INFLUENCE OF SUPERPLASTICIZERS ON WORKABILITY OF CONCRETE

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ABSTRACT: This paper outlines the theoretical foundations governing the rheological properties of concrete. The rheological equation for fresh concrete is given as a modification of Bingham's equation. The shear resistance of the concrete mix is explained in terms of two constants—yield value and plastic viscosity. The complex nature of the yield value is described. It is pointed out that there are three different zones of rheological behavior of fresh concrete, which arise as a result of the relation between shear stress and yield value of the mix. This paper also describes an experimental study that measures the effects of superplasticizer, water-to-cement (w/c) ratio, condensed silica fume (CSF) and elapsed time on the rheological parameters for fresh concrete. The rheological tests were carried out on a ROD1E rotational rheometer. In total, 102 flow curves were obtained from which the yield values g and the plastic viscosities h for a wide range of concrete mixes were determined. The results showed that superplasticizers became less effective with increase in w/c ratio and that different superplasticizers have widely different effects on changes in g and h. It was also established that CSF additions generally reduce workability, although above a certain CSF content a sharp reduction in plastic viscosity occurs. In addition it was observed that superplasticizers generally extend the period over which a mix remains workable. The results are discussed in terms of the theoretical foundations.

INTRODUCTION

Superplasticizers used in concrete technology make it possible to obtain very low water-to-cement (w/c) ratios while maintaining the required concrete workability. Although admixtures have been widely recognized, their application in concrete technology is still subject to imprecision and uncertainty, due in part to insufficient reliable qualitative and quantitative data concerning their influence on concrete workability. Tattersall (1973) demonstrated the limitations and deficiencies of Vebe tests, slump tests, and cone flow tests in fully defining and quantifying workability, yet those tests are still used extensively because of their simplicity and portability. The main reason for the absence of more meaningful data on workability is the difficulty in testing fresh concrete mixes by rheometrical methods, although these are considered to be the most definitive tests for workability (Tattersall 1983; Szwabowski 1987; Wallevik and Gjørv 1990; Szwabowski et al. 1995). Rheometers for concrete mixes are to be found only in a few research centers. Hence, although the effects of superplasticizers on cement paste have been extensively tested using commercially available viscometers (Roy and Asaga 1980a,b; Collepardi et al. 1980; Chioccio and Paolini 1985; Mierzwa 1989), only limited research results have been published on fresh concrete mixes (Banfill 1980; Kikukawa 1990; Faroug 1994; Malhotra 1990; Wallevik and Gjørv 1990). The potential for greater precision and control over concrete workability by use of superplasticizers is thus restricted, and, in consequence, the improvement of concrete quality is inhibited, especially with regard to high strength concrete and high performance concrete, which are practically unworkable without superplasticizers. An objective estimation of the influence of superplasticizers (i.e., their type, dosage volume, and dosage time) on fresh concrete mix workability can be provided only if the changes in the rheological parameters of fresh concrete are identified.

Such tests are especially critical because the combination of a low w/c ratio with condensed silica fume (CSF) and superplasticizer (SP) has a complex influence on workability. To identify precisely the influence that these variables have on the fundamental rheological properties of concrete, tests have been conducted on a ROD1E rheometer in the Division of Building Materials and Process Technology in the Silesian Technical University, in Gliwice, Poland. The results are discussed in this paper.

THEORETICAL FOUNDATIONS

The definition of workability in concrete technology should be considered in terms of the state of the system (i.e., the composition of the concrete mix and the method of processing). This state is determined by the relationship between two factors: (1) The rheological parameters of a given mix; and (2) the dynamic forces acting on it during processing (Szwabowski 1987). The rheological properties are determined by the structure of the mix only. They characterize its strain and stress behavior. Therefore, concrete mix workability is determined by the reaction of the mix to the forces acting on it during transport and mechanical processing and by the resistance of its structure to these forces. A concrete mix can be considered as a three-phase dispersed system in which shear resistance τ is a fundamental property of the system. Shear resistance results from a combination of the effects of cohesion τ_c, internal friction τ_ς, and viscous resistance τ_η (Szwabowski 1987); that is

$$\tau = \tau_c + \tau_\varsigma + \tau_\eta \quad (1)$$

The relative contribution that each of these three components makes to the resistance depends on the composition of the concrete mix and, consequently, on its structure. For liquid concrete with high paste content, viscous resistance is predominant. Alternatively, for low paste content mixes, internal friction is pivotal. The first two components of shear resistance may be described according to Szwabowski (1987) as follows:

$$\tau_c + \tau_\varsigma = c + \sigma_{ef} \tan \varsigma = (H + \sigma_{ef}) \tan \varsigma \quad (2)$$

where H = pressure of cohesion; σ_{ef} = effective normal stress; ς = angle of internal friction; and c = cohesion. $H \tan \varsigma$ describes the shear resistance of the concrete mix without normal stresses to the shear plane, which corresponds to the yield value in Bingham's classical model.

Pressure of cohesion in a concrete mix, as a result of capillary pressure in interparticle pores, depends on the volumetric

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ratio of water to pores in the mix (Szwabowski 1990). According to Laplace's equation, capillary pressure is directly proportional to the surface tension of water and to the cosine of the contact angle between solid and water, and it is inversely proportional to the capillary diameter. Therefore, cohesion of a concrete mix can vary according to changes of the w/c ratio, angle of contact, fineness, modulus of the solid particles, and binder paste content.

Internal friction for a given mix depends on the effective normal stress, that is

$$\sigma_{ef} = \sigma - \sigma_n \tag{3}$$

where σ = normal stress; and σ_n = neutral hydrostatic pressure in the fluid phase. The effective normal stress depends on the volume concentration of aggregate and the volume of paste in the concrete mix. Taking into account a unit volume of the mix, the area of the plane of shear can be divided into two parts: (1) Area occupied by grains of aggregate A_a; and (2) area occupied by binder paste with air bubbles A_p. Denoting the ratio of intergranular pore volume to the concrete mix volume as υ_{pm} the following relations can be obtained:

$$A_p = 1\upsilon_{pm} \tag{4}$$

$$A_a = 1(1 - \upsilon_{pm}) \tag{5}$$

Therefore, normal stress to the plane of shear is

$$\sigma = \sigma A_a + \sigma A_p = \sigma(1 - \upsilon_{pm}) + \sigma\upsilon_{pm} \tag{6}$$

where

$$\sigma(1 - \upsilon_{pm}) = \sigma - \sigma\upsilon_{pm} = \sigma_{ef} \tag{7}$$

Viscous resistance is given by

$$\tau_\eta = \eta_{pl}\dot{\gamma} \tag{8}$$

where η_{pl} = coefficient of viscosity (plastic viscosity); and $\dot{\gamma}$ = shear rate. Thus the shear stress in the concrete mix has the form

$$\tau = (H + \sigma_{ef})\tan\varsigma + \eta_{pl}\dot{\gamma} \tag{9}$$

where the expression $(H + \sigma_{ef})\tan\varsigma$ is the yield stress τ_0 of the concrete mix. Eq. (9) is a rheological equation of the concrete mix. It is also a generalized form of the Coulomb and Bingham equations.

The analysis of the stress behavior of the concrete mix indicates three characteristic zones—finite strain, plastic flow, and viscous flow. The rheological criteria for the occurrence of the three zones are, at the same time, the general criteria of workability. When the shear stress is lower than the total value of cohesion and internal friction, the mix behaves like a solid body for which the strain value is limited and proportional to the stress value. That is

$$\tau/(c + \sigma_{ef}\tan\varsigma) << 1 \quad \text{and} \quad \tau/(\gamma G) \approx 1 \tag{10}$$

where G = shear modulus of the solid. Because no distinct boundary is observed between the solid body zone and the viscous liquid zone of the concrete mix, the conditions in (10) have a ''blurred'' form. The two behavior zones are separated by the plastic flow zone, which partly converges with them. If the ultimate shear resistance (termed the yield stress τ_0) is assumed, condition (10) has the form

$$\tau/\tau_0 << 1 \quad \text{and} \quad \tau/(G\gamma) \approx 1 \tag{11}$$

This form of the equation is more useful, because in rheological work it is easier to determine τ_0 than to determine c and $\tan\varsigma$ separately.

The mix behaves like a viscous liquid when the stress value is higher than the total of cohesion and internal friction resistance, and the difference between the stress value and the cohesive and frictional resistance is proportional to the shear rate; that is

$$\tau/(c + \sigma_{ef}\tan\varsigma) >> 1 \quad \text{and} \quad (\tau - (c + \sigma_{ef}\tan\varsigma))/\eta_{pl}\dot{\gamma} \approx 1 \tag{12}$$

where $1/\eta_{pl}$ = measure of the susceptibility of the concrete mix to viscous flow, also called the mobility in Bingham's media.

Plastic flow of the concrete mix occurs when the shear stress values are close to the total value of resistance of cohesion and internal friction; that is when

$$\tau/(c + \sigma_{ef}\tan\varsigma) \approx 1 \tag{13}$$

For this state, if $c/\sigma_{ef}\tan\varsigma >> 1$ then the resistance of the concrete mix against plastic flow is mainly due to cohesion and if $c/\sigma_{ef}\tan\varsigma << 1$ it is mainly due to internal friction. The use of superplasticizers evokes changes in the rheological characteristics of concrete mixes, making them more liquid. These changes result from the high negative value of the electrokinetic potential (zeta potential) at the cement-water interface, which increases cement dispersion in concrete paste and facilitates the release of water by reducing the adsorptive and capillary forces within the cement paste (Roy and Asaga 1980a,b; Malhotra 1990). The type, dosage volume, and application method of the superplasticizer are not the only factors that determine its influence on a given concrete mix. Concrete type, mix composition, and concrete mix temperature also contribute to this influence.

Because the rheological properties of the concrete mix are of a nonlinear character and its shear resistance is a function of the shear rate, the measurements of the rheological properties should be taken at no less than two considerably different strain rate values. If the shear rate is changed and the corresponding shear stress values are measured, the flow curve of the concrete mix that relates shear stress to strain rate may be obtained (i.e., the concrete mix behavior at $\tau > \tau_0$). The flow curve, described by (9), makes it possible to designate the rheological parameters that determine concrete mix workability (i.e., the plastic viscosity η_{pl} and yield stress τ_0) under given mechanical processing conditions.

EXPERIMENTAL MEASUREMENTS

The purpose of the current research is to determine the influence of different types and dosages of superplasticizer on the rheological properties of concrete when applied to concrete mixes of differing w/c ratios. This will include, in particular, modifications to the mix by microsilica. The mix components included portland cement 35 (OPC), sand grain sizes up to 2 mm, granite aggregate sizes of 4–8 and 8–16 mm, and, in some selected mixes, ''Laziska'' microsilica. The superplasticizers applied were Betoplast 1 and Betoplast 2 (naphthalene formaldehyde admixtures) both manufactured by ITB, Warsaw, Poland, and SK1 (a melamine formaldehyde admixture) manufactured by Nitrogen Works, Kędzierzyn. A pan mixer of 0.04-m^3 nominal size was used for the preparation of the concrete mixes. The changes in the rheological parameters τ_0 and η_{pl} were assessed by detecting the corresponding changes in $\mathbf{g}$ and $\mathbf{h}$ from the flow curve characteristics. The relations between τ_0 and $\mathbf{g}$ as well as η_{pl} and $\mathbf{h}$ (Banfill and Tattersall 1983) are given by

$$\tau_0 = \frac{K}{G_a}\mathbf{g} \tag{14}$$

$$\eta_{pl} = \frac{1}{G_a}\mathbf{h} \tag{15}$$

where G_a = apparatus constant; and K = mean shear rate. The constants **g** (Nm) and **h** (Nms) are determined by regression analysis of the measurement data set consisting of eight pairs of corresponding T and N values for each rotational velocity of the impeller, according to the relation

$$T = \mathbf{g} + N\mathbf{h} \tag{16}$$

where T = torque; and N = velocity of the impeller. By suitable calibration it is possible to determine the values of G_a and K, if it is necessary to express the yield value and plastic viscosity in fundamental units. In the present investigation where the object was to determine the relative changes in the rheological constants of concrete mixes in relation to silica fume content and superplasticizer type and content, calibration was considered unnecessary.

Measurements were carried out with the ROD1E rheometer. The concrete mix under test was contained in a 300-mm-diameter and 330-mm-deep cylinder, which could be raised and lowered by a jackscrew. The cross vane type 150-mm-diameter and 200-mm-long impeller was immersed in the concrete mix and was rotated about its own axis, coaxially with the cylinder, by means of a 2-kW electric motor operating through gear transmission. The rotational velocity of the impeller was controlled within the range 0–1 rps. The range of the torque measuring device was 0–40 Nm.

Altogether, 102 flow curves were obtained. The procedure was repeated for over 50 flow curves selected randomly. The research scheme was designed for a greater number of tested mixes, but the number was restricted due to mix segregation at high superplasticizer dosages and to shear resistance values exceeding the rheometer's range for the low workability mixes. The correlation coefficients calculated for the flow curves used to determine **g** and **h** were generally in the range of 0.95–0.99 with only 9% falling below 0.9. The procedures adopted using the ROD1E rheometer were as follows:

1. The cylinder was filled with a given concrete mix while the vane type cross-shaped impeller was in motion, rotating at 1.5 rpm.
2. The rotational speed of the impeller was gradually increased to 45 rpm over 10 s and then reduced to 41 rpm. Measurements of the concrete mix resistance and corresponding angular velocity values were taken at rotational speeds of 33, 15, 6.5, and 0 rpm. For a given angular velocity, the measurement time did not exceed 15 s, during which eight readings of angular velocity and torque were obtained.
3. Finally the rotational speed was increased to 33 rpm, the torque value measured, the impeller stopped, and the mix allowed to settle. The cylinder was then emptied, and any sample segregation was estimated visually.

Three sets of tests were carried out.

In the first set, the changes produced by each superplasticizer were determined. Different dosages were used in concrete mixes with w/c ratios ranging from 0.25 to 0.50 and with a constant cement content of 335 kg/m^3. The results of the measurements obtained in Set 1 are presented in Figs. 1–6.

In the second set of tests, the rheological changes to silica fume concrete produced by the Betoplast 1 superplasticizer were determined. The concrete mix parameters were w/c = 0.45; cement content = 335 kg/m^3; and percent of microsilica = 0, 2.5, 5, 7.5, and 10 added to mix, or 0, 10, 15, 20, 30 as cement replacement. In the former case percentages are expressed in terms of weight of OPC and in the latter case as percentages of total binder weight (i.e., OPC + CSF). In the latter case the total binder is 335 kg/m^3, and the water-to-binder (w/b) ratio is 0.45. The superplasticizer dosage used was 0 and 1.0% when microsilica was added and from 0.5 to 4.0% when cement was partially replaced by microsilica. The concrete mix parameters, and in particular the superplasticizer dosage levels, were selected to enable measurements at very high microsilica levels while taking into account the measuring range of the rheometer and the compositions for which segregation was observed in preliminary tests. The preparation of mixes for both the first and second set of experimental measurements involved mixing cement with granite aggregate for 30 s, then adding water and mixing it for 3 min, and, after adding the superplasticizer, mixing it again for two more minutes. The results of measurements obtained in Set 2 are presented in Figs. 7–10.

The third set of experiments involved the introduction of the given dosage of the superplasticizers into the concrete mix (w/c = 0.45) and observing the changes of **g** and **h** occurring with time, starting from the dosage time. The mix was not sheared continuously but was stirred before each measurement was taken. The results are presented in Figs. 11 and 12.

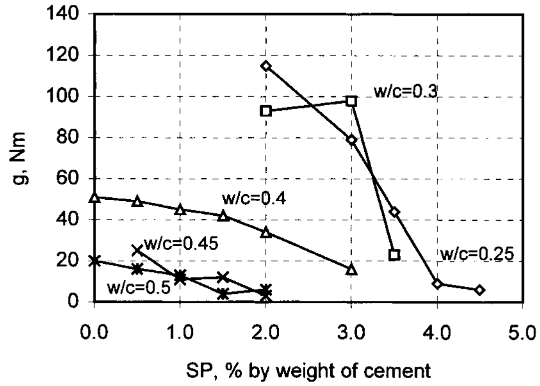

FIG. 1. Relationship between Betoplast 1 Dosage and Yield Value at Different w/c Ratios

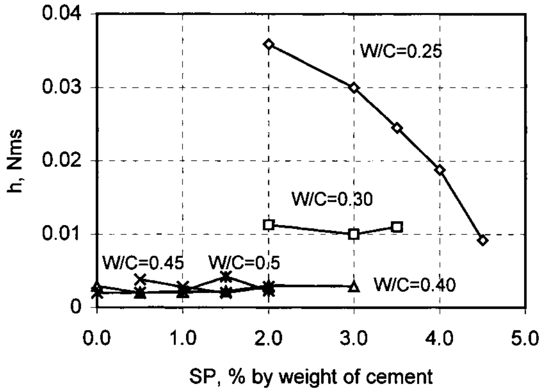

FIG. 2. Relationship between Betoplast 1 Dosage and Plastic Viscosity at Different w/c Ratios

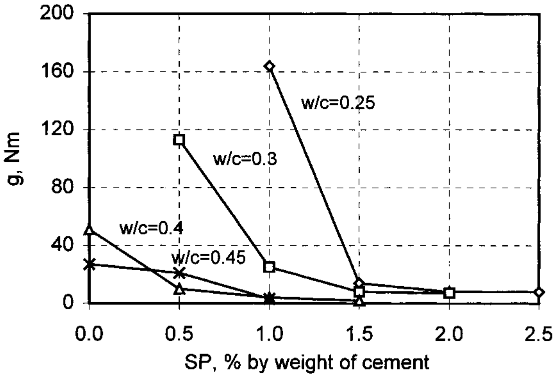

FIG. 3. Relationship between Betoplast 2 Dosage and Yield Value at Different w/c Ratios

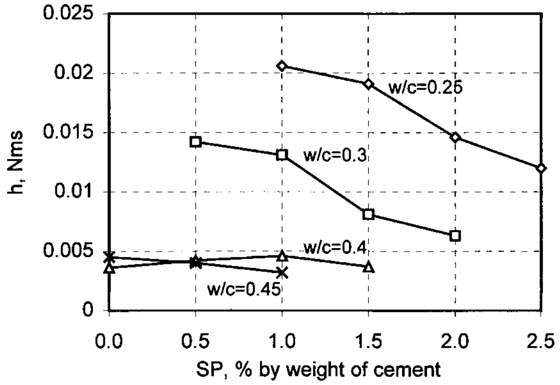

FIG. 4. Relationship between Betoplast 2 Dosage and Plastic Viscosity at Different w/c Ratios

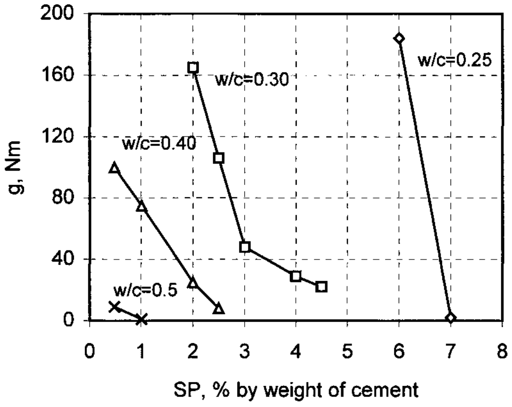

FIG. 5. Relationship between SK1 Dosage and Yield Value at Different w/c Ratios

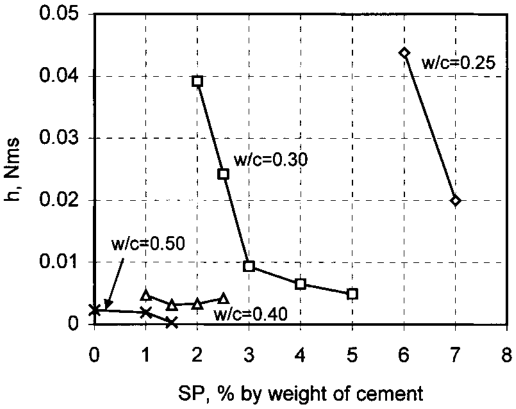

FIG. 6. Relationship between SK1 Dosage and Plastic Viscosity at Different w/c Ratios

DISCUSSION OF RESULTS

Influence of Superplasticizer Type and Dosage

As might be expected, the introduction of superplasticizers into the concrete mix resulted in substantial reductions in yield value and plastic viscosity. The range of the changes depended on the superplasticizer type. In Figs. 1–6, the test results indicate that, at the same dosages and w/c ratios, the application of NF superplasticizer (Betoplasts 1 and 2) is more effective than MF superplasticizer (SK1) in reducing yield value **g** and plastic viscosity **h**. Also, the w/c ratio has a big influence on the relative performance of the different superplasticizers and on the total effect they have in reducing **g** and **h**. High w/c ratios result in a reduction in the performance of the superplasticizers.

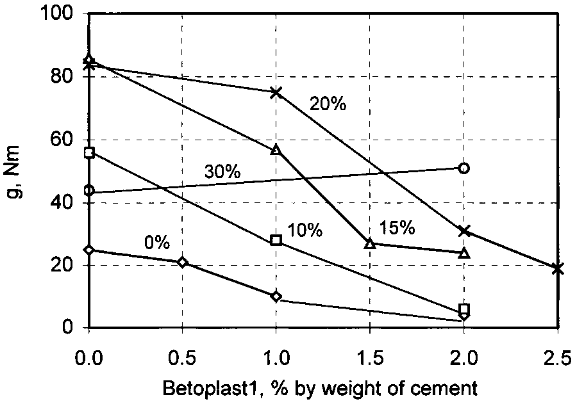

FIG. 7. Relationship between SP Dosage and Yield Value for Different CSF Contents, Mix w/b Ratio of 0.45

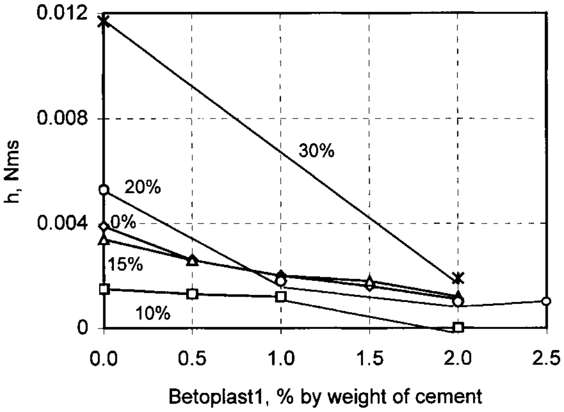

FIG. 8. Relationship between SP Dosage and Plastic Viscosity for Different CSF Contents, Mix w/b Ratio of 0.45

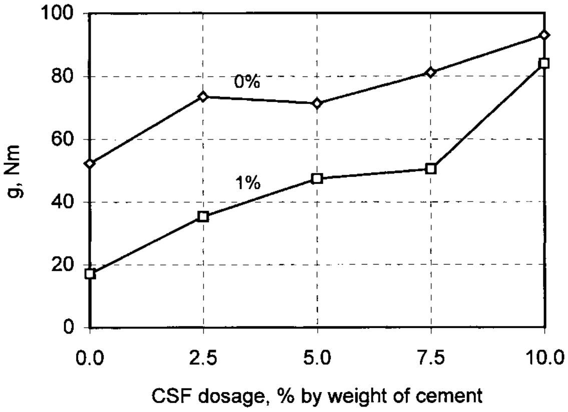

FIG. 9. Relationship between CSF Dosage and Yield Value at 0 and 1% Addition of Betoplast 1, Mix w/b Ratio of 0.45

According to the results of the experimental measurements (Figs. 1–6), for w/c > 0.5 the changes in the rheological properties of the concrete are minimal, and there is increasing likelihood of mix segregation. This phenomenon results because with an increasing w/c ratio the proportion of total water to the adsorbed capillary and floc water increases. Therefore the water released by the superplasticizer constitutes a decreasing proportion of the total water in the mix. Even a small increase in the free flowing water may result in loss of stability of the concrete mix and its internal segregation, at which stage any further increase in superplasticizer is pointless. As would be expected when the w/c ratio increases a smaller superplasticizer dosage is required to obtain the same mix workability, and when w/c decreases the dosage must accordingly be larger. The test results indicate clearly that it is not practical to apply the recommended dosage without referring to the mix composition, because the optimal superplasticizer dosage depends

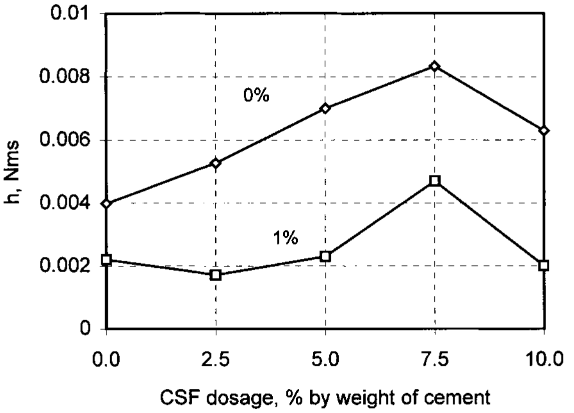

FIG. 10. Relationship between CSF Dosage and Plastic Viscosity at 0 and 1% Addition of Betoplast 1, Mix w/b Ratio of 0.45

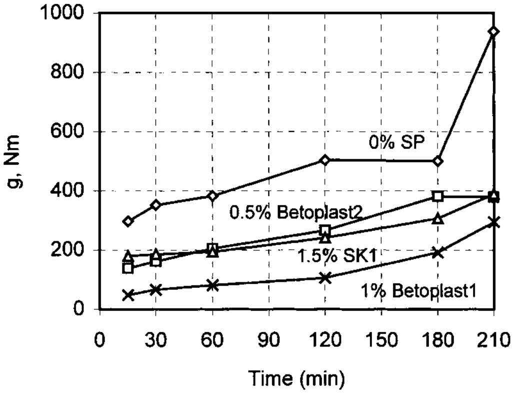

FIG. 11. Variation of Yield Value with Time

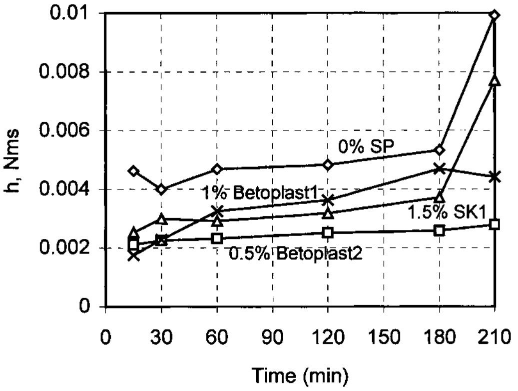

FIG. 12. Variation of Plastic Viscosity with Time

not only on w/c ratio but also on cement type and volume, as well as on the fineness of the sand used and of any other component such as microsilica. On the scale selected, the figures indicate that superplasticizers have a greater influence on the values of **g** than they do on the values of **h**. It should be emphasized, however, that the changes of the two constants are not comparable, because, unlike the ultimate yield value, plastic viscosity is only a resistance to the unitary change in the shear rate. It follows that the flow resistance change, due to the plastic viscosity change, is proportional to the shear rate. The extent of the yield value change depends on the change in the magnitude of capillary cohesion in the mix. Szwabowski (1990) pointed out that the influence of capillary cohesion on the yield value varies with concrete mix composition and that the relationship between the magnitude of capillary cohesion and the volume of liquid phase for a concrete mix shows a distinct zone where the yield value is at a maximum. Within this zone, cohesive resistance is the dominant component of the yield value; therefore, superplasticizers produce a very significant decrease in yield value. Unlike capillary cohesion, internal friction decreases systematically with increase in liquid phase (binder paste) volume, but in relation to capillary cohesion its contribution to the yield reduction is much less significant. The influence of superplasticizers on plastic viscosity reduction depends on the w/c ratio, and for w/c $\geq$ 0.4 their effect is negligible for all three superplasticizers investigated. For w/c > 0.5, Betoplast 2 superplasticizer addition produces mix segregation. Thus, summing up, it is evident that both the superplasticizer type and the dosage volume are important modifiers of the rheological properties of concrete mixes but over a limited range of w/c ratios.

Influence of CSF and Superplasticizer

Microsilica added to cement mixes changes their rheological properties. It may be applied as a replacement of a part by weight of the cement or as an admixture. Figs. 7 and 8 illustrate the changes in **g** and **h**, with increasing superplasticizer dosage (Betoplast 1) at various microsilica cement replacement levels and at a w/b ratio of 0.45.

If the microsilica content is below 20% (by weight of binder), the yield value rises with increase in microsilica content. However, any further increase in microsilica content above 20% results in a lowering of the yield value. Also at 30% microsilica content the yield value is higher for 2.0% Betoplast 1 addition than it is for the mix without the application of superplasticizer. In the case of the plastic viscosity, at low doses of Betoplast 1 its value initially decreases with increase in CSF content and subsequently increases for CSF replacement levels above 10%. As the superplasticizer dosage is increased, the plastic viscosity decreases. Also the greater the rise of viscosity produced by the microsilica, the greater is the reduction brought about by the superplasticizer. Thus at high superplasticizer dosages the plastic viscosity is similar for all microsilica replacement levels investigated. For example, if the concrete mix contains 30% of microsilica as cement replacement and w/b = 0.45, a 2% addition of Betoplast 1 makes it possible to reduce the plastic viscosity to the same level as in the equivalent concrete mix without microsilica.

Figs. 9 and 10 illustrate the influence of microsilica when used as an admixture. If the amount of microsilica addition is increased for a w/c ratio of 0.45, the yield value is also increased, irrespective of the presence of the superplasticizer. Comparison of the curves in Fig. 9 demonstrates that, for the same 1% dosage of Betoplast 1, its influence on the yield value decreases with increase in the addition of microsilica, which is an indication of the need to increase the superplasticizer dosage if the content of microsilica is concurrently increased. The changes in plastic viscosity are more complex. The plastic viscosity increases with increase in the addition of microsilica but only up to a microsilica addition of 7.5%; beyond this microsilica level the plastic viscosity decreases, even reaching a value equal to the corresponding concrete mix without microsilica, for the mix containing Betoplast 1 (1% content). In view of these results, the simple universal adage that microsilica admixtures reduce concrete mix workability cannot be wholly justified.

Influence of Superplasticizer on Changes in Rheological Parameters with Time

Superplasticizers not only improve the workability of concrete mixes (lowering the yield stress and plastic viscosity) but also extend the workable period before setting. Figs. 11 and 12 illustrate the changes in the rheological parameters of the concrete mixes with time, starting from the time of mixing. As can be observed, even small dosages of the superplasticizers improve concrete mix workability. The concrete mix without the superplasticizer rapidly loses its workability after 180 min, whereas with the application of superplasticizers this effect is prolonged for at least a further 30 min with respect to the yield value. Plastic viscosity does however show a sharp increase after 180 min for the addition of 1.5% SK1.

Figs. 1–6 show the effect of dosage levels of the three different superplasticizers on the rheological constants **g** and **h** at various w/c ratios. If the effects of time are not considered, an indication of the influence on these rheological constants is demonstrated in Figs. 13 and 14 using a particularly low w/c ratio (0.25). According to these results much smaller doses of Betoplast 2, than Betoplast 1 and SK1, are required to bring about equivalent reductions in **g** and **h** and provide high workability.

CONCLUSIONS

The introduction of superplasticizers into concrete mixes improves their workability, by lowering the shear and flow resistance. However, this effect gradually disappears with the passage of time. Nevertheless, the period of loss of workability of the concrete mixes with time is extended when superplasticizers are added, in comparison with the corresponding concrete mixes without superplasticizers. Better workability is mainly a result of lowered yield value, as plastic viscosity decreases proportionately less than yield value. The range of the changes depends on w/c ratio, superplasticizer type, and dosage.

The lower the w/c ratio, the more effective is the superplasticizer in increasing the mix workability when applied at constant dosage. The range of possible workability improvements increases along with decreasing w/c ratio, yet, conversely, this requires bigger dosages of superplasticizer. The optimal dosage depends on the mix composition, and it can be determined by experimental methods only. At high w/c ratios (e.g., w/c = 0.5), the superplasticizer becomes ineffective and segregation of the mix may occur. Among the superplasticizers tested at low w/c ratios, for a given dosage NF superplasticizers are more effective in increasing workability than are MF superplasticizers.

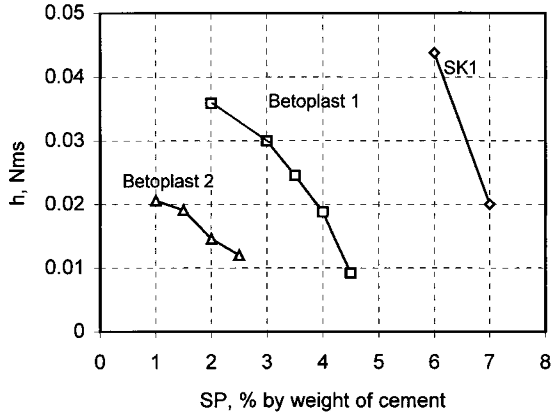

FIG. 13. Effect of SP type on Plastic Viscosity, Mix w/c Ratio of 0.25

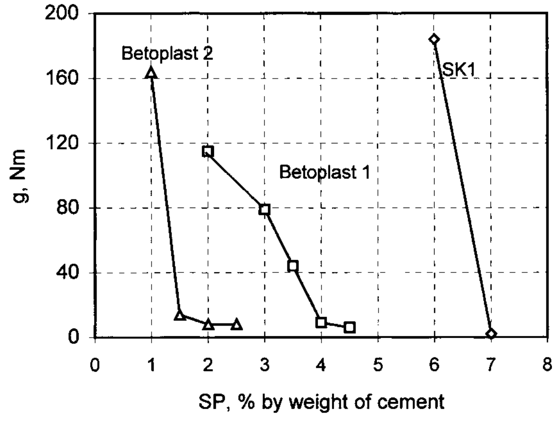

FIG. 14. Effect of SP Type on Yield Value, Mix w/c Ratio of 0.25

In general, microsilica reduces the workability of concrete mixes, irrespective of whether the microsilica has been applied as an admixture or as replacement of a part of the cement volume. This is a result of the considerable increases (often many times higher) in the values of the yield value and plastic viscosity, depending on microsilica content. However changes in **g** and especially **h** show a complex nonlinear relationship with microsilica content, and over particular ranges **g** or **h** may decrease with increase in microsilica. The optimal selection of superplasticizers and the dosage required makes it possible to recover or even increase the workability of a concrete mix to which microsilica has been added.

APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

A_a = area on plane of shear occupied by aggregate grains;
A_P = area on plane of shear occupied by binder paste;
c = cohesion;
G = shear modulus;
G_a = apparatus constant;

$\mathbf{g}$ = rheological constant proportional to yield value;
H = pressure of cohesion;
$\mathbf{h}$ = rheological constant proportional to plastic viscosity;
K = mean shear rate;
N = rotational velocity;
T = torque;
υ_{pm} = ratio of intergranular pores volume to concrete mix volume;
γ = shear strain;
$\dot{\gamma}$ = shear rate;
η_{pl} = plastic viscosity;
σ = normal stress;
σ_{ef} = effective normal stress;
σ_n = neutral hydrostatic pressure;
τ = shear resistance;
τ_c = resistance of cohesion;
τ_η = viscous resistance;
τ_ς = resistance of internal friction;
τ_0 = yield value; and
ς = angle of internal friction.