Rheological simulation of precast concrete and correlation with standard laboratory tests

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Abstract. Rheological measurement is a useful tool to characterize the behaviour of precast concrete (PC) in fluid stage and to solve problems of mix design. Indeed, empirical methods are often not adequate as they are affected by the operator’s subjective evaluation and they are not accurate for a proper evaluation of the effects of raw materials, such as the type of cement and the amount of admixture. In particular, we will use rheological characterization to study the influence of admixture amount and on yield and viscosity of fresh concrete. This information can used for a better mix design and to optimize the use of precast concrete in its final destination.

1. Introduction
Due to the particular application of PC, its rheological properties are extremely important for its self-compacting and the properties of resistance that might vary due to different reasons. In particular small variations in the admixture content influence water demand of the mix and this strongly influences the rheological properties of PC. The effect of admixture content is a function of the relative amounts of aggregate and binder. To study the rheological effects of the amount of admixture several approaches in literature have been described [1]. In this paper an experimental approach using a mortar is presented to evaluate admixture properties that allow it to have a possible forecast of the admixture behavior. Moreover, it can give a description of its action in the short term with less material consumption and hence with a more sustainable approach also in lab practice.

2. Experimental
Flowable concrete has become increasingly important in application such as systems with highly reinforced concrete with a complex formwork or SCC. For these applications it is necessary to have tailored rheological properties obtained by using the correct admixture. A rheometer can provide a useful tool for the most correct identification of the admixture and allow us to evaluate yield stress and plastic viscosity [2]. Before analyzing its effects in concrete, it is good practice to see the rheological behavior of an admixture in a mortar. In this study the assessment of rheological admixture effect in mortar and concrete was investigated by using a combination of stress controlled rheometer and laboratory tests. As the rheological behavior of the fine mortar it is able to predict the behavior of concrete, we used a rheometer by Anton Paar mod. 302 MCR (Figure 1).
The device employed for the mortar characterization was a “ball measuring system” (Figure 2): it consists of a big cup where mortar has been placed and a special tool which has a ball in a non-coaxial position applies the shear needed to measure the flow curve [3]. This device has been designed to avoid problems that occur when a composite material such as mortar is characterized. So it guarantees the non-slip condition and eludes the problem related to a compressed material by ensuring that during all the measurements a normal force is close to zero. Moreover, this tool is adapted to apply uniform stress – in shear condition – also to the system with aggregate sizes up to 4 – 6 mm. The rheometer is equipped also with a cryostat bath so the temperature is kept constant. Investigations were performed at a constant temperature of 20°C because rheological properties strongly depend on temperature. Afterwards, a flow curve was plotted using the measuring values in the shear range imposed by the measurement protocol. The evaluations of the flow curves are made by assuming the Bingham model which well describes cement based material [4]:

\[
\tau = \tau_0 + \mu \cdot \dot{\gamma}
\]  

1)

\( \tau \) = shear stress  
\( \tau_0 \) = yield stress  
\( \mu \) = viscosity  
\( \dot{\gamma} \) = shear rate  

The yield is a measure of the rheological behavior of the mortar in a quasi-static motion condition. Usually it is convenient to assume that value as the zero-shear viscosity that means the viscosity as the system is starting to flow. If its value is high the mortar has a thickening behavior and it cannot flow. A low zero shear viscosity corresponds to shear-thinning for which the mortar usually flows but segregation and/or bleeding could occur.

3. Laboratory tests  
Mortar was characterized using the MBE (mortier de béton équivalent) method, measuring spread (Figure 3) and slump (Figure 4) [6].
PC concrete was characterized with empirical tests, that represent the application on job sites:

- Slump test according to EN 12350-2
- Specific gravity according to EN 12350-6
- Air content according to EN 12350-7

Slump test, performed with Abrams cone is a method used to control the workability class of concrete.

4. Materials and sample preparation.

4.1. Cement and Aggregates

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

- CEM I 52,5R (Manufactured by Cementi Rossi S.p.A.)
- Blaine = 400 m²/kg
- C₃A = 5,5 %
- Density = 3.10 g/cm³

Granitic aggregates from Italy were used in this study, characteristics are reported in Figure 5.

![Figure 5. Aggregates curves.](image)
4.2. Concrete Specification
We used a concrete prescription representative one of the most typical mix of concrete of the market. Below we summarized all prescriptions as defined by EN 206:

- Class of resistance C55
- Class of Exposure respected XC1
- Class of workability: S5
- Maximum diameter of aggregate: 20
- Dosage of cement: 400 kg/m$^3$
- Maximum water cement ratio: 0.40

The mix design has been 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 1 gives the mix design and the graph in Figure 6 comparing the Bolomey curve and what obtained in our mixes.

Table 1. Concrete mix design.

|           | kg/m$^3$ |
|-----------|----------|
| Cement    | 400      |
| Sand 0/4  | 183      |
| Sand 0/8  | 927      |
| Gravel 10/20 | 720   |

4.3. MBE Specification
The MBE mix was prepared by using the same materials of the reference concrete, with re-proportioning the composition using fine aggregates to 8 mm only. In Table 2 we report MBE composition:

Table 2. MBE mix design.

|           | kg/m$^3$ |
|-----------|----------|
| Cement    | 400      |
| Sand 0/4  | 192      |
| Sand 0/8  | 974      |

4.4. Chemical Admixtures
In order to understand how different PCE admixtures might affect on concrete and mortar rheological properties, five different types have been selected and tested. All admixtures are High Range Water Reduce (HRWR) according to table 11 of EN 934-2, from the Mapei Dynamon product range. In Table 3 we report the technical specifications of the chemical admixtures used:
Table 3. Admixture.

|      | DC [%] | SG [kg/l] | pH |
|------|--------|-----------|----|
| 1    | Dynamon NRG 1035 | 27.0 | 1.05 | 6.0 |
| 2    | Dynamon NRG 1030 | 24.0 | 1.04 | 4.5 |
| 3    | Dynamon NRG 1022 | 26.0 | 1.06 | 6.5 |
| 4    | Dynamon NRG 1010 | 26.0 | 1.05 | 6.0 |
| 5    | Dynamon SP 1     | 30.5 | 1.08 | 6.5 |

5. Results

5.1. Mortars
In modern concrete design a wide variety of additives have been used to adjust the rheological properties and to fine tune its workability. Furthermore, having targeted a selection of possible admixture, knowing the mode of action and time interactions with cement is a crucial aspect. Mortar formulation quite often involves three ingredients and the development of such formulation does not require great effort, especially if the study is helped by a rheological approach. In fact, it is able to minimize the number of the experimental tests and properly recognize the behavior of the mortar. The flow curves test obtained on mortar samples are shown in Figures 7,8 and 9.

Figure 7. MBE Flow curve at 0.20 % of admixtures.
The viscosity profile has been measured on these cement based systems by maintaining the same w/c ratio of 0.37. Flow curve profiles have a slope indicating a pseudo-plastic behavior that is typical of cement materials rheology. The curve shows viscosity variation by increasing shear deformation: when the material starts to flow the viscosity is higher but at incipient flowing condition a shear thinning occurs. From the comparison of the three graphs the results are that the viscosity is strictly related to the amount of the admixture. For each graph it is possible to comprehend that the zero shear viscosity is governed by the type of admixture, while the viscosity at high shear is mostly the same and it depends on the cement matrix and w/c ratio. The admixture here appears to have a negligible effect but actually it plays an important role concerning the mortar’s stability. The mortars formulated with 0.2% of additive (Figure 7) have the yield viscosity higher than $10^4$ Pa·s and there is no differentiation between the different admixtures that means the formulations need more additive. In
In fact, the viscosity profile of mortars made with 0.21\% of additive (Figure 8) shows a differentiation in yield value; at 0.23\% all systems are represented in two classes: Mix \textsuperscript{n}\textsuperscript{o}1-2 with low viscosity and 3-4-5 with high viscosity. The measurement results are summarized in the following table:

Table 4. Rheological and laboratory results on mortars.

|               | 1-NRG1035 | 2-NRG1030 | 3-NRG1022 | 4-NRG1010 | 5-SP1 |
|---------------|------------|------------|------------|------------|-------|
| \%            | Yield (Pa·s) | Viscosity at 1s\textsuperscript{-1} (Pa·s) | Viscosity at 10s\textsuperscript{-1} (Pa·s) | Spread (mm) |
| 0.20          | 6950       | 210        | 5150       | 239       |
| 0.21          | 710        | 2050       | 11095      | 339       |
| 0.23          | 615        | 655        | 2110       | 310       |
| \%            | 1210       | 770        | 950        | 310       |
| 0.21          | 415        | 330        | 880        | 330       |
| 0.23          | 380        | 330        | 415        | 305       |
| \%            | 240        | 155        | 305        | 305       |
| 0.23          | 50         | 180        | 210        | 275       |
| \%            | 339        | 310        | 240        | 275       |
| 0.23          | 350        | 325        | 318        | 318       |

Results show viscosity values at zero-shear (yield), at 1 and 10 s\textsuperscript{-1}[7]. The yield is related also to the consistency and it indicates mortar homogeneity. It behaves like an elastic solid body up to a certain load – the so called “flow limit” – and above it, it behaves like a liquid with a plastic viscosity. The viscosity at 1s\textsuperscript{-1} corresponds to a sort of plastic viscosity (1) and indicates the workability of the system. It describes its resistance to flow and could change according to the function of the load. The 10 s\textsuperscript{-1} shear is approximately what might occur when a fluid flows in a pipe and hence the viscosity at such a shear rate defines the “pumpability” of the concrete. Moreover from Table 4 it appears clear that the viscosity at low shear is related to spread measurement. In this case we have a good correlation between spread and yield value: the yield is inversely proportional to the diameter of the mortar that flows through the cone (Figure 10-11).

Figure 10. Spread of mortars.  
Figure 11. Yield of mortars.
Admixture 3 and especially admixture 5 at low dosage have a high consistency (Figure 10) and flowability very comparable to that of the other systems (Figure 13).

**Figure 12.** Mortars’ viscosity at shear rate of 1s$^{-1}$.

**Figure 13.** Mortars’ viscosity at shear rate of 10s$^{-1}$.

Admixture 1 has the best performance as a superplasticizer because it has a moderate consistency at low amount (viscosity at low shear rate – Figure 11) and good fluidity (Figure 12 and 13); increasing this content the texture decreases and the fluidity is very high.

5.2. Scale-up test: concrete

To verify the results obtained with mortars, a precast concrete with the same w/c ratio and amount of admixtures, were prepared like suggested in [8]. Table 5 shows characterization results obtained by standard laboratory tests.

| Mix 1 – NRG 1035 | Air (%) | Spec. Gravity (kg/m$^3$) | Slump (mm) |
|------------------|---------|--------------------------|------------|
| Mix 2 – NRG 1030 | 2.6     | 2408                     | 210        |
| Mix 3 – NRG 1022 | 2.8     | 2414                     | 40         |
| Mix 4 – NRG 1010 | 2.4     | 2410                     | 195        |
| Mix 5 – SP1      | 2.5     | 2405                     | 80         |

The following diagram displays a good correspondence between yield of mortars and the slump of concrete:
Figure 14. Correlation between yield value and slump at w/c = 0.37 and 0.21% admixture

The relationship between these two properties validate the method used but the rheological characterization better highlights admixture behavior [9]: for example Mix 2 and 4 have the same slump (about 200 mm), but the viscosity at low shear is very different. Mortars designed are far from normal w/c ratio in PC concrete: in fact their flowability is too poor. Because of that a new mix design was devised by increasing the w/c ratio at 0.4. Table 6 illustrates their characteristics: the concrete was prepared only for three representative admixtures.

| Mix   | Air (%) | Spec. Gravity (kg/m³) | Slump (mm) |
|-------|---------|------------------------|-------------|
| 1 – NRG1035 | 1.6 | 2413 | 240 |
| 3 – NRG 1022 | 2.4 | 2420 | 110 |
| 4 – NRG 1010 | 1.7 | 2407 | 240 |

The Mix 3 has presented a very low slump value and no flow attitude, probably because the admixture amount should be increased. Mix 1 and Mix 4 have the same flowability because the same slump value, even if the admixtures engaged have been different with different behavior.

6. Conclusions

This study demonstrates that it is possible to predict the precast concrete behavior by performing measurements on simpler systems such as mortar. Even if w/c ratios were low, the behavior found in the mortars was confirmed by concrete scale up tests. Concerning admixtures, with the rheometer, it is possible to discriminate the workability, its short time effect and the behavior during incipient flow. In fact, it was recognized that the admixture 1 was a good superplasticizer due to its ability to decrease the viscosity. Admixtures 3 and 5 at low dosage do not appear to have a good flowability, but they can be tuned easily to modify the final rheology of concrete. The admixtures 2 and 4 give around the same characteristics at 0.2%, by increasing that amount, differences in rheological behavior can occur. Hence the flow curves also provide evidence of the effect of the superplasticizer in the mortar in order to finely adjust the mix design and satisfy the customer’s requests. Because growing demands on high performance material like precast concrete can be satisfied thanks to a sophisticated measurement technology as rheology.
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