statistical analysis showed that significant difference can be found in upper sections from lower sections. However, linear models were not suitable to describe the segregation phenomenon because explained up to the 34.6% of the experimental data. The described work provides an example on how numerical models, with different complexity, can achieve up to 98.9% of explanation of the experimental results. This research allows confirming that segregation phenomenon and segregation index can be described using numerical models.

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