FULL SCALE PUMPING TESTS ON SCC: APPLICATION OF THE MODIFIED HATTORI-IZUMI THEORY

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INTRODUCTION

Studying the flow of fresh concrete is influenced by time dependency of the rheological properties of the concrete. This time dependency can be divided into two parts: the non-reversible part, being loss of workability and the reversible part, called thixotropy (1). Loss of workability can be neglected in some cases, when comparing with the effects of thixotropy, but it is advised to keep track of it, especially in case of SCC for precast industry.
Several attempts have been made to characterize the thixotropic properties of concrete, but no general test procedure is known at this moment to universally describe thixotropy. In most cases, the study of the thixotropic properties is restricted to the area of interest of the authors, mostly the variation of static yield stress (2)(3)(4). Only one theory takes into account the influence of thixotropy on both viscosity and yield stress: the Hattori-Izumi theory, modified by J.E. Wallevik (1). This theory will be used to provide a qualitative description of the observed phenomena occurring during pumping of SCC, but due to the large complexity of both the theory and the practical application, a quantitative approach is beyond the scope of this study.

THIXOTROPY

Definition

Throughout history, the definitions of thixotropy are numerous, but one particular definition is able to clearly describe the effect of thixotropy in concrete: “thixotropy is an reversible increase of viscosity in a state of rest, and a reversible decrease of viscosity when submitted to a constant shearing stress.” (5) Of course, the meaning of the word ‘viscosity’ in this definition is the apparent viscosity, being the shear stress divided by the shear rate.

Description

From this definition, one can clearly imagine what must be happening (from a macroscopic point of view) when a material is subjected to an instantaneous variation in shear rate (Fig. 1). When increasing the shear rate, the shear stress shows an overshoot, and ends up at the equilibrium value after a certain amount of time, provided that the material started at the equilibrium value of the shear stress at the first (lower) shear rate. In the opposite case, being a sudden decrease in shear rate, a shear stress value lower than the equilibrium value is obtained, until the equilibrium is reached again. The first effect, being the decrease in shear stress, is known as breakdown (2)(5). The second effect is known as build-up. Generally, build-up occurs slower than breakdown.

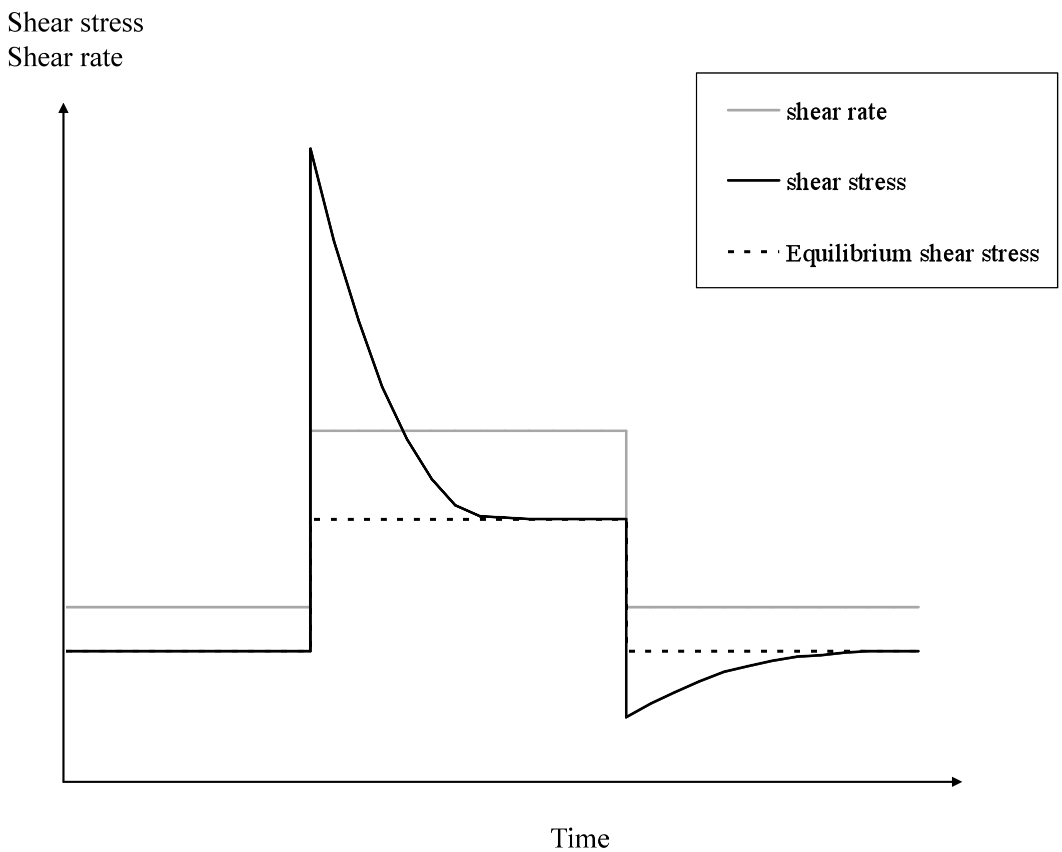

Figure 1: Evolution of shear stress when a sudden increase or decrease of shear rate occurs. The dashed line represents the response of a non-thixotropic material.

The modified Hattori-Izumi theory

The Hattori-Izumi theory provides a description of thixotropy through a microscopic point of view. This theory evaluates the number of reversible connections between cement particles, when submitted to a certain shear rate, or in resting conditions. Increasing the number of connections, which is physically increasing the coagulation state, reduces the mobility of the particles and hence increases resistance to flow (eq. 1) (1).

$$\frac{J_t}{n_3} = U_3 = \frac{U_0 \cdot (\dot{\gamma} \cdot H \cdot t^2) + H \cdot t}{(H \cdot t + 1) \cdot (\dot{\gamma} \cdot t + 1)} \qquad (1)$$

Where:

J_t = number of reversible connections
n_3 = number of particles between which connections can occur
U_3 = relative number of reversible connections, varying between 0 and 1.
U_0 = original relative number of reversible connections
H = coagulation rate function

The modifications presented by J.E. Wallevik mainly incorporate a yield stress and provides the material with two fading memory functions. By the incorporation of the yield stress, both variations of yield stress and plastic viscosity can be described (assuming that the Bingham-model is valid) and the fading memory functions create the ability of the material to recall its past actions (substitution of H and $d\gamma/dt$ by the integrals Θ and Γ respectively). This modified theory has been tested by means of simulations on the outcome of rheometer tests (1). As a large disadvantage of this theory, one can mention the difficulty to obtain the values of all parameters (1).

QUALITATIVE APPLICATION ON THE RESULTS OF THE PUMPING TESTS

Regular pumping tests.

The description of the setup of the pumping tests, together with the testing procedure can be found in (6). The results indicate that the pressure losses are decreasing during the first three/four pumping cycles applied. At this stage, a kind of equilibrium has been reached and finally, pressure losses increase again (Fig. 2).

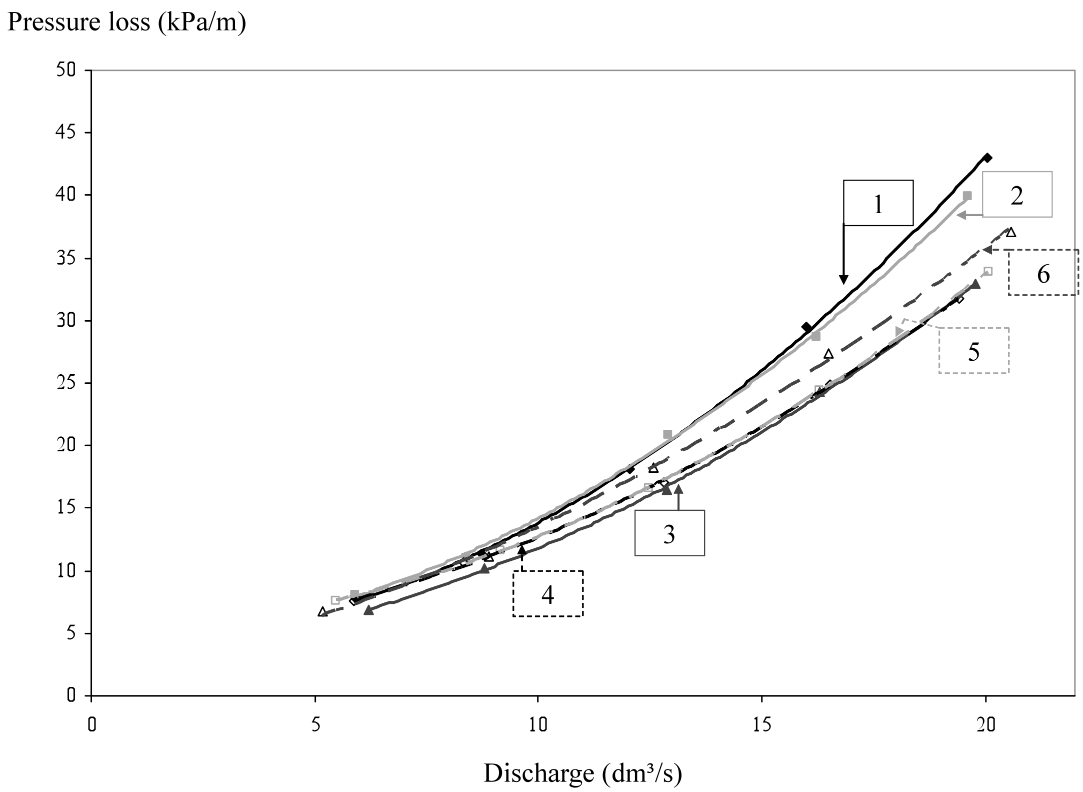

Figure 2: The pressure losses are decreasing during the first three cycles (1-3), remaining constant during cycles 3 to 5 and finally, they are increasing again during cycle 6.

This last effect, the increase in pressure loss when going from cycle 5 to 6 is contributed to the loss of workability, due to a concrete age of 3.5 hours. The decrease of pressure losses during the first three cycles is contradictory to the loss of workability. This effect may be caused by two phenomena, most probably acting together: an increase in air content (7) during pumping and thixotropy. The increase in air content is still under investigation, but thixotropy on its own can already describe these phenomena.
The concrete itself needed at least 30 minutes of transport between the production plant and the laboratory. During this transport, it is subjected to very low shear rates and it has time to build up the connections. The emptying of the truck into the reservoir of the pump does not cause a sufficient breakdown (shear rate too low and time too short) and as a result, a coagulated concrete enters the pipes. As the same 1m³ of concrete is pumped continuously, it undergoes several times high shear rates and can undergo breakdown. Most probably, one pumping cycle is not sufficient to reach the equilibrium at the higher discharges, and in this way, this apparently strange result is obtained.

Special thixotropy test

A special thixotropy pumping test has been worked out in order to verify the above mentioned theory. The grey, dashed curve in figure 3 has been obtained by pumping the concrete at steps of increasing discharge (5 points) and each time waiting to obtain equilibrium. After the reaching of the equilibrium at discharge 5, a concrete sample has been taken and the downward (black-full) curve has been determined in the regular way (5 strokes per discharge).

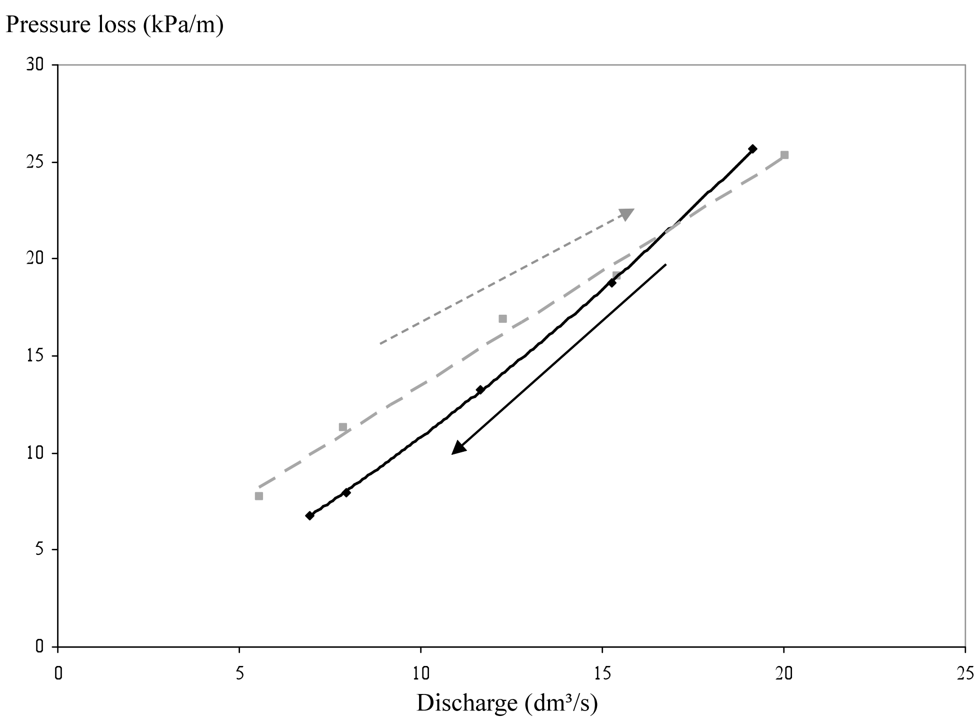

Figure 3: Thixotropy tests: the grey, dashed curve is obtained by stepwise increasing discharge and waiting for equilibrium. The black, full curve is obtained by the stepwise decreasing discharge, as performed in the regular pumping tests.

CONSEQUENCES

Segregation resistance

As SCC has a very sensitive equilibrium between yield stress and plastic viscosity in order to assure the stability, the influence of thixotropy during high speed pumping of SCC can break that equilibrium and can cause segregation to occur.

Non-linear dependency of pressure losses on the length of the pipes

One of the fundamental laws in hydraulics is that the pressure loss is linearly dependent on the length of the pipes, no matter the flow conditions, no matter the material. Thixotropy can cause an apparent non-linear dependency of the pressure losses on the length of the pipes, because during the first meters, a high amount of structure must be broken. This causes extra pressure losses, at a constant discharge, which decrease over the length of the pipe. If the pipe is long enough, all internal (reversible) structure is broken and the linear dependency is obtained again.

Influence of thixotropy on velocity profile

In pipes, the shear stress varies linearly between 0 in the centre and its maximal value at the pipe wall. Consequently, the shear rate varies according to the rheological law of the material. Suppose that the concrete flows in concentric layers in the pipes and that no interchange between the layers occurs, then the layers near the wall are subjected to a higher shear rate, compared to the layers near the centre. This means that along the pipe radius, the equilibrium thixotropic levels vary and that a very complicated velocity profile is obtained.

As a result, calculations and simulations of pumping of concrete are quite complicated and the determination of thixotropic properties out of pumping tests is almost impossible. On the other hand, any other device to determine the thixotropic properties of the pumped concrete must be powerful enough to provide sufficiently large shear rates and shear stresses.

Formwork pressure

Formwork pressures are reported to be non-hydrostatic due to the thixotropic build-up of the concrete when it is at rest at the bottom. Near hydrostatic pressures have been recorded when the casting rates were very high. Could high speed pumping have an influence on the maximal pressure measured at the bottom of the formwork, and can it have an influence on the time evolution of the formwork pressures?

CONCLUSIONS

From all thixotropic theories applied in concrete rheology, only the modified Hattori-Izumi theory takes into account the influence on both yield stress and plastic viscosity. On the other hand, it is very difficult to determine the parameters applied in the M.H.I.-theory.

Due to this complexity, a quantitative application of the M.H.I.-theory is quite difficult, but a qualitative application can explain some of the effects observed during full scale pumping tests.

A special pumping test clearly points out the influence of thixotropy on the obtained results so far.
Thixotropy will/can have an effect on the following items during high speed pumping:

- Stability/segregation
- Apparently non-linear pressure distribution with the length of the pipes, at least in the upstream part
- A very complicated velocity profile is created
- Does pumping affect formwork pressures?

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