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Rheological Characterization of Self-Compacting Concrete: V-Funnel and Horizontal Plexiglas Channel

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Abstract*— *The appearance of new concretes increases the need to reliably characterize the behavior of concrete when flowing. The importance of the rheology and its measurement can be certified by the existing literature on the characterization of fresh concrete [1]-[2]-[3]. Many constitutive equations have been proposed to characterize the rheology of fresh concrete in the form of suspensions, but only the Bingham model and the Herschel-Bulkley model received wide acceptance. The composition of the mixture such as the water/cement ratio, cement, mineral additions (Silica fume, limestone filler) and the superplasticizer affect the rheological behavior of concrete. By isolating each of these factors, it is possible to distinguish the general trends such as their effect on the threshold shear and/or on the plastic viscosity of self-compacting concrete (SCC). In addition to traditional experimental methods such as the V-funnel, slump flow, sieve stability test and the L-box, a new Rheological characterization test has been used: it is the flow of concrete first in a V-Funnel and then in a horizontal Plexiglas channel. The main objective of this document is to determine both the flow time in the V-Funnel (indicator of the viscosity of mixture) and the threshold shear of concrete by means of a single rheological test.

Index Terms— **Bingham, Plastic Viscosity, Rheology, Self-Compacting Concrete, Super plasticizer, Yield Stress.**

I. INTRODUCTION

For self-compacting concrete, experimental data [4] - [5]-[6] have confirmed that the flow of fresh concrete follows the Bingham model: $\tau = \tau_0 + \mu \dot{\gamma}$, τ is the shear stress (Pa), τ_0 yield stress (Pa), μ plastic viscosity (Pa.s) and $\dot{\gamma}$ the shear strain rate (1/s). The first property (τ_0) provides a measure of the shear stress required to initiate the flow and the second (μ) a measure of the resistance to the flow of materials. These two rheological properties are therefore necessary to characterize quantitatively the flow of fresh concrete.

Some empirical tests to measure the workability of the concrete are sometimes contradictory. A good example is presented by Baron [7]. In an experimental campaign, this author has formulated concrete by varying the water dosage and sand/gravel report and has performed the measurements of workability with both the Abrams cone and the LCL maniabilimetre [8]. He found that an X concrete could slump more than a Y concrete with the Abrams cone but have a slower elapse with the LCL maniabilimetre. Therefore, the characterization of the workability of fresh concrete by a single parameter by means of a technology trial (slump, flow time, slump flow [9]) is not sufficient. We must look for other methods of characterization to measure the intrinsic characteristics of fresh concrete. The majority of authors agree on the need to use at least two different empirical tests to establish relationships between specific greatness and characteristic rheological properties of concrete [10]. The advantage of our method is to determine the flow time in a V-Funnel and the flow characteristics in a horizontal Plexiglas channel by using a single rheological test. M Thus, it is now accepted that viscosity is correlated with the flow time measured with the V-funnel while yield stress depends on the slump flow (Figure 1).These graphs show that SCC that has a slump flow of between 600 and 800 mm and a flow time inferior to 14 s (standard values of SCC) have a yield stress inferior to 100 Pa and a viscosity inferior to 100 Pa.s. The purpose of this article is to see the effect of composition of self-compacting concrete using local materials (Aix-Marseille, France) and new superplasticizers on the rheological characteristics of the mixture. The experimental study is conducted in a laboratory at constant temperature and is based on the determination of both flow time in the V-Funnel (indicator of the viscosity of mixture) and yield stress of concrete using a single rheological test: flow of concrete in a V-Funnel and then in a horizontal Plexiglas channel (Figure 2).

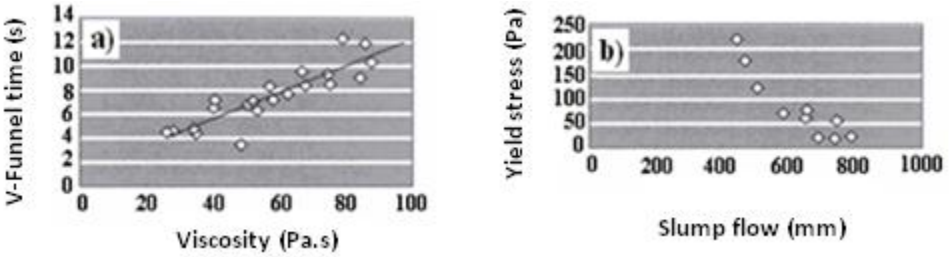

Fig. 1. A) V-Funnel in Relation to Plastic Viscosity. B) Slump Flow in Relation to Yield Stress Measured With a Contec Viscometer [11].

Fig.2. Flow of Concrete in A V-Funnel and Then in A Horizontal Channel in Plexiglas

It is important to underline that the experimental data reported in the literature show that the slump test is not a sufficient measure to characterize the flow properties of fresh concrete. According to Roussel [12] the result of a slump flow test is representative of concrete rheological behavior if the sample is representative of the material (Fig. 3.a). This means that the thickness of the material in the case of a flow generated by the slump flow is greater than the size of the larger particles composing the concrete. This condition is not always met in the slump flow tests since it means that the thickness in the middle (maximum thickness) has to be at least 5 times greater than the diameter of the largest grain. To improve these concepts Roussel, 2007 [13] proposed another rheological test, the LCPC box test (see Fig.3.b).

(a) Slump flow test (b) LCPC box

Fig.3. a) Slump flow tests with Abrams cone. b) LCPC box test.

In this test, Roussel [13] has shown that we can express yield stress as:

$$\tau_0 = \frac{\rho g l_0}{2L_0}\left[h_1 - h_2 + \frac{l_0}{2} ln\left(\frac{l_0 + 2h_2}{l_0 + 2h_1}\right)\right] \qquad (1)$$

Where ρ is the density, l_0 is the width of the channel, h (x) is the stopped-flow and g is the gravity.

In the case of the LCPC box test, if you change the operator, using a bucket may disrupt the speed and the way the concrete flows.

The test proposed in this article therefore allows showing that: (1) for a given formulation, the concrete flow velocity remains the same (use of a standard V-Funnel); (2) regardless of the operator, the way the concrete flows remains the same regardless of the behavior of concrete considered. In addition, the rheological tests most commonly used for the characterization of self-compacting concrete give just one indication on the behavior of concrete, For example, the L-box test characterizes the capacity to fill a formwork, the sieve stability test indicates the static segregation of concrete, the slump flow allows the filling capacity of concrete in a medium that is not scrapped to be characterized, and the V-Funnel gives us an indication of the viscosity by calculating flow time. The advantage of our test is to give several indications at the same time such as the flow time in the V-Funnel and in the horizontal canal and the filling capacity of concrete while visualizing the flow profile.At every moment we can determine the time and the flow profile (fig. 4).

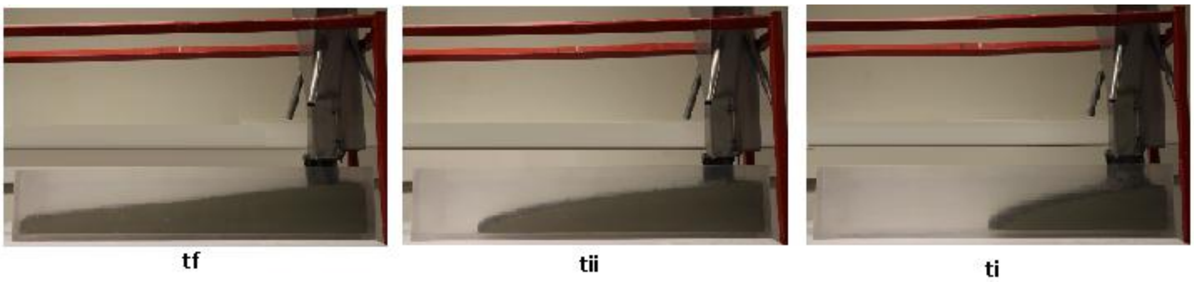

Fig. 4. Profile shape to every moment of flow.

The experimental device used is a horizontal Plexiglas channel with a 0.90m length, a 0.20m width and a 0.16m height. A volume of 12 liters of material is emptied in a V-Funnel, then in a horizontal channel (Fig. 2). One minute after stopping the flow, the pictures are taken through one of the sidewalls of the channel (See Figure 5).

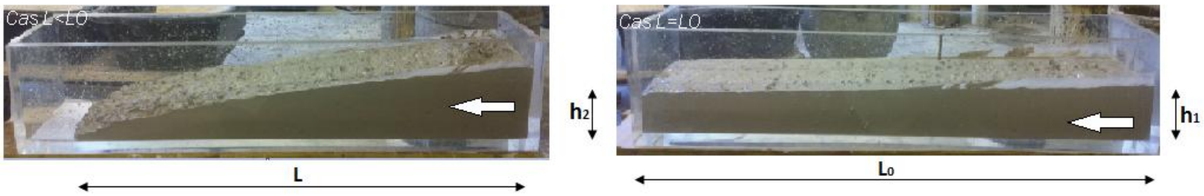

Fig. 5. Concrete flow in a horizontal Plexiglas channel.

After the exploitation of the results, the yield stress is determined by using the equation (1) described by N.Roussel [14] and the plastic viscosity is determined with the R. Zerbino formula [15] :

$$\mu = \ln(T_v / 3{,}04) / 0{,}013 \qquad (2)$$

Formulas (1) and (2) are used in the comparative term. See also [16]-[17]-[18].

II. MATERIALS USED

Many mineral additives and superplasticizers have made their appearance in recent decades.The cement used in the manufacture of test specimens is CEM I 52.5 N CE CP2 PM-ES-CP2 NF “HRC” essentially intended for concrete works subjected to water with high levels of sulphates or moderately and strongly aggressive chemical environments and the cement CEM II/B-LL 32.5 R R CE CP2 NF is intended for construction work, industrial Civil Engineering and road works. The limestone fillers were also used for the preparation of mixtures. The physicochemical characteristics of the materials are presented in Tables 1 and 2.

Table 1: Cement Characteristics

Description of Product		**CEM I 52.5 N CE PM-ES-CP2 NF “HRC”**	**CEM II/B-LL(ll-S) 32.5 R CE NF**
Clinker $\geq 95\%$	C_3A	2.3	8.9
	C_3S	-	68.5

	C_2S	10.2	11
Mechanical strength mortar (MPA)	1 day	18	-
	2 days	31	19
	28 days	63	47
Initial setting		3h10	3h00
Blaine (cm²/g)		4280	3720
SO_3		2	3.2
Na_2O Equivalent		0.32	0.31

Table 2: Physical Characteristics of Limestone Filler - CARMEUSE Society

TESTS	Value	Standard
Surface Blaine	540 m²/Kg	NF EN 196-6
Absolute density	2,70 g/ml	NF P 18-558
Value blue of fillers	0,66 g/Kg	NF EN 933-9
Humidity	0,11%	NF EN 1097-5
Index of activity	0,76	NF EN 196-1

The gravel used is crushed limestone from the Marseille region. It is class 5/10 gravel and has a density of 2,600 Kg/m3, a humidity of 1% with a Los Angeles coefficient of 23.2%. The sands also come from the Marseille region, they have a specific gravity of 2.7, a fineness modulus of 2.63 and a sand equivalent ratio of 62.53. The superplasticizers used are TEMPO 9, TEMPO 16 and KRONO 20 produced by SIKA France. Technical data is provided in Table 3.

Table 3: Technical Data of Superplasticizers

Superplasticizer	**KRONO 20**	**TEMPO 9**	**TEMPO 16**
Notation	K 20	T 9	T 16
Density	1,085 ± 0,01	1.07 ± 0.01	1,055 ± 0,015
pH	4,5 ± 1	4.5 ± 1	3 ± 1
Dry extract (%)	41 ± 1,5%	33 ± 1.5	24 ± 1,2%
Cl^- content	≤ 0,1 %	≤ 0.1 %	≤ 0,1 %
Na_2Oeq content	≤ 1 %	≤ 1 %	≤ 1 %

III. RESULTS AND DISCUSSION

A. Effect of Water / Cement Ratio (W/C)

Increasing the W/C ratio decreases the yield stress and the plastic viscosity. The authors [19] who noted this effect performed a mixture of concrete with a low W/C ratio and successively added the quantities of water; which was also our experimental approach. Tables 4 and 5 show the composition of the SCC performed in our laboratory at Polytech Marseille and the rheological characteristics obtained from tests such as L-box, slump flow, V-Funnel and sieve stability. And Table 5 shows the characterization of hardened concrete. Initially, the objective of this section is to determine the E/C ratio that respects both the rheological characteristics and the desired mechanical properties.

Table 4: Characteristics of the different compositions of SCC with KRONO 20

SCCs	Superplasticizer	SP(%)	W/C	Composition (Kg /m^3)				
				Cement	Water	SP	Sand	Gravel
SCC1	KRONO 20 Recommended dosage (0.2% à 1.5 %)	0.5	**0.4**	470.00	196.67	5.71	858.58	850
SCC2		0.5	**0.35**	470.00	173.33	5.71	841.44	900
SCC3		0.5	**0.3**	470.00	150.2	5.73	903.00	900

Table 5: Tests Characterizing Fresh and Hardened Concrete Made With KRONO 20

SCCs	Rheological characteristics					Compressive strength (MPa)		
	Slump flow (mm)	T500 (s)	L-box H2/H1	Sieve stability (%)	V-Funnel Tv(s)	1 day	7 days	28 days
SCC1	800	1	1	30	9	24.4	32.5	47
SCC2	765	2	0.9	22	12	27.2	41.6	51.05
SCC3	750	3	0.84	14	14	32.9	50.3	56.8

Generally, with a slump flow greater than 600 mm, a gradient filling greater than 0.80, a segregation rate inferior to 15%, a T500 spreading time inferior to 5 s and a V-Funnel flow time inferior or equal to 14 s (see the recommendations of the AFGC [20] and EFNARC [21]), the rheological characteristics above show that SCC3 meet the requirements to qualify as SCC. Water has an important role regarding the workability of concrete by increasing its fluidity but the large amount of water negatively affects mechanical strength in hardened concrete. For example, after 28 days the compressive strength of SCC3 (W/C=0.3) is 56 MPa, while for SCC1 the compressive strength is about 47 MPa.

B. Effect of Cement Type

The type of cement affects especially the initial rheology of the concrete mixture. The composition of cement, for example the C_3A content which reacts very quickly, will determine the rheology of the mixture. Tables 6 and 7 show the composition of SCC performed in our laboratory and rheological and mechanical characteristics obtained from tests such as L-box, Slump flow, V-Funnel and sieve stability. In this part, in addition to conventional empirical tests, a new test for rheological characterization has been used: this is the flow of concrete in a V-Funnel and then in a horizontal Plexiglas channel (Table 8 and Fig. 6).

Table 6. SCC compositions depending on the type of cement

SCCs	SP(%)	Cement type	W/C	Composition (Kg /m^3)					
				Cement	limestone filler	Water	SP	Sand	Gravel
SCC4	0.3	**CEM I 52.5 N CE PM-ES-CP2 NF “HRC”**	0.3	305.5	164.5	159.2	5.88	870	900
SCC5	0.3	**CEM II/B-LL(ll-S) 32.5 R CE NF**	0.3	305.5	164.5	159.2	5.88	870	900

Table 7. Rheological and mechanical characterization of SCC (depending on the type of cement)

SCCs	Rheological characteristics					Compressive strength (MPa)		
	Slump flow (mm)	T500 (s)	L-box H2/H1	Sieve stability (%)	V-Funnel Tv(s)	1 day	7 days	28 days
SCC4	670	4,5	0,8	5,62	17	28,8	43,6	53,4
SCC5	550	5	0,6	5,02	25	17	34,5	43,8

Table 8. Horizontal channel analysis

SCCs	flow characteristic			
	Flow length (cm)	initial height H1 (cm)	final height H2 (cm)	H2/H1
SCC4	90	7	6.5	0.93
SCC5	90	8.5	1.1	0.13

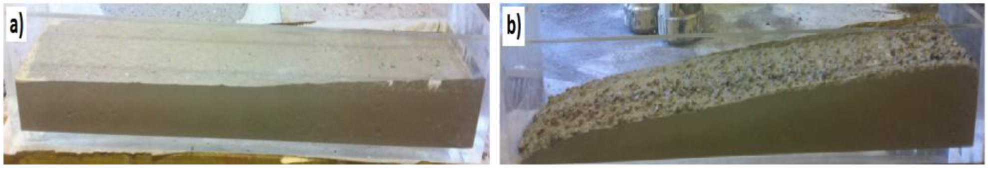

Fig. 6: Flow profile: (a) SCC4- CEM I 52.5 N CE PM-ES-CP2 NF "HRC". (b) SCC5- CEM II/B-LL(ll-S) 32.5 R CE NF

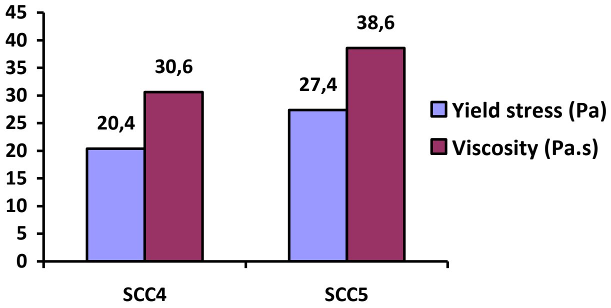

Fig.7. Yield stress and plastic viscosity

Yield stress and viscosity are calculated by equations (1) and (2). The SCC formulated with cement type CEM I 52.5 N CE PM-ES-CP2 NF "HRC" shows a lower yield stress and a low viscosity; the SCC formulated with cement type CEM II/B-LL(ll-S) 32.5 R CE NF shows the highest yield stress and a high viscosity (Fig.7). We admit that the concrete has a length equal to Lmax and a height H1 near to H2 thus meeting the requirements to qualify as SCC. This is the case of SCC4 (Fig. 6. a) that represents a Blaine specific surface greater than that of CEM II/B-LL(ll-S) 32.5 R CE NF and C_3A content inferior to that of CEM II/B-LL(ll-S) 32.5 R CE NF (Table 1). Table 7 and 8 show that for a gradient fill inferior to 0.6 in L-box, the ratio measured on the channel is approximately 0.2, and that for a concrete that has a ratio higher than or equal to 0.8 in the L-Box, the ratio measured on the channel exceeds 0.9. Therefore, the visualization of the flow profile gives us a clear idea of the viscosity of concrete. For comparison, the use of this test means the concrete can be characterized rheologically the concrete considered without going through other conventional tests such as the L-box or the slump flow.

C. Effect of Superplasticizer

Superplasticizers are generally used for concrete with low W/C ratio. The main action of superplasticizers is to deflocculate the cement grains [22] (Figure 8).

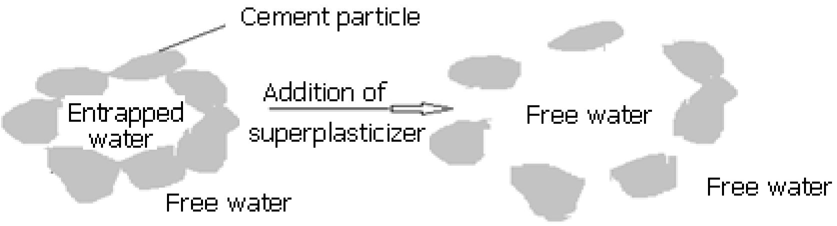

Fig. 8. Action of superplasticizers: deflocculation of cement grains.

Tables 9 and 10 show the composition and rheological characteristics of SCC made during this study. The test responses of rheological modeling, using a horizontal Plexiglas channel made on made-up concrete are shown in Figure 9.

Table 9. SCC composition depending on the type of superplasticizer

SCCs	SP	SP(%)	W/C	Composition (Kg /m 3)					
				Cement	limestone filler	Water	SP	Sand	Gravel
SCC6	KRONO 20	0.3	0.3	258.5	211.5	161	3.44	870	900

SCC7	TEMPO 9	0.3	0.3	258.5	211.5	160.5	4.27	868	900
SCC8	TEMPO 16	0.3	0.3	258.5	211.5	159.6	5.88	864	900

Table 10. Rheological and mechanical characterization of SCC (depending on the type of superplasticizer)

SCC	Rheological characteristics					Compressive strength (MPa)		
	Slump flow (mm)	T500 (s)	L-box H2/H1	Sieve stability (%)	V-Funnel Tv(s)	1 day	7 days	28 days
SCC6	740	2	0.68	1.66	14	20.2	30.0	46.7
SCC7	700	2	0.85	7.77	11	20.4	29.66	40.8
SCC8	700	2.5	0.89	12.29	11	19.93	26.26	34.9

Fig. 9. Flow profile: a) SCC6 - KRONO 20. b) SCC7-TEMPO 9. c) SCC8-TEMPO 16.

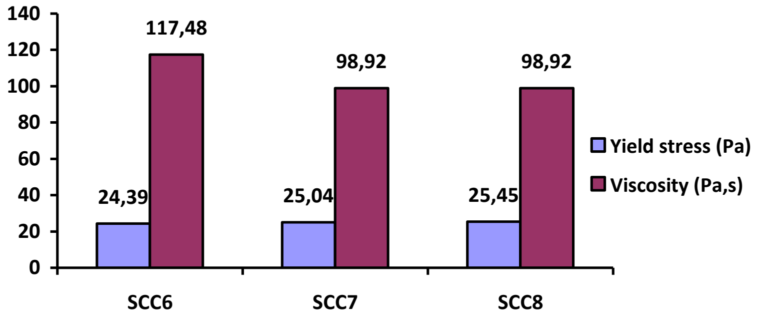

Fig. 10. Yield stress and plastic viscosity

All concretes have a length equal to Lmax. But in a practical way, the rheological characteristics above (Fig. 10) show that SCC manufactured with TEMPO9 and TEMPO16 have a viscosity value inferior to 100 Pa.s, in addition, the visualization of profiles (Fig. 9) shows that the gradient of fill in the case of KRONO20 is the same as the one presented by the other concretes with however a larger flow time in the V-Funnel. Table10 shows that the slump flow test does not give a clear idea of the viscosity of the mixture because if the slump flow increases it means that the concrete becomes more fluid with a lower viscosity but this is not the case in Figure 10. For example, SCC6 has a slump flow of about 740 mm and a viscosity exceeding 100 Pa.s while SSC7 has a slump flow of 700 mm and its viscosity does not exceed 100 Pa.s. Therefore, to confirm the rheological behavior of a mixture it is advisable to use our test: the flow of concrete in a V-Funnel and in a horizontal Plexiglas channel. The superplasticizers thus allow very fluid concrete to be obtained by reducing the friction between the cement grains and releasing a certain amount of water. Their use is not sufficient in the case of SCC. The interactions between the larger grains must also be reduced. To increase the amount of paste, you can then consider increasing the amount of cement. However this would lead to a significant increase in the cost of the material but also to problems of shrinkage due to the rise in temperature during the hydration of cement. It is therefore necessary to replace a portion of the cement with mineral additions.

D. Substitutes for Cement: Effect of Limestone Filler

The replacement of a portion of the cement by limestone fillers has a strong influence on the yield stress and the viscosity of the cement pastes. Their use can improve the fluidity, because their shape / size reduces the friction between the cement grains. The passage of 35 to 45% of limestone filler relative to cement mass improves in a clear manner the flow in the horizontal channel (fig. 11).

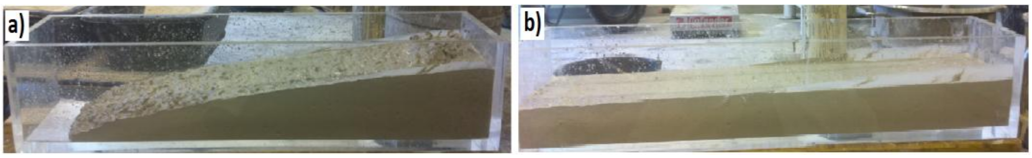

Fig. 11. Flow profile: a) SCC6-35% of limestone filler. b) SCC6- 45% of limestone filler.

E. Substitutes for Cement: Effect of Silica Fume

The replacement of a portion of the cement by Silica fume can generally increase the yield stress and the viscosity of the concrete by increasing the compactness of the mixtures [23].

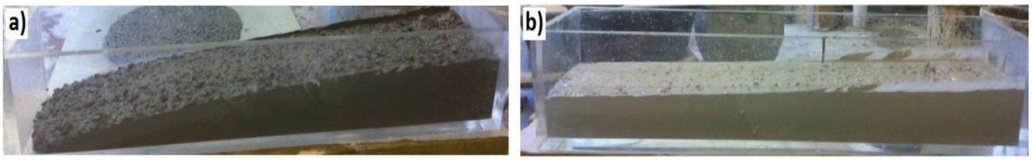

Fig. 12. Flow profile: a) SCC7- Silica fume. b) SCC7

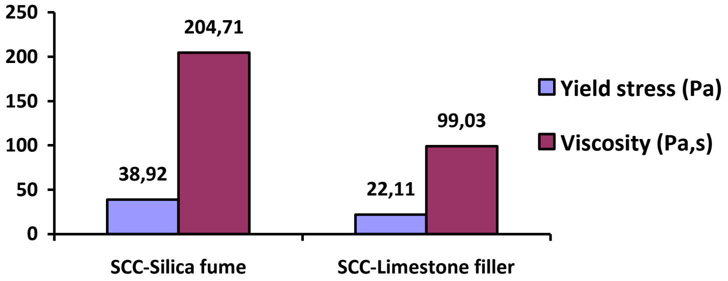

Fig. 13. Yiled stress and plastic viscosity

Compared to the rheology of SCC - Limestone filler, our results show that the use of Silica fume increases the demand for water and for superplasticizer. This result is well-known, but the use of our test (the practical visualization of flow in the horizontal Plexiglas channel) gives us a rapid idea of this property without performing the other empirical tests. The SCC manufactured with Silica fume has a large yield stress (See Fig. 12 and 13) and a viscosity exceeding 200 Pa.s.

IV. CONCLUSION

The composition of the mixture, W / C ratio, the type of cement and superplasticizer affect the rheological behavior of concrete. By isolating each of these factors, it is possible to distinguish general trends to know how they will affect yield stress or plastic viscosity. However, these factors are not independent of each other and the prediction of yield stress and / or viscosity becomes relatively complicated when all factors are considered. In comparison with ordinary concrete, SCC must have a low flow for that flow to begin quickly and its viscosity should be moderate to limit flow time. This is why it is necessary: (1) of replace a portion of the cement with mineral additives (limestone filler) that cause a decrease in the yield stress, (2) to use a superplasticizer to increase the fluidity of SCC significantly. This paper presents classic results, approved by several authors, but our method allows us to determine the role of each component of concrete on its rheology by visualizing the flow profile in the horizontal plexiglas channel with the ability to theoretically calculate yield stress and by determining the time of flow in the V-Funnel (viscosity indicator). The works collected in this document respond to a set of questions: how can the rheological performance of concrete and its compatibility with the new superplasticizers be assessed in a simple manner? How can the use of mineral additives with a low W/C ratio be optimized in concrete? How can the workability of a concrete with a fluid character be assessed in a laboratory or in the field by using a different method than the slump flow test?

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