Rheological properties of concrete: scale up from mortar paste to concrete mix with different PCI admixtures.

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ABSTRACT

For many years concrete properties have been investigated by means of practical tests.

In particular slump test was the only practical way to assess concrete workability. Providing however only a partial description of concrete flowability. This paper shows a rheological approach to better define concrete mix design. Rheology will offer the possibility to translate concrete characterization in two parameters: yield stress and plastic viscosity. The combination of the two main properties offers the possibility to fine tune mix design. Furthermore understanding and controlling them, is not only a way to design more economical and better performing mixes but also to conceive more complex concrete structures and improve concrete construction processes.

INTRODUCTION

Concrete materials can be divided in two classes, one called ready mix concrete (RMC) and the other precast concrete (PC). RMC is produced in the concrete factory and then transported fresh to the jobsite where it is cast. PC is produced by precasting in forms, where it is cured in a controlled environment. This factory-made piece is then transported to the construction site to become a part of a larger structure.

In order to obtain a good PC in terms of flowability, stability and robustness, all properties concurring in defining the concrete workability, an appropriate measurement by means of apt devices of its rheological properties is necessary.

This paper is particular focused on the study of the role of polyethercarboxylate–based superplasticizers (later called PCE) in precast concrete, that allow the manufacturing of concrete endowed with superior characteristics such as an excellent water reducing effect, accelerating the development of mechanical strength. This property can be achieved balancing electric repulsion provided by an negatively charged group and a steric effect given by non-ionic group. A proper balancing of these two effects allow to obtain admixtures capable to impart to concrete the ability of reducing water and to obtain concrete capable of developing high mechanical strength at early times without having to be subjected to particular curing conditions.

The results presented in this study were carried out by the experimental comparison between ConTec Viscometer5 and stress controlled rheometer (Anton Paar MC302).

MATERIAL

Cement and Aggregates

A blended cement was selected for testing. In according to EN 196 and EN 197 the characteristics are:

- CEM II/B-M 42,5R NORCEM
- Blaine = 450 m^2/kg
- C_3A = 5,3%
- Density = 3.00 g/cm^3

Granitic aggregates from Norway were used in this study, their granulometries is reported in Figure 1.

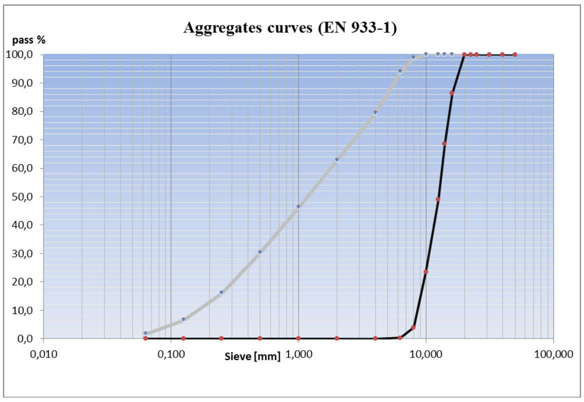

Figure 1. Aggregates curves

Chemical Admixtures

In order to understand how PCE admixtures with different properties might affect concrete rheological properties, three different types have been selected and tested. All admixtures are High Range Water Reduce (HRWR) according to EN 934-2 (see Table 1).

Table 1. Admixtures

Id.	Classification according to Table EN 934-2	Description
PCE I	3 + 7	HRWR with accelerating effect
PCE II	3	HRWR
PCE III	3 + 7	HRWR with accelerating effect

Concrete Specification

A concrete prescription representative one of the most typical mix of concrete of the market was used.

Below we summarized all prescriptions as defined by EN 206:

- Class of resistance C55
- Class of Exposure respected XC1
- Class of workability: S4/S5
- Maximum diameter of aggregate: 16
- Dosage of cement: 400 Kg/mc
- Maximum water cement ratio: 0,45

The mix design was selected on the base of the sieve analysis of aggregates and comparing the proportion of aggregates with the ideal grading of the Bolomey curve.

Table 2 gives the mix design and the graph in Figure 2 comparing the Bolomey curve and what obtained in our mixes.

Table 2. Mix design

	kg/m^3
Cement	400
Sand 0/4	987
Gravel 8/16	810

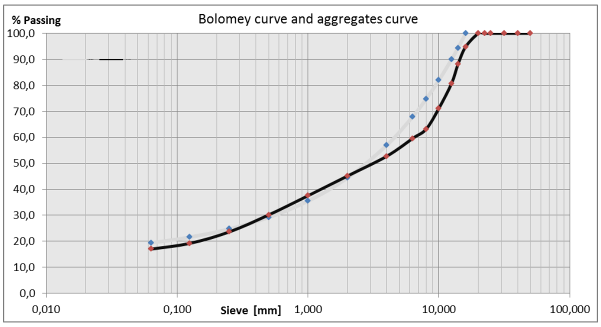

Figure 2. Comparison the Bolomey curve vs. our mix

The mixes were prepared such to provide the possibility to study the characteristics of concrete at different water cement ratio and dosing admixtures to reach different initial slumps as in Table 3.

The volume indexes were verified in order to have an information on cement paste, matrix and finesse of mix. Cement paste is, on liters volume, the sum of water, cement, admixtures and air. The matrix is the sum of cement paste and all material passing to sieve 0,125. The mortar is the sum of cement paste and all material passing to sieve 4.

Table 3. Description of the samples

Id.	Admixture	%	w/c	Slump [mm]
Mix 1	PCE I	0,12	0,45	220
Mix 2	PCE II	0,12		
Mix 3	PCE III	0,12		
Mix 4	PCE I	0,15		240
Mix 5	PCE II	0,17		
Mix 6	PCE III	0,19		
Mix 7	PCE I	0,25	0,38	240
Mix 8	PCE II	0,31		
Mix 9	PCE III	0,34		

All these values give the volume indexes that are considered the fundamental values to be controlled when preparing the mixture. The volume indexes are the representation of the mix and their values show the good proportion of all parts needed produce the precast concrete (Figure 3).

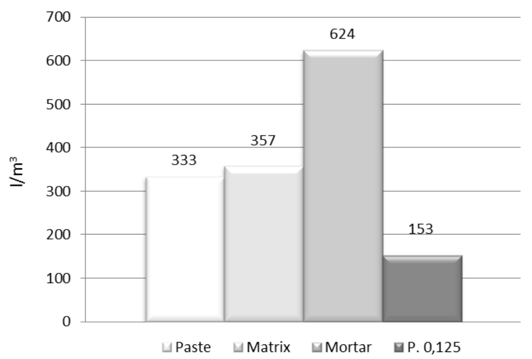

Figure 3. Proportion of precast concrete

Mix Procedures

This method to add the superplasticizers (PCE) and mix ingredients for the test was followed:

- 2 minute mix of aggregates and ¾ of water
- 2 minute wait
- cement addiction
- for 30 s mix and addition of remaining water and admixture
- additional 1 minute mixing

TESTING METHODS

The rheological study on precast concrete was performed by using two instruments that allow to translate the behaviour in terms of viscosity and yield value. We used Viscometer 5 from ConTec and a strain controlled rheometer MCR302 by Anton Paar.

The viscometer[2] uses the Rheiner-Ririhin model (to interpolate the data) and the G. H. Tattersall equation (1)

$$\text{Torque} = G + H \cdot \text{Speed} \qquad (1)$$

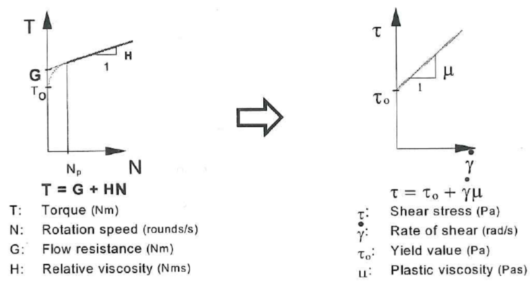

Figure 4. Equation

that links Newtonian equation to the parameters measured by the instrument (see Figure 4) where G is a measure of the force necessary to start a movement of concrete (called “flow resistance”) and H is a measure of the resistance of the concrete against an increased speed of movement (called “viscosity factor”).

The rheometer expresses concrete behaviour by using Bingham law:

$$\tau = \tau_0 + \mu \cdot \dot{\gamma} \quad (2)$$

This is the simplest equation capable to represent constitutive equations for mortars and concrete. The viscometer (Fig. 5) is equipped by a coaxial cylindrical tool, working according to the principle of Couette viscometer[3] at constant shear rate:

Figure 5. ConTec Viscometer

the rotational speed of the outer cylinder is varied while the torque is measured on the inner rotor and flow resistance G and viscosity factor H can be determined.

The rheometer, in order to evaluate concrete, is equipped with a ball measuring system (Fig. 6), a special tool for fluids with grain size up to 10 mm.

Figure 6. Anton Paar rheometer with ball measuring system

The sphere is dragged through a sample of approximately 0,5l volume and the viscosity is measured in one rotation to avoid the measurements into the 'channel' made by the tool during the test .

LABORATORY TESTS

Precast concrete[4] was characterized with empirical tests related to the application on job sites:

. slump test according to EN 12350-2
. specific gravity according to EN12350-6
. air content according to EN 12350-7

Slump test, performed with Abrams' cone, is a method used to control the workability class of concrete. In particular if the slump is higher than 24-26 cm concrete can be used for precast concrete.

Figure 7. Slump test with Abrams' cone on precast concrete

RESULTS

Special rheological tests were performed as well as complementary techniques to assess the flow behaviour of that building materials. The tests[5,6] needed the use of both the viscometer and rheometer, equipped with special devices to avoid slip or segregation, by proper application of rheological models. Table 4 shows the results from laboratory tests in terms of slump and air content.

Table 4. Laboratory results

Id.	Specific Gravity [Kg/m^3]	Air [%]	Slump [mm]
Mix 1	2395	0,9	220
Mix 2	2403	1,0	220
Mix 3	2380	1,5	210
Mix 4	2400	0,5	245
Mix 5	2408	0,6	240
Mix 6	2388	0,9	240
Mix 7	2433	0,6	240
Mix 8	2430	0,9	240
Mix 9	2433	0,7	245

Table 5 shows the results of viscometer tests, where: G is the force necessary to the system in order to start the flow; H is a sort of plastic viscosity and the software provides to carried out from measurements a ‘plug speed value’. That means the viscosity at a calculated shear when the flow occurs.

Table 5. Viscometer results

Id.	G flow res. [Nm]	Plug speed [rps]	H $\eta_{pl.}$ [Pa·s]
Mix 1	2,9	0,22	44
Mix 2	3,9	0,26	51
Mix 3	3,0	0,21	48
Mix 4	1,95	0,17	41
Mix 5	2,1	0,20	36
Mix 6	1,9	0,20	44
Mix 7	1,8	0,05	118
Mix 8	2,0	0,05	138
Mix 9	1,9	0,045	153

Fig. 8-10 show flow curves as assessed by rheological tests. Flow curve profiles have a slope indicating a pseudoplastic behaviour typical of cement based materials rheology. Tests have revealed a clear effect of increasing the amount of PC in Mix 4, 5 and 6 with respect to Mix 1, 2 and 3. That modification in the mix design causes a decrease of the yield value while maintaining the viscosity at high-medium shear quite unchanged.

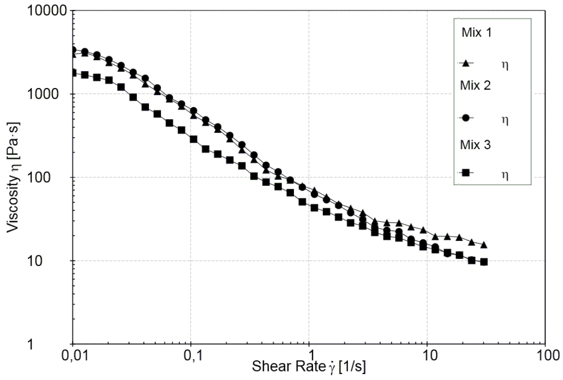

Figure 8. Rheological results: flow curve of Mix 1 ▲, 2● and 3■

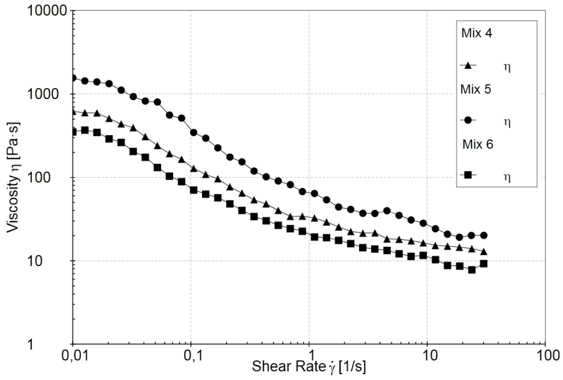

Figure 9. Rheological results: flow curve of Mix 4 ▲, 5 ● and 6■

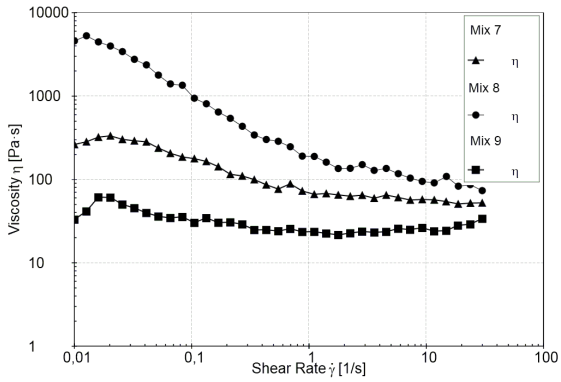

Figure 10. Rheological results: flow curve of Mix 7 ▲, 8 ● and 9■

Mix 7, 8 and 9 represent a modification of the previous recipes, where w/c ratio was changed (decreased) and the PCE content was increased in order to have a slump value comparable to that previously obtained. The effect of this modification is very significant. The Mix 9 flow curve profile appears to be Newtonian, while Mix 7 maintained the previous profile and Mix 8 shows an improvement of the yield value, so that probably an optimization of the mix design could improve the behaviour of the mix from that point of view. Figure 11 compares specific gravity and air content of the nine sample.

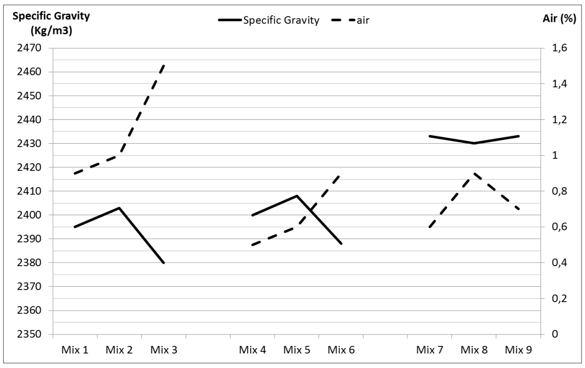

Figure 11 Specific Gravity vs. Air content

These curves show opposite effects in terms of air and mass: in fact as the quantity of air increases, total mass decreases; only mix 2 and 5 show a contrary effect probably due for the use of PCE II.

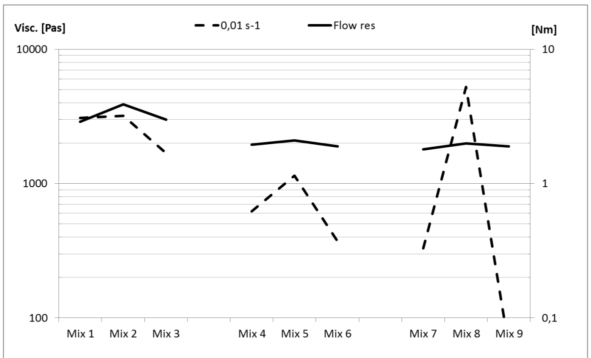

Figure 12 Viscosity at 0,01s^{-1} vs. Flow Resistance [G]

The diagram shown in Figure 12 correlates the viscosity at 0,01 s^{-1} measured by the rheometer with the flow resistance [G] directly measured by viscometer. Results appear correlated and stress controlled rheometer offers the possibility to predict the effect of admixtures on yield value[7,8].

The first six mixes have the same w/c and two levels of three different superplasticizers. For all the yield value decreases at the higher superplasticizier dosage. In the last three mixes, w/c ratio was decreased but compensated by an increase dosage of the three superplasticizers.

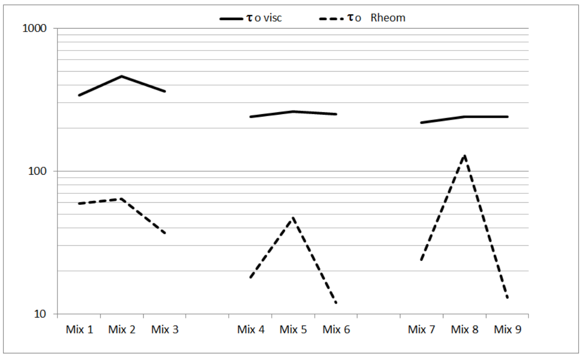

Figure 13. Yield (τo) viscometer vs. rheometer

There is a good agreement with the τo measurements, even if rheometer seems more sensitive to admixture effects. The last diagram (Figure 14) shows the relationship between slump, viscosity at 10 s^{-1} and "plug speed". This is obtained by the viscometer and it represents the velocity the system needs in order to flow during an incipient flow condition.

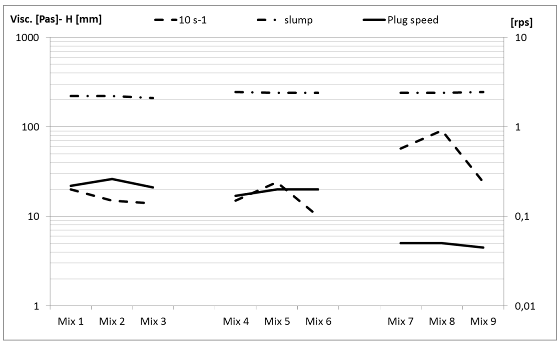

Figure 14 Viscosity and Slump vs. plug speed.

These curves show that as viscosity increase, speed decreases: mixes 5 and 8 show an opposite behaviour possibly due to short time allowed for the measurement. As a matter of fact the time along which the test is performed in the viscometer might be too low respect to the time needed for the admixture to fully display is action in the concrete. This is a fairly well-known fact, and it is often exploited in the job site practice. Finally Figure 14 shows a very low sensitivity of slump test measurements that therefore seems to poorly represent the behaviour of the mix design.

CONCLUSIONS

This article described the rheological behaviour of fresh concrete, where problems arising from a practical jobsite context are addressed. In particular the different possibilities of assessing by rheological measurements main concrete characteristics are discussed. We demonstrated that rheology is more sensitive than common practical tests, and therefore represents more precisely the flow properties of concrete, to be further assessed by job site tests.

ACKNOWLEDGMENTS

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