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Correlation Between V-funnel and Mini-slump Test Results with Viscosity

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Abstract

Self-Compacting Mortars (SCM) can be regarded as high flowing mortars, which must show both a good fluidity (to fill complex formwork shapes) and sufficient viscosity (to avoid segregation). The characterization and control of fresh properties are proving to be critical for the success of SCM design. Usually, this task is performed through technological tests such as v-funnel and mini-slump. However, the use of viscometers can successfully perform better access of fresh properties. The objective of the present work is to correlate experimental results of v-funnel and mini-slump tests with viscosity of SCM, measured at different rotational speeds, and with constants *a* and *b* calculated from the power-law viscosity model. Linear relationships between both v-funnel and mini-slump tests and viscosity were demonstrated. Statistical models are also established to highlight the influence of constants *a* and *b* on the v-funnel and mini-slump variations. Results indicate the usefulness of established models to better understand the trade-off between constants *a* and *b* on fresh properties measured by v-funnel and mini-slump tests.

Keywords: *correlation, v-funnel, mini-slump, viscosity, power-law model constants*

1. Introduction

Research on the fresh properties of self-compacting mortars (SCM) has been the subject of many studies in the past few decades. It has been observed that the final quality of such mortars will strongly depend on their behaviour in fresh state. Currently, technological tests such as v-funnel and mini-slump, which have been developed for a rapid fresh properties characterization, can be helpful to decide whether or not, a mixture is acceptably workable. Yet, it is not possible to perform a complete characterization of fresh properties by using only these empirical tests (Bartos, 2005).

Further information on the fresh properties of flowable mortars can be effectively obtained using viscometers (Ferraris *et al.*, 2001). However, their use is usually more expensive and difficult in field applications.

Flowability of cementitious-based mixtures can be characterized by the viscosity, which represents a measure of resistance of the mixture to an increase in the rate of flow. Such mixtures are commonly characterized using a power-law rheological model (or Ostwald-de Waele model), in which the viscosity μ (in centipoise) is related to the rotational speed γ (in revolutions per minute) as given by the Eq. (1):

$$\mu = a\gamma^b \tag{1}$$

Where a is the consistency index and b is the power-law exponent or flow index. The model constants a and b can be calculated by the help of best-fit equations (Felekoǧlu *et al.*, 2006).

In the power-law model, the cementitious-based mixtures show a pseudoplastic behaviour (called also shear thinning), which will display a decreasing viscosity with an increasing flow rate.

Even though there has been much work on the relationships between rheological parameters and empirical test results, there is scarce amount of works concerning the correlation between viscosity and any results that can be obtained from field tests. The importance of establishing this correlation is clearly evident due to the key role that viscosity plays in determining the static and dynamic stability of fresh concrete (Assaad *et al.*, 2004; Khayat *et al.*, 2004). In principle, optimal design of high flowing concretes should allow for the easy flow movement of the fresh material and, at the same time, it should not cause any segregation (Nielsson and Wallevik, 2003).

Using a programmable DV model viscometer, Felekoǧlu *et al.* (2006) showed in a study on the viscosity of self-compacting mortar pastes, that v-funnel time correlate in certain cases with the viscosity. The authors have found that the best correlation between v-funnel flow time and viscosity was derived from the rotational speed 10 rpm. In a recent study, Güneyisi *et al.* (2009)

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have found a best correlation at 0.5 rpm.

It was also observed that the slump test can be related to the viscosity. Esping *et al.* (2007) presented experimental results for self-compacting concrete showing that this relation is more pronounced, especially at low viscosities. As shown by Bui *et al.* (2002), a minimum viscosity is required to avoid segregation, which also depends on the slump flow diameter as well as the aggregate characteristics. They have also demonstrated a simple relationship between the viscosity/yield-stress ratio and the time it takes to reach the final mini-slump flow spread for cement paste. Recent experimental work on the viscosity of cement pastes has links specifically the viscosity to the time it takes to reach either a prescribed or the final spread, as measured from camera recording of mini-slump test (Tregger *et al.*, 2008).

This paper attempts to establish a correlation between technological test results (v-funnel and mini-slump) and viscosity of SCM measured at different rotational speeds. Moreover, a statistical approach is carried out to model the v-funnel and mini-slump results as a function of constants (*a* and *b*) of power-law viscosity model.

2. Experimental Program

2.1 Materials

An ordinary Portland cement and a marble powder limestone-type, derived from marble production, sites were used. The chemical and physical properties of cement and marble powder are given in the Table 1. The sand used was a mixture of dune sand and river sand. The particle size gradation obtained through sieve analysis method and physical properties of used sands are presented in Table 2. A polycarboxylate-type superplasticizer, high water reducing, conforming to the NF EN 934-2 standard was used (AFNOR, 2002). The solid content, pH and specific gravity are 30%, 6 and 1.07, respectively.

2.2 Test Procedure

All mixtures were prepared in constant mixing process in order to obtain the same homogeneity and uniformity. The mixing process consisted of homogenizing the binder and sands for one minute using a standard mixer described by NF EN 196-1 (AFNOR, 2003). Then, half of the mixing water was added and mixed for another minute. Next, the superplasticizer and the remaining water were added and mixing was continued for three minutes. The mix proportions of the studied mixtures are summarized in Table 3. The dosage of cement was kept constant (350 kg/m^3).

Table 1. Chemical Composition and Physical Properties of Cement and Marble Powder

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 (m²/kg)	279.2	212.6

Table 2. Sieve Analysis and Physical Properties of Sands

Sieve size (mm)	Cumulative passing (%)	
	Dune sand	River sand
5	100	99.5
4	100	97.09
2.5	100	83.56
1.25	99.92	63.27
0.63	98.09	34.85
0.315	82.86	13.65
0.16	19.36	2.44
0.08	1.63	0.84
Specific density	2.7	2.56
Fineness modulus	1	3.03
Absorption (%)	5.18	1.79

The fresh properties of the studied mixes were investigated by v-funnel, mini-slump and a programmable viscometer tests. V-funnel and mini-slump tests were carried out according to EFNARC recommendations (EFNARC, 2002).

The viscosity measurements were conducted at different rotational speeds, using a rotational viscometer, programmable DV-II+ type, equipped with the RV4 geometry (Fig. 1). After mixing, the SCM mix was placed in the pot of the viscometer. Pre-

Table 3. Mix Proportions of SCM Mixes

Mix No.	Superplasticizer		Marble powder (kg/m^3)	Dune sand (kg/m^3)	River sand (kg/m^3)	Water (kg/m^3)
	(kg/m^3)	(%)				
1	9	1.8	150	290	1210	215
2	9.8	1.4	350	290	1210	301
3	7	1.4	150	290	1210	225
4	12.6	1.8	350	85	1415	301
5	9.8	1.4	350	85	1415	315
6	7	1.4	150	85	1415	215
7	9	1.8	150	85	1415	225
8	12.6	1.8	350	290	1210	315
9	9.6	1.6	250	196	1304	264
10	9.6	1.6	250	196	1304	276
11	9.6	1.6	250	196	1304	252
12	12.3	1.6	418	196	1304	338
13	6.9	1.6	82	196	1304	190
14	11.4	1.9	250	196	1304	264
15	7.8	1.3	250	196	1304	264
16	9.6	1.6	250	346	1154	264
17	9.6	1.6	250	0	1500	264

Fig. 1. Programmable DV-II+ Viscometer

mixing was performed by increasing the rotational speed from 0 to 60 rpm in 120 s. When the highest rotational speed was reached, the viscometer was stopped. After this initial preparation, a full cycle of increasing rotational speed by eight steps (0.3, 0.6, 1.5, 3, 6, 12, 30 and 60 rpm) and back to reset with the same eight steps were performed. The averages of viscosity values, determined at upwards and downwards of each rotational speed step were recorded and recapitulated in Table 4. Results of v-funnel and mini-slump as well as viscosity power-law model constants and the coefficients of correlation are presented in Table 5.

Table 5. Test Results of v-Funnel, Mini-Slump and Viscosity Model Constants

Mix No.	v-funnel (s)	mini slump (cm)	viscosity power law model constants		
			a	*b*	R^2
1	/	16.8	19785	-0.5046	0.9816
2	2.2	32.7	2486	-0.9299	0.9761
3	8.9	22	32245	-0.5968	0.9917
4	1.9	33.1	23970	-0.9192	0.9933
5	1.5	40.7	50405	-1.0143	0.9944
6	8.8	18.8	52665	-0.6679	0.9894
7	4.5	28	55118	-0.9225	0.9785
8	2.2	32.2	38824	-0.9151	0.9915
9	3.2	30.1	58440	-0.9688	0.9844
10	2	31	77472	-0.9998	0.9939
11	3.4	30	48069	-0.8856	0.9758
12	1.4	35.7	9396	-0.9288	0.9739
13	/	11.1	59669	-0.644	0.9993
14	2.6	30.4	86022	-1.0191	0.9914
15	2.3	30.4	68707	-1.0295	0.9857
16	3.6	30.3	48071	-0.9156	0.982
17	2	30.6	88958	-1.0232	0.9917

3. Results and Discussion

3.1 Correlation between v-Funnel and Mini-Slump Tests and Viscosity

A correlation is first sought between v-funnel and mini-slump results and viscosity at different rotational speeds. As shown in Fig. 2 and Fig. 3, linear relations between both v-funnel time and mini-slump and viscosity at high speeds (12, 30 and 60 rpm) are obtained, with acceptable coefficients of correlation. The highest values of correlation coefficients are obtained at 30 rpm for v-

Table 4. Test Results of Viscosity Measured at Different Rotational Speeds

Mix No.	Rotational speed (rpm)							
	0.3	0.6	1.5	3	6	12	30	60
	Viscosity (cP)							
1	42566.7	26466.7	15526.7	9976.7	7103.3	4952.5	3682.3	3040.0
2	103400.0	43566.7	15786.7	7263.3	3503.3	1871.7	1072.3	860.7
3	74166.7	45916.7	24400.0	15130.0	9810.0	6679.2	4444.3	3217.3
4	82300.0	39350.0	16700.0	8186.7	3960.0	2075.8	1012.3	717.0
5	204966.7	83283.3	29973.3	16200.0	7683.3	3539.2	1465.3	1018.3
6	113933.3	89833.3	37873.3	21960.0	14733.3	10241.9	5968.3	/
7	207600.0	101650.0	36886.7	16523.3	7845.0	4280.0	2362.0	1949.7
8	127566.7	68016.7	26846.7	13793.3	6106.7	3260.0	1719.3	1193.3
9	194900.0	111300.0	42473.3	19130.0	8866.7	3611.7	2005.0	1642.0
10	211566.7	146566.7	59693.3	27326.7	13751.7	5433.3	2245.3	1460.7
11	146100.0	101100.0	33153.3	16310.0	7265.0	3940.8	2259.7	1971.3
12	37100.0	17350.0	5913.3	2880.0	1373.3	655.0	388.7	344.0
13	129500.0	85533.3	44106.7	29210.0	18911.7	12192.5	/	/
14	254866.7	168133.3	70440.0	27346.7	12683.3	5431.7	2404.7	1675.3
15	276166.7	125416.7	51540.0	17880.0	8530.0	4160.8	1968.0	1509.0
16	150466.7	87733.3	34913.3	18693.3	7255.0	3470.8	1986.0	1673.0
17	282800.0	186616.7	58960.0	30306.7	12300.0	5607.5	2479.0	1772.7

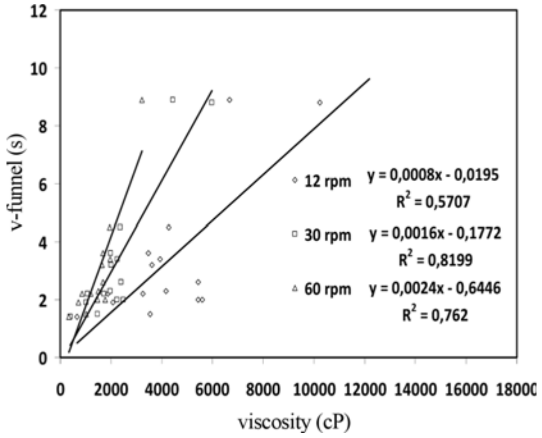

Fig. 2. Correlations between v-Funnel and Viscosity Measured at 12, 30 and 60 rpm

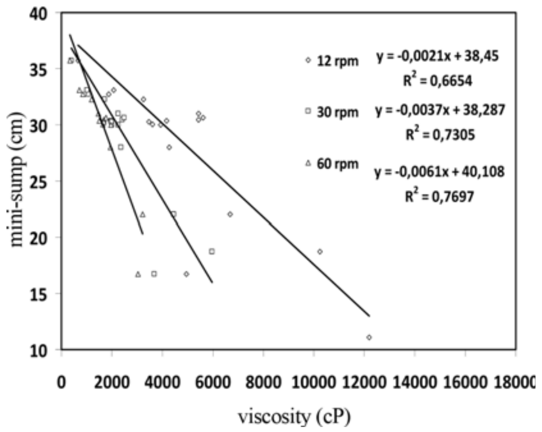

Fig. 3. Correlations between Mini-slump and Viscosity Measured at 12, 30 and 60 rpm

funnel ($R^2 = 0.82$) and at 60 rpm for mini-slump ($R^2 = 0.77$). Fig. 2 and Fig. 3 show respectively that by increasing the viscosity, v-funnel time increases and mini-slump decreases.

As it is known, v-funnel and mini-slump tests measure the flowability of self-compacting mortars and concretes. In fresh state, when the yield stress is exceeded, flow start and the shear stress will increase linearly with an increase in strain rate, as defined by viscosity as a measure of the ease of flow (Güneyisi *et al.*, 2009). Therefore, good linear correlations are obtained at high rotational speeds. The linear relationships between v-funnel and mini-slump results and viscosity are similar to some findings of other researchers testing self-compacting mortars, which obtained acceptable coefficients of correlation (Felekoğlu *et al.*, 2006; Güneyisi *et al.*, 2009).

3.2 Statistical Correlation between v-Funnel and Mini-Slump Tests and Viscosity Model Constants

Basing on a standard least square fitting, the following first-order model is used to approximate all responses:

$$y = a_0 + \sum_{i=1}^{K} a_i x_i + \varepsilon \qquad (2)$$

Where y is the response; x_i are the independent variables; a_0 is the intercept of the model (also called the constant term); a_i are the coefficients of independent variables; ε is the random error term representing the effects of uncontrolled variables (not included in the model). This model (Eq. (2)) is performed to examine the relation between viscosity model constants (a and b) and both v-funnel and mini-slump results. Where, v-funnel and mini-slump are assigned as responses and constants a and b as independent variables.

All coefficients of derived models are found by a standard least-square fitting. With *t*-tests, based on Student's distribution, the effect of each independent variable is evaluated to eliminate Non-Significant terms (NS), on other words, to evaluate the probability (*p*-value) that the coefficient of this effect is different from zero. The acceptance probability for the coefficients is set at a *p*-value of 0.05 (i.e. if the *p*-value is less than 0.05, the coefficient is significant). The ratio of the parameter estimate to its standard error lists the test statistics for the hypothesis that each parameter is zero. If the hypothesis is true, then this statistic has a Student's *t*-distribution. Looking for a *t*-ratio greater than 2, in absolute value, is a common rule for judging significance because it approximates the 0.05 significance level.

Model coefficients, correlation coefficients (R^2), *t*-ratios, *p*-values and standard errors (Std. Err.) for each term are presented in Table 6. The derived statistical models of v-funnel and mini-slump are given in Eqs. (3) and (4):

$$v\text{–}funnel\ (s) = 19.9 + 0.000033 * a + 19.9 * b \qquad (3)$$

$$mini\text{–}slump\ (cm) = –0.0001 * a – 38.4 * b \qquad (4)$$

As presented in Table 6, we check to see that all derived models have good coefficients of correlation (R^2), and that the *p*-value of the coefficients selected are all less than 0.05, except for the intercept coefficient of mini-slump model (*p*-value > 0.05 and *t*-ratio < 2). We can also see that the main effect in all derived models is due to the constant b. A negative coefficient indicates that the increase in the given parameter, results in a

Table 6. Parameter Estimates of Model Coefficients

Terms	v-funnel (s)				mini-slump (cm)			
	$R^2 = 0.94$				$R^2 = 0.80$			
	Coeff.	*t*-ratio	*p*-value	Std. Err.	Coeff.	*t*-ratio	*p*-value	Std. Err.
Intercept	19.9	16.1	<0.0001	1.24	NS	0.05	0.9625	4.93
a	3.3E-05	4.7	0.0005	7.1E-06	-0.0001	-3.6	0.0035	2.8E-05
b	19.9	13.8	<0.0001	1.43	-38.4	-6.7	<0.0001	5.72

reduction of the measured response (Sonebi, 2001).

The predicted-to-observed plots, obtained with all the mixture trials, of v-funnel and mini-slump test results and viscosity model constants (*a* and *b*) are shown in Fig. 4 and Fig. 5 respectively, with 95% confidence limit (the dash-dotted curves, which defines an interval that is very likely to contain the mean of the corresponding response). In Fig. 4 and Fig. 5, the mean lines do not fall inside the bounds of 95% confidence curves, which indicate that the proposed models are accurate (Goupy and Creighton, 2007).

3.3 Trade-off between Constants *a* and *b*

Contour diagrams showing the influence of constants *a* and *b* on v-funnel and mini-slump are presented in Fig. 6. As expected, for a given *b* value, the contour diagrams indicate that the increase in constant *a* value increases the v-funnel time, while the mini-slump decreases.

Using the viscosity power-law model constants, the initial viscosity can be characterized by the constant *a* (also called the consistency index) and the needed energy to attain a flowable consistency can be characterized by constant *b* (also called the flow index). The isoresponse curves in Fig. 6, allow us to select mixtures with high constant *a* and low constant *b* or mixtures with low constant *a* and high constant *b* while keeping the same fluidity. For example, as shown in Fig. 6, mixtures with *a* = 20000 and *b* = -0.72, have approximately the same mini-slump

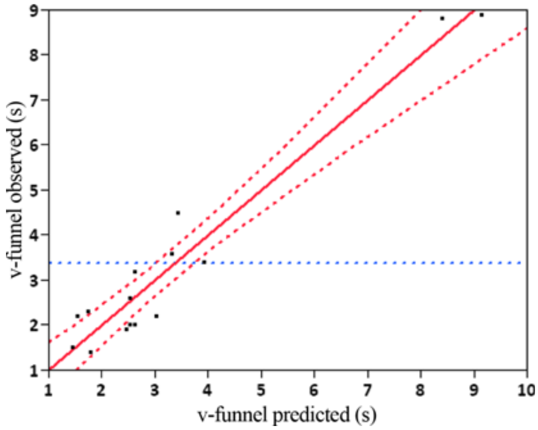

Fig. 4. Observed versus Predicted Values from v-Funnel Model

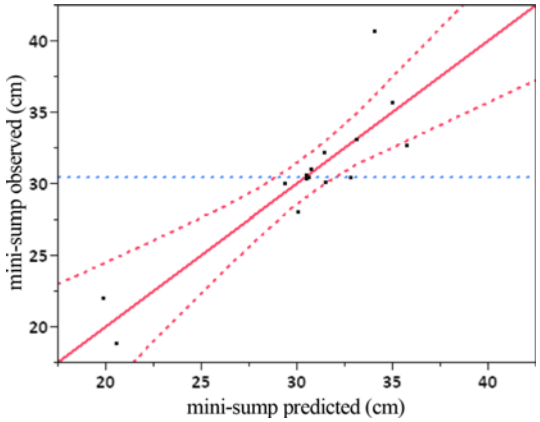

Fig. 5. Observed versus Predicted Values from Mini-slump Model

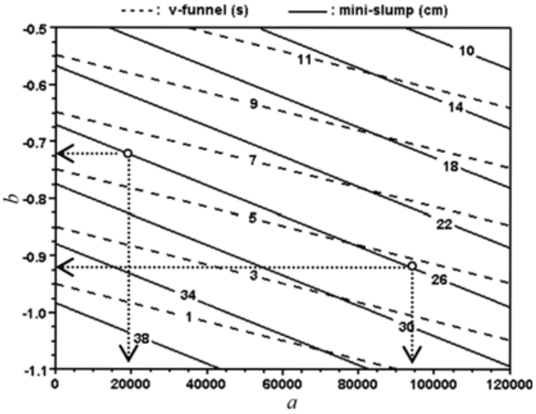

Fig. 6. Contour Diagrams of v-Funnel and Mini-slump

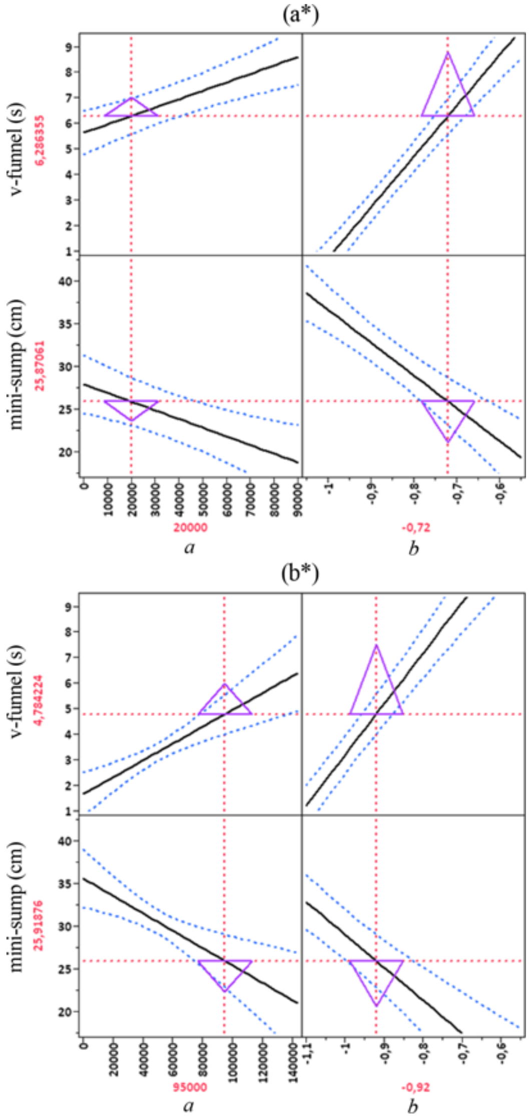

Fig. 7. Prediction Profilers of v-Funnel and Mini-Slump Responses: (a*) for *a* = 20000 and *b* = -0.72, (b*) for *a* = 95000 and *b* = -0.92

(26 cm) with mixtures having *a* = 95000 and *b* = -0.92. By using the response prediction profiler (Fig. 7), we can get a closer look at the response changes and help us to find the settings that produce the best response target. It is a way to interactively change variables and look at the effect on the predicted response. As illustrated in Fig. 7, when mini-slump is kept constant (approximately 26 cm) for the selected mixtures, the response in v-funnel decreases from 6.3 s (for the mixture with *a* = 20000 and *b* = -0.72) to 4.8 s (for the mixture with *a* = 95000 and *b* = -0.92). To select the appropriate mixture, we should consider their stability as a criterion. In general, the higher is constant *a* higher is the initial viscosity and, consequently, we get more stability; and, the lower is constant *b* higher is the flowability. For this reason, mixtures with high constant *a* and low constant *b* values should be selected.

4. Conclusions

Based on the findings of the study the following conclusions may be drawn:

1. Linear relationships between viscosity of Self-Compacting Mortar (SCM) and technological characterization test results (v-funnel and mini-slump), with acceptable coefficients of correlation, show that by increasing the viscosity, v-funnel time increases and mini-slump decreases. However, these correlations are obtained only with viscosities measured at high rotational speeds (12, 30 and 60 rpm).
2. Good correlations between viscosity model constants (*a* and *b*), calculated using the best-fit equations, and v-funnel and mini-slump test results are obtained by a statistical modelling approach. The established models indicate that the main effect on v-funnel and mini-slump variations is due to constant *b*.
3. Better correlations obtained with viscosity model constants (*a* and *b*) than those with viscosity, indicate that viscosity model constants are more effective in predicting v-funnel and mini-slump variations.
4. The established models can provide an efficient mean to understand the trade-off between rheological viscosity constants *a* and *b* on fresh properties (characterized by v-funnel and mini-slump tests) and can help us in selecting the adequate mix parameters to ensure high fluidity and stability.

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