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RESEARCH ARTICLE

The Robustness of Self Consolidating Concrete Due to Changes in Mixing Water

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Abstract
Although self consolidating concrete (SCC) has been developed for more than two decades, its practical use is still limited. This is partly because its properties are not fully known and partly because its performance is highly sensitive. In the current study, an experimental program was undertaken to evaluate the robustness of eight selected SCCs. According to the obtained results, the variations of SCC robustness that determined by using innovative method (multi attribute decision making) are studied based on the variations of rheology parameters. The results indicate that there is a direct relationship between robustness and segregation resistance of SCC. Also the greatest reduction in robustness occurs in increase in yield stress together with plastic viscosity. Moreover, the scattering of compressive strength results show that there is a level of robustness in fresh state that after that the scattering of results in hardened state may be affected.

Keywords
Self Compacting Concrete, Robustness, Mix proportion, Rheology Parameters, Multi Attribute Decision Making

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1 Introduction

Self-compacting or self-consolidating concrete (SCC) can be regarded as a high-performance material, which flows under its own weight over a long distance without the need of using vibrators to achieve consolidation [1]. This concrete is defined as a concrete that has excellent deformability and high resistance to segregation and can be filled in heavily reinforced or restricted area without applying vibration. SCC must achieve high workability and flow into the formwork under its own weight without compaction and with no segregation.

In rheological terms, it is accepted that SCC has a low yield stress while the plastic viscosity can vary significantly. An appropriate combination of the two parameters is required to obtain a concrete with adequate fluidity and stability [2-6]. Rheology is defined as the scientific description of the flow and deformation of matter [7-9]. For concrete, rheology is typically used to describe workability, which is defined by the American Concrete Institute (ACI) [7] as "the ease with which [concrete] can be mixed, placed, consolidated, and finished to a homogenous condition."

As mentioned, a good approximation of the fundamental rheological quantities for cement based material can be obtained in terms of yield stress (τ_0) and plastic viscosity (μ). A rheograph is defined as a graph that X axis is plastic viscosity (μ) and Y axis is yield stress (τ_0). According to Wallevik and Wallevik [10] the rheograph is a convenient and essential tool to compare different concrete batches and examine the behavior relative to changed constituents, quantities of constituents, and/or relative to different times from water addition (and so forth). Thus rheograph is a systematical way to reveal the effects of slight decrease and increase in mixing water.

Although SCC has been developed for more than two decades, its practical use is still limited. This is partly because its properties are not fully known and partly because its performance is highly sensitive to small changes in the mix design parameters [11-13]. SCC is more susceptible to changes than ordinary concrete because of a combination of detailed requirements, more complex mix design, and inherent low yield stress and viscosity [11]. Therefore some mixture designs of SCC mixtures may not provide adequate robustness.

Various definitions for concrete robustness have been proposed by different researchers. According to RILEM TC 288MPS [14] definition, the concrete robustness is the characteristic of a mixture that encompasses its tolerance to variations in constituent characteristics and quantities, variations during concrete mixing, transport, and placement, as well as environmental conditions. However, in the case of SCC due to the specific properties of fresh concrete, the robustness definition has focused on these properties. The European Guidelines for SCC [15] defined the robustness of SCC as the capacity of concrete to retain its fresh properties when small variations in the properties or quantities of the constituent materials occur.

Up to the present, there are a few methods available to assess the robustness of SCC. The first method was suggested by the European Guidelines for SCC [15] in which a well-designed and robust SCC should tolerate a change in water content of up to 5 to 10 L/m^3 without falling outside the specified class of performance. Such a change in water content can correspond to approximately +6%. Similar recommendations are given for the variation of water content of +6% of targeted values of avoiding changes in SCC Performance [12]. The advantage of this method is its simplicity in application. However, since a given SCC mix can only pass or fail the test, the robustness of different concrete mixes cannot be compared quantitatively using this assessment method.

Nunes et al. [16, 17] have proposed a method to assess the robustness of SCC in terms of the frequency of satisfying the acceptance criteria for SCC despite daily fluctuations in the ingredients. In this method, a factorial design plan is required to establish empirical relationships between the mix design parameters and the performance indicators using statistical equations deviated from the experimental results. However, this method has the disadvantage that the relationship between the mix design parameters and the concrete performance must be known in advance and this requires a larger number of trial concrete mixes to be produced.

Kwan and Ng [13, 18], according to their researches, have suggested that the width of the acceptable range of Superplasticizer dosage as well as the acceptable range of slump flow (i.e. the range of SP dosage or slump flow satisfying all the performance requirements for SCC) may be taken as a quantitative measure of the robustness of SCC.

Naji et al. [12] used the coefficient of variation (COV) for comparison and ranking of SCCs robustness. To evaluate the robustness of SCC, eight SCC mixtures were subjected to variations in three levels of sand humidity. Twenty properties of SCC were determined for each concrete. For each property, the COV of the responses obtained for the three sand humidity values were calculated and used to estimate the relative spread of each response. Based on the COV values, the SCC mixtures were ranked.

According to the importance of SCC robustness, the present research studies the SCC robustness and its changes with mix proportion. First, the effects of mix proportion on the rheology parameters are investigated. Then, variations of SCC robustness that determined by using innovative method (multi attribute decision making) are studied according to the variations of rheology parameters.

2 Experimental works and analysis methods

2.1 Materials

In this study an ASTM type I Portland cement as well as limestone powder as filler were used. The chemical compositions and physical properties of cement and limestone powder are presented in Table 1.

Crushed limestone aggregate was used as coarse aggregate with a nominal maximum size of 19.5 mm. The apparent specific gravity and water absorption of coarse aggregate are 2.55 and 1.8% respectively that were measured according to ASTM C127-12 [19]. As fine aggregate, limestone sand with nominal maximum aggregare size of 4.75 mm was used. The apparent specific gravity and water absorption of sand are 2.60 and 3.9% respectively that were measured according to ASTM C 128-12 [20]. Particle size distribution of both fine and coarse aggregates is falling within the permissible limits stipulated in ASTM C33 [21]. Grading curves of aggregates are presented in Fig. 1.

A third generation polycarboxylate-based superplasticizer was used. It was a brown solution with a apparent specific gravity of 1.1. As a third-generation SP, it improves the workability of a concrete mix by both electro-static repulsion and steric hindrance [22]. A synthetic detergent air-entraining admixture (AEA) was used in order to a proper air-void system in concrete. A microbial polysaccharide (welan gum) was used as a viscosity-modifying admixture (VMA) to enhance stability of the combination type SCC.

Table 1 Characteristics of cement and limestone powder

Components	Cement	Limestone Powder
SiO_2 (%)	20.74	2.80
Al_2O_3 (%)	4.90	0.35
Fe_2O_3 (%)	3.50	0.5
CaO (%)	62.95	51.22
MgO (%)	1.2	1.8
SO_3 (%)	3.00	1.24
LOI (%)	1.56	42.06
SG	3.150	2.660

Abbreviations: LOI = Loss on ignition; SG: Specific gravity.

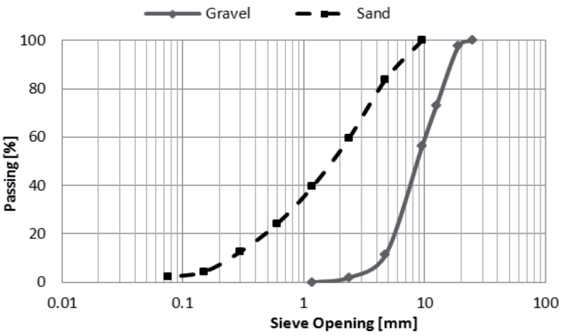

Fig. 1 Particle size distribution of sand and gravel

2.2 Mix Proportions

A total of eight SCC mixes were produced and their workability properties, rheology parameters and compressive strength were tested. A control mix (C) was the initial target and, seven series of mixes were developed with variations of each of the principal properties (i.e. filling and passing ability and segregation resistance) or using of AEA and VMA admixture. Table 2 gives details of mix proportion of eight reference SCCs.

In order to evaluate the robustness of each mixture, in addition to the reference mixture, four mixtures were made that the water content of each mix was changed ±3% and ±6% relative to the base water content. For example, five batches of mix F(SP) were made that the water content of these batches were 188 (F(SP)-6%), 194 (F(SP)-3%), 200 (F(SP)), 206 (F(SP)+3%) and 212 (F(SP)+6%) kg/m^3.

2.3 Mixing procedure and test methods

Each batch of SCC was mixed in a gravity mixer with 60 L capacity in volume of 45 L. In order to minimize the effect of water absorption of aggregates on the fresh properties of SCC, the moisture of aggregates were equal or greater than saturated surface dry (SSD) condition [23]. Each batch of SCC was mixed for 4 min and then was allowed to rest for 1 min.

The determination of the workability specifications were started after 5 min from contact time of cement with water. Concurrent with measuring tests, concrete was agitated for 1 min at 5 min intervals. The preferred workability properties were determined by using slump flow, T_{50} and J-ring according to PCI methods [24] and sieve segregation tests Version II according to European Guidelines for SCC [15].

The rheology parameters (yield stress, plastic viscosity) values were determined by a coaxial rheometer. This automated rheometer, which is shown in Fig. 2, is a rate-controlled rheometer that was employed to carry out rheological measurements 10 minutes after the initial contact between water and cement. It consists of a four-bladed vane that is immersed into the concrete and rotated at various speeds while the torque acting on the vane is measured [25].

Fig. 2 Rheometer for determining the rheology parameters

According to BS 1881 [26], for compressive strength test, 2 cubic samples (100 mm) were molded without applying any tamping or vibration so that the concrete in the cubes was self-compacted.

Table 2 Proportioning of SCC mixtures

Mix Code	W/C	Water	Cement	Limestone powder	Fine aggregate	Coarse aggregate	Fine/Total aggregate	SP
		kg/m^3						%*
C	0.50	200	400	175	916	611	0.6	0.92
F(SP)	0.50	200	400	175	916	611	0.6	1.11
F(SP+W)	0.46	185	400	175	927	618	0.6	1.30
P	0.50	200	400	175	763	763	0.5	1.04
S(L)	0.50	200	400	100	960	640	0.6	0.78
S(C+L)	0.49	185	375	160	987	658	0.6	1.07
Air$^+$	0.50	200	400	175	916	611	0.6	0.74
VMA$^\times$	0.50	200	400	100	960	640	0.6	0.88

* Percent of cement content

+ Include 0.22kg/m^3 air entraining admixture

× Include 0.33kg/m^3 viscosity modifying admixture

After 24 hour curing of samples in the laboratory condition with temperature controlled 18±2 Celsius, these samples were removed from the mold and were cured in the curing container at 20±2 Celsius until 28 days. At the age of 28-days, the compressive strength of the samples was measured by the hydraulic jack with a maximum loading capacity of 2000 KN.

2.4 Analysis methods

The robustness of SCCs is evaluated by analysing the workability tests results through one of the multi attribute decision making (MADM) methods. MADM is applied in the evaluation facet, which is usually associated with a limited number of predetermined alternatives and discrete preference rating. Decision-making processes involve a series of steps: identifying the problems, constructing the preferences, evaluating the alternatives, and determining the best alternatives [27].

Among the various methods of decision-making, in this research, The Vlse Kriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method is used for ranking of SCCs in terms of robustness. VIKOR method focuses on ranking and selecting from a set if alternatives in the presence of conflicting criteria. It introduces the multicriteria ranking index based on the particular measure of closeness to the "ideal" to solution [28].

3. Experimental results and analysis

The main properties of fresh SCC including filling ability, passing ability and segregation resistance have been measured using slump flow, J ring and sieve segregation (GTM) tests. The obtained results of principal properties and rheology parameters of eight mixtures are described in the following:

3.1 Study of principal properties based on the workability tests

Filling Ability (Slump Flow)

Slump flow test as filling ability index of SCC is one of the main quality control tests in fresh SCC. The obtained results of 8 mixtures are shown in Fig. 3. The aim of this study is to achieve to two level of slump flow of 600 and 700 mm. Thus, the slump flow of mixes F(SP) and F(SP+W) is about 700 mm and the other mixtures is about 600 mm.

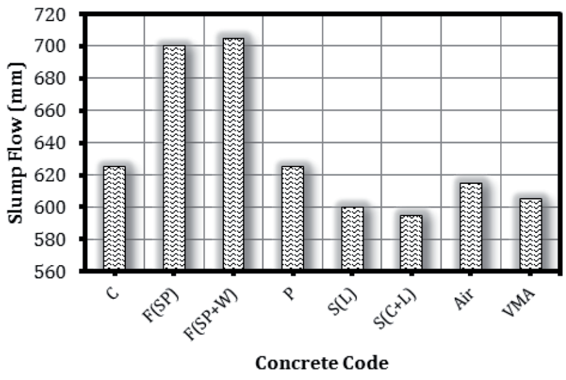

Fig. 3 Slump flow values of mixtures

Passing Ability (J Ring)

The passing ability of mixtures in this study is assessed by J ring Test (Fig. 4). As can be seen, mix P (decreased fine to totale aggregate ratio) and also mixes S(L) and S(C+L) (decreased paste volume) have the highest J ring values. In addition, Increase in slum flow of control mix, only using superplasticizer (mix F(SP)) and also replacement a part of limestone powder with VMA (mix V) lead to decrease in passing ability.

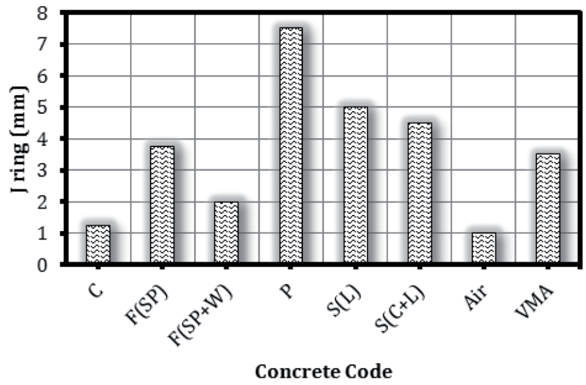

Fig. 4 J ring values of mixtures

Segregation Resistance (Sieve stability test)

The index of segregation resistance in this study is sieve stability (GTM) test version II (Fig. 5). These results indicate that the decrease in paste volume (mixes S(L) and S(C+L)) cause the most decrease in segregation resistance. This decrease is more in mix S(L) than mix S(L+C) that the decrease in paste volume is only due to decrease in limestone powder. After that, increase in slump flow of control mix only with superplastisizer (mix F(SP)) and also decrease in sand amount (mix P) lead to increase in GTM test. On the contrary, addition of AEA to mixture cause to significant decrease in segregation.

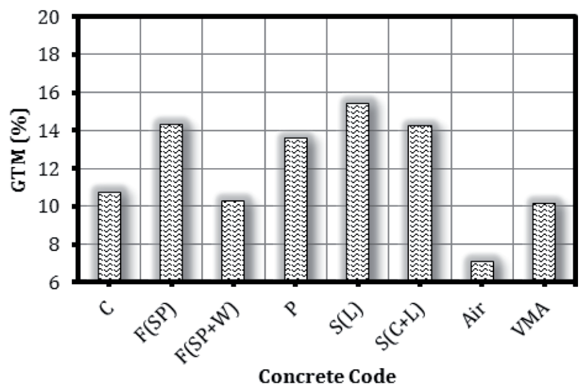

Fig. 5 Sieve segregation values of mixtures

3.2 Study of rheology parameters

Yield stress

The rheological properties of cement-based suspensions, such as mortar and concrete, are often described by the Bingham model. Bingham plastic materials behave as solids below the yield stress and flow like a viscous liquid when the yield stress is exceeded. The yield stress, often displayed by particle suspension, is determined by the number and strength of the particle-particle bonds per unit volume required to break in order to allow flow or consolidation to occur. An increase in magnitude of the interparticle attraction will increase the strength of the bonds and, thus, increase the yield stress [29].

In self compacting concretes the yield stress is usually proportional to spreading value of slump flow test. As mentioned, the concrete mixtures of this study were designed for two levels of slump flow 600 and 700 mm. But the yield stress variations were considerable for different concretes (Fig. 6). As expected, the yield stress of F (SP) and F(SP+W) mixtures with spreading values of about 700 mm have been decreased considerably. Particularly in mix F(SP) that the increase in slump flow is only due to superplastisizer. On the contrary, mixes S(L) and S(C+L) that their yield stresses have increased. Particularly in mix S(L) that the total decrease in paste volume is due to decrease in limestone powder.

Plastic Viscosity

Viscosity is an important material property which describes the resistance towards flow or the "internal friction". It is defined as the shear stress divided by the rate of shear and has the SI- unit Pascal second (Pa s) [29].

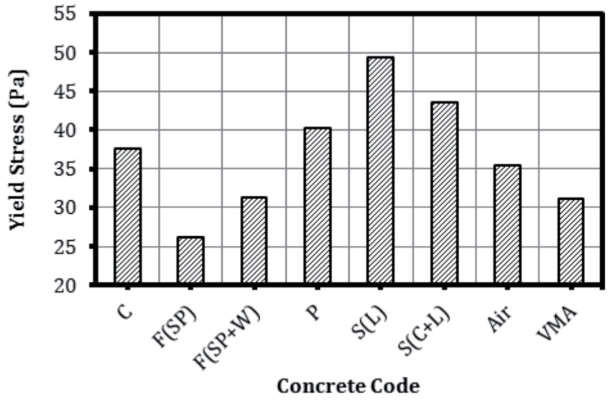

Fig. 6 Yield stress values of mixtures

Plastic viscosity values in different concretes are shown in Fig. 7. As can be observed, decrease in mixing water in mix F(SP+W) and decrease in paste volume particularly due to decrease in limestone powder (mix S(L)) have led to considerable increase in plastic viscosity.

Of course, it is clear that the type of viscosity increase in mix F(SP+W) is distinct from mix S(L). In mix F(SP+W) that increase in flow ability has been obtained by decrease in mixing water and increase in SP dosage, the distance between fine particles (powder) are reduced and surface forces that only exist between fine particles are increased. For this reason, increase in viscosity in mix F(SP+W) is due to paste of concrete and therefore lead to increase in stability of concrete. On the contrary, in mix S(L) the volume of paste has decreased and thus the volume of aggregate has increased. It is clear that high aggregate content in the concrete mix is detrimental to the performance of SCC mixes.

As pointed out by Khayat [30], the solid-to-solid friction resulting from the particle interactions and shearing actions of the aggregate particles when they are moving relative to one another limits the deformability and the speed of flow of the fresh SCC, thus requiring greater shear stresses to maintain a given capacity and speed of deformation. Therefore, high coarse aggregate content in the concrete mix would increase the viscosity and reduce the deformability of the concrete.

On the other side, adding AEA to mixture has led to considerable decrease in plastic viscosity. Also, change of SCC type from powder to combination type (VMA+powder) cause decrease in viscosity.

Rheograph

In this study a rheograph is defined as a plot of changes in the relation between yield stress τ_0 (the y-axis) and the plastic viscosity μ (the x-axis). That is, the rheograph is a plastic viscosity μ–yield stress τ_0 diagram established in order to reveal in a systematical way the effects of change in mix proportion.

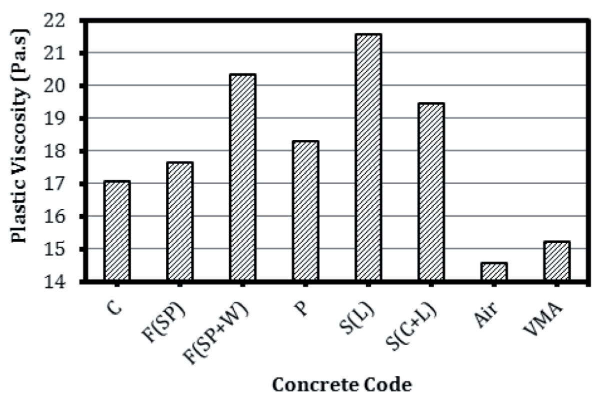

Fig. 7 Plastic viscosity values of mixtures

According to Wallevik and Wallevik researches [10], the rheograph is a convenient and essential tool to compare different concrete batches and examine the behavior relative to changed constituents, quantities of constituents, and/or relative to different times from water addition (and so forth).

Rheological parameters are obtained with the assumption of a uniform and homogeneous concrete and disregarding the situation of its segregation. Therefore in rheogarph Fig. 8, to study the change in rheological parameters together with segregation resistance, the sieve segregation results are written beside of each concrete mark. In general, movement in zone 2 decreases the stability of concretes. In other word, the increase in yield stress and plastic viscosity leads to reduce of segregation resistance. This situation is visible with the less growth in the decrease in yield stress without a significant change in plastic viscosity (zone 3b). In contrast to these two situations, rheological parameter variations in zone 4 (in this study have been obtained using admixtures) improve and stabilize the segregation resistance. Also, this situation is observed in the zone 3a (reduced yield stress together with increased plastic viscosity) that the variation leads to approximately constant segregation resistance.

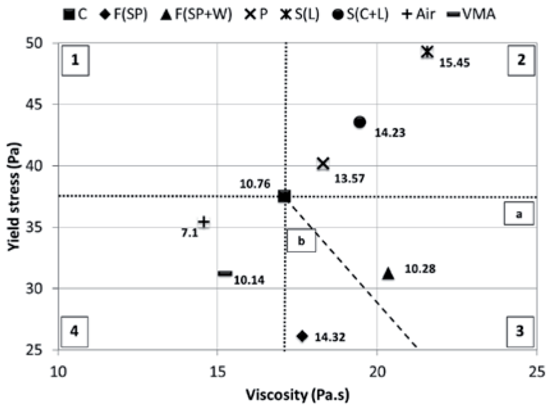

Fig. 8 Effect of mix proportion on rheology parameters and segregation resistance

4. Results analysis

4.1 The scattering of workability tests results on rheograph

The aim of this research is the study of slight changes in the ingredient on the properties of fresh and hardened SCC. Accordingly, SCCs were made and tested in slight changed mixing water (±3 and ±6%). Then the scattering of results is estimated by the standard deviation of results. The standard deviation of results of each test is shown on the rheograph and in the following is interpreted:

The scattering of filling ability

The scattering of slump flow results of each SCC on rheograph is shown in Fig. 9. As can be seen, the increase in yield stress together with plastic viscosity (zone 2) lead to increase in dispersion of slump flow results under the slight change in water content. This increase in dispersion is observed in mixes P, S(L) and S(C+L) respectively. Also, in the zone 3b that decreased yield stress is accompanied with no significant change in viscosity, the scattering of results has increased. On the contrary, in zone 4 that the decrease in yield stress is accompanied with increase in plastic viscosity, the dispersion of results has decreased significantly. This is also visible in the zone 3a that the decrease in yield stress is accompanied with increase in plastic viscosity.

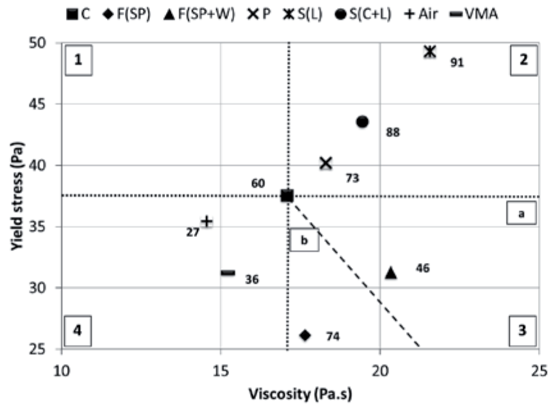

Fig. 9 Standard deviation of slump flow results on rheograph

The scattering of passing ability

The scattering of J ring results of each SCC on rheograph is shown in Fig. 10. These results show that the scattering of J ring results of all concretes are higher than control mixture. However, theses increases are different in various zones. In zone 2 and 3b, the increase in dispersion of results is significant while in zone 3a is limited and the minimum increase has occurred in Zone 4.

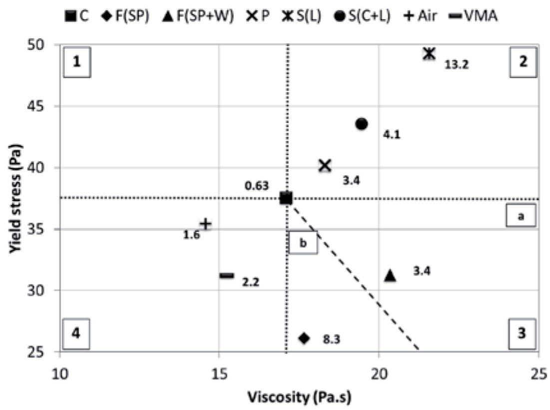

Fig. 10 Standard deviation of J ring results on rheograph

The scattering of segregation resistance

Fig. 11 indicates the scattering of sieve stability test on rheograph. The layout of sieve stability test scattering is similar to slump flow dispersion. The scattering of results have increased in zones 2 and 3b (especially in zone 2) while the movement of rheological parameters in zones 4 and 3a lead to reduction of dispersion.

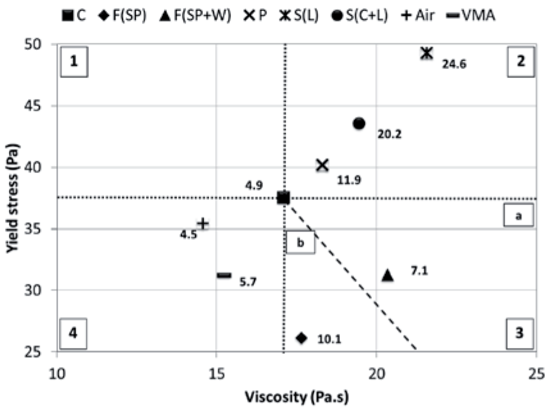

Fig. 11 Standard deviation of sieve segregation test results on rheograph

4.2 SCCs ranking based on the robustness

Since, several tests are required to show the fresh properties of SCCs and variations (and sensitivity) of these tests is not systematic (and similar), the comparison of changes of individual tests is not useful for comparing the robustness of SCCs. To achieve this purpose, it is required to employ analysis methods that consider changes in all tests together. Hence, in order to compare the robustness of SCCs, multi attribute decision making are used.

According to the description in section 2.4, among of different methods of MADM, the Viekriterijumsko kompromisno rangiranje (VIKOR) method is used. In the first step, the ranking of SCCs in terms of robustness should be defined as a Decision-Making (DM) problem. The desired DM problem is the evaluation of difference between tests results in the mixtures with changed and unchanged water content. Therefore in this case, the alternatives are reference mixtures and criteria are the amount of difference between tests results in the case of mix with changed mixing water and reference concretes. The criteria values of SCCs in various changed water content is presented in Table 3.

The aim of this research is the comparison of robustness of the reference SCCs. Therefore, the total difference in four level of variation in water (in each test) is considered as the criterion value. Then, the normalized preferred ratings should be calculated to transform the scale into [0, 1].

Table 3 The difference of tests results in various changed water content of SCCs

Mix	Water variations	Slump Flow	J-Ring Height	sieve segregation
		mm	mm	%
C	-6%	55	0	3.64
	-3%	15	0.25	2.46
	+3%	35	0.25	2.9
	+6%	105	1.25	8.74
F(SP)	-6%	75	0.75	4.98
	-3%	5	0.25	2.07
	+3%	70	4.25	6.18
	+6%	120	18.75	20.23
F(SP+W)	-6%	40	0.25	2.28
	-3%	20	0.5	1.23
	+3%	30	1	2.42
	+6%	80	7.5	17.25
P	-6%	15	1.25	3.07
	-3%	5	2.5	3.07
	+3%	105	2	12.22
	+6%	150	6.25	24.25
S(L)	-6%	30	0.5	2.95
	-3%	15	0.5	1.15
	+3%	100	5	28.25
	+6%	185	30	52.98
S(C+L)	-6%	30	1.25	1.11
	-3%	10	1.75	0.05
	+3%	130	4.5	21.33
	+6%	160	7.5	44.94
Air	-6%	0	3.5	2.27
	-3%	10	2	1.17
	+3%	35	0	0.85
	+6%	65	0	9.18
VMA	-6%	15	3.5	2.14
	-3%	20	4	1.64
	+3%	40	1	6.06
	+6%	65	1	11.16

Table 4 shows the normalized decision criteria in different alternatives. In this table the criteria of slump flow, J ring and sieve segregation tests are presented by X_1, X_2 and X_3 respectively.

Table 4 Normalized decision matrix of SCC robustness

Concrete	X_1	X_2	X_3
C	0.31	0.04^{-}	0.14
F(SP)	0.39	0.48	0.26
F(SP+W)	0.25	0.19	0.18
P	0.40	0.24	0.33
S(L)	0.48^{+}	0.73^{+}	0.67^{+}
S(L+C)	0.48	0.30	0.53
Air	0.16^{-}	0.11	0.11^{-}
VMA	0.20	0.19	0.16

$^{-}$ is the worst value of criteria

$^{+}$ is the best value of criteria

The DM problem is included various criteria (fresh SCC tests), therefore, it is essential to know weight of each criterion. The weight of each criterion implies its relative importance compared to the other criteria. Since, the SCCs are not designed for a specific application, therefore the weights of criteria are considered equal. The weights of criteria are shown in follow matrix.

$$W_j = [1/3 \ 1/3 \ 1/3] \quad (1)$$

By using the equations, values of Q index for each concrete were determined. Then, we can rank the alternatives according to the Q_j values. On the basis of the preferred order of the alternatives, the ranking of concretes based on the robustness is shown in Table 5.

Table 5 Ranking of SCCs robustness according VIKOR method

Ranking	Alternatives	Q_J
1	Air	0.00
2	VMA	0.13
3	F(SP+W)	0.18
4	C	0.26
5	F(SP)	0.61
6	P	0.59
7	S(C+L)	0.85
8	S(L)	1.00

The scattering of synthesized performance

The results of synthesized performance of three tests (slump flow, J ring and sieve segregation) on rheograph are shown in Fig. 12. This index (based on the VIKOR method) is between 0-100% that the lower index is correspond to the more robust SSC (low sensitivity to slight change in ingredient weight). According to these results, there are two categories of zones. First, Zones 2 and 3b that movement of concrete (due to change in mix proportion) in these directions lead to increase in sensitivity. On the other hand, in zones 3a and 4, changes in rheological parameter are along with increase in robustness.

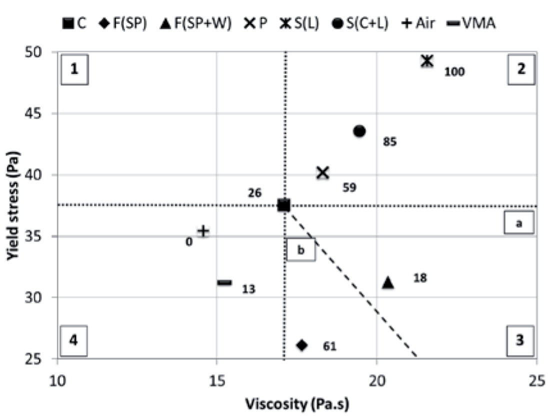

Fig. 12 Variation of synthesized performance SCCs on rheograph

4.3 The robustness of SCC based on the compressive strength test

To study of SCC robustness in the hardened state, the dispersion of compressive strength results has been used. The scattering of compressive strength results of each SCC on rheograph is shown in Fig. 13. According to these results, the scattering of results just has increased in zone 2 while in other zones, the dispersion of strength results have decreased. By comparing of fresh and hardened results, it becomes clear that the increase in rheological parameters in zone 2 lead to decrease in SCC robustness.

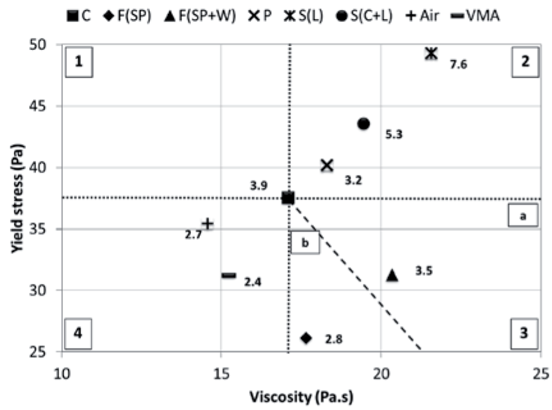

Fig. 13 Standard deviation of compressive strength results on rheograph

5 Conclusions

1. Different tests are required to show the major properties of SCCs in fresh state and variations in any of these tests due to small changes in weight of materials are not systematic. Therefore the comparison of robustness (or sensitivity) of concretes in the individual tests is not useful. In this research, the multi attribute decision making (MADM) are suggested as an appropriate analysis method for comparing the robustness of SCCs. by using MADM, there is possibility to consider various criteria with different unites and even qualitative criteria are allowed to considering different SCC tests in the evaluation of robustness. Also the capability of MADM to assign weight for each criterion provides the possibility to investigate the robustness of SCC for specific application.
2. The results obtained from the evaluation of robustness by VIKOR method indicate that the minimum robustness between seven SCCs derived from control mix design corresponding to reduced segregation resistance SCCs (mixes S(L) and S(C+L)). Moreover, the decreased passing ability SCC (mix P) is more sensitive than the increased filling ability concretes (F(SP)). Also, the results of this research indicated that using air entrained admixture (A) lead to increase robustness but change the SCC type from powder type to composition type (replacing part of limestone powder with VMA) lead to decrease in robustness slightly.

3. The variations of rheology parameters due to change in mix proportion might decrease segregation resistance in two cases. The greatest reduction in segregation resistance occurs if the rheological parameters of mixtures increase. Also, if the yield stress reduction accompanied by minimal viscosity changes, the segregation resistance is reduced less than before case. Conversely, the segregation resistance is improved if the rheological parameters are reduced. This situation occurs with lower growth in yield stress reduction with increasing viscosity.
4. Robustness position of SCCs on the rheograph indicates that the layout of robustness of mixtures is similar to segregation resistance. Thus, the greatest reduction in robustness occurs in the area of increase in both rheological parameters. Also, the SCC robustness is improved in the area of reducing the rheological parameters. So, it is concluded that there is a direct relationship between robustness and segregation resistance of SCC. In other words, increasing the segregation resistance might be increased SCC robustness.
5. According to the robustness and scattering of compressive strength results (due to variation in mixing water), when SCCs have robustness up to a certain level, the variations of compressive strength to slight change in water content is not significant. After a certain level of robustness, the high sensitivity of SCCs in fresh state affects on the sensitivity of compressive strength results. This situation occurs in the area of increase in rheological parameters.

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