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# THE RHEOLOGY OF FRESH HIGH-PERFORMANCE CONCRETE

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## ABSTRACT

The rheological properties of fresh high-performance concrete were investigated with a new rheometer for concrete, BTRHEOM. It was found that, in a steady state, this category of concrete, without or under vibration, behaves as a Bingham material, and can be characterized by the shear yield stress (in Pa) and the plastic viscosity (in Pa.s). For the tested concretes, vibration reduced the yield stress to about half that without vibration, but little influenced the plastic viscosity. A new method for characterizing the evolution of workability is presented, which emphasizes an increase of the shear yield stress versus time. The thixotropy of concrete was confirmed, and it was noted in particular that the yield stress of a concrete after a resting period, called *resting yield stress*, can be several times that of the concrete in a steady state. The dilatancy of concrete was observed in some tests. Several factors influencing this phenomenon are discussed. Finally, a model is proposed for estimating the plastic viscosity of high-performance concrete from the mixture proportions.

## Introduction

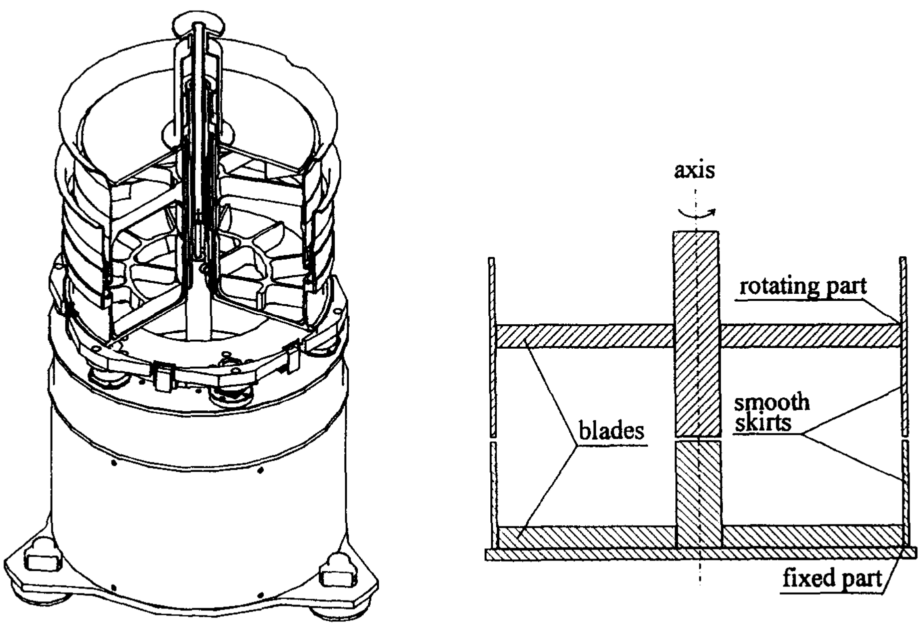
The high-performance concrete (HPC) has been widely used for the last decade. With superplasticizer, this concrete has a better compactness, owing to the reduction of water. The silica fume used in certain cases increases even more the concrete compactness by filling of some intergrain voids. Hence, the HPC presents numerous advantages, such as high strength, high elastic modulus, less bleeding, less creep, and high durability (1). However, few fundamental rheological studies of this concrete have been performed. Some authors (2,3,4) have claimed that ordinary concrete is a Bingham material, whose behaviour under shear is characterized by an affine relationship between the shear stress and the shear rate. For HPC, Smeplass (5) has investigated the rheological influence of paste content and of silica fume content with a coaxial cylinders viscometer, assuming that this concrete is also a Bingham material. However, this assumption remains to be confirmed.

In this study, the behaviour of HPC was first investigated with a new rheometer for concrete, BTRHEOM. The authors have described (6) its design and demonstrated the method of deducing the behaviour law in a steady state. In this torsion rheometer (cf. FIG. 1), a ring of concrete having a vertical axis is sheared between two horizontal sections, of which the inferior one is fixed by a system of blades, and the superior one can rotate, driven by another system of blades linked with the axis of motor. It is also possible to apply a vibration to the concrete sample by the plate which supports the container. In the case of Bingham material, the relationship between the macroscopic measurements (torque Γ and rotation velocity N) in this apparatus should be also affine. The two Bingham characteristics, the shear yield stress $\tau_0$, in Pa, and the plastic viscosity μ, in Pa.s, can be obtained with the following equations:

$$\tau_0 = \frac{3\Gamma_0}{2\pi(R_2^3 - R_1^3)} \tag{1}$$

$$\mu = \frac{h\dfrac{\partial\Gamma}{\partial N}}{\pi^2(R_2^4 - R_1^4)} \tag{2}$$

where $\Gamma_0$ is the ordinate at the origin of the straight line Γ(N) and ∂Γ/∂N its slope. It is therefore easy to verify whether a material is Binghamian. The calibration of the sensors of the apparatus, and its validation, and the various testing procedures have already been presented in previous publications (7,8,9).




(a) 3-D Diagram of the apparatus

(b) 2-D diagram of the container (sample dimensions: H 10 × ϕ 10 cm)

FIG. 1.
The prototype of the BTRHEOM rheometer.

With the BTRHEOM rheometer, various rheological aspects of HPC are investigated as well. The influence of vibration, the evolution of the workability, the thixotropy and the dilatancy will be discussed in later paragraphs. A model for predicting the plastic viscosity of HPC from its mixture proportions, which might be useful for HPC mixture proportioning, is also proposed in this paper.

## High-Performance Concrete: A Bingham Material

In a very large series of tests of different concretes, we have observed (9) that concrete with a slump value over 8 cm and without heavy segregation behaves as a Bingham material in the steady state. Generally, HPC satisfies these criteria. It therefore belongs to the family of Bingham materials. FIG. 2 (a) shows an example of experimental results. It is seen that the measured points fit a straight line quite well. For most of the HPCs tested, the correlation coefficient of the regressed line was around 0.99. As mentioned in the previous paragraph, this means that their behaviour law can be described by the Bingham model. Some researchers doubt the existence of the yield stress; therefore, measurement at very low shear rate seems to be interesting. FIG. 2 shows a test where the rotation velocity was decreased from 0.78 to 0 revolution/second (corresponding to shear rates of 6 to 0 $s^{-1}$). It is found not only that the yield stress exists, but also the measured torques at very low shear rates (here $N \leq 0.06$ r/s or shear rate $\dot{\gamma} \leq 0.5\ s^{-1}$) are even a little higher than those extrapolated from the regressed straight line based on measurements at higher shear rates (say $N \geq 0.1$ r/s or $\dot{\gamma} \geq 0.8\ s^{-1}$). The reason may be that the links between particles, related to the thixotropy of concrete, broken during the strong shearing, began to recover when the shear rate is low enough. In consequence, the shear strength increases.

Table 1 gives the Bingham characteristics of 40 HPCs measured with the BTRHEOM rheometer, together with their slump values. The mixture proportions of all these concretes can be

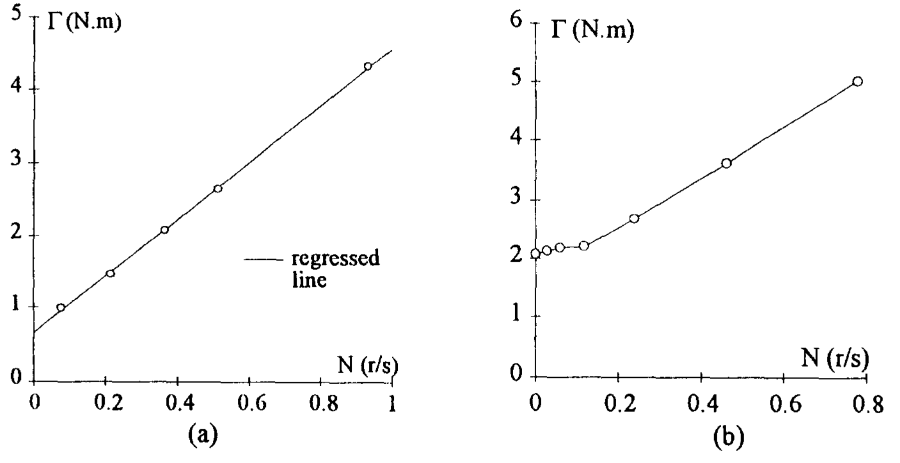



FIG. 2.
Examples of relation between the torque Γ (in N.m) and rotation velocity N (in revolution/ second) measured with the BTRHEOM rheometer.

TABLE 1

Bingham Constants of 40 High-Performance Concretes Tested with the BTRHEOM Rheometer

| concrete | b2 | b3 | b4 | b5 | b6 | b7 | b8 | b9 | b10 | b11 |
|---|---|---|---|---|---|---|---|---|---|---|
| $\tau_0$ (Pa) | 715 | 316 | 671 | 747 | 216 | 306 | 721 | 292 | 1190 | 655 |
| $\mu$ (Pa.s) | 282 | 229 | 165 | 209 | 262 | 354 | 172 | 255 | 82 | 350 |
| slump (cm) | 20 | 23.5 | 22.5 | 23 | 25 | 22.5 | 23.5 | 26.5 | 17 | 13 |
| **concrete** | **b12** | **b13** | **b14** | **b15** | **b16** | **b22** | **b23** | **b24** | **b25** | **b26** |
| $\tau_0$ (Pa) | 380 | 1600 | 671 | 748 | 2000 | 368 | 745 | 190 | 113 | 572 |
| $\mu$ (Pa.s) | 68 | 71 | 149 | 536 | 410 | 143 | 217 | 310 | 303 | 321 |
| slump (cm) | 23.5 | 12.5 | 23.5 | 11 | 8 | 22 | 20 | 23.5 | 22 | 23 |
| **concrete** | **b27** | **b28** | **b29** | **b30** | **b31** | **b32** | **b33** | **b34** | **b35** | **b37** |
| $\tau_0$ (Pa) | 534 | 624 | 1450 | 502 | 176 | 162 | 173 | 181 | 51 | 845 |
| $\mu$ (Pa.s) | 317 | 405 | 146 | 138 | 110 | 113 | 138 | 172 | 140 | 146 |
| slump (cm) | 23 | 22.5 | 18 | 27 | 28 | 27.5 | 26.5 | 28 | 28 | 21 |
| **concrete** | **b38** | **b39** | **b40** | **b41** | **b42** | **b45** | **b46** | **b47** | **b48** | **b49** |
| $\tau_0$ (Pa) | 298 | 913 | 317 | 1450 | 1840 | 302 | 361 | 244 | 868 | 309 |
| $\mu$ (Pa.s) | 199 | 163 | 149 | 174 | 192 | 247 | 196 | 184 | 140 | 140 |
| slump (cm) | 26.5 | 18.5 | 24 | 13.5 | 9 | 24 | 22 | 24 | 13 | 20.5 |

found in reference (9). The ranges of the mix-design parameters were as follows: the maximum size of coarse aggregate varied from 8 to 25 mm, cement content from 266 to 600 kg/m$^3$, silica fume/cement ratio 0 or 10%, water/cement ratio from 0.26 to 0.45, superplasticizer/cement ratio from 0 to 2.5%. The slump values of these concretes covered a range from 8 to 28 cm (cf. table 1). Even though the slump test is not suited to very fluid concretes, the slump values of these mixes were measured for comparison with the other concretes. The ranges of the two Bingham constants are as follows: the yield stress varied from 50 to 2000 Pa, the viscosity from 70 to 500 Pa.s. For the high workable concrete, it is important to verify if there is the segregation of

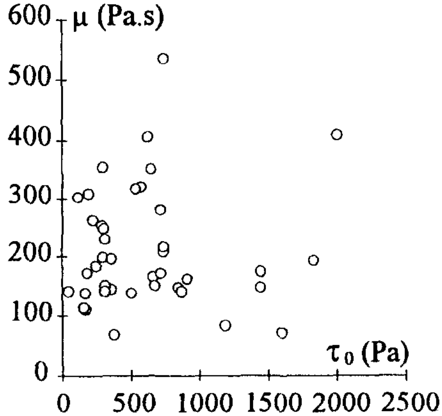



FIG. 3.
No correlation between yield stress and plastic viscosity for the concretes tested.

aggregate particles, which will affect the results. However, the shearing way (plane-plane) used in the BTRHEOM seems better for resisting the segregation of aggregate particles comparing with other shearing ways, such as that of coaxial cylinders viscometers (9).

It is noted that there is no correlation between the two Bingham constants (cf. FIG. 3), which shows the inadequacy of tests determining only one characteristic. In particular, it can be seen in table 1 that for concretes having the same slump value, the plastic viscosity can vary from 1 to 4 in relative value.

### Evolution of Bingham Characteristics Versus Time

With HPCs, a common problem encountered on site is the too rapid loss of workability. To ensure stable rheological behaviour for some time, adequate characterization of the evolution of workability is important. Generally, the classical laboratory tests require heavy work. It is necessary to keep a 50-to-100-litre batch in the mixer and periodically take a sample for testing. The BTRHEOM rheometer makes it easier to monitor the evolution of workability of concrete. The single sample put in the container can be kept as long as necessary for successive shear tests, making it possible to follow the evolution of the Bingham characteristics. It has been shown (8) that repeated shear does not modify the evolution of the microstructure of concrete.

According to the authors' experience, the process of loss of workability is generally reflected by an increase of yield stress (and a correlative reduction of slump); however, in most cases, the plastic viscosity is nearly constant during the test period (generally less than 90 minutes). Beaupré (10) also made the same observation for the pseudo-yield stress and pseudo-plastic viscosity measured with a "Two-point test" type rheometer. Several examples of measurements with the BTRHEOM rheometer are given in FIG. 4. The corresponding slump values are also given in table 2. The only difference between the 3 HPCs was the nature of the superplasticizers, which were all used at saturation content (9). It is noteworthy that the different superplasticizers did not lead to the same effect on the rheological properties of HPC.

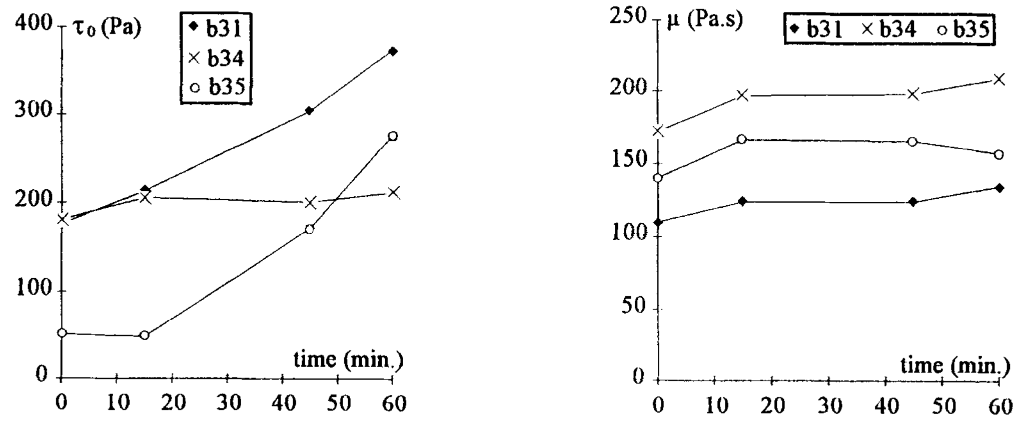



FIG. 4.
Evolutions of the yield stress $\tau_0$ and plastic viscosity $\mu$ of 3 HPCs (b31, b34 and b35).

TABLE 2

Evolutions of the Slump of 3 HPCs
(b31, b34 and b35)

| | | time (min.) | | | |
|---|---|---|---|---|---|
| | | **0** | **15** | **45** | **60** |
| **slump (cm)** | **b31** | 28 | - | 21.5 | 16.5 |
| | **b34** | 28 | 28 | - | 26.5 |
| | **b35** | 28 | 27.5 | - | 22.5 |

## Effect of Vibration

It has been found that concrete under vibration remains Binghamian. The criteria of validity of this conclusion are almost the same as those for concrete without vibration; moreover, it seems to apply to even drier concretes (slump value over 6 cm instead of over 8 cm in the case without vibration (9)).

For most of the HPCs tested, it was not found that vibration cancels the yield stress, as claimed by Tattersall et al. (11) for ordinary concrete. With an applied vibration of 50 Hz and 4 g, it was found that, compared with measurements without vibration, the yield stress values were reduced about 50%; however, the plastic viscosity values were little influenced, and even increased for the low-viscosity concretes (cf. FIG. 5). It is possible to estimate the Bingham constants under vibration ($\tau_{0v}$,$\mu_v$) from those without vibration ($\tau_0$,$\mu$) with the following fitted equations:

$$\tau_{0v} = 0.50\ \tau_0 \tag{3}$$

$$\mu_v = 0.66\ \mu + 73 \quad \text{(Pa.s)} \tag{4}$$

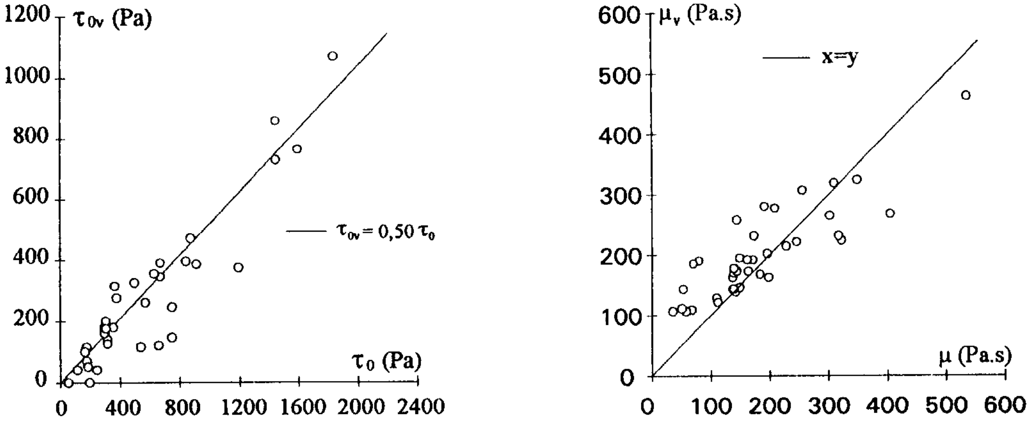



FIG. 5.
Correlation between the Bingham characteristics of HPC without and under vibration.

TABLE 3

Comparison of Resting Shear Yield Stress $\tau_{r0}$ and Shear Yield Stress $\tau_0$ for the Same Concretes

| | without vibration | | under vibration | |
|---|---|---|---|---|
| | $\tau_0$ (Pa) | $\tau_{r0}$ (Pa) | $\tau_{0v}$ (Pa) | $\tau_{r0v}$ (Pa) |
| **b46** | 361 | 1476 | - | - |
| **b49** | 309 | 1840 | | - |
| **bx1** | 1500 | 2960 | - | - |
| **b45** | - | - | 200 | 181 |

However, these relationships exhibit a certain scattering. Therefore, it is recommended to measure the rheological parameters under vibration.

## Effect of Thixotropy on the Shear Yield Stress

The thixotropic phenomenon is characterized by a decrease of stress versus time while the shear rate is constant. This might be due to the existence of an unstable structure in the material, which could be broken down with a certain energy. The structure of the material attains a stable state (12), and the material is then in a steady state. It should be noted that the broken structure is reversible. Generally, during the dormant period of a concrete, if the hydration of the cement does not progress too quickly, the concrete seems to be a thixotropic material. According to the authors' experience, the reconstitution of the broken structure in concrete seemed to be accomplished rapidly, after a few minutes.

From practical point of view, an important effect of the thixotropy of concrete is a large increase of the yield stress during resting. The *resting shear yield stress* $\tau_{r0}$ is distinguished from the shear yield stress $\tau_0$ measured in a steady state. In fact, for concrete after a period of rest, it is $\tau_{r0}$ that characterizes such properties as the capacity to hold a slope and the facility to be

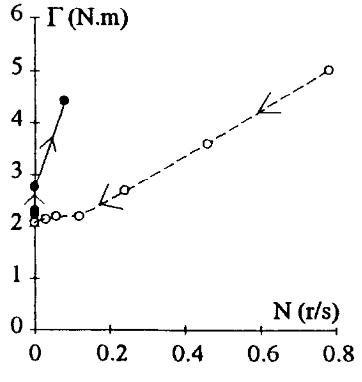



FIG. 6.
Measurements of torque and rotation velocity of an HPC without vibration.

"finished". The resting yield stress can be obtained by performing a controlled stress test (8). In table 3, it can be seen that the value of $\tau_{r0}$ can be several times that of $\tau_0$. However, an example of measurements under vibration shows little difference between the two yield stresses.

This could mean that the applied vibration cancelled the thixotropy of this concrete. FIG. 6 displays all measurements of the test shown in FIG. 2 (b). The order of the measurements is indicated by the arrows. It was observed that, after the rotating part was stopped, at a torque of about 2.1 N.m, rotation could not be restarted until the torque was increased to greater than 2.8 N.m after standing about 1 minute (cf. the full set of points in FIG. 6). It can be seen that the thixotropy is recovered rapidly. However, it is possible that the torque value may be higher after a longer standing time, in the case of incomplete recovery of the thixotropy.

## Dilatancy

The dilatancy of concrete can be studied with the BTRHEOM rheometer, by measuring the variation of sample height (6). It is mentioned above that the shearing way used in this apparatus helps to resist the segregation of aggregate particles. We ask then if this kind of shearing will induce the dilatancy. However, it is found that a quite large number of concretes with different maximum sizes of aggregate (up to 25 mm) have no dilatancy (or near zero). This may assure that the measured dilatancy would rather be related to materials then to the testing method.

The following observations were obtained from a preliminary study:

- no relationship exists between the dilatancy and the Bingham characteristics;
- the dilatancy seems more noticeable for concretes in which the maximum size of coarse aggregate is greater;
- the dilatancy seems to be more noticeable in crushed-aggregate concretes than in round-aggregate ones;
- increasing the volume of fines (particle diameter less than 400 μm) seems to be a good way to limit dilatancy (cf. FIG. 7).

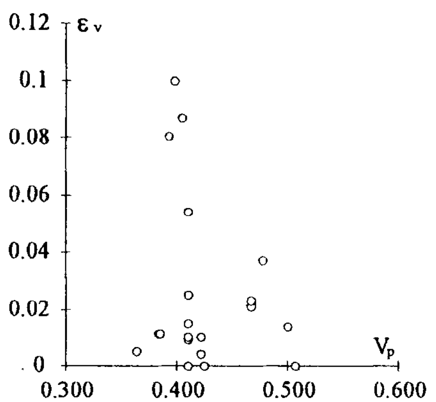



FIG. 7.
Relation between dilatancy ($\varepsilon_v$) and partial volume ($V_p$) of paste (particle size less than 400 μm).

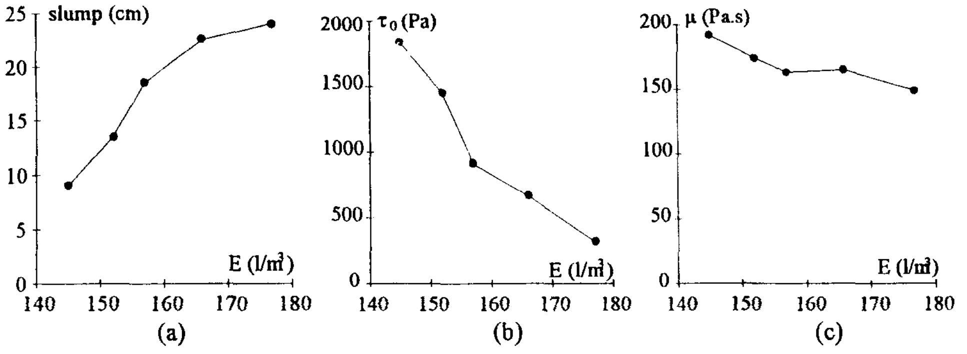



FIG. 8.
Rheological properties (slump, $\tau_0$, $\mu$) versus water content (E) (9).

## A Model Predicting the Plastic Viscosity from Mixture Proportions

The general variation tendencies of the rheological properties of HPCs due to variations of mixture composition are shown in FIG. 8 to 10. Some other authors (3,10,13) have observed the same trends, except the fact that the plastic viscosity increases at high superplasticizer dosage (cf. FIG. 9 (c)), which we have already reported in a previous publication (14).

To reduce the work of mixture proportioning of concrete, it is interesting to use some models predicting the Bingham characteristics from the mixture proportions. Based on Farris's model (15) for concentrated suspension, we have proposed (14) a viscosity model for HPCs as follows:

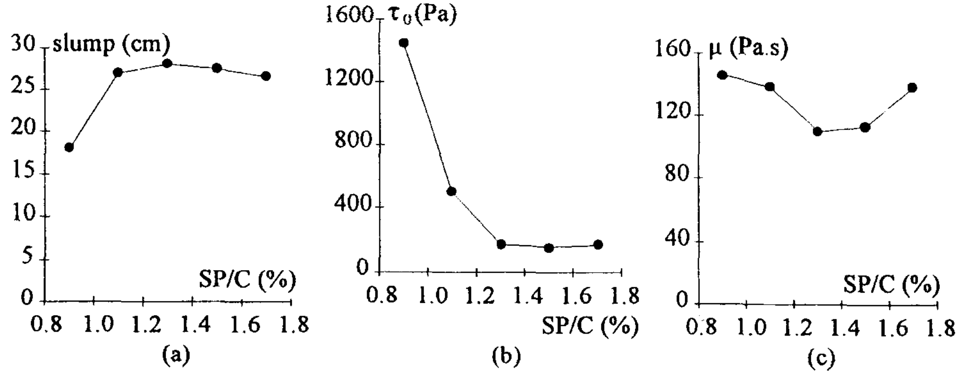



FIG. 9.
Rheological properties (slump, $\tau_0$, $\mu$) versus superplasticizer/cement ratio (SP/C) (9).

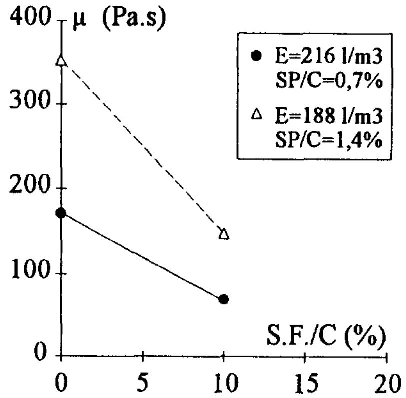



FIG. 10.
Plastic viscosity versus silica fume/cement ratio (S.F./C) (8).

$$\mu = \mu_0(1 + k_s p_s)\left(1 - \frac{\phi_F}{\alpha_F}\right)^{-25\alpha_F}\left(1 - \frac{\phi_C}{\alpha_C}\right)^{-k\alpha_c}\left(1 - \frac{\phi_G}{\alpha_G}\right)^{-k\alpha_G} \tag{5}$$

with:

$$\phi_F = \frac{V_F}{V_0 + V_F} \tag{6}$$

$$\phi_C = \frac{V_C}{V_0 + V_F + V_C} \tag{7}$$

$$\phi_G = \frac{V_G}{V_0 + V_F + V_C + V_G} \tag{8}$$

$$\alpha_x = 1 - 0,45\left(\frac{d_x}{D_x}\right)^{0.19} \qquad x = F,\ C,\ G,\ \text{respectively} \tag{9}$$

where $k_s$ and k are the only two parameters to be fitted to the materials used. The other symbols mean:

- $\mu_0$: viscosity of water (0.001 Pa.s at 20 °C);
- $p_s$: proportion of superplasticizer as fraction of its saturation dosage;

- $\phi_F$, $\phi_C$, $\phi_G$: volume concentration of silica fume, cement, and aggregate, respectively, defined by equations (6) to (8), where $V_0$, $V_F$, $V_C$, $V_G$ are the partial volumes of water, silica fume, cement, and aggregate, respectively;
- $\alpha_F$, $\alpha_C$, $\alpha_G$: maximum packing density of silica fume, cement, and aggregate, respectively, defined by equation (9), a modified Caquot model (16,17), where $d_x$ and $D_x$ are the sieve sizes corresponding to 10% and 90%, respectively, of the material concerned (herein silica fume, cement and aggregate) passing the sieve.

This model was applied to 3 series of tests using the materials from Norway and two different French sites, respectively. As the three superplasticizer/cement couples were very different (9), parameter $k_s$, which reflects this aspect, therefore had three different values: 33, 81, and 53 for different series. However, as concerns parameter k, the same value, 4.2 for all series, seemed to give the best fit. This might mean that it would depend little on the origin of the materials. The comparison of the predicted viscosity $\mu_{\_p}$ and the measured viscosity $\mu_{\_m}$ is shown in FIG. 11. The correlation coefficient is 0.93, while the relative error is less than 20%. This result is quite encouraging.

## Conclusion

Some rheological properties of fresh high-performance concrete are discussed in this paper. The following conclusions have been drawn from the experimental results measured with the BTRHEOM rheometer:

(1) Common fresh HPC (slump value over 10 cm) without heavy segregation and in a steady state, either without or under vibration, seems to be a Bingham material. It can therefore be characterized by two constants: the yield stress ($\tau_0$ and $\tau_{0v}$ without and under vibration, respectively, in Pa) and the plastic viscosity ($\mu$ and $\mu_v$ without and under vibration,

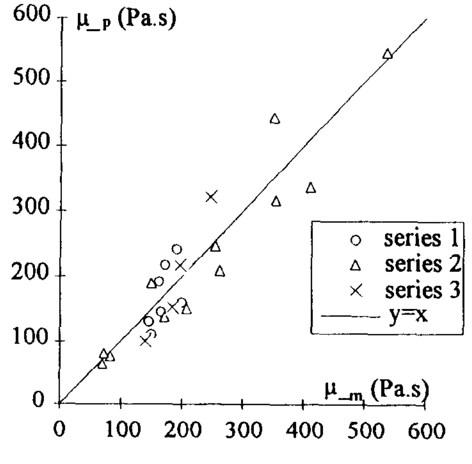



FIG. 11.
Comparison of the predicted viscosity ($\mu_{\_p}$) and the measured viscosity ($\mu_{\_m}$) (9).

respectively, in Pa.s). Compared with the concrete without vibration, concrete under vibration shows a reduced yield stress (by about 50%), but with a comparable plastic viscosity.

(2) The evolution of the workability of concrete can be described by the evolutions of the yield stress and of the plastic viscosity, and determined by their combined effect according to the particular application. In the first hour, the viscosity of HPC is nearly constant.

(3) HPC is a thixotropic material. This is why the *resting yield stress* ($\tau_{r0}$ in Pa) of the concrete after a period of rest can be several times the yield stress measured in a steady state. On the other hand, vibration seems capable of cancelling the thixotropy.

(4) There is dilatancy in some HPCs. However, the main controlling factors are not very clear; the volume of fine particles seems to play an important role.

(6) A model is proposed for predicting the plastic viscosity of HPC from the mixture proportions. The comparison with the experimental results is satisfactory. However, more experimental confirmations are needed.

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