STATIC AND DYNAMIC YIELD STRESS MEASUREMENTS OF SCC

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INTRODUCTION

Concrete exhibits different rheology when at rest than when flowing due to thixotropy, which is defined as the reversible, time-dependent decrease in the viscosity of a fluid subjected to shearing. Therefore, the distinction between static and dynamic rheology measurements is important for evaluating self-consolidating concrete (1,2). This paper presents the results of a research program to evaluate the effects of static and dynamic rheological properties on SCC segregation resistance (3).

When concrete is at rest, a thixotropic, built-up structure is formed. The result is a high static yield stress, defined as the stress to initiate viscous flow from rest. Upon shearing of concrete, this thixotropic structure is destroyed, resulting in a low dynamic yield stress, defined as the stress above which viscous flow occurs in a material with no thixotropic structure. In SCC, a low dynamic yield stress is needed to ensure that concrete can flow and consolidate under its own mass. The magnitude of the static yield stress is important for zero-shear rate conditions, such as segregation resistance and formwork pressure (1,2,4). The static yield stress should increase quickly to improve segregation resistance and reduce formwork pressure.

RHEOLOGICAL PROPERTIES FOR SEGREGATION RESISTANCE

The paste in SCC is a thixotropic, Bingham fluid and must exhibit appropriate rheology to prevent the settlement of aggregates. The movement of a single sphere in a Bingham material has been studied experimentally, analytically, and numerically (5,6). Such work can be extended to the case of aggregates in cement paste. For the general case of a sphere in a Newtonian fluid, gravitational and buoyant forces act on the sphere. If the density of the sphere is greater than that of the fluid, the gravitational force will exceed the buoyant force, resulting in a net downward force, *F*, given in Equation 1:

$$F = \frac{4}{3}\pi R^3 \left(\rho_{sphere} - \rho_{fluid}\right) g \qquad \text{(Eq. 1)}$$

where R is the sphere radius, ρ_{sphere} is the density of the sphere, ρ_{fluid} is the density of the fluid, and g is acceleration due to gravity. If the fluid exhibits a yield stress, however, an opposing force attributable to the yield stress will offset the net downward force and—depending on the magnitude of the yield stress—can prevent the sphere from settling. If the yield stress is insufficient, the rate of descent of aggregates is affected by both yield stress and plastic viscosity (7). The settlement of an aggregate in paste is complicated by many factors, including the shape of individual aggregate particles (8) and interaction from neighboring aggregate particles (5).

Bethmont et al. (9) compared three equations relating yield stress to segregation resistance (Table 1) by experimentally determining whether glass spheres of varying sizes would settle in pastes of varying yield stresses. The equations of Beris et al. (7) and Jossic and Magnin (8) were found to be suitable.

Table 1: Comparison of Equations for Segregation Resistance

Reference	Minimum Yield Stress to Prevent Settlement
Berris et al., 1985 (7)	$\tau_0 \geq \frac{2}{3} Y_g g(\rho_{sphere} - \rho_{fluid})R = (0.09533) g(\rho_{sphere} - \rho_{fluid})R$
Jossic and Magnin, 2001 (8) (rough sphere)	$\tau_0 \geq Y_{\max} g(\rho_{sphere} - \rho_{fluid})2R = (0.124) g(\rho_{sphere} - \rho_{fluid})R$
Saak et al., 2001 (10)	$\tau_0 \geq \frac{4}{3} g(\rho_{sphere} - \rho_{fluid})R$

In evaluating paste rheology, however, a distinction must be made between static and dynamic yield stress, which is illustrated conceptually in Figure 1 (4). The static and dynamic yield stresses are equal immediately after mixing. The dynamic yield stress increases due to the loss of admixture efficacy and hydration. The static yield stress of un-agitated, at-rest SCC increases faster than the dynamic yield stress because of the build-up of an easily destroyed thixotropic structure, which acts in addition to the effects of reduced admixture efficacy and hydration. When the concrete is placed, the resulting shearing fully breaks down the thixotropic at-rest structure, such that the static yield stress again equals the dynamic yield stress. Once the concrete is again at rest in the formwork, the thixotropic at-rest structure rebuilds and the static yield stress increases.

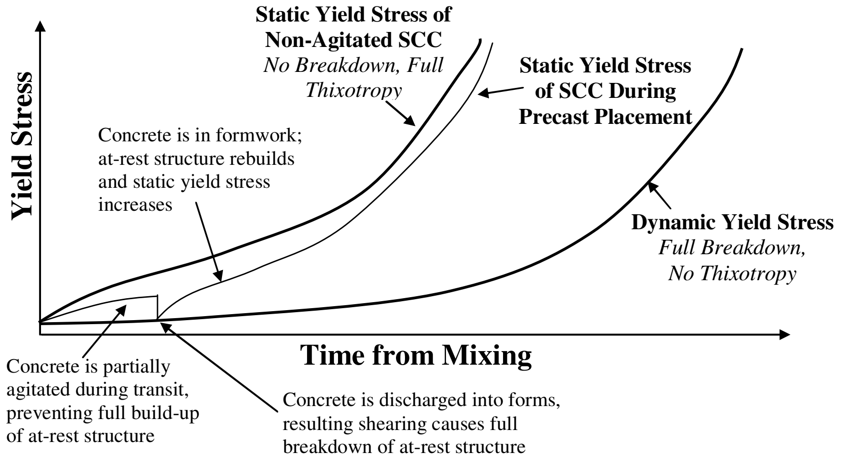


Figure 2: Conceptual Changes in Static and Dynamic Yield Stress Over Time (4)

In evaluating segregation susceptibility, the static yield stress should be considered because the concrete is at rest. The dynamic yield stress is important because the static and dynamic yield stresses are initially equal. The difference between static and dynamic yield stress at any given time reflects the extent of build-up of the thixotropic, at-rest structure. It is the absolute magnitude of the static yield stress—not the amount of thixotropy per say—that ultimately should determine whether an aggregate settles.

EXPERIMENTAL PROGRAM

Materials, Mixture Proportions, and Test Methods

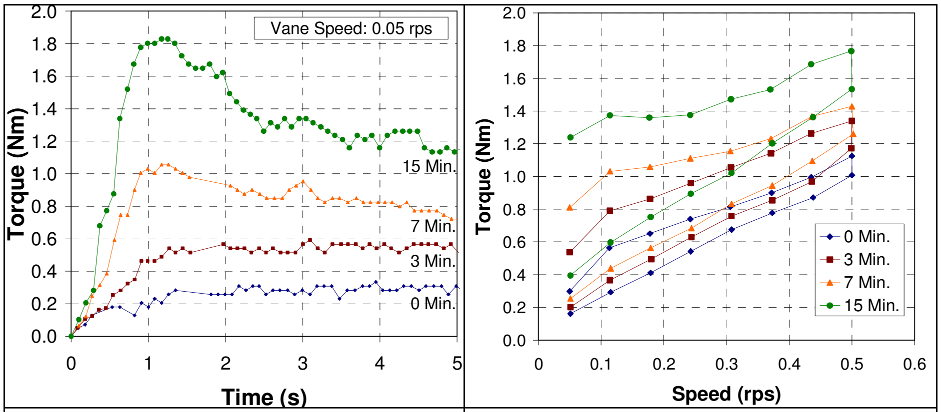
Measurements of rheology and segregation resistance were conducted on 31 concrete mixtures. The mixtures varied in paste volume (30 to 38%), sand-to-aggregate ratio (0.40 to 0.50), and w/cm (0.24 to 0.39). All mixtures included a natural sand, a rounded siliceous river gravel with ¾-inch (19-mm) maximum size, a Type III cement, and 25% Class F fly ash. The dose of a polycarboxylate-based high-range water-reducer was adjusted in each mixture to achieve a slump flow of 28 to 30 inches (710 to 760 mm).

The segregation resistance of each mixture was evaluated with the column segregation test (ASTM C 1610). Slump flow, T_{50}, and VSI were measured in accordance with ASTM C 1611. Rheology was measured with the ICAR Rheometer, which is a portable rheometer with vane geometry. Rheometer measurements were started as soon as practical after mixing ended and concrete was transferred to the rheometer. First, a stress growth test was performed by rotating the vane at a constant speed of 0.05 rps, with the maximum measured torque used to calculate yield stress. A flow curve test was then conducted by increasing the speed from 0.05 to 0.50 rps in 8 discrete steps, holding the speed constant at 0.50 rps for 20 seconds, and decreasing the speed from 0.50 to 0.05 rps in 8 discrete steps. The dynamic yield stress and plastic viscosity were calculated from the descending flow curve and the area between the ascending and descending curves was calculated as a measure of thixotropy.

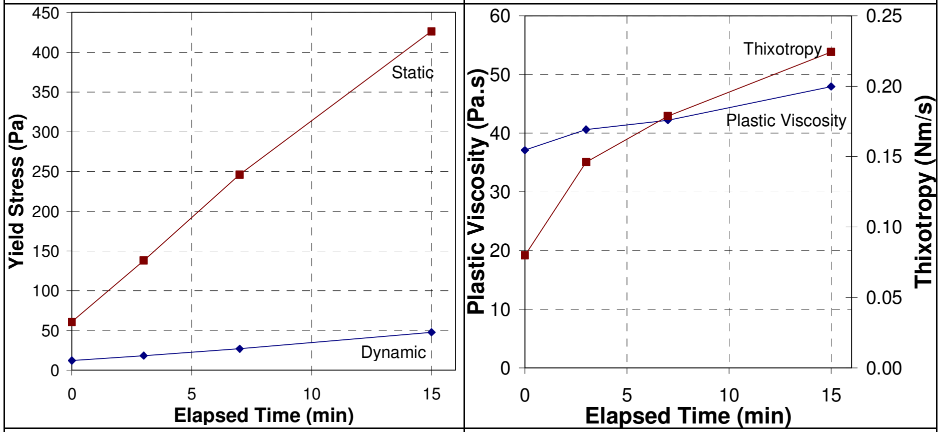
Although paste rheology is more directly relevant than concrete rheology to segregation resistance, the correlation of paste rheology measurements to concrete performance suffers from experimental artifacts (11). Therefore, concrete rheology measurements were used.

Results and Discussion

The changes in rheology with time are illustrated in Figure 3 for one typical mixture that exhibited good segregation resistance. Rheological measurements were conducted on separate fresh concrete specimens that were sampled from the same concrete batch immediately after mixing and allowed to remain undisturbed until testing. The stress growth test indicated that the static yield stress—a function of the maximum torque achieved and the geometry of the vane—increased with time. The flow curve test indicated that the dynamic yield stress, plastic viscosity, and thixotropy increased with time. Although the dynamic yield stress remained low, the static yield stress increased at a much faster rate, which was beneficial for simultaneously achieving static segregation resistance when the concrete was at rest and high flowability when the concrete was flowing. The static and dynamic yield stresses were not initially equal because of the few seconds required to start the rheometer after filling the rheometer container.



Stress Growth Test **Flow Curve Test**



Static and Dynamic Yield Stress **Plastic Viscosity and Thixotropy**

Figure 3: Typical Rheology Measurements

Figure 4 indicates that no single rheological parameter was directly correlated to segregation resistance. Increasing either the static or dynamic yield stress resulted in increased segregation resistance; however, the scatter was high. Mixtures with static yield stress less than approximately 40 Pa exhibited poor segregation resistance. Although the static yield stress should be closely associated with segregation resistance, the measurement of static yield stress at one point in time did not take into account subsequent changes in static yield stress. A mixture with low static yield stress may exhibit adequate segregation resistance if the viscosity is sufficient to slow the descent of aggregate particles while the static yield stress increases. Similarly, plastic viscosity alone was insufficient for predicting segregation because the magnitude of yield stress must also be considered. The thixotropic breakdown areas were not correlated with segregation resistance because it is the magnitude of the yield stress, not the amount of thixotropy per se, that should determine segregation resistance. A mixture with high initial yield stress but low thixotropy could have similar segregation as a mixture with low initial yield stress but high thixotropy.

Because no single parameter was adequate for predicting segregation resistance, Figure 5 indicates combinations of rheological parameters that distinguished different levels of segregation resistance. The plots indicate that as the dynamic yield stress decreases, the thixotropy or plastic viscosity must increase to prevent segregation. High plastic viscosity reduces the extent of segregation until the static yield stress increases sufficiently to support aggregate particles. Mixtures with higher thixotropy are likely to experience a greater rate of increase in static yield stress. All mixtures exhibited relatively low dynamic yield stress because of their high slump flows (28 to 30 inches, or 710 to 760 mm). The use of lower slump flows would have likely resulted in higher yield stresses and lower susceptibility to segregation. More data is needed to define more fully the zones of acceptable rheology.

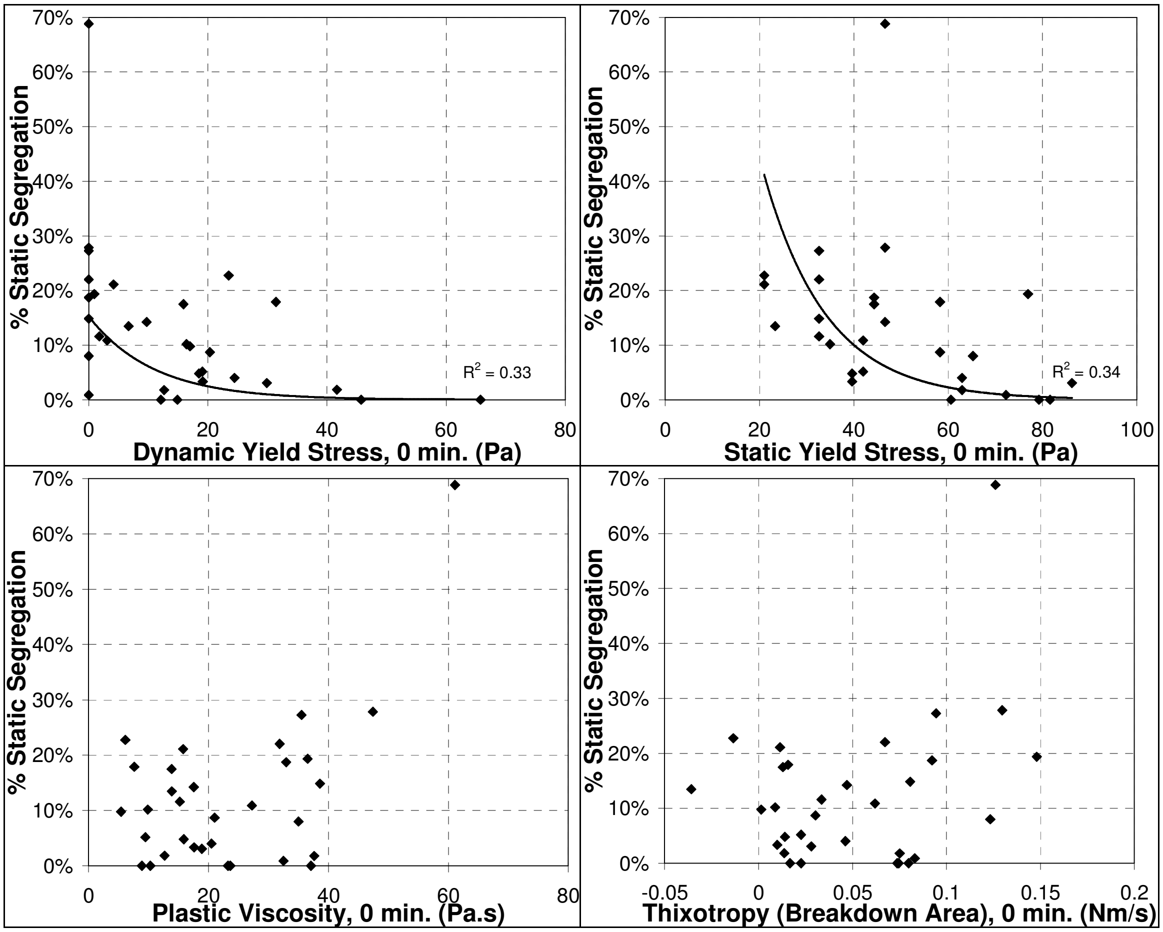


Figure 4: Relationships Between Rheological Parameters and Segregation

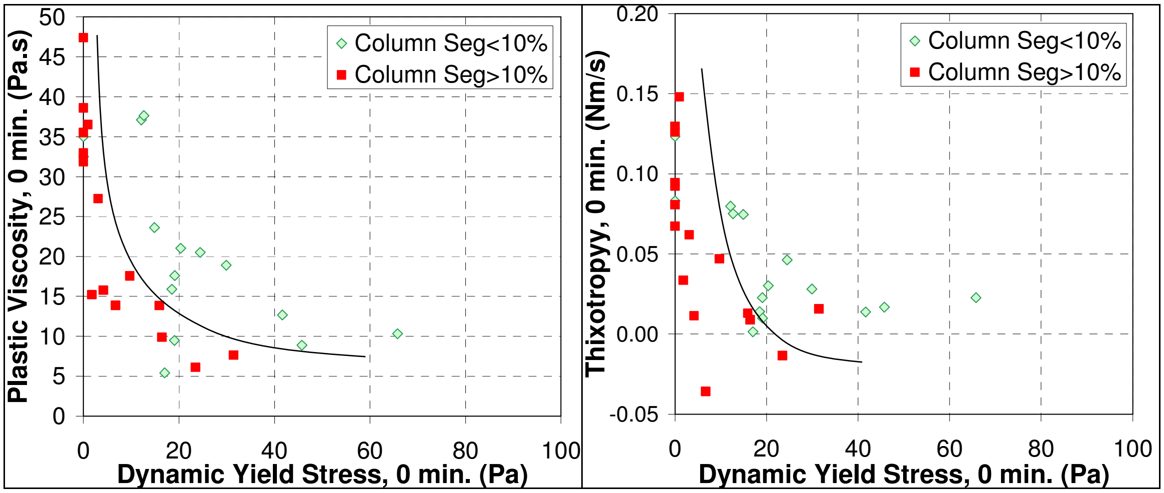


Figure 5: Relationships Between Multiple Rheological Parameters and Segregation

CONCLUSIONS

It is important to evaluate the static yield stress when evaluating segregation resistance. In terms of rheology, yield stress is the main fundamental difference between the workability of SCC and conventionally placed concrete—the plastic viscosity is often similar. The static yield stress must be sufficiently high to prevent segregation while the dynamic yield stress must be sufficiently low for self-flow. The static yield stress at any time is a function of the starting yield stress, the loss of workability, and thixotropy. Higher plastic viscosity can slow the descent of particles; however, the magnitude of plastic viscosity provides no assurance of segregation resistance.

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