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RHEOLOGY OF SELF-COMPACTING CONCRETE USED FOR SUPERTALL BUILDINGS

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Nowadays, self-compacting concrete (SCC) is widely being used for supertall building construction in Vietnam. With high workability, SCC allows us to speed up pumping, placing, and surface finishing, which results in a reduction in building cost. Popular methods such as slump flow, T_{500}, and V funnel test are used to indirectly determine rheological properties of SCC. However, these methods do not present yield stress and plastic viscosity, which are the most parameters affecting the pumping property. In this paper, the SCC rheology is determined directly through yield stress and plastic viscosity with the flow curve test and stress growth test by using the rheometer equipment. Thereby, limitation of the yield stress and the plastic viscosity is recommended for vertically pumping to supertall building project without segregation and bleeding.

Keywords: Yield stress, Plastic viscosity, Workability, Pumping, Rheology.

1 INTRODUCTION

In 2018, Vietnam topped the "The Landmark 81" building with a height of 461.2m, which is the tallest building in Vietnam and the seventh highest in Southeast Asia. This shows that the demand for concrete pumped for high buildings in Vietnam is huge. There have been many types of research on concrete mixes for tall buildings as well as the relation between rheological parameters and the pumping process. Few studies have addressed the problem of pumping for buildings over 300m high. In technical terms, self-compacting concrete (SCC) is suitable for the requirements for concrete pumped for high-rise buildings because minimum size of coarse aggregate is under 12.5mm helping to reduce the pressure when pumping SCC mixture up (Riding *et al.* 2016). In addition, due to the continuous grading of the SCC mixture, the molecular bonding force is large, therefore, under high pumping pressure, the SCC mixture is highly stable compared to the normal concrete mix with the same flow rate (Wallevik 2003). The ACI 237R (2007), the EN 12350 (2010) and the European Guidelines for SCC (2005) have specifications of the test procedure, classification, and evaluation of SCC mixtures. Besides, the rheological property of the SCC mixture is a useful tool for assessing, designing and managing SCCs through static yield stress, dynamic yield stress, and plastic viscosity. Rheological property can be optimized to ensure the workability of the SCC (Koehler and Fowler 2007). The rheological parameters of the SCC mixture, including yield stress and viscosity, can be determined indirectly through field experiments such as slump flow, T_{500} (s) and T_v (s) as shown on Table 1.

Table 1. Methods of indirect evaluation of rheological parameters of the SCC mixture.

Method	Measurement value	Rheological parameters
Slump flow	Measure the slump diameter	Yield stress
T500	Measure the time for the flow to reach the 500mm diameter	Viscosity
V funnel	Time of V-shaped funnel flow	Viscosity

The concrete ingredients affect the rheological parameters of the concrete mix. Specifically, the higher the water content in the mix, the lower the stress yield and viscosity of the concrete mixture. The superplasticizer increases leading to the decrease of yield stress but the viscosity of the concrete mix changed insignificantly (Wallevik 2003).

Rheometer used to measure the rheological property of SCC is useful, thus adjusting the water, air, silica fume content and different dispersants for each SCC. Becomes easier based on the yield stress value and plastic viscosity, the rheological graph divides the areas for use by SCC (Wallevik and Wallevik 2011). Furthermore, the author also gives the lowest slump flow value which concrete mixture can be considered as SCC on Figure 1, for each slump flow range there will be a viscosity range and yield stress range simultaneously. If the viscosity is less than 40 Pa.s, the SCC will have significant yield stress depending on its viscosity. On the other hand, if the SCC is too viscous with plastic viscosity greater than 70 Pa.s, the yield stress is close to zero. The authors also recommended that concrete mixtures with yield stress greater than 40 Pa and viscosity less than 50 Pa.s are completely pumpable, with the corresponding rheometer.

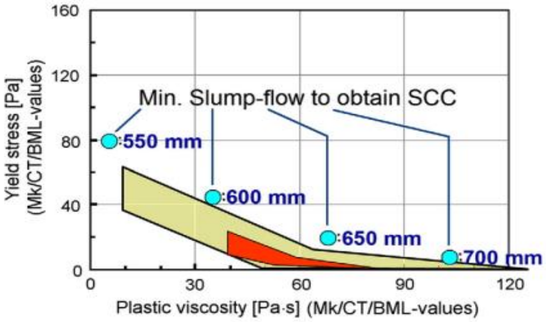


Figure 1. Proposed rheography for SCC (Wallevik 2002).

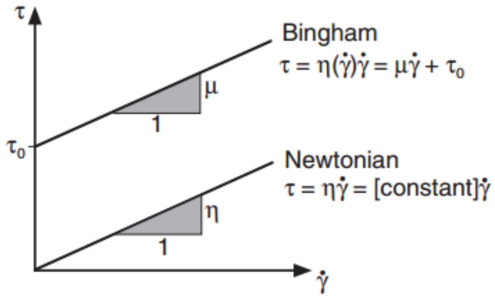


Figure 2. Flow curve for Newtonian and Bingham fluids.

There are many rheological models, but the Bingham model in Figure 2 is the best fit (Riding *et al.* 2016 and Schmidt 2014). Concrete mixtures always have initial tremendous yield stress due to the flocculation of the cement particles. It is necessary to provide the concrete mixture initial shear stress greater than the yield stress to break the flocculation structure so that produce the initial flow in the concrete mix (Ferraris 1999). Therefore, the Newton model is not suitable for describing the rheological behavior of the concrete mix. Bingham suggested the model in Eq. (1) as follows:

$$\tau = \tau_0 + \mu \times \gamma \tag{1}$$

where :

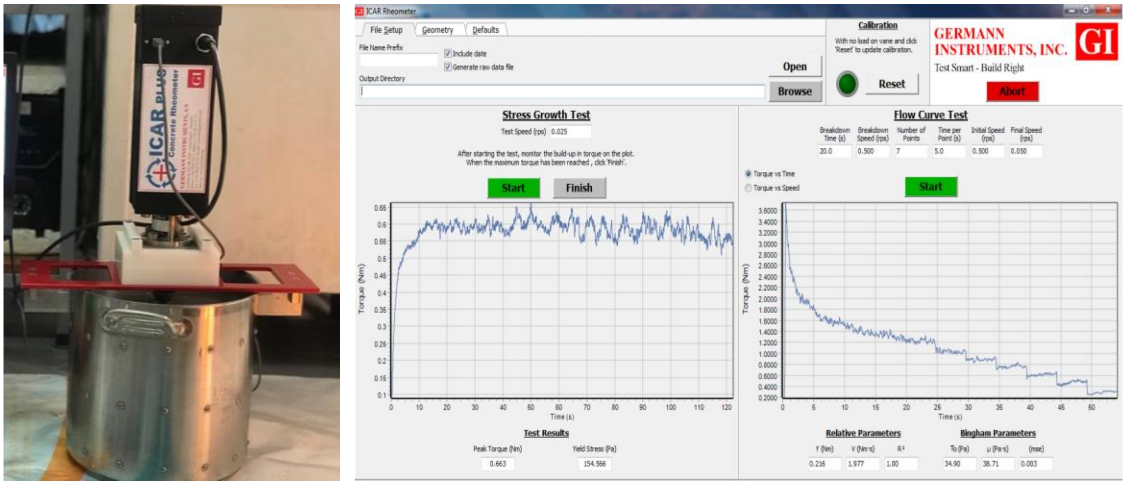
τ *= shear stress (Pa);* τ_0 *= yield stress (Pa);* μ *= plastic viscosity (Pa.s);* $\dot{\gamma}$ *= shear rate (1/s)*

In this study, the SCC mixture design with a grade of 60MPa, water to binder ratio (W/B) from 0.34 to 0.37, fly ash varying from 15 to 25% and silica fume from 4 to 8%, is investigated in terms of slump flow, yield stress and viscosity.

2 EXPERIMENTAL PROGRAM

Concrete mixture design with a grade of 60MPa which has total cementitious content of 540kg, including cement, fly ash and silica fume. The coarse aggregate with a maximum size of 12.5 mm is used. Sand is mixed between crushed sand and river sand where river sand occupies 65% by volume. The concrete mixing proportions are shown in Table 2.

The workability of the SCC mixture was measured by slump flow, T_{500} and V funnel flow T_v tests at the mixing time and at every 30 minutes after mixing until the SCC lost the ability to maintain the flow. At these times, the yield stress and viscosity were determined by the flow curve test with four-bladed propeller ICAR (Koehler and Fowler 2005). The results of SCC rheology properties is in terms of slump flow, V flow, yield stress, and viscosity as shown in Table 3, and the Rheometer ICAR is shown in Figure 3.



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Output Directory

With no load on vane and click 'Reset' to update calibration.

Stress Growth Test

Test Speed (rps) 0.025

After starting the test, monitor the build-up in torque on the plot. When the maximum torque has been reached , click 'Finish'.

Flow Curve Test

Breakdown Time (s)	Breakdown Speed (rps)	Number of Points	Time per Point (s)	Initial Speed (rps)	Final Speed (rps)
20.0	0.500	7	5.0	0.500	0.050

● Torque vs Time

○ Torque vs Speed

Test Results

Peak Torque (Nm)	Yield Stress (Pa)
0.663	154.566

Relative Parameters

Y (Nm)	V (Nm·s)	R²
0.216	1.977	1.00

Bingham Parameters

To (Pa)	μ (Pa·s)	(mse)
34.90	38.71	0.003

Figure 3. Rheometer ICAR.

Table 2. SCC mix proportions.

Sample	Cement (kg/m^3)	Water (kg/m^3)	Fly ash (kg/m^3)	Silicafume (kg/m^3)	Admixture (l/m^3)	W/B
SCC1	389	195	108	43.2	8.370	0.36
SCC2	400	188	108	32.4	8.370	0.35
SCC3	410	188	108	21.6	7.830	0.35
SCC4	373	186	135	32.4	8.370	0.34
SCC5	362	196	135	43.2	7.830	0.36
SCC6	383	190	135	21.6	7.830	0.35
SCC7	416	198	81	43.2	7.830	0.37
SCC8	427	198	81	32.4	7.830	0.37
SCC9	437	194	81	21.6	7.830	0.36

Table 3. Results of the rheology of SCC.

Sample	Slump flow (mm)	T_{500} (s)	T_v (s)	τ_0 (Pa)	η (Pa.s)
SCC1	760	2.4	4.5	15.21	31.12
SCC2	780	2.2	4.67	17.13	31.39
SCC3	730	1.86	4.7	31.37	32.59
SCC4	740	2.4	5.1	26.9	32.7
SCC5	780	1.88	5.47	18.89	29.1
SCC6	770	2.19	4.72	16.88	33.2
SCC7	750	1.57	3.72	32.07	30.46
SCC8	720	2.51	4.82	27.78	32.59
SCC9	720	2.56	4.78	30.2	35.3

3 TEST RESULTS AND DISCUSSIONS

The relation between the yield stress and slump flow on Figure 4 is inversely proportional, i.e., the yield stress decreases as slump flow increases and vice versa. This relation is appropriate as the SCC mixture has a higher slump flow value, the higher the flowability so that the shear stress value provided to the concrete mixture to produce the initial flow is smaller (yield stress is small). This is perfectly beneficial as the concrete mixture is easily pumped up under low pressure. However, the greater the slump flow, the less segregation resistance of the concrete mixture, so that the optimal slump flow of the SCC mixture pumped up for actual structures is recommended within the range from 650 to 780 mm. As the yield stress increases, the SCC mix hardly moves in the pipeline because of the tremendous friction between the SCC mixture and the pipeline wall. This causes great pumping pressure to compensate for the loss in the pipe. Inadequate pumping up pressure can lead to blockage in the pipeline.

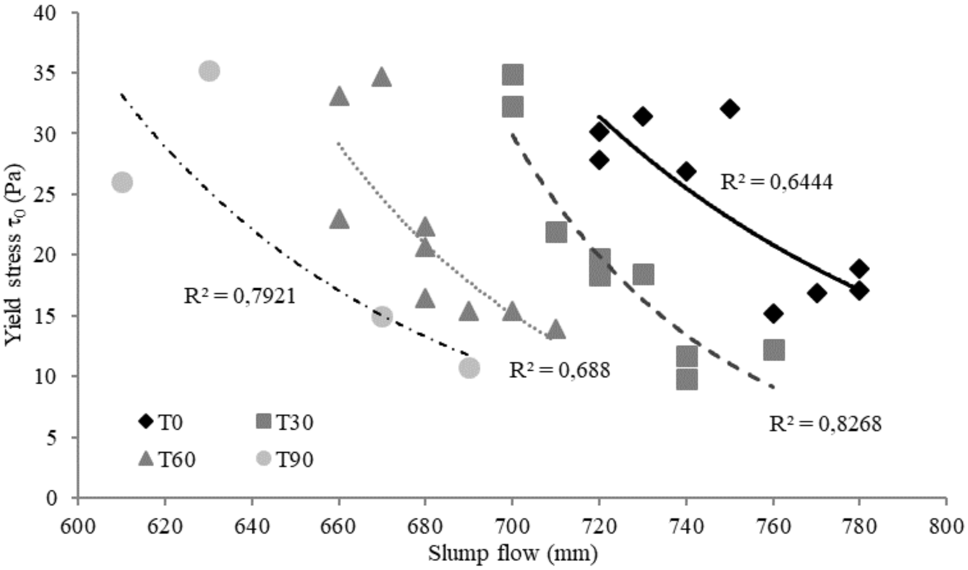

Figure 4. The relation between yield stress τ_0 (Pa) and slump flow (SF) (mm).

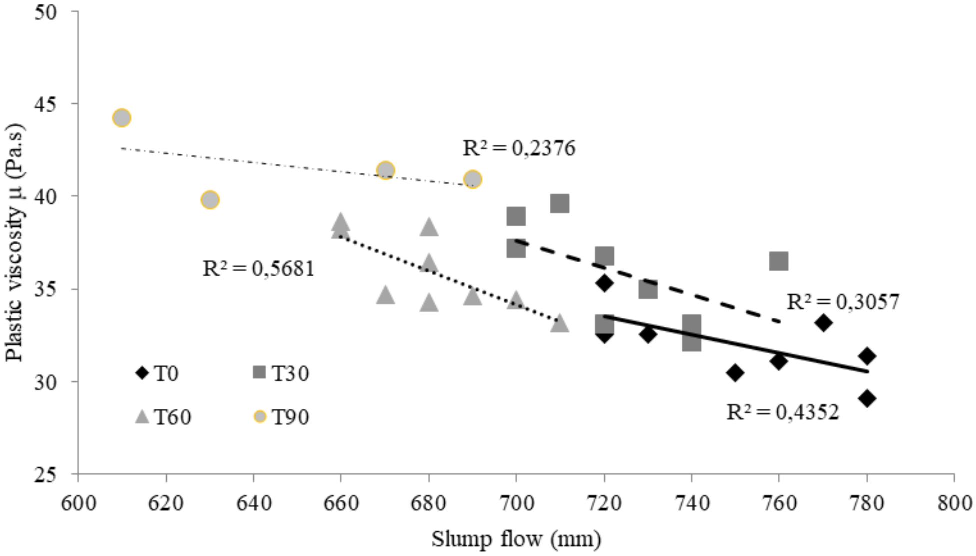

Figure 5. The relation between viscosity η (Pa.s) and slump flow (mm).

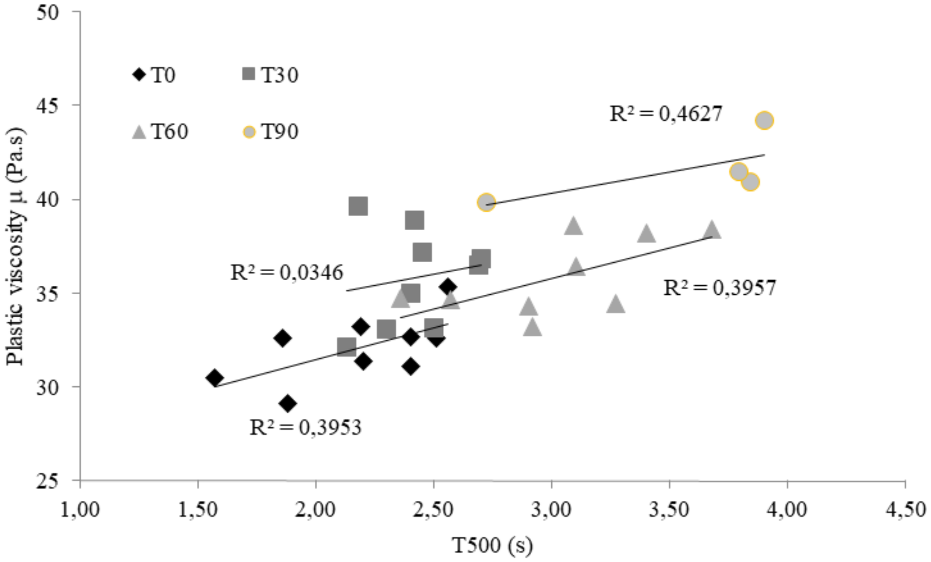

Figure 6. The relation between viscosity η (Pa.s) and T_{500} (s).

The viscosity characterizes the resistance of material flow so that when the SCC has a high viscosity value corresponding to the small SF value on Figure 5. The viscosity depends on the internal friction and molecular force between the particles. As viscosity is greater, the concrete mixture becomes more stable (hard to be segregation, bleeding during the pumping up process). However, too high viscosity will cause the concrete mixture to move hardly in the pipe due to the large friction between the concrete mixture and the pipe, which means that a huge pumping pressure is required.

As stated in Figure 6, the high T_{500} value reducing flowability of concrete mixtures is one of the causes of blockage in the pipeline. This does not mean that low viscosity will benefit the pumping process. With low viscosity, the concrete mixture is susceptible to segregation and bleeding. Therefore, a suitable range of viscosity values at which the SCC mixture can be pumped should be selected.

Workability is also demonstrated by the ability to maintain the SCC, most of the grades are maintained up to 90 minutes, corresponding to the time from mixing to pumping up. The relations between the experimental parameters at the survey times have the same trend, which illustrates the stability, homogeneity of SCC.

4 CONCLUSIONS

The rheological property of the SCC mixture is determined directly through yield stress and plastic viscosity. From the results, conclusions are drawn as follows:

- The relationship between the yield stress and the slump flow is non-linear. The lower the yield stress as the slump flow increases and vice versa.
- The relationship between the viscosity and the slump flow is linear as well. The SCC has a high viscosity value corresponding to the low slump flow value.
- The SCC mixture with W/B from 0.34 to 0.37, fly ash content from 15 to 25% and silica fume content from 4 to 8% has the rheological parameters such as yield stress τ_0 ranging from 20 Pa to 40 Pa and viscosity η ranging from 25 Pa.s to 40 Pa.s respectively. These values are suitable to the SCC to avoid segregation and ensure the stability together with the homogeneity when directly pumped up to the supertall buildings in the vertical direction.

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