*Chiara F. Ferraris*[1] *and François de Larrard*[2]

# Modified Slump Test to Measure Rheological Parameters of Fresh Concrete

---

**REFERENCE:** Ferraris, C. F. and de Larrard, F., "**Modified Slump Test to Measure Rheological Parameters of Fresh Concrete,**" *Cement, Concrete, and Aggregates,* CCAGDP, Vol. 20, No. 2, Dec. 1998, pp. 241–247.

**ABSTRACT:** The ease of placement of concrete depends upon at least two physical properties, the yield stress and plastic viscosity. Currently the most common field test is the slump test, and it is related only to the yield stress. Therefore, a simple field test method intended to provide an evaluation of the two Bingham rheological parameters, yield stress and plastic viscosity, was developed. To determine the plastic viscosity the time necessary for the upper surface of the concrete in the standard slump cone to slump 100 mm was measured. The apparatus and test procedure are described. Semi-empirical models are proposed for the yield stress and for the plastic viscosity as function of the final slump and slumping time. The application of the modified slump test for the evaluation of the viscosity is limited to concretes with a slump of 120 to 260 mm. If the validity of this test is confirmed in the future, it could be used as a field quality control test.

**KEYWORDS:** concrete rheology, slump test, plastic viscosity, yield stress, workability field test

The ease of placement of concrete is usually referred to as workability. This word is usually ill defined, hiding at least two characteristics: the yield stress and the plastic viscosity. These two parameters were first used in concrete by Tattersall 1991 using the definition given by the Bingham equation as follows

$$\tau = \tau_0 + \mu\dot{\gamma} \qquad (1)$$

where

$\tau$ = shear stress (in Pa) applied to the fresh concrete,
$\dot{\gamma}$ = shear strain rate (also called the strain gradient, in $s^{-1}$),
$\tau_0$ = yield stress (in Pa), and
$\mu$ = plastic viscosity (in Pa·s). The yield stress and the plastic viscosity (the Bingham parameters) characterize the flow properties of the fresh concrete (Fig. 1).

Tattersall proposed using an instrumented mixer to obtain a more complete characterization of the flow behavior of fresh concrete (Tattersall 1991) than was previously done. Recently an improved rheometer has been developed by the Laboratoire Central des Ponts et Chaussées (LCPC), the BTRHEOM rheometer (de Larrard et al. 1997, de Larrard et al. 1996, and Hu et al. 1995). This rheometer, which was used in the present study, allows the quantitative determination of the yield stress and the viscosity of plastic concretes. The major difference between this instrument and its predecessors is the parallel plate geometry, while others have a vane or bob rotating in a cylindrical container. The parallel plate geometry allows a mathematical description of the velocity field, which permits analytical calculations of the yield stress and plastic viscosity in terms of rheometer measurements.

While the standard slump test Standard Test Method for Slump of Hydraulic Concrete Cement (ASTM C 143-95), the most widely used of all field tests of fresh concrete, provides an indication that is reasonably well correlated to the yield stress (de Larrard 1997), other tests, such as the DIN flow table and VEBE apparatus (de Larrard et al. 1994), provide results that are not very useful in terms of quality insurance in the field. In most of these tests, the concrete flows under the effect of a dynamic sollicitation. Thus, the behavior of the concrete under a single, apparently arbitrary, level of vibration is examined, with no possibility of determining fundamental rheological parameters and no obvious relationship to fresh concrete in the field.

A survey of the state of the art (Ferraris 1996) shows that none of the current field tests (in distinction to rheometers) is able to assess the plastic viscosity of the fresh concrete. However, this parameter is of increasing importance in modern concretes. For high-performance concretes, it frequently constitutes the critical parameter that controls pumpability (de Larrard 1997) and ease of finishing.

Concerning the standard slump cone test (Tanigawa et al. 1989, 1991) performed measurements of the slump as a function of time. They found that the slump-time curve could be simulated by finite element analysis of the fresh concrete assuming that the concrete is a Bingham material. The slump-time curve depends on both the yield stress and the plastic viscosity. Since the final slump is related directly to the yield stress, it is reasonable to assume that the time-dependence of slump is likely to be controlled by the plastic viscosity. Considering that the slump test is currently the only field test in the world for most practitioners, the test procedure was modified slightly to make possible measurements of both the yield stress and the plastic viscosity of fresh concrete. This paper describes the modification made to the standard slump test apparatus, test procedure and calculation to determine both the yield stress and the plastic viscosity.

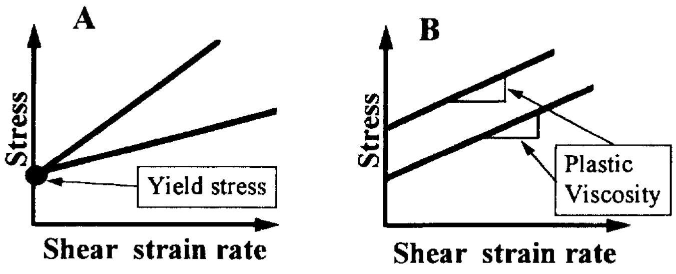
## Experimental Procedure

### *Materials*

The coarse aggregates and the sand used in this study were a siliceous-limestone alluvial material from the area of Washington,

---

[1] National Institute of Standards and Technology, Gaithersburg, MD 20899.
[2] Laboratoire Central des Ponts et Chaussées, Rt. de Bouaye BP 19, 44340 Bouguenais, France.



Identical Yield Stress
but
Different Plastic Viscosity

Identical Plastic Viscosity
but
Different Yield Stress

FIG. 1—*Yield stress and plastic viscosity of fresh concrete.*

DC. The aggregates are rather rounded in shape with a maximum size of 10 mm for the coarse aggregate. To assure continuity in the particle size distribution of the mixtures, a single-size rounded fine sand (density 2.65, water absorption 0%) was used to correct the deficiencies in gradation of the alluvial sand. An ASTM Type I/II Portland Cement, Standard Specifications for Portland Cement (ASTM C 150-95), was used in all of the tested concrete mixtures. A silica fume provided in the form of slurry containing 54% solids, was also used. The specific gravity of the silica fume was taken as 2.2. A sulfonated naphthalene, in an aqueous solution with 40% dry extract by mass, was used as a high-range water reducing admixture (HWRA) in half of the mixtures. The material properties and various particle size distributions are given in Ferraris et al. 1997.

### *Methodology*

The concretes were mixed in a vertical-axis pan mixer with a maximum capacity of 16 L. The aggregates were oven dried before being used. Details of the mixing procedure are given elsewhere (Ferraris et al. 1997). In brief, the total mixing time was 3 min 30 s for the concretes without HWRA, and 5 min for concretes with HWRA. The mixing time for the concretes with HWRA was longer because of the addition of some admixtures was delayed.

The slump was measured in accordance with ASTM Test Method C 143-90, except that the apparatus was provided with an axial vertical rod and a stainless steel disk that could slide down the rod. This plate was placed on top of the concrete cone (see section on Design and Dimension of Modified Slump Test Apparatus). The effect of these modifications on the final slump was found to be negligible. To measure the rheological parameters, yield stress and plastic viscosity in a more fundamental way, a BTRHEOM rheometer was used. Details of the rheometer operation and data interpretation are beyond the scope of this paper and are described by Ferraris et al. 1997.

The experimental plan (Ferraris et al. 1997) consisted of systematically testing most of the mixtures that could be designed using the three basic materials: gravel, corrected sand (a mixture of alluvial sand and fine sand in fixed proportions), and cement. Based on a certain number of "dry" compositions, three fresh concrete mixtures with different water/solid ratio were selected so as to cover the range of consistencies that could be evaluated with the rheometer. The lower limit was a slump of about 100 mm for mixtures without HWRA (Hu et al. 1995), while the upper limit was reached when bleeding or segregation was considered to be excessive.

### *Design and Dimensions of the Modified Slump Test Apparatus*

Since the goal was to develop a test that was above all simple, robust, and inexpensive, it was not practical to record the slump as a function of time. To do a complete recording, it would have been necessary to use an electronic data acquisition. The interpretation of the resulting curve would also have been too complex. Therefore, it was decided to try to characterize the plastic viscosity based on an average rate of slumping in the slump test. Thus, measurement of the time necessary to reach an intermediate height between the initial and final values appeared a priori to be a good means of discriminating among the concretes according to their plastic viscosity.

The choice of this partial slump took into consideration two potential problems: (1) a height that was too small would lead to very small slump times and thus poor relative precision of measurement, and (2) a partial slump that was too large would have ruled out all concretes with a smaller final slump. Since the range of concretes that can be characterized by the rheometer is, as already stated, approximately that for which the slump is greater than 100 mm, this value was chosen for the partial slump.

The Tanigawa setup for measuring slump as a function of time would be too fragile for a work-site environment (Tanigawa 1991). Therefore, we adopted the use of a plate, allowed to slide on a centrally located rod as the means for monitoring the time to reach the 100-mm slump. The rod was at the axis of symmetry of the conic frustum. Since the axis of symmetry of the concrete did not change significantly during the flow of the concrete, it was assumed that the rod would not greatly disturb the slump. This point was later verified. The dimensions of the apparatus and the test setup are shown in Fig. 2 and Fig. 3.

In order to measure the partial slump time, it was found satisfactory to use a stopwatch controlled by the operator on the basis of a visual criterion (such as in the VEBE test). The stopwatch is started as soon as the slump cone is lifted, and is stopped when the sliding plate placed on the fresh concrete had fallen 100 mm and reached the stop on the rod (Fig. 4).

### *Procedure for Measuring the Slump Time*

The following components are needed to conduct the modified slump test:

- A horizontal base to which the rod is attached.
- A standard mold for the slump test (ASTM C 143-90).
- A sliding disk (the upper plate).
- A rubber O-ring seal, the purpose of which is to prevent fine materials from interfering with the fall of the disk.
- A rod to consolidate the concrete.
- A small trowel to finish the upper surface of the concrete.
- A ruler graduated in mm to measure the slump.
- A stopwatch which could be read to the nearest 0.01 s.

The concrete was placed in the same manner as in the standard slump test (ASTM C 143-90). The various steps are as follows.

1. Carefully clean the rod and coat it with petroleum jelly (down to the stop).
2. Using a wet sponge, moisten the base and the inside wall of the mold.
3. Place the mold on the base, assuring its axis coincide with the rod.
4. While keeping the mold in place on the base (either with attachments provided for this purpose or by standing on the foot pieces welded to the outside of the mold), fill it in three layers, rod each layer 25 times.
5. Strike off the surface of the concrete using a trowel.

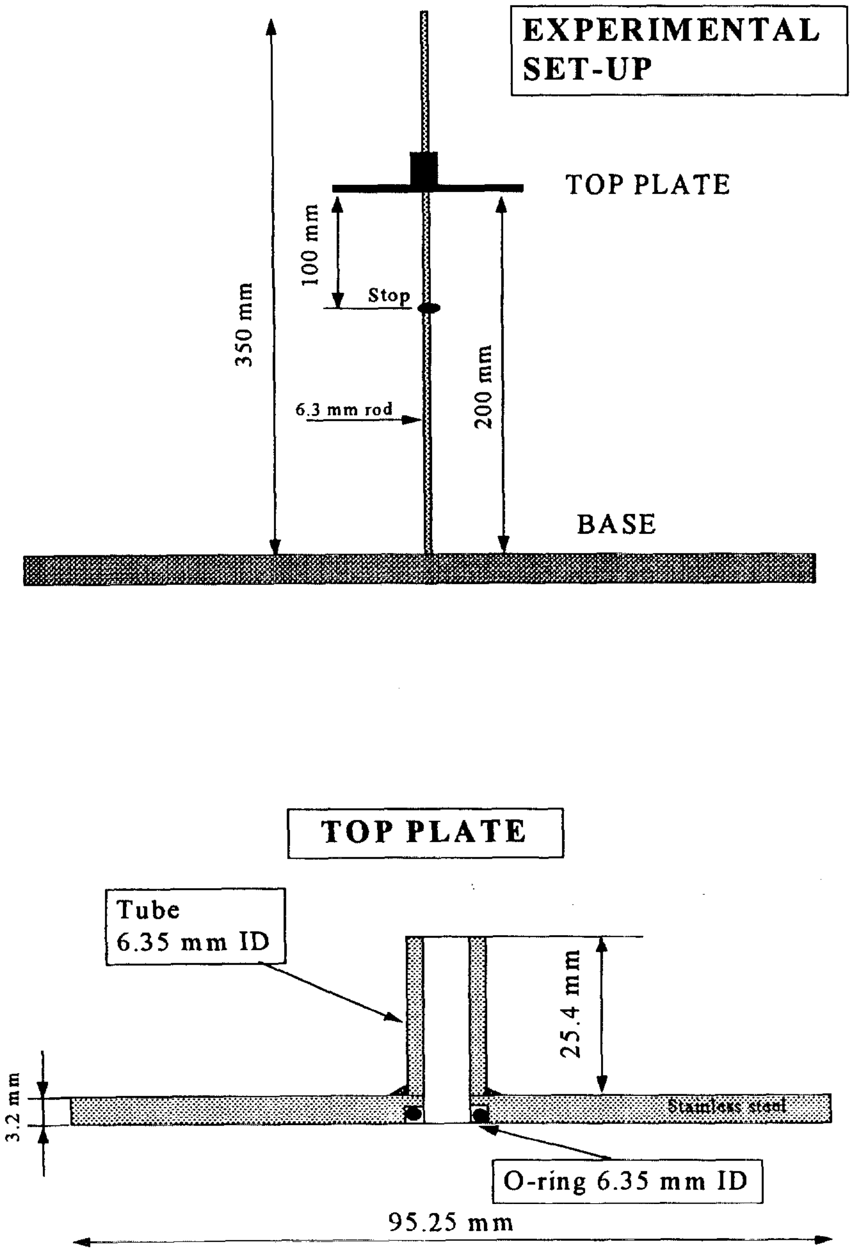


FIG. 2—*Rod and top plate in the modified slump apparatus.*

6. Using a rag, clean the part of the rod that projects above the concrete specimen.
7. Slide the disk along the rod until contact is made with the surface of the concrete.
8. Raise the mold vertically while starting the stopwatch.
9. While the concrete is slumping, continually observe the disk (through the top of the mold) and stop the stopwatch as soon as the disk stops moving.
10. Once the slump has stabilized, or no later than one minute after the start of the test, remove the disk and measure the slump with the ruler.

## Results

The modified slump test as described was performed on all of the mixtures and the partial slump times (which will hereafter be called the slump times) are given by Ferraris et al. 1997. After the mortars and concretes for which the final slump was less than 100 mm are excluded, the measured times range between 0.63 and 15.97 s.

One question was to find out if the minimum time was controlled by the slump of the concrete or whether, the disk separated from the concrete during the fall. The theoretical drop time of a body subject to gravity to fall a distance h of 100 mm is $\sqrt{2h/g}$, or 0.14 s. Two measurements of this time (without concrete) gave values of 0.16 and 0.15 s. Hence, it was concluded that any separation is unlikely (at least with the concretes tested). In addition, the precision of measurement is on the order of 1/10 of a second due to the reaction times of the operator. Also, the precision reflects the fact that the cone lifting is not precisely controlled (Bartos 1992).

The coherence of the measurements was examined by examining the variation in slump time within each mixture group. With rare

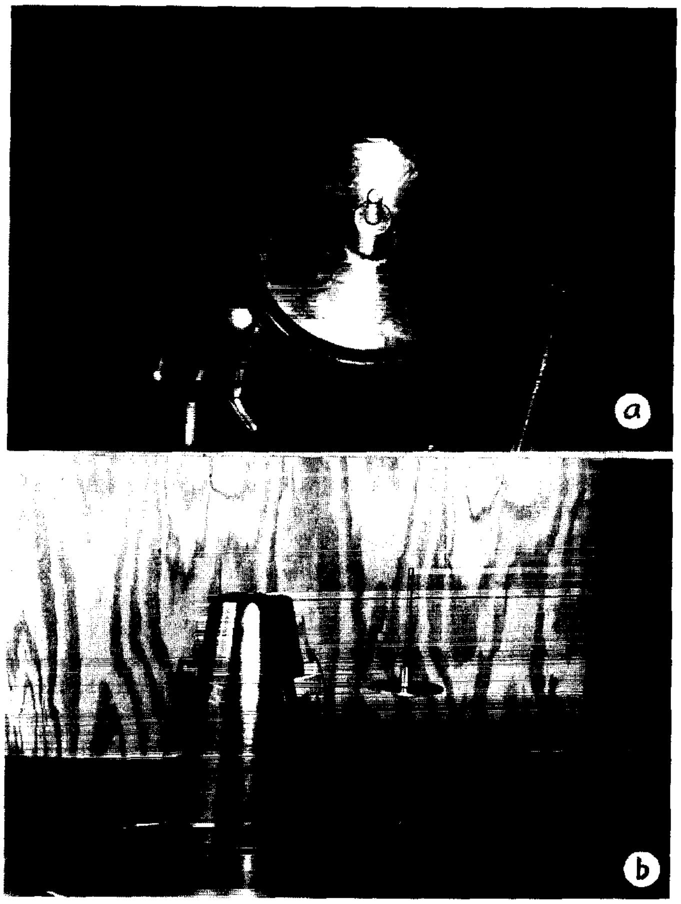


FIG. 3—*The experimental setup:* (a) *View of the mold and top plate from above;* (b) *View of the mold, the rod attached to the base and the top plate at the final position.*

exceptions, the times are arranged very well as a function of the volume of water: they decrease regularly as the water dosage increases. On the other hand, comparison of the average values of series of measurements is equally instructive and encouraging. The slump times of all mixtures without the HWRA average 1.51 s (range ±0.54 s), while the values for all mixtures with HWRA are generally greater and more widely spread (average of 4.80 s, range of ±4.66 s). Therefore, this test will be more useful in determining the plastic viscosities of concretes containing HWRA.

### *Comparison of Final Slumps Obtained with the Standard Test and the Modified Test*

A check was done to determine whether the modification to the standard slump test affected the final slump measurement. This was necessary to have complete compatibility with the unmodified test.

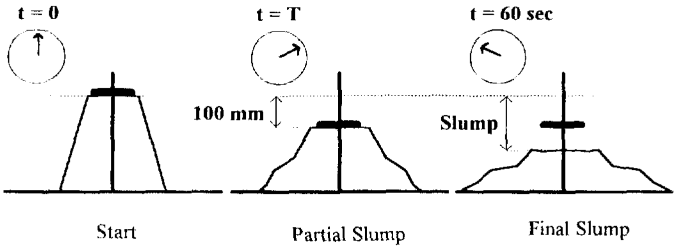


FIG. 4—*Schematics of the modified slump test.* T *is the slump time.*

The mass of the disk (212 g) increases the vertical stress on the sample by a maximum value equal to its weight divided by the upper area of the frustum, this was 0.27 kPa. When the disk reaches the stop, the height, *h*, of the concrete is 200 mm. Hence, the vertical compression stress at the base of the sample equals $\rho g h$ (where $\rho = 2400\ \text{kg/m}^3$ is the density of the fresh concrete and $g$ is the acceleration due to gravity), that is, about 4.8 kPa. Thus it is seen that the vertical stress due to the disk is at most on the order of 6% of the stress due to the concrete. Moreover, the friction of the concrete along the rod would tend to reduce the final slump. To verify that these effects are negligible, a comparative study was done with six compositions chosen because they are representative of the range of slumps obtained. The two tests (the standard slump test and the modified test) were conducted in parallel. Figure 5 shows the comparison between the two tests. The best fit line passing through the origin has a slope of 1.01 ± 0.03. This regression leads to a standard deviation of 17 mm. Therefore, the slumps measured with the two tests can be considered identical.

## Estimation of the Fundamental Rheological Parameters on the Basis of the Modified Slump Test

### *Models to Evaluate Yield Stress*

Based on finite element analysis of the slump test and on measurements of the yield stress using the rheometer and the slump, Hu proposed a general formula relating the slump *s* to the yield stress $\tau_0$ (de Larrard et al. 1994) in the following form

$$\tau_0 = \frac{\rho}{270}(300 - s) \qquad (2)$$

where $\rho$ (density) is expressed in kg/m$^3$, $\tau_0$ in Pa, and *s* in mm. A correlation with experimental data was shown to give a reasonable prediction of the Bingham yield stress. However, despite the fact that the plastic viscosity is not taken into account in the Eq 2, it does play a role. Hu found that the correlation is poor if the concrete's plastic viscosity is greater than 300 Pa·s.

In the present case, the predictions for the yield stress provided by this model are quite reasonable. There is an average error of

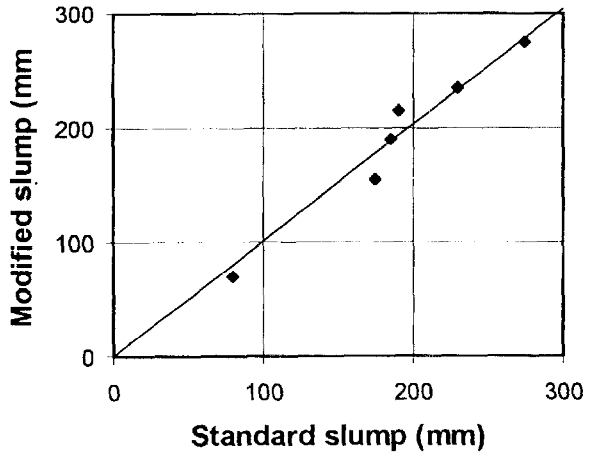


FIG. 5—*Comparison of the slump values between the standard slump test and the modified test. The slope of the best fit straight line passing through the origin is 1.01 with* $R^2 = 0.95$.

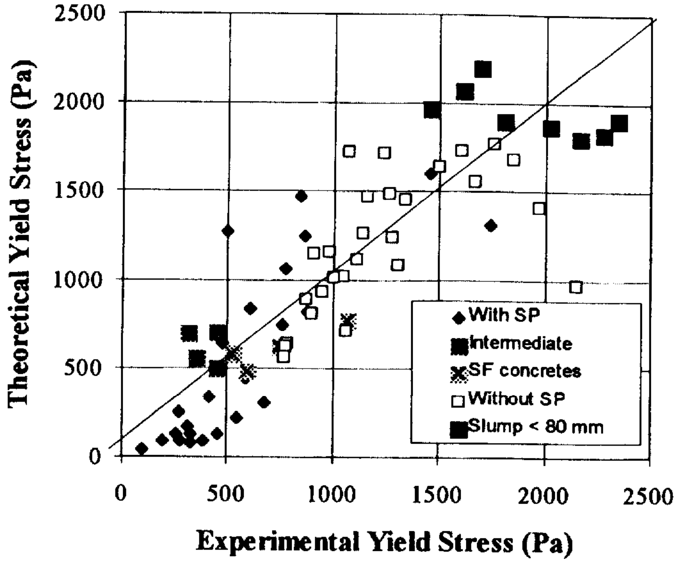


FIG. 6—*Comparison between the experimental yield stress measured using the rheometer and predictions from Hu's model (Eq 2) [de Larrard (1994)] (SP = HRWRA).*

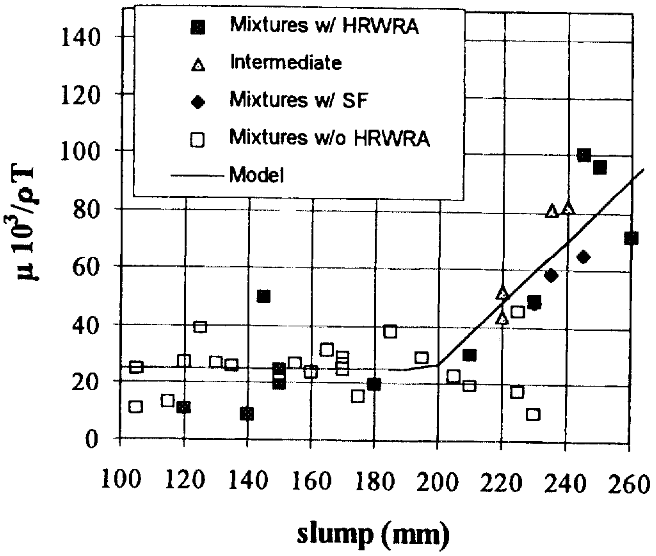


FIG. 8—*Relationship between the ratio* μ/ρT *and the final slump.*

195 Pa for the yield stress in the range (100 to 2000 Pa), (Fig. 6). However, one finds a systematic underestimate of the yield stress in the low range, that is for self-leveling concretes. The accuracy of Hu's model can be improved empirically by adding a constant term and modifying the slope term. The following equation

$$\tau_0 = \frac{\rho}{347}(300 - s) + 212 \qquad (3)$$

results in a 162 Pa average deviation with respect to the measurements (Fig. 7). The improvement is particularly notable for the very fluid mixtures.

### *A Semiempirical Model to Evaluate Plastic Viscosity*

To evaluate the plastic viscosity from the results of the modified slump test, the following assumption was invoked: for the same final slump and the same density concrete; a difference in slump time can be attributed to a difference in plastic viscosity. From a dimensional analysis, it is to be expected that the factor $\mu/\rho g T$ (where $\mu$ is the plastic viscosity calculated from the measurements done with the rheometer and $T$ the slump time) are functions of the final slump. The density is expressed by $\rho$ and $g$ represent the gravitational acceleration. The relationship between $\mu/\rho g T$ and the final slump is shown on the plot on Fig. 8, excluding the self-leveling concretes (right area of the diagram, slump higher than 260 mm). For these mixtures, the scatter is larger because of the very short slump times and the higher probability of segregation.

If we consider only concretes having a slump lower than 260 mm, the best fit to the data is given by the following equation

$$\mu = \rho T \cdot 1.08 \cdot 10^{-3}\,(S - 175) \quad \text{for } 200 < S < 260 \text{ mm}$$
$$\mu = 25 \cdot 10^{-3}\,\rho T \quad \text{for } S < 200 \text{ mm} \qquad (4)$$

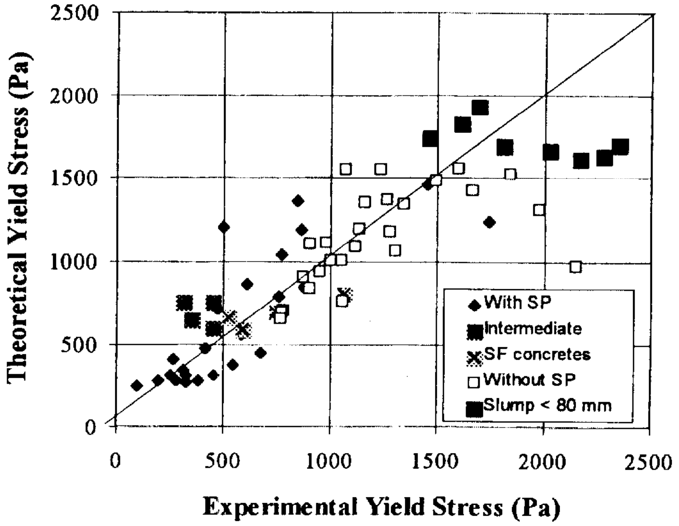


FIG. 7—*Comparison between experimental yield stress measured using the rheometer and predictions from Eq 3 (SP = HRWRA).*

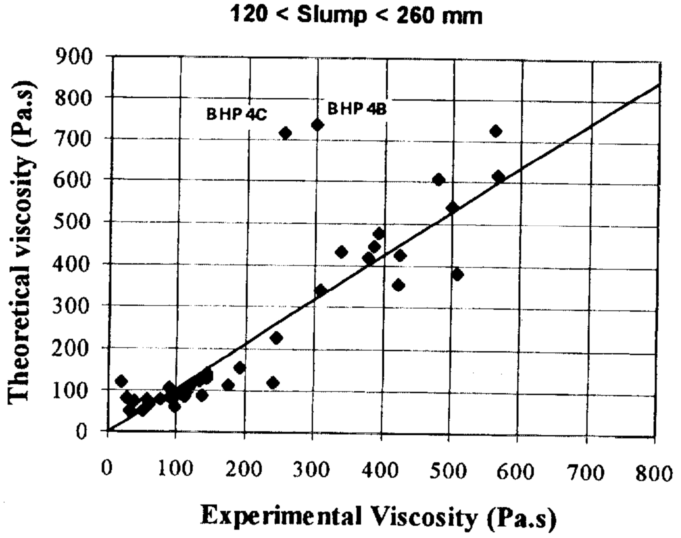


FIG. 9—*Comparison between experimental measured using the rheometer and predictions of the plastic viscosity model (Eq 4) for concretes with a slump between 120 and 260 mm. The slope of the best fit straight line, shown, passing through the origin is 1.09 ± 0.03.*

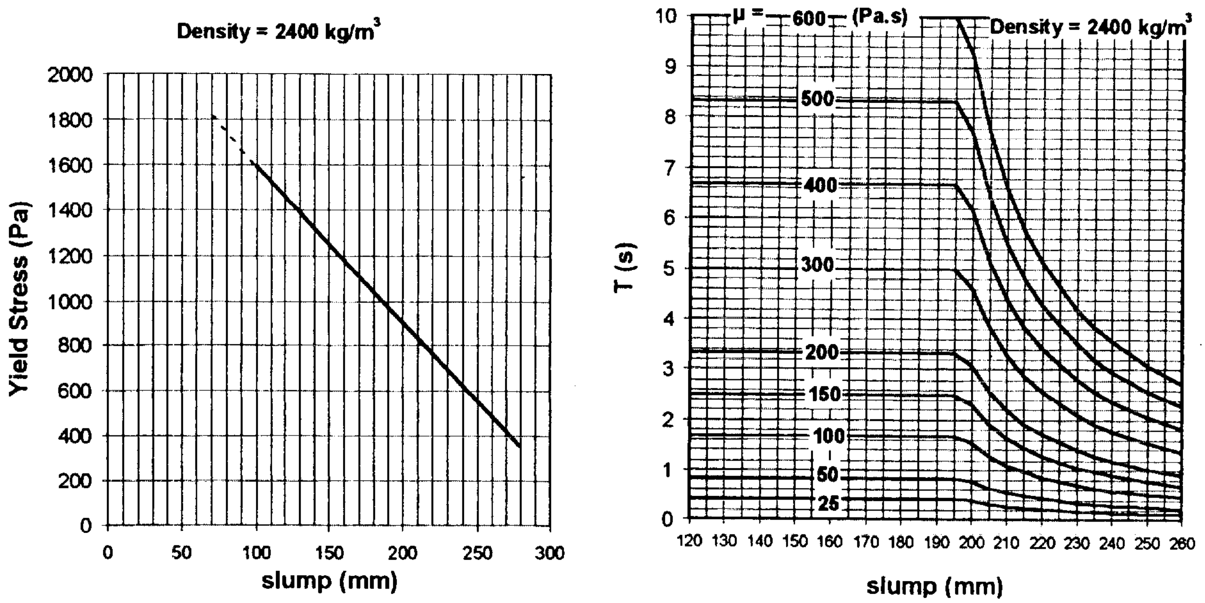


FIG. 10—*Nomographs for estimating the yield stress and plastic viscosity of concrete from the results of the modified slump test (for a concrete with a density of 2400 kg/m³).*

From these equations, the plastic viscosity can be estimated from the unit mass, the final slump (in mm), and the partial slump time in seconds. The average error for this model for all the concretes with a slump between 120 and 260 mm is 66 Pa·s (Fig. 9). Two mixtures that deviated significantly from the correlation (Ferraris et al. 1997), can be considered outliers because their compositions included an excess of gravel (which is rare in practice especially for concretes containing HWRA), and because there was a lack of cohesion during the slump tests (Ferraris et al. 1997). Excluding the two outliers, a linear correlation having a slope of 1.09 ± 0.03 (Fig. 9) is found between the theoretical and measured viscosity. This slope indicates a very good correlation between the two entities. To avoid calculations using Eq 4, nomographs are given on Fig. 10 to rapidly calculate the yield stress (in Pa) and the viscosity (Pa·s) from the measurements of the final slump and the slumping time with the modified slump test for a concrete with a unit mass of 2400 kg/m³.

In conclusion, the model presented gives an evaluation of the plastic viscosity of concrete from the measurements with the modified slump cone with a lower precision than the rheometer. Nevertheless, the new test should be useful for quality control in the field, while the rheometer is to be preferred as an instrument for determining the optimum mixture design for a specific application.

## Summary and Conclusions

A modification of the standard slump test intended to evaluate the two Bingham characteristics of fresh concrete is presented. This test allows a better quality control of the fresh concrete in the field. The procedure has been described in detail, and the results of tests obtained on 78 mixtures have been reported. The conclusions are as follows:

1. The final slump combined with the unit mass of the concrete allows an estimation of the yield stress of the concretes in the field for concretes with slumps greater than 100 mm.
2. The slump time combined with the preceding measurements can provide an estimate of the plastic viscosity for concretes with a slump comprised between 120 and 260 mm. The range of application is therefore limited, fortunately, this is the slump range of most useful high-performance concretes, currently being used.

Additional areas of research to support the development of a standard test method include the following:

1. The reproducibility of the measurements made with this modified slump test should be further evaluated.
2. The suitability of a model linking the slump time to the plastic viscosity should be verified with other concretes made with different components.
3. The range of values of the viscosity and the yield stress that are required for placement and finishing under different conditions should be determined.

## *Acknowledgments*

The authors wish to specially thank John Winpigler of the National Institute of Standards and Technology (NIST) for his participation in the preparation of materials and for the conduct of the rheological tests and Frank Davis, also from NIST, for repair of the concrete mixer. Finally, they wish to mention the contributions of W. R. Grace Co. which provided the mixer and the HWRA and the Elkem Company which provided the silica fume. We also would like to thank Drs. James Clifton, Edward Garboczi, Nicholas Carino, and Geoffrey Frohnsdorff for the review of this paper.

## References

Bartos, P. (1992), "*Fresh Concrete: Properties and Tests*," Elsevier, London.

de Larrard, F., Hu, C., Sedran, T., Sitzkar, J. C., Joly, M., Claux, F., and Derkx, F., 1997, "A New Rheometer for Soft-to-Fluid Fresh

Concrete," *ACI Materials Journal*, Vol. 94, No. 3, May–June, pp. 234–243.

de Larrard, F., Sedran, T., Hu, C., Szitkar, J. C., Joly, M., and Derkx, F., 1996, "Evolution of the Workability of Superplasticized Concretes: Assessment with BTRHEOM Rheometer," *Proceedings*, International RILEM Conference on Production Methods and Workability of Concrete, Paisley, P. J. M. Bartos, D. L. Marrs, and D. J. Cleland, Eds., June, pp. 377–388.

de Larrard, F., Szitkar, J. C., Hu, C., and Joly, M., 1994, "Design of a Rheometer for Fluid Concretes," *Proceedings*, International RILEM Workshop on Special Concretes: Workability and Mixing, P. J. M. Bartos., Ed., E & FN Spon, pp. 201–208.

Ferraris, C. F., 1996, "Measurement of Rheological Properties of High-Performance Concrete: State-of-the-Art Report," NISTIR 5869, National Institute of Standards and Technology, July, 33 p.

Ferraris, C. and de Larrard, F., 1997, "Testing and Modelling of Fresh Concrete Rheology," NISTIR 6094, National Institute of Standards and Technology.

Hu, C., de Larrard, F., and Gjφrv, O. E., 1995, "Rheological Testing and Modelling of Fresh High-Performance Concrete," *Materials and Structures*, Vol. 28, pp. 1–7.

Tanigawa, Y. and Mori, H., 1989, "Analytical Study on Deformation of Fresh Concrete," *Journal of Engineering Mechanics*, Vol. 115, No. 3, March.

Tanigawa, Y., Mori, H., and Watanabe, K., 1991, "Analytical and Experimental Studies on Casting of Fresh Concrete into Wall Form," *Transcription of the Japan Concrete Society*, Vol. 13.

Tattersall, G. H., 1991, *Workability and Quality-Control of Concrete*, E & FN Spon, London.