Workability of Cement Pastes

P A Claisse

J P Lorimer

and

M H Omari

School of The Built Environment
Coventry University
Priory Street
Coventry
CV1 5FB UK
email: p.claisse@coventry.ac.uk

ABSTRACT

This paper reports an investigation into problems which have occurred when superplasticisers have been used with different cements. The literature survey showed that previous work had indicated that the problems were caused by the specific surface area, sulphate morphology and aluminate content of the cements. The experimental work involved a comprehensive analysis of 14 different cements. A full statistical analysis of the results indicated that the sulphates were not a significant factor when superplasticisers were used but the chromate content of the cement is significant.

keywords: workability, rheology, chromate, sulphate.

INTRODUCTION

Cement grouts are used for a wide range of applications in the construction industry. These grouts require a high workability and superplasticising admixtures are used to achieve this.

It had been found that some cement pastes perform better (i.e. flow faster and are workable for longer times without bleed and segregation) in some countries than in others These problems may be solved on an empirical basis when they arise. However this project investigated the basic mechanisms involved in order that the performance of the cement pastes might be predicted more effectively.

To do this, a relationship between the rheological properties of the cement paste and the chemical components, especially the different kinds of sulphates, of the Portland cement was established. First, a relationship between the simple industrial tests such as the flow cone and the rheological properties obtained by a rheometer was established. This has been reported elsewhere (1,2). Subsequently, more tests were performed such as X-ray Fluorescence (XRF) spectroscopy to determine the chemical composition of cement, Thermo Gravimetric Analysis (TGA) to determine the different types of sulphates, Particle Size Distribution (PSD) and Specific Surface Area (SSA) tests. In order to relate the chemical composition to the rheological properties 14 different cements from various countries were analysed.

The TGA system used was unable to differentiate between the amount of gypsum or hemihydrate present. In order to estimate the amounts of gypsum and hemihydrate it was necessary to use X-Ray Diffraction (XRD) and then calculate the mass of water in that amount (that represented the water content in hemihydrate). It was then subtracted from the results obtained from the TGA system to obtain the mass of water that represented gypsum.

LITERATURE SURVEY

Properties affecting paste rheology

Numerous studies of the rheological properties of cement pastes have proved these properties depend on many factors. The following have been frequently cited: the water / cement ratio (w/c) [3,4], specific surface area, mineral composition [3,5,6], conditions during measurements and their duration [3,7] (i.e., time dependency, mixing time and mixing intensity) and temperature [5,8]. Previous researchers found that the cement paste had better workability when using high w/c ratio, low SSA cement and high mixing speed. It has been shown that the most important of these are the w/c ratio and specific surface area [3]. Studies performed on cement pastes of different chemical composition indicated this factor has less effect on the rheology than the w/c ratio and/or the fineness of the cement [9,10] (this is already optimised in commercial cements). The most significant reported influence of chemical composition is in the retardation of the aluminate hydration by calcium sulphate [11]. Due to the considerable reaction rates of these processes they are very important when determining rheological features of cement pastes at early hydration stages and also affect the development of rheological properties [3].

The effect of cement chemistry on paste rheology

The most relevant study to this study was performed by Greszczyk and Kucharska [3]. Their experiments were carried out using 21 industrial clinkers and cements. All cements contained an equal amount of gypsum (5% wt). Both clinkers and cements were ground to the specific surface area of 300 ± 20 m^2/kg. The chemical composition of the clinkers were recorded (%wt.) stating the four main phases (see 1.3.1) C_3S, C_2S, C_3A and C_4AF and Na_2O, K_2O, SO_3 and free CaO. The rheology measurements were obtained using a rotary viscometer Rheotest RV-2. Measurements were performed at a constant temperature of 21° C and the w/c for clinker and cement pastes were 0.50 and 0.40 respectively. The preparation of the pastes included manual mixing for 3 minutes immediately after the clinker and/or cement contacted water. The paste was left to stand for 5 minutes before it was fed into the viscometer. Then 1 minute of mixing was performed at a shear rate 146 s^{-1} after which it was left for a further 1 minute at rest before the start of measurements. Thus, measurements were started after 10 minutes of the contact of cement with water. The rheological behaviour of the tested clinker and cement pastes were determined based on the obtained flow curves and results on stress change measurements taken within a one hour period at a constant shear rate (146 s^{-1}). The plastic viscosity and shear stress values for cement and clinker were measured at 30 and 60 minutes. Greszczyk and Kucharska found that the shear stress at 30 and 60 minutes increased with the increase of C_3A content. The increase in the alkali content increased the shear stress at 30 and 60 minutes. The efficiency of gypsum as a setting control agent was reduced when using a highly reactive clinker (i.e. clinker with an orthorhombic morphology of tricalcium aluminate (C_3A) and a high content of alkalies) due to the increased reactivity of C_3A caused by alkalis (potassium).

However in the author's opinion, the sample preparation techniques were not adequate. For example a manual mixing procedure of 3 minutes produces an inadequate mixed cement paste. Banfill [12] and Hakansson, Hassler and Stille [8] showed that a mixing time of about five minutes is the required minimum to obtain constant properties for both the yield stress and the plastic viscosity [8]. Inadequate mixing will result in non-reproducible properties [8]; this effect was tested in this project. Low shear mixing (manual mixing in case of Greszczyk and Kucharska) and a mixing time below 4 minutes is inadequate. Greszczyk and Kucharska's study was limited since the gypsum content and the specific surface area were controlled to a very limited range of values. Testing the rheological properties of a clinker with no added sulphates is unrealistic due to the false set of the clinker paste. The study should have used commercial clinker with controlled addition of sulphates.

The effect of sulphate compounds on paste rheology

The second important study in this area was performed by Mork and Gjoerv [13]. During the grinding of cement clinker and gypsum in cement production, relatively high temperatures occur which may reduce the gypsum to hemihydrate or soluble anhydrite. The amount of this reduction may also depend on the quality of the gypsum and the conditions used later during storage and transportation of the cement. Since the solubility of hemihydrate and soluble anhydrite is approximately three times higher than gypsum, an uncontrolled variation in the gypsum-hemihydrate ratio may cause an uncontrolled variation in the chemical reactivity of the system and hence on the workability properties of the fresh cement pastes. An uncontrolled variation in the gypsum-hemihydrate ratio may also cause an incompatibility between the cement and certain types of admixtures such as superplasticisers. Such incompatibility may cause false set or quick set of the fresh cement pastes [13,14]. Mork and Gjoerv used three different gypsum-hemihydrate ratios, namely 80/20, 50/50 and 20/80. Their testing program was further based on two different types of clinker, one more reactive (i.e. with an orthorhombic morphology of C_3A and a high content of alkalies) than the other. The "reactive" clinker was ground to two different levels of fineness, namely 300 and 400 m^2/kg and 3% of sulphates were added with different gypsum-hemihydrate ratios. The less reactive clinker was ground to a fineness of 300 m^2/kg and 1,2 and 3% of sulphates were added with different gypsum-hemihydrate ratios. The mixtures which contained sulphonated melamine formaldehyde were mixed using a water-cement ratio of 0.45. The mixtures which did not contain superplasticiser were mixed using a water-cement ratio of 0.61. The mixtures were tested After 1, 20, 30, 50 and 70 minutes of mixing using a coaxial viscometer of type BML-Viscometer. Mork and Gjoerv [13] concluded the following:

1. For the most reactive type of clinker with a high content of both C_3A and alkalis, a reduced gypsum-hemihydrate ratio from 80/20 to 20/80 reduced the yield stress, while plastic viscosity was not much affected. The initial yield stress and the increased yield stress over time were reduced by the reduction of gypsum-hemihydrate ratio.
2. For the less reactive type of clinker, the effect of the gypsum-hemihydrate ratio was not so pronounced. A tendency to false set was observed only for the lowest ratio of 20/80. For this type of clinker, the change over time in rheological properties was also

smaller. However, a reduced total sulphate content from 3% to 1% reduced both yield stress and plastic viscosity.

3. In the presence of a melamine-based superplasticiser, a more pronounced effect of the gypsum-hemihydrate ratio on the rheological properties of fresh cement pastes was observed. However, for the most reactive type of clinker, a reduced gypsum-hemihydrate ratio increased the yield stress, while for the less reactive type of clinker the effect was still less pronounced. An increased fineness of the cement increased the effect of gypsum-hemihydrate ratio, while a reduced total sulphate content reduced the observed yield stress.

It's the author's belief that most commercial cements have a much lower content of hemihydrate than those explained in Mork and Gjoerv's study. A cement manufacturer attempts, where possible, to produce 0% of hemihydrate in the final product since it "kills" the workability of cement pastes. Some companies add Anhydrite instead of gypsum to ensure that the hemihydrate content is zero. Temperature controlled grinding may be used to convert the hemihydrate where the cost of Anhydrite is too high. The author believes that Mork and Gjoerv's study would have been more useful if the gypsum-anhydrite and the anhydrite-hemihydrate ratios had also been investigated. However the study of Mork and Gjoerv gave the author the idea for the tests which are described in this paper. These tests include 12 different mixes with different ratios between gypsum, hemihydrate, and anhydrite.

An initial trial from this programme has been reported (1,2). In this experiment cement clinker without added sulphate was ground and mixed with pure gypsum and pure anhydrite. The results are shown in table 1, and indicate a substantially higher workability with Gypsum.

TABLE 1 Effect of Sulphates [1,2]

Plasticiser	Property	Gypsum	Anhydrite
SMF	Viscosity Pa s × 10^{-7}	12.7	105.5
SMF	Yield Pa × 10^{-7}	575.2	2524.2
SNF	Viscosity Pa s × 10^{-7}	6	68
SNF	Yield Pa × 10^{-7}	102.6	1611

EXPERIMENTAL METHODS

Materials

Cements were obtained from different commercial suppliers. Three different superplasticising admixtures were used:

Sulphonated Melamine Formaldehyde (SMF)

Sulphonated Napthalene Formaldehyde (SNF)

Lignosulphonate (LS)

Rheological Tests

The Rheometer: This test measures the viscosity and the shear stress of a cement paste. A Rheology International Series 2 viscometer Model RI:2:M was used. The viscometer was chosen with a medium spring to be able to obtain more accurate data at low speeds. The Bingham model was used to determine the plastic viscosity and the yield value.

It should be noted that the rheology of Bingham plastics is not very sensitive to temperature, but the rate of change of rheology with time in a chemically reacting system containing cement is affected by temperature. It is preferable to standardise both the test temperature and the time after mixing at which the test is performed [Banfill 1994]. All the tests reported here were performed at 20 ± 1° C. The test materials were stored at this temperature for at least 48 hours before use.

A four-bladed vane spindle (Figure 1) was used for this work. The vane had four rectangular blades of radius, Rv, 9.5 mm and height, h, 38 mm and was placed in a cup of radius 27.5 mm centrally mounted on the lower plate. Because of the restricted torsion of the spring which moves the spindle, these actual dimensions do not comply with those recommended the ASTM [ASTM D2573] (Rv=19.05 mm and h=76.2 mm). However, the actual rheometer used was capable of producing comparative data on which decisions regarding mix could be made.

The shear stress, τ, was calculated from the torque (T) using the following conversion formulae:

$$\tau = 3T/(2\pi(R_v^3+3\,R_v^3h)) \qquad [15]$$

The Testing Cycle

The testing cycle (Fig. 2) was chosen in order to keep within the restrictions of the apparatus and reduce the anti-thixotropic behaviour that the material might have. It was noticed that reducing the readings on the down-curve from 20 data points to 10 did not affect the accuracy in obtaining the yield value and the viscosity. However, reducing the number of points on the down curve helped obtain a positive value of the slope (viscosity). This was because shortening the cycle reduced the effect of shear-thickening (anti-thixotropy) which some cement pastes have. The up-curve utilised 20 data points to ensure that the break point could be determined more accurately

The testing cycle was checked by performing a series of "single point" tests at fixed speeds and comparing the results with a test using the normal testing cycle. The results were very similar which indicated that they were not a product of the particular testing cycle that was used.

Figure 2 also shows how the viscosity, yield point and break point are derived from the results of the cycle. Relating these to practical applications, the break point indicates how easily a mix may be moved from a static position (e.g. resting in a pipe). The yield shows the resistance to flow (e.g. pumping pressure) at slow speeds and the viscosity shows how the resistance to flow increases as the speed (e.g. the rate of pumping) increases.

.

The effect of mixing speed and time on the rheological properties

It was noticed that the speed of mixing affected the initial flow of the cement paste when mixed for 5 minutes. A standard mixing speed and mixing time had to be chosen for the final testing. A series of tests on trial samples were carried out. Different mixing speeds (900, 1100, 1300, 1500 and 1900 rpm) and mixing times (2, 3, 4 and 5 minutes) were tested. The samples were tested 3 minutes after finishing mixing

It was found that (Figure 3) mixing for longer times (4 & 5 minutes) gave a better workability and stability for the cement pastes. Mixing for 2 or 3 minutes was inadequate, and that caused the unexpected increase of break point value with the increase of speed. Mixing at very high speeds (>1100 rpm) gave a high workability and made the cement paste too thin for the rheometer (anti-thixotropic behaviour). Therefore the following mixing method was used:

After pouring all the material into the mixing beaker, while the mixer's spindle was rotating at 1100 rpm, the timing was started. After 40 seconds the speed was raised to 1900 rpm for 20 seconds to ensure that all the lumps were broken. The speed was reduced to 1100 rpm for 2 minutes and 40 seconds (i.e. 160 seconds) and again raised to 1900 rpm for 20 seconds. Finally the speed was lowered to 1100 rpm for 1 final minute of mixing. This made the total mixing time equal to 5 minutes. When not using any water reducer or when using lignosulphonate plasticiser, the mixing speed was kept at 1900 rpm for the complete 5 minutes to ensure that the material would be workable enough for the rheometer. This mixing method was used to ensure that no lumps would form and the cement paste would be properly mixed.

Relating this mixing to the methods used in practice is difficult because no shearing was used. In a commercial grout mixer the pumping action will shear the mix and this will provide effective mixing at relatively low speeds. In concrete the aggregate will shear the paste during mixing.

The standing time of the cement paste

The standing time of the cement paste before testing affected its rheological properties. Three samples were tested at different standing times; 0.5, 1, 2, 3 and 4 minutes. Increasing the standing time increased the yield value (Figures 4a and 4b). A standing time of 1 minute was chosen to give enough time to load the sample into the rheometer and start testing.

Mix Designs

After studying all the initial tests the final mix designs were chosen as follows:

Blank sample without any plasticiser

Cement	100%
W/c	0.50

SNF/SMF sample

Cement	99.70%
SNF/SMF	0.30%
W/c	0.40

LS sample

Cement	99.70%
LS	0.30%
W/c	0.45

The amount of powder used in the samples was 300 g.

Measurement of Particle Size and Specific Surface Area

Testing of particle size was performed using the Malvern 2600 particle sizer with dry-powder feeder. This semi-computerised particle sizer has three lenses to cover a range from 0.5 μm to 568 μm. The analyses were in the range of 1.22 - 188 μm. The SSA was automatically calculated by the computer. The tests were performed in triplicate, each time with approximately 150 g. If any drift in the results was observed, the analysis was repeated. Six sieve sizes were used: 90.9 μm, 73.1 μm, 50.8 μm, 30.6 μm, 10.3 μm, 3.46 μm and < 3.46 μm.

ThermoGravimetric Measurements

A Setaram TG system was used and it was able to detect the free water (<105º C) and combined water (>105º C) present. The heating rate was 2º C/minute and the sample size was 150mg.

X-Ray Fluorescence

Cement samples were analysed for the following oxides: SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O, Mn_3O_4, P_2O_5, SO_3, TiO_2, ZrO_2, Cr_2O_3, BaO and SrO. The analysis was carried out using a Philips PW2400 XRF spectrometer

X-Ray Diffraction

XRD was used to determine the quantity of hemihydrate ($CaSO_4.½H_2O$) in the cement. In order to measure this, preliminary scans were performed on:

- Anhydrite ($CaSO_4$) to check that the peaks of calcium sulphates and help in predicting the region where the distinctive peaks of hemihydrate might appear,

- hemihydrate to determine the distinctive peaks of hemihydrate,
- clinker with added gypsum to check that the peaks of gypsum do not overlap with the distinctive peaks of hemihydrate.
- clinker (with no added sulphates) to be able to compare it with the analysis graphs of the tested samples.

After considering the XRD spectrum, it was decided to discard the first peak of hemihydrate since it overlapped with the gypsum peaks. Calculating the amount of hemihydrate was easy, the distinctive peak of hemihydrate height represented 100% of hemihydrate content, while the same "region" in clinker represented 0% of hemihydrate. The XRD analyses of 14 cements were compared with the clinker analysis to detect the hemihydrate peak and calculate its content.

RESULTS

The results are shown in Tables 2 to 4. These results will not have been as accurate as the resolution shown in the table but, in line with statistical practice, they were not rounded before use in the calculations. The chemical and physical properties of the cements were correlated to the rheological properties of cement pastes using statistical computer programs. It was observed that the flow of cement paste is dependent mainly on SSA and Particle Size Distribution which is correlated to SSA. The effect of SSA was removed to reveal other factors which could affect the flow. The other main factors were removed in turn. The most important factor to consider when building a model is the *level of significance (P-value)* of each estimated coefficient. The lower the

P-value, the more significant the contribution of that variable to the model. A 0.05 P-value indicates a 5% probability that the relationship between two variables could have happened by chance. The highest acceptable level of significance in the present analysis was 0.05.

It was noted that multiple regression can sometimes suggest spurious relationships between variables, particularly where the independent variables are themselves highly correlated. Care was taken to ensure that relationships can be supported by experimental evidence. Precautions were also taken against the danger of building a theory on one or two pieces of influential data which could be “rogue” values or “outliers”.

- The final flow models for the Break Point were (Figure 6):

Break Point (Blank) [Pa] = –1171[Pa] + 1178 Hemihydrate%[Pa] + 6 SSA [Pa kg/m^2]

Break Point (SMF) [Pa] = – 7205[Pa] – 22380 Cr_2O_3%[Pa] – 10890 Na_2O%[Pa] + 1242 Al_2O_3%[Pa]+ 17 SSA [Pa kg/m^2]

Break Point (SNF) [Pa] = – 20344[Pa] + 2343 Al_2O_3%[Pa] + 31 SSA [Pa kg/m^2]

Break Point (LS) [Pa] = – 6244[Pa] –24468 Cr_2O_3%[Pa] + 1128 Al_2O_3%[Pa] + 7 SSA [Pa kg/m^2]

- The final flow models for the Yield value were (Figure 7):

Yield (Blank) [Pa] = –1259[Pa] + 1352 Hemihydrate%[Pa] + 6 SSA[Pa kg/m^2]

Yield (SMF) [Pa] = – 8999[Pa] – 26012 Cr_2O_3%[Pa] + 1228 Al_2O_3%[Pa] + 17 SSA [Pa kg/m^2]

Yield (SNF) [Pa] = – 17278[Pa] + 1965 Al_2O_3%[Pa] + 28 SSA[Pa kg/m^2]

Yield (LS) [Pa] = – 10504[Pa] + 1138 Al_2O_3%[Pa] + 19 SSA [Pa kg/m^2]

- The final flow model for the Plastic Viscosity was (Figure 8):

Plastic Viscosity (blank) [Pa s] = 77[Pa s] + 50 Hemihydrate% [Pa s] – 14 Al_2O_3%[Pa s]

No models for plastic viscosity for the superplasticised samples could be developed.

DISCUSSION

The main observations from these results are:

- The present results do not indicate that there is no effect of any given factor- they only indicate that it is not an effect which is statistically significant at the 5% level
- It is not indicated that the effect of sulphate morphology (i.e the relative amounts of gypsum, hemihydrate and anhydrite) is very significant. The hemihydrate is only significant where no admixtures are used. This partially contradicts the findings which were indicated in the literature and the preliminary work however these results refer to total amounts present rather than the amounts in solution. Another factor (e.g. the chromate discussed below) could be controlling solubility and thus be more significant.
- The significance of the Aluminate phases. This was expected from the literature.
- An unexpected effect of the Chromate phases was observed. A brief additional experimental programme was carried out to investigate this observation.

Blue Circle Wardale (BCW) cement was chosen to study the effect of various levels of Cr_2O_3 (0, 0.05, 0.07, 0.10, 0.15 and 0.20%) on the flow. This particular cement was chosen since it contains no Cr_2O_3. All mixes were performed using the standard mixing method used for Blank mix. Figure 5 illustrates the effect of Cr_2O_3. These experimental results suggest that the significant relationship between Break Point and Cr_2O_3 found by statistical analysis is genuine. Chromates are known to be retarders and in some cements special measures are taken to reduce the adverse effects of Cr^{VI} by reducing it to Cr^{III}. Further investigation would be required to determine how this would affect the models for their workability when superplasticised. In particular the effect of chromates on sulphate solubility may be significant.

CONCLUSIONS

- For all cementitious mixtures the Specific Surface Area of the cement has the greatest influence on workability.
- For cementitious paste mixtures without admixtures the hemihydrate content has a significant effect on workability.
- For cementitious mixtures with SMF, SNF or LS admixtures the workability generally increases with decreasing aluminate content.
- For mixes with SMF and LS admixtures the workability generally increases with increasing chromate content.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of Fosroc International in this work.

REFERENCES

1. Claisse P A and Al Omari M 1999, The Effect of Changes in Cement on the Properties of Cement Grouts with Superplasticising Admixtures, Proc. "The Role of Admixtures in

High Performance Concrete", RILEM International Symposium, Monterrey, Mexico, March 21-26

2. Omari M A, 1999, Workability of Cement Pastes, PhD Thesis, Coventry University.

3. Greszczyk S. and Kucharska L., 1991, “The Influence of Chemical Composition of Cement on the Rheological Properties”, Rheology of Fresh Cement and Concrete, Edit by Banfill PFG, pp 27-36.

4. Collepardi M., 1971, “The Rheological Behaviour of Cement Pastes”, Il Cemento, Vol 68, pp 99-106.

5. Von Berg W, 1979, “Influence of Specific Surface and Concentration of Solid upon the Flow Behaviour of cement pastes”, Magazine of Concrete Research, Vol 31, pp211-216.

6. Oaler I., Becker I. and Weiss B., 1978, “Rheological Properties of Cement Pastes”, Il Cemento, Vol 3, pp 303-310.

7. Banfill P.F.G., 1981, “On the Viscometric Examination of Cement Pastes”, Cement and Concrete Research, Vol11, pp 363-370.

8. Hakansson U., Hassler L. and Stille H., 1997, “Rheological Properties of Microfine Cement Grouts”, Tunnelling and Underground Space Technology, Vol 7, No 4, pp 453-458.

9. Older I., Duckstein U. and Becker T., 1978, Cement and Concrete Research, Vol 8, pp 469.

10. Banfill P.F.G., 1981 b, “A viscometric examination of cement pastes containing superplasticisers with a note on experimental techniques”, Magazine of Concrete Research, pp 33, 37-47.

11. Bombled J.P., 1980, "Influence of sulphates on the rheological behaviour of cement pastes and their evolution", Proceedings of the 7th Int. Congress on the Chemistry of Cement, Vol 3, pp 164-169.
12. Banfill P.F.G., 1983, "A Viscometric Study of Cement Pastes Containing Superplastesizers with a Note on Experimental Techniques", Magazine of Concrete Research, Vol 33, pp 37-47.
13. Mork J.H. and Gjoerv O.E., March-April 1997, "Effect of Gypsum-Hemihydrate Ratio in Cement on Rheological Properties of Fresh Concrete", ACI Materials Journal, pp 142-146.
14. Dodson V.H. and Hyden T.D., 1990, "Another Look at the Portland Cement/Chemical Admixture Incompatibility Problem: How Effectively Use the Newest Admixtures", SCM 23-90, American Concrete Institute, Detroit.
15. Banfill P.F.G. and Kitching D.R., 1990, "Use of a Controlled Stress Rheometer to Study the Yield Stress of Oilwell Cement Slurries", pp 125-135.

Table 2. Chemical Properties of the Cements

Cement	%SiO_2	%TiO_2	%Al_2O_3	%Fe_2O_3t	%Mn_3O_4	%MgO	%CaO	%Na_2O	%K_2O	%P_2O_5	%SO_3	%Cr_2O_3	%SrO
Jordan	21.02	0.40	5.30	2.60	0.05	2.71	63.14	0.14	0.77	0.10	2.30	0.01	0.06
Gulf	21.29	0.27	4.74	3.53	0.12	1.29	65.29	0.08	0.35	0.04	1.80	0.02	0.05
Dubai National	20.72	0.25	5.06	3.38	0.06	1.19	64.93	0.19	0.42	0.08	2.20	0.07	0.07
Sharjah	20.73	0.32	5.13	3.90	0.08	1.45	64.60	0.15	0.39	0.09	1.70	0.02	0.06
Blue Circle Aberthaw	20.55	0.21	4.21	2.15	0.12	2.14	64.51	0.12	0.63	0.06	2.50	0.01	0.07
Castle Padeswood	21.15	0.20	5.02	1.73	0.05	1.14	66.21	0.13	0.78	0.05	2.30	0.01	0.08
Rugby Southam	21.12	0.20	4.47	2.23	0.08	1.20	66.13	0.14	0.76	0.20	2.20	0.01	0.09
Castle Ribblesdale	20.98	0.23	4.94	2.82	0.05	2.45	64.60	0.27	0.68	0.04	2.50	0.01	0.10
Blue Circle Masons	20.45	0.22	4.67	3.37	0.09	0.64	64.27	0.20	0.55	0.17	2.40	0.01	0.17
Castle Ribblesdale-RA	20.83	0.23	4.48	3.17	0.06	2.45	64.55	0.23	0.53	0.04	2.30	0.02	0.10
Canada	21.13	0.22	3.91	2.80	0.05	2.05	63.42	0.22	0.81	0.24	2.60	0.01	0.08
Castle Ketton	21.78	0.42	4.34	2.79	0.05	1.06	64.89	0.12	0.67	0.06	2.60	0.01	0.05
Blue Circle Cauldon	20.22	0.26	5.20	2.81	0.10	2.24	64.38	0.12	0.79	0.10	2.40	0.01	0.05
Blue Circle Weardale	19.97	0.22	5.14	3.11	0.22	1.78	64.24	0.11	0.76	0.12	2.20	0.00	0.17

Table 2 continued

Cement	%ZrO_2	%BaO	LOI	Total%	C_4AF	C_3A	C_2S	C_3S	%Anhydrite	%Gypsum	Hemihydrate
Jordan	0.01	0.01	1.23	99.85	7.90	9.65	16.61	57.89	1.35	0.75	0.30
Gulf	0.00	0.01	1.08	99.96	10.73	6.60	10.50	67.03	0.90	0.60	0.30
Dubai National	0.01	0.01	1.32	99.96	10.28	7.70	8.16	67.96	1.10	0.78	0.32
Sharjah	0.01	0.02	1.57	100.22	11.86	7.00	10.18	65.32	0.40	1.11	0.19
Blue Circle Aberthaw	0.01	0.04	2.57	99.90	6.54	7.52	2.35	75.01	0.95	1.40	0.15
Castle Padeswood	0.01	0.02	1.15	100.03	5.26	10.38	5.95	72.53	1.27	0.83	0.20
Rugby Southam	0.01	0.01	1.20	100.05	6.78	8.08	3.68	75.41	1.25	0.70	0.25
Castle Ribblesdale	0.01	0.02	0.68	100.38	8.57	8.33	10.20	66.24	1.62	0.67	0.21
Blue Circle Masons	0.01	0.02	2.66	99.90	10.24	6.68	5.88	69.96	1.45	0.50	0.45
Castle Ribblesdale-RA	0.01	0.02	0.79	99.81	9.64	6.51	7.11	69.77	1.60	0.34	0.36
Canada	0.02	0.03	2.24	99.83	8.51	5.63	9.87	67.25	1.80	0.20	0.60
Castle Ketton	0.02	0.02	1.07	99.95	8.48	6.79	13.11	65.42	1.91	0.54	0.15
Blue Circle Cauldon	0.01	0.02	1.09	99.80	8.54	9.03	5.64	69.39	1.70	0.50	0.20
Blue Circle Weardale	0.01	0.02	2.02	100.09	9.45	8.37	3.94	70.70	1.20	0.70	0.30

- The cements were separated into three groups according to their SSA.
- The Bouge equations were used to calculate the amount of phases.

Table 3. Physical Properties of the Cements

Cement	SSA m^2/kg	PSD 90.9 μm	PSD 73.1 μm	PSD 50.8 μm	PSD 30.6 μm	PSD 10.3 μm	PSD 3.46 μm	PSD <3.46 μm
Jordan	290.20	5.20	3.10	12.40	21.30	29.90	20.20	7.90
Gulf	305.40	5.20	2.80	5.50	15.20	38.70	24.80	7.80
Dubai National	306.70	5.90	3.90	9.10	17.40	33.40	21.70	8.60
Sharjah	323.70	3.40	2.70	6.50	18.60	36.60	23.20	9.00
Blue Circle Aberthaw	358.80	1.40	1.20	5.00	18.30	39.00	24.90	10.20
Castle Padeswood	361.00	2.80	2.20	8.10	17.80	32.00	26.50	10.60
Rugby Southam	364.00	2.80	2.70	8.30	17.60	32.10	25.40	11.10
Castle Ribblesdale	375.40	0.70	0.70	3.90	15.50	41.30	27.30	10.60
Blue Circle Masons	376.40	3.40	0.20	2.40	12.40	42.80	28.00	10.80
Castle Ribblesdale-RA	377.80	1.50	1.30	4.20	14.40	39.80	27.80	11.00
Canada	379.40	1.00	1.10	6.00	17.90	36.60	26.10	11.30
Castle Ketton	381.20	1.30	1.00	4.40	14.90	40.00	27.30	11.10
Blue Circle Cauldon	397.80	1.70	1.60	6.00	18.10	34.90	25.30	12.40
Blue Circle Weardale	434.30	2.20	1.60	5.90	17.20	32.00	27.00	14.10

Table 4. Results from the Rheological Tests

Cement	Blank Break Point	Blank Viscosity	Blank Yield	SMF Break Point	SMF Viscosity	SMF Yield	SNF Break Point	SNF Viscosity	SNF Yield	LS Break Point	LS Viscosity	LS Yield
Jordan	1043.20	18.42	1041.20	2061.30	36.99	1574.30	811.80	13.26	721.66	1923.60	39.46	1352.00
Gulf	885.50	21.46	957.52	2919.10	100.48	2015.00	1165.40	41.62	1415.50	487.00	15.75	709.90
Dubai National	870.00	10.84	986.88	401.10	3.98	521.12	129.00	6.86	166.98	159.40	5.10	136.37
Sharjah	1263.30	22.63	1248.30	3203.20	77.22	2891.60	2189.50	29.56	2431.50	1781.50	26.23	1902.70
Blue Circle Aberthaw	1008.30	21.02	1122.10	2725.00	57.66	2759.4	1371.60	9.81	1703.70	953.10	17.90	1353.90
Castle Padeswood	1192.30	18.32	1151.30	3050.80	54.55	3047.50	1938.30	21.53	2261.40	1490.30	21.16	1712.20
Rugby Southam	1312.30	35.02	1229.90	2452.30	61.46	2317.60	1536.80	18.10	1985.00	865.00	7.69	1293.10
Castle Ribblesdale	1237.30	25.14	1251.50	2172.20	100.91	3317.20	4007.40	91.31	3833.50	1960.00	43.10	2367.60
Blue Circle Masons	1514.90	33.54	1570.90	2394.00	60.33	3078.7	1182.70	8.66	1791.00	1549.30	20.47	2497.20
Castle Ribblesdale-RA	1417.70	33.45	1347.20	1983.30	39.00	2510.30	768.50	10.05	1132.30	587.50	9.58	1064.60
Canada	1926.73	57.50	2079.70	1411.52	27.87	1278.40	473.41	13.18	284.59	1404.60	66.15	941.33
Castle Ketton	1282.40	21.28	1340.50	2674.80	62.22	2865.00	1544.90	14.28	2175.70	1273.70	14.95	1903.30
Blue Circle Cauldon	1582.20	20.88	1664.40	4445.90	89.02	3920.3	4123.50	59.90	4048.90	2407.10	28.34	2773.40
Blue Circle Weardale	1772.60	19.15	1874.90	5428.40	Stiff	Stiff	5542.80	Stiff	Stiff	2927.00	40.50	3587.40

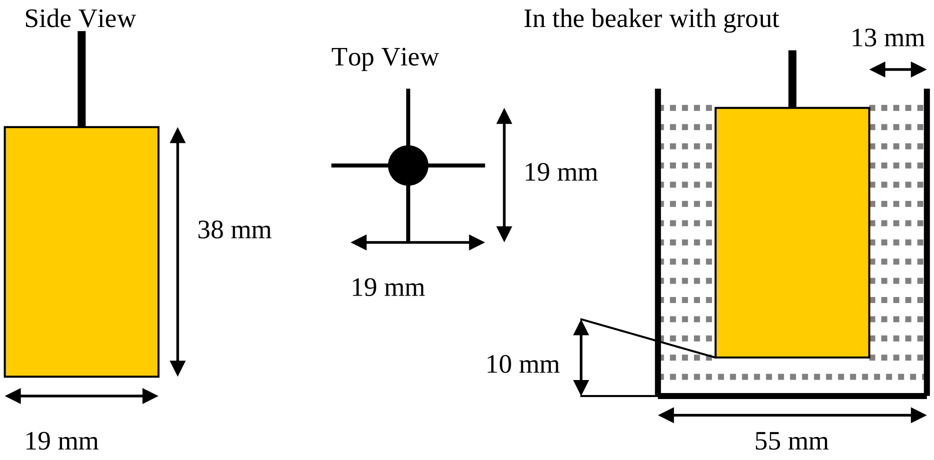

Figure 1 Schematic diagram showing the dimensions of the four-bladed vane spindle and the beaker during testing.

Break Point (Nm^{-2} x 10^{-7})

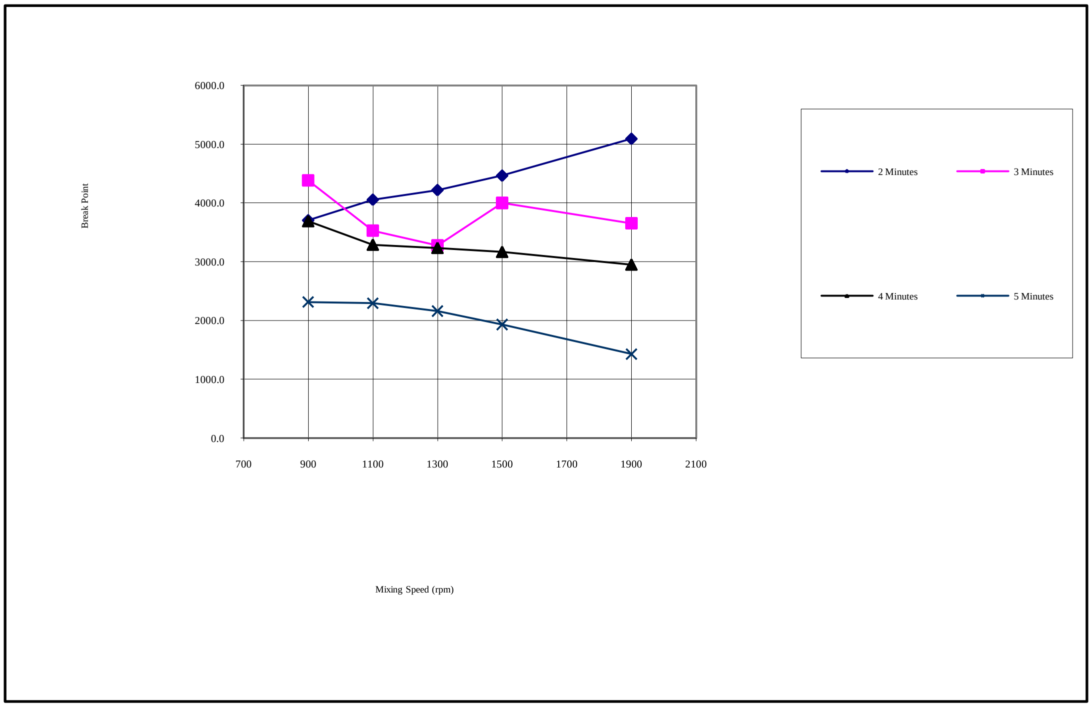

Figure 3 The effect of mixing speed and mixing time on the rheology of cement pastes.

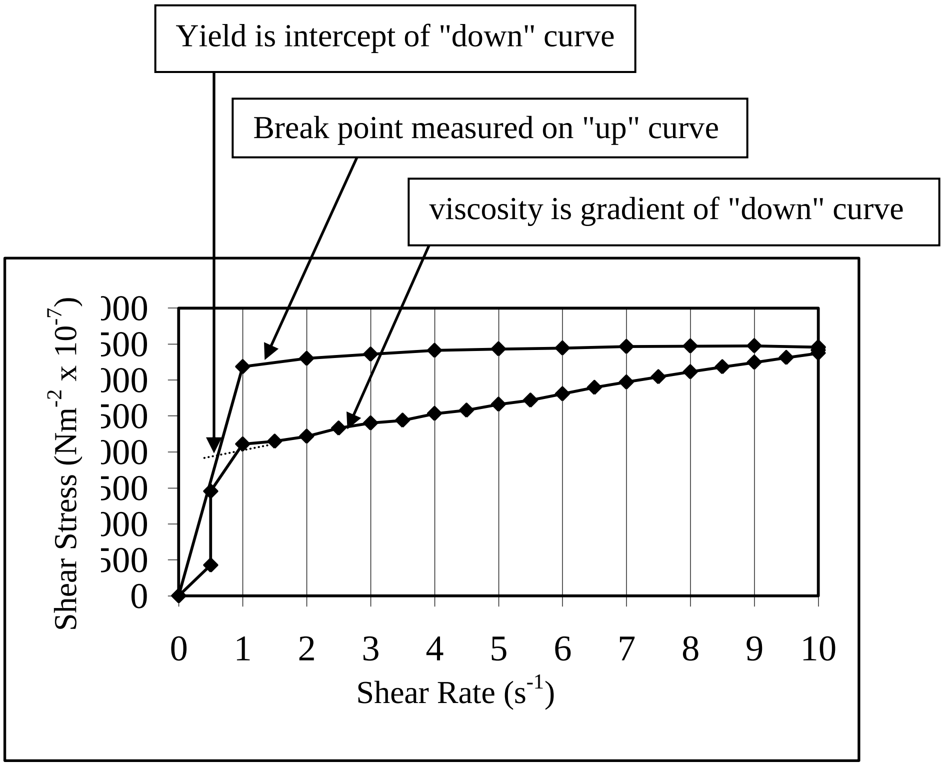

Figure 2 The testing cycle.

Yield Stress (Nm^{-2} x 10^{-7})

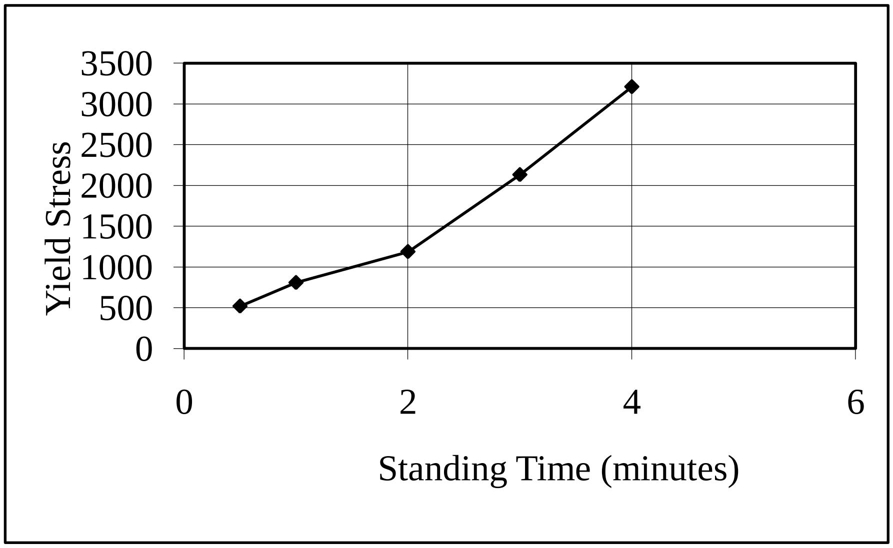

Figure 4a Standing time determination using SMF.

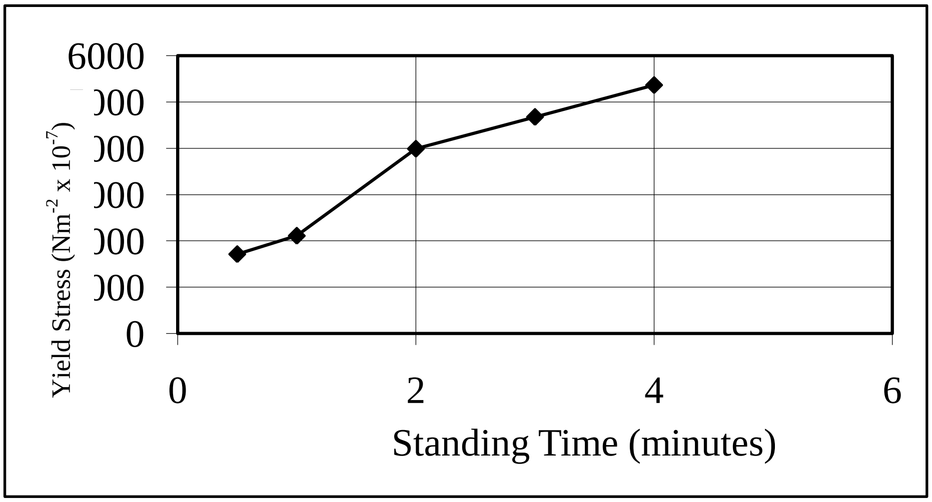

Figure 4b Standing time determination using SNF.

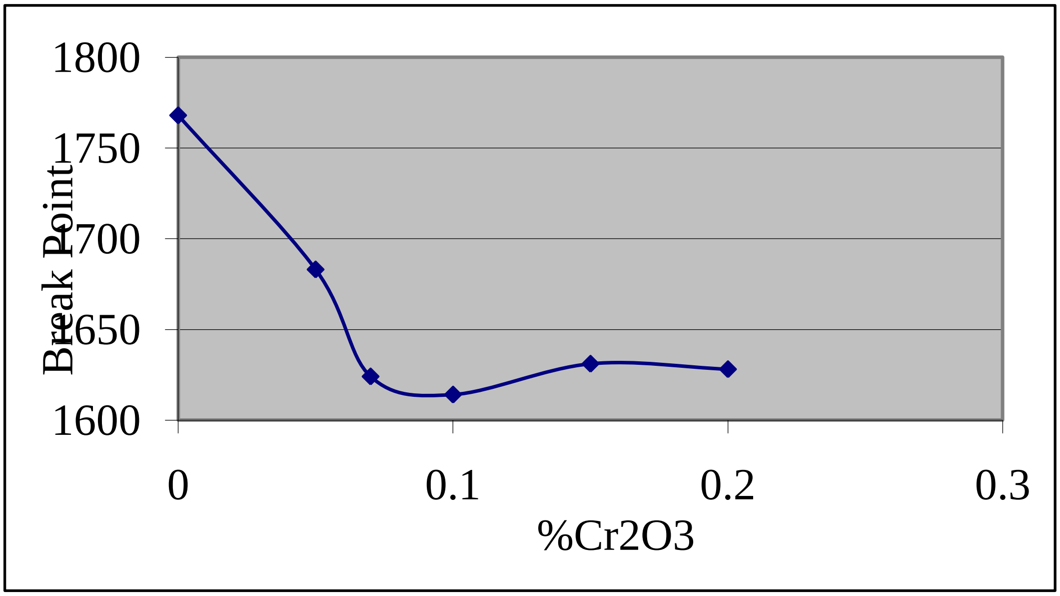

Figure 5 The effect of Cr_2O_3 on the Break Point.