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Understanding the relationship between the segregation of concrete and coarse aggregate density and size

Ivan Navarrete [a], Mauricio Lopez [a,b,*]

[a] Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Catolica de Chile, Vicuña Mackenna 4860, Casilla 306, Correo 22, Santiago, Chile

[b] Center for Sustainable Urban Development (CEDEUS), Pontificia Universidad Catolica de Chile, Santiago, Chile

HIGHLIGHTS

- Segregability of concrete with different CA RSSA and $|\Delta\rho|$ are presented.
- Concrete segregation is mainly related to the interaction between CA RSS*A* and $|\Delta\rho|$.
- The segregation rate of concrete was shown to be independent of the time of vibration.
- A VI of 20% is proposed as a conservative limit for acceptable segregation in concrete.
- CA RSSA explained the concrete segregation rate more precisely than MSA.

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ABSTRACT

Segregation of aggregate, which ultimately influences the strength and durability of concrete, is one of the major problems during construction. Two factors and their effects on the segregation of fresh concrete under vibration were studied. Based on the statistical analysis of the experimental results, it was concluded that the observed rate of segregation is an intrinsic property of concrete and is independent of the vibration time applied. The segregation tendency of a concrete mixture is mainly explained by the interaction between the specific surface of coarse aggregate and the difference in density between the aggregate and mortar phase rather than by each individual factor independently.

1. Introduction

Segregation, the tendency for coarse aggregate to separate from mortar, remains one of the major problems in fresh concrete. The consequences of segregation are numerous and may affect the strength and durability of structures [1]. However, the construction workforce is mainly unskilled [2]. Thus, control of the mixture design is necessary to assess a good final quality of the construction.

ACI 238 defines two kind of segregation, which are dynamic and static segregation [1]. The dynamic segregation happened when a mixture is being handled, placed, and transported. On the other hand, the static segregation happened when a mixture is not flowing.

The rheology of fresh concrete is complex owing to its multi-composition and the changes in properties upon hydration. Previous researchers [3] have shown that the flow behavior of fresh concrete can be reasonably approximated by the Bingham model:

$$\tau = \tau_0 + \eta_p \cdot \dot{\gamma} \quad (1)$$

where τ is the shear stress, τ_0 is the yield stress, η_p is the plastic viscosity, and $\dot{\gamma}$ is the shear rate. Therefore, the flow of concrete can be described by two parameters: yield stress and plastic viscosity.

Fresh concrete may be considered as a two-phase composite material with coarse aggregate particles in a mortar matrix. The settlement of a particle in a fluid with Bingham plastic behavior has been predicted by Beris et al. [4]. They concluded that a sphere

* Corresponding author at: Department of Construction Engineering and Management, School of Engineering, Pontificia Universidad Catolica de Chile, Vicuña Mackenna 4860, Casilla 306, Correo 22, Santiago, Chile.

E-mail address: mlopez@ing.puc.cl (M. Lopez).

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will settle when the yield stress parameter (Y_g), defined in Eq. (2), is less than 0.143, assuming that the particle density is higher than that of the fluid.

$$Y_g = \frac{3 \cdot \tau_0}{2 \cdot R \cdot |\Delta_\rho| \cdot g} \tag{2}$$

where $|\Delta_\rho|$ is the density difference between the particle and the fluid, R is the radius of the particle, and g is the gravitational acceleration. Thus, in fresh concrete, the beginning of coarse aggregate settlement is related to the yield stress of the mortar, the density difference between coarse aggregate and mortar, and the size of the coarse aggregate. Once the settlement starts, a spherical particle will sink into the Bingham fluid with a velocity U, which may be derived from Stoke's drag equation [5]:

$$U = \frac{2}{9} \cdot \frac{R^2 \cdot |\Delta_\rho| \cdot g}{\eta_p \cdot C_s} \tag{3}$$

where η_p is the plastic viscosity of the fluid, and C_s is Stoke's drag coefficient. Therefore, the velocity of the aggregate settlement is directly dependent on the difference in density between the coarse aggregate and the mortar and the size of coarse aggregate, and it is inversely dependent on the plastic viscosity and drag coefficient. When the aggregates' density is lower than that of the mortar, the principal parameters that affect the stability of the fresh concrete are the same; i.e., Eq. (3) is still valid and predicts an upward movement of coarse aggregate [6].

Tattersall and Baker [7] showed that when vibration is applied, there is a significant reduction in the yield stress and a decrease in the viscosity of the concrete. However, de Larrard et al. [8] found that the plastic viscosity is unaffected by vibration, which is consistent with previous research [6,9,10] that found that concrete viscosity is more important than yield stress for concrete segregation during vibration.

Petrou et al. [5] studied the aggregate settlement in concrete in real time using a scintillation camera to observe and record the settlement of radioactively "tagged" aggregate in mortar and concrete during vibration. They found a linear relationship between aggregate settlement and vibration time.

Chia et al. [6] and Petrou et al. [5] studied the settlement of lightweight and heavyweight aggregates in concrete, respectively. Both found that concrete mixtures that present a higher difference between the densities of coarse aggregate and mortar have a greater segregation tendency.

The relationship between aggregate size and shape and segregation tendency has been studied in different types of concrete [5,6,11,12]; such as, normal-weight, lightweight and self-compacting concrete. Shen et al. [11] showed that a reduction of 30% in the maximum size of aggregate (MSA) greatly reduces dynamic segregation. The lower segregation tendency shown in mixtures with lower MSA was mainly attributed to the increased drag force provided by mortar on smaller aggregates, which have a higher specific surface (i.e., surface area-to-volume ratio). In contrast, Esmaeilkhanian et al. [12] compared dynamic segregation in concrete using either crushed aggregate or rounded aggregate with similar particle size distribution and found that the segregation tendency was not significantly different between the two mixtures. This result was explained by the fact that the aggregate surface-to-volume ratio does not change considerably between the two mixtures.

The relationship between the aggregate properties and segregation tendency of concrete during vibration has been studied by several researchers over the last decade. However, the combined effect or interaction between coarse aggregate properties requires further investigation.

2. Research significance

The stability of fresh concrete without segregation is an important issue to be considered for concrete mixture design. The aim of this research is to assess the combined effects of coarse aggregate size, shape and the difference in density between coarse aggregate and mortar on the dynamic segregation of fresh concrete under vibration. This will provide a more adequate understanding and estimate of the intrinsic segregation tendency of a concrete mixture.

3. Materials and methods

3.1. Material properties and mixture proportion

Ordinary Portland cement (OPC) with a specific gravity of 3.14 and Blaine fineness of 410 m^2/kg was used, and a natural river sand with a fineness modulus of 3.18 was used as fine aggregate (FA) for all mixtures. The absorption of FA was 0.97%, and the specific gravity was 2.72 at the saturated surface dry (SSD) condition. Additionally, high-range water reducer admixture (HRWA) was used in a dosage of 0.25% by cement weight for all mixtures.

A normal-weight aggregate (NWA)—namely, gravel—and three lightweight aggregates (LWA)—namely, expanded shale, expanded clay and expanded polystyrene—were used as coarse aggregate (CA). The four types of CAs were sieved to obtain different single-sized aggregates. The physical properties of single-sized NWA and LWA used in the study are given in Table 1. The absorption of LWA was obtained after 72 h immersion to maximize the pore saturation [13].

Stereology, a well-known technique used for interpreting three-dimensional characteristics of materials based on two-dimensional cross sections, was chosen to quantify the aggregate specific surface area (SSA) of CA. The estimation of SSA was made from vertical uniform random (VUR) sections using an unbiased stereology technique based on cycloids. Cycloids were used because they are considered to be isotropic lines on VUR sections in 3D space [14]. SSA is estimated from Eq. (4).

$$SSA = 2 \cdot \frac{\sum I}{\sum P \cdot l} \cdot \frac{V_c}{V_a} \tag{4}$$

where $\sum I$ is the number of intersections, $\sum^P$ is the number of points counted, l is the length of cycloid per point, V_c is the volume of concrete of the sample, and V_a is the volume of aggregate of the sample. Since, V_c and V_a are given by the mixture design, the actual procedure is based on the estimation of $\frac{\sum I}{\sum P \cdot l}$.

To illustrate the estimation of SSA from VUR sections, consider the vertical section shown in Fig. 1. A cycloidal test system has been randomly placed on the image. The test system has a known length of cycloid per point (l). In order to estimate SSA, two counts need to be made on this figure:

a. The number of intersections between the test lines and the boundary of interest (I). For example, in the case showed in Fig. 1 there are 20 intersections.
b. The number of points that land within the reference space (P). For example, in the case showed in Fig. 1 there are 16 points.

In this study, two series of concrete mixtures were prepared. Series I consisted of ten mixtures used to assess the relationship between the segregation of concrete under vibration and coarse aggregate size and the difference in density between coarse aggregate and mortar. Series II consisted of two additional mixtures used to validate the findings and the relationship established with the concretes of Series I. The concrete mixtures had a water–cement ratio (W/C) of 0.45 and consisted of approximately 70% mortar and 30% coarse aggregate by volume; the proportion of each constituent was kept constant in all mixtures. Table 2 presents the mixture proportions of both series. The moisture states of FA and CA in the given mixture proportions were SSD.

3.2. Mortar characterization

Table 3 lists the mixture proportions and physical properties of the mortar used (M1). The rheological behavior of the mortars is determined by the W/C ratio and the ratio of sand to mortar (s/m) [15]. Previous researchers established procedures for computing normal-weight [16] and lightweight [17] concrete. According to these procedures, the ratio of s/m and the ratio of W/C of M1 are similar to those of conventional mortars.

Several authors [5,9,10,18] have shown that the segregation tendency of concrete is related to its mortar viscosity and has no relation to its mortar yield stress. However, Hafidi et al. [19] established that a direct relation exists between the mortar viscosity and its V-funnel flow time (V-time) [1]. Therefore, the V-funnel test