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Estimating the segregation of concrete based on mixture design and vibratory energy

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HIGHLIGHTS

- Five segregation degrees are proposed to evaluate the segregation of concrete.
- Proposal of a model for segregation based upon mixture design and vibratory energy.
- Segregation trend is mainly related to mixture design rather than to vibration process.
- Aggregate properties is the factor that most affect the vibrated concrete stability.

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ABSTRACT

Controlling the segregation of concrete during construction is important for assuring design strength and durability. This paper aims to model segregation by assessing how the stability of fresh concrete is affected by the maximum size and density of coarse aggregates (CA), mortar viscosity, maximum acceleration during vibration, and vibration time. The results show that CA properties have the greatest effect on the stability of concrete under vibration, followed by the mortar viscosity and the energy applied by unit mass of concrete. Therefore, the tendency of a concrete mixture to segregate or remain uniform is mostly controlled by the mixture design rather than by the vibration process.

1. Introduction

A major problem that affects fresh concrete is the tendency for coarse aggregates (CA) to separate from the mortar, causing decreased uniformity and greater variability in properties. Among the consequences of segregation, the most important are deleterious effects on the strength and durability of structures [1]. Since the construction workforce is generally unskilled [2], controlling the mixture design is necessary to ensure the quality of any construction.

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

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

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. Thus, the flow of concrete can be described by two parameters, τ_0 and η_p.

Abbreviations: τ_0, yield stress; η_p, plastic viscosity; $|\Delta_\rho|$, density difference between the aggregate and the mortar; a_{max}, maximum acceleration during the vibration; A_p, aggregate segregation parameter; ANOVA, analysis of variance; CA, coarse aggregate; FA, fine aggregate; LWA, lightweight aggregate; MLR, multiple linear regression; MSA, maximum size aggregate; NWA, normal-weight aggregate; OPC, ordinary Portland cement; SSA, specific surface area; SSD, saturated surface dry; VI, volumetric index; V_p, viscosity segregation parameter; V_{time}, V-funnel time; VUR, vertical uniform random; W_{mr}, energy rate by unit mass; W_m, energy applied by unit mass of concrete.

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Fresh concrete can be considered as a two-phase composite material with CA particles embedded in a mortar matrix. Beris et al. [4] used Bingham plastic behavior to predict how particles would settle in a fluid. A sphere will settle when the yield stress parameter (Y_g), is less than 0.143, assuming the particle density is greater than that of the fluid; this parameter is defined as follows:

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

where $|\Delta_\rho|$ is the density difference between the particle (i.e., CA) and the fluid (i.e., mortar), R is the radius of the particle, g is the gravitational acceleration. Once settling begins, the movement of a spherical particle in a Bingham fluid can be derived from the Stokes equation [5], defined as follows:

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

where U is the velocity of the sphere's movement in the fluid and C_s is the Stokes drag coefficient.

Eqs. (2) and (3) show that the time at which CA in fresh concrete begin moving depends on the τ_0 of the mortar, the density difference between the CA and the mortar matrix, and the size of the CA. Once movement occurs, its velocity is affected by the η_p of the mortar, the density difference between the CA and the mortar, and the size of the CA. When the CA density is lower than that of the mortar, the principal factors that affect the stability of the fresh concrete are the same; that is, the fresh concrete follows Eq. (3), which predicts an upward movement of CA [6].

The vibration of concrete decreases its τ_0 which makes concrete to flow easily under the same τ compare to the un-vibrated state [7], at least at low $\dot{\gamma}$ [8,9]. In addition, as concrete is vibrated, the η_p at a particular $\dot{\gamma}$ is reduced. Therefore, the tendency to segregate is expected to increase when concrete is vibrated.

Previous studies [6,10–12] have focused on the relationship between CA properties and the concrete tendency to segregate. Concrete mixtures with a greater $|\Delta_\rho|$ tend to segregate more [6,10]. In contrast, mixtures with lower maximum size aggregates (MSA) tend to segregate less [11,12].

Banfill et al. [13] found that segregation occurs when the energy input by a vibratory wave is high enough to overcome the attraction force between the cement particles, reducing the τ_0. The energy equation postulated by Kirkham and White [14] is as follows:

$$W = c_1 \cdot m \cdot s^2 \cdot f^3 \cdot t \quad (4)$$

where W is the energy input from vibration; c_1 is a constant, depending on the stiffness and damping of the concrete; m is the concrete mass; s is the amplitude of vibration; f is the frequency of vibration; and t is the vibration time. The equation is a function of the vibratory amplitude and frequency, which are related to the maximum acceleration (a_{max}), calculated as follows:

$$a_{max} = 4 \cdot \pi^2 \cdot f^2 \cdot s \quad (5)$$

The effect of amplitude and frequency of vibration on the segregation of concrete have been studied separately [15–17]. However, according to the authors' knowledge, the relationship between energy and the tendency to segregate has not been assessed.

Previous studies have examined separately the relationship between mixture design parameters, vibrational characteristics and the tendency of concrete to segregate. However, the effect of the interaction between mixture design parameters and vibrational characteristics on the stability of fresh concrete requires further investigation.

2. Research significance

The ability of fresh concrete to remain uniform (i.e., not to segregate) during consolidation is a critical issue in the mixture design. The aim of this study is to assess the effect of size and unit weight of the coarse aggregate, mortar viscosity, energy applied during consolidation by unit mass of concrete, and their interactions on the stability of fresh concrete. This will improve the understanding and estimation of the concrete segregation.

3. Materials and methods

3.1. Material properties and mixture proportions

All mixtures used Ordinary Portland cement (OPC), with a specific gravity of 3.14 and Blaine fineness of 410 m^2/kg, and a natural river sand with a fineness modulus of 3.18 was used as the fine aggregate (FA). The absorption of the FA was 0.97%, and the specific gravity was 2.72 at the saturated surface dry (SSD) condition.

The CAs included a normal-weight aggregate (NWA), specifically crushed gravel, and three lightweight aggregates (LWA), expanded shale, expanded clay and expanded polystyrene. The four types of CAs were sieved to obtain different single-sized aggregates. The physical properties of the single-sized NWA and LWAs used in the study are given in Table 1. The absorption of the expanded shale and the expanded clay was obtained after 72 h of immersion to maximize pore saturation [18].

Stereology parameters were used to measure the specific surface area (SSA) of the CA of concrete samples. The SSA was estimated from vertical uniform random (VUR) sections using an unbiased stereology technique based on cycloids. Cycloids were used because they are considered isotropic lines on VUR sections in 3D space [19]. The SSA is estimated using the following equation:

$$SSA = 2 \cdot \frac{\sum I}{\sum P \cdot l} \cdot \frac{V_c}{V_a} \quad (6)$$

where $\sum I$ is the number of intersections; $\sum P$ is the number of points counted; l is the length of one test line; V_c is the volume of concrete in the sample; and V_a is the volume of aggregate in the sample.

Three mortars were used, all of which had the same proportion of water, OPC and FA and; their viscosities were modified by varying their respective high range water reducer admixture (HRWRA) dosages [20,21]. The mortars mixture design was based on that of a self-compacting mortar from a previous study [22], with very low τ_0; therefore, τ_0 is expected to be negligible in the mortars used herein. Additionally, based on Hafidi et al. [23] findings between a direct relationship between mortar η_p and the V-funnel time (V_{time}) [1], the V-funnel test was selected to characterize the η_p of each mortar. Table 2 shows the V_{time} and HRWRA dosage by OPC weight of each mortar.

Table 1
Physical properties of single-sized aggregates.

Aggregate	Size (mm)	SSA (1/mm)	SSD density (kg/m^3)	$\|\Delta_\rho\|$ (Ton/m^3)	Absorption, 72 h (%)
Crushed gravel	19.0–25.4	0.69	2600	0.42	2.44
	12.7–19.0	0.97	2630	0.42	1.74
Expanded shale	12.7–19.0	0.90	1370	0.89	12.47
Expanded clay	9.5–12.7	1.38	950	1.30	22.72
Expanded polystyrene	4.8–9.5	1.98	15	2.25	–
	2.4–4.8	2.48	15	2.25	–