Development of a New Test Method to Evaluate Dynamic Stability of Self-Consolidating Concrete

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Abstract Although many different test methods have been proposed to evaluate the static stability of self-consolidating concrete (SCC), limited test methods have been developed to determine dynamic segregation of SCC. In this study, a new apparatus was developed for testing the dynamic stability of SCC. The new method was called as "Dynamic Sieve Segregation Test" (DSST) which provides a numerical result referred to the "dynamic segregation ratio" (DSR). Higher DSR values indicate dynamically less stable mixtures. Several correlations were successfully established between the test results. SCC mixtures with higher slump flow, higher coarse aggregate-to-total aggregate ratio or higher maximum aggregate size (D_{max}) resulted in higher DSR values. A maximum DSR value of 30% was proposed for a dynamically stable SCC. The repeatability of DSST was found to be high with a COV value of 5.30%. Based on the results, DSST was found to be a suitable method to evaluate the dynamic stability of SCC.

Keywords: Dynamic stability, New test method, Stability, SCC.

Introduction

Stability is an important property of self-consolidating concrete (SCC) in the fresh state. Due to the high flowability of SCC, it is much more vulnerable to stability problems than conventionally vibrated concrete [1]. Stability includes two aspects: Static stability and dynamic stability.

Static stability is the resistance of the fresh concrete to segregation, bleeding, and surface settlement once the concrete is cast into formwork and until concrete gains rigidity. Dynamic stability can be defined as the resistance of the concrete to the separation of constituents during transport, placement, and casting processes" [2].

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In other words, it is the stability when the concrete is in motion. During motion, the fluid structure breaks down which can cause aggregate particles to settle if the yield stress is reduced significantly [3,4]. Higher viscosity can support the movement of aggregate as concrete flows and reduce the rate of settlement until the concrete comes to rest. At this point, the fluid structure can be rebuilt, thus restoring the yield stress and preventing further static segregation [4].

Beyond the inhomogeneity of the aggregate and homogeneity of the distribution of other components in fresh state, a lack of stability can also weaken the interface between the aggregate and the cement paste and can adversely affect bond between steel and concrete which reduces the hardened properties of SCC [5,6]. Limited test methods such as Flow Through, T-box, and Penetration Test with L-box [4, 7-9] have been proposed to evaluate the dynamic stability and the relationship between segregation and rheology of SCC. In this study, a new apparatus was developed for testing the dynamic stability of SCC. The method is called as “Dynamic Sieve Segregation Test” (DSST) and will be presented below.

Dynamic Sieve Segregation Test

The proposed DSST method consists of a rectangular steel channel box with a sieve at the bottom having 6-mm sieve opening. This size, which is larger than commonly used 4.75 mm, was selected considering the clustering of the fine particles in the fresh mixture. The inner dimensions of the device, which is hinged in the middle to a support, are shown in Fig. 1. The aim of DSST is to evaluate the dynamic stability of SCC in fresh state to flow over long distance. The idea is to check whether the mortar has the ability to hold the coarse aggregate while the concrete is moving. The ends of the box can move up and down, which allows it to produce possible flow cycles. This method is similar to T-box test introduced by Esmailkhanian et al. [8] for simulation of concrete flow and similar to static sieve segregation test (GTM) as both tests use a sieve to detect segregation.

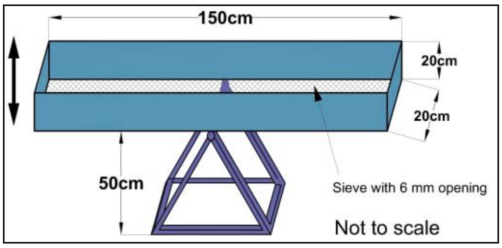

Figure 1. Proposed DSST test apparatus

The procedure of this method is as follows: (1) the empty box is weighed (W_d); (2) the box is placed on the support stand in the middle; (3) a sample of concrete weighing 18 kg (W_c) is poured into the box from the middle, while the box is horizontal; (4) the box is cycled four times by the up and down movement of the ends, which is equivalent to a travelling distance of ~5.25 m. The duration of each cycle is 15 sec to allow the concrete to flow in the box, (5) then the box is hold horizontally on the stand for 10 sec; (6) finally, the box with remained concrete is weighed (W_f).

The dynamic segregation ratio (DSR) is calculated as the ratio of the mass of materials that pass through the sieve (W_{ps}) to the total initial mass of concrete sample cast in the channel box (W_c). The dynamic segregation ratio is calculated from Eqn. (1).

$$DSR = (W_{ps} / W_c) \times 100 = [(W_d + W_c - W_f)/ W_c] \times 100 \qquad (1)$$

In order to decide the test parameters (such as number of cycles, duration of each cycle, etc.), six concrete mixtures having different stability levels were tested initially. Based on the observations, the values for these parameters were decided as follows: the four cycles of channel box were fixed by trial and error based on the results of the passing rate of concrete through the sieve. When the number of cycles was less than four, the passing rate was high, and when it was more than four, the amount of concrete passing the sieve was low. The frequency of the cycles was determined as 15 sec per cycle, again by trial and error. The concrete was able to reach the ends of the channel box only after 15 sec. In the 5th step of the test procedure, the channel box is hold horizontally on support stand for 10 sec to minimize the passing by resting the concrete from dynamic state. At the end of the study, it was confirmed that the selected values for the test paramaters were proper for all of the mixtures.

Experimental Study

Materials

A blended cement, CEM IV/B (P-W) 32.5 R, conforming to TS EN 197-1 was used. Limestone powder was added to the mixtures to adjust the water to powder ratio (w/p) of SCC mixtures. A polycarboxylate-based superplasticizer was used.

Two aggregate groups (Agg1 and Agg2) were used. Agg1 contained mostly coarse aggregate (87%) and had maximum aggregate size (D_{max}) of 15 mm. Agg2 was fine aggregate. Agg1 was crushed limestone, while Agg2 was a river sand. Three different D_{max} values were employed. In most of the mixtures, D_{max} was 15 mm. To have a D_{max} of 10 mm, Agg1 was sieved through the 9.75 mm sieve. To have a D_{max} of 20 mm, particles with the same source having a diameter of 15 – 20 mm was added. The ratio of the new particles to Agg1 was 1/5. This ratio was selected to satisfy the grading limits given in TS EN 706 Aggregates for Concrete.

Testing Methods

Slump flow, T_{500}, visual stability index (VSI), V-funnel, L-box, static sieve segregation (GTM), rheology, and DSST tests were performed as soon as the mixing was finished. Where relevant, EFNARC guidelines were followed. VSI test was made according to ASTM C1611.

Rheology tests were made using Tattersall type pallet rheometer (Contec 4SCC). The impeller of the rheometer was rotated at six different speeds (0.8, 0.70, 0.55, 0.40, 0.25, and 0.10 rps). Fresh concrete shearing procedure was started at the highest speed and finished with the slowest speed (down-curve). The torque value corresponding to each speed value was recorded, and the Bingham model was constructed by adding a linear trend line to the torque-speed data points. The intersection of the trend line with the torque axis and slope of this line are considered as the apparent yield stress and torque plastic viscosity, respectively.

Mixture Proportions and Testing Program

The mix-design variables and mixture proportions are summarized in Tables I and II.

The cement and limestone powder contents were kept constant at 400 and 20 kg/m^3, respectively. The water to cement ratio (w/c), coarse aggregate to total aggregate ratio (CA/TA), slump flow, and D_{max} were varied to investigate their effects on the dynamic stability of SCC. The w/c was either 0.42 or 0.50, and the CA/TA was set to 0.45, 0.50, or 0.53. For CA/TA of 0.50, for a given w/c, the slump flow values were set to 550, 650, and 720 ± 20 mm by changing the superplasticizer dosage. When the w/c was 0.42, CA/TA of 0.50, and slump flow of 650 mm, D_{max} was changed as 10, 15, and 20 mm, respectively.

Table I. SCC mix design variables

w/c	**CA/TA**	**Slump flow diameter (mm)**	**D_{max} (mm)**
0.42	0.45	650	15
	0.50	550, 650, 720	Slump flow = 650, D_{max} = 10, 15, and 20
	0.53	650	15
0.50	0.45	650	15
	0.50	550, 650, 720	15
	0.53	650	15

Since the testing sequence can affect the test results, the following sequence was kept the same for all mixtures: (1) slump flow diameter, T_{500} time, and VSI; (2) V-funnel test; (3) L-box test; (4) rheometer test; (5) DSST; (6) GTM. All tests were completed in 12 min after mixing has finished.

Table II. Mixture proportioning of tested SCC[*]

No.	**Slump-flow, mm**	**D_{max}, mm**	**W/C**	**W/P**	**CA/TA**	**C**	**W**	**LP**	**CA**	**FA**	**SP, L/m^3**
						kg/m^3					
1	650 ± 20	15	0,42	0.98	0.45	400	168	20	775	948	6.4
2	550 ± 20	15		1.00	0.50	400	168	20	862	862	4.9
3	650 ± 20	15		1.00		400	168	20	862	862	5.6
4	720 ± 20	15		1.00		400	168	20	862	862	6.6
5	650 ± 20	10		1.00		400	168	20	862	862	6.6
6	650 ± 20	20		1.00		400	168	20	862	862	5
7	650 ± 20	15		1.01	0.53	400	168	20	913	810	5.3
8	650 ± 20	15	0,50	1.18	0.45	400	200	20	739	903	4.1
9	550 ± 20	15		1.20	0.50	400	200	20	820	820	3.3
10	650 ± 20	15		1.20		400	200	20	820	820	3.4
11	720 ± 20	15		1.20		400	200	20	820	820	3.8
12	650 ± 20	15		1.21	0.53	400	200	20	869	771	3.3

[*] W/P, C, W, LP, CA, FA and SP are water-to-powder ratio (by volume), cement, water, limestone powder, coarse aggregate, fine aggregate, and superplasticizer, respectively. (Powder = C+LP)

Results and Discussions

The results are summarized in Table III. Since the emphasis of this manuscript is on the development of a new method, the discussions on the other tests are reported in [10].

The effect of slump flow and w/c on DSR for a constant CA/TA ratio of 0.50 is given in Fig. 2, which suggests that the SCC mixtures with high slump flow resulted in higher DSR. On the other hand, increasing the w/c decreased the DSR due to the lower demand of superplasticizer. When high slump flow value is aimed with low w/c, the need of superplasticizer increased. Therefore, in this case the high dose of superplasticizer creates excessive flow and increases bleeding which causes instability. Also the increased superplasticizer content led to further dispersion of cement particles and contributed to higher flow which caused separation of the mortar.

The effect of CA/TA ratio and w/c on the DSR for a constant slump flow diameter of 650 mm was given in Fig. 3. The results show that increasing the CA/TA of SCC increased DSR as well. Similarly, increasing D_{max} of coarse aggregate increased DSR, as illustrated in Fig. 4. The principal factor contributing to less stable concrete can be explained as follows: when the D_{max} is increased the drag force exerted by the mortar is decreased on the coarse aggregate. Increasing the D_{max} decreases the aggregate surface area-to-mass ratio which is directly proportional to the magnitude of the drag force [7,8]. Therefore, increasing the CA/TA increased the DSR as well.

Table III. Summary of Test Results

No.	**Slump flow - Dmax - W/C - CA/TA**	**T500, s**	**VSI**	**V-funnel flow time, s**	**L-box**		**GTM, %**	**g, N.m**	**h, N.m.s**	**DSR %**	**SP demand, L/m^3**
					H2/H1	**Flow time, s**					
1	650 - 15 - 0.42 - 0.45	3.66	1	*	0.82	6.5	3.90	0.57	3.24	25.00	6.38
2	550 - 15 - 0.42 - 0.50	4.53	1.5	**	0.65	14	1.40	0.53	4.81	17.30	4.88
3	650 - 15 - 0.42 - 0.50	3.5	1.5	*	0.75	8	4.75	0.50	2.98	26.20	5.55
4	720 - 15 - 0.42 - 0.50	2.03	2	14.5	0.81	4	5.55	0.39	2.20	27.90	6.63
5	650 - 10 - 0.42 - 0.50	5.09	1.5	*	0.79	4.96	3.40	0.24	3.21	24.20	6.63
6	650 - 20 - 0.42 - 0.50	2.19	2	*	0.60	9.44	6.65	0.66	4.34	33.10	5.00
7	650 - 15 - 0.42 - 0.53	2.25	2	*	0.70	12	5.25	0.30	1.88	28.40	5.25
8	650 - 15 - 0.50 - 0.45	1.25	0	13	0.85	3	0.40	0.68	1.26	21.20	4.13
9	550 - 15 - 0.50 - 0.50	2.96	0.5	**	0.66	9	0.25	0.88	1.66	14.00	3.25
10	650 - 15 - 0.50 - 0.50	1.1	1	11	0.81	4.3	1.75	0.60	1.12	24.00	3.43
11	720 - 15 - 0.50 - 0.50	1.03	1	7	0.88	2.8	2.60	0.42	0.61	26.70	3.75
12	650 - 15 - 0.50 - 0.53	0.85	1.5	8	0.79	6	2.05	0.42	0.90	24.90	3.25

* Flow was discontinuous.
** Flow was too slow.

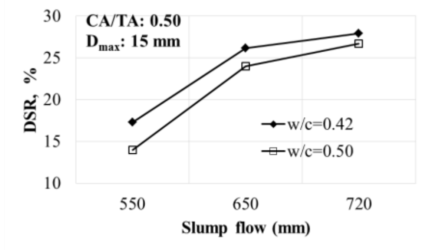

Figure 2. Effect of slump flow and w/c on DSR

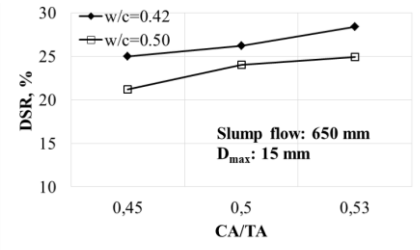

Figure 3. Effect of CA/TA and w/c on DSR

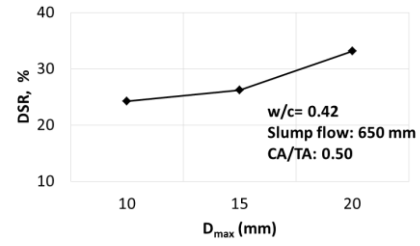

Figure 4. Effect of D_{max} on DSR

The DSR values follow the expectations established according to the literature. In other words, the effects of the test parameters (w/c, CA/TA, D_{max}, and slump flow) on the measured quantities were in good agreement with the related literature [11,14]. These effects could be identified by the proposed method.

Correlation of DSST with Other Tests

The DSST data were plotted against the data of the other tests (T_{500}, VSI, L-box, GTM test, and rheology) in Figures 5-11. The correlations were studied by inserting trend lines on these data. However, it was noticed that the data points outside the dashed lines in these Figures show great deviations from the trend lines. Therefore, correlations were revised by excluding these data. The new trend lines and R^2 values are shown in Figures 5-11. Table IV provides the initial and the revised R^2 values to make comparison. It was found that the new correlation coefficients were always higher. The excluded data points belong to Mixtures 2, 6, and 9. Mixtures 2 and 9 have low slump flow value and lowest H_2/H_1 values. Mixture 6, which has the highest D_{max} value, showed the most severe segregation as can be seen from VSI, V-funnel, H_2/H_1, L-box flow time and GTM test results (Table III). The dashed line for 20% is not a limit for DSST but it was drawn to distinguish outlying data points. On the other hand, the above discussion proposes a maximum DSR limit of 30% for dynamically stable SCC.

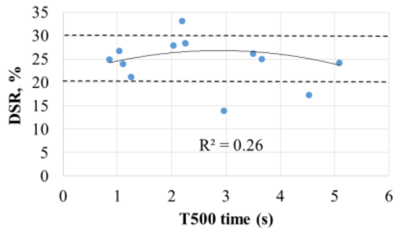

Figure 5. Correlation between DSR and T_{500} time

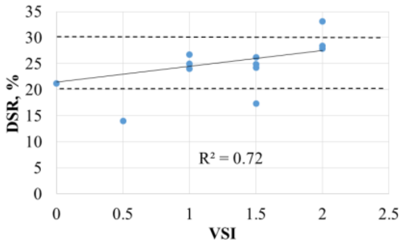

Figure 6. Correlation between DSR and VSI

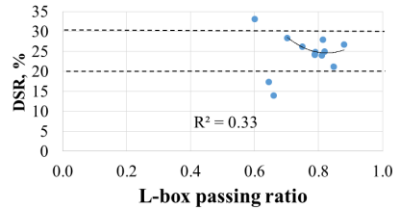

Figure 7. Correlation between DSR and L-box passing ratio

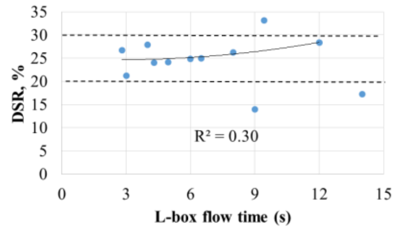

Figure 8. Correlation between DSR and L-box flow time

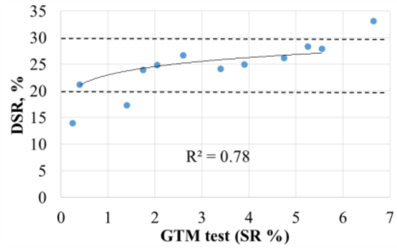

Figure 9. Correlation between DSR and GTM test

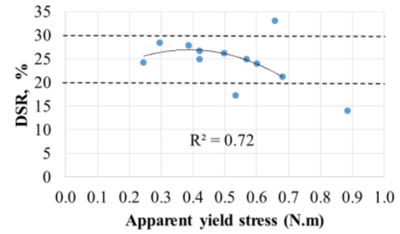

Figure 10. Correlation between DSR and g from rheometer

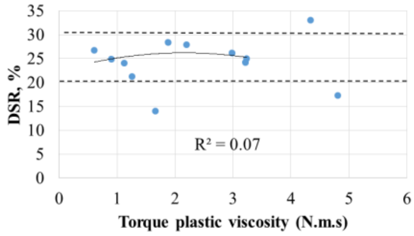

Figure 11. Correlation between DSR and h from rheometer

Table IV. Correlation coefficients (R^2)

Test results	**Correlation Coefficient (R^2)**	
	All mixtures	All mixtures except no. 2, 6, and 9
DSR vs. T_{500} time	0.10	0.26
DSR vs. VSI	0.41	0.73
DSR vs. g	0.36	0.72
DSR vs. h	0.02	0.07
DSR vs. GTM SR	0.75	0.78
DSR vs. L-box flow time	0.08	0.30
DSR vs. L-box PR	0.05	0.33

The correlations between L-box parameters (passing ratio and flow time) and DSR are given in Figs. 7 and 8. As recommended in the literature, L-box passing ratio should be greater than 70%. The data points between the dashed lines conform to this recommendation. Similarly, L-box flow times between the lines are within the recommendations (1.9 – 14.4 sec) of Khayat et al. [11].

Figure 9 shows the correlation between GTM results and DSR. The graph shows a strong linear positive relationship. The dynamic segregation ratio increased with an increase in GTM test segregation ratio for all 12 tested mixtures.

Repeatability of Tests

Mixture 8 was prepared three times. The standard deviation, mean, and coefficient of variation (COV) values for each test method are presented in Table V. The repeatability of apparent yield stress was found to be lowest since it had the highest COV value. This was followed by the L-box flow time. The rest of the test methods had similar COV values (between ~3% and ~6%). Table V indicates that the new method has high repeatability since it has a low COV of 5.3%. Its repeatability was better than the tests for apparent yield stress, L-box flow time, GTM, and H_2/H_1.

Table V. Repeatability of the tests

	Slump flow		**L-box**		**GTM**	**Rheometer**		**DSR**	**SP demand**
	T_{500}	**VSI**	**H_2/H_1**	**Flow time**		**g**	**h**		
Mean	1.21	0	080	266	0.43	0.49	1.21	21.00	4.13
Standard Deviation	0.04	0	004	040	003	0.18	0.06	1.11	0.13
Coeff. of Var., %	2.98	-	540	1502	666	37.01	4.59	5.30	3.03

Conclusions

Based on the results presented here, it was found that the new proposed test can be suitable to evaluate dynamic stability of SCC. The DSR results showed good correlations with most of the other tests. The increase in superplasticizer dosage and maximum size of aggregate are shown to increase DSR. A maximum DSR value of 30% is recommended for a dynamically stable SCC. The repeatability of the new test method, which was better than those of apparent yield stress, L-box flow time, GTM, and H_2/H_1 tests, was found to be high with a COV value of 5.30%.

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