

SEGREGATION ROBUSTNESS OF SELF-CONSOLIDATING CONCRETE: NEW TESTING METHOD AND EFFECT OF AGGREGATE PROPERTIES

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ABSTRACT

The fresh properties of self-consolidating concrete (SCC) are typically sensitive to small changes of material properties such as moisture content of aggregates, dosage of superplasticizer, etc. To consistently maintain the desired performance in mass production of SCC, it is essential to design and select a SCC mix which is robust against small variations in raw materials. A new testing method, modified Segregation Probe, was found to be able to quickly quantify and rank the stability robustness of various candidate mixes. This test can be performed in a pan or drum mixer and finished in about 15 minutes. It was found that higher paste volume, smaller aggregate size, better gradation, and higher aggregate packing density can improve robustness. Among these factors, smaller aggregate size and better gradation seem to have more significant effects than higher paste volume and higher aggregate packing density.

Keywords: self-consolidating concrete; robustness; segregation; aggregate packing

1. INTRODUCTION

The three major functional requirements for self-consolidating concrete (SCC) during the fresh state are flowing ability, passing ability, and stability (segregation resistance). In order to satisfy the three requirements simultaneously, the rheology of cement paste and the size, gradation, as well as moisture content of the used aggregates should be well controlled within small ranges of variations. Therefore, it is of great importance to have a robust mixture, which is minimally affected by the external

sources of variability [1]. Robustness checking has been recognised as a critical step in SCC design process [2]. It should be mentioned that 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 [3]. Moreover, stability could be further classified as to a mix's resistance to 1) dynamic segregation during casting and placement, and 2) static segregation after placement and finish. In the remainder of this paper, robustness simply refers to the ability of a mix to resist static segregation. A mix's ability to resist dynamic segregation will be discussed in a future paper of the authors. To study the robustness of SCC, fast and accurate test methods are essential, and the authors presented the Segregation Probe (Figure 13(a)) test for quantifying static segregation in a previous manuscript [4]. It was found the Segregation Probe can actually measure the thickness of the paste/mortar layer on top of segregated SCC and clear direct correlation was found between the Segregation Probe and Column Segregation test [4, 5]. The stability rating criteria based on penetration depth is shown in Table 9. Finite element model has been used to simulate internal stress of concrete due to shrinkage gradient because of static segregation. It was found that Stability Index of 0 and 1 do not significantly increase internal stress of concrete due to shrinkage gradient, while Stability Index of 2 and 3 increase the tensile stress significantly and may result in cracking [4].

Table 9 Stability Rating for Segregation Probe Method (for concrete with ~300mm thickness)

Depth of Settlement mm	Stability Index, SI
< 4	0, stable
4 – <7	1, stable
7 – 25	2, unstable
> 25	3, unstable

Commonly used static segregation tests include Column Segregation [5], Penetration Apparatus [6], V-Funnel test [7], Electrical Conductivity [8], Sieve Segregation Resistance Test [9], and Hardened Visual Stability Index [10], among others. Compared with other static segregation tests, the Segregation Probe is especially suitable for the assessment of robustness against fluctuations in mix proportions due to several reasons. First of all, it can be performed directly in a pan or drum mixer as long as the depth of concrete is around 300mm (12"), making it convenient to slightly modify the mix proportions. Secondly, setup frame, mold, or sampling is not required during the robustness test. Finally, the robustness test which including a series of mixing, testing, and remixing takes only around 15 min and the effects of thixotropy and hydration are minimized.

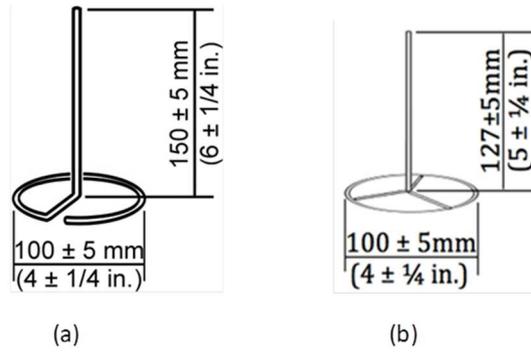


Figure 13. (a) Segregation Probe, and (b) Modified Segregation Probe.

2. OBJECTIVES

It was found in several cases that when concrete became highly unstable, the Segregation Probe may tilt during settlement and cause incorrect reading (Figure 14). The tilted probe is mainly due to its asymmetric design. 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. The main objectives of the research are: 1) to resolve the inclination issue by modifying the probe design, 2) to study the effects of mix proportions such as aggregate properties on robustness.



Figure 14. Tilted Segregation Probe in a severely segregated mix.

3. MODIFIED SEGREGATION PROBE

As shown in Figure 13 (b), the modified Segregation Probe has a 100-mm (4") diameter ring connected to 127-mm (5") rod marked with a scale. The probe is made of 2.38-mm (3"/32) diameter stainless steel wire with a total mass of around 24g. The modified Segregation Probe adopted a symmetric design around its vertical rod, which

effectively eliminates the cause of inclination. Figure 15 shows a side-by-side comparison between the modified Segregation Probe and the original design in a highly unstable mix.



Figure 15. Modified Segregation Probe (left) and tilted original design (right).

The weight and geometry of the modified Segregation Probe were designed to be able to penetrate a suspension with a yield stress of less than 36 Pa, which was found to be higher than the yield stress of the mortar of a typical SCC, but lower than the yield stress the concrete itself. Figure 16 compares the results from Penetration Test (ASTM C1712-09 [252]) and modified Segregation Probe. Since the penetration limit for a stable mix is 10mm for Penetration Test and 7mm for modified Segregation Probe, any point in Zone 1 and 2 indicates disagreement between the two tests. Similarly, points in Zone 3 and 4 denote agreement between the two tests. Clearly, there is a good correlation between the Penetration Test and modified Segregation Probe test as the majority of the data points are in Zone 3 and 4. The results of modified Segregation Probe and the original design also agreed reasonably well. The details of design, verification, and reproducibility of the modified Segregation Probe will be presented in a later paper.

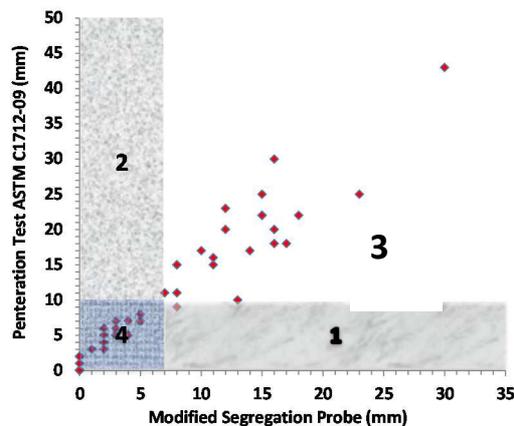


Figure 16. Results of Penetration Test (ASTM C1712-09) and modified Segregation Probe.

4. ROBUSTNESS TEST

The robustness test was done directly in a drum mixer with a concrete thickness of around 300mm (12”) at the measuring point. In total, fifteen mixes with various concrete parameters were tested in this project, while the focus of this paper is on the effects of aggregate properties on robustness and results of six relevant mixes will be presented. As shown in Table 10, six mixes with different aggregate volume, size, gradation, and packing density were tested. Coarse aggregate CA1 has Max. size of 19mm, Bulk Specific Gravity of 2.56, Bulk Density of 1473 kg/m³, and packing density of 0.55. Coarse aggregate CA2 has Max. size of 9.5mm, Bulk Specific Gravity of 2.67, Bulk Density of 1491 kg/m³, and packing density of 0.54. Fine aggregate FA has Bulk Specific Gravity of 2.51, Bulk Density of 1677 kg/m³, Fineness Modulus of 3.50, and packing density of 0.63. The slump flow at target w/cm was controlled at 660 ± 25mm and the following procedure was used:

1. Aggregates and water were put in a pan mixer and mixed for 30 s.
2. Cement and mineral admixture, if any, were put in the mixer and mixed for 3 min.
3. Mixer was stopped, and there was a 3 min wait.
4. Mixer was started, and the superplasticizer or VMA, or both, were added and mixed for 2 min.
5. Mixer was stopped, modified Segregation Probe was gently placed on the concrete surface and allowed to settle until it stopped (in about 15 sec).
6. The penetration depth was measured.
7. The w/cm was increased stepwise by 0.01 (or 0.02 for highly stable mixes to save time) by adding water and mixing for 1 min.
8. Steps 5–7 were repeated until clear evidence of excessive segregation was observed.

Table 10 Mix design and results for robustness tests.

Mix ID	Target w/cm	Material (kg/m ³)					%AGG by vol.	Φ _m	Admixture		Slump (mm)	TMS0 (Tolerable Moisture To SI of 0, w/cm)	TMS1 (Tolerable Moisture To SI of 1, w/cm)
		Cement (Type I)	CA1 19mm	CA2 9.5mm	Fine AGG	Water			SP % of cement	VMA % of water			
Base	0.41	514	854	0	728	209	62	0.66	0.22	0.23	710	0.06	0.13
More Paste	0.41	582	783	0	670	236	57	0.66	0.18	0.12	710	0.10	0.14
Small Coarse	0.42	506	0	712	936	212	63	NA	0.32	0.25	660	0.17	0.21
Well Graded 1	0.42	538	533	115	965	226	61	NA	0.25	0.19	660	0.13	0.15
Well Graded 2	0.42	538	509	136	967	226	61	NA	0.37	0.19	660	0.17	0.20
High Packing	0.41	585	468	593	585	238	59	0.71	0.51	0.20	685	0.12	0.14

5. RESULTS AND DISCUSSIONS

The robustness of a mix can be quantified based on the Tolerable Moisture to Stability Index of 1 (TMS1), which is defined by the difference between the target w/cm and the w/cm corresponding to the limiting penetration depth of 7mm. Compared with a mix with lower TMS1, a mix with higher TMS1 can tolerate more moisture (due to daily aggregate moisture fluctuation, metering inaccuracies...) while maintaining its stable state. Figure 17 shows the effects of total aggregate volume and aggregate size on robustness of SCC. Compared with the “Base” mix, “More Paste” mix had 5% more paste volume and “Small Coarse” mix had smaller maximum and average aggregate size. The TMS1 of Base, More Paste, and Small Coarse mix was 0.13, 0.14, and 0.21, respectively. Clearly reducing the aggregate size had a significant effect on improving robustness, while increasing paste volume was not as effective.

The relatively minor impact of higher paste volume can be further checked by comparing the TMS0 (Tolerable Moisture to Stability Index of 0) of the Base and More Paste mixes. Increasing 5% of paste volume improved the Base mix’s TMS0 from 0.06 to 0.10, indicating a more robust design. The effect of higher paste volume is also demonstrated in Figure 17, as the penetration depth of the More Paste mix was constantly less than the Base mix until both mixes became unstable.

Figure 18 illustrates how robustness was influenced by the aggregate gradation and packing density. The “Base” mix had only large (19-mm) coarse aggregate, and the “Well Graded 1”, “Well Graded 2”, and “High Packing” mixes had both large and medium (9.5-mm) sized coarse aggregate. Compared with “Well Graded 1” and “Well Graded 2” mixes, the “High Packing” mix had higher aggregate packing density and larger average aggregate size. The TMS1 of Base, Well Graded 1, Well Graded 2, and High Packing mix was 0.13, 0.15, 0.20, and 0.14, respectively. And the corresponding TMS0 values are 0.06, 0.13, 0.17, and 0.12. Results from Figure 18 imply: 1) introducing medium sized coarse aggregate to reduce average aggregate size may improve the robustness, 2) higher packing density seems not to be as effective as smaller aggregate size.

Table 10 summarizes the TMS1 and TMS0 values for all the mixes and the “Small Coarse” and “Well Graded 2” mixes can be easily identified as the most robust among the mixes. It was found from the analysis above that while higher paste volume, smaller aggregate size, better gradation, and higher aggregate packing density can all improve robustness of SCC mixes, smaller aggregate size and better gradation seem to have more significant impact on robustness than the other two factors. More tests are being planned to further study the relative impacts of aggregate properties on robustness.

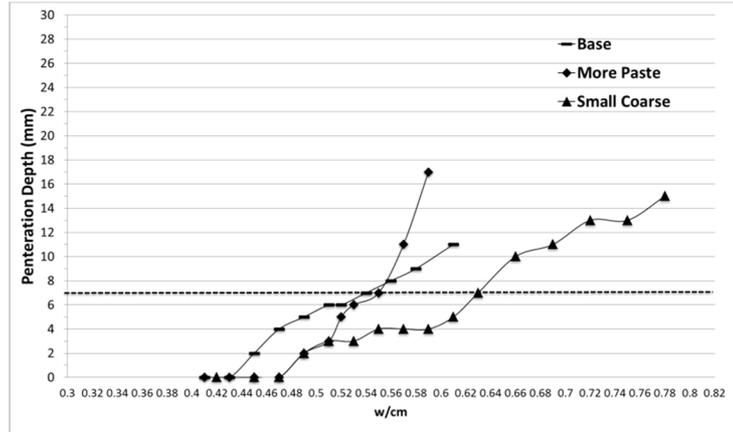


Figure 17. Effect of aggregate volume and size on robustness (TMS1 for B, MP, and SC mix: 0.13, 0.14, and 0.21; TMS0: 0.06, 0.10, and 0.17)

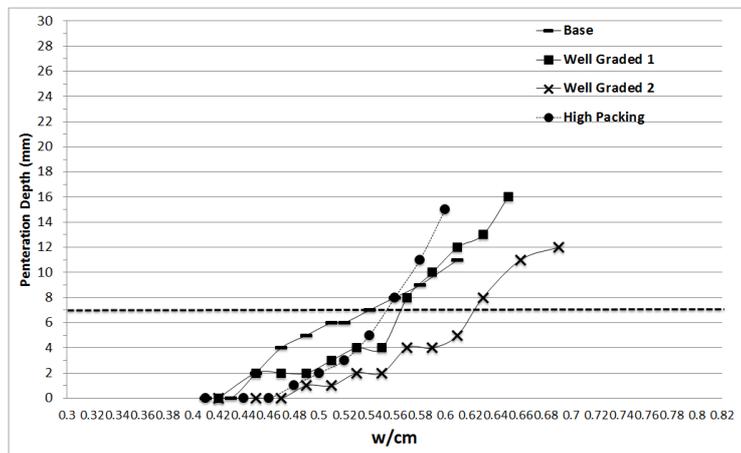


Figure 18. Effect of aggregate gradation and packing density on robustness. (TMS1 for B, WG1, WG2, and HP mix: 0.13, 0.15, 0.20, and 0.14; TMS0: 0.06, 0.13, 0.17, and 0.12)

6. CONCLUSIONS

The following conclusions were drawn from the results on modified Segregation Probe and robustness tests:

- 1) The modified Segregation Probe fixed the original design's tendency to tilt in extremely unstable mixes.
- 2) The results of modified Segregation Probe agreed well with the Penetration Test from ASTM C1712-09.

- 3) The robustness of SCC mixes can be well quantified and compared based on the robustness curves, as well as the values of TMS1 and TMS2.
- 4) Higher paste volume, smaller aggregate size, better gradation, and higher aggregate packing density can improve the robustness of SCC mixes. Among these factors, smaller aggregate size and better gradation seem to have more substantial influence on robustness than higher paste volume and higher aggregate packing density.

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