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Measuring static stability and robustness of self-consolidating concrete using modified Segregation Probe

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HIGHLIGHTS

- Modified Segregation Probe resolved the occasional tilting problem of the original design.
- The design based on rheology and mechanics analysis.
- Procedure to test and quantify stability robustness using modified Segregation Probe.

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ABSTRACT

Compared with normal concrete mixes, the segregation resistance of self-consolidating concrete (SCC) are more sensitive to small variations of properties such as gradation and moisture content of aggregates, type and dosage of superplasticizer, etc. To study segregation and design an SCC mix, which is robust against small variations in raw materials, it is critical to be able to quickly quantify static segregation and stability robustness. In this paper, a modified Segregation Probe is introduced as a simple and fast method for testing static segregation and stability robustness of fresh concrete. The modified Segregation Probe resolved the occasional tilting problem of the original design. The design of the modified Segregation Probe was explained based on rheology and mechanics analysis. The results of the modified Segregation Probe agreed well with the Penetration Test (ASTM C1712-09), the Column Segregation test (ASTM C1610/C1610 M-10), and the original Segregation Probe (when no tilting problem happened). Lastly, the procedure to test and quantify stability robustness using modified Segregation Probe is presented.

1. Introduction

The three major fresh property requirements for self-consolidating concrete (SCC) are flowing ability, passing ability, and stability (static and dynamic segregation resistance). Segregation is the separation of coarse aggregate from the mortar. The separation after SCC is cast into place is called static segregation, while the separation during the process of placement is called dynamic segregation [5].

In order to satisfy the three requirements simultaneously, the viscosity and yield stress of cement paste, the volume, Maximum size, gradation, as well as moisture content of the fine and coarse aggregates should be well controlled within small acceptable ranges of variations. Therefore, it is of great importance to have a robust mixture, which is minimally affected by the external sources of variability [5]. In fact, robustness checking has been recognized as a critical step in mix design of SCC [6].

To study the segregation and stability robustness of SCC, it is much desired to be able to measure segregation quickly and accurately. The authors introduced the Segregation Probe (Fig. 1(a)) test for static segregation in a previous manuscript [13].

The basic procedure is summarized as follows:

(1) Raw materials are mixed in a mixer according to standard procedure (Sand, coarse aggregate, and water were put in a drum mixer and mixed for 30 s. Then Cement and mineral admixture, if any, were put in the mixer and mixed for 3 min. Mixer was stopped for 3 min. after that, Mixer was restarted, and superplasticizer and/or VMA were slowly poured and mixed for 2 min).
(2) Fresh concrete is cast into a 150 × 300 mm cylinder with one lift and allowed to rest for 2 min before the test, during which time vibration of the cylinder is avoided.

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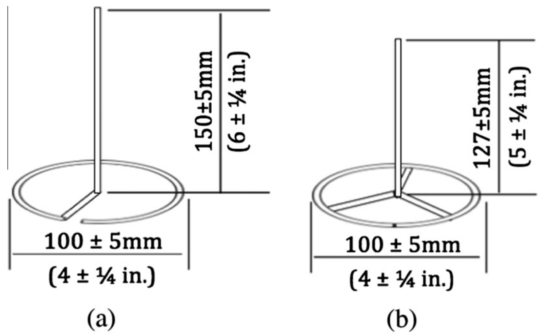

Fig. 1. (a) Original Segregation Probe (18 g), and (b) modified Segregation Probe (24 g) made of 2.38-mm (3/32 in.) diameter stainless steel wire.

(3) The Segregation Probe is placed gently on the concrete surface and allowed to settle for 1 min.
(4) The penetration depth is measured using the scale marked on the rod. This depth is used to determine the stability rating according to Table 1.

Verified by image analysis of cut cylinders, the Segregation Probe was found to be able to measure the actual thickness of the paste/mortar layer on the top surface of a segregated mix [13]. Clear correlation was also found between the Segregation Probe and the Column Segregation test [13,2]. A layered finite element model has been developed to analyze the development of internal stress due to shrinkage gradient caused by static segregation. The results showed that Stability Indices of 0 and 1 do not significantly increase internal stress of concrete due to shrinkage gradient, while Stability Indices of 2 and 3 increase the tensile stress significantly and could result in surface cracking [13].

Commonly used static segregation tests include Column Segregation [2], Penetration Test [3], V-Funnel test [7], Electrical Conductivity [8], Sieve Segregation Resistance Test [10], Hardened Visual Stability Index [1], Image Analysis of Hardened Cylinder [12], among others. Compared with other static segregation tests, the Segregation Probe is especially suitable for the assessment of a mix's robustness against fluctuations in mix proportions due to several reasons. First of all, only the Segregation Probe and a concrete mixer are needed for the robustness test. Setup frame, mold, slump cone, electrical devices, or even sampling is not required during the test. Secondly, robustness test can be performed directly in a pan or drum mixer as long as the depth of concrete is controlled at around 300 mm (12″), making it convenient to slightly modify the mix proportions. Finally, a robustness test which including a series of mixing, Segregation Probe test, and remixing takes only around 15 min and the effects of thixotropy and hydration are minimized.

It should be mentioned that the term "robustness" could refer to the insensitivity of a SCC mix's flowing ability, passing ability, or stability to small changes of material composition, mixing and casting process, and environmental factors [4]. For simplicity purpose, the term "robustness" in the remainder of this paper only refers to the ability of a mix to resist static segregation. A mix's ability to resist dynamic segregation (dynamic stability robustness) will be discussed in a future paper of the authors.

Table 1
Stability rating for Segregation Probe (for concrete with ~300 mm thickness) (Data from [13].

Depth of settlement mm	Stability index, SI
<4	0, highly stable
4–<7	1, stable
7–25	2, unstable
>25	3, highly unstable

2. Objectives

It was found in several cases that when a mix is severely segregated (SI = 3, e.g.), the Segregation Probe may tilt during the relatively long settling process and cause incorrect readings. The tilted probe is mainly due to its asymmetric design around the vertical axis. As the probe settles, the unevenly distributed gravitational force and drag force from the paste may cause the probe to tilt, and the effect of unbalanced forces amplifies with lower paste viscosity and yield stress when the mix becomes highly unstable.

The main objectives of the research are: (1) to resolve the inclination issue by modifying the probe design, (2) to verify the design of the modified Segregation Probe theoretically based on mechanics analysis, (3) to verify the results of modified Segregation Probe with the original Segregation Probe, the Penetration Test, and the Column Segregation test, (4) to check the reproducibility of the modified Segregation Probe, and (5) to study robustness of SCC mixes using modified Segregation Probe.

3. Modified Segregation Probe

3.1. The design

As shown in Fig. 1(b), the modified Segregation Probe has a 100-mm (4″) diameter ring connected by three legs to a 125-mm (5″) rod marked with a scale. The whole probe is made of 2.38-mm (3″/32) diameter stainless steel wire and the total mass is around 24 g. The modified Segregation Probe was described more briefly in an earlier paper [11]. Because of its symmetric design, the modified Segregation Probe eliminates the cause of inclination in the original design. Figs. 2 and 3 compare the modified Segregation Probe and the original design.

The size, geometry, and weight of the modified Segregation Probe were designed based on mechanics analysis so that the probe can penetrate the mortar/paste layer, but sit on top of coarse aggregate. The modified Segregation Probe can be simplified as a long cylinder with a diameter 2.38-mm. The probe in a fresh concrete mix experiences two opposing forces before it is released from at rest, a buoyancy force B_F and a gravitational force G_F, as shown in Fig. 4(a). Since steel has a higher density than the concrete, the probe will start to settle vertically due to the unbalanced force ($G_F - B_F$) if the yield stress is not high enough to hold off the probe.

When the probe is settling downward, the suspension will provide another force called the drag force, F_D, as shown Fig. 4(b). Drag force F_D resists the settling of the probe, increases with higher speed, reduces the acceleration, and will eventually become equal to the original driving force ($G_F - B_F$) unless other forces break the balance. Then there are no unbalanced forces acting on the probe and it continues to travel at a constant settling velocity, u_∞.

According to fluid mechanics, the drag force F_D can be expressed as [15]:

$$F_D = 0.5\rho \times u^2 \times A \times C_D \quad (1)$$

where ρ is density of the suspension, u is settling speed, A is reference area (projective area perpendicular to the settling direction), which equals $d \times (\pi D + 1.5D)$ —where d (0.00238 m) is the diameter of the cylinder cross section and D (0.1 m) is the diameter of the