Computers and Concrete, *Vol. 21, No. 2 (2018) 111-116*
DOI: https://doi.org/10.12989/cac.2018.21.2.111

A simple test method to assess slump flow and stability of self-compacting concrete

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(Received March 30, 2017, Revised June 6, 2017, Accepted July 28, 2017)

Abstract. Establishment of test methods to assess the fresh properties of self-compacting concrete (SCC) are required to ensure the homogeneity in fresh and hardened states. This paper discusses the suitability of a simple test method for assessing the slump flow and stability of SCC by testing on self-compacting mortar (SCM) fraction. The proposed test method aims at investigating slump flow diameter test and sieve stability test of SCC by testing SCM fraction with a plunger penetration apparatus. A central composite modeling design was performed to evaluate the effects of water/cement ratio (W/C), superplasticizer dosage (SP) and powder marble content (MP) on slump flow diameter, stability and plunger penetration test of fresh SCC. The responses of the derived statistical models are slump flow (Sf), sieve stability (S) and plunger penetration (P). Relationships obtained in this study show acceptable correlations between plunger penetration test value and slump flow diameter test results and stability. It should note that the developed relationships are very useful to predict slump flow diameter and stability of studied SCC mixtures by carrying out a simple plunger penetration test on its mortar, which can save labour and time in laboratory experiments.

Keywords: SCC; statistical modeling; slump flow; stability; plunger penetration test

1. Introduction

Self-compacting concrete (SCC) is a highly deformable concrete which can be compacted into every corner of a framework, only by means of its own weight and without the need of vibration. However, a successful SCC not only involves high deformability but also should exhibit adequate passing ability and resistance to segregation between coarse aggregate and self-compacting mortar (SCM) (Esmaeilkhanian *et al*. 2014, Okamura and Ouchi 2003). The segregation of coarse aggregate can lead to heterogeneous properties of the hardened concrete with direct impact on mechanical, transport properties, and durability. Control of stability is therefore critical for SCC to avoid surface defects; including bleeding and settlement and to achieve adequate mechanical properties and structural performance (Mesbah *et al*. 2011, Ghoddousi *et al*. 2014, Assaad 2016). Preventing segregation is a matter of SCM that must be sufficiently fluid to avoid the blockage of coarse aggregate and viscous to prevent the segregation (Boukhelkhal *et al*. 2015). The selection of effective test methods to assess stability is important for the successful design and placement of SCC (Cussigh *et al*. 2003, Shen *et al*. 2015).

Several empirical test methods are proposed to assess fresh properties of SCC. Among the existing test methods, slump flow, *v*-funnel and *L*-box tests are commonly used to evaluate deformability and passing ability of SCC. The sieve stability test is considered as the largely adopted test method for segregation resistance, because of its rapidity and simplicity (De Schutter 2005, Shi *et al*. 2015).

It is well-known that the deformation of SCC, especially in narrowed sections, is mainly due to the deformation of the mortar. Conventional mortar tests are developed for SCC to evaluate the effect so that water/powder ratio or superplasticizer content can be evaluated at the mortar scale, which may result in saving labor for experiments (Ouchi and Edamatsu 1999, Carro-López *et al*. 2015). Okamura and Ouchi (2003) have proposed mini-slump flow and *v*-funnel tests for mortar to characterize materials used in SCC mix-proportioning. However, none of the proposed methods allow predicting passing ability and stability of SCC with a satisfactory manner. More investigation is needed to better evaluate fresh properties at the mortar scale and to improve existing tests. As is known, the fresh properties of SCC fresh mixture is strongly dependent on the mix proportions (Perrot and Rangeard 2017), that consist in selecting water/cement ratio (W/C), superplasticizer percentage (SP) and fine materials content such as marble powder (MP).

In this paper, the fresh properties of several SCC are reported. The main objectives are to show, at first, the effect of mix parameters (W/C ratio, SP content and MP content) on the slump and flow stability of SCC, and second, to establish some correlations between test methods for SCC and plunger penetration test for SCM. Besides, the adopted statistical design approach that consists in a central composite design with three factors and two levels is chosen since it involves fewer combinations than classical mix-design approaches, while it can be satisfied by finding out which of the main effects are significant and, in some cases, which second-order interactions come into play.

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ISSN: 1598-8198 (Print), 1598-818X (Online)

Table 1 Chemical and physical properties of cement and MP

Analysis (%)	Portland cement	Marble Powder
CaO	65.9	55.6
SiO_2	21.9	0.6
Al_2O_3	4.8	0.4
Fe_2O_3	3.5	0.2
MgO	1.6	0.1
K_2O	0.5	-
SO_3	0.48	-
$CaCO_3$	-	90
Na_2O	-	-
Cl	0.1	0.1
LOI	1.2	43
Specific density	3.1	2.7
Blaine Surface (cm²/g)	2792	2126

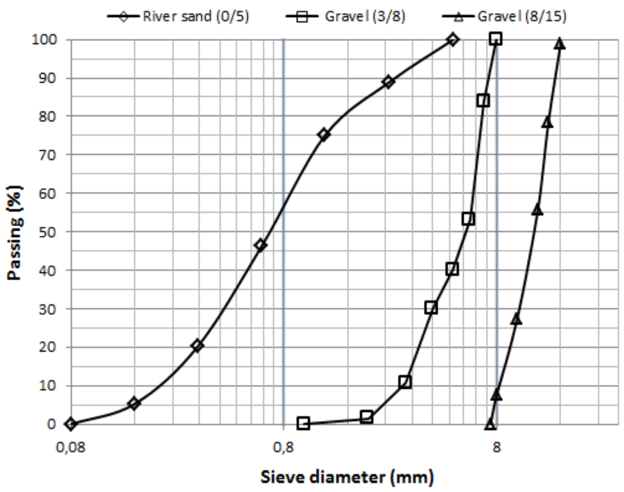


Fig. 1 Particle size gradations of river sand and gravels

2. Experimental program

2.1 Materials

An ordinary Portland cement (CEM I 42.5) from Algerian Cement Company (ACC) and a limestone type marble powder (MP) from limestone quarries and marble stone cutting sites in Algeria, were used as fine materials in this study. The physical and chemical properties of fine materials are reported in Table 1.

River siliceous sand (0/5 mm) with a density of 2.65 g/cm^3, a fineness modulus of 3.03 and an absorption coefficient of 1.79% was used. Crushed limestone type gravels (3/8 mm and 8/15 mm) with a density of 2.75 g/cm^3 and an absorption coefficient of 1.83% were also used. The particle size gradations obtained through sieve analyses method of selected sand and gravels are presented in Fig. 1. A polycarboxylate-type high range water reducing superplasticizer (SP) was used. The solid content, pH and specific gravity of the superplasticizer are 30%, 6 and 1.07 respectively.

2.2 Central composite design

Table 2 Coded and absolute values of studied factors

Coded value	W/C	MP (kg/m^3)	SP (%)
-1.682	0.37	66	1.56
-1	0.4	100	1.7
0	0.45	150	1.9
+1	0.5	200	2.1
+1.682	0.53	234	2.24

Statistical modeling approaches are proved to be ideal for optimizing SCC mix-design parameters and achieving desired properties while minimizing the number of trials (Khayat *et al*. 2000, Sonebi 2001, Nunes *et al*. 2006, Bouziani *et al*. 2012). In the present study, experiments were selected according to a central composite design with a rotatable axial value of 1.682 using JMP7 statistical software from statistical American Society Institute. In rotatable central composite designs, all points at the same radial distance from the center point have the same magnitude of prediction error. The design consisted of eight fractional points augmented with six axial points. Four central points were replicated to estimate the experimental error.

The following second-order model was used to approximate the responses

$$y = a_0 + \sum_{i=1}^{k} a_1 x_i + \sum_{i=1}^{k} a_2 x_i^2 + \sum_{i=1}^{k-1}\sum_{j=1}^{k} a_{ij} x_i x_j + \varepsilon \text{x} \tag{1}$$

The model's coefficients (a_i) represent the contribution of the associate independent variables (x_i) on the response *Y*. These coefficients are determined by a standard least-square fitting. Analyses of variance are used to evaluate the significance of each term in the model.

The derived models for slump flow diameter (Sf), Sieve stability ratio (S) and plunger penetration value (P) are established based on the following factors: W/C ratio, MP content and SP percentage. The effect of each factor is evaluated at five levels (-1.682, -1, 0, 1 and +1.682) as recapitulated in Table 2.

2.3 Mix proportions and testing procedures

A total of 18 SCC mixtures were prepared for this investigation. In all the mixtures, the amounts of cement, sand and gravels were kept constant. The mix proportioning has been designed according to French Association of Civil Engineering (AFGC) recommendations (AFGC 2008). In other words, the gravels/sand ratio was kept equal to 1 and the volume of paste was chosen 393 l/m^3 (in the range 330-400 l/m^3). Cement, sand, gravel (3/8) and gravel (8/15) contents were 390 kg/m^3, 788 kg/m^3, 305 kg/m^3 and 473 kg/m^3 respectively.

All SCC mixtures were prepared in a constant mixing sequence. First, gravels, sand, cement and MP were blended then SP and water were added to the mixture. Immediately after mixing, the following tests were evaluated: slump flow diameter (cm), sieve stability (expressed by the percentage S of the mass of mortar which passed through the sieve) and

Fig. 2 Plunger apparatus

Table 3 Test results of studied SCC

Mix No.	Factors			Test results		
	W/C	SP (%)	MP (kg/m^3)	Sf (cm)	S (%)	P (cm)
1	0.40	1.70	100	48.25	1.95	0.4
2	0.40	1.70	200	35.5	1.22	0.4
3	0.40	2.10	100	72	13.81	5.3
4	0.40	2.10	200	55	1.75	0.3
5	0.50	1.70	100	82.5	29.53	5.7
6	0.50	1.70	200	83	26.34	6.5
7	0.50	2.10	100	85.5	26.83	5
8	0.50	2.10	200	86	22.81	6.5
9	0.37	1.90	150	33.75	0	0.5
10	0.53	1.90	150	90	30.93	6.6
11	0.45	1.56	150	62.5	5.43	3.5
12	0.45	2.24	150	60.25	2.97	2
13	0.45	1.90	66	74.75	14.78	6.5
14	0.45	1.90	234	76	18.23	3.9
15	0.45	1.90	150	77.5	13.69	4.5
16	0.45	1.90	150	77.75	13.67	3.9
17	0.45	1.90	150	81.25	20.05	3.6
18	0.45	1.90	150	81.75	14.63	3.4

plunger penetration (measured by the vertical penetration P of a defined plunger rod which has been allowed to fall freely through a given height into the fresh mortar sample (Fig. 2), according NF EN 413-2 standard (2006). The fresh mortar sample was dripped through the sieve used for stability test and collected by the base receiver.

3. Test results and discussion

3.1 Mathematical models

Test results of selected 18 mixtures are summarized in Table 3. These experimental results are used to establish mathematical models that can be used to describe the effect of W/C, SP and MP variations as well as all possible interactions, on the variation of studied responses Sf, S and P. The found coefficients of mathematical models are

Table 4 Models coefficients estimate for studied responses

Term	Sf (cm)		S (%)		P (cm)	
	R^2=0.95		R^2=0.89		R^2=0.90	
	Estim.	$P>\|t\|$	Estim.	$P.>\|t\|$	Estim.	$P>\|t\|$
Intercept	78.53	<.0001	17.05	<.0001	3.72	<.0001
W/C	16.17	<.0001	10.16	<.0001	2.02	<.0001
SP	3.33	0.0387	0.15	0.8913	0.11	0.6800
MP	-1.95	0.1935	-1.04	0.3945	-0.52	0.0883
W/C*SP	-4.65	0.0291	-2.33	0.1176	-0.69	0.0841
W/C*MP	3.84	0.0619	0.69	0.6579	0.91	0.0299
SP*MP	/	/	-1.52	0.3427	-0.54	0.1634
(W/C)²	-5.41	0.0034	/	/	/	/
(SP)²	-5.6	0.0028	-3.53	0.0055	-0.38	0.2024

Table 5 Analysis of variance for established models

Item		Model	Error	Total
Sf (cm)	DF	7	10	17
	SS	4750.5081	267.5926	5018.1007
	F-ratio	25.3611	/	/
S (%)	DF	4	13	17
	SS	1624.7597	200.5530	1825.3127
	F-ratio	26.3295	/	/
P (cm)	DF	8	9	17
	SS	78.280850	9.028595	87.309444
	F-ratio	9.7541	/	/

evaluated based on student distribution which can help to eliminate not-important terms.

The acceptance probability for the coefficients is set at *p*-value less or equal to 0.05. Estimated coefficients of derived models (Estim.), correlation coefficients (R^2) and *p*-values for the studied responses are shown in Table 4.

As illustrated in Table 4, derived models parameters indicate that all responses have good coefficients of correlation. The estimate coefficients with a negative sign indicate that the increase in the corresponding factor results in a decrease in the response. It can be also seen that the main effect in all responses models is due to the W/C ratio. The interaction with coupled terms indicates that the influence of the associate parameter is quadratic (Sonebi 2001).

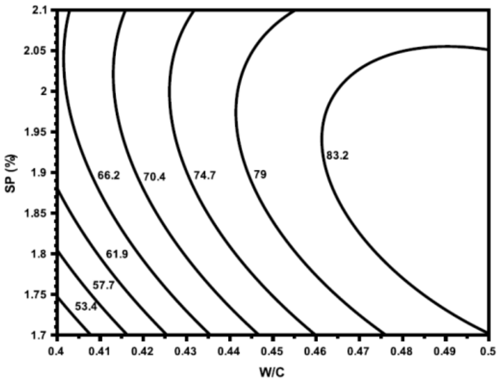
The validity of derived models is verified using analysis of variance. Degrees of freedom (DF) variation, sum of squares (*SS*) for the variability measured in the response and *F*-ratio (this parameter tests the hypothesis that all the regression parameters are zero, except the intercept) are summarized in Table 5.

As can be seen from this table, the *F*-ratio for all responses are high (i.e., a small probability that the models are only influenced by the mean). Thus, it can be said that the variations of the observed responses are likely due to variations of the parameters in main and coupled terms.

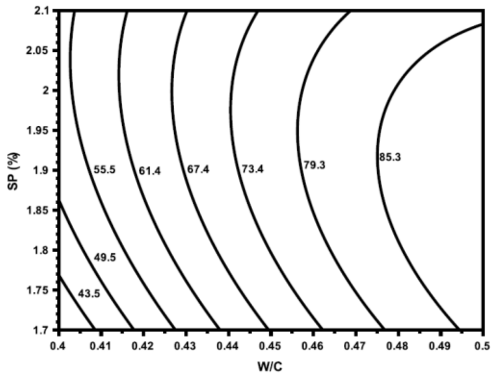
Table 6 displays the results of mean, standard deviation (Std. Dev.), standard error of the mean (Std. Err. Mean, upper and lower 95% confidence limits for the mean (Up. 95% Mean and Lo. 95% Mean respectively) and coefficient of variation (CV) for the four repeated central point.

Table 6 Repeatability of experimental results

Term	Sf (cm)	S (%)	P (cm)
Mean	79.56	15.51	3.85
Std. Dev.	2.25	3.06	0.48
Std. Err. Mean	1.12	1.53	0.24
Up. 95% Mean	83.14	20.37	4.61
Lo. 95% Mean	75.98	10.64	3.09
CV	5.06	19.72	12.46



(a) MP=100 kg/m^3



(b) MP=200 kg/m^3

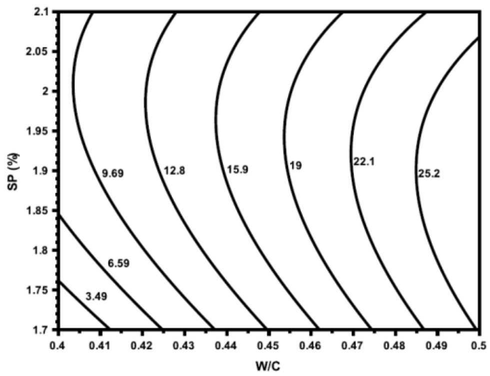
Fig. 3 Influence of SP content and W/P ratio on slump flow (cm), for MP=100 kg/m^3 and MP=200 kg/m^3 content

It can be seen from Table 6, that each value of upper and lower 95% limits defines the suitable interval to contain the mean of the corresponding response. The 95% confidence intervals for Sf, S and P are ±3.58 cm, ±4.86% and ±0.76 cm respectively. It can be also seen that the measure of dispersion characterized by CV values reveals that Sf is around 5%, while S and P are about 20% and 13% respectively.

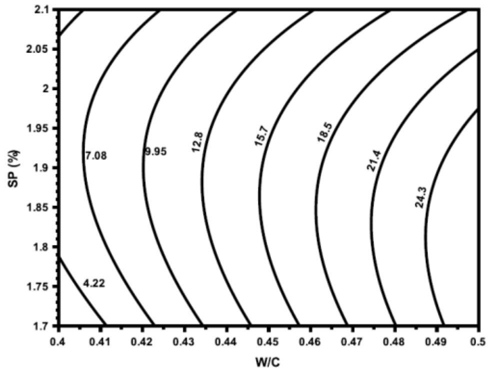
The accuracy of proposed models can be evaluated by comparing the predicted-to-observed ratios obtained with the four replicated points. The values of predicted-to-observed ratios for Sf, S and P are 1.01, 0.91 and 1.03 respectively. Thus, it indicates good accuracy for the proposed models to predict studied responses, except for the sieve stability response (with a ratio of 0.91).

3.2 Exploitation of derived models

The derived models can be exploited to highlight the



(a) MP=100 kg/m^3



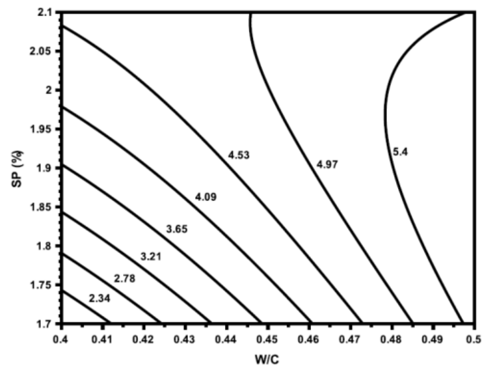
(b) MP=200 kg/m^3

Fig. 4 Influence of SP content and W/P ratio on stability (%), for MP=100 kg/m^3 and MP=200 kg/m^3 content

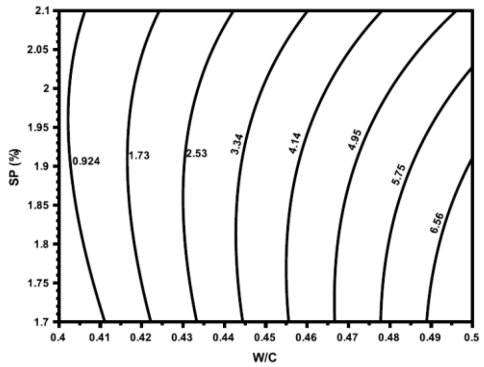
effects of studied factors on the selected responses. The influences of W/C ratio, SP dosage and MP content on Sf, S and P are presented on Figs. 3-5.

Isoresponses curves presented in Fig. 3 show that the increase in W/C ratio and/or the SP content increased slump flow diameter. The obtained results indicate that slump flow diameter values are mostly well ranged in the limits prescribed by the AFGC, from 55 cm to 85 cm (AFGC 2008). Obtained results show also that for a given values of W/C and SP, the increase of MP content from 100 kg/m^3 to 200 kg/m^3, slump flow diameter decreased. Furthermore, for a given W/C ratio, SP percentage higher than 2% slump flow diameter decreased. This may be a result of coarse aggregates segregation in SCC mixtures at high SP dosages. It can be also observed that SCC mixtures with MP content of 200 kg/m^3 required higher values of W/C ratio and/or SP content to achieve similar slump flow diameter for SCC mixtures with MP content of 100 kg/m^3.

Fig. 4 shows the influence of W/C ratio and SP percentage on the stability of SCC mixtures prepared with different MP content. In general stability decreases with the increase of W/C ratio and/or SP percentage whatever MP content. Conversely, for a given W/C and SP percentage, increasing of MP content from 100 kg/m^3 to 200 kg/m^3 in SCC mixtures, increased the stability. However, a decrease in stability values (enhancement of stability) is observed for SP percentages higher than 2%, and this behavior will be also expected for SP percentages lower than 2%, when increasing W/C ratio. Similar results on the effect of un-



(a) MP=100 kg/m^3



(b) MP=200 kg/m^3

Fig. 5 Influence of SP content and *W/P* ratio on penetration (cm), for MP=100 kg/m^3 and MP=200 kg/m^3 content

adsorbed SP at high SP dosage were recorded by Kordts and Breit (2003).

The effect of W/C ratio and SP percentage on the penetration values is illustrated in Fig. 5. The results presented in Fig. 5 indicate that increasing W/C ratio and/or SP dosage led to increase the penetration values. Nevertheless, penetration test values decrease by increasing MP content from 100 kg/m^3 to 200 kg/m^3. As can be expected from Fig. 5, for MP content of 100 kg/m^3 a quadratic effect of SP dosage is observed at W/C values above 0.48 (the maximum value is recorded for SP dosage around 2%).

It is well known that the achievement of deformability and stability is an important task for the success of SCC mix design. Hence, it is very interesting to assess these properties at mortar scale to save time and labour for experiments. Some test methods have been proposed to predict deformability of SCC by its mortar, such as mini-slump and *v*-funnel tests (Okamura and Ouchi 2003). Nevertheless, none of these methods permit predicting the stability with a satisfactory way.

Fig. 6 illustrates the relationship between slump flow (Sf) and stability (S) with penetration test results (P). The results show that the relationships found between Sf and S with P seemed to follow linear model with acceptable correlation coefficients (R^2=0.7554 and R^2=0.7505 for equations 2 and 3 respectively)

$$Sf\ (cm) = 6{,}5893\ P(cm) + 45{,}105 \qquad (2)$$

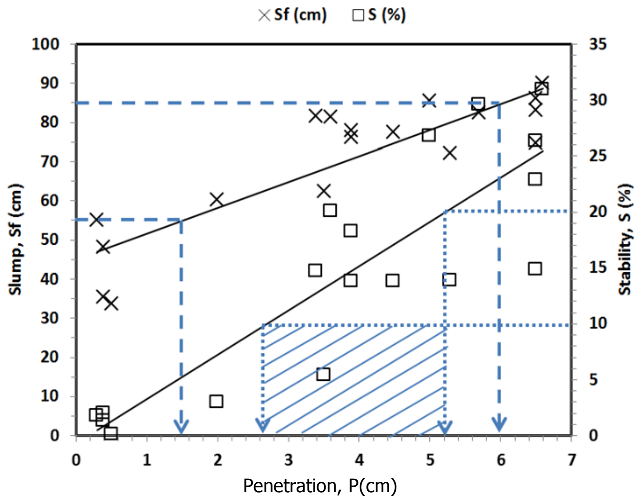


Fig. 6 Correlations between slump flow and sieve test stability with plunger test penetration

$$S\ (\%) = 3{,}961\ P(cm) - 0{,}7059 \qquad (3)$$

From these results, it is found that penetration test values between 1.5 cm and 6 cm leads to a SCC having a Sf range between 55 cm and 80 cm respectively (values recommended by AFGC (2008)). Even though, for stability requirements (between 10% and 20%), penetration test values should be between 2.6 cm and 5.2 cm. To ensure an adequate SCC mix design, it is necessary to consider both the flowability and the stability requirements. Hence, to develop a satisfactory SCC, penetration values should be between 2.6 cm and 5.2 cm (hachured zone in Fig. 6). It is remarkable to note that the slump flow and the stability of SCC can be predicted, with a reasonable approximation, by carrying out a simple penetration test (by plunger apparatus) on its mortar.

4. Conclusions

Based on the findings of the present experimental work, the following conclusions may be drawn:

- The establishment of statistical models to evaluate the effect of W/C, SP and MP variations as well as all possible interactions, on the variation of slump flow diameter (Sf), stability (S) and plunger penetration values (P), while minimizing the number of trial batches needed to select W/C, SP and MP optimums for a given SCC mixture.
- The increase of W/C ratio and/or SP dosage in SCC mixtures, increased slump flow and plunger penetration test values and decreased stability. However, incorporating MP content improved stability and decreases slump flow and penetration test values.
- An acceptable correlations between Sf and P (with R^2=0.7554) and between S and P (with R^2=0.7505) have been established. The derived relationships can be very helpful to predict both slump flow and stability of SCC fresh mixes only by performing the plunger penetration test on its mortars. To develop a satisfactory SCC

mixture in this study, penetration values should be between 2.6 cm and 5.2 cm.

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