DOI: 10.14256/JCE.1136.2014

Primljen / Received: 22.9.2014.
Ispravljen / Corrected: 30.11.2014.
Prihvaćen / Accepted: 29.12.2014.
Dostupno online / Available online: 10.2.2015.

# Effect of mix proportion on robustness of self-compacting concrete

Authors:

Assoc.Prof **Parviz Ghoddousi**, PhD. CE
Iran University of Science and Technology
Teheran, Iran
Ghoddousi@iust.ac.ir

**Amir Masoud Salehi**, MSc. CE
Iran University of Science and Technology
Teheran, Iran
am_salehi@iust.ac.ir

Scientific paper - Preliminary report

Parviz Ghoddousi, Amir Masoud Salehi

## Effect of mix proportion on robustness of self-compacting concrete

An experimental program aimed at evaluating robustness of four distinct types of self-compacted concrete (SCC) is presented in this paper. A control mix was designed and three series of mixes were made, with variation of principal fresh mix properties. In order to evaluate robustness, the selected mixes were subjected to variations in water content. The tested mixes were then ranked using the multi-attribute decision making method. The results indicate that the reduction in segregation resistance, and the decrease in the obstacle passing ability, lead to a considerable decrease in robustness of self-compacting concrete.

Key words:

self-compacting concrete, robustness, mix proportion, multi-attribute decision making

Prethodno priopćenje

Parviz Ghoddousi, Amir Masoud Salehi

## Utjecaj sastava mješavine samozbijajućeg betona na robusnost

U ovom radu prikazan je eksperimentalni program ocjenjivanja robusnosti za četiri različita samozbijajuća betona (eng. Self Compacting Concrete - SCC). Projektirana je kontrolna mješavina te tri serije mješavina s razlikama u osnovnim svojstvima u svježem stanju. Za ocjenu robusnosti u odabranim mješavinama se mijenjala količina vode. Ispitane mješavine su zatim rangirane primjenom metode višeatributnog odlučivanja. Rezultati pokazuju da smanjenje otpornosti na segregaciju i smanjenje sposobnosti zaobilaženja prepreka uzrokuje značajno smanjenje robusnosti samozbijajućih betona.

Ključne riječi:

samozbijajući beton, robusnost, sastav mješavine, višeatributno odlučivanje

Vorherige Mitteilung

Parviz Ghoddousi, Amir Masoud Salehi

## Einfluss der Zusammensetzung selbstverdichtenden Betons auf die Robustheit

In dieser Arbeit wird ein Versuchsprogramm zur Beurteilung der Robustheit vier verschiedener Arten selbstverdichtenden Betons (eng. Self Compacting Concrete - SCC) dargestellt. Eine Kontrollmischung und drei Mischungsserien verschiedener grundlegender Eigenschaften im frischen Zustand sind vorbereitet worden. Um die Robustheit der ausgewählten Mischungen zu bewerten, ist der Wasseranteil variiert worden Die getesteten Mischungen wurden dann durch Multi-Attribut-Entscheidungen eingestuft. Die Ergebnisse zeigen, dass eine Verringerung der Beständigkeit gegen Segregation und eine reduzierte Fähigkeit der Umgehung von Hindernissen, die Robustheit des selbstverdichtenden Betons bedeutend verringern.

Schlüsselwörter:

selbstverdichtender Beton, Robustheit, Mischungszusammensetzung, Multi-Attribut-Entscheidungen

## 1. Introduction

The self-compacting concrete (SCC) is a high-performance concrete that can readily flow under its own weight, pass through narrow gaps, penetrate into far-reaching corners, remain homogeneous with no segregation during and after placing and, finally, achieve full consolidation without compaction. In short, a SCC should be characterized by high flowability, high passing ability, high filling ability, and high segregation stability [1-4].

Although the SCC has been developed more than two decades ago, its practical use is still limited. This is due to the fact that its properties are not fully known, while its performance is highly sensitive to small changes in the mix design parameters [5-7]. The SCC is more susceptible to changes than ordinary concrete because of a combination of detailed requirements, more complex mix design, and an inherent low yield stress and viscosity [5]. Therefore, some SCC mixture designs may not provide adequate robustness.

Different researchers have proposed various definitions for the robustness of concrete. For example, according to the definition given by RILEM TC 288-MPS [8], the concrete robustness is the characteristic of a mixture that is tolerant to variations in constituent characteristics and quantities, variations during concrete mixing, transport, and placement, as well as variations with regard to environmental conditions. However, In the case of SCC, due to the specific properties of fresh concrete, the robustness definition has focused on these properties. For example, European Guidelines for SCC [9] define the robustness of SCC as the capacity of concrete to retain its fresh-state properties in case of small variations in the properties or quantities of constituent materials.

Several methods are currently available for assessing robustness of SCC [10, 11]. The first method is suggested in the European Guidelines for SCC [9]. According to this method, 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 of 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 % from targeted values without changes in SCC Performance [6]. The advantage of this method lies in its simplicity. 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. [12, 13] propose a method to assess the SCC robustness in terms of frequency of satisfying the SCC acceptance criteria 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 experimental results. However, the disadvantage of this method is that the relationship between the mix design parameters and the concrete performance must be known in advance, and so a larger number of trial concrete mixes is needed.

Based on their research, Kwan and Ng [7, 14] suggest that an acceptable range of SP dosage, as well as an acceptable range of slump flow (i.e. the range of SP dosage or slump flow satisfying all SCC performance requirements), may be taken as a quantitative measure of the SCC robustness.

Naji et al. [6] use the coefficient of variation (CV) for comparing and ranking the SCCs robustness. To evaluate the robustness of SCC, eight SCC mixtures were subjected to variations involving three levels of sand humidity. Twenty properties of SCC were determined for each concrete. For each property, the CV of the responses obtained for the three sand humidity values were calculated and used to estimate the relative spread of each response. The SCC mixtures were ranked based on these CV values.

The SCC mix design may meet better workability and economy requirements via targeted variations in mix proportion. However, these variations lead to problems such as change in the robustness of SCC. In other words, to optimize the SCC mix proportion, the robustness of SCC must be considered in addition to the workability and economy restrictions. Hence, the main objective of this study is the evaluation of the SCCs robustness. To this end, the multi-attribute decision making is proposed to compare the robustness of SCC.

## 2. Experimental works and analysis methods

### 2.1. Materials

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

The crushed limestone aggregate with a nominal maximum size of 19.5 mm was used as coarse aggregate. The specific gravity and water absorption of coarse aggregate, measured according to ASTM C127-88 [15], amounted to 2.55 and 1.8 percent, respectively. The sand with the nominal size of 4.75 mm was used as fine aggregate. The Specific gravity and water absorption of sand, measured according to ASTM C 128-88 [16], amounted to 2.60 and 3.9 percent, respectively. The fineness modulus, also measured according to ASTM C136-84a [17], amounted to 3.85. The particle size distribution of both fine and coarse aggregates was situated within the permissible limits stipulated in ASTM C33 [18].

A third generation polycarboxylate-based superplasticizer (SP) was used. It was a brown solution with the specific gravity of 1.1. As a third-generation SP, it improves workability of concrete mixes by both electro-static repulsion and steric hindrance [19].

**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 | 0.50 |
| CaO [ %] | 62.95 | 51.22 |
| MgO [ %] | 1.20 | 1.80 |
| $SO_3$ [ %] | 3.00 | 1.24 |
| LOI [ %] | 1.56 | 42.06 |
| SG | 3.150 | 2.660 |
| Abbreviations: LOI - Loss on ignition; SG - Specific gravity | | |

## 2.2. Mix Proportions

The aim of this research was to evaluate robustness of four SCCs. A Control mix considered to be a "good" SCC was the initial target and it was designed based on the ICAR mix design method [21]. Three series of mixes with the variation of principal properties, i.e. the filling ability, passing ability and segregation resistance, were developed based on the following principles. The ratio of cement to water was decreased, and the amount of SP was increased so as to increase the filling ability of the control mix (F), without changing the aggregate ratio. To decrease the passing ability (P) while keeping the same mortar composition, the volume of coarse aggregate was increased and the SP was slightly decreased. For designing the modified segregation concrete based on the control mix proportion, the volume of paste was decreased and a moderate increase in the amount of water and SP was applied [21]. The mix proportion of these four reference SCCs is presented in Table 2.

In order to evaluate robustness of each mixture, four batches were made in addition to the reference mixture. The water content of each batch was changed by ±3 and ±6 % relative to the base water content. For example, five batches of mix F were made and the water content of these batches amounted to 181.42 (F-6 %), 187.21 (F-3 %), 193 (F), 198.79 (F+3 %), and 204.58 (F+6 %) kg/m$^3$.

## 2.3. Mixing procedure and test methods

Each SCC batch was mixed in a 60 L gravity mixer with 35 L in volume. In order to minimize the effect of aggregate water absorption on fresh SCC properties, the moisture of aggregate used in each batch was equal to or greater than the saturated surface dry (SSD) condition [21]. Each batch of SCC was mixed for 4 min and was then allowed to rest for 1 min.

The determination of workability started 5 min after the contact of cement and water. Concurrent with measuring tests, the concrete was agitated for 1 min at 5 min intervals. The preferred workability properties were determined using the slump flow, $T_{50}$, J-ring, V-funnel at 0 and 5 min, according to PCI methods [22], and sieve segregation tests Version II according to European Guidelines for SCC [9]. For compressive strength test, 2 cubic samples (100 mm) were moulded without applying any tamping or vibration, as per BS 1881 [23], so that the concrete in the cubes was self-compacted. After 24-hour curing of samples in laboratory conditions, at the controlled temperature of 18±2 Celsius, the samples were removed from the mould 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 were measured by hydraulic jack with the maximum loading capacity of 2000 kN.

## 2.4. Analysis methods

The robustness of SCCs is compared and ranked by two methods.

### 2.4.1. Coefficient of variation

The coefficient of variation of each test was calculated for 5 different values of water content (in each reference concrete) according to the first method proposed by Naji et al. [6]. This index was used to estimate the relative spread of each response. In order to rank different SCCs based on robustness, the preferred test CV values were compared and ranked in descending order. It is clear that the lowest CV value indicates the best robustness in each test. Ultimately, the final ranking was based on the sum of sub-ranking values for each SCC.

**Table 2. Proportioning of concrete mixtures**

| Concrete | w/c | Water | Cement | Limestone powder | Fine aggregate | Coarse aggregate | Fine/Total aggregate | Superplasticizer [ %*] |
|---|---|---|---|---|---|---|---|---|
| | | [kg/m$^3$] | | | | | | |
| C | 0.5 | 200 | 400 | 175 | 611 | 916 | 0.6 | 0.64 |
| F | 0.483 | 193 | 400 | 175 | 618 | 927 | 0.6 | 0.75 |
| P | 0.5 | 200 | 400 | 175 | 763 | 763 | 0.5 | 0.58 |
| S | 0.514 | 192.6 | 375 | 160 | 633 | 949 | 0.6 | 0.81 |
| * Percent of cement content | | | | | | | | |

### 2.4.2. Multi attribute decision making

Decision-making processes involve a series of steps: problem indentification, definition of preferences, evaluation of alternatives, and determination of best alternatives. Decision making is extremely intuitive when considering single-criterion problems, since we only need to choose the alternative with the highest preference rating. However, when DMs evaluate alternatives with multiple criteria, many problems, such as the weight of criteria, preference dependence, and conflicts among criteria, seem to complicate the issue and need to be overcome by more sophisticated methods [24].

To facilitate systematic research in the field of MCDM, Hwang and Yoon suggest that MCDM problems be classified into two main categories: Multiple Attribute Decision Making (MADM), and Multiple Objective Decision Making (MODM), based on different purposes and different data types. The MADM is applied in the evaluation facet, which is usually associated with a limited number of predetermined alternatives and discrete preference rating [25].

*Simple additive weighting method*

The Simple additive weighting (SAW) method is probably the best known and the most widely used method for multiple attribute decision making. If there are *m* alternatives and *n* attributes, then the best alternative is the one that satisfies (in the maximization case) the following expression:

$$A^* = \left\{ p_i \middle| \max_i p_i \middle| i = 1,2,3,m \right\} \qquad (1)$$

also

$$p_i = \sum_{j=1}^{m} w_i r_{ij} \qquad (2)$$

Where: $A^*$ is the best alternative (in the maximization case), $p_i$ is the synthesized performance of *i*-th alternative; $w_j$ denotes the weight of importance of the *j-th* criterion; and $r_{ij}$ is the normalized preferred rating of the *i-th* alternative in terms of the *j-th* criterion. The criteria are assumed to be independent of each other. In addition, the normalized preferred rating ($r_{ij}$) of *i*-th alternative with respect to *j*-th criterion can be defined according [24]:

- For the case that larger is better, $r_{ij} = (x_{ij} - x_j^-)/(x_j^* - x_j^-)$, where $x_j^* = \max_i x_{ij}$ and $x_j^- = \min_i x_{ij}$ or let $x^*_j$ tbe the aspired/desired level and $x^-_j$ the worst level.
- For the case that smaller is better, $r_{ij} = (x_j^- - x_{ij})/(x_j^- - x_j^*)$.

**Table 3. Experimental results**

| Mix | Variation of water | Slump flow [mm] | $T_{50}$ [s] | J-ring [mm] | $V_{0min}$ [s] | $V_{5min}$ [s] | Sieve segregation [ %] | Compressive strength [MPa] |
|---|---|---|---|---|---|---|---|---|
| C | -6 % | 570 | 1,54 | 1,25 | 4,28 | 5,19 | 7,12 | 52,1 |
| | -3 % | 610 | 1,39 | 1 | 4,1 | 4,5 | 8,3 | 46,8 |
| | 0 | 625 | 1,43 | 1,25 | 3,81 | 4,31 | 10,76 | 46,9 |
| | +3 % | 660 | 1,05 | 0,01 | 3,81 | 4,31 | 13,66 | 42,7 |
| | +6 % | 730 | 1,02 | 2,5 | 2,69 | 3,22 | 19,5 | 42,6 |
| F | -6 % | 670 | 1,35 | 4,75 | 4,88 | 3,22 | 16,28 | 48,3 |
| | -3 % | 690 | 1,4 | 5 | 3,91 | 2,97 | 15,23 | 48,0 |
| | 0 | 710 | 1,45 | 4,5 | 4,97 | 4,32 | 14 | 43,4 |
| | +3 % | 740 | 1,17 | 3,5 | 2,22 | 2,63 | 16,42 | 43,0 |
| | +6 % | 790 | 1,24 | 12 | 2,16 | 2,45 | 31,25 | 40,5 |
| P | -6 % | 610 | 1,31 | 6,25 | 4 | 7,8 | 10,5 | 46,4 |
| | -3 % | 630 | 1,3 | 5 | 4,16 | 7,25 | 10,5 | 42,1 |
| | 0 | 625 | 1,09 | 7,5 | 1,28 | 3,16 | 13,57 | 39,6 |
| | +3 % | 730 | 1,02 | 7,5 | 2,78 | 4,13 | 25,79 | 39,2 |
| | +6 % | 775 | 0,96 | 13,75 | 3,38 | 7,3 | 37,82 | 38,5 |
| S | -6 % | 580 | 1,08 | 3,75 | 2,4 | 3,7 | 13,19 | 40,5 |
| | -3 % | 600 | 1,07 | 3,25 | 1,85 | 3,13 | 14,35 | 36,2 |
| | 0 | 610 | 1,27 | 5 | 1,31 | 1,84 | 14,3 | 33,4 |
| | +3 % | 740 | 0,83 | 9,5 | 2,74 | 5,53 | 45,63 | 27,3 |
| | +6 % | 770 | 0,68 | 12,5 | 5,85 | 9,69 | 63,24 | 16,4 |

## 3. Results and analysis

To achieve the reference mixes (C, F, P, and S), a mix with appropriate fresh properties (C) was initially designed, and then the modified mixes (F, P, S) were developed. Afterwards, in order to evaluate the robustness of these SCCs, the amount of water of each mixture was changed by ±3 % and ± 6 % relative to the base water content. Then, the fresh properties listed in Section 2.4 were measured. The mixtures code, corresponding to each amount of water, consists of the first letter of the mixture name and of the percentage of altered water, with the sign + or -. For example C+6 % refers to the control mix with the 6 % increase in water. The fresh properties of mixtures in different water contents are presented in Table 3.

Since several tests are required to show fresh properties of SCCs, and as variations in any of these tests is not systematic, the comparison of changes of individual tests is not useful for comparing the robustness of SCCs. To achieve this purpose, analytic methods that consider changes in all tests simultaneously have to be applied. Hence, the coefficient of variation method and multi attribute decision making are used in order to compare the robustness of SCCs

### 3.1. Coefficient of variation analysis

The coefficient of variation (CV) refers to a statistical measure of the distribution of data points in a data series around the mean value. It represents the ratio of the standard deviation from the mean value. The coefficient of variation is a helpful statistic for comparing the degree of variation from one data series to another, although the mean values are considerably different from each other. Therefore, based on the method proposed by Naji et al. [6], the values of the coefficient of variation were determined for each test in different SCCs, after calculation of the mean and standard deviation values. In the next step, the various SCCs were ranked based on the CV values of each test. Table 4 gives details of results. It is clear that the lower CV value means lower scattering of test results and, therefore, the concrete is more robust in the desired test.

**Table 4. Statistical results of workability test and ranking of different concrete in each test**

| Test | Parameter | Mix | | | |
|---|---|---|---|---|---|
| | | C | F | P | S |
| **Slump flow** | Mean | 639,00 | 720,00 | 674,00 | 660,00 |
| | Standard deviation | 60,25 | 46,90 | 73,77 | 88,03 |
| | Coefficient of variation | 9,43 % | 6,51 % | 10,95 % | 13,34 % |
| | Rank | 2 | 1 | 3 | 4 |
| **$T_{50}$** | Mean | 1,29 | 1,32 | 1,14 | 0,99 |
| | Standard deviation | 0,24 | 0,12 | 0,16 | 0,23 |
| | Coefficient of variation | 18,34 % | 8,71 % | 14,17 % | 23,49 % |
| | Rank | 3 | 1 | 2 | 4 |
| **J-ring** | Mean | 1,20 | 3,95 | 8,00 | 6,80 |
| | Standard deviation | 0,89 | 3,43 | 3,38 | 4,03 |
| | Coefficient of variation | 73,84 % | 86,83 % | 42,22 % | 59,25 % |
| | Rank | 3 | 4 | 1 | 2 |
| **$V_0$** | Mean | 3,74 | 3,63 | 3,18 | 2,83 |
| | Standard deviation | 0,62 | 1,38 | 1,23 | 1,77 |
| | Coefficient of variation | 16,56 % | 37,96 % | 38,69 % | 62,68 % |
| | Rank | 1 | 2 | 3 | 4 |
| **$V_5$** | Mean | 4,31 | 3,12 | 5,93 | 4,78 |
| | Standard deviation | 0,71 | 0,74 | 2,12 | 3,05 |
| | Coefficient of variation | 16,42 % | 23,58 % | 35,81 % | 63,83 % |
| | Rank | 1 | 2 | 3 | 4 |
| **Sieve segregation** | Mean | 11,87 | 18,64 | 19,64 | 30,14 |
| | Standard deviation | 4,95 | 7,12 | 11,96 | 23,04 |
| | Coefficient of variation | 41,70 % | 38,20 % | 60,91 % | 76,43 % |
| | Rank | 2 | 1 | 3 | 4 |

**Table 5. SCC ranking in terms of robustness using the coefficient of variation method**

| Concrete | Sub-ranking of fresh concrete tests | | | | | | SUM | Robustness ranking |
|---|---|---|---|---|---|---|---|---|
| | Slump flow | $T_{50}$ | J-ring | $V_0$ | $V_5$ | Sieve segregation | | |
| C | 2 | 3 | 3 | 1 | 1 | 2 | 12 | 2 |
| F | 1 | 1 | 4 | 2 | 2 | 1 | 11 | 1 |
| P | 3 | 2 | 1 | 3 | 3 | 3 | 15 | 3 |
| S | 4 | 4 | 2 | 4 | 4 | 4 | 22 | 4 |

The sub-rankings of each fresh SCC test and their sums are presented in Table 5. The sum of sub-rankings for SCCs is the main index for robustness ranking. Therefore, it can be seen that the mix F is the robust mix proportion, while the mix C has earned the second place. Based on these results, the SCC with a reduced segregation resistance has the lowest robustness. In other words, the mix S is the most sensitive concrete compared to other SCCs.

However, the use of the CV method leads to two problems in the ranking of SCCs in terms of robustness. First, in order to determine the coefficient of variation, the value of standard deviation is divided by the mean value. Therefore, the difference values between CVs are adjusted based on the mean values. For example, in the comparison of mixes C and F based on the sieve segregation test, it can be seen from standard deviation that the mix C has minimum changes in the sieve segregation test. However, because of the high mean value, the mix F exhibits a lower change in the sieve segregation test based on the CV value. Therefore, the ranking of SCCs may be inaccurate due to adjustment by the mean value.

In addition, in order to determine the sub-rankings, the effect of difference between the CV values is eliminated. For example, in the comparison of the slump flow and J-Ring tests results in mixes C and F, the difference between the sub-rankings is unit. But the differences between CV values are 3 % and 13 %, corresponding to the slump flow and J-Ring, respectively. In other words, by converting the CV value to rank, the high differences between test results cannot be considered in the final ranking.

## 3.2. Multi attribute decision making

According to the description given in Section 3.1, the second method is the simple additive weighting (SAW) method that is the simplest and the most widely used method for MADM. 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 the changed and unchanged water content. Therefore, in this case, the alternatives are reference mixtures while criteria are the difference between tests results in the case of changed mixing water and reference concretes. Two cases are considered in the determination of criteria values. In the first case, relative differences are considered as criteria values for the comparison of two methods (CV and MADM) and to demonstrate validity of MADM. In the second case, the absolute differences are used to achieve more accurate results.

### 3.2.1. Relative difference of tests

In this case, the relative difference of tests is used as criteria values. So, the absolute value of the relative difference (RD) is obtained based on the following equation::

$$RD = \left| \frac{R_{CM} - R_{RM}}{R_{RM}} \right| \tag{3}$$

$R_{CM}$ - test result in mixture with changed water content

$R_{RM}$ - test result in reference mixture

The RD values of SCCs at various water contents are presented in Table 6.

**Table 6. Relative difference (RD) of tests results at various water contents of SCCs**

| Test | Mix "C" | | | | Mix "F" | | | | Mix "P" | | | | Mix "S" | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -6 | -3 | +3 | +6 | -6 | -3 | +3 | +6 | -6 | -3 | +3 | +6 | -6 | -3 | +3 | +6 |
| Slump flow | 0.09 | 0.02 | 0.06 | 0.17 | 0.06 | 0.03 | 0.04 | 0.11 | 0.02 | 0.01 | 0.17 | 0.24 | 0.05 | 0.02 | 0.21 | 0.26 |
| $T_{50}$ | 0.08 | 0.03 | 0.27 | 0.29 | 0.07 | 0.03 | 0.19 | 0.14 | 0.20 | 0.19 | 0.06 | 0.12 | 0.15 | 0.16 | 0.35 | 0.46 |
| J-ring | 0.00 | 0.20 | 0.99 | 1.00 | 0.10 | 0.20 | 0.40 | 3.00 | 0.17 | 0.33 | 0.00 | 0.83 | 0.25 | 0.35 | 0.09 | 1.50 |
| $V_0$ | 0.12 | 0.08 | 0.00 | 0.29 | 0.02 | 0.21 | 0.55 | 0.57 | 2.13 | 2.25 | 1.17 | 1.64 | 0.83 | 0.41 | 1.09 | 3.47 |
| $V_5$ | 0.20 | 0.04 | 0.00 | 0.25 | 0.25 | 0.31 | 0.39 | 0.43 | 1.47 | 1.29 | 0.31 | 1.31 | 1.01 | 0.70 | 2.01 | 4.27 |
| GTM* | 0.34 | 0.23 | 0.27 | 0.81 | 0.16 | 0.09 | 0.17 | 1.23 | 0.23 | 0.23 | 0.90 | 1.79 | 0.08 | 0.00 | 2.19 | 3.42 |

* Sieve segregation test

The aim of this research is to compare robustness of the reference SCCs. Therefore, the total RD at four levels of variation in water (in each test) is considered as the criterion value. The decision matrix of the robustness evaluation problem is shown in Table 7. In this table, the criteria of slump flow, $T_{50}$, J-Ring, $V_0$, $V_5$, and sieve segregation tests, are represented by $X_1$, $X_2$, $X_3$, $X_4$, $X_5$ and $X_6$, respectively.

**Table 7. Decision matrix (RD) for evaluation of SCC robustness**

| Mix | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| **C** | 0.34 | 0.66 | 2.19 | 0.50 | 0.49 | 1.65 |
| **F** | 0.24 | 0.44 | 3.70 | 1.39 | 1.35 | 1.66 |
| **P** | 0.44 | 0.58 | 1.33 | 4.38 | 7.19 | 3.14 |
| **S** | 0.54 | 1.12 | 3.00 | 7.98 | 5.80 | 5.69 |

The normalized preferred ratings should be calculated to transform the scale into [0, 1]. Table 8 shows the normalized decision criteria in different alternatives.

**Table 8. Normalized decision matrix (RD) for evaluation of SCC robustness**

| Mix | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| **C** | 0.32 | 0.32 | 0.36 | 0.00 | 0.00 | 0.00 |
| **F** | 0.00 | 0.00 | 1.00 | 0.12 | 0.13 | 0.00 |
| **P** | 0.67 | 0.20 | 0.00 | 0.52 | 1.00 | 0.37 |
| **S** | 1.00 | 1.00 | 0.70 | 1.00 | 0.79 | 1.00 |

The DM problem is included in various criteria (fresh SCC tests). Therefore, it is essential to know the weight of each criterion. The weight of each criterion implies its relative importance compared to other criteria. Since we are interested in achieving comparable results with the CV method, and as the SCCs are not designed for a specific application, the weights of criteria are considered equal. The weights of criteria are shown in the following matrix.

$$w_j = [1/6\ 1/6\ 1/6\ 1/6\ 1/6\ 1/6] \tag{4}$$

So, the synthesized performance of SCCs, which is the index of robustness ranking, is obtained by means of Equation 2. Table 9 shows the synthesized performance and ranking of SCCs based on robustness. It is clear that the lower the synthesized performance, the lower the difference between the results and, therefore, the SCC is more robust.

**Table 9. Synthesized performance (RD) of SCCs for robustness ranking**

| Mix | Synthesized performance [ %] | Rank |
|---|---|---|
| **C** | 17 | 1 |
| **F** | 21 | 2 |
| **P** | 46 | 3 |
| **S** | 92 | 4 |

The comparison of results obtained by two methods (CV and SAW) indicates that the rank of mixes B and F has switched. It is due to the fact that the difference between tests results is not eliminated in SAW.

### 3.2.2. Absolute difference of tests

In fact, taking the absolute difference (AD) between tests results as criteria values is more accurate compared to relative difference. This is due to the fact that, for example, the 50 mm slump flow change in SCC with 600 mm base slump flow can be as critical as the SCC with the 700 mm base slump flow. But in the case of relative difference, the 50 mm slump flow change is adjusted to 0.083 and 0.071, corresponding to SCCs with the base slump flow of 600 and 700 mm, respectively.

Thus, the SCC robustness problem is solved in this section using the SAW method based on the absolute difference (Equation 5). The procedure of determining the synthesized performance is the same as the one mentioned in the previous section. The results obtained at various stages are shown in Tables 10 through 12, and the matrix of the weight of criteria is the same as the one shown in Equation 4. Finally, the SCC robustness ranking is determined based on the synthesized performance, the results of which are shown in Table 13.

**Table 10. The absolute difference (AD) of tests results at various water contents of SCCs**

| Test | Mix "C" | | | | Mix "F" | | | | Mix "P" | | | | Mix "S" | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | -6 | -3 | +3 | +6 | -6 | -3 | +3 | +6 | -6 | -3 | +3 | +6 | -6 | -3 | +3 | +6 |
| **Slump flow** | 55 | 15 | 35 | 105 | 40 | 20 | 30 | 80 | 15 | 5 | 105 | 150 | 30 | 10 | 130 | 160 |
| **$T_{50}$** | 0.11 | 0.04 | 0.38 | 0.41 | 0.10 | 0.05 | 0.28 | 0.21 | 0.22 | 0.21 | 0.07 | 0.13 | 0.19 | 0.20 | 0.44 | 0.59 |
| **J-ring** | 0.00 | 0.25 | 1.24 | 1.25 | 0.25 | 0.50 | 1.00 | 7.50 | 1.25 | 2.5 | 0.00 | 6.25 | 1.25 | 1.75 | 4.5 | 7.5 |
| **$V_0$** | 0.47 | 0.29 | 0.00 | 1.12 | 0.09 | 1.06 | 2.75 | 2.81 | 2.72 | 2.88 | 1.50 | 2.10 | 1.09 | 0.54 | 1.43 | 4.54 |
| **$V_5$** | 0.88 | 0.19 | 0.00 | 1.09 | 1.10 | 1.35 | 1.69 | 1.87 | 4.64 | 4.09 | 0.97 | 4.14 | 1.86 | 1.29 | 3.69 | 7.85 |
| **GTM*** | 0.34 | 0.23 | 0.27 | 0.81 | 0.16 | 0.09 | 0.17 | 1.23 | 0.23 | 0.23 | 0.90 | 1.79 | 0.08 | 0.00 | 2.19 | 3.42 |

* Sieve segregation test

$$AD = \left| R_{CM} - R_{RM} \right| \qquad (5)$$

$R_{CM}$ - test result in mixture with changed water content
$R_{RM}$ - test result in reference mixture

As can be seen in Table 13, the ranking obtained from the absolute difference is similar to the relative difference. However, a considerable point is the greater difference existing between the synthesized performances, in this case (AD) and RD. Due to the lack of adjustment of tests, the changes are more realistic.

**Table 11. Decision matrix (AD) of the SCC robustness evaluation**

| Mix | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| C | 210.00 | 0.94 | 1.88 | 2.16 | 2.74 | 17.74 |
| F | 170.00 | 0.64 | 6.71 | 6.01 | 9.25 | 23.18 |
| P | 275.00 | 0.63 | 9.20 | 13.84 | 10.00 | 42.61 |
| S | 330.00 | 1.42 | 7.60 | 14.69 | 15.00 | 81.43 |

**Table 12. Normalized decision matrix (AD) of the SCC robustness evaluation**

| Mix | $X_1$ | $X_2$ | $X_3$ | $X_4$ | $X_5$ | $X_6$ |
|---|---|---|---|---|---|---|
| C | 0.25 | 0.39 | 0.00 | 0.00 | 0.00 | 0.00 |
| F | 0.00 | 0.01 | 0.66 | 0.31 | 0.53 | 0.09 |
| P | 0.66 | 0.00 | 1.00 | 0.93 | 0.59 | 0.39 |
| S | 1.00 | 1.00 | 0.78 | 1.00 | 1.00 | 1.00 |

**Table 13. Synthesized performance (AD) of SCC for robustness ranking**

| Mix | Synthesized performance [%] | Rank |
|---|---|---|
| C | 11 | 1 |
| F | 27 | 2 |
| P | 60 | 3 |
| S | 96 | 4 |

### 3.3. The robustness of SCC influenced by mix proportion

As mentioned in Section 2.2, the mixes F, P and S were designed to display special features relative to the mix C. The mix F was designed to study the effect of increase in filling ability on the robustness. On the other hand, to examine of the decrease in passing ability, the mixes P and S were designed to examine the decrease in segregation resistance.

The aim of this study is to evaluate robustness changes due to small variation in mix proportion that may dramatically change fresh properties of SCCs. The results of this research show that the reduction of segregation resistance by decreasing the powder content leads to the greatest decrease in robustness. Thereafter, the reduction of passing ability by increasing the coarse aggregate content actually causes a decrease in robustness. Also, the sensitivity of mix F has increased slightly due to an increase in filling ability without an increase in powder content.

It may therefore be possible to optimize, in the SCC mix design, the basic mix proportion based on the workability and economy requirements by making targeted changes in mix proportion. But these changes may alter the robustness (sensitivity) of concrete. For example, based on the results provided by various researchers, and according to the present study, the decrease in powder content that can probably result in a more economical mix proportion will lead to a decrease in robustness. Therefore, the robustness should be seriously considered in the optimization of the SCC mix design.

## 4. Conclusion

Three mixtures were designed in this research by making small changes in the mix proportion of a good SCC (C). These mixtures included the mix F with an increased filling ability, the mix P with a decreased passing ability, and the mix S with a reduced segregation resistance. The following conclusions can be made by comparing robustness of SCC mixtures using various methods:

1. The comparison of robustness (or sensitivity) of concrete in individual tests is not useful for a complete comparison of concrete robustness. Therefore, the multi-attribute decision making is suggested in this research as an appropriate method for comparing the robustness of SCC.
2. The robustness evaluation results obtained by MADM indicate that the reduced segregation resistance concrete exhibits the minimum robustness. Also, the decreased passing ability concrete is more sensitive than the increased filling ability concrete.
3. The ability of MADM to consider various criteria with different units, including qualitative criteria, allows the use of different SCC tests in the evaluation of robustness.
4. The ability of MADM to assign weight to each criterion enables investigation of the SCC robustness for specific applications.
5. According to the MADM capabilities, a multi-objective optimization can be made based on the workability, economy and robustness criteria.

## REFERENCES

[1] Skarendhal, A., Billberg, P.: Casting of Self Compacting Concrete, *final report of RILEM technical committee 188-CSC*, 2006.

[2] ACI Committee 237. ACI 237R-07: Self-Consolidating Concrete, *Farmington Hills (USA): American Concrete Institute*; 2007.

[3] Khayat, K., Workability, Testing and Performance of Self-Consolidating Concrete, *ACI Materials Journal*, 1999, Vol. 96, pp. 346-353.

[4] Hwang, S., Khayat, K.: Performance of Hardened Self-Consolidating Concrete Designated for Repair Applications, *ACI SP-233*, 2006.

[5] Bonen, D., Deshapande, Y., Olek, J., Shen, L., Struble, D., Lange, D., Khayat, K.: Robustness of Self-Consolidating Concrete, *Proceedings of the Fifth International RILEM Symposium on Self-Compacting Concrete*, 2007.

[6] Naji, S., Hwang, S., Khayat, K.: Robustness of Self-Consolidating Concrete Incorporating Different Viscosity-Enhancing Admixture, *ACI materials journal*, 2011.

[7] Kwan, A., Ng, I.: Improving Performance and Robustness of SCC by Adding Supplementary Cementitious Materials, *Construction and Building Materials*, 2010, pp. 2260-2266, doi: http://dx.doi.org/10.1016/j.conbuildmat.2010.04.030

[8] Khayat, K., De Schutter, G.: Mechanical properties of self-compacting concrete, *State-or-the-art report of RILEM Technical Committee 228-MPS*, RILEM Publications, 2013.

[9] BIBM, CEMBUREAU, EFCA, EFNARC, and ERMCO,: The European Guidelines for Self-compacting Concrete. Specification, Production and Use., 2005.

[10] Rigueira, J., García-Taengua, E., Serna-Ros, P.: Self-Consolidating Concrete Robustness in Continuous Production Regarding Fresh and Hardened State Properties, *ACI Materials Journal*, 2009, Vol. 106, pp. 301-307.

[11] Gettu, R., Shareef, S., Ernest, K.: Evaluation of the Robustness of SCC, *Indian Concrete Journal*, 2009, Vol. 83, pp. 13-19.

[12] Nunes, S., Figueiras, H., Oliveira, P., Coutinho, J., Figueiras, J.: A Methodology to Assess Robustness of SCC Mixtures, *Cement and Concrete Research*, 2006, pp. 2115-2122, doi: http://dx.doi.org/10.1016/j.cemconres.2006.10.003

[13] Nunes, S., Figueiras, H., Oliveira, P., Coutinho, J.: Robust SCC Mixes through Mix-Design, *Journal of Materials in Civil Engineering*, 2012.

[14] Kwan, A., Ng, I: Optimum superplasticiser dosage and aggregate proportions for SCC, *Mag Concr Res* 2009, pp. 281–292, doi: http://dx.doi.org/10.1680/macr.2008.00010

[15] ASTM C127-88, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate; American Society for Testing and Materials; 2001.

[16] ASTM C 128-12, Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate; 2012.

[17] ASTM C136-06, Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates; 2006.

[18] ASTM C33 / C33M-13, Standard Specification for Concrete Aggregates; 2013

[19] Newman, J., Choo, B: Advanced Concrete Technology 1, *Butterworth-Heinemann*, 2003.

[20] Koehler, E., Fowler, D.: ICAR Mixture Proportioning Procedure for Self-Consolidating Concrete; *RESEARCH REPORT ICAR 108-1*, 2007.

[21] ACM Centre, Measurement of Properties of Fresh Self-Compacting Concrete, *TESTING SCC-Project Co-Ordinator*, University of Paisley, UK, 2005.

[22] PCI. Interim guidelines for the use of self-consolidating concrete in precast/prestressed concrete institute plants (TR-6-03). Chicago (IL): Precast/Prestressed Concrete Institute; 2003.

[23] BS Standard 1881: Part 116. Standard test method for compressive strength of cubic concrete specimens: British Standards Institution.

[24] Tzeng, G., Huang, J.: Multiple Attribute Decision Making: Methods and Applications, *CRC press*, 2011.

[25] Triantaphyllou, E.: Multi-criteria Decision Making Methods: A Comparative Study, *Springer science+Business media Dordrecht*, 2000.