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Feasibility of assessing segregation in internally cured mortar based on the variation of properties

Dinghua Zou *, Kun Li, Silin Xie, Ying Liu, Weifan Ren, Lijie Shi, Zhenzhen Liu

School of Materials Science and Engineering, Henan Polytechnic University, 2001 Century Avenue, Jiaozuo, Henan, 454000, PR China

HIGHLIGHTS

- Dynamic modulus, dry and saturated densities is sensitive to LWA content.
- Most relative experiment errors of dry and saturated densities tests are low than 1%.
- Only when ICW/C is more than 1% that the variations of dry and saturated densities at 28 day are significant.
- Saturated densities are more appropriate than the rests to assess the segregation.

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ABSTRACT

This paper focuses on the feasibility of assessing the segregation of internally cured mortar accompanying lightweight aggregate (LWA) by quantifying the variation of pore-related properties between top and bottom layers of mortar. Twelve internally cured mortars, with different LWA contents, were prepared. Dry and saturated densities, dynamic modulus and water absorption of hardened mortar at 1 day, 7 and 28 days were tested. Sensitivity of the properties to LWA content was analyzed by linear regression. Experiment errors of tests were compared. Multiple comparisons, a method of Analysis of Variance (ANVOA), was adopted to reveal the significance of variations. The results show that, densities and dynamic modulus varied linearly with the LWA content but not for water absorption. The experiment errors of densities tests are far lower than that of dynamic modulus and water absorption tests. It is revealed that saturated density is the most suitable property to evaluate the segregation of internally cured mortar.

1. Introduction

Saturated lightweight aggregate (LWA) has significant benefit to reduce the high shrinkage of low water to cement ratio (w/c) mortar and prevent it from cracking [1] or damage [2]. This was named as internal curing since the water, which is brought into mortar by LWA, takes the same effect as exterior curing water in ordinary concrete. Moreover, enhanced hydration due to the internal curing water generates expanded productions [3], which induces the expansion of internally cured mortar when there is extra water.

However, high segregation tendency of fresh internally cured mortar due to the high density difference between LWA and the paste would result in the problem of heterogeneity. The segregation leads to the assembling of LWA in top layer of internally cured mortar. Few or less LWA would be found in bottom layer. Presented researches revealed that content of LWA has intense impact on volume deformation [4–8], strength [9] and elastic modulus [2] of mortar. Inconsistence of volume deformation between upper and lower layers of internally cured mortar under free or load-carrying condition arises. This induces the performance deterioration. The uniformity of internally cured mortar should be focused on.

A simple and quick method might be used to determine whether the segregation happened by quantifying the variation of the properties between the top and bottom layers of the mortar. Due to the fact that it could be higher or lower than that of an ordinary counterpart [10–12], variation of compressive strength is not helpful to confirm the segregation. However, dry and saturated densities, dynamic modulus and water absorption should change linearly with the content of lightweight aggregate. The dry and saturated densities and dynamic modulus of top layer of mortar should be lower than that of bottom one while water absorption

* Corresponding author.
E-mail address: zoudinghua@hpu.edu.cn (D. Zou).

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be higher if segregation happened. Here the property variation is defined as the result of subtracting dry and saturated densities and dynamic modulus of top layer of mortar from that of bottom layer and water absorption of bottom layer from that of top layer. The variation should be positive. Nevertheless, negative variation might be obtained due to the experiment errors. In this situation, it could not be confirmed whether the segregation happened or not. Moreover, in a multi-samples test, the direct comparison between two averages of results could not give a precise judgment due to the ignorance of experiment error.

In this research, 12 mortars, with different LWA content, were prepared. Dry and saturated densities, dynamic modulus and water absorption of hardened mortars were tested. Linear regression was employed to reveal the sensitivity of properties to content of LWA. Experiment error and negative variations were observed. A more complicated statistic method, multiple comparisons, was adopted to analyze the significance of variations of properties. This paper aims to provide a quantitative comparison among dry and saturated densities, dynamic modulus and water absorption to clarify whether they could be used to assess the segregation.

2. Multiple comparisons

Multiple comparisons [13] is one method of Analysis of Variance (ANVOA). If the test results were obtained as what are shown in Table 1 and the null hypothesis H_0: $\mu_1 = \mu_2 \ldots = \mu_n$ was rejected, the inequalities among the different group means are what should be clarified. In multiple comparisons, the variation between two averages would be compared with a critical value, which takes the experiment errors into account, to clarify the inequalities. It is a more rigorous method to confirm the difference between group means than direct comparison between averages.

In multiple comparisons, sum of squares would be derived at first as Eqs. (1) and (2) to calculate the critical value.

$$SS_A = \sum_1^n \sum_1^m (\bar{y}_i - \bar{y}) \tag{1}$$

$$SS_{error} = \sum_1^n \sum_1^m (y_{ij} - \bar{y}_i) \tag{2}$$

where SS_A, SS_{error} are between-group and within-group sum of squares, respectively; $\bar{y}$ is the mean of all results; $\bar{y}_i$ is the mean of all results when factor is at level i. Between-group and within-group degrees of freedom could be determined by Eqs. (3) and (4), respectively.

$$df_A = n - 1 \tag{3}$$

$$df_{error} = (m-1).n \tag{4}$$

The critical value ($D_{ab,}$) of multiple comparisons could be derived from Eq. (5).

$$D_{ab} = \sqrt{\left(\frac{1}{n_a} + \frac{1}{n_b}\right) . \frac{SS_{error}}{(m-1).n} . (r-1) . F_\alpha(n-1, (m-1).n)} \tag{5}$$

where a and b are levels of factor; n_a and n_a are number of test results at level a and b, respectively; $F_\alpha(r-1, n-r)$ is the critical value of F test (determined by significance level (α) and degrees of freedom of factor ($n-1$) and error ($(m-1)n$)). It could be found in a table of critical values for the F distribution. There are two D_{ab} used here which correspond to the significance level of 0.05 and 0.01, respectively.

If $|\bar{y}_a - \bar{y}_b| > D_{ab}$, the null hypothesis H_0: $\mu_a = \mu_b$ would be rejected and the variation between the two group means should be considered as significant. If $|\bar{y}_a - \bar{y}_b| \leqslant D_{ab}$, the null hypothesis would be accepted. The variation is insignificant and the difference between properties of different mortar could not be confirmed. However, the variations, not the absolute value of them, were used in this research to discover the negative ones.

3. Materials and methods

3.1. Materials and mixtures

A 42.5 grade ordinary Portland cement was used. Properties of cement are shown in Table 2. An expanded clay, with SSD density of 1.48 g/cm^3 and 24 h water absorption of 28.4% was taken as internal curing agent. Gradation of clay is shown in Fig. 1. Fine aggregate was river sand. The 24 h water absorption, dry apparent density and fineness of fine aggregate are 2.08%, 2.48 g/cm^3 and 3.06, respectively. Polycarboxylate plasticizer was employed as water reducer.

The w/c and fine aggregate volume fraction were fixed as 0.3 and 0.55, respectively. To quantify the content of LWA, a term, internal curing water to cement ratio (ICW/C), was used. Twelve mixtures with the ICW/C from 0 to 0.11, as shown in Table 3, were adopted.

3.2. Test methods

For each mixture, 3 prism samples, with the dimensions of 100 mm × 100 mm × 400 mm, were prepared for dynamic modulus test. Nine cubic samples, with the size of 100 mm × 100 mm × 100 mm, were prepared for water absorption, dry and saturated densities tests. After casting, all samples were vibrated twice on a vibrate table. The time of each vibrating is 5 s. Frequency and amplitude of vibration table were 2860 Hz and 0.3–0.6 mm respectively. All samples were demoulded about 23 h.

Ultrasonic resonance method was used to measure the dynamic modulus of prism samples at 1 day, 7 and 28 days according to Chinese standard GB/T 50082-2009 [14]. Densities and water absorption were tested according to ASTM C 642-06 [15]. Three cubic samples were sawed into cuboids with the dimensions of 50 mm × 100 mm × 100 mm at 1 day, 7 and 28 days and then dried at 105 °C for 48 h. Mass of dried samples (M_d) were measured by an electric balance accurate to 0.01 g. Samples soaked in water in a vacuum chamber for 6 h. SSD mass (M_s) of samples were weight after water absorption. Then the mass of samples immersing in water (M_w) were measured by a hydrostatic balance accurate to 0.01 g. Water absorption, dry and saturated densities were derived from the Eqs. (6), (7) and (8), respectively.

$$W = \frac{M_s - M_d}{M_d} \times 100\% \tag{6}$$

$$D_d = \frac{M_d}{M_s - M_w} \tag{7}$$

$$D_s = \frac{M_s}{M_s - M_w} \tag{8}$$

where W, D_d and D_s are water absorption, dry and saturated densities of samples, respectively.

Table 1
Test results of a certain properties.

Level of factor	Results			
A_1	y_{11}	...	y_{1j}	y_{1m}
...	...	...	...	...
A_i	...	...	y_{ij}	...
...	...	...	...	...
A_n	y_{n1}	y_{n2}	...	y_{nm}