The influence of mineral admixtures on the rheology of cement paste and concrete

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CEMENT AND CONCRETE RESEARCH

The influence of mineral admixtures on the rheology of cement paste and concrete

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Abstract

Rheological tests on cement paste were used to successfully select the type and dosage of mineral admixtures that improved concrete workability. Among the six different mineral admixtures tested, the ultrafine fly ash (UFFA) was determined to give the best results by reducing the yield stress and viscosity. These improved rheological properties were not achieved by increasing the water demand and/or the high-range water reducer (HRWR) admixtures dosage. Therefore, the addition of UFFA improved the concrete flow without a potential decrease of the hardened properties or an increase in cost. The conclusions reached based on cement paste tests were validated by concrete slump tests. The cement paste rheological data were also compared using two simpler tests, minislump and Marsh cone. The goal was to determine whether the simpler tests could be used to characterize the rheology of cement paste adequately. The conclusions are that these simpler tests are unreliable for measuring workability.

Keywords: Rheology; Cement paste; Workability; Fresh concrete

1. Introduction

High-performance concrete (HPC) is a complex mixture often containing 5–10 different materials. Interaction between the various materials can cause wide variations in workability, which also depends on the specific materials and proportions used. Determining workability properties by testing concrete is not always practical. Extensive concrete testing requires a large amount of materials and labor, which is expensive. There is, therefore, a need to predict the workability of concrete through a simpler, cheaper laboratory approach. This paper describes an attempt to utilize rheological measurements in cement paste as a reasonable indicator of concrete workability. Concrete workability is defined, according to American Concrete Institute (ACI), as the ease of placement of concrete and is usually quantified by the result of the slump cone test.

Rheological tests on cement paste were used to select the type and dosage of mineral admixtures that improved concrete workability. The conclusions reached based on cement paste tests were validated by concrete slump tests. It was also deemed interesting to compare the fundamental parameters (yield stress and viscosity) measured with a fluid rheometer with the results from two commonly used empirical tests, the minislump and the Marsh cone tests. If a relationship could be established, the empirical tests could be used to design materials for a given yield stress and viscosity or, at the very least, rank different materials base on yield stress or viscosity.

The decision to study the influence of mineral admixtures was dictated by the recent increase in use of mineral admixtures for improved concrete durability. Economics (lower cement requirement) and environmental considerations have also had a role in the growth of mineral admixture usage. The lower cement requirement also leads to a reduction in the amount of carbon dioxide generated by the production of cement, while the use of a mineral admixture utilizes a product that would ordinarily be bound for the land fill. Thus, there is a double environmental benefit from using mineral admixtures.

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2. Background

2.1. Concrete workability characterization

Concrete workability cannot necessarily be sacrificed for improved hardened properties, such as durability or strength. Workability is typically quantified in the field by the result of the slump cone test. Nevertheless, a survey [1] conducted by the National Ready-Mixed Concrete Association (NRMCA) and the National Institute of Standards and Technology (NIST) determined that, for HPC, the slump cone value is not representative of the ease of handling HPC in the field. It was reported that concrete mixtures with the same slump might not behave the same way during placement. This implies that the slump value does not give enough data to fully characterize concrete flow.

In the construction field, terms like workability, flowability, and cohesion are used, sometimes interchangeably, to describe the behavior of concrete under flow. The definitions of these terms are very subjective. Therefore, there is a need for a more fundamental and quantitative description of concrete flow. Rheological measurements of concentrated suspensions can be used to describe the flow of concrete. Numerous researchers [2–4] have successfully used the Bingham equation. Two parameters define the flow: yield stress and plastic viscosity [5]. Yield stress is related to slump [6,7], but plastic viscosity is usually ignored because only a few type of instruments exist to measure it [8]. However, the viscosity may be related to properties such as stickiness, placeability, pumpability, and finishability. In addition, segregation could be defined as the ability of the aggregate to migrate (or sink) in the cement paste. This phenomenon is linked to the viscosity of the cement paste and the concrete mixture design. Therefore, methods to predict concrete workability need to take into account more than just the yield stress.

2.2. Concrete rheology from cement paste rheology

Admixtures mainly affect the flow behavior of the cement paste without altering the composition or behavior of the aggregates. Therefore, it seems reasonable to try to select admixtures, chemical and mineral, by only testing the cement paste. Ideally, the results will then be related to the concrete workability. Unfortunately, the relationship between cement paste rheology and concrete rheology has never been completely established. The main reason for this is that cement paste rheology is typically measured under conditions that are never experienced by the cement paste in concrete. Therefore, the measured cement paste rheological parameters may differ from those estimated from concrete parameters. The values usually reported in the literature for cement paste do not take into account the contribution of the aggregates [9]. The aggregates act as heat sinks and shear the cement paste during the mixing process. A computerized model to simulate the concrete being sheared is under development at NIST [10]. This model will predict concrete rheology from constituent properties that will include rheological measurements on cement paste.

However, the cement paste flow properties, if measured "properly," can be used to screen mineral admixtures. The details of the methodology are presented elsewhere [11], but the following principles should be reiterated. The cement paste needs to be mixed and tested under the conditions similar to those that it will experience in concrete, primarily shear and temperature history. Therefore, a high-shear, temperature-controlled mixer should be used. To measure the rheological parameters of cement paste flow, a parallel plate rheometer must be used because it is the only rheometer with variable geometry. It has been established [12] that the rheological properties of cement paste change if the material is squeezed between two surfaces or aggregates as in concrete. The distance between the surfaces is called the "gap." In a parallel plate fluid rheometer, the gap or distance between the plates can be varied easily to more closely represent the shearing action imposed on paste in concrete. In this paper, cement paste rheological parameters were measured using the above method as a function of type and dosage of mineral admixture.

2.3. Role of fine powder additions on workability

It is usually reported that, if the volume concentration of a solid is held constant, the addition of mineral admixtures improves concrete performance but reduces workability. The most common reason for poor workability is that the addition of a fine powder will increase the water demand due to the increase in surface area. This belief is supported by test results that show that the addition of fine silica fume (SF) particles increases the water demand to attain specific workability levels. However, in certain cases, it is reported in the literature that the use of fine mineral admixtures can reduce the water demand or increase the slump. Lange et al. [13] measured the water demand of mortars with increasing additions of a very fine blast furnace slag. He found that, for a specific flow, an optimum amount of blast furnace slag reduced the water demand of the mortar. A popular hypothesis put forward to explain the workability enhancement due to the use of certain fine mineral admixtures, especially fly ash (FA) or SF, is that the spherical particles easily roll over one another, reducing interparticle friction [14]. The spherical shape also minimizes the particle's surface to volume ratio, resulting in low fluid demands. Out of all 3D shapes, a sphere gives the minimum surface area for a given volume [15]. Sakai et al. [16] reported that a higher packing density was obtained with spherical particles as compared to crushed particles in a wet state. This resulted in lower water retention in the spherical case and subsequently lower water demand for a specific workability. A strong dependence of fluidity (defined as the inverse value of the viscosity) on the average particle size was reported with a pessimum value [16]. It was explained that, at an optimal particle size, the packing density was maximum, which helped to achieve maximum fluidity. Recently, Collins and Sanjayan [17] reported that in concrete containing alkali-activated ground granulated slag as the binder, the workability was improved by replacing part of the binder with ultrafine materials. This material had 90% by mass of the particles smaller than 13.7 μm. It was also reported that some similar materials were not effective in improving the workability. It can be concluded from this survey of the literature that the selection of a fine mineral admixture for improved concrete workability is not a trivial problem. At present, this selection cannot be predicted from the physical or chemical characteristics of the admixture, and can only be determined using a properly designed test.

3. Materials, mixing, and testing details

The materials, mixing, and testing requirements provided here are for the cement paste tests only. The details for the concrete test program are provided in Section 5.

3.1. Materials

The cement was an ASTM Type I portland cement whose composition is described in Table 1. This cement was used for all tests, both concrete and cement paste. The high-range water reducer (HRWR) was a naphthalene sulfonate-based product with a mass fraction of 43% active ingredients. The mineral admixtures used are shown on Table 2 with their mean particle diameters (PDs). The mean PD was measured using a laser diffraction particle size analyzer. Four different FAs, all from the same plant, were tested. FA was the standard FA available in that plant and used in concrete type applications. Coarse fly ash (CFA) was a coarse ash that is usually rejected as it does not meet the ASTM C618 requirements for particle size. Fine fly ash (FFA) is a finer form of ash obtained by separation from a coarser ash using a classifier. Ultrafine fly ash (UFFA) is an ultrafine ash obtained by still more rigorous separation.

Table 1
Cement composition

Chemical composition	Percentage by mass
Loss on ignition (LOI)	1.29
Sulfur trioxide (SO_3)	2.79
Silica dioxide (SiO_2)	20.86
Ferric oxide (Fe_2O_3)	3.47
Magnesium oxide (MgO)	1.21
Aluminum oxide (Al_2O_3)	4.60
Equivalent alkalies (as Na_2O)	0.46
Calcium oxide (CaO)	64.34
Free lime	–
Insoluble residue (IR)	0.1
Tricalcium silicate (C_3S)	59.57
Tricalcium aluminate (C_3A)	6.31

Table 2
Mineral admixtures

No.	Name	Mean PD [μm]
1	Coarse Fly Ash (CFA)	18.0
2	Fly Ash (FA)	10.9
6	Fine Fly Ash (FFA)	5.7
3	Ultra Fine Fly Ash (UFFA)	3.1
4	Metakaolin (MK)	7.4
5	Silica Fume (SF)	≈0.1

The cement paste composition was varied to explore the influence of mineral admixture dosage and type on the rheological properties. The performance differences in the paste due to the addition of mineral admixture were measured either by the rheological properties at constant water content or by the water reduction at constant mineral and chemical admixture dosage. The compositions of the cement pastes can be summarized as follows:

- water/cement ratio: 0.28–0.35;
- dosages of mineral admixtures: 0–16% of cement, replacing cement by mass; and
- dosage of HRWR (based on naphthalene sulfonated condensate): 0.45–0.70% solid by mass of cementitious materials.

3.2. Cement paste preparation

The cement paste preparation is very important because the shear history of a mixture will influence its rheological behavior. In this case, we wanted to have the same shear history as in the concrete in order to be able to compare the neat cement paste behavior and the concrete flow. Two types of mixers were considered: a standard paddle mixer [18] and a high-speed blender. The cement paste was mixed using a paddle mixer according to the procedure of ASTM C305, except that no sand was added.

The second mixer used was a large (4 L) blender. This blender was not temperature controlled. The cement paste mixture was prepared according to the following procedure.

- The cement and the mineral admixture (if any) were mixed dry for about 5 s by hand outside the mixer.
- Water was poured into the 4-L blender.
- The mixer was started at slow speed and the cement–mineral admixture mixture was added over a 50-s period.
- The HRWR was added in 5 s.
- The mixture was mixed for another 60 s at slow speed.

3.3. Cement paste testing details

Fresh cement paste specimens were tested first in a parallel plate fluid rheometer and then using the minislump and Marsh cone. The testing details are given below.

3.3.1. Parallel plate rheometer

The parallel plate rheometer was used to determine the yield stress and the plastic viscosity as defined by Bingham. The distance between the two plates of the parallel plate rheometer should be selected based on the cement paste content in the concrete mixture to be characterized. However, as this method was used here as a screening test, and no comparison was sought with a specific concrete mixture design, the gap (distance between the plates) was arbitrarily fixed at 0.4 mm, based on the median value of distance between aggregates in concrete [11]. The shear rate used ranged from 3 to 50 s^{-1}. This range was selected to correspond to the shear rates used in a concrete rheometer [7]. The surfaces of the two plates were serrated, as provided by the manufacturer, to avoid slippage. The following is a list of the sequence of the measurements done.

- One milliliter of cement paste was placed, using a syringe, on the bottom plate.
- The two plates were brought together to the desired distance of 0.4 mm.
- The computer driven system imposed a slowly increasing shear rate from 0 to 70 s^{-1} in 160 s. As soon as the highest shear rate was reached, the plate stopped rotating.
- After this first phase (needed to homogenize the specimen), a full cycle of increasing shear rate by 10 steps from 3 to 50 s^{-1} and back to 0 shear rate with another 10 steps was performed. At each step, the stress was measured and the value of constant stress was recorded. If the constant stress was not achieved in 20 s, the computer took the average of the last five values recorded.
- The slope of the down-curve (decreasing shear rate) was used to calculate the plastic viscosity, while the intercept at zero shear rate was used to calculate the yield stress. An example of the curve obtained is shown in Fig. 1.

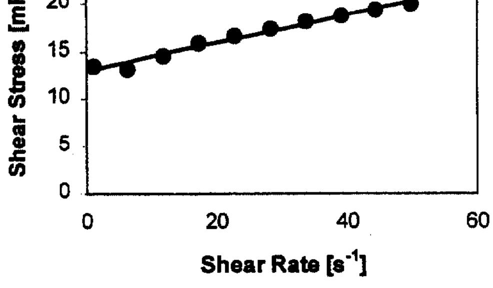

Fig. 1. Typical curve obtained from the fluid rheometer.

3.3.2. Minislump cone test details

Kantro [19] developed the minislump cone test. The test was conducted as follows:

- A square piece of flat glass on which the diagonals and the median were traced was covered with a plastic sheet. The plastic sheet is needed to avoid water or very fluid paste leakage under the minicone.
- The minislump cone was placed in the center of the glass plate and filled with the cement paste.
- The cone was gently lifted and after one minute the diameter of the pad formed was measured along the marked line on the glass in four directions.
- All four diameters were recorded and the average diameter was calculated.

3.3.3. Marsh cone test details

The Marsh cone is a funnel with a long neck and an opening of 5 mm, currently used to test oil well cement [20]. This test is not a standard test. The test was conducted using the following procedure.

- A Marsh cone was attached to a stand so that the small orifice was pointing down and a glass graduated cylinder was placed under the cone.
- Closing the small orifice with a finger, 1 L of cement paste was poured into the cone.
- The orifice was opened and a stop watch started.
- The time for a certain amount of cement paste to flow was recorded. The volumes selected were 300, 500, and 700 mL. These settings were selected from research conducted by Nehdi et al. [21] that showed a nonlinear flow of the cement paste for amounts higher than 700 mL.

4. Results and discussion

4.1. Effect of mixer type on rheological properties of cement paste

The goal of testing cement paste instead of concrete is to save materials and labor. However, to be useful, the cement paste results need to predict concrete performance. Therefore, the cement paste needs to be sheared with about the same intensity, as it would have experienced while being mixed in concrete. One way to determine if the mixing method selected is appropriate is to select several cement paste compositions and compare the rheological behavior of the cement paste with the concrete performance. In this paper, we selected cement paste with and without mineral admixtures. The key result, which would tell us that we had the correct mixing method, is that the mineral admixture that resulted in the larger reduction in yield stress or viscosity compared to the control, which had no mineral admixture, would be the same in cement paste and in concrete. The two mixers available to us were a Hobart and a blender.

To perform the comparison, we selected three mineral admixtures (metakaolin (MK), UFFA, and SF) to test in cement pastes. If the selection of the best mineral admixture was based on the data shown in Fig. 2, the result would depend on the mixer used. Consider the yield stress (YS) behavior (bars and left axis). The best admixture should reduce the yield stress compared to the control (no admixtures). If the black bars (paddle mixer) are examined, the best admixture will be the MK, while if the gray bars are examined, the choice will be UFFA. In examining the results obtained with concrete [23], for equivalent slumps, the water demand is the lowest for mixtures containing UFFA. In other words, UFFA increases slump in concrete when water content is kept constant. In conclusion, UFFA is the "best" admixture both in concrete and in cement paste if mixed in a blender. Therefore, concrete performance was more accurately predicted by the cement paste mixed in the blender and not in the Hobart mixer. This confirms a study by Helmuth et al. [22] stating that in concrete, during mixing, the cement paste is sheared with an energy and rate more closely reproduced in a blender as opposed to the low shear rate of the Hobart mixer. Therefore, to predict concrete behavior, it is essential to use the correct mixer while preparing cement paste. Thus, the rest of the data reported in this paper were obtained using the blender.

4.2. Comparisons between rheological and empirical tests

A fluid rheometer for cement paste is not widely available in the construction industry for many reasons. The two main reasons are: (1) the instrument is relatively expensive (on the order of US$40,000) and (2) the importance of using such a device for cement paste was not advocated until recently [11,12]. Therefore, it would be advantageous to be able to use simpler tests such as the minislump and the

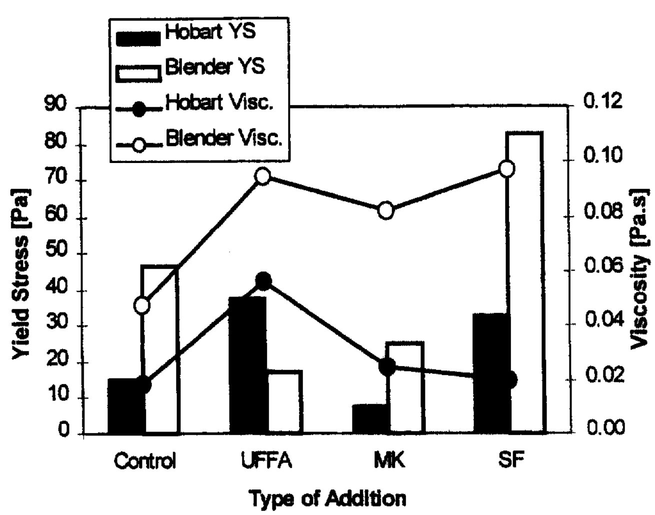

Fig. 2. Influence of the mixer on the rheological properties of cement paste. "YS" is the yield stress and "Visc." is the plastic viscosity.

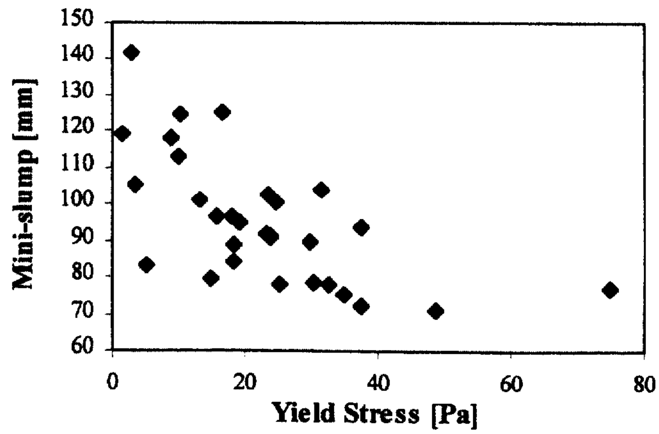

Fig. 3. Comparison between the minislump spread and yield stress. Each point represents a measurement (not an average), therefore, no estimate of the uncertainty can be calculated.

Marsh cone tests. A comparison between the rheometer and the other test results is presented in Figs. 3 and 4. These figures are a compilation of all the tests conducted in this research program using a blender to mix the cement paste. Each point represents various mineral admixture additions at various dosages, W/C, and HRWR dosages.

The plot of yield stress vs. minislump spread diameter (Fig. 3) shows a weak correlation: Higher yield stress corresponds to a lower spread in the minislump. Therefore, an indication of the yield stress could be obtained using the minislump. This result was expected because the cement paste in a minislump test will only flow if the stress due to the weight of the cement paste contained in the cone is high enough, i.e., higher than the yield stress of the cement paste. It should be kept in mind that the minimum diameter that can be measured is 70 mm, corresponding to the diameter of the bottom of the cone. Therefore, despite some of the scatter of the data shown on Fig. 3, an approximation of the yield stress could be obtained by fitting a straight line through the data. This

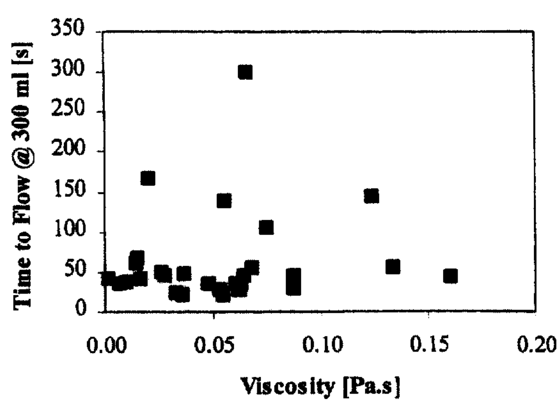

Fig. 4. Comparison between the marsh flow time and plastic viscosity. Each point represents a measurement (not an average), therefore, no estimate of the uncertainty can be calculated.

fit will not be done here because it has a limited significance due to the wide scatter of the data.

In contrast, the plot of time to flow for 300 ml (Marsh cone flow test result) and the viscosity (Fig. 4) shows no correlation at all. If outliers are removed, a "shot gun" distribution can be observed. Similar results were obtained when the times to flow for 500 or 700 ml were plotted, because the time to flow had a linear relationship with the amount of material measured. Nevertheless, in some limited cases, a lower time to flow does correspond to a lower viscosity. However, it would be dangerous to rely on the Marsh cone to select a material for a certain viscosity requirement or even to rank materials based on viscosity due to the overall lack of correlation. This result is somewhat unexpected because it was assumed that the weight of the cement paste was high enough to overcome the yield stress and therefore the speed of the cement paste flow through the flow cone would depend on its viscosity. From the results obtained, it seems that other factors contribute to the flow, such as friction and sedimentation.

4.3. Effect of mineral admixture type on cement paste rheological properties

In Fig. 5, the yield stress and viscosity are shown for mixtures composed of cement paste with the same W/C ratio of 0.35 and varying dosages of HRWR. The amounts of the various mineral admixtures by mass as replacement of cement are indicated on the figure. It is clear that the replacement of cement with UFFA leads to a decrease in the HRWR dosage over the control (no mineral admixtures) at a given yield stress or viscosity. In contrast, the replacement of cement by SF significantly increases the HRWR dosage at a given yield stress and viscosity. The addition of MK shows no significant improvement in yield stress and plastic viscosity over the control. Therefore, there are no significant rheological benefits or drawbacks in using MK as a mineral admixture, at least at the dosages tested.

4.4. Effect of PD on cement paste rheological properties

In Fig. 6, the rheological measurements for the four FA/cement pastes are plotted against the mean particle size of the FAs. All tests were conducted at the same dosage of mineral admixture (12% replacement of cement by mass), same W/C ratio (0.35) and same dosage of HRWR (0.45% solid by mass of cement). It is clear that the lowest yield stress and viscosity are obtained at a mean PD of 3 μm. This value corresponds again to UFFA. It also seems that maximum viscosity is reached at a mean PD of about 11 μm, and maximum yield stress at a mean PD of 5.7 μm. This result seems to indicate an optimum and a pessimum PD, with the optimum at 3 μm and the pessimum at 5.7 μm. Unfortunately, a FA with a smaller PD than 3 μm was not available to determine if the correct optimum was reached. Sakai et al. [16] also showed that there is a pessimum at 18 μm, but he used limestone powder and not FA. It is conceivable that the optimum and pessimum value depends on the type of mineral admixture used, and the chemistry and physics of the individual particles.

4.5. Effect of W/C on rheological properties of cement paste

Fig. 7 shows the results of tests performed on cement pastes with UFFA (at 12% replacement) at various W/C ratios, plotted vs. HRWR dosage. There are several ways to use or to interpret these results: (1) determine the correct dosage of HRWR needed to obtain the same yield stress and/or viscosity with the UFFA mixes and the control at various W/C; (2) determine the water reduction achieved by using UFFA and maintaining the same yield stress and/or viscosity; or (3) determine the reduction in HRWR

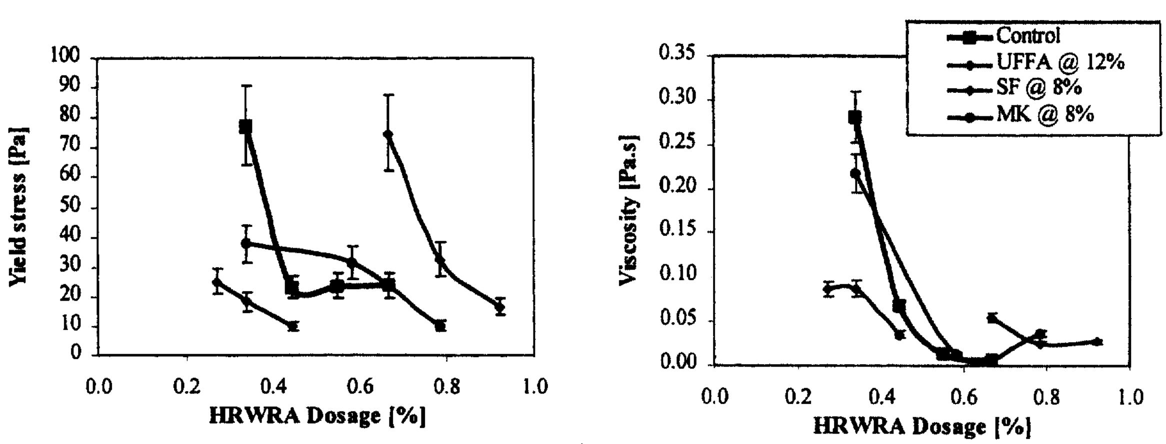

Fig. 5. Dosage of HRWR and its effect effect on the flow of properties. The W/C ratio was 0.35. The error bars represent an estimate percentage error: 1.7% on yield stress and 10% viscosity. This error was estimated from the numerous tests done.

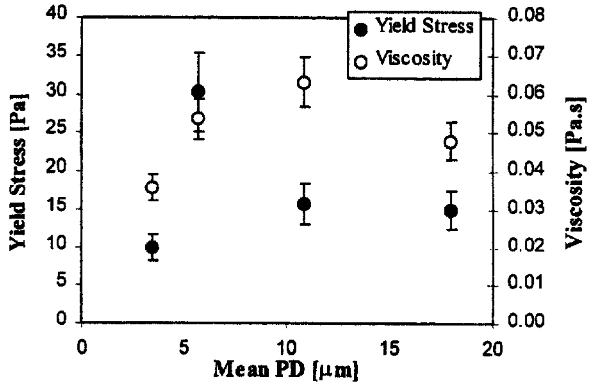

Fig. 6. Influence of mean PD on the flow properties of cement paste. The W/C ratio was 0.35. The error bars represent an estimate percentage error: 17% on yield stress and 10% viscosity. This error was estimated from the numerous tests done.

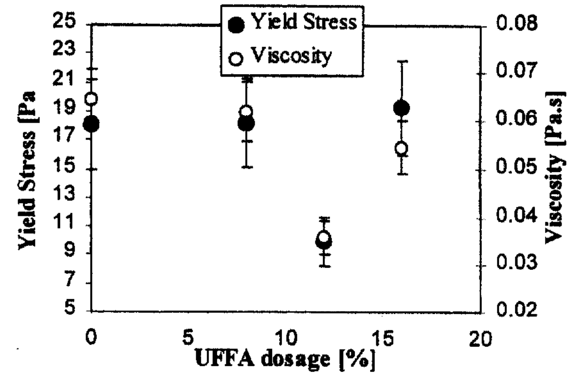

Fig. 8. Influence of the dosage of UFFA on the rheological properties of cement paste with constant dosage of HRWRA (0.44% (13 oz/100 lb of cementitious materials)). The W/C ratio was 0.35. The error bars represent an estimate percentage error: 17% on yield stress and 10% viscosity. This error was estimated from the numerous tests done.

dosage achieved while maintaining the same yield stress and/or viscosity.

In summary, the addition of UFFA improves the rheological properties. If the goal is to add UFFA and achieve the same yield stress and viscosity as the control, Fig. 7 shows that the W/C ratio can be reduced by 10% and the HRWR dosage can be reduced by 40%. On the other hand, if the water content is reduced by 20% (W/C ratio of 0.28) a significant increase of the HRWR dosage (almost double) is needed to maintain the yield stress or viscosity, giving the same rheological behavior as the SF mixes.

4.6. *Effect of dosage of UFFA on cement paste rheological properties*

Fig. 8 shows the influence of dosage of UFFA on cement paste rheological properties. The tests were done at a W/C ratio of 0.35 and a fixed HRWR dosage of 0.45% solid by mass of cement. The plot suggests that a dosage of 12% by mass is optimal for the best rheological properties. The dosage shows an optimum value corresponding to the lowest value achieved by the yield stress for a 12% UFFA by mass dosage. The shape of the curve (Fig. 8) is an important result because it corresponds to the same type of behavior seen in concrete, as will be shown in Section 6 and in Fig. 10.

5. Concrete testing

5.1. *Concrete mixture*

The purpose of the concrete measurements was to validate the conclusions drawn from the data obtained in the cement paste for the best type and dosage of mineral admixture. The concrete rheological behavior was tested using the standard slump cone test. Therefore, only an indication of the yield stress was available for comparison.

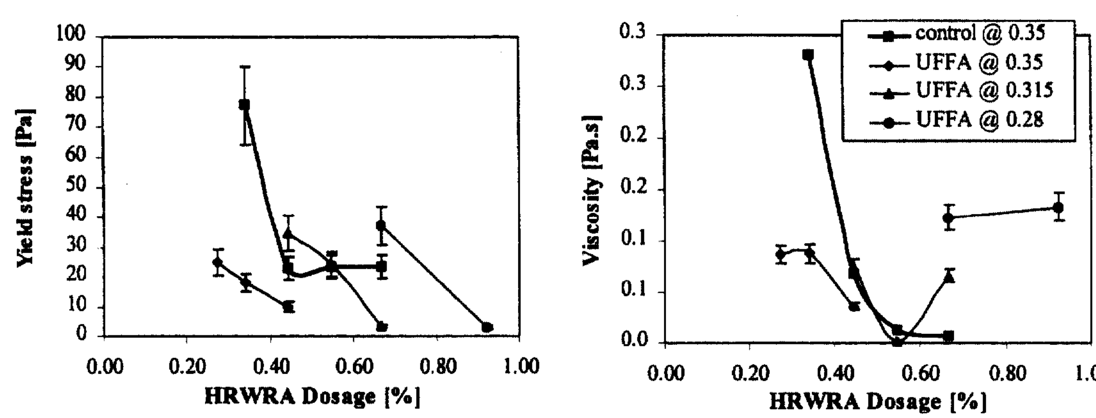

Fig. 7. Influence of W/C ratio on the rheological properties of cement paste with UFFA at 12% replacement of cement by mass. The numbers in the legend indicate the W/C ratio used. The error bars represent an estimate percentage error: 17% on yield stress and 10% viscosity. This error was estimated from the numerous tests done.

Table 3
Mixture proportions (Test A)

360 Series

Material	Control	SF	UFFA 3	UFFA 4	UFFA 5	UFFA 6
Cement	360	331	331	331	331	331
SF	0	29	0	0	0	0
UFFA	0	0	43	29	43	43
CA	1035	1035	1035	1035	1035	1035
FA	745	735	733	778	764	789
Water	142	143	141	130	129	120
W/C	0.39	0.4	0.38	0.36	0.34	0.32
HRWR	655	1047	524	589	655	818
$HRWR_{mix}$/ $HRWR_{control}$	1.00	1.60	0.80	0.90	1.00	1.25
AEA	33	39	52	46	52	52
Slump, mm	200	190	185	165	210	190
Air content, vol.%	6.4	5.0	5.6	5.4	5.4	6.5

420 Series

Material	Control	SF	UFFA 9	UFFA 10
Cement	420	386	386	386
SF	0	34	0	0
UFFA	0	0	50	50
CA	1041	1041	1041	1041
FA	673	661	689	713
Water	148	156	133	120
W/C	0.35	0.37	0.31	0.28
WR	0	0	0	0
HRWR	655	1178	655	982
$HRWR_{mix}$/ $HRWR_{control}$	1.00	1.80	1.00	1.50
AEA	33	46	59	52
Slump, mm	210	230	250	230
Air content, vol.%	4.7	6.3	5.0	2.6

Cement, SF, UFFA, CA, FA, and water are in kilograms per cubic meter. WR, HRWR, and AEA are in milliliters per 100 kg of cementitious materials.

The effect of the addition of a mineral admixture was detected by an increase in the slump or a reduction of the water content and/or a reduction of HRWR dosage needed to obtain the same slump.

Two different concrete test programs were conducted. These are identified as Test A and Test B. Both of these test programs involved determining both fresh and hardened concrete properties. Only the rheological results will be discussed here. More details are published elsewhere [23]. In all the concrete tests, only SF or UFFA were used. None of the other mineral admixtures were tested because these two seemed to encompass the range of rheological behaviors. In addition, it would have been too expensive to test all the mineral admixtures in concrete. The cement used was the same as described on Table 1.

Test A was divided in two series: the 360 series and the 420 series (Table 3). The series are named after the cementitious (cement and mineral admixtures) material contents of 360 and 420 kg/m^3, respectively. The UFFA dosage and the W/C ratio were varied to obtain about the same slump and to determine the influence of these factors on the slump. Table 3 gives the details of the concrete composition and the slump and air content of the concrete.

Test B concretes had 370 kg/m^3 of cementitious materials. The W/C ratio was kept to 0.4 for all but two mixes. The UFFA dosage was varied between 8% and 16% by mass of cement. Two mixtures were made with SF replacements of 8% and 12% by replacement by mass of cement. Table 4 gives the composition, slump, and air content of the concretes.

5.2. Concrete workability

To determine the influence of the mineral admixtures in concrete, the HRWR dosages and W/C ratio were compared. The HRWR dosage was reported as the ratio between the dosage used for mixtures with mineral admixtures and the dosage used for the control, with no mineral admixtures. A value below 1 indicates that the mineral admixture addition

Table 4
Mixture proportions (Test B)

	Mixture I.D.							
		UFFA	UFFA	UFFA	UFFA	UFFA		
	Control	8/0.4	12/0.4	16/0.4	12/0.35	12/0.31	SF 8	SF 12
Cement	370	340	326	310	340	340	340	326
UFFA	–	30	44	59	44	44	–	–
SF	–	–	–	–	–	–	50	75
Total CM	370	370	370	369	384	384	390	401
Water	148	148	148	148	133	118	148	148
W/CM	0.4	0.4	0.4	0.4	0.35	0.31	0.4	0.4
HRWR[1]	516	364	298	258	397	622	668	774
$HRWR_{mix}$/ $HRWR_{control}$	1.00	0.70	0.58	0.50	0.77	1.20	1.30	1.50
Slump (mm)	146	133	158	133	146	158	190	146

Cement, SF, UFFA, CA, FA, and water are in kilograms per cubic meter. CM stands for cementitious materials, i.e., cement and SF or UFFA. HRWR dosage is expressed as milliliters per 100 kg of cementitious materials. The first number in the mixture I.D. indicates the dosage in mineral admixture and the second number (after the slash "/") indicates the W/C ratio.

improved flow compared to the control, while a value above 1 indicates the opposite. A reduction in the W/C ratio implies that the addition of mineral admixture was beneficial. Therefore, the results in Fig. 9 should be interpreted to determine the composition that reduces both the HRWR and the W/C ratio. It can be seen from Fig. 9 that for all three series the addition of SF never leads to a value below the control. However, the addition of UFFA leads to a reduction of both HRWR dosage and W/C in almost all mixtures. The only exception to this improvement was when the W/C was less than 0.31 corresponding to a reduction in water content of more than 20% compared to the control with a W/C of 0.40 (plot 3 in Fig. 9).

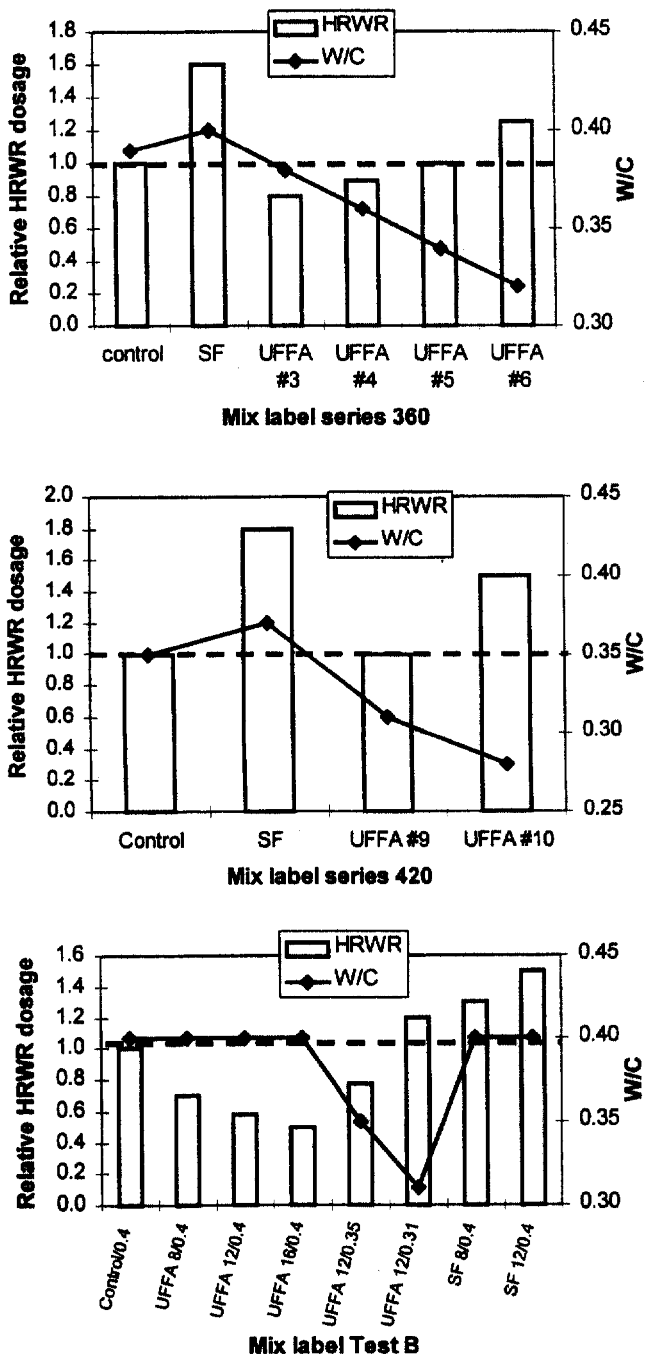

Fig. 9. Comparison of water and HRWR requirement of SF and UFFA concretes at different cementitious contents: (a) 360; (b) 420; and (c) Test B. The relative HRWR dosage is the ratio between the dosage used in the mixes with mineral admixtures and the control. The dotted line indicates the value of the control for the relative HRWR dosage, i.e., equal to 1. These are unique tests, therefore, no error can be estimated.

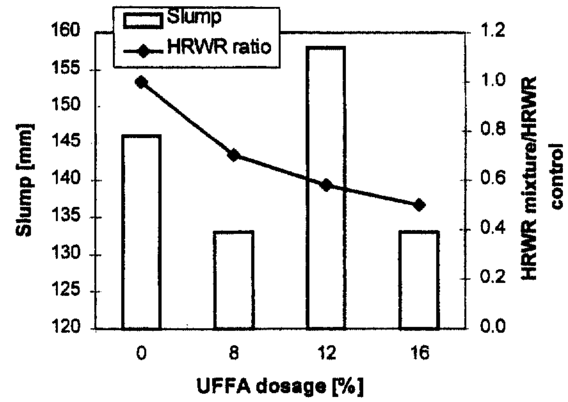

Fig. 10. Influence of partial replacement of cement by UFFA dosage on concrete slump. These are unique tests, therefore, no error can be estimated.

In more detail, it can be observed that for the 360 series, with slumps ranging from 180 to 210 mm, the UFFA mixtures needed only 50–63% as much HRWR dosage as did the SF concrete mixture. This was achieved even with 10% less water than was used in the SF concrete mixture. When the UFFA concrete mixture had 16% less water, it still needed only 78% of the HRWR dosage of the SF concrete mixture. For the 420 series, at slumps ranging from 210 to 250 mm the UFFA mixtures needed only 56% and 83% of the HRWR dosage and had 15% and 23% less water as compared to the SF concrete mixture. In Test B, at the same water and cementitious amounts, SF increased the HRWR dosage by 30% and 50% over the control, when used at 8% and 12% replacements, respectively. In contrast, UFFA reduced the HRWR dosage by 30%, 42%, and 50% when used at 8%, 12%, and 16% replacements, respectively. The HRWR demand decreased as the amount of cement replaced by UFFA increased. It should be noted that the slump was significantly lower for a 12% addition than for 8% or 16% (Table 4).

These concrete tests have shown that if the goal was to reduce any or all of the slump, W/C ratio and HRWR dosage in a mixture containing a mineral admixture, the best selection would be to use UFFA and not SF. These tests are limited as they did not address other types of mineral admixtures, but they are enough to be used as a validation of some of the cement paste tests.

6. Discussion and conclusions

The purpose of this research was to determine if the rheological properties of cement pastes containing mineral admixtures could be used to predict the rheological properties of the equivalent concrete mixtures. In cement paste, several mineral admixtures were examined and it was determined that mixtures with UFFA represented the best rheological improvement while SF represented the worst. It was shown that the replacement of cement by SF results in an increase in the water demand and HRWR dosage to maintain the rheological properties of the control. In contrast, the replacement of cement by UFFA resulted in a reduction of the water demand and HRWR dosage to maintain the same rheological properties of the control. The other mineral admixtures, MK, CFA, FA, and FFA, gave results in between the SF and UFFA and, therefore, were not as extensively studied as SF and UFFA.

The concrete tests, due to the amount of materials and labor needed, were limited to SF and UFFA and also to selected dosages of HRWR and mineral admixtures. The results obtained showed that the replacement of cement by UFFA up to 12% by mass of cement reduces the HRWR dosage and W/C needed to obtain the same slump as in the control. Additional concrete tests were not possible due to the time and labor needed.

Another goal of this research was to determine the optimum replacement level of cement (dosage) by UFFA as defined by the highest reduction in yield stress or plastic viscosity (higher slump). The dosage of UFFA also depended on the W/C and the HRWR dosage. Using the cement paste measurements, it could be concluded that the optimum dosage of UFFA is 12% for replacement of cement by mass (Fig. 8). This result needed to be validated with the concrete data. Unfortunately, the concrete measurements were not done at a constant dosage of HRWR as were the cement paste. Therefore, it is harder to determine if the best dosage of UFFA (Fig. 10) should be attributed to the increased HRWR dosage (compared to 16%) or entirely to the UFFA optimum dosage. These concrete results further show the value of the cement paste tests: It is easier and less labor intense to prepare extra mixes to examine the influence of various factors.

It can be concluded that cement paste measurements of rheological properties to screen the dosage and type of mineral admixture to be used in concrete is a promising approach, provided the tests are conducted following the methodology developed at NIST. This implies that the cement paste should be mixed using a blender and not an Hobart mixer and that the measurements of yield stress and viscosity should be performed using a fluid rheometer.

Less sophisticated tests, such as those using the minislump and the Marsh cone, cannot be relied upon. The minislump test results correlate in certain cases with the yield stress, but there is a wide scatter of the data. However, no correlation was observed between the time of flow in the Marsh cone vs. plastic viscosity.

Further testing is needed to confirm that the cement paste rheological measurements can be used as a standard test to predict concrete rheological parameters of a wide variety of compositions.

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