Evaluation of the robustness of SCC

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Ravindra Gettu, Shaik Nawaz Shareef and Kingsley J.D. Ernest

Self-compacting concrete is generally less tolerant to changes in the characteristics and dosages of its constituents. The present work analyzes the robustness of a typical SCC, in terms of the fresh properties and strength, when changes are made in the dosages of the constituents within the tolerances that could occur in ready mix concrete plants. The results indicate that the most critical changes that can render an SCC unacceptable are excess cement, excess fly ash, less fly ash, less water, excess superplasticizer, excess sand and excess gravel. It was also observed that the most sensitive tests for robustness evaluation are the slump flow and the J-ring tests. The incorporation of a viscosity modifying admixture improved the robustness of the SCC significantly.

Keywords: *Robustness, self compacting concrete, testing, fresh concrete, compressive strength.*

The creation of a durable concrete structure is highly dependent on compaction, which is an important part of the construction sequence. In spite of technological advances in the field of compaction, its effectiveness is far from consistent in areas with congested reinforcement and complex forms, and depends significantly on the workers involved. It is against this background that self-compacting concrete (SCC), which eliminates the need for compaction, has been developed and its advantages exploited.

SCC is, however, more susceptible than conventional concrete to changes in ingredients and their proportions, and is especially sensitive to changes in the fluidity of the paste due to variation in the free water and admixture dosage. A variation in the uniformity of the constituents could result in inadequate filling/passing ability or segregation resistance. This means that, for practical purposes, the properties of the fresh concrete are influenced by changes in ingredients properties and proportions, and moisture content of the aggregates implying that care has to be taken in all the processes starting from batching to placement to limit the variations[1].

A well designed SCC can exhibit acceptable tolerance, easing the pressure on testing/production control and reducing the possibility of problems on the job site. This tolerance is usually termed 'robustness'. In other words, robustness is the capacity of concrete to retain its fresh properties when small variations in the characteristics or quantities of the constituent materials occur. A well-designed and robust SCC can typically accept a 5 to 10 litre/m^3 change in water content without falling outside the specified class of performance. Consequently, it can be helpful to vary the water content by ±10 litres when designing an SCC mix and check if the fresh state properties are within the acceptable limits. This confirms the robustness of the mix or indicates that further adjustments to the design are needed. Nevertheless, stringent quality control is compulsory for SCC.[1,2,3]

The incorporation of a viscosity modifying admixture (VMA) in concrete significantly enhances resistance to bleeding, settlement and segregation.[4] Such stabilising agents can produce SCCs with low powder contents and with good flow.[5] Viscosity agents are reported to extend the range of practical mixture compositions and characteristics of SCC and increase its robustness, especially for mixes that have higher water content.[6]

The objectives of this study were to investigate the variations in properties of SCC due to small unexpected variations in parameters related to the material components, to identify the critical parameters that cause variation in the properties of SCC and to check whether a VMA can be used to make SCC robust. The parameters chosen for the study were cement, fly ash, water, superplasticizer, sand and gravel (5-10 mm and 10-25 mm fractions). The variations were based on data from the Indian standard IS 4926 (2003), the French standard P 18 - 305 (1994) and observations in readymix concrete plants.[7,8] The fresh properties determined were the slump flow, J-ring flow, and V-funnel time determined immediately and after 5 minutes. The hardened properties measured were the concrete cube compressive strengths at 3 and 28 days.

Experimental details

Materials used

The cement used for the study was a 53 grade ordinary portland cement (OPC) conforming to Indian standard IS 12269 (1987).[9] The chemical properties of the cement are given in Table 1. The other important properties like fineness, setting time, etc., are summarized in Table 2. A Class F fly ash (confirming to ASTM Standard C 618-05, 2005[10]) with a specific gravity of 2.13 and Blaine specific surface area of 500 m^2/kg was chosen. It was obtained from the Ennore power plant (Chennai, India). The chemical characteristics of the fly ash are given in Table 1.

The chemical admixtures used were a superplasticizer and a viscosity modifying agent; the properties of the admixtures are given in Table 3.

The fine aggregate was river sand (grain size range of 0-5 mm) with specific gravity and coefficient of absorption of 2.64 and 2.0%, respectively. Two gravel (i.e., crushed coarse aggregate) fractions – 10-25 mm and 5-10 mm – were used in the study. They had specific gravity and absorption values of 2.90 and 0.2%, and 2.87 and 0.4%, respectively.

Reference SCC

The mixture proportions of an M40 reference concrete fixed after several trials, are given in Table 4, considering

Table 1. Chemical properties of cement and fly ash

Compound	Cement (%)	Fly ash (%)
SiO_2	19.50	61.16
Fe_2O_3	6.06	4.62
Al_2O_3	4.12	30.08
CaO	60.81	1.75
MgO	1.52 (6% max)	0.18
Na_2O	0.05	0.76
K_2O	0.28	0.36
SO_3	2.48 (2.5% max)	0.19
Total loss on ignition	3.41 (4% max)	0.60

Table 2. Physical characteristics of cement

Characteristics	Values
Blaine Specific Surface (m^2/kg)	316
Soundness: Le chatelier (mm) Autoclave (%)	 2.0 max 0.2 max
Setting Time: Initial Set (min) Final Set (min)	 99 min 184 min
Consistency (w/c)	0.33
Compressive strength: 3 days (MPa) 7 days (MPa) 28 days (MPa)	 40.1 51.0 74.3

Table 3. Characteristics of chemical admixtures

Admixture type	Superplasticizer (polycarboxylate based)	Viscosity modifying agent
Density (g/ml) at 25°C	1.09	1.01
Solid content (%)	33	2

the aggregates to be in a dry state. Note that the water added includes the water needed for the hydration of the cement and saturating the aggregates, and excludes the water content of the superplasticiser.

Preparation and casting

The mixing process for all batches was as follows. The coarse aggregate, cement, fly ash and sand were mixed for a minute in a pan type mixer of 60 litre capacity. Then, three quarters of the mixing water was added and mixed for 2 minutes. Later, superplasticizer with some amount of remaining water was added and the mixture was mixed for an additional two minutes. VMA, if any, was added to the mix with the remaining water and mixed for another two minutes. After the mixing was completed, tests were conducted on the fresh concrete to determine slump flow, T_{50} time, J-ring flow, V-funnel time and V-funnel time after five minutes. For each mix, five cubes were cast (without any tamping or vibration), demoulded after 24 hours and kept under water for curing. Two cubes were tested at 3 days and remaining three were tested at 28 days. Cubes were tested with a loading rate of 0.25 MPa/sec as per Indian Standard IS 516 (1959).[11]

Parameter variation

The imposed parameter variations are given in Table 5. Each variation was repeated three times on different batches of concrete. Note that a positive variation means that the final mix proportions correspond to a volume of the concrete (i.e., the yield) that was slightly more than 1 cubic metre while a negative variation results in less than 1 cubic metre of concrete. The mix nomenclature used in the rest of the paper is given in Table 6.

Testing

The slump flow and T_{50} time were determined as per Italian standard UNI 11041.[12] This test evaluates the filling ability and is a primary check for consistency of SCC. Under this test, the slump cone is placed on a plate and filled with concrete without tamping. The cone is lifted and concrete is allowed to spread freely

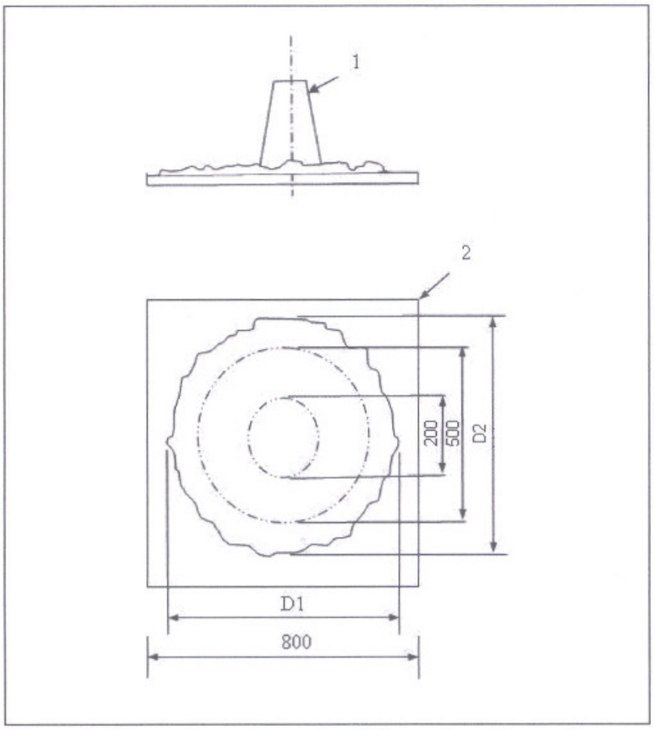

Figure 1. Slump flow apparatus (dimensions in mm)

Table 4. Composition of reference mix

Component	Quantity (kg/m^3)
Cement	450
Fly ash	120
Sand	830
Gravel	
20 mm	415
10 mm	415
Water added	196.4
Superplasticizer (0.90% w/w of cement)	4.0
w/c ratio	0.40
w/p ratio	0.32
28 day compressive strength (MPa)	40

Table 5. Parameter variation

Component	Relative variation	Absolute quantity (kg/m^3)
Cement	± 5%	± 22.5
Fly ash	± 10%	± 12.0
Water	± 4 %	± 7.2
Superplasticizer	± 5 %	± 0.2
Gravel		
10-20 mm	± 10 %	± 41.5
5-10 mm		± 41.5
Sand (0-5 mm)		± 83.0

Table 6. Nomenclature

Description	Variation in the component, kg/m^3	Notation
Reference mix	-	M1
Excess cement	+22.5	M1-CP
Less cement	-22.5	M1-CM
Excess fly ash	+12.0	M1-FP
Less fly ash	-12.0	M1-FM
Excess water	+7.2	M1-WP
Less water	-7.2	M1-WM
Excess superplasticizer	+0.2	M1-SPP
Less superplasticizer	-0.2	M1-SPM
Excess 10 mm aggregate	+41.5	M1-G1P
Less 10 mm aggregate	-41.5	M1-G1M
Excess 20 mm aggregate	+41.5	M1-G2P
Less 20 mm aggregate	-41.5	M1-G2M
Excess sand	+83.0	M1-SP
Less sand	-83.0	M1-SM

on the plate as in Figure 1 (where the slump cone according to EN 12350-2 is labelled as "1" and the base plate with minimum dimensions of 800 × 800 mm is labelled as "2").[13] Slump flow (D_f) is the mean diameter of the spread (from two perpendicular measurements) and T_{50} is the time taken by the spread to reach a diameter of 500 mm.

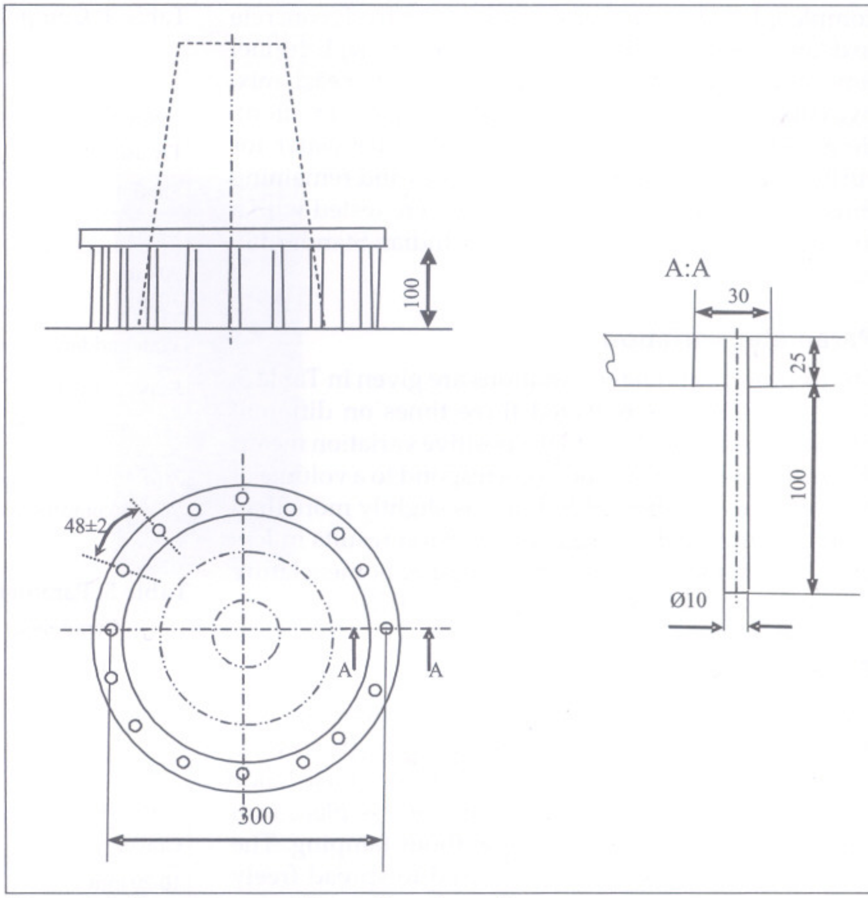

Figure 2. J-ring apparatus (dimensions in mm)

The J-ring flow test was carried out as per Italian standard UNI 11045.[14] This test evaluates the passing ability of SCC in unconfined conditions. While conducting this test, the slump cone is placed in the centre of J-ring as shown in Figure 2, and filled with concrete. The cone is lifted slowly and concrete is allowed to flow horizontally through the bars of J-ring. The difference in the horizontal spread without and with the J-ring is used as a measure of the passing ability.

The V-funnel test is used to assess the viscosity, flowability and segregation resistance of SCC. The funnel, as shown in Figure 3, is fully filled with concrete and the flap at the bottom of the funnel is opened. The flow time for the concrete to exit the funnel is then recorded. The test is described in detail in the Italian Standard UNI 11042 (2003), the European Guidelines on Self Compacting Concrete (2005)and in Gettu *et al* (2004).[1,15,16] To evaluate the segregation resistance, the flow value was measured again with the concrete remaining in the funnel for 5 minutes. A significant increase in flow time for the second measurement indicates greater susceptibility of concrete to segregation.

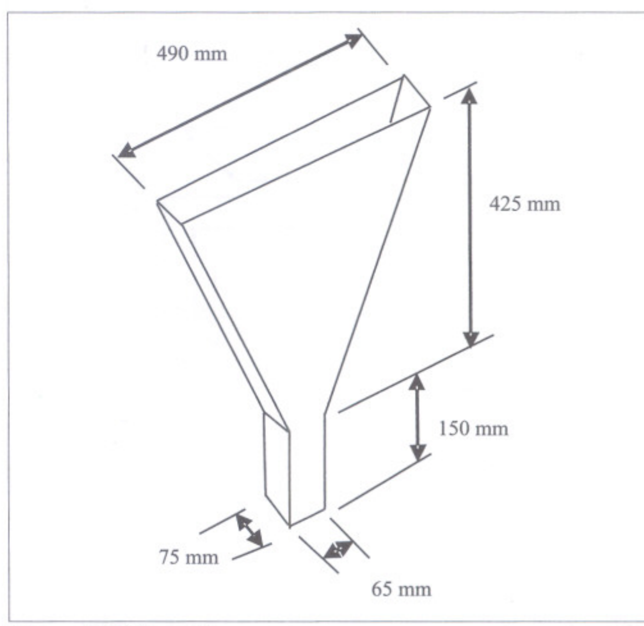

Figure 3. V-funnel

Selection of self-compactability criteria

The SCC to be used in this study was expected to possess certain minimum properties in the fresh state. In order to set the appropriate criteria, the following were proposed based on the European Guidelines for Self-Compacting Concrete (2005), the Italian UNI standards and previous experience at IIT Madras[1]:

- Slump flow in the range of 650-750 mm, for a reference flow of about 700 mm[17]

- Slump flow spread time (T_{50}) equal to or more than 2 seconds[1]
- V-funnel flow time of 5-8 seconds
- The difference between the V-funnel times determined initially and after 5 minutes should not be more than 3 seconds[3]
- J-ring flow difference (i.e., difference in slump flow with and without J-ring) should not be more than 50 mm[14]

Test results and discussion

As mentioned earlier, the robustness of the SCC mix was studied by altering the reference mix composition (see Tables 5 & 6), and evaluating the self-compactability and compressive strength of the altered mixes. The experimental results are presented in Table 7, where the properties and mix that fail the corresponding acceptance criterion are underlined; when an altered mix cannot be considered as self-compactable because the properties were significantly outside the allowable range, such cases are underlined with a double line.

Note that the data is represented in terms of the mean value (from 3 trials) and the standard deviation (in parentheses). The variability in the results was generally low, with the slump flow having a maximum standard variation of only 23 mm (i.e., coefficient of variation of about 3%). With the J-ring, the slump flow variability was slightly higher but the repeatability of the test results was consistently good. The V-funnel times had relatively higher variability due to the dependence on the operator in timing the flow and the low times to be measured. The standard deviation of the V-funnel time was generally less than 1 second but was seen to be as high as 1.7 seconds in a few cases.

It can be seen that the reference mix M1 has satisfactory properties with a slump flow of about 700 cm, moderate passing ability (indicated by a J-ring flow difference of 24 mm) and good segregation resistance. The strength is more than adequate at both 7 and 28 days for a M40 grade concrete.

Effect of variations in the cement content

The increase in cement content (i.e., M1-CP mix) leads to a significantly low slump flow compared to the reference mix due to the higher paste viscosity caused by the lowering of the water-cement ratio (w/c). A consequent increase is also observed in the values of T_{50} and V-funnel time. The passing ability seems to improve with

Table 7. Results of variations on the mix composition

Mix	Properties related to self-compactability							Compressive strength	
	Slump flow (mm)	T_{50} (sec)	J-ring flow (mm)	J-ring flow difference (mm)	V-funnel			3-day (MPa)	28-day (MPa)
					at 0 min	at 5 min	Difference between 0 and 5 min values		
Allowable range	650 - 750	≥ 2	-	≤ 50	≤ 8	-	≤ 3	≥ 20	≥ 44
M1 (reference)	708 (±10)	2.3 (±0.2)	684 (±17)	24	6.6 (±0.7)	7.1(±0.9)	0.5(±0.6)	34.0	58.2
M1-CP	638 (±13)	4.1 (±0.1)	628 (±15)	10	8.4 (±1.4)	8.7 (±1.2)	0.3 (±0.2)	35.2	60.8
M1-CM	658 (±9)	2.3 (±0.2)	629 (±17)	29	4.6 (±1.7)	6.8 (±1.7)	2.2 (±0.2)	31.1	54.5
M1-FAP	687 (±9)	2.7 (±0.7)	612 (±6)	75	8.3 (±0.3)	10 (±0.5)	1.7 (±0.3)	33.1	62.1
M1-FAM	718 (±20)	2.8 (±0.9)	638 (±25)	80	4.1 (±0.5)	5.0 (±0.6)	0.9 (±0.3)	32.4	57.5
M1-WP	743 (±23)	2.1 (±0.2)	717 (±18)	26	3 (±0.7)	3.7 (±0.3)	0.7 (±0.5)	28.4	51.1
M1-WM	627 (±23)	4.5 (±1)	532 (±28)	95	9 (±0.8)	11.3 (±0.8)	2.3 (±0.2)	41.5	65.3
M1-SPP	742 (±15)	1.8 (±0.4)	687 (±21)	55	6.5 (±0.5)	8.4 (±0.4)	1.9 (±0.2)	34.1	58.7
M1-SPM	682 (±7)	2.4 (±0.1)	631 (±12)	51	6.9 (±0.2)	7.3 (±0.3)	0.3 (±0)	34.3	58.2
M1-SP	713 (±8)	1.7 (±0.2)	678 (±13)	35	6.9 (±0.9)	7.5 (±0.8)	0.6 (±0.2)	36.4	59.8
M1-SM	677 (±8)	2.3 (±0.2	647 (±8)	30	6.2 (±0.4)	7.1 (±0.8)	0.9 (±0.4)	34.1	56.1
M1-G1P	682 (±8)	2.6 (±0.1)	615 (±10)	67	7.8 (±0.4)	9.4 (±0.1)	1.6 (±0.3)	36.8	62.7
M1-G1M	715 (±5)	2.1 (±0.1)	683 (±10)	32	6.3 (±0.2)	7.9 (±0.4)	1.6 (±0.5)	32.2	54.7
M1-G2P	662 (±13)	2.5 (±0.2)	618 (±8)	44	7.7 (±0.5)	9.0 (±0.4)	1.3 (±0.3)	35.7	59.9
M1-G2M	723 (±8)	2.2 (±0.3)	682 (±8)	42	6.5 (±0.3)	7.9 (±0.4)	1.4 (±0.3)	33.3	54.2

the additional cement content while the segregation is unaffected. When there is a decrease in cement content (in M1-CM), the self-compactability is not affected significantly though the segregation resistance is lowered appreciably. The effect of cement variation on strength is as expected, with the 28-day value changing slightly along with the cement content.

Effect of variations in the fly ash content

Changes in the fly ash dosage, within the ranges and conditions of this work, do not alter the self-compactability significantly, except in terms of the passing ability which appears to be sensitive to the fines content. Both the increase (in M1-FAP) and decrease (in M1-FAM) in fly ash dosage increase the J-ring flow difference significantly indicating an increase in the blocking. There is also a slight decrease in the segregation resistance with an increase in the fly ash content.

Effect of variations in the water content

Reducing or increasing the amount of water is expected to have a significant influence on the self-compactability. However, it is observed in Table 7 that the mix is self-compactable even when the water content increases by 7 litres/m^3 (in M1-WP). There is, however, an increase in the slump flow and a decrease in the V-funnel time, as expected. There is no decrease in the passing ability or segregation resistance. On the other hand, it is clear that the reduction of water (in M1-WM) reduces the flowability considerably and, more importantly, increases the tendency for blocking and segregation.

Effect of variations in the superplasticizer content

The sensitivity of the self-compactability to the superplasticizer dosage is surprisingly high with both the increase (in M1-SPP) and decrease (in M1-SPM) in dosage causing a lowering of the passing ability. There is a slight increase in the tendency for segregation when the superplasticizer is overdosed. Since the superplasticizer dosage governs the flowability; the slump flow increases, and the T_{50} and V-funnel times decrease with higher superplasticizer dosage and vice versa, however, the strength is practically unaffected.

Effect of variations in the sand content

Addition of sand (in M1-SP) seems to decrease the viscosity of the concrete leading to an increase in the slump flow and a decrease in the T_{50}. In general, the variation of sand content does not affect the self-compactability adversely.

Table 8. Performance of the modified mix without and with variations in the composition

Mix	Properties related to self-compactability						
	Slump flow (mm)	T_{50} (sec)	J-ring flow (mm)	J-ring flow diff-erence	V-funnel		
					at 0 min	at 5 min	Difference between 0 and 5 min values
M2	710	2.3	690	20	5.8	6.2	0.4
M2-CP	670	3.8	635	35	7.1	7.4	0.3
M2-FAP	685	2.5	650	35	6.8	6.9	0.1
M2-FAM	730	2.2	695	35	5.4	5.8	0.3
M2-WM	665	4.2	625	40	7.5	8.1	0.6
M2-SPP	745	2.1	735	20	5.1	5.3	0.2
M2-SP	715	2.4	685	30	6.1	6.4	0.3
M2-G1P	680	2.6	630	50	6.9	7.1	0.2

Effect of variations in the gravel content

Gravel quantity has a direct bearing on the effective amount of paste available for facilitating the flow and the segregation that can occur during the flow. Excess gravel is expected to reduce the flowability and increase segregation and blocking. The experimental results in Table 7 are in agreement with the expected trends, with the increase in either the 5-10 mm fraction (in M1-G1P) or the 10-25 mm fraction (in M1-G2P) causing lower slump flow, slightly higher T_{50} and V-funnel times. The decrease in gravel content does not cause any significant loss of self-compactability but the tendency to block and segregate seems to increase.

Modified reference mix performance

The incorporation of a VMA is expected to decrease the sensitivity of the fresh concrete properties to variations in the constituent proportions, especially those that govern the flowability. Consequently, the mix becomes more robust. This hypothesis was tested by incorporating a VMA in the original reference mix (M1) with a slight increase in the dosage of superplasticizer in order to get a slump flow that was comparable to that of M1. The modified mix, denoted as M2, had a VMA dosage of 0.25% (by weight of cement) and a superplasticizer dosage of 1.15% (by weight of cement). The properties of the modified reference mix M2 are given in Table 8. The cases that failed in the previous trials with M1 (see Table 7) were checked on the M2 mix; i.e., the variations that caused loss of self-compactability alone were imposed on mix M2 and the properties were determined in the altered mixes. The results for the mixes with variations are presented in Table 8 using the same nomenclature as before.

It can be seen in Table 8 that all the cases pass the self-compactability criteria after the incorporation of the VMA. In general, the passing ability and segregation resistance are significantly improved due to the VMA. The trends in the parameters due to the mix alterations are in accordance with those observed in the tests on the M1 mixes. As in the tests on the M1 variations, the most sensitive test parameters are the slump flow and the J-ring flow difference with appreciable changes due to the modification of the mix proportions.

Conclusions

As a result of this experimental study, the following conclusions can be drawn for the materials and proportions used. The evaluation of the mixes with variations indicates the more critical changes in self-compactability occur when there is excess cement, excess fly ash, less fly ash, less water, excess superplasticizer, excess sand or excess gravel. However, the original mix maintained self-compactability under most of the variations but is not robust in the strict sense. Since the variations produced only small deviations beyond the acceptability criteria, it appears that most problems can be avoided if the dosages of the constituents do not vary by more than 1% of the reference mix proportions. The most critical tests for evaluating self-compactability loss seem to be the slump flow and J-ring tests; i.e., robustness is assured if the parameters of these tests are satisfied. The incorporation of a VMA seems to increase the robustness of SCC significantly (in the present case, a non-robust SCC is made robust by the addition of 0.25% of VMA and a slight increase in the dosage of superplasticizer). The present work makes a strong case for robustness studies to be performed before any SCC mix is specified for field application. Such studies also provide useful information on the critical parameters and the cause-effect relations between the dosage and parameter variations.

Acknowledgements

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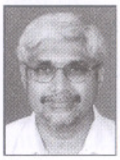

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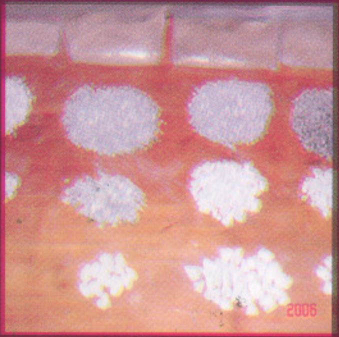

Self Compacting Concrete