Advances in Concrete Construction, *Vol. 7, No. 2 (2019) 97-105*
DOI: https://doi.org/10.12989/acc.2019.7.2.097

Effect of coarse aggregates and sand contents on workability and static stability of self-compacting concrete

Sahraoui Mohamed[a] and Bouziani Tayeb*

Structures Rehabilitation and Materials Laboratory (SREML), University Amar Telidji- Laghouat, Algeria

(Received July 7, 2018, Revised January 17, 2019, Accepted January 27, 2019)

Abstract. In this paper, the workability and static stability were evaluated using a proposed test method. Workability and static stability represent a key property of self-compacting concrete (SCC) in fresh state. A number of standardized test methods were developed to assess these properties. However, no accelerated test method reliably predicts both workability and static stability of SCC. In the present work, a modified K-slump test method was developed to evaluate workability and static stability of SCC. In order to take implicit mixture variations of SCC constituents that can affect fresh SCC properties, a central composite design was adopted to highlight the effect of gravel to sand ratio (G/S), gravel 3/8 to gravel 8/15 ratio ($G1/G2$), water to cement ratio (W/C), marble powder to cement ratio (MP/C) and superplasticizer content (SP) on workability measured with slump and flow time ($T50$) tests and static stability measured with sieve stability test (Pi), segregation test index (SSI), Penetration test (Pd) and the proposed K-slump test (Km). The obtained results show that G/S ratio close to 1 and $G1/G2$ ratio close to 60% can be considered as optimal values to achieve a good workability while ensuring a sufficient static stability of SCC. Acceptable relationships were obtained between Slump flow, Pi, Pd and Km. Results show that the proposed K-slump test allow to assess both workability and static stability of fresh SCC mixtures.

Keywords: coarse aggregates; sand; workability; static stability; modified K-slump test; SCC

1. Introduction

Self-compacting concrete (SCC) can be considered as a flowable multiphase material, containing cement based paste, fine aggregate and coarse aggregate in a well determined range of gradation (Long *et al.* 2017). SCC is required to flow and fill narrow forms under its own weight, it shall be able to pass through highly confined area, and must have a certain cohesiveness to avoid the segregation of coarse aggregates (Ling and Kwan 2015). To achieve these properties, this kind of concrete must be very flowable and stable simultaneously, which is possible by the use of superplasticizers and cementetious materials (Li and Kwan 2015, Aïtcin 2000). High flowability is required to easily fill formworks during placement and stability is crucial property that is also necessary after placement of SCC (Yahia and Aïtcin 2016). Static stability can be regarded as the ability of SCC mortar to suspend coarse aggregate in SCC mixes at reset (Ghoddousi *et al.* 2014). The static segregation phenomenon occurs after casting of SCC, notably at high and vertical column parts. Stability is a critical property for a successful pouring and to avoid heterogeneous of hardened material which has a direct impact on its mechanical properties as well as its durability (Mesbah *et al.* 2010).

Static segregation can progressively evolve when the fresh SCC is casted in relatively high elements. Such stability is governed by the mix design parameters and the rheological properties of SCC. In order to better insights the effect of mix parameters on static stability, several researchers have considered SCC mixtures as two-phase material: coarse aggregates and the suspending mortar (Bouziani 2013, Petrou *et al*. 2000). Based on this consideration, it is generally supposed that after placing fresh SCC, coarse aggregate tend to move down while the suspending mortar is pushed upward, which results segregation and bleeding. The increase of water and superplasticizer contents can improve workability and hence affect negatively static stability. It is also known that static stability can be affected by increasing the maximum size of coarse aggregate and using aggregates with poor particle size distribution (Naji *et al.* 2017). So as to enhance the static stability of SCC, it will be necessary to use important powder content (usually limestone powder), a well graded aggregates as well as a reduced maximum size of coarse aggregates.

During the last two decades, limited test methods were developed to evaluate static stability of SCC (Bouziani 2018). It should be noted that the most recognized static stability tests are: sieve segregation test (EN 12350-11 2010, EFNARC 2005), column test (ASTM C 1610 2017, Bensebti *et al*. 2007) and penetration test (Bensebti *et al*. 2007, Van *et al.* 1998, ASTM C1712 2014). The sieve test method (GTM test), developed by the French contractor, consists allowing 10 litres to stand for a period to observe any occurred internal segregation, half of the 10 litre is poured on a 5mm sieve, which stands on a sieve pan

*Corresponding author, Ph.D.
E-mail: t.bouziani@lagh-univ.dz
[a]Ph.D Student
E-mail: med.sahraoui@lagh-univ.dz

ISSN: 2287-5301 (Print), 2287-531X (Online)

following a weigh scale. The proportion of the passed mortar to initial concrete on the sieve is reported (EFNARC 2005). In the column test, fresh SCC is poured in PVC mold and allowed to stand for 15 min. SCC from top and bottom portions of the column are then collected and washed over a 3.15 mm sieve. The masses of coarse aggregates in the top and the bottom sections of the column are recorded to calculate the segregation index (Bensebti *et al*. 2007). Penetration test consists of measuring the penetration depth of a cylinder by allowing it to penetrate freely during 45 s into a SCC sample. When the cylinder has a penetration less than 8 mm, the concrete can be considered to exhibit suitable segregation resistance (Bensebti *et al*. 2007, Van *et al*. 1998, ASTM C1712 2014). Despite the simplicity of these tests, they have some disadvantages including their application on construction sites. In the case of sieve test, the use of weight scale is required. In addition, it must be kept at least 10 litres of concrete and wait for 10 min in order to get an idea about SCC stability. In column test, we need also a weight scale and waiting until the final setting time to take measurements. As for Penetration Test, it lacked precision despite its simple procedure because it lowered on concrete surface only.

In the present research work, a new simple test method that can evaluate both workability and static stability of fresh SCC is proposed. The flowability and static stability are assessed by means of a rapid penetration apparatus developed as part of this work. The repeatability variations of the proposed test method are then assessed using a statistical modeling approach that allows taking in consideration the main mix parameters of SCC, such as the gravel to sand ratio (G/S), gravel 3/8 to gravel 8/15 ratio (*G*1/*G*2), water to cement ratio (W/C), marble powder to cement ratio (MP/C) and superplasticizer content (SP) which cover a wide range of workability and stability characteristics.

2. Mixture design approach

The design of experiments is a very useful method, based on statistical approaches, for parametric studies and optimization of main effects and all possible interaction between studied factors (Khayat *et al*. 2000, Nunes *et al*. 2006, Bouziani *et al*. 2012). Therefore, a central composite design (CCD) was used to evaluate the effect of G1/G2 and G/S, MP/C, W/C ratios and SP content on the properties of SCC. The application of CCD design, based on proposed different factors limits (Table 1), has issued to a totally 31

Table 1 Range of code values of composite factorial design

Coded values	-1.607	-1	0	+1	+1.607
G1/G2	0	18.89	50	81.11	100
G/S	0.68	0.8	1	1.2	1.32
MP/C (%)	0	4.72	12.5	20.28	25
W/C	0.35	0.36	0.375	0.39	0.40
Sp (%)	0.8	0.84	0.9	0.96	1

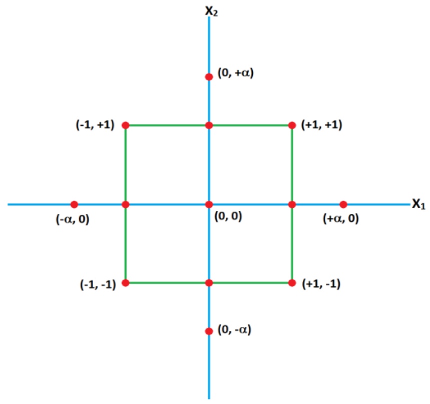

Fig. 1 Central composite designs for 2 factors (X_1, X_2)

compositions, consisted initially of 16 factorial design, 5 central points and 10 stars points.

A CCD is made orthogonal by the choice of the distance α of the axial runs from the design center. The value of α for rotatable depends on the number of points in the factorial portion of the design. Fig. 1 shows the CCD for 2 factors (Murali and Kandasamy 2009, Khayat *et al*. 1999).

A second-order polynomial model (Eq. (1)) obtained by multiple regression technique for five factors, was adopted to describe all responses.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_i \sum_j \beta_{ij} x_i x_j + \varepsilon \quad (1)$$

Where y is the predicted response, x_i and x_j are the coded values of the independent variables, i is the linear coefficient, j is the quadratic coefficient, β is the regression coefficient and ε is the random error (Montgomery 2008, Rezaifar *et al.* 2016).

3. Materials and methods

3.1 Materials

Ordinary Portland cement CEM I 42.5 and marble powder were used in this work. The chemical compositions and physical properties of cement and marble powder are given in Table 2. Crushed limestone coarse aggregates (3/8 and 8/15 mm) and river sand (0/6 mm) were used. The particle size distribution and chemical compositions of selected gravels and sand are presented in Fig. 2 and Table 2 respectively. Physical properties of used aggregates are presented in Table 3. A polycarboxylate based superplasticizer high range water reducer was used. The solid content, pH and specific gravity of the superplasticizer are 30%, 6 and 1.07 respectively.

3.2 Mixture proportions

For this study, a 31 SCC mixes were prepared based on proposed independent factors limits. All possible mixtures combinations are presented in Table 4. The mix proportioning has been designed according to AFGC recommendations with a volume of paste of 340 l/m^3 (in the range 330-400 l/m^3) (AFGC 2008).

Table 2 Chemical composition and physical properties of cement, marble powder, river sand, 3/8 and 8/15 gravel

Analysis (%)	Portland cement	Marble powder	River sand	Gravel 3/8	Gravel 8/15
CaO	64.1	55.6	4.73	54.55	48.48
SiO_2	19.48	0.6	82.91	1.17	6.06
Al_2O_3	5.02	0.4	1.05	0.30	0.44
Fe_2O_3	6.55	0.2	0.86	0.19	0.50
MgO	1.53	0.1	0.09	0.94	3.37
K_2O	0.48	-	0.18	0.07	0.09
SO_3	2.29	-	0.06	0.10	0.17
$CaCO_3$	-	90	-	-	-
Na_2O	-	-	0.03	-	-
Cl	0.028	0.1	-	-	-
LOI	2.04	43	-	-	-
Specific density	3.1	2.7	-	-	-
Blaine Surface (cm^2/g)	3420	2126	-	-	-

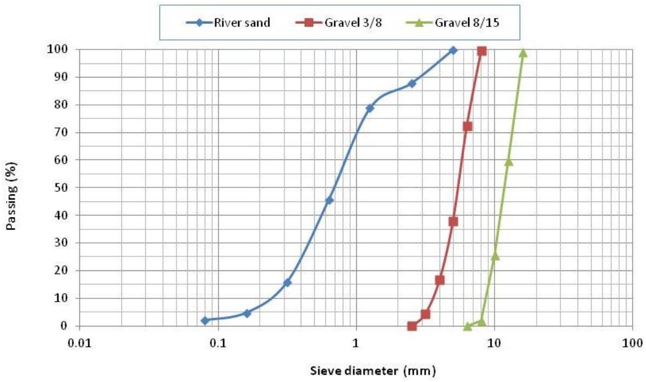

Fig. 2 Grading curves of River sand, 3/8 and 8/15 gravel

Table 3 Physical properties of aggregates

Property	Aggregate		
	River sand	Gravel 3/8	Gravel 8/15
Specific gravity	2.65	2.66	2.64
Fineness modulus	2.69	-	-
Sand equivalent	0.71	-	-
Absorption (%)	1.39	3.1	0.7

3.3 Preparation and test methods

The mixing procedure consists of homogenizing aggregates, cement and marble powder for 30 s, before introducing 2/3 of water during 1 min. Then high-range water reducing superplasticizer diluted in the remaining water was added during 1 min. The mixing procedure continues for another 5 min, after that the hole mix is kept for settling for 2 min before remixing for 30 s.

After mixing, the fresh properties of SCC were evaluated using the following tests:

- The workability was measured by slump flow and T50 flow time according to the EN 12350-8 (2010).
- The static stability was measured by sieve segregation test, column test and penetration test.

Table 4 Mixture proportions and test results of prepared SCC mixtures

Mix N°	Mixture proportioning					Test results					
	G1/G2 (%)	G/S	MP/C (%)	W/C (%)	SP (%)	Slump flow (cm)	*Km* (cm)	*T*50 (s)	*Pi* (%)	*Pd* (mm)	SSI
1	0	1	12.5	37.5	0.9	83	0	1.21	56.81	50	16.4
2	18.89	0.8	4.72	36	0.84	66	12.5	2.09	8.22	3	0.7
3	18.89	0.8	4.72	39	0.96	75	1	1.72	40.21	40	14.9
4	18.89	0.8	20.28	36	0.96	85	0	1.2	60.82	50	15.5
5	18.89	0.8	20.28	39	0.84	73	8	1.58	20.88	4	7.6
6	18.89	1.2	4.72	36	0.96	51	13	1.32	0	0	0.4
7	18.89	1.2	4.72	39	0.84	72	6	1.73	22.82	16	10.6
8	18.89	1.2	20.28	36	0.96	73	5	3.28	4.31	3	6.4
9	18.89	1.2	20.28	39	0.84	86	0	1.17	37.54	37	7.1
10	50	0.68	12.5	37.5	0.9	75	4	1.55	20.65	30	10
11	50	1	0	37.5	0.9	72	8	1.48	14.65	19	5.6
12	50	1	12.5	35	0.9	75	4.5	3.77	12.17	17	9.6
13	50	1	12.5	37.5	0.8	78	4	2.34	12.63	21	3.1
14	50	1	12.5	37.5	0.9	77	5	2.46	9.03	25	3.4
15	50	1	12.5	37.5	0.9	77	4	2.54	14.99	24	2.6
16	50	1	12.5	37.5	0.9	82	0	1.37	11.72	40	10.3
17	50	1	12.5	37.5	0.9	81	3	1.61	16.87	29	7.4
18	50	1	12.5	37.5	0.9	79	1	1.57	23.61	25	5.4
19	50	1	12.5	37.5	1	78.5	3.5	1.26	15.13	33	3.2
20	50	1	12.5	40	0.9	77	5	2.17	8.21	24	0.3
21	50	1	25.0	37.5	0.9	78	2.5	1.23	19.72	35	9.3
22	50	1.32	12.5	37.5	0.9	74	6	0.91	14.26	16	2.8
23	81.11	0.8	4.72	36	0.96	74.5	7.5	1.52	7.04	4	9.1
24	81.11	0.8	4.72	39	0.84	77	5	0.96	10.72	6	3.3
25	81.11	0.8	20.28	36	0.84	71	7	3.21	10.14	13	6.8
26	81.11	0.8	20.28	39	0.96	79	0	1.46	12.89	34	6.8
27	81.11	1.2	4.72	36	0.84	73.5	4	1.16	28.95	19	0.2
28	81.11	1.2	4.72	39	0.96	78	2	1.01	16.91	27	7.8
29	81.11	1.2	20.28	36	0.96	76	6	1.31	16.96	16	7.6
30	81.11	1.2	20.28	39	0.84	73	7	1.62	15.33	14	2.4
31	100	1	12.5	37.5	0.9	76	8	1.29	7.68	6	10

3.4 Proposed modified K-slump test

As a part of this experimental work, a new test apparatus for evaluation of static stability of SCC is proposed. This test is inspired from a K-Slump apparatus (Nasser 1976, ASTM C1362-97 2002). Two technical requirements were considered for the choice of proposed apparatus. First, a practical apparatus should not be time-consuming in site construction and second, the testing apparatus should be portable and simple for use.

3.4.1 Apparatus description

The apparatus consists of smooth steel rods spaced evenly of 5 mm, measuring 240 mm length and 5 mm in diameter. The rods are fixed at the top in a steel ring measuring 50 mm in diameter, equipped with steel lateral collars to hold in place the apparatus during the test and fixed at bottom in a tube point. A steel rod measured 2 mm

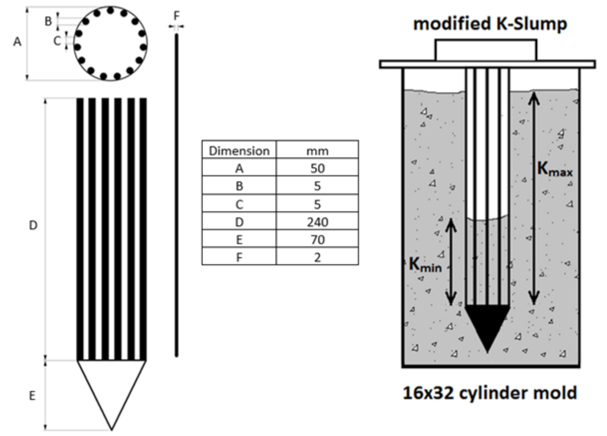

Fig. 3 Dimensions of modified K-Slump test apparatus

Fig. 4 Proposed modified K-Slump test apparatus

in diameter is used for gauging the height of fresh mortar through the ring (Fig. 3).

3.4.2 Test procedure

The fresh SCC is cast in a 160×320 mm cylinder mold to a preset level of 280 mm. The apparatus is then inserted in the fresh SCC sample, slowly and vertically without any vibration or agitation until the lateral collars rest on the top limit of the mold. A portion of the fresh mortar is allowed to flow between steel rods for a period of 1 min. The height of fresh mortar ($k_{\min}$) and of fresh SCC ($k_{\max}$) are measured in (cm) with the steel rod as illustrated in Fig. 4 (Nasser and Biswas 1996).

The *Km* value can be calculated as follows

$$Km = k_{\max} - k_{\min} \tag{2}$$

4. Results and discussion

Test results issued from the application of CCD statistical design are presented in Table 4 and models parameters estimates of studied responses are presented in Table 5. The resulting models are established by a standard least-square fitting. Using this statistical approach, the effect of studied different mixture components (*G*1/*G*2, G/S, MP/C, W/C and SP) on resulting responses (Slump

Table 5 Model parameters estimates of responses

Term	Slump flow (cm)		*Km* (cm)		*T*50 (s)		*Pi* (%)		*Pd* (mm)		SSI	
	R^2=0.91		R^2=0.73		R^2=0.85		R^2=0.87		R^2=0.79		R^2=0.74	
	Coeff.	*p*-value	Coeff	*p*-value	Coeff	*p*-value	Coeff	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value
Constant	79.09	<.0001	3.50	<.0001	1.86	<.0001	15.69	<.0001	27.31	<.0001	5.94	<.0001
G1/G2	0.46	0.4714	0.27	0.5812	-0.08	0.3379	-7.31	0.0003	-4.29	0.0368	-1.39	0.0295
G/S	-0.93	0.1597	0.25	0.6236	-0.1	0.2291	-1.82	0.2607	-2.11	0.2802	-1.6	0.0142
MP/C	2.77	0.0007	-1.27	0.019	0.14	0.1109	2.47	0.1330	3.87	0.0567	0.91	0.1418
W/C	2.24	0.004	-1.21	0.0279	-0.31	0.0018	1.66	0.3166	3.95	0.0585	-0.08	0.8947
Sp	1.24	0.0653	-1.20	0.0247	-0.31	0.0014	3.49	0.0388	6.95	0.0018	1.46	0.0224
G1/G2*G/S	1	0.1863	-	-	-0.19	0.067	6.43	0.0026	3.75	0.1024	-	-
G1/G2*MP/C	-3.56	0.0003	1.31	0.0325	0.16	0.1060	-3.79	0.0512	-	-	-	-
G1/G2*W/C	-1.23	0.1215	-	-	-	-	-3.59	0.0720	-	-	-1.34	0.0739
G1/G2*Sp	-	-	-	-	-	-	-5.86	0.0051	-4.5	0.0541	-	-
G/S*MP/C	1.13	0.1405	-	-	-	-	-	-	-	-	-	-
G/S*W/C	1.82	0.0297	-	-	-	-	2.85	0.1455	2.73	0.2428	-	-
G/S*Sp	-1.69	0.0349	1.44	0.0206	-	-	-4.44	0.0253	-4.63	0.0484	-	-
MP/C*W/C	-2.01	0.0181	1.30	0.0406	-0.16	0.1164	-3.38	0.0888	-3.64	0.1254	-2.51	0.0021
MP/C*Sp	2.88	0.0015	-1.06	0.0771	-0.26	0.0135	5.26	0.0101	4.75	0.0433	-1.54	0.0357
W/C*Sp	1.3	0.1047	-1.36	0.0325	0.25	0.0209	-	-	4.28	0.0748	-	-
G1/G2*G1/G2	-	-	-	-	-0.22	0.0378	6.22	0.0044	-	-	2.42	0.0028
G/S*G/S	-1.98	0.0212	0.76	0.2176	-0.23	0.0321	-	-	-3.67	0.1243	-	-
MP/C*MP/C	-1.76	0.035	0.85	0.1683	-0.18	0.0824	-	-	-	-	-	-
W/C*W/C	-1.37	0.0982	-	-	0.44	0.0005	-2.31	0.2440	-4.47	0.0711	-	-
Sp*Sp	-	-	-	-	-	-	-	-	-	-	-1.34	0.0610

Table 6 Analysis of variance of developed models

Source Mean	Degree of freedom	Sum of squares	Mean square	F-ratio
Slump flow (cm)	17	1045.36	61.49	7.4825
Km (cm)	12	249.76	20.81	4.0521
T50 (s)	14	12.76	0.91	6.4285
Pi (%)	11	642.74	58.43	1.8890
Pd (mm)	14	4502.38	321.6	4.2898
SSI	10	424.02	42.4	5.6857

Table 7 Moments of a distribution for the 5 centrals point mixture

Moments	Slump flow (cm)	*Km* (cm)	*T*50 (s)	*Pi* (%)	*Pd* (mm)	SSI
Mean	79.2	2.6	1.91	15.24	28.6	5.82
Std Dev	2.28	2.1	0.547	5.56	6.65	3.12
Std Err Mean	1.02	0.93	0.25	2.49	2.98	1.39
Upper 95% Mean	82	5.17	2.59	22.15	36.86	9.69
Lower 95% Mean	76.4	0.025	1.23	8.34	20.33	1.94

flow, *Km*, *T*50, *Pi*, *Pd* and SSI) is affined by eliminating non-considered coefficients, i.e., to evaluate that the probability of high-impact coefficients is different from zero. Table 5 indicates that the derived models have good correlation coefficients. Non-considered coefficients are not recorded. The increase in values of factor's coefficients indicates an increase in correspond modelled response and an increase by a negative values results in a reduction of the response.

4.1 Repeatability of test results

In order to evaluate the repeatability of responses results and validate their established models, analysis of variance is estimated for all studied responses by mean of models sources variations (Table 6). For models sources of variation, the degree of freedom, the sum of squares attributed to models, the mean of the square and the F-ratio (model mean square divided by the error mean square) are calculated. Whole-model analysis of variance presented in Table 6 is for testing that all the parameters are zero except the linear parameters. These parameters are used to calculate an F-ratio that evaluates the validity of proposed models. In general, if the probability related with the F-ratio is insignificant, then the model is considered a better statistical fit for the results than the response mean alone. In addition, moment's table of five replicated central points are shown in Table 7. This table displays the mean, standard deviation (Std Dev), the standard error of the mean (Std Err) and the confidence limits about the mean (Upper and Lower 95% Mean). Based on the results presented in Table 7, the standard errors mean in estimated slump flow, *Km*, *T*50, *Pi*, *Pd* and SSI are 1.02 cm, 0.93 cm, 0.25 s, 2.49%, 2.98 mm and 1.39 respectively. From these results it can be seen that modified K-slump test results have the lower standard error mean bound of estimates. This indicates that the repeatability and variability of the modified K-slump test are sufficient to characterize static stability of SCC.

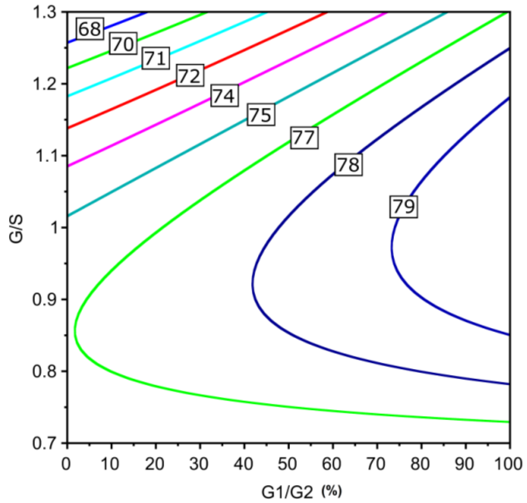

Fig. 5 Contour plots of the Slump flow (cm) as function of G/S and *G*1/*G*2 ratios

4.2 Effect of G/S and G1/G2 ratios on fresh SCC properties

Results from Table 5 indicate that the greatest effect of *G*1/*G*2 and G/S ratios are recorded on *Pi* (-7.31) and *Pd* (-2.11) respectively. These can be explained by the sensibility of sieve stability test and penetration test to the coarse aggregates contents.

The derived models (Table 5) are very helpful to present the effects of G1/G2 and G/S ratios on fresh properties of SCC in contours plots. In order to highlight the effects of G/S and G1/G2 on studied properties, cement content and MP/C ratio, W/C ratio and SP content were kept constant (420 kg/m^3, 10%, 37% and 0.9% respectively). These values are selected to cover a wide range of fresh characteristics variability.

Fig. 5 presents contour plots of slump flow as function of G/S and *G*1/*G*2 ratios. According to results in Fig. 5, all measured slump flow values are in the recommended range (AFGC 2008). It can be also seen that the increase in *G*1/*G*2 ratio increases slump flow, however the increase of G/S ratio increases slump flow until a maximum value and then decreased. For example, as shown in Fig. 5 and depending on the *G*1/*G*2 ratio, the maximum values of slump flow are 77 cm and 79 cm for approximately G/S=0.85 (with *G*1/*G*2 ratio less than 5%) and G/S=0.95 (with *G*1/*G*2 ratio of 75%) respectively. These results are in agreement with proposed G/S ratio (close to 1) (AFGC 2008, Okamura *et al*. 1993). Compared to slump flow ranges recommended by AFGC, three classes are clearly distinguishable: For G/S>1.1 and *G*1/*G*2<30%, the Slump Flow falls in the group SF2. For G/S<1 and whatever the value of *G*1/*G*2, the Slump Flow falls in the group SF3. For *G*1/*G*2>85% and whatever the value of G/S, the Slump Flow also falls in the group SF3.

The effects of G/S and G1/G2 ratios variations on the flow time *T*50 is given in Fig. 6. As clearly shown, SCC

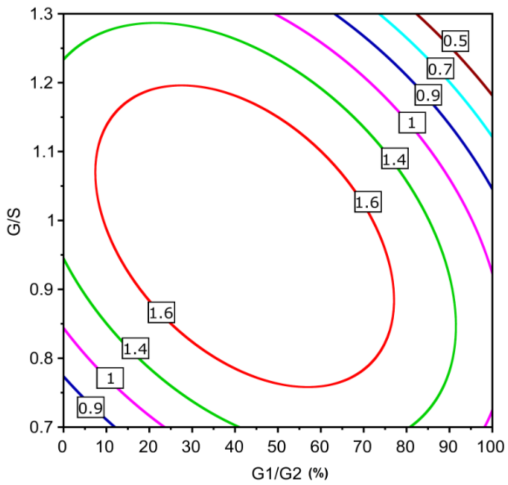

Fig. 6 Contour plots of *T*50 (s) as function of G/S and *G*1/*G*2 ratios

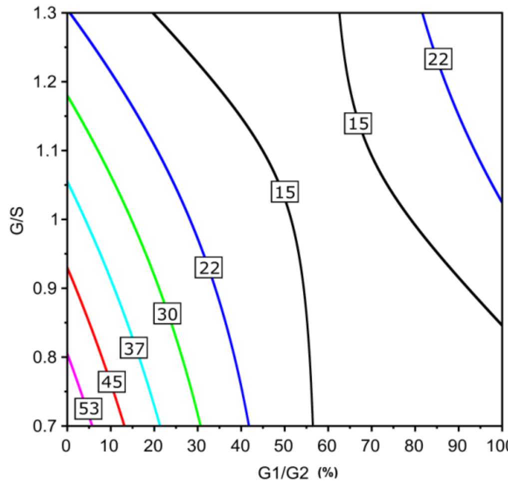

Fig. 8 Contour plots of sieve stability *Pi* (%) as function of G/S and *G*1/*G*2 ratios

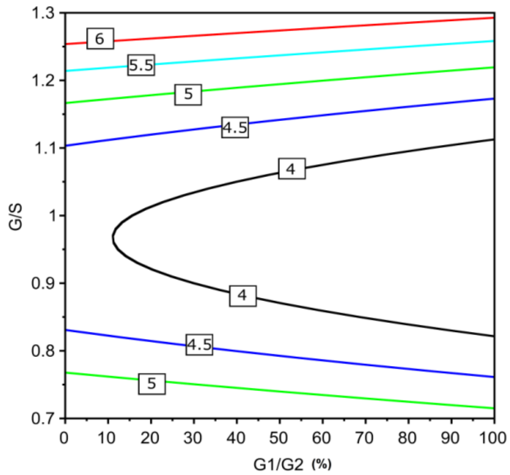

Fig. 7 Contour plots of *Km* (cm) as function of G/S and *G*1/*G*2

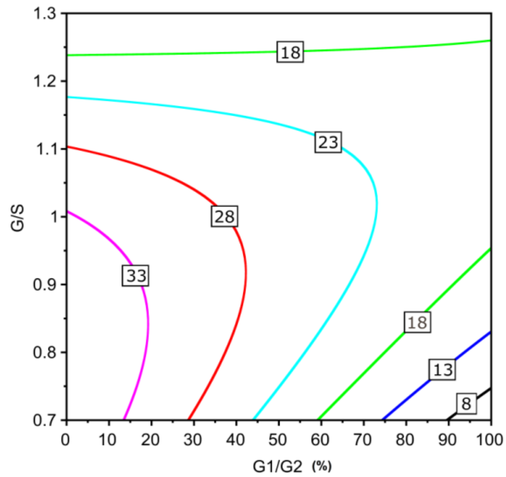

Fig. 9 Contour plots of penetration *Pd* (mm) as function of G/S and *G*1/*G*2 ratios

mixtures prepared with approximately G/S=1 and *G*1/*G*2=45% exhibited highest *T*50 value compared to all other combinations. This may be due to the packing effect of fine aggregates; i.e., 3/8 gravel and sand filled spaces between the coarser aggregates, thus increasing the compactness of solid content, which results in a reduced volume of voids to be occupied and hence larger volume of paste is gained for workability purpose and homogeneity in SCC mixture (Sebaibi *et al*. 2013, Bouziani 2013). Once the voids were completely filled, fine aggregates then began to lodge between coarser ones, and therefore the compactness of the mixture decreases.

The contour plots of modified K-slump (*Km*) in Fig. 7 illustrates the trade-offs between G/S and *G*1/*G*2 ratios. The increase in *G*1/*G*2 ratio decreases *Km* values, while the increase of G/S ratio decreases *Km* values until a minimum value (from G/S=0.95 to 1) and then decreased. It can be also noted that the effect of *G*1/*G*2 ratio on *Km* is more pronounced when G/S have values close to 1. This phenomenon can be explained by the fact that both G/S and *G*1/*G*2 influence the vertical force exerted on mortar by coarse aggregates. An increase in *G*1/*G*2 ratio especially at G/S ratio close to 1 (value recommended for SCC mix-design (AFGC 2008)) increases excess paste volume, which leads to an increase in volume of mortar filtered through steel rods of modified K-slump apparatus. Thus, an increase in *G*1/*G*2 ratio leads to a decrease in capacity of the mortar to maintain coarse aggregates in suspension. It follows from the above results that slump flow, *T*50 and *Km* tests are very useful in optimizing G/S ratio for a given SCC.

Sieve stability contour plots are presented in Fig. 8 as a function of G/S and *G*1/*G*2 ratios variations. As shown in Fig. 8, for a relatively low *G*1/*G*2 ratio values (approximately lower than 60%), the increase in G/S ratio can lead to a reduction in *Pi* values. On the other hand, an increase of *G*1/*G*2 ratio above this value (60%), can lead to a reduction in *Pi* values of fresh SCC. This means that the minimum static segregation measured with sieve test is related to SCC mixtures designed with *G*1/*G*2 ratio around 60% and G/S around 1.1. It could be due to the maximum packing density of aggregates that causes a reduction in *Pi* values and consequently increasing static stability of SCC fresh mixtures (Khayat and Laye 2002).

The results of measured penetration *Pd* of cylinder test

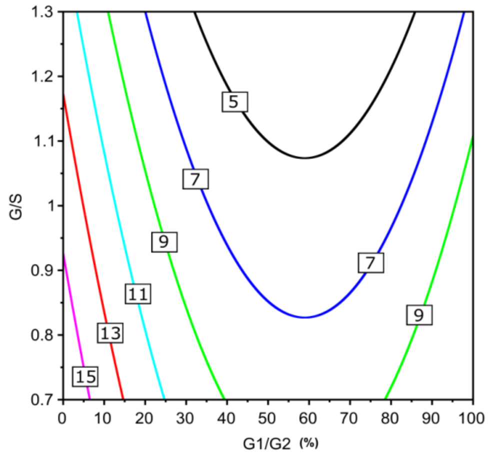

Fig. 10 Contour plots of SSI as function of G/S and *G*1/*G*2

are presented in Fig. 9 by contour plots according to G/S and *G*1/*G*2 ratios variations. From these results, it can be observed that for lower values of G/S ratio (lower than 1), the increase in *G*1/*G*2 ratio exhibit a significant reduction in *Pd* values, but when G/S ratio increases (above 1), the effect of *G*1/*G*2 ratio on penetration *Pd* is not important. The penetration test measures the depth of mortar (or paste) at the top of fresh SCC. A higher penetration depth on surface of tested fresh SCC corresponds to a poorer static stability (Shen *et al.* 2005). Thus this test is suitable for static stability control of SCC mixes with high fine aggregates content.

Fig. 10 shows the effect of G/S and *G*1/*G*2 ratios on SSI index of SCC mixtures, measured by column test. As shown in this figure, the increase in G/S ratio decreases SSI values. It can be also seen that for any given values of G/S ratio, the *G*1/*G*2 ratio required to obtain minimum SSI values is approximately 60%. This could mainly be to the high packing density that can be reached around 60% of *G*1/*G*2 ratio (Ghoddousi *et al.* 2014). Static stability measured by column test is based on examination of the coarse aggregates distribution at the top and the bottom of the column. Lower or higher *G*1/*G*2 ratio can cause a poor packing density of aggregates and therefore increases the mortar content, thus increases segregation of SCC mixtures.

4.3 Relationships between Km values and other test results

A scatter plot matrix with Pearson correlation is presented in Fig. 11 to demonstrate the association between all responses (Slump flow, *T*50, *Pi*, *Pd*, SSI and *Km*) and determine whether responses are correlated and whether the correlation is positive or negative. From this figure, the best relationships can be observed between Slump flow, *Pd* and Km, which confirm the relation between workability and stability (Bouziani 2018). A moderate relationship exists between *Pi* and *Pd*. This refers to the fact that the results of *Pi* and *Pd* are dependent on the thickness of mortar in the top layers of fresh SCC (Sonebi 2005). Furthermore, there seems to be no correlation between *T*50 and the other response.

Fig. 12 shows the relation between slump flow and modified K-slump test results. It reveals that there is a moderate linear correlation between slump flow and modified K-slump values (R^2=0.72). Slump flow diameter is shown to decrease with the increase of Km values. The obtained relationship can be used to predict slump flow of SCC in terms of *Km*. The found correlation clearly reflects the interdependence of *Km* values that are measured for relatively high slump flow diameters (above 70 cm). The modified K-slump test method is therefore shown to be

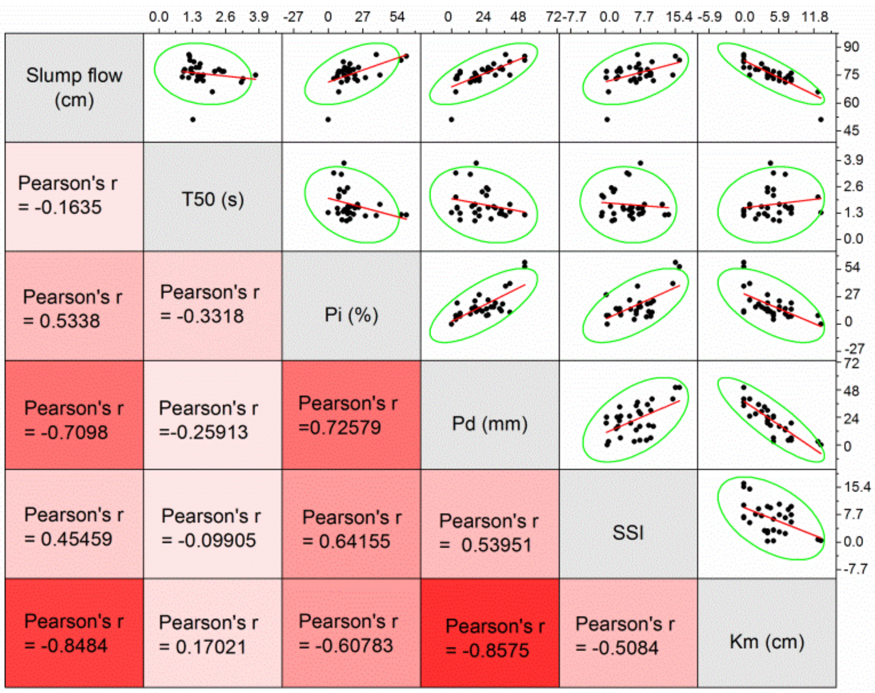

Fig. 11 Scatterplot matrix and Pearson correlation of all responses

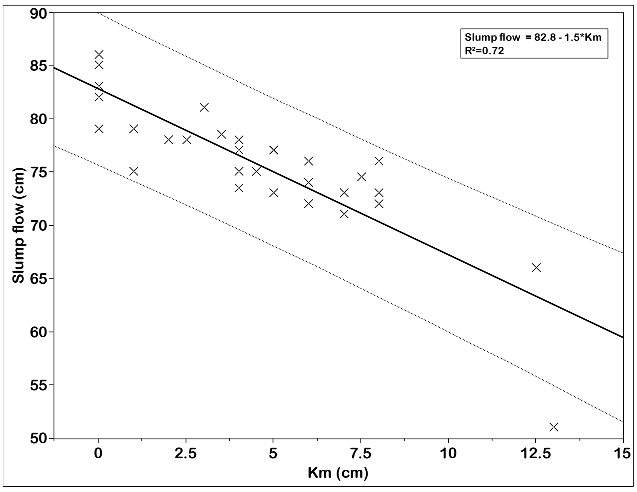

Fig. 12 Correlation between *Km* and slump flow

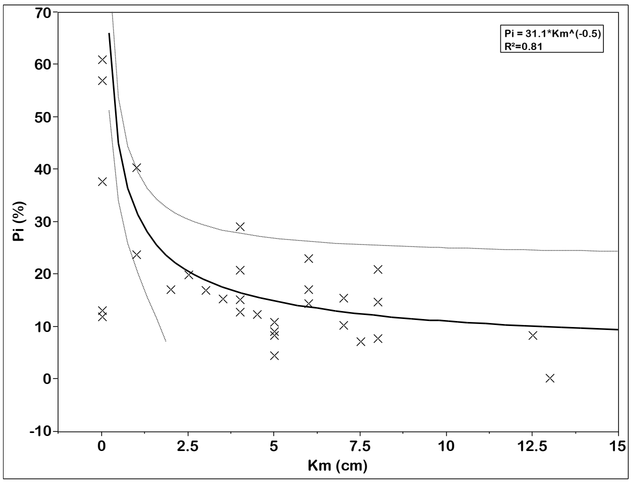

Fig. 13 Correlation between *Km* and *Pi*

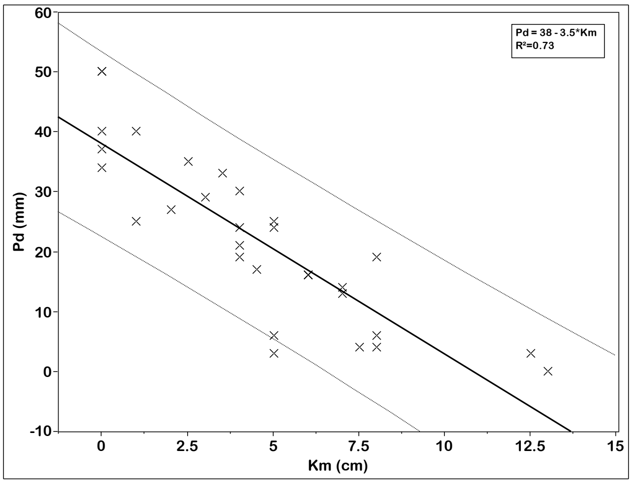

Fig. 14 Correlation between *Km* and *Pd*

highly sensitive to observing changes in the slump flow of highly flowable SCC mixtures.

The results of sieve stability test and modified K-slump test are compared in Fig. 13. An acceptable relationship between experimental sieve test and modified K-slump test results is obtained (R^2=0.81). Based on *Pi* values in Fig. 13, the zone limited by *Pi* values lower than 20%, corresponding to *Km* values higher than 2.5 cm, represents the area of acceptable static stability.

The relationship between experimental results of *Km* and penetration *Pd* is plotted in Fig. 14. The presented results indicate that there is a linear correlation (R^2=0.74) between *Pd* and *Km* values. The limit for *Pd* values that indicates whether SCC mixture is sufficiently resistant to segregation ($Pd \leq 8$ mm, proposed by Bui *et al.* 2002) corresponds to approximately $Km \geq 8.5$ cm.

5. Conclusions

In view of this experimental work, the following conclusions can be drawn:

- The validity of established models, the repeatability of proposed modified K-slump test were studied as well as the influence of mix parameters was evaluated using a statistical central composite design.
- Coarse aggregates to sand ratio (G/S) and finer gravel (3/8) to coarser gravel (8/15) ratio (*G*1/*G*2) have appreciable effects on workability and static stability of fresh SCC.
- For slump flow, *T*50 and modified K-slump results, there is an optimum of G/S ratio (close to 1), that enhance workability and homogeneity of fresh SCC. These tests are useful for determining the optimal workability for a given SCC mixture by tailoring G/S ratio close to 1, with respect to *G*1/*G*2 ratio.
- Sieve stability test, penetration test and column test results of SCC are significantly affected by *G*1/*G*2 ratio when G/S ratio is about 1. In order to secure static segregation and confers good coarse aggregates distribution, SCC mixtures should have *G*1/*G*2 close to 60%.
- There is acceptable correlation between slump flow and proposed K-slump test results. The proposed modified K-slump test can reflect the flowability of SCC mixtures. The sensibility of this test is found to adequate for differentiating between SCC mixtures of high flowable levels. There are also acceptable correlations between sieve stability and penetration test results.
- Modified K-slump test is appropriate to evaluate static stability and reflects the workability of high flowable SCC mixtures with (C=420 kg/m^3, MP/C=10%, W/C=37% and SP content=0.9%).

References

AFGC (2008), Association Française de Génie Civil, Recommendations for use of self- Compacting Concrete, Scientific and technical documents, P N B@P.

Aïtcin, P.C. (2000), “Cements of yesterday and today: concrete of tomorrow”, *Cement Concrete Res*., **30**(9), 1349-1359.

ASTM C 1610 (2017), Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique, ASTM International, West Conshohocken, PA.

ASTM C1362-97 (2002), Standard Test Method for Flow of

Freshly Mixed Hydraulic Cement Concrete, ASTM International, West Conshohocken, PA.

ASTM C1712 (2014), Standard Test Method for Rapid Assessment of Static Segregation Resistance of Self-Consolidating Concrete Using Penetration Test, ASTM International, West Conshohocken, PA.

Bensebti, S., Aggoune, S. and Houari, H. (2007), "Essai de caractérisation expérimentale de la ségrégation verticale des bétons autoplaçants", *Sci. Technol. B*., **25**, 59-64.

Bouziani, T. (2013), "Assessment of fresh properties and compressive strength of self-compacting concrete made with different sand types by mixture design modelling approach", *Constr. Build. Mater*., **49**, 308-314.

Bouziani, T. (2018), "A simple test method to assess slump flow and stability of self-compacting concrete", *Comput. Concrete*, **21**(2), 111-116.

Bouziani, T., Benmounah, A. and Bédérina, M. (2012), "Statistical modelling for effect of mix-parameters on properties of high-flowing sand-concrete", *J. Central South Univ*., **19**(10), 2966-2975.

Bui, V.K, Montgomery, D., Hinczak, I. and Turner, K. (2002), "Rapid testing method for segregation resistance of self-compacting concrete", *Cement Concrete Res*., **32**(9), 1489-1496.

EFNARC (2005), The European Guidelines for Self-Compacting Concrete: Specification, Production and Use, The Self-Compacting Concrete European Project Group.

EN 12350-11 (2010), Partie Béton Autoplaçants-Essai de Stabilité au Tamis.

EN 12350-8 (2010), Testing Fresh Concrete, Part 8.

Ghoddousi, P., Javid, A.A.S and Sobhani, J. (2014), "Effects of particle packing density on the stability and rheology of self-consolidating concrete containing mineral admixtures", *Constr. Build. Mater*., **53**, 102-109.

Khayat, K.H., Ghezal, A. and Hadriche, M.S. (1999), "Factorial design models for proportioning self-consolidating concrete", *Mater. Struct.*, **32**, 679-686.

Khayat, K.H., Ghezal, A. and Hadriche, M.S. (2000), "Utility of statistical models in proportioning self-consolidating concrete", *Mater. Struct*., **33**(5), 338-344.

Khayat, K.H., Hu, C. and Laye, J.M. (2002), "Importance of aggregate packing density on workability of self-consolidating concrete", *Proceedings of the First North American Conference on Design and Use of Self-Consolidating Concrete*, Center for Advanced Cement-Based Materials.

Li, L.G. and Kwan, A.K. (2015), "Effects of superplasticizer type on packing density, water film thickness and flowability of cementitious paste", *Constr. Build. Mater*., **86**, 113-119.

Ling, S.K. and Kwan, A.K.H. (2015), "Adding ground sand to decrease paste volume, increase cohesiveness and improve passing ability of SCC", *Constr. Build. Mater.*, **84**, 46-53.

Long, G., Liu, H., Ma, K., Xie, Y. and Li, W. (2017), "Development of high-performance self-compacting concrete applied as the filling layer of high-speed railway", *J. Mater. Civil Eng.*, **30**(2), 04017268.

Mesbah, H.A., Yahia, A. and Khayat, K.H. (2010), "Validation of electrical conductivity method to assess static stability of SCC", *Proceedings 6th International RILEM Symposium on Self-Compacting Concrete*, Montreal, Canada, September.

Montgomery, D.C. (2008), *Design and Analysis of Experiments*, John Wiley & Sons.

Murali, T.M. and Kandasamy, S. (2009), "Mix proportioning of high performance self-compacting concrete using response surface methodology", *Open Civil Eng. J.*, **3**, 93-97.

Naji, S., Khayat, K.H. and Karray, M. (2017), "Assessment of static stability of concrete using shear wave velocity approach", *ACI Mater. J*., **114**(1), 105-115.

Nasser, K.W. (1976), "New and simple tester for slump of concrete", *J. Proc.*, **73**(10), 561-565.

Nasser, K.W. and Biswas, S. (1996), "A new method and apparatus for evaluation of the K-slump of concrete", *Can. J. Civil Eng*., **23**(1), 124-133.

Nunes, S., Figueiras, H., Oliveira, P.M., Coutinho, J.S. and Figueiras, J. (2006), "A methodology to assess robustness of SCC mixtures", *Cement Concrete Res.*, **36**(12), 2115-2122.

Okamura, H., Maekawa, K. and Ozawa, K. (1993), *High Performance Concrete*, Gihoudou Publisher, Tokyo, Japan.

Petrou, M.F., Wan, B., Gadala-Maria, F., Kolli, V.G. and Harries, K.A. (2000), "Influence of mortar rheology on aggregate settlement", *ACI Mater. J.*, **97**(4), doi: 10.14359/7415.

Rezaifar, O., Hasanzadeh, M. and Gholhaki, M. (2016), "Concrete made with hybrid blends of crumb rubber and metakaolin: optimization using response surface method", *Constr. Build. Mater*., **123**, 59-68.

Sebaibi, N., Benzerzour, M., Sebaibi, Y. and Abriak, N.E. (2013), "Composition of self-compacting concrete (SCC) using the compressible packing model, the Chinese method and the European standard", *Constr. Build. Mater*., **43**, 382-388.

Shen, L., Struble, L. and Lange, D. (2005), "Testing static segregation of SCC", *Proceedings of the 2nd North American Conference on The Design and Use of SCC*, SCC2005.

Sonebi, M., Rooney, M. and Bartos, P.J.M. (2005), "Evaluation of the segregation resistance of fresh self-compacting concrete using different test methods", *SCC'2005: 1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete*, RILEM Publications SARL, China.

Van, B.K., Montgomery, D.G., Hinczak, I. and Turner, K. (1998), "Rapid testing methods for segregation resistance and filling ability of self-compacting concrete", *Spec. Publ.*, **179**, 85-104.

Yahia, A. and Aïtcin, P.C. (2016), "Self-consolidating concrete", *Science and Technology of Concrete Admixtures*, Woodhead Publishing, Elsevier, Sawston, UK.

CC