Pergamon

Cement and Concrete Research, Vol. 25, No. 1, pp. 209-220, 1995
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0008-8846/95 $9.50+.00

0008-8846(94)00128-6

EFFECT OF DIFFERENT SUPPLEMENTARY CEMENTITIOUS MATERIALS ON MECHANICAL PROPERTIES OF HIGH PERFORMANCE CONCRETE

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(Refereed)
(Received June 10; in final form October 5, 1994)

ABSTRACT

High performance concrete prepared from general purpose (GP) portland cement and various supplementary cementitious materials are increasingly finding their use in construction worldwide. This study was undertaken to compare mechanical properties as well as fresh concrete properties of concretes containing silica fume, ground granulated blast furnace slag (slag), fly ash and GP portland cement. The aim of the study was to enable evaluation of the suitability of a particular binder system for an application based on fresh concrete properties and mechanical properties. Concrete mixes were prepared with GP portland cement, high slag cement and slag cement, and also mixes were prepared with the addition of silica fume and fly ash. The work focussed on concrete mixes having a fixed water/binder ratio of 0.35 and a constant total binder content of 430 kg/m^3. Apart from measuring fresh concrete properties, the mechanical properties evaluated were development of compressive strength, flexural strength, elastic modulus, and strain due to creep and drying shrinkage. Results indicated that the addition of silica fume to GP portland cement concrete marginally decreased the workability of the concrete but significantly improved the mechanical properties. However the effect of addition of silica fume to high slag cement concrete was less pronounced.

Introduction

Supplementary Cementitious Materials (SCM) such as, fly ash, ground granulated blast furnace slag (slag) and silica fume are extensively used in construction. The primary advantage of concretes prepared from these materials and GP portland cement is in the enhancement of fresh and hardened properties of the concrete, ecological benefits resulting from industrial by-products utilisation ratios and the benefits achieved in terms of overall economy. However the degree to which a particular property is improved or the rate at which a property is improved is dependent on the type and amount of supplementary cementitious material /s used. The aim of the present study is to compare fresh and hardened properties of concretes prepared from fly ash, slag and silica fume. The comparison would enable the evaluation of a SCM for a particular application.

It has been very well established that concretes prepared from fly ash and slag have significantly lower permeability which results in a highly durable concrete but the compressive strength development is slower than concrete prepared from normal portland cement (1,2). This is due to large particle size and hence reduced surface area of fly ash and slag, which causes it to hydrate slowly in the presence of alkaline solution formed by the dissolution of cement particles. The mechanism of hydration of SCM is a dissolution and diffusion controlled process and thus the particle size or surface area plays an important role in the rate of reactivity of SCM in alkaline solution. Silica fume has extremely fine particle size (0.1 - 0.3 μm) compared to the average particle size of fly ash and slag (10 - 20 μm). Hence the rate of hydration of silica fume is considerably higher than those of fly ash and slag (2). As a result, silica fume starts to contribute to the strength development as early as one day after mixing of concrete, whereas slag takes more than three days and fly ash takes more than seven to fourteen days before they make any significant contribution to the development of strength of concrete (2).

Several studies have been carried out to study the elastic modulus, creep and drying shrinkage of concrete prepared with silica fume (3,4,5,6). However the findings of various studies are conflicting. Based on the studies carried out by Hooton (3), the drying shrinkage of silica fume concretes was 10 to 22% higher than that of normal portland cement concrete of same water/binder ratio and same binder content. On the other hand, Tazawa and Yonekura (4) found that the drying shrinkage of silica fume concrete was lower than that of normal portland cement concrete of same water/binder ratio but marginally lower binder content. Buil and Acker (5) also found that silica fume concrete had lower drying shrinkage than that of a plain cement concrete with same binder content but marginally lower water/binder ratio. The lower drying shrinkage of silica fume concrete could be attributed to its lower water/binder ratio.

Houde et al (6) found that creep characteristics were improved by replacing 5 to 10% of the normal portland cement by silica fume while keeping the same water/binder ratio. However Buil and Acker (5) found that creep characteristics of silica fume concrete were not superior to concrete prepared from normal portland cement and, they observed similar creep characteristics for concretes prepared with and without silica fume in spite of marginally higher water/binder ratio in concrete containing no silica fume.

To elucidate the effect of the addition of silica fume, drying shrinkage and creep properties were evaluated for GP portland cement concrete prepared with, and without silica fume. Also there is limited data available on the effect of the addition of silica fume on drying shrinkage and creep characteristics of concrete already containing slag and fly ash. Thus drying shrinkage and creep properties were evaluated for concrete containing only slag, concrete prepared with slag and silica fume, and concrete containing fly ash and silica fume. Flexural strength and elastic modulus were also evaluated for all the concrete mixes. Fresh concrete properties studied were setting times, density, air content and flow.

Experimental Details

Materials and Concrete Mix Proportions

In this study, seven mixes were cast. The binder content of all the mixes was 430 kg/m^3 and the water/binder ratio was kept at 0.35. A range of binder types were used and the notation used in the mix designation is given below. Table 1 shows the details of the constituents of the binder used in the mixes. The numerals in mix designation corresponds to the percentage of SCM present in the binder, for example GP/10SF/25F means that 10% of the binder is silica fume, 25% of the binder is fly ash and the rest is GP portland cement. Table 2 shows the chemical composition and loss of ignition (LOI) of the various binders.

- GP - General purpose portland cement conforming to Australian Standard AS3972 and similar to ASTM Type I.
- HS - High slag cement (nominally 65% slag and 35% GP cement)
- SC - Slag cement (nominally 65 % GP cement and 35 % slag)
- F - Fly Ash (Class F) from Eraring Power station in New South Wales, Australia
- SF - Silica Fume from Barrack Silicon in Western Australia, Australia

Table 1 - Details of Binders Used in the Mixes

Mix Designation	% GP	% HS	% SC	% F	% SF
GP	100				
HS		100			
GP/10SF	90				10
HS/10SF		90			10
SC/10SF			90		10
GP/10SF/15F	75			15	10
GP/10SF/25F	65			25	10

Table 2 - Chemical Composition by Percentage of various Binders

Oxides	GP	HS	SC	F	SF
CaO	64.9	49.1	55.1	1.3	0.2
SiO_2	20.9	28.3	25.0	65.2	98.5
Al_2O_3	4.5	10.3	8.5	26.0	0.2
Fe_2O_3	3.7	2.5	2.9	3.1	0.1
MgO	1.8	4.0	3.3	0.7	0.5
TiO_2	0.4	0.6	0.5	1.1	0.1
SO_3	2.5	3.4	3.3	0.17	0.1
K_2O	0.66	0.47	0.48	1.66	0.2

This set of mixes enables evaluation of the effect of the addition of silica fume to concretes prepared from GP, slag blended cements and fly ash plant blended cements. Table 3 gives the mix designs of the mixes cast. The 20 mm and 10 mm aggregates were crushed river gravel, coarse sand was a river sand and fine sand was a dune sand. A water reducing admixture (WRA) and a superplasticer admixture (SP) were used in all mixes. The water reducing admixture was a modified sodium salt lignosulphonic acid and the superplasticiser was a calcium salt naphthalene formaldehyde condensate. The water reducing admixture was added into the mixes at a dosage of 0.5 litres per 100 kg of binder. Variable dosages of superplasticiser were added to the mixes to ensure that the minimum slump achieved was 120 mm.

Table 3 - Mix Designs for the Mixes Cast (All values in kg/m^3)

MIX DESIGNATION	GP	HS	GP/10SF	HS/10SF	SC/10SF	GP/10SF/15F	GP/10SF/25F
Coarse Agg.	1082	1087	1089	1087	1090	1087	1094
Fine Agg.	744	721	741	729	731	718	708
GP	425	-	384	-	-	320	282
HS	-	425	-	386	-	-	-
SC	-	-	-	-	384	-	-
FLY ASH	-	-	-	-	-	65	106
SILICA FUME	-	-	45	45	45	45	46
TOTAL BINDER	425	425	429	431	429	430	434
W : B	0.35	0.35	0.34	0.35	0.35	0.34	0.34

Samples and Testing Procedures

Relevant Australian Standards were followed for the preparation of concrete and the testing of fresh and hardened concrete. Equivalent ASTM standards are given in brackets. Concrete mixes were prepared in accordance with AS 1012-2 (ASTM C192). All the materials were charged and were mixed in the dry state in a pan mixer followed by the addition of water and water reducing agent. Slump was measured at this stage and was called the "initial slump". The mixing of concrete was continued and superplasticizer was added at this stage to achieve a slump of at least 120 mm. Slump measured after the addition of superplasticizer was called "final slump". Fresh concrete properties measured were initial slump, final slump, density, flow, air content, initial and final setting times. Procedures described in AS 1012-3, AS 1012-4, AS 1012-5 and AS 1012-18 were used to determine slump, air content, density and setting times of fresh concrete, respectively (ASTM C143, C231, C138, and C403). The flow of fresh concrete was determined by the procedure outlined in British Standard BS 1881-105 (ASTM C939).

Compressive strength determination was carried out on cylindrical specimens of 100 mm diameter and 200 mm height and the samples were continuously cured in saturated lime water until the time of test. Testing was carried out on two specimens at each age and the average value has been reported. Drying shrinkage was measured for prisms of dimensions 75 x 75 x 285 mm and the reported value is average of three specimens. The samples were cured in lime water till the age of seven days and thereafter stored under standard laboratory conditions in a controlled temperature (23±2°C) and humidity (50±5%), and air circulation environment conforming to specifications outlined in AS 1012 - 13. Flexural strength measurements were carried out on three beams of dimensions 100 x 100 x 380 mm and the average value has been reported. Modulus of elasticity was measured for cylindrical specimens of diameter 150 mm and height 300 mm and the reported value is the average of three specimens. Flexural strength and elastic modulus samples were continuously cured in lime water until the time of test. Strain due to creep was measured on two cylindrical specimens of diameter 150 mm and height 300 mm. Three strain measurements were performed on each cylinder and thus the reported value is the average value of six measurements. The samples were subjected to a nominal stress of 40% of the compressive strength in a creep rig (with the exception of the specimens of HS/10SF which were subjected to 30% of the compressive strength). Till the age of seven days the samples were cured in lime water and thereafter stored under standard laboratory conditions at controlled temperature (23±2°C) and humidity (50±5%). All samples for measuring hardened properties of concrete remained in the mold for 24 hours and subsequently were stripped and were subjected to lime water curing. Australian Standards followed to determine compressive strength, flexural strength, elastic modulus and strain due to drying shrinkage and creep were AS 1012-9, AS 1012-11, AS 1012-17, AS 1012-13 and AS 1012-16, respectively (ASTM C39, C293, C469, C426 and C512).

Results and Discussion

Characteristics of Fresh Concrete

Table 4 shows the dosage of superplasticiser and also the data on air content, initial and final slumps, initial and final setting times and flow are presented for the mixes investigated. It can be observed that the mixes incorporating silica fume tended to require higher dosages of superplasticiser relative to the mixes without silica fume. The higher demand of superplasticiser with the concrete containing silica fume can be attributed to the fine particle size of silica fume which causes some of the superplasticiser being adsorbed on its surface. Hooton (3) and Carette et al (7) also found that for similar slump, concrete containing silica fume had higher demand of superplasticiser in comparison to the plain concrete. Mantegazza et al (8) and Kohno and Komatsu (9) found that the mortar prepared with silica fume had lower flow than plain mortar for the same water/binder ratio and same dosage of superplasticiser. During mixing, it was observed that mixes incorporating silica fume were more "cohesive" when compared to non-silica fume mixes and this is in agreement with the findings of Radjy et al (10).

Table 4 - Fresh Concrete Properties for the Mixes Investigated

MIX DESIGNATION	DOSAGE OF SUPERPLAS. (kg/m^3)	AIR CONT. (%)	INITIAL SLUMP (mm)	FINAL SLUMP (mm)	INITIAL SET (min)	FINAL SET (min)	FLOW (mm)
GP	3.6	2.0	15	110	530	600	385
HS	4.3	1.6	15	200	930	1100	435
GP/10SF	7.3	1.4	0	170	400	470	410
HS/10SF	7.8	1.2	5	210	870	1020	485
SC/10SF	7.7	1.4	5	170	690	790	415
GP/10SF/15F	5.9	1.4	0	160	550	620	450
GP/10SF/25F	5.4	1.8	5	120	630	730	395

Figure 1 shows the setting times of the mixes investigated. It is evident from the Figure that addition of 10% silica fume to both GP and HS concretes reduces both the initial and final setting times by at least one hour. This can provide considerable advantage in the case of the HS concrete. Both GP/SF/F mixes have similar setting times to the GP concrete. The decrease in the setting times by the addition of silica fume can be explained by taking into account the effect of fine particle size on the hydration process. Owing to their small size, silica fume particles fill the interstices of the cement particles and act as nucleation sites for the hydration and thus accelerate the rate of cement hydration. Furthermore in the interstitial sites the silica fume particles are readily available to react with alkali hydroxide and $Ca(OH)_2$ liberated by the hydration of cement. Mategazza et al (8) also found that setting times of mortar decrease with the addition of silica fume.

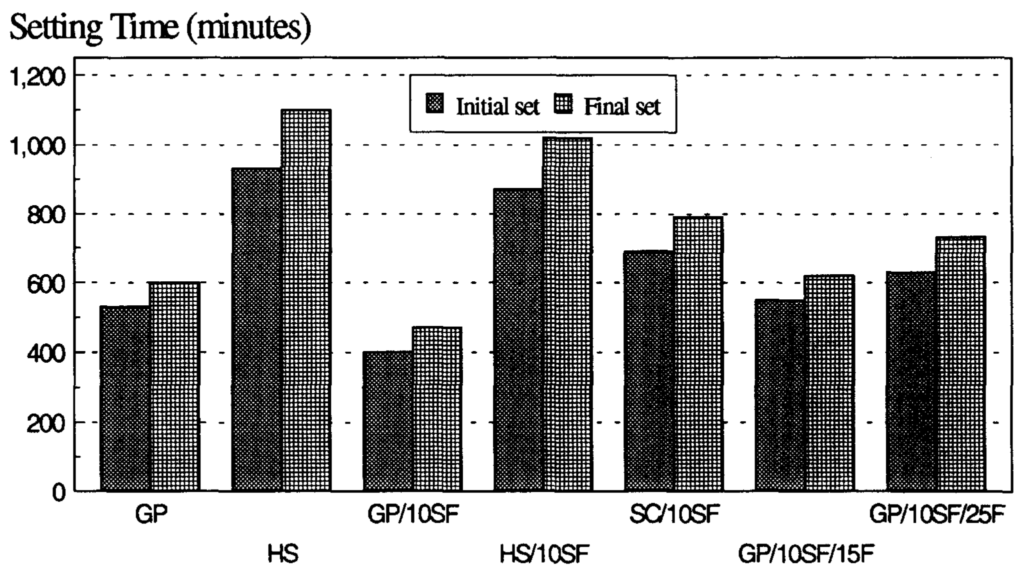

Figure 1 - Initial and Final Setting Times for the Mixes Studied

Compressive Strength

Figure 2 shows the compressive strength development under continuous moist curing of GP and HS concrete prepared with and without silica fume. The figure on left hand side shows the strength development up to 28 days and the figure on the right shows the strength development up to one year.

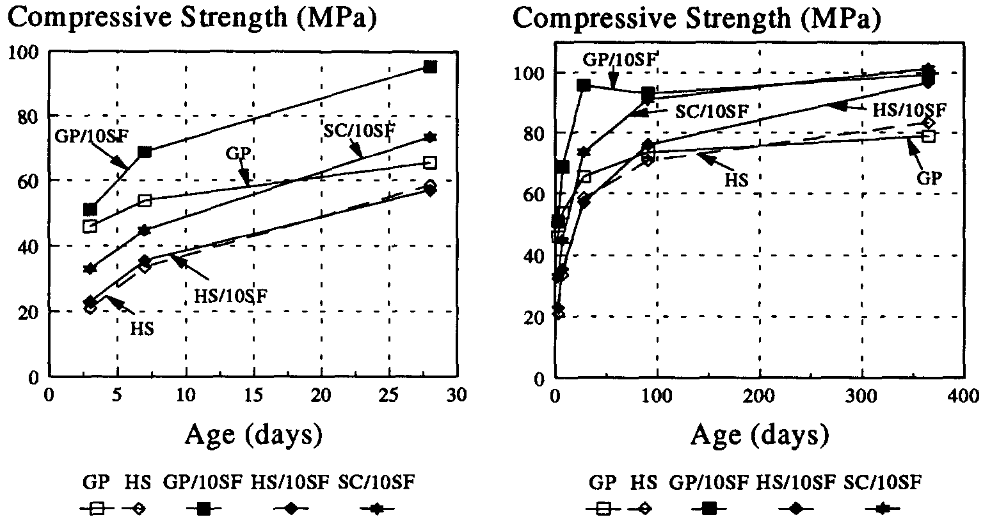

Figure 2 - Compressive Strength Development Characteristics of GP, HS, GP/10SF, HS/10SF and SC/10SF concretes.

Comparing the strength development of GP and GP/10SF concrete, it is clear that addition of silica fume to GP portland cement improves the strength at all ages and the silica fume contributes to the strength from as early as the age of 3 days. On the other hand comparing HS and HS/10SF concrete it can be seen that the addition of silica fume to high slag cement significantly increases the strength at the age of one year, however silica fume has no effect on the compressive strength up to the age of 91 days. Thus the addition of silica fume to GP portland cement increases the compressive strength at all ages, however the addition of silica fume to high slag cement increases the compressive strength at the age of one year, but has no effect on the early age compressive strength.

Compressive strength development of concrete produced from low slag cement and silica fume (SC/10SF) is also shown in Figure 2. It is evident that the strength of SC/10SF is considerably more than that of GP at the age of 28 day and onward, however the early age (3 day and 7 day) strength of SC/10SF is less than the respective strength of GP concrete. Also it can be seen that strength of HS/10SF is less than the strength of GP at the age of 3, 7 and 28 days, and at the age of 91 days the strengths of GP and HS/10SF are similar. Thus it can be concluded that based on equal binder content and equal W/B ratio, the effect of the addition of silica fume on early age compressive strength is more pronounced in low slag cement than in high slag cement. The effect of the addition of silica fume to the compressive strength of specimen at later ages is similar for all three cements.

The effect of silica fume on the strength development in concrete already containing fly ash was also studied. Figure 3 shows the effect of addition of silica fume on the compressive strength development of concretes already containing fly ash. Similar to SC/10SF concrete, compressive strength of concrete containing GP cement, fly ash and silica fume is higher than the compressive strength of concrete containing only GP cement at the age of 28 day and later. However the early age (3 day and 7 day) strengths of both GP/SF/15F and GP/SF/25F mixes are less than the respective strength of GP concrete. Comparing the compressive strengths of GP/10SF/15F and GP/10SF/25F with GP/10SF, it can be seen that by the age of 91 days the compressive strengths of all three concretes are similar whereas, the early age strength (3, 7 and 28 day) of fly ash concrete is lower than that of GP/10SF.

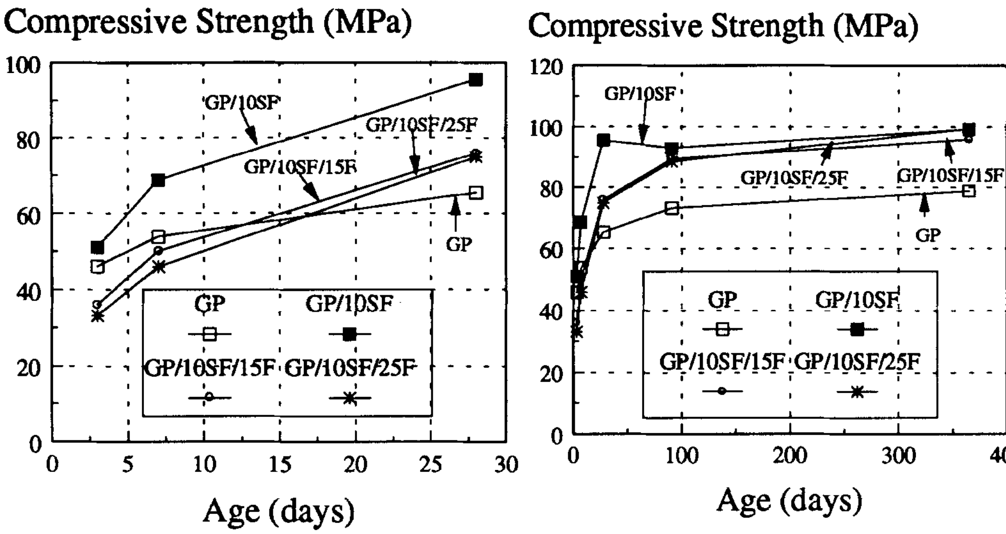

Figure 3 - Compressive Strength Development Characteristics of GP, GP/10SF, GP/10SF/15F and GP/10SF/25F concretes.

Flexural Strength and Elastic Modulus

Figure 4 shows the 28 day and one year flexural strength of concrete investigated in this study. It can be observed that the addition of silica fume significantly increases the flexural strength of GP concrete. The increase in flexural strength of HS concrete by the addition of silica fume is marginal. The effect of inclusion of silica fume on the flexural strength of concrete is similar to its effect on compressive strength. This is in agreement with the findings of Carette et al (6) and Luther et al (11).

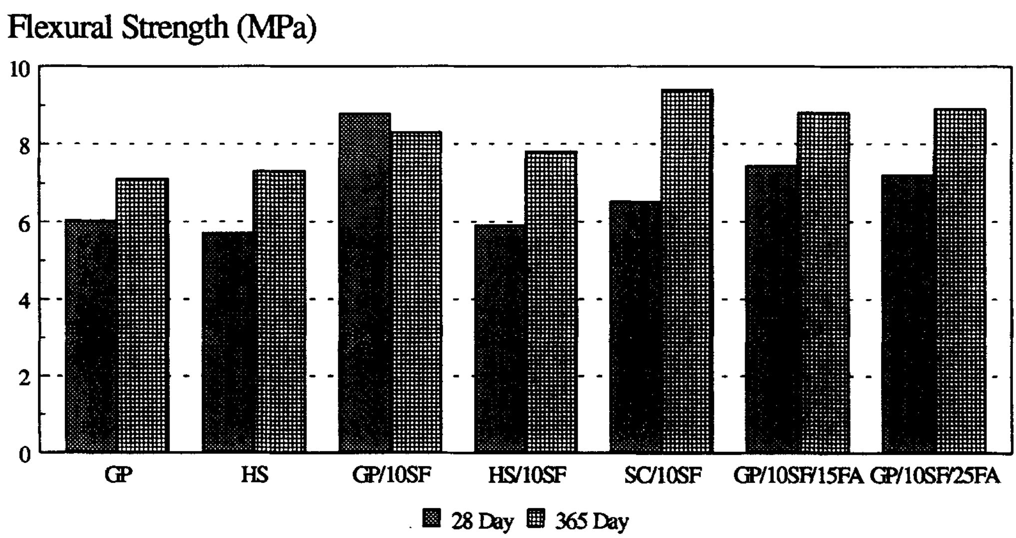

Figure 4 - 28 day and 365 Day Flexural Strength of Concretes.

Flexural strengths were found to increase with increasing compressive strengths and were plotted against their compressive strength as shown in Figure 5. It was found that at a 90% confidence level, flexural strengths can be expressed as 0.81 x $(F_c)^{0.5}$, where F_c is compressive strength. As per AS 3600 on "Concrete Structures" (12), a similar relationship exists between flexural strength and compressive strength of a concrete made from GP portland cement, however the value of the constant is 0.60 (ASTM C823).

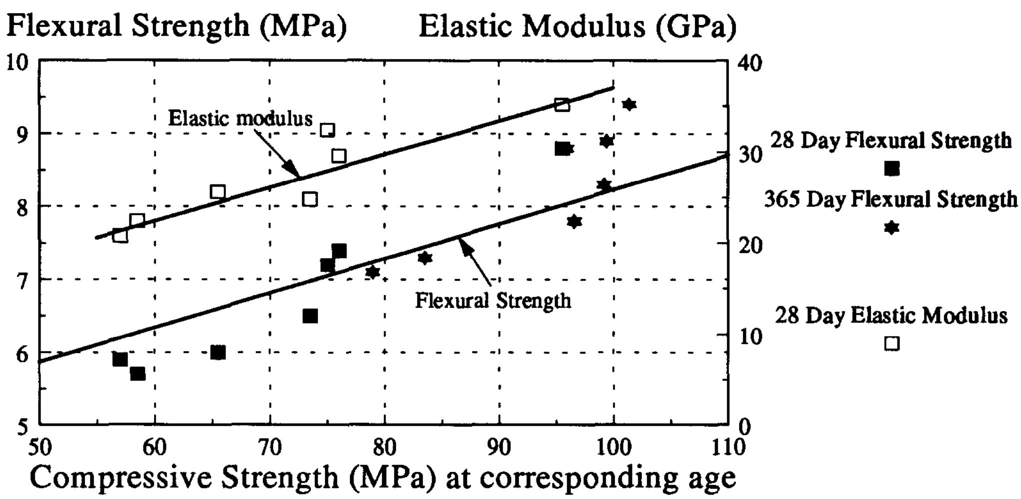

Figure 5 - Variation of Flexural Strength and Elastic Modulus with Compressive Strength.

Elastic moduli measured at the age of 28 days are shown in Figure 6. The addition of silica fume improved the elastic modulus of GP concrete, however it had no effect on the elastic modulus of HS concrete. Also the 28 day compressive strength of GP/10SF was considerably higher than that of GP concrete and, the 28 day strength of HS/10SF and HS concretes were similar. The effect of inclusion of silica fume on elastic modulus of concrete shows similar trends to its effect on compressive and flexural strength. Hooton (3) and Luther et al (11) also found that elastic modulus is primarily a function of compressive strength. Elastic moduli of concretes were found to increase with increasing compressive strength and are shown in Figure 5.

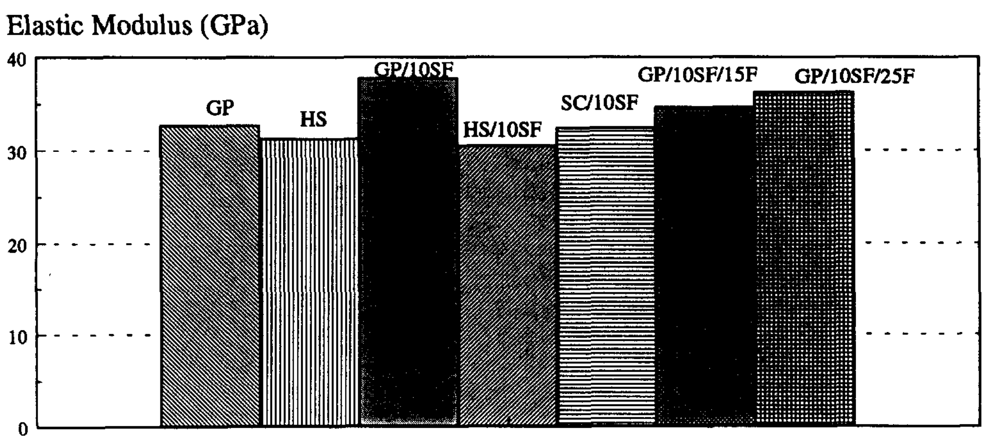

Figure 6 - 28 days Elastic Modulus of Concretes.

Creep and Drying Shrinkage

Figure 7 shows the specific creep (strain due to creep per unit stress that the cylinders are subjected to) of GP, HS, GP/10SF, HS/10SF and SC/10SF concretes. It can be observed that the addition of silica fume considerably reduces the specific creep of concrete prepared from GP cement. Furthermore on adding silica fume to HS binder, the specific creep of the aged specimen is marginally reduced whereas, it has very little effect on the early age specific creep. The creep characteristics of HS/10SF concrete are marginally better than that of GP concrete. Also the creep characteristics of SC/10SF concrete are better than that of GP concrete. Comparing mixes HS/10SF, SC/10SF and GP/10SF, it appears that concrete with lesser slag content in its binder gave lower specific creep.

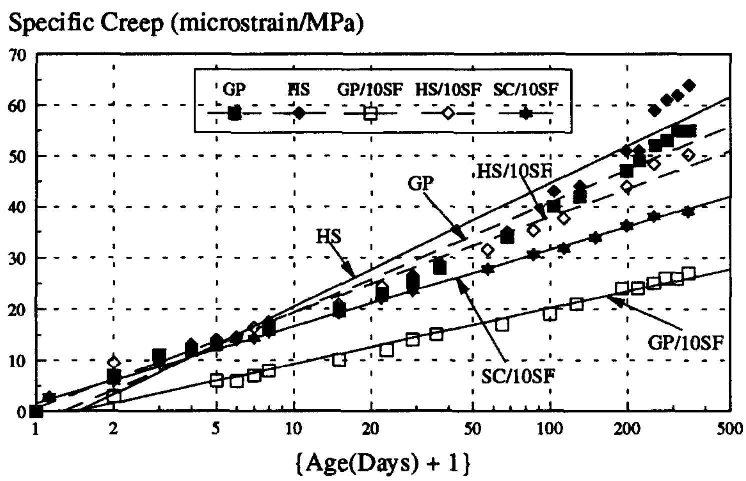

Figure 7 - Specific Creep against Time for GP, HS, GP/10SF, HS/10SF and SC/10SF Concretes.

The effect of inclusion of fly ash on concrete creep characteristics is shown in Figure 8. It is evident from the Figure that the creep characteristics of concrete containing fly ash and silica fume are superior to that of GP concrete. However the specific creep increases with the inclusion of fly ash into the GP/10SF mix. The amount of fly ash (15% and 25%) does not influence the creep property of triple blend concretes significantly.

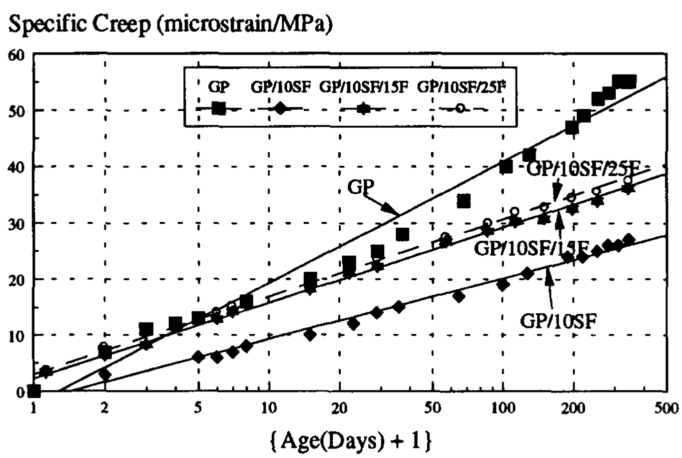

Figure 8 - Specific Creep against Time for GP, GP/10SF, GP/10SF/15F and GP/10SF/25F concretes.

The drying shrinkage characteristics of GP, HS, GP/10SF, HS/10SF and SC/10SF concretes are shown in Figure 9. It is evident from the Figure that the addition of silica fume reduces the longer term drying shrinkage of concrete prepared with GP cement, particularly after the age of 28 days. However the addition of silica fume increases the early age shrinkage of concrete prepared with GP cement. On adding silica fume to HS binder it was found that while the addition had a marginal effect on the long term drying shrinkage (over 56 days), it increased the early age drying shrinkage. Also it is evident from the Figure that long term drying shrinkage of SC/10SF concrete is lower than that of HS concrete. However the early age shrinkage of SC/10SF is more than that of HS concrete. Comparing mixes HS/10SF and SC/10SF, it can be seen that the early age shrinkages of both mixes are similar, whereas the longer term shrinkage of SC/10SF is marginally lower than that of HS/10SF. Drying shrinkages of all slag mixes were found to be higher than that of mixes prepared from GP cement

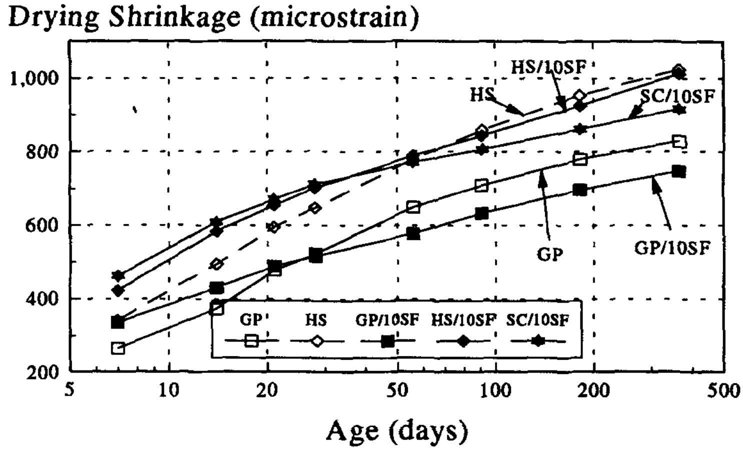

Figure 9 - Drying Shrinkage Characteristics of GP, HS, GP/10SF, HS/10SF and SC/10SF Concretes.

Figure 10 shows the effect of inclusion of fly ash in GP/10SF concrete on the drying shrinkage characteristics. It can be seen from the Figure that the inclusion of fly ash to GP/10SF concrete increases the drying shrinkage over GP/10SF concrete as well as over GP concrete. The amount of fly ash (15% and 25%) does not appear to influence the drying shrinkage characteristics.

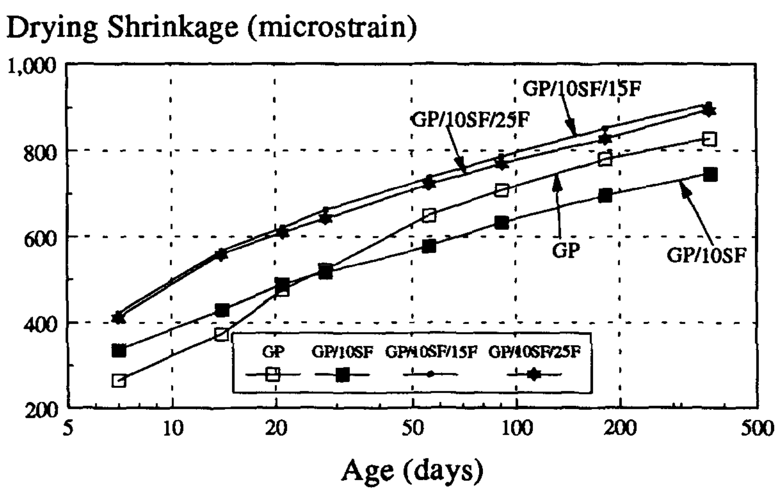

Figure 10 - Drying Shrinkage Characteristics for GP, GP/10SF, GP/10SF/15F and GP/10SF/25F concretes.

From this study it is clear that the addition of silica fume increases the compressive strength of concrete prepared from GP cement and this could be explained by higher pozzolanicity of silica fume (5). It has been very well established that the silica fume starts to contribute to the strength from the age of 1 day and makes significant contribution between the age of one week to four weeks and almost no contribution thereafter (2,13,14). Silica fume starts to contribute to strength at the age of one day but does not make any significant contribution to the strength till the age of one week. Thus the addition of silica fume to concrete prepared with low slag cement (SC/10SF) as well as concrete prepared with GP cement and fly ash (GP/10SF/15F and GP/10SF/25F) have 3 day and 7 day strengths lower than the respective strengths of GP concrete (Figures 2 and 3). However silica fume makes significant contribution to strength between the age of one week and four weeks. The 28 day compressive strengths of SC/10SF, GP/10SF/15F and GP/10SF/25F were found to be higher than that of GP concrete. Furthermore the contribution of silica fume to the strength after the age of four weeks is negligible and this is apparent in the strength development of GP/10SF, the increase in compressive strength after the age of 28 days is minimal (Figure 3).

The addition of silica fume decreases the specific creep at all ages and also decreases the long term drying shrinkage in concrete prepared from GP cement. However the early age drying shrinkage of GP/10SF was found to be higher than that of GP concrete. It has been well established that strain due to both creep and drying shrinkage is caused by the removal of adsorbed water (15). In the case of drying shrinkage the cause of removal of water is ambient relative humidity and in the case of creep the cause is the applied stress. Mehta (2) and Hooton (3) have found that the addition of silica fume refines the pore size distribution of the cement paste. Addition of silica fume does not change the total pore volume in the cement paste but increases the percentage of fine pores. The pore refinement could be the cause of reduced loss of water and thus decreases the strain due to creep and drying shrinkage. Creep is also known to be influenced by the microstructure in the transition zone of concrete (2). Based on the studies carried out on mortars, Cheng-Yi and Feldman (14) concluded that addition of silica fume improves the transition zone and this mechanism could be also be responsible for the decrease in strain due to creep by the addition of silica fume to GP concrete.

Unlike GP portland cement concrete, the addition of silica fume has little influence on the early age compressive strength, creep characteristics at all ages, and long term drying shrinkage characteristics of the concrete prepared from high slag cement. However, the one year compressive strength of high slag cement concrete was improved significantly by the addition of silica fume. The early age drying shrinkage of HS/10SF concrete was higher than that of HS concrete. This ineffectiveness of silica fume in the presence of large proportions of slag could be due to the reduced availability of alkali hydroxide and $Ca(OH)_2$. Since there is smaller amount of GP portland cement present in the high slag cement, less $Ca(OH)_2$ is liberated by the hydration of GP portland cement and, as a result silica fume is unable to increase the rate of strength development at early ages, creep characteristics at all ages and the long term drying shrinkage. The contribution of silica fume to strength development at the age of more than 91 days can be attributed mainly to physical mechanisms in this particular case (16). The addition of silica fume increases the compressive strength at later stages by acting as a "microfiller" or by increasing the efficiency of packing of solid particles in the cement paste system by dispersing itself in the interstices of the cement particles.

Conclusions

(a) The addition of silica fume decreases the setting times but increases the superplasticiser demand for similar workability. Also on addition of silica fume, the compressive strength improved at all ages and the strain due to creep was found to be lowered. The early age drying shrinkage was observed to increase with the addition of silica fume, however the long term drying shrinkage of concrete prepared with GP cement and silica fume was lower than the concrete containing GP cement only.

(b) The addition of silica fume to high slag cement concrete had no effect on the compressive strength till the age of 91 days and significantly increased the compressive strength at the age of one year. Creep and drying shrinkage characteristics of high slag cement concrete were not affected by the addition of silica fume.

(c) Long term strength of concrete containing GP cement and silica fume was similar to those concretes containing GP cement, silica fume and 15 or 25% of the binder as fly ash. However the inclusion of fly ash into concrete containing GP cement and silica fume caused the early age strength to decrease and the strain due to drying shrinkage and creep to increase.

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