Construction and Building Materials 229 (2019) 116849

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A new method to quantify the robustness of self-consolidating grouts

Tahir Kemal Erdem *, Esra Bilgiç, Züleyha Kanpara Cıvaş

İzmir Institute of Technology, Department of Civil Engineering, Urla, İzmir, Turkey

HIGHLIGHTS

- A new and easy method is proposed to evaluate the robustness of grouts.
- Effects of SP type, w/b and mineral admixtures on robustness are discussed.
- SP type was the most important factor affecting the robustness.
- Grouts with NS type SP were more robust than those with PC type SP.
- Mineral admixture type and amount had the least effect on robustness.

ARTICLE INFO

Article history:
Received 24 January 2019
Received in revised form 2 August 2019
Accepted 1 September 2019
Available online 14 September 2019

Keywords:
Robustness
Superplasticizer
Workability
Self-consolidating grouts

ABSTRACT

There are different methods in literature to evaluate the robustness of highly fluid cementitious mixtures. However, no one of them gained widely acceptance due to the relative advantages and disadvantages involved in each of them. Therefore, there is still need for further research on this topic. This study proposes a new and relatively easy method for quantifying the robustness of self-consolidating grouts by calculating so-called robustness indices. Due to the more difficulty to produce robust mixtures for highly fluid mixtures obtained by very powerful chemicals, the method is based on the variations in the superplasticizer (SP) type and amount. Mineral admixture (fly ash or limestone powder) usage and water-to-binder ratio (w/b) were other parameters investigated in this study. It was found that SP type was the most important factor affecting the robustness. The effect of w/b was less when compared to SP type. The mixtures containing naphthalene-based SP were more robust than those containing polycarboxylate-based SP. Mineral admixture type and amount had the least effect on robustness.

1. Introduction

Self-compacting grouts are widely used in ground improvement, concrete repair works, reducing rock and soil permeability, rock anchorage, and post-tensioning applications [1,2]. In such cases, the grout is required to enter the cracks or pores easily. High fluidity is achieved by the use of a superplasticizer (SP) however the paste has to remain its homogeneity or stability during all stages of the application. Although it is easy to increase the fluidity by use of a SP, its excessive usage can disturb the homogeneity by the separation of water and the solid particles in the mixture. The non-homogeneous mixtures can decrease the performance (such as strength and volume stability) of the hardened material. Since highly flowable mixtures are more susceptible to the changes in material properties than mixtures with lower consistency [3], a greater attention is required to make such mixtures less sensitive (or more robust) to the variations in the ingredients.

There are different definitions of robustness in the literature. Robustness can be defined as the capacity of a cement-based mixture to retain its fresh properties when small variations in the quantities of the constituent materials occur [4]. However, the variations in the mixing parameters (such as mixing time, mixing speed and the addition time of superplasticizer) and temperature should also be considered for more robust mixtures [5]. Nunes et al. [6] states that in studying the robustness, one has to take into account the specific characteristics of the production center like the existing level of quality control, equipment performance, skills and knowledge of the personnel involved. In a study of Amini et al. [7], the term "robustness" is referred to resistance to time-dependent variation in fluidity and stability of mixtures subjected to prolonged agitation, which was employed to simulate transport to casting location at job site. Robustness was also considered as stability by Bonen et al. [8]. Billberg and Khayat [9] defined the

---

* Corresponding author.
E-mail address: tahirkemalerdem@iyte.edu.tr (T.K. Erdem).

https://doi.org/10.1016/j.conbuildmat.2019.116849

robustness as reducing the sensibility of the concrete to daily changes in key material characteristics and production parameters.

Increasing the robustness of self-consolidating mixtures has been a concern of many researchers. In general, it was stated that robustness can be increased by increasing the viscosity, reducing SP content, using viscosity modifying admixtures (VMA), increasing the matrix density, decreasing the size of coarse aggregate, paying a greater attention to moisture variations in successive batches, careful metering of chemical admixtures and water, and adhering to the mixing protocol [8]. Despite many recommendations made by the researchers to qualitatively increase the robustness of self-consolidating mixtures, there is no one single and a widely accepted method to quantify the robustness. Several researchers proposed different methods to evaluate the robustness as discussed below and summarized in Table 1.

Billberg and Khayat [9] prepared concrete-equivalent mortars (CEM) simulating self-consolidating concretes (SCC) having different VMA types. After plotting the plastic viscosity vs. yield stress of the mixtures in a figure, two methods were proposed for robustness evaluation. First method calculates the so-called rheology area which is equal to total spread in yield stress times the total spread in plastic viscosity. In the second method, coefficient of variation (COV), which is defined as standard deviation divided by mean value, of rheological parameters (plastic viscosity and yield stress) was calculated. The mixtures with smaller rheology area and lower COV were found as more robust.

Hwang and Khayat [10] evaluated the robustness by an index of minimum water content (MWC), which is determined from the slope of the increase in flow diameter of a mini slump flow cone vs. the increase in w/cm. Similar to the study of Billberg and Khayat [9], CEM mixtures were used instead of SCC mixtures. A mixture with a greater MWC, i.e. a more robust mixture, shows lower degree of increase in flow after a given increase in water content. The robustness of the CEM mixtures containing polycarboxylate-based SP were less than that of the mixtures with naphthalene-based SP.

European Guidelines for SCC [4] states that most of the constituent variability that would threat robustness can be equated to a change in water requirement since changes in moisture content of the materials or changes in grading/specific surface result in a change in the water demand of the mix. Accordingly, a well-designed and robust SCC is defined as the one that can typically accept a 5–10 L/m^3 change in water content while maintaining its properties inside the specified limits. Therefore, it is proposed to test at ±5 and 10 L of the target water content and measure the change in fresh state properties. Nunes et al. [6], however, finds this method too simplistic because it does not take into account the specific characteristics of the production center like the existing level of quality control, equipment performance, skills and knowledge of the personnel involved. Ghoddousi and Salehi [11] states that the advantage of the EFNARC [4] 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 [11].

Another method to assess the robustness was proposed by Nunes et al. [6,12]. The method is based on factorial design method. The influence of five mixture properties, which are water to powder volume ratio (V_w/V_p), filler to cement weight ratio (w_f/w_c), superplasticizer to powder weight ratio (SP/p), sand to mortar volume (V_s/V_m) and solid volume (V_{ap}), and their coupled effects on slump flow, t_{50}, V-funnel flow time, L-Box filling height and 28-day compressive strength were mathematically modeled. Simulations of mixture parameters were made by using the derived models and a measure of robustness was computed that represents the probability that SCC mixture properties fall inside the acceptance limits. Bootstrap technique was applied to the original data sample to estimate the robustness value and its accuracy. The study considered the real data of variations of material constituents collected from a precast factory. It was found that V_w/V_p exhibited the greatest effect on all five measured responses. According to Ghoddousi and Salehi [11], the method given in [6,12] has the disadvantage that the relationship between the

Table 1
Different approaches to evaluate robustness.

Source	Mixture type	Approach to evaluate robustness	Comment
Billberg and Khayat [9]	CEM	- Calculation of rheology area (total spread in yield stress times the total spread in plastic viscosity) - COV of plastic viscosity and yield stress	Requires rheometer and knowledge of statistics
Hwang and Khayat [10]	CEM	Calculation of minimum water content (MWC) index, which is determined from the slope of the increase in flow diameter of a mini slump flow cone vs. the increase in w/cm	Stability was not considered as a parameter
European Guidelines for SCC [4]	SCC	Using ±5 and 10 L of the target water content and measuring the change in fresh state properties	- Not quantitative [11] - Not possible to compare robustness of different mixtures [11] - Too simplistic because it does not take into account the specific characteristics of the production center [6]
Nunes et al [6,12]	SCC	Factorial design to determine the probability that SCC mixture properties fall inside the acceptance limits	- 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 [11] - Heavy statistics for engineers
Naji et al. [13]	SCC	For each of the several concrete properties, the COV of the responses obtained for the three sand humidity values were calculated and used to estimate the relative spread of each response	- Comparison of changes of individual tests is not useful for comparing the robustness because variations of several tests on fresh SCC are not systematic (and similar) [11] - Heavy statistics for engineers
Ghoddousi and Salehi [11]	SCC	SCC mixtures with slightly different water content (±3 and ±6%) were tested. The scattering of results is estimated by the standard deviation of results. The robustness is evaluated by analysing the workability tests results through one of the multi attribute decision making methods (VIKOR method).	Heavy statistics for engineers
Kwan and Ng [14,15]	SCC	Determining the width of the range of SP dosage satisfying all the performance requirements	Concretes with different variations in performance within the same SP range will have the same robustness

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 [11].

Naji et al. [13] proposed a COV-based method in which eight SCC mixtures were subjected to variations in three sand humidity values. Twenty properties of SCC mixtures (nine workability characteristics, seven rheological properties, and four mechanical properties) 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 in descending order. The lowest COV value indicated the highest robustness. On the other hand, Ghoddousi and Salehi [11] stated that variations of several tests on fresh SCC are not systematic (and similar). Therefore, the comparison of changes of individual tests is not useful for comparing the robustness of SCC. Accordingly, multi attribute decision making methods that consider changes in all tests together are necessary to compare the robustness of SCC [11].

Kwan and Ng [14,15] proposed to evaluate the robustness of SCC as the width of the range of SP dosage satisfying all the performance requirements. They also suggested that the optimum SP dosage for maximum robustness should be set as the middle value of the acceptable range of SP dosage.

Although there are several methods to evaluate the robustness proposed in the literature, no one of them gained a widely acceptance and was used by another researcher. Each of them has its own advantages and disadvantages as stated above. Therefore, there is a need for further research to quantify the robustness. This study aims to propose a different method to quantify the robustness of self-consolidating grouts. Variations in SP dosages were taken as the basis for this study. The new generation SPs, which are used in relatively very small quantities, are so powerful that very small changes in their quantities can affect the workability significantly. On the other hand, measuring the SP dosage require accurate equipment at the plants which would result in a non-robust product if it is not so. In addition to the variations in SP content, the mixtures in this study were designed to have different water-to-binder ratios (w/b), SP types, limestone filler contents, and fly ash contents to determine how and to what extent the variations in SP dosage affect the robustness of the mixtures with different design parameters.

2. Research significance

A workable cement-based mixture should be designed to tolerate variations in the mixture ingredients. Therefore, this requirement necessitates quantifying the robustness of the mixtures. Although some attempts have been made by a number of researchers, there is no widely accepted method for this goal. Some of them were found very simplistic while some others are not practical due the necessity of high number of trials or relatively deep knowledge of statistics which are not preferable for engineers. As a result, the need for evaluating the robustness still exists. This study proposes a new and relatively easy method to quantify robustness and make a contribution to fill this gap in the literature. Moreover, with the help of the investigated parameters, this study can help the engineers design more robust mixtures.

3. The method proposed to evaluate the robustness

The method proposed here, which is only mentioned in [16], partly used in [12] and an extension of the method in [14,15], is based on the measurement of the change in a response of a mixture with the change in a variable that affects the related response. Considering Fig. 1, when the change in the response is high with a small change in the variable, the mixture is said to be less robust. Accordingly, Mixture B is more robust than Mixture A.

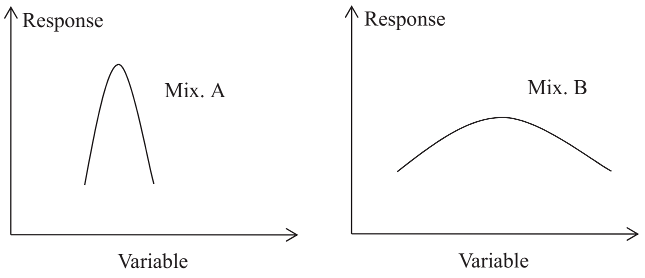


Fig. 1. Mixtures with different robustness.

In this study, workability (the ease of processing of a mixture while keeping it stable) was taken as the response and the variable was taken as SP content (Fig. 2). Upon an increase in the SP dosage the consistency (and workability) increases continuously until reaching the peak point in Fig. 2. After a certain dosage, the stability problems become dominant and workability decreases due to the more proneness of the mixture to segregation. In other words, workability should be expressed by simultaneously considering consistency (slump flow in this study) and stability (bleeding test in this study) depending on the SP dosage. Further explanation of Fig. 2, the experimental approach and the method proposed to evaluate the robustness are explained below:

In the experimental part, firstly, a mixture is prepared with very low SP dosage (point A) which gives a lower consistency than a predefined minimum slump flow requirement (point B). Then, only the SP dosage is increased slightly in a new mixture to obtain point B. SP dosage is increased further in new mixtures until no significant increase in slump flow is observed. This level corresponds to point D beyond which stability starts to govern the workability. Further increase in SP dosage results in points E, F and G. Beyond point F, the mixture exceeds the allowable stability limit and therefore it is no more workable. Once the points B, D and F are obtained, the robustness index (R) of the mixture can be evaluated from Eq. (1):

$$R = \frac{(SP\%\ \ at\ \ Point\ \ F) - (SP\%\ \ at\ \ Point\ \ B)}{(slump\ \ flow\%\ \ at\ \ Point\ \ D) - (slump\ \ flow\%\ \ at\ \ Point\ \ B)} \tag{1}$$

In Eq. (1), the slump flow values of the mixtures were expressed as percentages of the predefined minimum slump flow requirement (point B), which was taken as 130 mm according to the recommendation made by Khayat et al. [1] for the same slump cone used in the current study (See Section 4.3). Accordingly, the slump flow percent at point B is taken as 100. The allowable limit for stability were determined based on the observations during the tests as will be explained in Section 5.1.

4. Materials, mixtures and test procedures

4.1. Materials

CEM I-42.5R portland cement complying with EN 197 [17] was used. Type F fly ash (according to ASTM C618) [18] and limestone powder (LP) were used as mineral additives (MA). Chemical composition and physical properties of the portland cement, fly ash (FA) and LP are presented in Table 2. The unburned coal in FA, which affects the amount of superplasticizer adsorption available for other binder materials, was determined as 2.87%. The SEM images and particle size distributions of the cement, FA and LP can be seen in Figs. 3 and 4, respectively. A polycarboxylic-ether

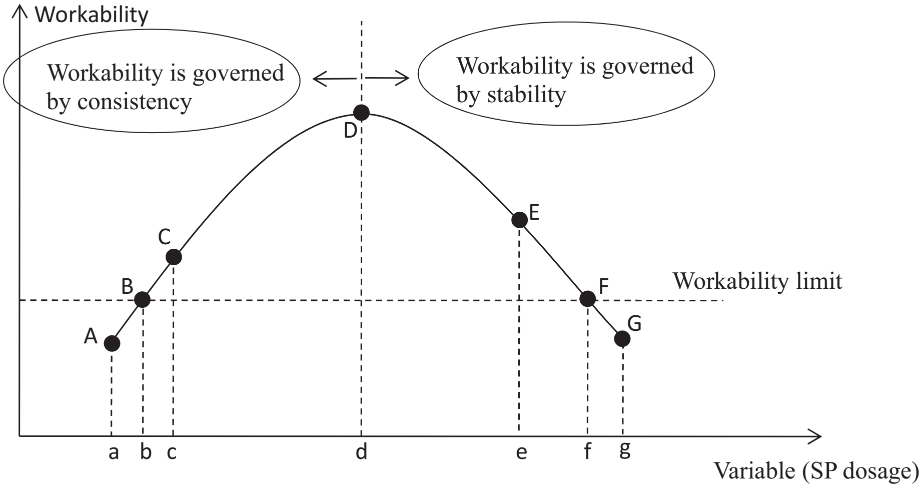


Fig. 2. Change of workability with SP dosage.

Table 2
Properties of the portland cement and the mineral admixtures.

	Portland Cement	FA	LP
SiO_2 (%)	5.72	52.28	0.001
Al_2O_3 (%)	7.85	27.06	0.21
Fe_2O_3 (%)	2.18	8.62	0.01
CaO (%)	68.97	3.30	95.16
MgO (%)	3.46	3.73	0.96
SO_3 (%)	1.92	0.26	0.001
K_2O (%)	0.53	2.26	0.001
Na_2O (%)	8.50	0.11	2.68
$SiO_2 + Al_2O_3 + Fe_2O_3$ (%)	–	87.96	–
Blaine fineness (cm^2/g)	3670	3440	3945
Specific gravity	3.11	2.40	2.75

type (PC) with a solid content of 37.3% and a naphthalene formaldehyde sulfonic acid based (NS) superplasticizer with a solid content of 46.8% were used in the mixtures.

4.2. Mixtures

The mixture types are shown in Table 3. Two different w/b ratios, by weight, were selected as 0.40 and 0.50. Mixing water was corrected by considering the water present in the SPs. For each w/b, the mixtures contained FA or LP in varying amounts (0, 15 and 30% of the binder weight). As seen from Table 3, there are 2 (w/b) × 5 (binder combinations) × 2 (SP types) = 20 types of mixtures. The SP content in these mixture types varied from low values to excessive amounts to determine the range of SP where the mixture can be regarded as workable. At least 5 different SP contents were used for each mixture type to find the points B, D and F in Fig. 2. Therefore, more than 100 grout mixtures were prepared by varying the SP amount.

4.3. Test procedures

The grouts were produced in a cylindrical container with 15 cm diameter and 30 cm height. A high speed mixer was used for mixing. The procedure of mixing was kept same for all mixtures to eliminate the external effects on robustness as proposed by [5]. Following standard procedure was applied: the water and SP were poured to the container and mixed for 15 s. Then, the cementitious materials were gradually introduced in 1 min while the mixer was running. After an additional mixing of 1 min, the grout was left to rest for 30 s. During the rest time, the binder stuck on the inner walls of the container was returned to the mixture. Finally, the grout was mixed again for additional 2 min. Immediately after the mixing operation, mini-slump flow test was performed to determine the consistency of the fresh grout mixtures. Then, bleeding test was made according to ASTM C940 [19].

In mini-slump flow test, the cone shown in Fig. 5 was filled with the grout and lifted vertically upwards. When the flow stopped, the diameter of the spread was measured at three different locations. The average of the measurements was recorded as slump flow diameter.

In the bleeding test, 1000-mL glass graduates were filled up to a level of 800 ml. The presence of segregation was inspected at every 15 min until 2 h. Bleeding or separation of the ingredients stopped at or before 2 h for all of the mixtures. Although there was no segregation or bleeding in very stable mixtures, it was possible to observe upto 4 segregation regions for some of the unstable mixtures (such as some mixtures containing excessive amounts of PC type SP). For such mixtures, the segregation occurred –from top to bottom- in the form of floating particles, bleed water, diluted grout and bottom grout (Fig. 6). The volume of each region (if any) was recorded with respect to time. The bleeding amount was calculated as the volume of bleed water at the end of 2 h divided by the total volume of the grout (800 ml) and multiplied by 100 to express the data in percent.

5. Results and discussion

5.1. Effects of design parameters on workability and SP range

The effects of w/b ratio, SP and mineral admixture type and amount on the slump flow and bleeding of the grouts were reported elsewhere and the detailed discussion can be found in [21]. Therefore, only a brief summary of these findings will be presented in this paper. Fig. 7, which shows the SP-slump flow relation for the mixtures with 30% fly ash, was used to illustrate the following discussions.

The slump flow of the mixtures increased with SP content regardless of the binder type, w/b and SP type until a certain SP content for a given mixture type (Fig. 7). Beyond the peak point, the addition of further SP did not increase the slump flow because the mixture was saturated to the SP molecules and the extra SP molecules did not interact with the binder particles.

As seen in Fig. 7, when w/b was relatively high, SP requirement for a given slump flow value was less because the water has already an effect to separate the solid particles, helping the

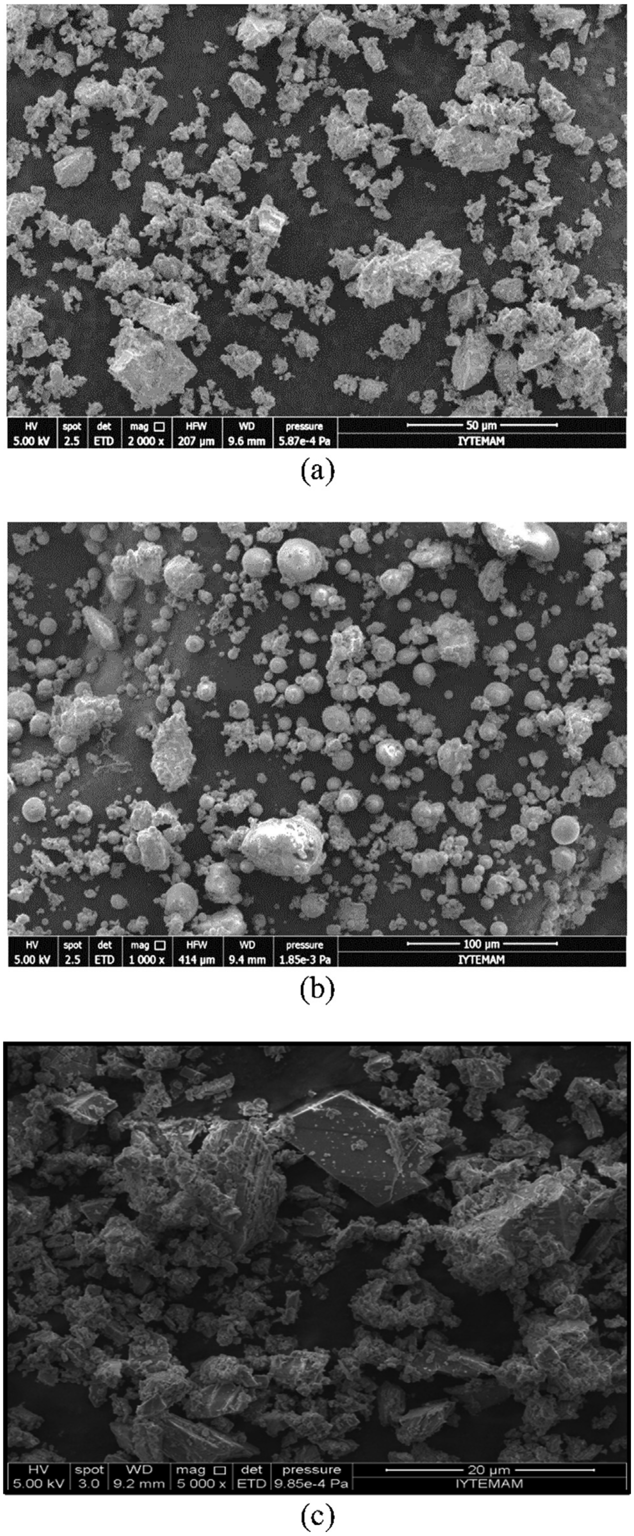


Fig. 3. SEM images of the a) portland cement, b) fly ash and c) limestone powder.

mixture to spread easily. Moreover, for a given slump flow, PC is used in much lower amounts when compared to NS. In other words, for the same amount of SP, PC was able to provide much higher slump slow values. This observation was same for all of the mixture types studied in this research.

As known, mechanism of action of SPs can be discussed under two headings: “Electrostatic repulsion” and “steric hindrance”. In

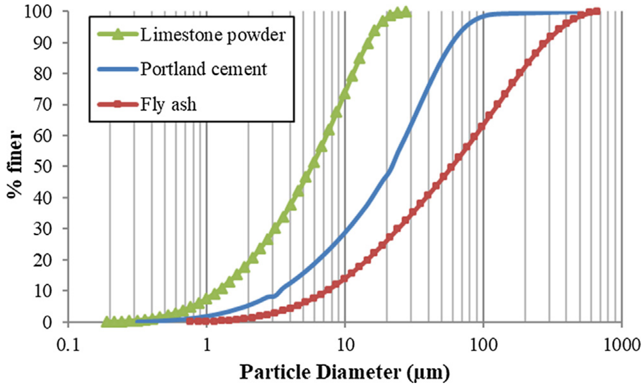


Fig. 4. Particle size distributions of the portland cement, FA and LP.

Table 3
Mixture types.

w/b	Portland cement, %	FA, %	LP, %	SP type
0.4	100	0	0	PC
	85	15	0	PC
	70	30	0	PC
	85	0	15	PC
	70	0	30	PC
	100	0	0	NS
	85	15	0	NS
	70	30	0	NS
	85	0	15	NS
	70	0	30	NS
0.5	100	0	0	PC
	85	15	0	PC
	70	30	0	PC
	85	0	15	PC
	70	0	30	PC
	100	0	0	NS
	85	15	0	NS
	70	30	0	NS
	85	0	15	NS
	70	0	30	NS

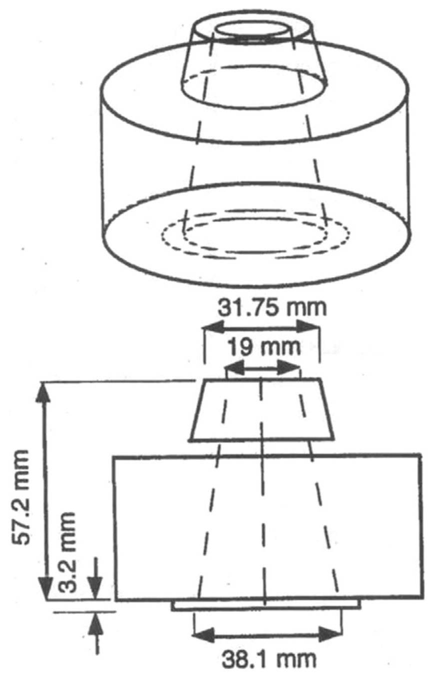


Fig. 5. Mini-Slump Cone [20].

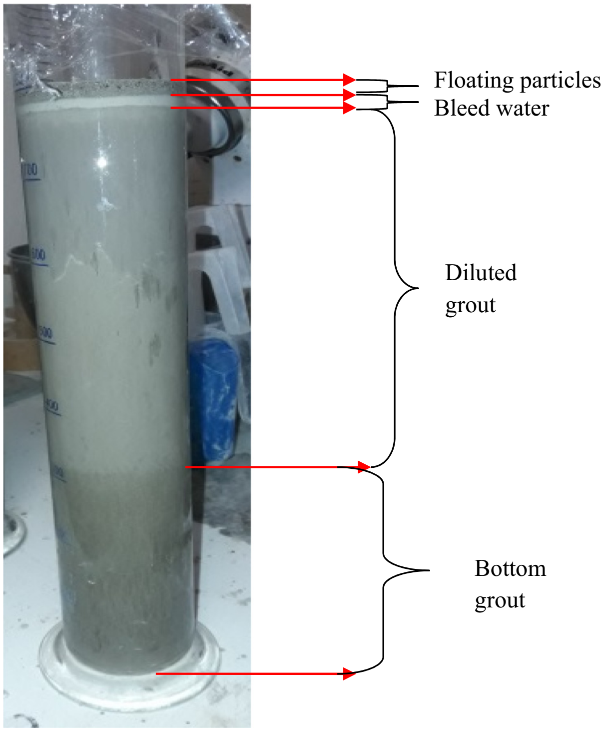


Fig. 6. Segregation in unstable mixtures.

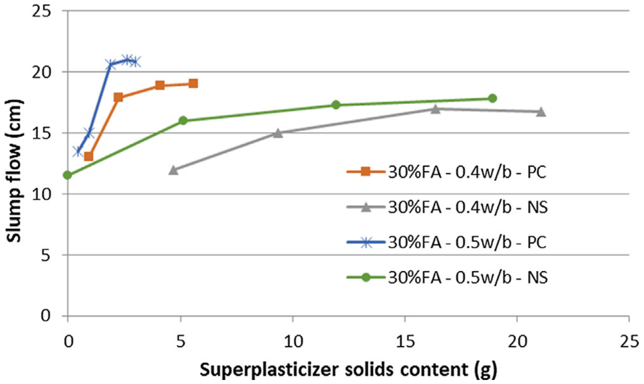


Fig. 7. SP-slump flow relation for the mixtures with 30% fly ash.

the former effect, molecules of the admixture neutralize the cement particles and cause all surfaces to carry uniform charges of same sign. The particles having the same charge repel each other and become separated. In the latter effect, long polymer chains adsorbed on the surface of the cement particles prevent them to come closer to each other. PC type admixtures show both effects (electrostatic repulsion and steric hindrance) and therefore have a higher ability to reduce the water content when compared to NS type where only electrostatic repulsion is present [21].

When SP type was PC, use of mineral admixtures (FA or LP) resulted in similar slump flow values as the mixtures containing only portland cement. However, in the case of NS, the mixtures with MA generally had lower slump flow values when compared to those without MA. Therefore, the ability of PC to separate the MA particles was found to be better than that of NS.

An acceptable stability criterion was determined considering i) the bleeding amount, ii) the visual inspection of the shape of the spread just after the slump flow test, and iii) different phases occurred during the bleeding test. It was observed that when bleeding is equal to or less than 1%, most of the grouts did not show any segregation and they were able spread with a circular shape in the slump flow test. For higher bleeding values, most of the mixtures showed a complete separation (all possible phases in Fig. 6) during the bleeding test and the slump flow spread occurred in irregular shapes. Therefore, 1% bleeding is a critical value for specifying the stability limit. However, it is important to note that 1% criteria, only, was not sufficient for stability criterion. Although the bleeding was less than 1% in some of the mixtures containing MA, they showed different separation phases in the test cylinder (Fig. 6). The separation of fly ash or LP particles from the grout can be explained by the differences in their specific gravities and by the possibly lightweight particles in the MA. Therefore, it was concluded in this study that for acceptable stability, the bleeding value has to be less than 1% and the grouts must not show separation in the test cylinder.

By using the above-mentioned criteria for stability, the stable mixtures with slump flow values greater than 13 cm were identified as workable mixtures. Among these mixtures, those corresponding to the points B, D and F according to Fig. 2 were used to establish Table 4. Then, Fig. 8 was prepared to show the SP boundary dosages for workability. The bars in Fig. 8 starts with an SP dosage to have 13 cm slump flow (point B) and ends when the SP dosage is at the stability limit (point F). As seen from the figure, the SP ranges for workable grouts are much wider for the mixtures with w/b = 0.4 when compared to higher w/b regardless of the MA type and amount. When w/b is high, the mixture shows bleeding problems more easily and the range becomes narrow.

Fig. 8 also shows that NS type of SP provides a wider SP range for workability when compared to PC. As known, even low amounts of PC can provide high fluidity due to its more improved mechanism of action (both steric hindrance and electrostatic repulsion) when compared to NS which has only electrostatic repulsion effect. This stronger effect can lead that the stability of the mixtures may be disturbed more easily and the range of SP for workable mixtures becomes narrower.

The effect of MA type and amount on the SP range varied for different mixtures, and a unique behaviour could not be identified from Fig. 8. Further discussion on the varying effects of MA type and amount on the results will be made in Section 5.2.

5.2. Effects of design parameters on robustness

The mixtures in Table 4 were ranked according to their robustness indices which were calculated according to Eq. (1) (the last column of the table). It is very apparent from the Table that all of the mixtures with NS occurred at the upper half of the table, meaning that they have higher robustness indices than the mixtures with PC. Therefore, it can be concluded that SP type has the highest effect on the robustness. The higher robustness indices found for NS mixtures are clear from the Fig. 9, as well. This finding suggests that due to the less robustness of PC mixtures, it is necessary to weigh PC type superplasticizer more precisely than NS type of SP during the mixture preparation.

The importance of SP type on robustness was emphasized also by [8,22,23]. In those studies, it is stated that polynaphthalene sulfonate and polyphosphonic based superplasticizers could result in more robust SCC mixtures than PC based superplasticizers. Accordingly, the findings of the proposed method (more robustness of NS mixtures than PC mixtures) are supported by the literature.

The second point that Table 4 shows is that for a given SP type, the mixtures with w/b = 0.4 are more robust than those with w/b = 0.5 regardless of the MA type and amount. For example, among the first 10 mixtures in Table 4, all of which contain NS, the first five of them have a w/b ratio of 0.4. Therefore, the second param-

Table 4
Data for points B, D and F in Fig. 2, robustness indices and ranking of the mixture types.

Mixture Name	SP Solids% for point B	Slump flow at point B, mm (%)	Slump flow at point D, mm (%)	SP solids % at point F	Stability criterion for point F*	Robustness index (R), $*10^{-3}$	Ranking according to SP range	Ranking according to R
w/b = 0.4 – No MA – NS	0.18	130 (100)	195 (150.0)	0.82	B + S	12.85	1	1
w/b = 0.4–30% LP – NS	0.36	130 (100)	205 (157.7)	0.94	B + S	9.94	2	2
w/b = 0.4–30%FA – NS	0.31	130 (100)	168 (129.2)	0.60	B	9.74	6	3
w/b = 0.4–15%LP – NS	0.28	130 (100)	200 (153.8)	0.73	B	8.26	3	4
w/b = 0.4–15%FA – NS	0.23	130 (100)	187 (143.8)	0.59	B	8.01	4	5
w/b = 0.5 – No MA – NS	0.04	130 (100)	180 (138.5)	0.28	B	6.36	7	6
w/b = 0.5–30%LP – NS	0.18	130 (100)	198 (152.5	0.49	B	6.03	5	7
w/b = 0.5–15%LP – NS	0.16	130 (100)	195 (150.0)	0.40	B	4.89	8	8
w/b = 0.5–30%FA – NS	0.06	130 (100)	175 (134.6)	0.22	B	4.62	13	9
w/b = 0.5–15%FA – NS	0.08	130 (100)	195 (150.0)	0.26	B	3.51	12	10
w/b = 0.4 – No MA – PC	0.05	130 (100)	210 (161.5)	0.22	B	2.79	10	11
w/b = 0.4–30%FA – PC	0.05	130 (100)	190 (146.2)	0.17	B + S	2.68	14	12
w/b = 0.4–30%LP – PC	0.05	130 (100)	223 (171.5)	0.24	B + S	2.54	9	13
w/b = 0.4–15%LP – PC	0.06	130 (100)	215 (165.4)	0.21	B	2.23	11	14
w/b = 0.4–15%FA – PC	0.06	130 (100)	210 (161.5)	0.17	S	1.82	15	15
w/b = 0.5 – No MA – PC	0.01	130 (100)	204 (156.9)	0.08	B	1.37	18	16
w/b = 0.5–30%FA – PC	0.02	130 (100)	207 (159.2)	0.10	B + S	1.32	17	17
w/b = 0.5–30%LP – PC	0.03	130 (100)	221 (170.0)	0.12	B	1.20	16	18
w/b = 0.5–15%LP – PC	0.02	130 (100)	215 (165.4)	0.09	B + S	1.14	19	19
w/b = 0.5–15%FA – PC	0.02	130 (100)	215 (165.4)	0.08	S	0.89	20	20

*B: Bleeding = 1%; B + S: Bleeding = 1% and Segregation with several regions; S: Segregation with several regions.

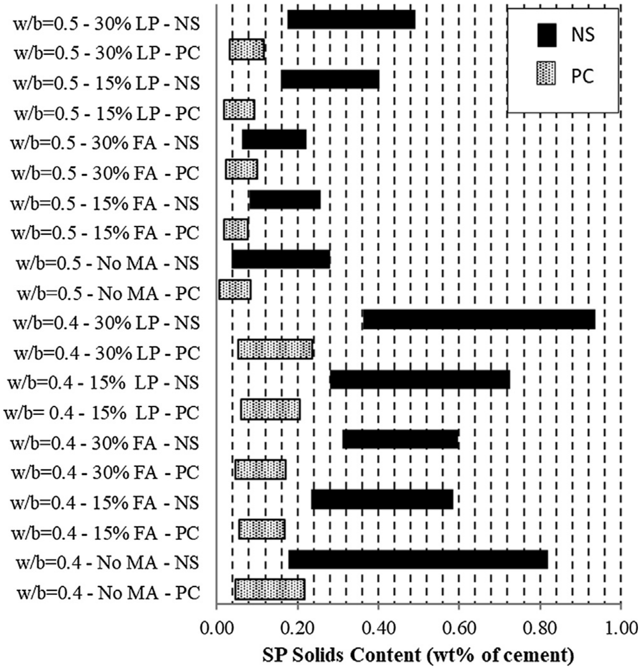


Fig. 8. SP ranges for workable mixtures.

eter that affects the robustness at most is w/b. The higher robustness of the mixtures with low w/b can also be seen in Fig. 9.

The lower robustness of the mixtures having higher w/b is possibly due to the more proneness of them to bleeding. It is clear from Table 4 that the SP values for the allowable stability limit (point F) are lower for the similar mixtures with higher w/b values. Moreover, it can be recalled from Fig. 8 that the mixtures with high w/b have narrower SP ranges.

The effects of w/b on robustness have been discussed by other researchers, as well. It was stated in the literature [8] that higher w/b can increase the susceptibility of the concretes to segregation and decrease the stability and robustness. Kwan and Ng [14,15] found that decreasing the water/cement ratio is an effective means of improving the performance and robustness of SCC. Billberg [24] was another researcher stating the more robustness of SCC with lower water-to-cement ratio (w/c). These studies coincide with the discussions made for the results of this study, indicating the properness of the method proposed to calculate the robustness index.

Fig. 10 compares the relative importance of SP type and w/b on robustness for a given MA type. It is important to note that the NS mixtures with w/b = 0.5 were more robust than the PC mixtures with w/b = 0.4 despite the fact that high w/b decreases the robustness. Therefore, it is clear that SP type has more effect on robustness than w/b. Observing this finding on both FA and LP mixtures (i.e. similarity of Fig. 10a and b) indicates that the approach for evaluating the robustness indices is consistent.

In order to understand the effect of MA type on robustness, Fig. 9b and c can be considered. These figures indicate that for a given w/b, SP type and replacement amount, the robustness of FA and LP mixtures were generally very close to each other. For the mixtures with w/b = 0.5 and NS, the robustness indices of the LP mixtures were slightly higher than FA mixtures.

The change of MA amount on robustness can be observed from Fig. 10a and b. Again, these figures show that the behavior of FA and LP mixtures were similar to each other. When the SP type was PC, the amount of MA (FA or LP) did not affect the robustness significantly (the values were slightly lower for 15% MA content). For both Fig. 10a and b, when the SP type was NS, use of FA or LP reduced the robustness. (However, it has to be kept in mind that NS mixtures were always more robust than similar mixtures with PC.) The adverse effect of MA usage on the robustness of NS mixtures can be related to the fact that for the same amount of SP, the NS mixtures with MA generally had lower slump flow values when compared to those without MA (See Section 5.1). In other words, MA increased the NS demand for the desired workability. Since higher values of SP/cement ratio can decrease robustness [8], the robustness indices of the mixtures without MA was higher than those with MA. Moreover, Bonen et al. [8] stated that robustness can be increased by increasing the matrix density. This can also explain the lower (for NS) or similar (for PC) robustness of the MA mixtures with the mixtures without MA, recalling that FA and LP have less specific gravity than portland cement (Table 2).

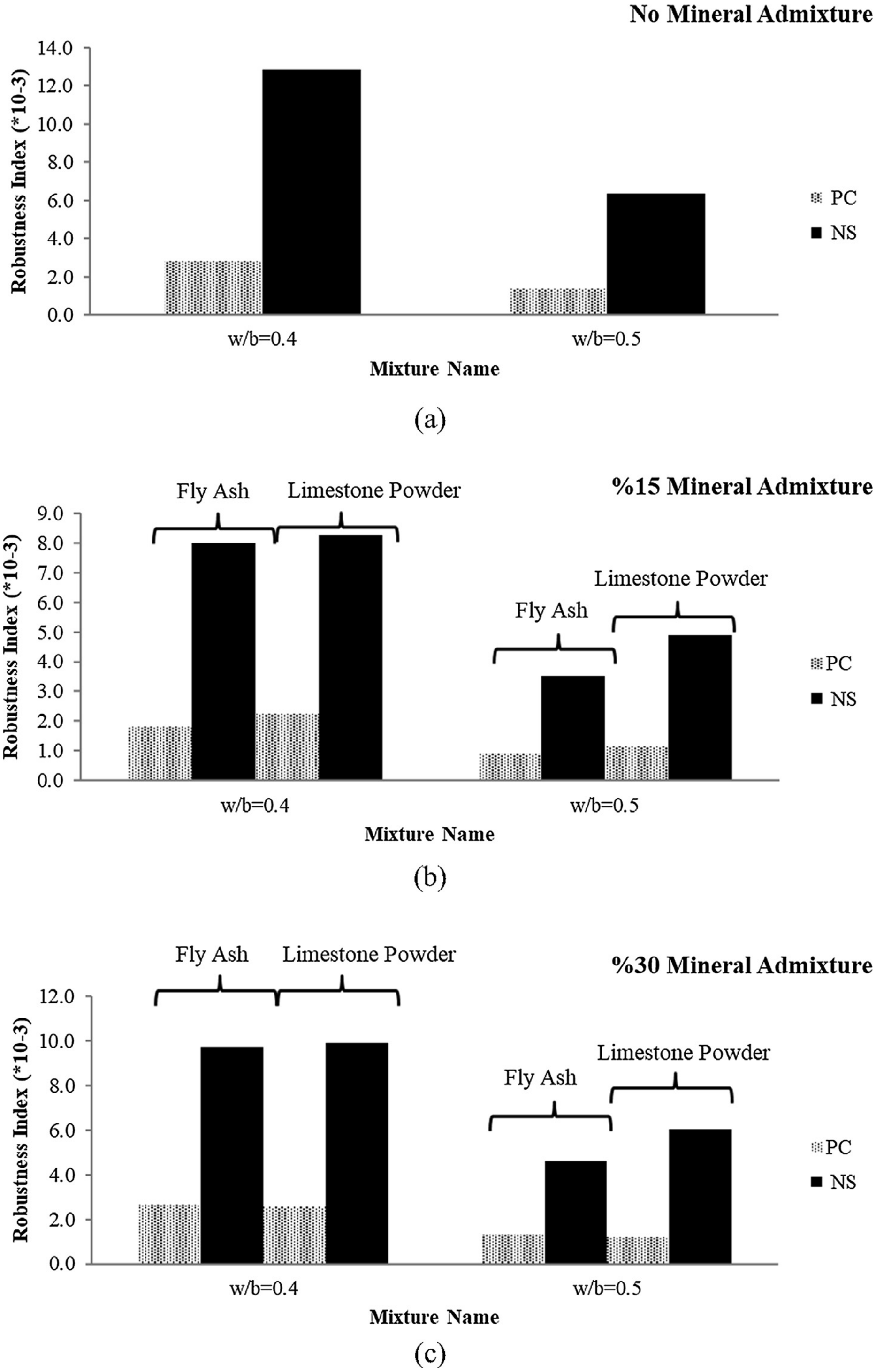
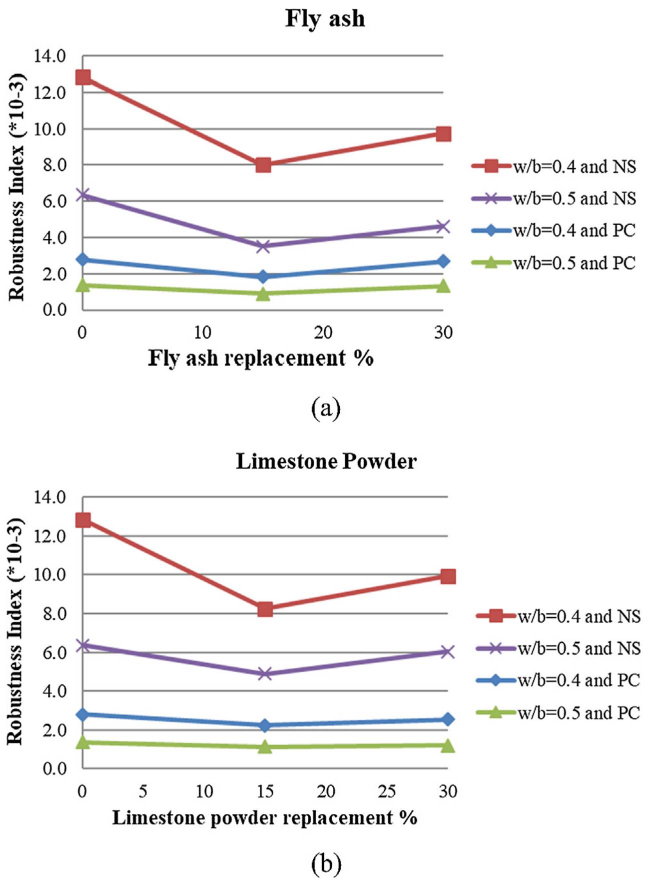


Fig. 9. Robustness indices of the mixtures a) without MA, b) with 15% MA and c) with 30% MA.

In this study, as stated in the above discussions, the effects of MA type and amount on robustness are not as definite as the effects of SP type and w/b. In some studies, the use of MA was found to increase the robustness [8,14]. However, there are disagreements in the literature on the effect of MA on fresh mixture properties [8] due to several reasons: One reason can be the complex binder system which involves the binder-SP interactions. For example, cement composition (especially the C_3A and sulfate content), the alkalinity, surface charge and fineness of the binder can affect the ratio of the adsorbed amount of superplasticizers to the surface area of the particles [25–32]. Another reason can be the interparticle distance in different binder systems as stated by [8]. The lower the interparticle distance, the higher the rate of coagulation and the higher the robustness. In the same study [8], the matrix density was also found to affect the robustness of the mixtures containing MA. The characteristics of the MA are also important for robustness. For example, fly ash has ball-bearing effect and enhance flowability while it can also reduce the flowability due to an increase in the solid volume as a result of its lower specific gravity [14]. Hence, fly ash has both positive and negative



(a)

(b)

Fig. 10. Effect of MA replacement % on robustness.

effects [14] and the total effect can change depending the specific properties of the fly ash used. Similarly, use of fine materials (such as silica fume and limestone filler) can improve the packing density of the granular skeleton [33] while they can also increase the total surface area of the solid particles and reduce the thickness of the water films coating the solid particles [14], the total effect being dependent on the fine powder amount. Therefore, they can have both beneficial and adverse effects on fresh concrete performance.

Table 4 gives the ranking of the mixtures according to the robustness which was calculated considering the SP range as made by Kwan and Ng [14], noting that the ranking based on Eq. (1) has already been discussed above. The ranking according to Eq. (1) and SP range are similar to each other indicating the properness of the proposed method. There are some differences in the two rankings but the method of Eq. (1) is more informative than the other because it considers both the maximum slump flow of the mixtures and the acceptable SP range while the other method considers only the latter. In other words, Eq. (1) involves the points B, D and F (in Fig. 2), while the other method involves only the points B and F. Recalling Fig. 1, two mixture types can have same change in the variable (such as SP ranges) but one of them can provide quite different change in the response (such as slump flow), and therefore can have quite different robustness.

6. Conclusions

This study proposed a new method for quantifying the robustness of self-consolidating grouts. The mixtures contained either of 2 types of superplasticizers (NS or PC) and various amount MA (FA or LP). The w/b was either 0.40 or 0.50. A so-called robustness index was calculated for each mixture by determining the SP range for workability and maximum slump flow values. Following conclusions can be drawn from the present study:

1. The mixtures were ranked according to their robustness indices. The ranking conforms to the knowledge gathered from the literature, indicating the properness of the proposed method.
2. SP type was found as the most important factor affecting the robustness. The effect of w/b on robustness was less when compared to SP type. Mineral admixture type (fly ash and limestone powder used in this study) and amount had the least effect on robustness.
3. All of the mixtures containing naphthalene-based SP were more robust than all of the mixtures with polycarboxylate-based SP.
4. For a given SP type, the mixtures with w/b = 0.4 were more robust than those with w/b = 0.5 regardless of the MA type and amount.
5. For a given w/b, SP type and MA replacement amount, the robustness of FA and LP mixtures were generally very close to each other.
6. When the SP type was PC, the amount of MA (FA or LP) did not affect the robustness significantly. For NS mixtures, use of FA or LP reduced the robustness.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] K.H. Khayat, G. Ballivy, M. Gaudreault, High-performance cement grout for underwater crack injection, Can. J. Civ. Eng. 24 (3) (1997) 405–418.
[2] K.D. Weaver, J. Evans, S.E. Pancoski, Grout testing for a hazardous waste application, Concr. Int. 12 (7) (1990) 45–47.
[3] L. Shen, L. Struble, D. Lange, Testing static segregation of SCC, in: 4th Intern. RILEM Confer. On Self-Consolidating Concrete, Chicago, 2005, pp. 729–737.
[4] The European Project Group, 'The European Guidelines for Self-Compacting Concrete', Eur. Guidel. Self Compact. Concr., May, 2005.
[5] A.A. Asghari, A. Margarita, L. Hernandez, D. Feys, G. De Schutter, Which parameters, other than the water content, influence the robustness of cement paste with SCC consistency?, Constr Build. Mater. 124 (2016) 95–103.
[6] S. Nunes, H. Figueiras, P. Milheiro, J. Sousa, J. Figueiras, in: A Methodology to Assess Robustness of SCC Mixtures, 2006, pp. 2115–2122.
[7] K. Amini, I. Mehdipour, S.D. Hwang, M. Shekarchi, Effect of binder composition on time-dependent stability and robustness characteristics of self-consolidating mortar subjected to prolonged agitation, Constr. Build. Mater. 112 (2016) 654–665.
[8] D. Bonen, Y. Deshpande, J. Olek, L. Shen, L. Struble, D. Lange, K. Khayat, Robustness of self-consolidating concrete, in: 5th Int. RILEM Symp. on Self-Consolidating Concrete, Ghent, 2007, pp. 33–42.
[9] P.H. Billberg, K.H. Khayat, Use of viscosity-modifying admixtures to enhance robustness of SCC, Proceedings of the Third North American Conference on the Design and Use of Self-Consolidating Concrete, 2008.
[10] S.D. Hwang, K.H. Khayat, Performance of hardened self-consolidating concrete designated for repair applications, in: C. Shi, K.H. Khayat (Eds.), ACI SP-233 'Workability of SCC: Roles of it's Constituents and Measurement Techniques, 2006.
[11] P. Ghoddousi, A.M. Salehi, The robustness of self consolidating concrete due to changes in mixing water, Periodica Polytech. Civ. Eng. 61 (2) (2017) 216–225.
[12] S. Nunes, P. Milheiro-Oliveira, J.S. Coutinho, J. Figueiras, Robust SCC Mixes through Mix Design, ASCE J. Mater. Civ. Eng. 25 (2) (2013) 183–193.
[13] S. Naji, S. Hwang, K.H. Khayat, Robustness of self-consolidating concrete incorporating different viscosity-enhancing admixtures, ACI Mater. J. 108 (4) (2011) 432–438.
[14] A.K.H. Kwan, I.Y.T. Ng, Improving performance and robustness of SCC by adding supplementary cementitious materials, Constr. Build. Mater. 24 (11) (2010) 2260–2266.
[15] A.K.H. Kwan, I.Y.T. Ng, Optimum superplasticiser dosage and aggregate proportions for SCC, Magaz. Concr. Res. 61 (4) (2009) 281–292.
[16] P.C. Nkinamubanzi, P.C. Aitcin, Cement and superplasticizer combinations: compatibility and robustness, Cem. Concr. Aggregat. 26 (2) (2004) 102–109.
[17] TS EN 197-1 'Cement – Part 1: Composition, specifications and conformity criteria for common cements', Turkish Standardization Institute, 2012.

[18] ASTM C618-17a ‘Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete’, ASTM International, West Conshohocken, PA, 2017.
[19] ASTM C940-16, Standard Test Method for Expansion and Bleeding of Freshly Mixed Grouts for Preplaced-Aggregate Concrete in the Laboratory, ASTM International, West Conshohocken, PA, 2016.
[20] R. Hooton, K. Khayat, A. Yahia, Simple field tests to characterize fluidity and washout resistance of structural cement grout, Cem. Concr. Aggregates 20 (1) (1998) 145.
[21] T.K. Erdem, E. Bilgiç, Z. Kanpara, An Investigation on the Factors Affecting the Range of Superplasticizers for Workable Self-Consolidating Grouts 8 – 10 May, in: 2nd Int. Conf. on Civil and Environmental Engineering, Nevşehir, Turkey, 2017, pp. 1–8.
[22] R. Gettu, S.N. Shareef, K.J.D. Ernest, Evaluation of the robustness of SCC, Indian Concr. J. 83 (6) (2009) 13–19.
[23] S.-D. Hwang, K.H. Khayat, O. Bonneau, Performance-based specifications of self-consolidating concrete used in structural applications, ACI Mater. J. 103 (2) (2006) 121–129.
[24] P. Billberg, Increase of SCC robustness to varying aggregate moisture content using VMA, in: 2nd Int. Symp. on Design, Performance and Use Self-Consolidating Concrete, China, 2009, pp. 473–482.
[25] A.A. Asghari, D. Feys, G. De Schutter, Mix design factors of self-consolidating cement paste affecting the magnitude of variations in rheological properties induced by the addition time of PCE-superplasticizer, Constr. Build. Mater. 159 (2018) 269–276.
[26] M.-A. Simard, P.-C. Nkinamubanzi, C. Jolicoeur, D. Perraton, P.-C. Aïtcin, Calorimetry, rheology and compressive strength of superplasticized cement pastes, Cem. Concr. Res. 23 (4) (1993) 939–950.
[27] D. Bonen, S.L. Sarkar, The superplasticizer adsorption capacity of cement pastes, pore solution composition, and parameters affecting flow loss, Cem. Concr. Res. 25 (7) (1995) 1423–1434.
[28] K.C. Hsu, J.J. Chiu, S. Da Chen, Y.C. Tseng, Effect of addition time of a superplasticizer on cement adsorption and on concrete workability, Cem. Concr. Compos. 21 (5–6) (1999) 425–430.
[29] S. Nunes, P.M. Oliveira, J.S. Coutinho, J. Figueiras, Rheological characterization of SCC mortars and pastes with changes induced by cement delivery, Cem. Concr. Compos. 33 (1) (2011) 103–115.
[30] K. Yamada, S. Henehara, Interaction mechanism of cement and superplasticizers-the roles of polymer adsorption and ionic conditions of aqueous phase, Concr. Sci. Eng. 3 (11) (2001) 135–145.
[31] K. Yoshioka, E. Sakai, M. Daimon, A. Kitahara, Role of steric hindrance in the performance of superplasticizers for concrete, J. Am. Ceram. Soc. 80 (10) (2005) 2667–2671.
[32] E. Sakai, K. Yamada, A. Ohta, Molecular structure and dispersion-adsorption mechanisms of comb-type superplasticizers used in Japan, J. Adv. Concr. Technol. 1 (1) (2003) 16–25.
[33] I. Mehdipour, K.H. Khayat, Effect of particle-size distribution and specific surface area of different binder systems on packing density and flow characteristics of cement paste, Cem. Concr. Compos. 78 (2017) 120–131.