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NON-REVERSIBLE TIME-DEPENDENT RHEOLOGICAL PROPERTIES OF FRESH SCC

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Abstract

The study of the rheological properties of fresh Self Compacting Concrete is a very complex matter, also due to time-dependent properties. In order to apply a model, like the Bingham model, in a steady state condition all time dependent effects, both reversible and non-reversible, must be eliminated. In this way, most concrete samples are tested by decreasing the shear rate stepwise, in order to eliminate thixotropy as much as possible. But concrete in general has a loss of workability in time, which is affecting the rheological properties also. Samples tested at a different ages will not show equal rheological properties.

In this paper, the evolution of the yield stress, the plastic viscosity at a certain shear rate and the shear thickening behaviour are evaluated in a time window of 2 hours, based on the modified Bingham model. Each parameter shows a typical mathematical relationship with time, but the magnitude of the loss is dependent on the composition of the concrete and the temperature. Comparison of the evolution of slump flow and yield stress in function of time shows that there is no general correlation between these parameters.

1. INTRODUCTION

From a rheological point of view, concrete in general is a very complex material. Several attempts have been made to estimate the viscosity of the material based on corrections for the grain size distribution of sand and coarse aggregates [1]. Several rheometers have been developed in order to be able to measure the rheological properties of cement-paste, mortar and concrete [2]. As a result, differences in the obtained data occur due to differences in equipment [3] or in the applied models. On the other hand, a general model has been proposed to describe the rheological properties of concrete, namely: the Bingham model [4][5].

By the application of plasticizers, superplasticizers, retarders, viscosity modifying agents,... the rheological behaviour has become even more complex, also in case of SCC [6][7][8].

As physical and chemical processes occur in the time window during which the concrete can be processed, the parameters defined by the Bingham model are varying. This variation can be divided into two parts: a reversible part: thixotropy, which can be eliminated by keeping the concrete at a constant shear rate; and the non-reversible part: the workability loss [2][9]. In this paper, the influence of the non-reversible time-dependent effects, being the workability loss, on yield stress (YS), viscosity, slump flow (SF) and V-funnel (VF) are described.

2. MATERIALS AND METHODS

2.1 SCC mixes

Several SCC mixes have been produced, containing different amounts of cement, filler, water and superplasticizer. The two types of SP used are both polycarboxyl ethers, with a large difference in workability retention. SP 1 is very efficient but has a short workability retention, SP 2 is less efficient (as a result, more SP had to be added to obtain SCC), but it has a longer workability retention. For each SCC mix, the slump flow, V-funnel flow time and L-box-ratio have been determined at 15 and 30 minutes after water addition [10]. If the workability was still sufficient, more tests were carried out at 60, 90, 120 and 150 minutes after water addition.

For the analyses, only one type of cement (OPC) and one type of limestone filler have been taken into account. Other types of cement and filler have also been tested, but not enough data have been obtained yet to perform a fundamental analysis. In table 1, the composition of the reference mix is shown.

Table 1: Composition of the reference mix.

Gravel 8/16 (kg/m³)	434
Gravel 2/8 (kg/m³)	263
Sand 0/4 (kg/m³)	853
CEM I 52.5 N (kg/m³)	360
Limestone filler (kg/m³)	240
Water (l/m³)	165

2.2 Rheometer

The rheological properties have been determined by tests with the Tattersall Mk-II rheometer [4][8], each time the workability has been tested by slump flow, V-funnel and L-box. Several results indicate that the Bingham model is not valid, due to the generation of a negative yield stress. As a result, for all tests performed, the modified Bingham model (eq.1) has been applied to determine yield stress, viscosity and shear-thickening [8][11].

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} + c \cdot \dot{\gamma}^2 \qquad (1)$$

The viscosity has been chosen as the inclination of the curve at a shear rate of 5 seconds, resulting in a value equal to $\mu + 10c$. Shear thickening is described by the ratio of c to μ.

The other time-dependent effect, thixotropy, has been eliminated from the results by stepwise decreasing the rotational velocity, in order to obtain steady state for each measuring point.

3. MATHEMATICAL DESCRIPTION

All parameters (SF, VF, yield stress, viscosity and shear thickening) at any time are divided by the corresponding value at 15 minutes, in order to avoid the influence of the magnitude of the parameter and to obtain a single-parameter relation with time. As a result, each parameter has a relative value of 1 at 15 min age (= t_0). In fig. 1, the evolution of relative SF, VF, yield stress and viscosity can be seen for the reference mix with SP 1 and SP 2. Shear thickening (c/μ) remains approximately constant in time, and as a result, the evolution of the viscosity is not influenced by shear thickening.

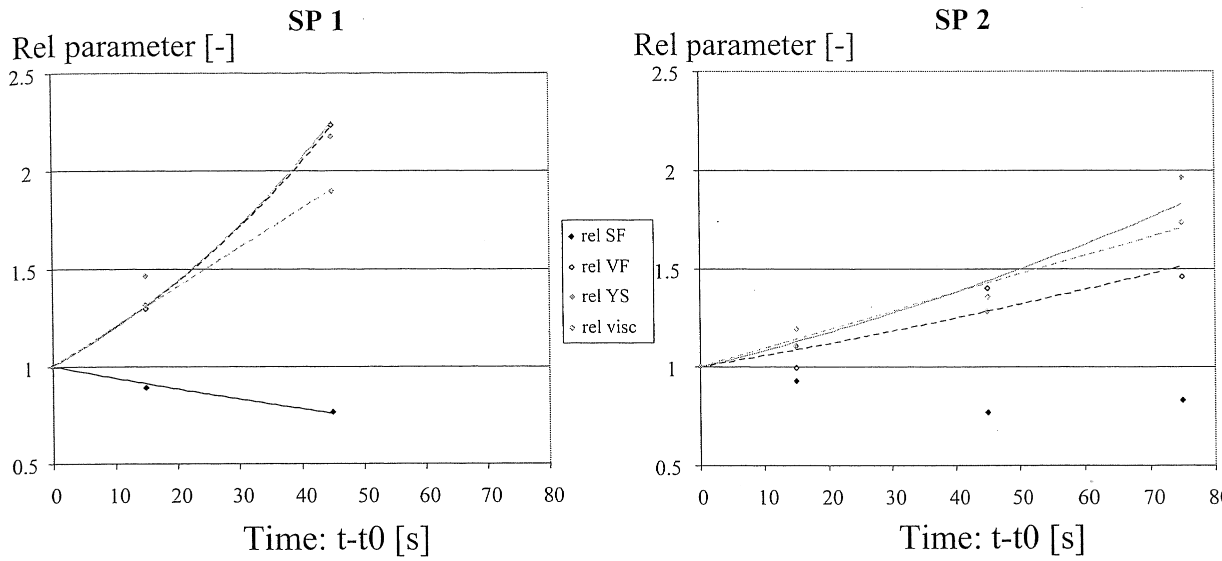

Fig. 1: Evolution of relative SF, VF, yield stress and viscosity in time for the reference mix with SP 1 (left) and SP 2 (right).

Analysis of all available data leads to the following general trends in function of time:

$$\frac{SF_t}{SF_{t0}} = \exp\left(-A_{SF} \cdot (t - t_0)\right) \quad (2)$$

$$\frac{VF_t}{VF_{t0}} = \exp\left(A_{VF} \cdot (t - t_0)\right) \quad (3)$$

$$\frac{YS_t}{YS_{t0}} = \exp\left(A_{YS} \cdot (t - t_0)\right) \quad (4)$$

$$\frac{visc_t}{visc_{t0}} = 1 + A_{visc} \cdot (t - t_0) \quad (5)$$

The results with SP 1 and SP 2 clearly indicate the difference in workability retention. The parameters A in eq. 2 to 5 are larger for SP 1 compared to SP 2, which is also visible in fig. 1. The authors would like to remark that eq. 2 is not valid for the evaluation of the slump flow for SP 2. In this case, the slump flow does not obey a clear mathematical law. The best approximation can be done by a linear relationship, but with very low correlation compared to the other mathematical laws. In some cases, the slump flow is even increasing in time.

From the above mathematical laws, no general correlation can be obtained between slump flow and yield stress, due to their different behaviour in time.

4 INFLUENCING PARAMETERS

4.1 Determination of influencing parameters

For 18 mixes with SP 1 and 9 mixes with SP 2, the influence of the concrete composition and temperature on the time dependent behaviour of SF, VF, yield stress and viscosity have been investigated. Due to the differences in workability retention, the analyses for SP 1 and SP 2 have been done separately. Only the test results which correlated to the above mentioned laws with a R^2 value > 0.8 and test results which contained more than two data points were retained for the analysis, except for the analysis of the slump loss (decrease of slump flow) for SP 2. In this case, data with a $R^2 > 0.5$, obtained for a linear law, have been taken into account.

In order to investigate the effect of a single parameter, the A-values have been corrected for the influence of the other parameters in an iterative process. In theory, all corrected A-values should show a high correlation ($R^2 \approx 1$) with the considered parameter. In practice, this is not the fact, and as a result, other parameters which have not been analysed (small deviations in grain size distribution, extra additions of SP during mixing,...) will also have an influence on the time dependent behaviour.

Once all influencing parameters are known, the sensitivity of the A-value to a certain parameter has been investigated. The correction for A has been determined for each parameter separately. The larger the correction, the larger is the sensitivity of the time dependent behaviour to the corresponding parameter.

4.2 Influence and sensitivity of different parameters

The influence of several parameters causing an increase in A-values, for both SP separately, is displayed in table 2.

Table 2: Influence of amount of cement (C), amount of powder (P = cement + filler), C/P-ratio, W/C-ratio, the amount of SP, SP/C-ratio and the temperature (T) on the A-values for slump flow, V-Funnel, yield stress and viscosity, for both SP separately.

	SP 1				SP 2			
	A_{SF}	A_{VF}	A_{YS}	A_{visc}	A_{SF}	A_{VF}	A_{YS}	A_{visc}
C						+		
P			+++				+	
C/P		- - -		++				
W/C	+++	- - -	++	+++	+		- -	- - -
SP	++							
SP/C	- -	+	+	+	- - -	- - -	- - -	- - -
T	++		++	++	+	- -		- -

A "+"-sign indicates that an increase of this parameter causes an increase in the corresponding A-value, a "-"-sign indicates the opposite effect. The more "+" or "-"-signs are displayed, the larger is the sensitivity of the corresponding A-value to the specific parameter.

4.3 Discussion

In table 2, a large difference can be seen between the two types of SP. For SP 1, an increase in W/C and/or temperature causes a large increase in slump loss and, the rate of increase of the yield stress and viscosity, while for SP 2, these factors mostly have the opposite effect. The SP/C-ratio is dominant for SP 2, which is in contradiction to the results for SP 1. In this case, the SP/C-ratio has a less dominant effect and it is working in the opposite sense. Further research on the nature and working principles of these SP is needed.

Apart from the differences between the SP; slump flow, V-Funnel and the rheological parameters are influenced by other parameters or in another way. On the other hand, the rheological parameters themselves, namely yield stress and viscosity, appear to be influenced mainly in the same way by the same parameters, for both SP. In fig. 2, the corrected A_{YS} and A_{visc} are compared with each other, and for both SP, the correlation is rather strong. As a result, if a high workability loss occurs, both yield stress and viscosity will increase rapidly.

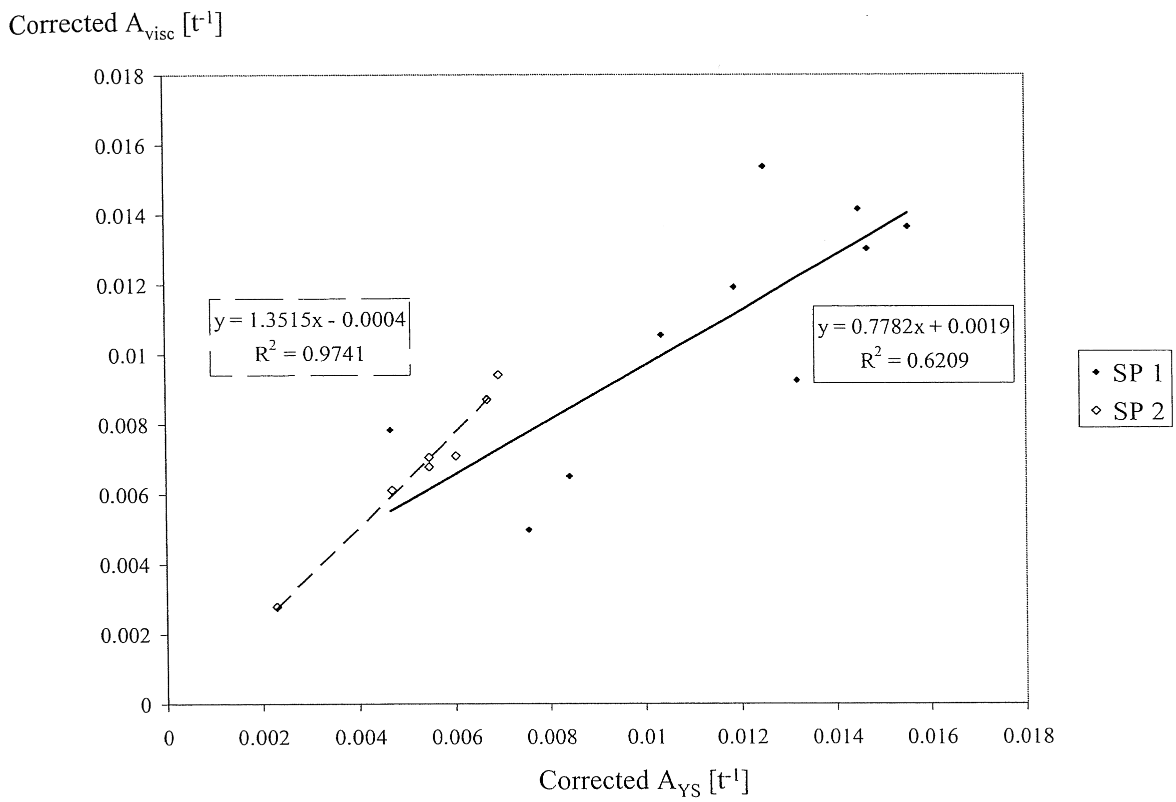

Fig. 2: Relation between the rate of yield stress increase (A_{YS}) and the rate of viscosity increase (A_{visc}), for SP 1 (full dots and full line) and SP 2 (hollow dots and dashed line).

The difference in workability retention between the two SP is also expressed in fig. 2 by the lower values for A_{YS} and A_{visc} for SP 2 (dashed), compared to the values of SP 1 (full).

5. CONCLUSIONS

The rheological parameters of SCC (yield stress, viscosity and eventually shear thickening) are varying in time due to thixotropy and loss of workability. The results in this paper describe the non-reversible time dependent behaviour (loss of workability) after elimination of thixotropy.

- In time, the relative slump flow is decreasing exponentially; the relative V-Funnel flow time and relative yield stress are increasing exponentially and the relative viscosity is increasing linearly. Shear thickening remains constant.
- The difference in workability retention between the two SP used has been observed in time. For SP 2 (longest workability retention), the decreasing exponential law to describe the relative SF is not valid.
- Due to the differences in time dependent behaviour, there is no general relation between yield stress and slump flow.
- Analysis of the coefficients in the exponential and linear laws (A-values) illustrates the importance of the composition of the SCC and the temperature.
- Large differences in influencing parameters have been observed between the two SP.
- Yield stress and viscosity increase are, for each type of SP separately, generally influenced by the same parameters. A larger loss in workability will lead to a large rate of increase for yield stress and for viscosity.

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