Concrete Beton, Volume 85, pp 5-11, April 1997

Workability, Initial Set and Compressive Strength Characteristics of Concrete made with South African CSF at Various Substitution Ratios

Authors: [1]Y Ballim and [2]I Scott

[1]Assistant Dean, Engineering Faculty, University of the Witwatersrand, Johannesburg
[2]Laboratory manager, Anglo Alpha Limited, South Africa

ABSTRACT:

This paper presents results of a project aimed at characterising the performance of South African CSF in concrete. Concretes were prepared using both densified and undensified CSF, at a replacement ratio of 8% and substitution ratios of 1:1, 2:1, 3:1 and 4:1. Concretes containing 300, 400 and 500 kg/m^3 were used to prepare control samples. All concretes contained andesite and aggregates and no watering-reducing admixture were used.

The project was focused on monitoring the effect of the addition of CSF on slump, initial set and compressive strength of concrete. Compressive strength was measured on continuously water-cured samples up to 91 days after casting.

It was found that the addition of CSF reduces the slump of OPC concrete, with the extent of reduction decreasing as the substitution ratio increased. CSF also causes a delay in the initial setting time, with the extent of the delay, increasing as the substitution ratio increases.

As an aid to the design of CSF concrete mixes, proposed forms of the water/binder ratio vs. compressive strength curves for undensified and densified is presented, based on the results of this investigation. The results are also used to determine strength efficiency factors for the 2 forms of CSF over a range of compressive strength grades.

Journal Contact Details:
PO Box 75364
Lynnwood Ridge
Pretoria, 0040
South Africa
+27 12 348 5305

CONCRETE SOCIETY
OF SOUTHERN AFRICA

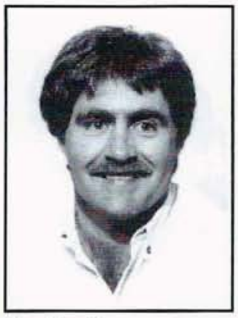
admin@concretesociety.co.za
www.concretesociety.co.za

TECHNICAL PAPER

WORKABILITY, INITIAL SET AND COMPRESSIVE STRENGTH CHARACTERISTICS OF CONCRETE MADE WITH SOUTH AFRICAN CSF AT VARIOUS SUBSTITUTION RATIOS

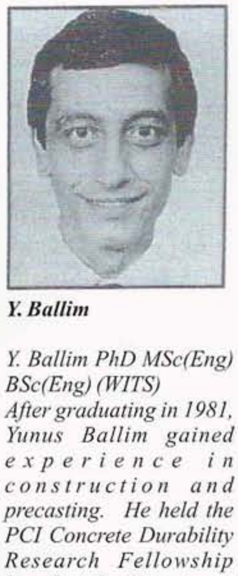
by: Y. Ballim* and I. Scott**

* Dept. Of Civil Engineering, University of the Witwatersrand.
** Laboratory Manager, Anglo Alpha Limited



Ivan Scott

Ivan Michael Scott obtained his BSc (Civil Eng) at WITS in 1974 and his Diploma in Advanced Concrete Technology (London) in 1993. He has spent 3 years working in the consulting engineering sector and 14 years as a contractor. In 1991, he joined Anglo Alpha as their concrete laboratory manager, a post he held for 3 years. He is presently resident in Vancouver, Canada.



Y. Ballim

Y. Ballim PhD MSc(Eng) BSc(Eng) (WITS)
After graduating in 1981, Yunus Ballim gained experience in construction and precasting. He held the PCI Concrete Durability Research Fellowship based at the Department of Civil Engineering, University of the Witwatersrand between 1989 and 1991. He is Assistant Dean (UG) in the Engineering faculty and recently received a PhD degree, his research topic being the influence of curing on the durability of concrete. He has published a number of papers on concrete materials and in particular, concrete durability.

ABSTRACT

This paper presents results of a project aimed at characterising the performance of South African CSF in concrete. Concretes were prepared using both densified and undensified CSF, at a replacement ratio of 8% and substitution ratios of 1:1, 2:1, 3:1 and 4:1. Concretes containing 300, 400 and 500 kg/m^3 were used to prepare control samples. All concretes contained andesite aggregates and no water-reducing admixtures were used.

The project was focused on monitoring the effects of the addition of CSF on slump, initial set and compressive strength of concrete. Compressive strength was measured on continuously water cured samples up to 91 days after casting.

It was found that the addition of CSF reduces the slump of OPC concrete, with the extent of reduction decreasing as the substitution ratio increased. CSF also causes a delay in the initial setting time, with the extent of delay increasing as the substitution ratio increases.

As an aid to the design of CSF concrete mixes, proposed forms of the water/binder ratio vs. Compressive strength curves for undensified and densified CSF is presented, based on the results of this investigation. The results are also used to determine strength efficiency factors for the 2 forms of CSF over a range of compressive strength grades.

1. INTRODUCTION

Condensed silica fume (CSF) first became commercially available as a cement extender in South Africa in 1987. Since then, it has been used in a relatively small number of concrete projects, most notably the new headquarters of the Development Bank of South Africa, the new Alusaf aluminium smelting plant and the Columbus Steel Project. However, CSF has not found general acceptance in concrete in South Africa, largely due to the dearth of local experience and data regarding the performance of CSF as a cement extender. The need for intensive investigation into the characteristics of local CSF before it can be confidently used is highlighted in Fulton (1).

Much information has been published in foreign literature on the properties of CSF concrete and a useful review of this literature is presented by Aitcin (2). Based on this information, it is generally accepted that the main benefits of CSF lies in its ability to enhance the strength and durability performance of concrete. However, past experiences with cement extenders like GGBS and FA have emphasised that some caution is necessary before foreign data on the performance of cementitious materials can be applied to local conditions. This derives mainly from the fact that local cements, extenders, aggregates and admixtures are usually different from those used in other countries.

As a contribution to the development of this information, this paper discusses the results of a research project which was undertaken to characterise the concrete making properties of South African CSF. The investigation was focused at the effect of the addition of CSF on:

- the workabibility of fresh concrete;
- initial setting time; and
- early-age compressive strength of concrete.

Three control concrete mixes were prepared using OPC contents of 300, 400 and 500 kg/m^3. Comparative CSF mixes were also prepared for each of these control mixes, using the CSF at a fixed replacement ratio of 8% and at substitution ratios of 1:1, 2:1, 3:1, 4:1.

2. TERMINOLOGY

Some conflict exists in the literature with regard to the use of various terms associated with CSF in concrete. A description of the relevant terms used in this paper is therefore presented below.

Undensified condensed silica fume (UCSF): This is CSF in its "natural" captured state. It is physically characterised by its extreme fineness (average particle size 0.1 um) and low bulk density (approximately 200 kg/m^3).

Densified condensed silica fume (DCSF): This is CSF after it has been subjected to a patented process aimed at increasing the particle size and bulk density to approximately 0.2 mm and 610 kg/m^3 respectively.

Replacement ratio: This indicates the mass of Portland cement which is replaced by an equal mass of CSF in the concrete mix. Hence, by way of an example, a mix containing 400 kg/m^3 of binder with a 10% CSF replacement, contains 360 kg/m^3 Portland cement and 40 kg/m^3 CSF. Replacement normally ranges between 5% and 15%.

Substitution ratio: This indicates the number of parts (by mass) of Portland cement which are substituted by one part of CSF at the stated replacement. As an example, in comparison with a mix containing 400 kg/m^3 of OPC, a CSF mix with 10% replacement and a 2:1 substitution ratio, contains 320 kg/m^3 OPC and 40 kg/m^3 CSF. Substitution is used in order to take advantage of the strength enhancing effect of CSF by reducing the total binder content of the mix (usually for economic reasons), while maintaining the compressive strength of the concrete.

OPC content equivalent mix: This refers to a mix which contains CSF at a stated replacement level and substitution ratio, which is intended to give an equivalent compressive strength as a reference OPC mix. Following on the example used above, a 400 kg/m^3 OPC equivalent mix with a 10% replacement and a 2:1 substitution ratio would contain 320 kg/m^3 OPC and 40 kg/m^3 CSF. In this case, the total binder content is reduced by 40 kg/m^3.

3. MATERIALS AND MIXES

3.1 Binders

Mixes were prepared using blends of OPC, UCSF and DCSF.
The chemical composition of these materials are shown in Table 1. ***see page 8***

3.2 Aggregates

Crushed andesite was used as both the coarse and fine aggregates in all the mixes. The coarse aggregate was a nominal 19 mm stone with the maximum particle size of 26.5 mm. The fine aggregate had a fineness modulus of 3.16 with 12% passing the 150 μm sieve.

3.3 Concrete Mix Design

Three control OPC mixes were prepared containing 300, 400 and 500 kg/m^3 of cement respectively. The water content of each mix was adjusted to give a concrete slump of 85 ±10 mm. It was decided that the stone content of all the mixes would be kept constant, with adjustments being made in the sand contents to maintain the yield of each mix.
A CSF replacement ratio of 8% by mass was used and, for each of the three control mixes, DCSF mixes were prepared using substitution ratios of 1:1, 2:1, 3:1 and 4:1. Also, as some concern had been expressed (3) regarding the reduced efficiency of DCSF, it was decided to include one series of mixes containing UCSF at a replacement ratio of 8% and substitution ratio of 1:1. Concrete mix design details as shown in Table 2. ***see page 8***
All mixes were prepared in a high-shear laboratory pan mixer of nominal capacity 50/

4. TEST METHODS

4.1 Slump Test

For each mix, a standard slump test was carried out at the end of the mixing period. This was the only measure of workability used in the test programme.

4.2 Initial Set Time

The initial set times of each of the mixes were measured in accordance with ASTM C403-85 (4). Test specimens were stored at a temperature of 23 ± 2°C and RH > 90%. Penetration resistance was measured using pocket and Proctor penetrometers and initial set was determined as the time when penetration resistance was 3.5 MPa.

4.3 Compressive Strength

The compressive strength of the concretes was measured using 100 mm cubes. Samples were prepared, water cured and tested in accordance with SABS 863 (5). For each mix, compressive strength was determined at 1, 7, 28, 56 and 91 days after casting, three cubes being tested at each test age. All samples were water cured until the time of testing.

5. RESULTS AND DISCUSSION

5.1 Slump

The results of slump measurements are shown in Figure 1. ***see page 8*** The following points are noted from this figure:

- the addition of CSF caused a reduction in the slump of all the mixes tested;
- at a 1:1 substitution ratio, UCSF has a larger effect in reducing slump than DCSF;
- the reduction in slump caused by the addition of DCSF increases with increasing binder content;
- the reduction in slump caused by the addition of DCSF decreases as the substitution ratio is increased from 1:1 to 4:1;
- at substitution ratios of 3:1 and 4:1, the addition of DCSF has only a marginal effect in reducing slump.

These results are in general agreement with most research findings on the effects of CSF on the slump of concrete (6). However, some caution is necessary since the relationship between slump and workability under vibration is not the same for CSF concretes as it is for other non-CSF concretes. This implies that the slump test, being a static test, is not a sufficient means of comparing the workability of CSF concrete for the normal structural applications. This aspect requires further investigation for South African CSF, especially for applications in which water-reducing admixtures are used. A further interesting aspect of these results is the difference in the effects of UCSF and DCSF on slump at a substitution ratio of 1:1. On the basis that the reduction in slump is as a result of the fineness of the CSF, the results indicate that the DCSF does not disperse to its original fineness when mixed with water. This would have negative implications for the efficiency of the pozzolanic reaction when DCSF is used.

5.2 Initial Set Time

The results of initial set times for the different mixes tested are shown in Figure 2. *see page 8* These results show that:

- initial set time generally decreases as the total binder content increases;
- aside from the 300 kg equivalent UCSF mix, the addition of CSF into the concretes had the effect of extending the initial set times, compared with the OPC concretes;
- in general, the addition of CSF at a 1:1 substitution ratio causes only a marginal extension of the initial set time.
- increases in initial set time increases as the substitution ratio increases and ,at a substitution ratio of 4:1, the initial set time can be increased by up to 75 minutes.

Again, these results confirm other research findings (6) on the extension of initial set times of CSF concretes. However, the practical relevance of these results may be brought into question as CSF is almost always used in concrete in combination with a water-reducing admixture.
For example, it has been found that the retardation effect of lignosulphonate as a plasticiser was greater in plain OPC pastes than in OPC/CSF pastes (7). This aspect will require further investigation in the light of changing technology in the admixture industry, especially in the South African context.

5.3 Compressive Strength

The results of the compressive strength tests are shown in figures 3, 4 and 5 for the 300, 400 and 500 kg equivalent mixes respectively. In these figures the UCSF results are shown as a dashed line while the control OPC results are shown as the thick line. The following observations are made from these results:

- the UCSF mixes generally gave the highest strength results over the full range of test ages;
- at a substitution ratio of 1:1 and in comparison with the control OPC mixes, the CSF concretes showed equivalent or higher strengths up to 7 days and gave significantly higher compressive strengths up to 56 days;
- at a 2:1 substitution ratio, the DCSF concretes gave similar 28 day strengths as the OPC mixes, but significantly lower 1 and 7 day strengths.
- at substitution ratios of 3:1 and 4:1, the DCSF mixes gave lower compressive strengths than the OPC mixes at all ages. In this regard, it must be noted that these DCSF mixes had higher b/w ratios than the corresponding OPC mixes;
- an important feature in these results is the decline in strength showed by the 400 and 500 kg equivalent DCSF mixes at a 1:1 substitution ratio. This is discussed in more detail below.

A number of researchers have noted medium to long term strength reductions with CSF concretes and a review of the relevant literature is presented in references 8 and 9. However, the results obtained in this investigation are unusual in that most of the earlier reports of strength regression with CSF concretes appear to relate to air-cured concrete samples. This has led to the postulate (9) that the strength regression is due to the development of internal stresses resulting from the loss of moisture in the pore structure during drying. All the samples in the present investigation were water cured until the time of testing.

Strength regression of CSF concrete under continuously moist conditions has also been noted by Clayton and Dunster (10). However, in testing concretes ranging in 28-day strength from 40 to 130 MPa, only the 130 MPa concrete showed a strength decline and this occurred between 3 months and 1 year. It is not clear whether this investigation was carried out using UCSF or DCSF.

In view of the small number of samples tested in this investigation and the unusual occurrence of the strength declines when compared to other experiences, it is possible that the reason for the observed strength regression may be found in factors other than inherent material behaviour. It will be necessary for a much wider range of

Table 1: Chemical composition (%) of the OPC, UCSF and DCSF used in the mixes

Compound	OPC	UCSF	DCSF
SiO_2	22.6	89.5	89.7
Al_2O_3	4.4	1.8	1.7
Fe_2O_3	2.5	1.9	1.9
CaO	64.5	1.1	1.0
MgO	1.6	0.6	0.6
K_2O	0.3	1.1	1.1
TiO_2	0.3	0.0	0.0
Mn_2O_3	0.1	0.2	0.2
P_2O_5	0.1	0.1	0.1
LOI	1.2	3.0	3.1

Table 2: Mix proportions (kg/m³) of the concretes tested

Mix ID	OPC	DCSF	UCSF	Sand	Stone	Water	w/b*
PC/300	300	-	-	832	1220	200	0.667
PC/400	400	-	-	736	1220	202	0.505
PC/500	500	-	-	637	1220	204	0.408
D1/300	276	24	-	824	1220	200	0.667
D1/400	368	32	-	722	1220	202	0.505
D1/500	460	40	-	620	1220	204	0.408
D2/300	252	24	-	847	1220	200	0.725
D2/400	336	23	-	751	1220	202	0.550
D2/500	420	40	-	655	1220	204	0.444
D3/300	228	24	-	867	1220	200	0.794
D3/400	304	32	-	780	1220	202	0.601
D3/500	380	40	-	693	1220	204	0.485
D4/300	204	24	-	890	1220	200	0.877
D4/400	272	32	-	809	1220	202	0.667
D4/500	340	40	-	730	1220	204	0.537
U1/300	276	-	24	824	1220	200	0.667
U1/400	368	-	32	722	1220	202	0.505
U1/500	460	-	40	620	1220	204	0.408

*w/b = water/total binder ratio

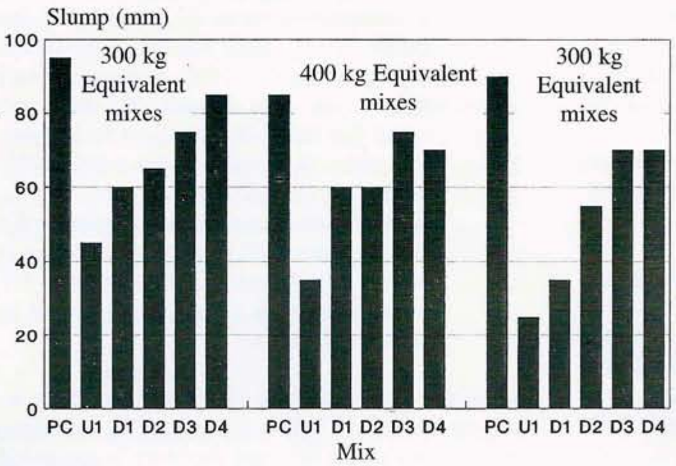


Figure 1: Results of slump measurements for the various mixes tested

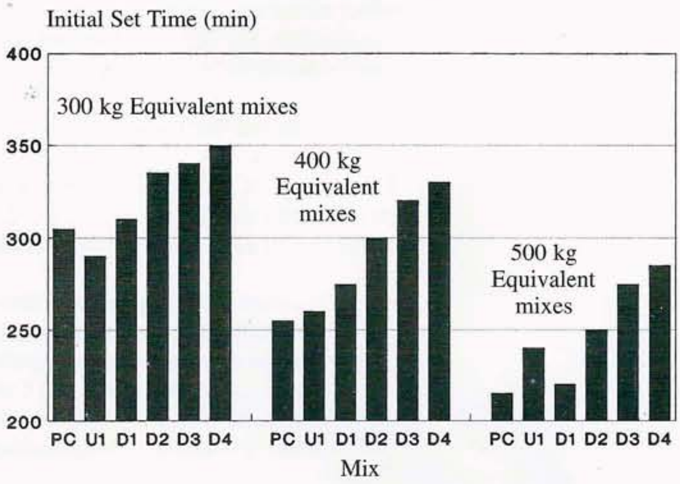


Figure 2: Initial set times for the various mixes tested

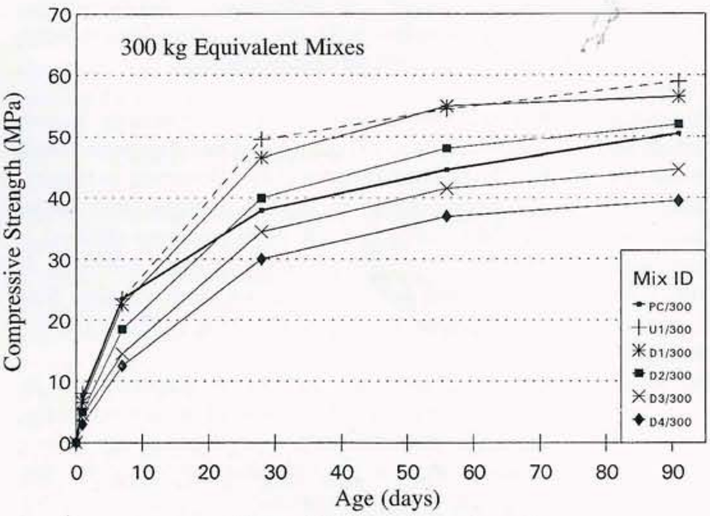


Figure 3: Compressive strength results for the 300 kg equivalent mixes

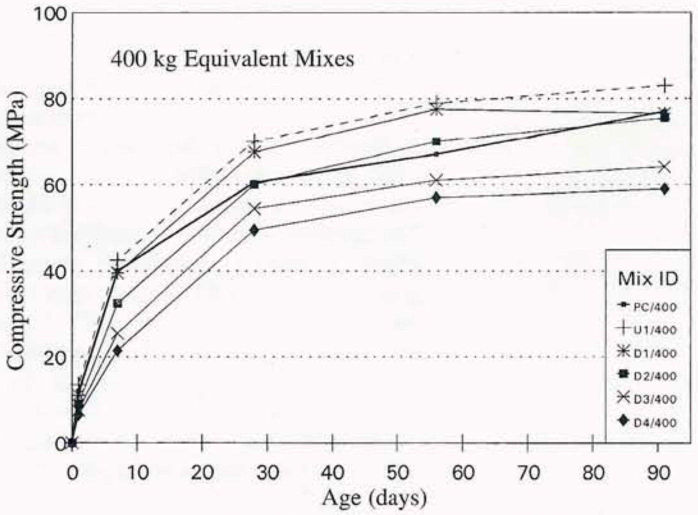


Figure 4: Compressive strength results for the 400 kg equivalent mixes

concretes to be tested over a longer period, before firm conclusions can be drawn as to the strength regression behaviour of South African CSF concretes. Furthermore, it will be necessary to monitor the effects of the addition of water-reducing admixtures on the rates of strength gain at later ages as it is more common for CSF to be used in concrete in combination with these admixtures.

5.4 Design Strength Curves and CSF Efficiency

As a contribution to the development of design strength curves for South African CSF, the 28-day strength results obtained in this investigation are plotted in Figure 6 against the w/b ratio of the corresponding mixes. For each of the binder types, a logarithmic regression curve has been fitted to the data. The regression curve is in the form:

$$F_{cu} = A + B.\ln\left(\frac{w}{b}\right)$$

where: f_{cu} is the 28-day compressive strength, and A and B are constants.

The calculated values for A and B are shown in Table 3. ***see page 10***

It should be noted that the regression curves for the OPC and OPC/UCSF concretes are based on only 3 results while that of the OPC/DCSF concretes is based on 12 results, with varying substitution ratios. The OPC/DCSF curve therefore represents an "average" relationship for 8% replacement of DCSF at any substitution ratio between 1:1 and 4:1.

Figure 6 shows that the UCSF curve has a similar shape to that of the OPC curve but is simply shifted upwards. On the other hand, the DCSF curve is rotated slightly to give lower strengths than the UCSF concretes at low w/b ratios. Also, at w/b ratios greater than approximately 0,6, the w/b ratio to compressive strength relationship of UCSF and DCSF concretes can be considered to be similar.

Figure 6 can also be used to determine the efficiency of CSF in concrete. Loland and Hustad (11) have proposed an efficiency factor, K, which converts an amount of CSF into an equivalent amount of OPC, based on the w/b ratios required to achieve "equivalent performance" of OPC and OPC/CSF concretes. In the present study, "equivalent performance" is interpreted as equal compressive strength.

The factor K is defined by the equation:

$$\left[\frac{w}{c}\right]_R = \left[\frac{w}{c+Ks}\right]_S$$

Where w, c and s are the water, OPC and CSF contents respectively. The subscripts R and S refer to the reference (OPC) and CSF concretes respectively. This expression can be re-written in the form:

$$K = \frac{\frac{Y}{X} + Z - 1}{Z}$$

Where	K	is the efficiency factor;
	X	is the w/b ratio required to achieve a particular strength level with a plain OPC mix;
	Y	is the w/b ratio required to achieve the same strength with a CSF mix;
	Z	is the replacement ratio expressed as a fraction.

Using this form of the expression for K and the regression curves shown in Figure 6 to determine the w/b ratios required to achieve strengths of 35, 55 and 75 MPa, the efficiency factors of the UCSF and DCSF were calculated. These factors are shown in Table 4.

TABLE 4: Efficiency factors for the UCSF and DCSF concretes ***see page 10***

These results indicate that the UCSF generally has a higher efficiency than DCSF at the higher strength levels. As noted with the slump results, this may also indicate an incomplete dispersion of the DCSF when added to the concrete mix. Furthermore, the efficiency of UCSF increases as the strength level increases, while the reverse trend occurs for DCSF.

Some caution is necessary in the assessment of the values shown in Table 5 since K is a "marginal" parameter which is sensitive to the accuracy of the results and the regression equation used. This sensitivity increases as the CSF replacement ratio decreases. It is therefore appropriate at this stage to accept the average efficiency factors of 2.9 and 2.6 for the UCSF and DCSF respectively for the purposes of concrete mix design.

6. CONCLUSIONS

For an 8% replacement ratio of CSF in concrete made with andesite aggregates and containing no water-reducing admixtures:

a. The slump of OPC concrete is reduced by the addition of CSF into the mix. UCSF has a larger effect in reducing slump than DCSF at a 1:1 substitution ratio. DCSF substitution ratios of between 3:1 and 4:1 causes only a marginal decrease in slump.

Table 3: Values of A and B for logarithmic regression curves shown in Figure 6

Binder Type	A	B
OPC	6.5	-78.3
OPC/DCSF	17.9	-82.0
OPC/UCSF	15.6	-73.8

Table 4: Efficiency factors for the UCSF and DCSF concretes

CSF Type	Efficiency factor (K) for a compressive strength of:		
	35 MPa	55 MPa	75 MPa
UCSF	2.69	2.86	3.04
DCSF	2.78	2.56	2.34

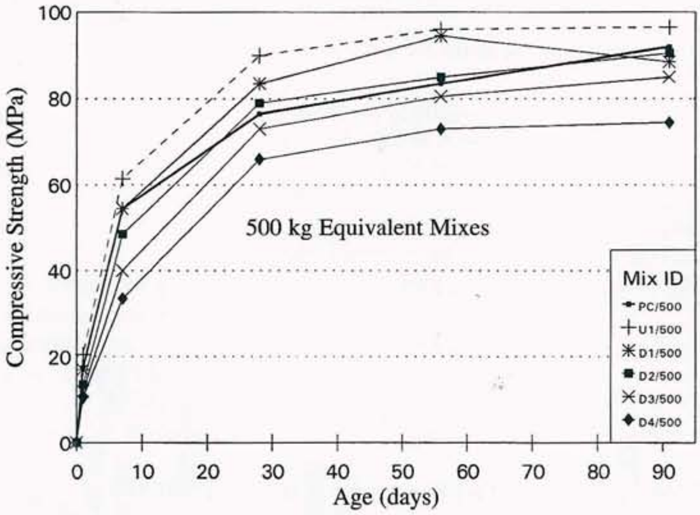


Figure 5: Compressive strength results for the 500 kg equivalent mixes

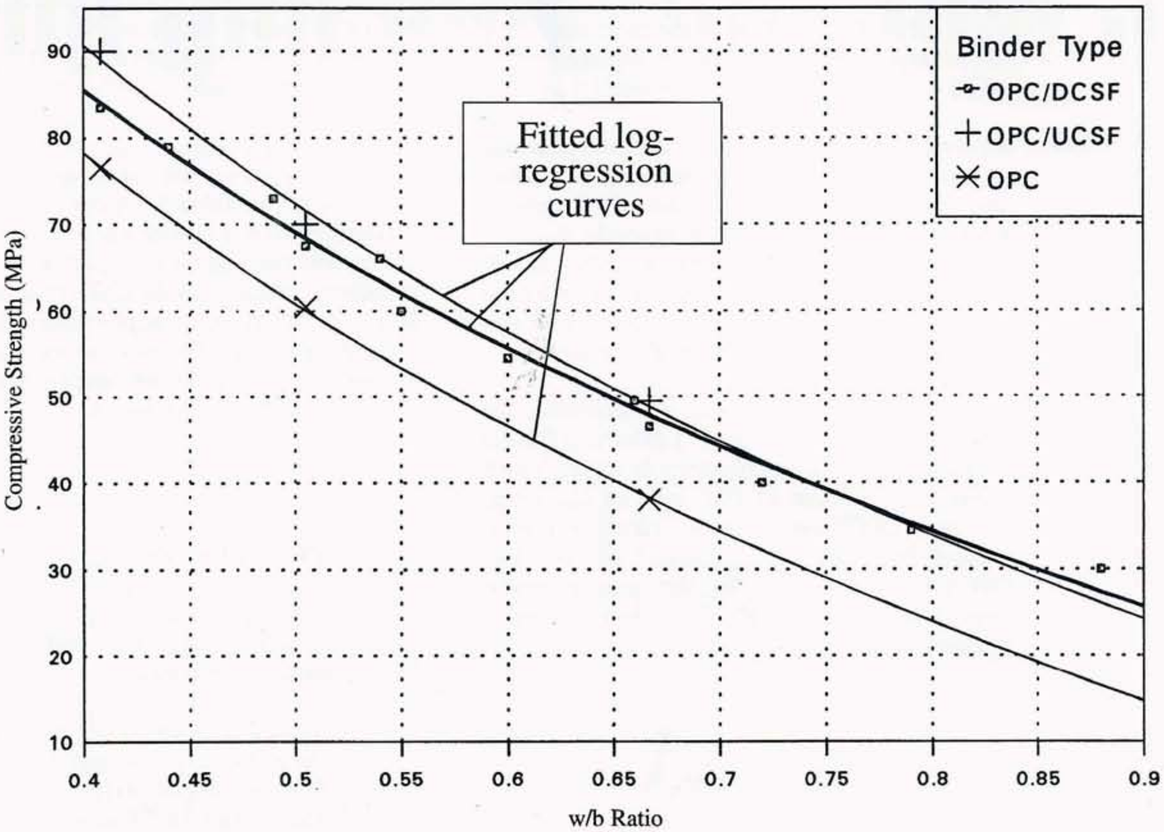


Figure 6: 28-day compressive strength vs. w/b ratio for the different binder types used

b. The addition of DCSF or UCSF at a substitution ratio of 1:1 causes a negligible extension in the initial setting time. Higher substitution ratios of DCSF cause significant delays in the initial setting time with a delay of 75 minutes being measured at a substitution ratio of 4:1.

c. Based on curves for w/b ratio vs. Compressive strength, the efficiencies of South African UCSF and DCSF are 2.9 and 2.6 respectively.

d. From the comparative effects of UCSF and DCSF on slump and compressive strength, it appears that the DCSF does not disperse uniformly throughout the concrete mix, resulting in a lower efficiency.

e. Two of the mixes containing a 1:1 substitution of DCSF, showed regressions In compressive strength between 56 and 91 days. However, unlike most previous experiences, the strength reductions noted occurred at relatively early ages and under continuously moist cured conditions. Further investigation, which includes the effects of water-reducing admixtures, is necessary before confident statements can be made as to the long-term strength behaviour of South African CSF concretes.

ACKNOWLEDGEMENTS

This paper is based on work conducted by Mr. I. Scott as part of the Institute of Concrete Technology (London) course in Advanced Concrete Technology. The authors would like to thank Anglo Alpha Limited and the Portland Cement Institute's School of Concrete Technology for their permission to publish this paper.

LIST OF REFERENCES

1. Addis, B.J. (Ed) *Fulton's Concrete Technology*. Sixth (Revised) Edition, Portland Cement Institute, Midrand, South Africa 1986

2. Aitcin, P.C., Influence of Condensed Silica Fume on the Properties of Fresh and Hardened Concretes, *Condensed Silica Fume*, Les Editions de l'Universite de Sherbrooke, Quebec, 1983, pp 25-27.

3. Anglo Alpha Limited, private communication.

4. American Society for Testing and Materials. ASTM C403-85, Standard test method for time of setting of concrete mixtures by penetration resistance. ASTM Vol 04.02, *Concrete and Mineral Aggregates*. 1985.

5. South African Bureau of Standards. Standard Method 863: Compressive strength of concrete (including making and curing of test cubes). SABS, Pretoria, 1976.

6. FIP State of the Art Report: Condensed silica fume in concrete. Thomas Telford, London. 1988.

7. Meland, I. Influence of condensed silica fume and fly ash on the heat evolution in cement pastes. *Special Publication SP-79.* American Concrete Institute. 1983.

8. De Larrard, F and Aitcin, P-C. Apparent strength retrogression of silica fume concrete. *ACI Materials Journal,* V. 90, No. 6, Nov/Dec 1993. pp 581-585.

9. De Larrard, F and Bostvironnois, J.L. On the long-term strength losses of high-strength silica fume concrete. *Mag. Of Concr. Res.* V43, No.155, June 1991. Pp 109-119.

10. Clayton, N and Dunster, AM, Discussion on Reference 8. *ACI Materials Journal,* V. 91, No. 5, Sept/Oct 1994. Pp 530-531.

11. Loland, K.E. And Hustad, T. Report 2: mechanical properties. FCB/SINTEF, *Norwegian Inst. Of Technology*, Trondheim, 1981.Report STF65 A81031.