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Strength Development and Drying Shrinkage of High-strength Concretes

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Abstract

Ten high to very high strength concretes with total cementitious contents of 550 and 600 kg/m^3 were made. The concretes consisted of plain cement, 5 and 10% condensed silica fume (CSF) and 10% silica fume with 20% fly ash or 20% ground granulated blast furnace slag. The specimens were either continuously fog cured or 3 or 7 days initially cured and then exposed to 40% R.H. drying regime. The results suggest that all laboratory made specimens irrespective of their composition (with or without cement replacement materials) give lower strength when inadequately cured and exposed to drying regimes for a long period of time. However, concretes made with 5 and 10% CSF resulted in the least loss in strength and drying shrinkage and had a superior quality cover concrete as indicated by the 24 h water sorption test. © 1996 Elsevier Science Limited.

Keywords: high strength concrete, condensed silica fume, fly ash, slag, drying shrinkage, water sorption.

INTRODUCTION

All concrete specimens are known to indicate a higher strength when they are dried over a period of time and tested dry as compared to when they are moist and tested in a saturated surface dry condition.[1–11] The reduction in the indicated strength of moist concrete is predominantly due to the reduction in the surface energy and dilation of the gel particles or, distention within a test specimen.[1,6,8]

Today's concretes invariably contain additional cementitious materials like condensed silica fume (CSF), ground granulated blast furnace slag (GGBFS) and fly ash (FA). The action of these cement replacement materials (CRMs) is essentially pozzolanic, i.e. the contribution of these CRMs to the hardened properties of concrete is by a secondary reaction. This secondary reaction proceeds favourably in the presence of moisture as does the hydration of cement itself. Accordingly, the full potential of the CRMs is better exploited in moist exposure conditions. This had led some researchers to conclude that the strength of concretes containing CSF, GGBFS and FA is more sensitive to lack of curing than the strength of the plain cement concretes.[2–4,12–14]

What really matters is the strength of the concrete in a structure, i.e. *in situ* strength. Cather[7] has recently reported 'it is clear from the available evidence that compressive strength development in structures is one of the properties least sensitive to curing'. Normally, 100 or 150 mm cylinders are cured (or exposed to differing exposure conditions) to determine short-term or long-term strength of concrete. In these smaller size specimens, as against the *in situ* concrete, a dominant volume of the concrete consists of curing affected zone (CAZ). For example in a 100 and 150 mm cylinder, the CAZ is 75 and 56% of the total volume of concrete in these specimens, respectively. In summary, the strength of concrete specimens under hot and dry exposure conditions depends on the composition of concrete, severity of the curing regime and size of the specimen. The harsher the exposure conditions and the smaller the size of the specimen, the lower is the indicated strength.[9,10]

The extent of drying or wetting and consequently the internal humidity of a test specimen is also dependent on the permeability of the CAZ. Not all concretes dry at the same rate. Accordingly, there always exist differing moisture gradients in different concretes.[6] These moisture gradients then set up internal stresses of varying magnitude which affect strength differently.

This paper describes the strength development of plain cement concrete specimens and those made using CSF, GGBFS and FA. The strength development, drying shrinkage and water sorption of different concrete specimens are presented. It is concluded that very good high-performing concretes can be made using condensed silica fume in the cementitious fraction.

TESTING PROGRAM

Materials used

Type GP (General Purpose) cement, similar to ASTM Type 1, was used and its chemical composition and other characteristics are included in Table 1. The properties of the FA, GGBFS and CSF are also included in Table 1.

A proprietary superplasticiser was used at a dosage of 1.2 l per 100 kg of the total cementitious materials. The maximum size of the coarse aggregate, crushed granite, was 10 mm.

Concrete cast

The main objective was to produce good workable concretes of the maximum possible strength. The basic parameter was that the slump should be approximately 100 mm and to achieve this the maximum recommended dosage of the superplasticiser was used. Initial trials suggested that for the given coarse and fine aggregates used, 30% sand of the weight of the total aggregate will have minimum void content and hence would be economical. The two reference mixes consisting of 550 and 600 kg of cement per cubic meter of concrete were chosen to produce the high strength concretes.

To the two reference concretes, the following cement replacement materials were included (all on equal weight basis):

replace 5% and 10% cement with CSF;
replace 10% cement with CSF and 20% cement with FA; and
replace 10% cement with CSF and 20% cement with GGBFS.

Due to the lower density of the cement replacement materials used, the sand content was decreased in each mix to allow a constant volume of the concrete to be produced.

The ten concretes cast are given the following designation:

$$Q\text{-}Q_1\text{-}Q_2\text{-}Q_3$$

where

Q = total mass of cementitious materials used per cubic meter of concrete;
Q_1 = percentage of cement replaced by CSF;
Q_2 = percentage of cement replaced by FA; and
Q_3 = percentage of cement replaced by GGBFS.

Table 1. Characteristics of the cement, GGBFS, CSF and FA

Chemical	*Percentage composition (%)*			
	Cement	*GGBFS*	*CSF*	*FA*
SiO_2	20.6	32.6	93	51.8
Al_2O_3	4.6	12.8	0.6	24.4
Fe_2O_3	5.0	1.3	1.0	9.62
CaO	64.7	41.0	0.2	4.4
MgO	1.1	7.2	1.2	1.5
Na_2O, K_2O	0.53	2.6	1.1	1.75
SO_3	2.4	0.03	0.3	0.26
L on I	0.9	0.2	0.5	0.3
Specific gravity	3.16	2.93	2.33	2.46
Fineness index (m^2/kg)	335	400	20,000	

The quantities of the cement and other cementitious materials required to produce 1 m^3 of various concretes and their slump values are included in Table 2. From each mixture, 30–100 × 200 mm cylinders, 2–150 × 300 mm cylinders and 2–285 × 85 × 85 mm shrinkage prisms were cast.

Specimen curing and testing

After casting the specimens were stored for 24 h in the laboratory environment, demoulded and then the following curing regimes were adopted:

F: the specimens were continuously cured in the fog room (23 ± 2°C and 95 ± 5%, relative humidity (RH)) until testing;

2FE: the specimens were placed in the fog room for two days after demoulding and then moved to the control room (23 ± 2°C and 40 ± 5% RH) until 24 h before testing;

6FE: the specimens were placed in the fog room for six days after demoulding and then moved to the control room until 24 h before testing.

All specimens (which were stored in the control room) were placed back into the fog room 24 h prior to testing to negate skin effects and to bring all specimens to a standard level of moisture condition. The surface moisture is known to affect the indicated strength of concrete.[15]

The 100 × 200 mm cylinders exposed to F curing regime were tested for compressive strength at 1, 3, 7, 28 and 91 days. A minimum of 3 cylinders were tested at each age. The modulus of elasticity of the concretes was determined on 150 × 300 mm cylinders at the age of 28 days.

The 24 h water penetration and water absorption test was performed on the 100 × 200 mm cylinders to assess and compare the quality of the skin concrete.

RESULTS AND DISCUSSION

Properties of fresh concrete

All the concretes made had a good to high workability as measured by slump which varied between 70 and 200 mm. No segregation occurred in any of the mixes produced. It was felt that most of the concretes were somewhat sticky. Perhaps a higher proportion of the sand than used in this investigation could have decreased the stickiness of the mixes.[16]

The original intention was to make all the mixes at a water/cementitious material ratio of 0.30. Due to differing additions of the different additional cementitious materials, this could not be achieved as it was desirable to have good workable mixes, neither too dry nor too wet. Most mixes have a water/cementitious material ratio in the range of 0.3 ± 0.02 (see Table 2).

The addition of silica fume both at 5 and 10% level seems to have markedly reduced the slump in comparison to the plain Portland cement mixes (Table 2).

Properties of hardened concrete

Compressive strength

Compressive strength of the fog cured concretes is included in Table 3. The 28 day strength of the concretes varies between 68 and 96 MPa

Table 2. Mix characteristics

Mix no.	*Mix designation*	*Cement (kg)*	*CSF (kg)*	*FA (kg)*	*GGBFS (kg)*	*Super (s) (ℓ)*	$\frac{w+s}{c_t}$	*Slump (mm)*
1	550-0-0-0	550	—	—	—	6.6	0.32	175
2	600-0-0-0	600	—	—	—	7.2	0.30	200
3	550-5-0-0	522.5	27.5	—	—	6.6	0.32	110
4	600-5-0-0	570.0	30.0	—	—	7.2	0.28	110
5	550-10-0-0	495.0	55.0	—	—	6.6	0.32	90
6	600-10-0-0	540.0	60.0	—	—	7.2	0.29	70
7	550-10-20-0	385.0	55.0	110.0	—	6.6	0.33	85
8	600-10-20-0	420.0	60.0	12.0	—	7.2	0.31	100
9	550-10-0-20	385.0	55	—	110.0	6.6	0.33	70
10	600-10-0-20	420.0	60.0	—	12.0	7.2	0.30	100

Table 3. Compressive strength of fog cured concretes (MPa)

Mix	*1 day*	*3 days*	*7 days*	*28 days*	*91 days*
550-0-0-0	33.5	54.8	60.6	68.2	82.4
600-0-0-0	40.1	60.3	64.9	82.6	91.5
550-5-0-0	37.7	54.6	62.7	83.7	88.1
600-5-0-0	41.2	59.2	69.4	87.8	96.8
550-10-0-0	31.5	52.4	56.2	81.0	104.2
600-10-0-0	35.5	61.0	73.5	96.0	101.3
550-10-20-0	20.6	42.4	51.2	76.3	94.7
600-10-20-0	16.5	42.8	55.9	84.5	94.4
550-10-0-20	24.1	38.3	57.9	83.7	85.0
600-10-0-20	30.1	38.1	60.4	95.6	94.9

which suggests that these concretes are high strength (HSC) to almost very high strength (VHSC).[17] Both in 550 and 600-series concretes, 5 and 10% silica fume addition resulted in a substantial increase in the compressive strength of the corresponding plain concretes. Of course, the highest 28 day strength of 96 MPa achieved in this investigation was with total cementitious contents of 600 kg with 10% CSF (see Table 3, mix 600-10-0-0). Further replacement of 20% cement with FA decreased the strength and the 20% replacement with GGBFS did not contribute much to changing strength in either way.

By 91 days there had been a marked development in strength of all the concretes and these concretes can be classified as VHSC. It appears that for the given mix proportions and materials, 550-10 concrete is the optimum with 104 MPa 91 day strength.

Strength development in other curing regimes

The 28 and 91 day compressive strength of the concretes in all the three curing regimes: fog curing, 2FE and 6FE are included in Tables 4 and 5, respectively. The effect of drying regime on strength of the concretes can be better observed from Table 5 as the specimens are 91 days old. First, after 3 days of curing and subsequent exposure to drying the strength of all the ten concretes decreased as compared to the continuously fog cured concretes. On average, this strength is 88% of the fully cured strength, a strength decrease of 12%. When a 7 day initial curing was provided, at 91 days the average loss in strength was 7%. After 6 days of fog curing, in certain concretes there was none or very minimal strength decrease as compared to continuously fog cured concretes. This suggests that concrete composition is also a factor.

At 28 days, there was on average, a decrease in strength of 6% after 3 days of initial curing, and a strength enhancement of about 1% after 7 days of fog curing. Again, age or more precisely, the extent of drying of specimens (concrete) is an important factor.

In order to highlight the effects of total cementitious contents and the effect of CSF, GGBFS and FA on the strength development

Table 4. Effect of curing regime on 28 day strength

		Compressive strength (MPa)		
Mix no.	*Mix designation*	*Fog cured*	*2 FE cured*	*6 FE cured*
1	550-0-0-0	68.2	73.8	76.4
2	600-0-0-0	82.6	75.6	70.5
3	550-5-0-0	83.7	79.7	86.4
4	600-5-0-0	87.8	88.9	91.6
5	550-10-0-0	81.0	79.4	85.7
6	600-10-0-0	96.0	94.3	103.5
7	550-10-20-0	76.3	72.8	80.5
8	600-10-20-0	84.5	74.6	85.4
9	550-10-0-20	83.7	74.7	83.6
10	600-10-0-20	95.6	76.2	84.5

Table 5. Effect of curing regime on 91 day strength

		Compressive strength (MPa)		
Mix no.	*Mix designation*	*Fog cured*	*2 FE cured*	*6 FE cured*
1	550-0-0-0	82.4	73.9	77.0
2	600-0-0-0	91.5	73.8	76.2
3	550-5-0-0	88.1	85.6	84.9
4	600-5-0-0	96.8	90.0	95.8
5	550-10-0-0	104.2	91.2	95.1
6	600-10-0-0	101.3	97.6	101.3
7	550-10-20-0	94.7	74.2	84.4
8	600-10-20-0	94.4	80.8	84.0
9	550-10-0-20	85.0	76.5	89.3
10	600-10-0-20	94.9	76.0	83.3

of inadequately cured concretes, the results included in Tables 4 and 5 are plotted in Figs 1–4. These graphs represent the strength of a concrete at a given age (28 or 91 days) in a drying regime as a percentage of the corresponding strength when fog cured.

Effect of total cementitious contents on strength development

A general impression that HSCs are less affected by lack of curing may not be true as indicated by the results of this investigation (see Figs 1–4). A comparison of Figs 1–4 suggest that on air-drying the decrease in strength of 600-series of concretes have been more than that of the 550-series of concretes. On average after 3 days of initial curing and at 91 days, the 550-series gave a decrease in strength of 11% and the 600-series 13%.

Effect of CSF, GGBFS and FA on strength development of inadequately cured concretes

The specific effects of the three additional cementitious materials used in this investigation on strength development can be observed from data in Tables 4 and 5 and Figs 1–4. Mixes 1 and 2 are made with normal Portland cement alone; mixes 3, 4, 5 and 6 contain CSF; mixes 7 and 8 contain CSF and FA and finally mixes 9 and 10 contain CSF and GGBFS. There are no concretes with GGBFS and FA of their own, GGBFS and FA are as triple blends.

The following discussion concentrates mainly on concretes tested at 91 days when the effect of drying regimes is more pronounced.

First, the maximum loss in the strength of plain concrete is 19% when 600-series concrete was cured for 3 days only. Second, concretes with 5 and 10% CSF also give loss in strength,

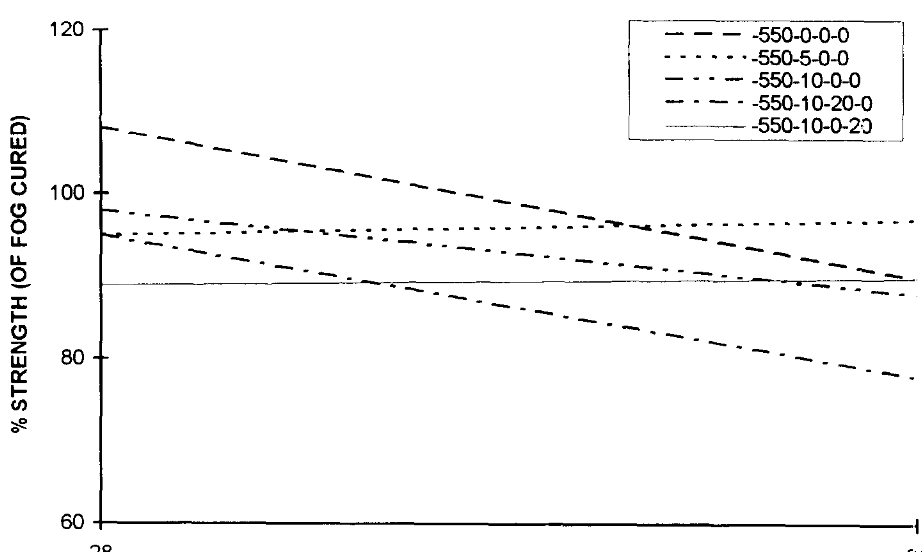

Fig. 1. Strength variation of 550-series concrete (after 3 days of fog curing).

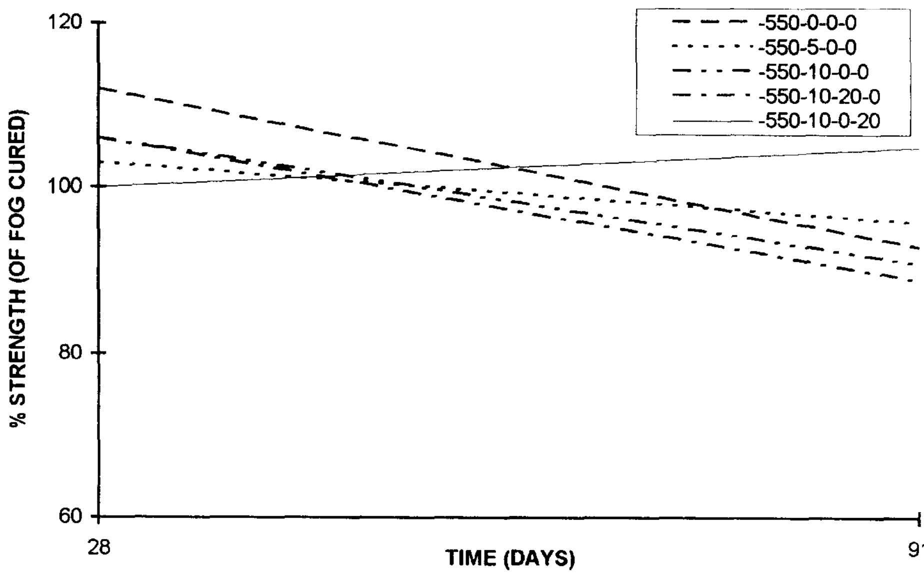

Fig. 2. Strength variation of 550-series concrete (after 7 days of fog curing).

the maximum loss is 12%, in mix 5. Thus decrease in strength in the CSF concretes is less than that in plain concretes. The difference between the two is significant. Third, maximum loss in strength of the fly ash concrete is 22%. This is more than that in the plain and CSF concretes. Finally, maximum loss in GGBFS concretes is 20%. This is somewhat less than that in concrete made with fly ash. In summary, all concretes tested showed loss in strength; concretes made with silica fume registered the minimum loss in strength, while the one with FA and CSF (triple blend) gave the maximum loss in strength on inadequate curing and subsequent exposure to drying regimes.

Modulus of elasticity

Modulus of elasticity (*E*) of the F and 2FE concretes was determined at the age of 28 days and the results are included in Table 6. There is not a lot of variation in the *E* values of both F and 2FE concretes. Although fog cured concretes have consistently higher values of *E* than those of the 2FE cured concretes, the difference is only marginal. Perhaps had the *E* value been determined at 91 days, the effects of drying and lack of curing would have been more obvious. As is apparent from Table 6, an *E* value of 40 GPa is a good approximation for the stiffness of the concretes tested. In the absence of 91 days

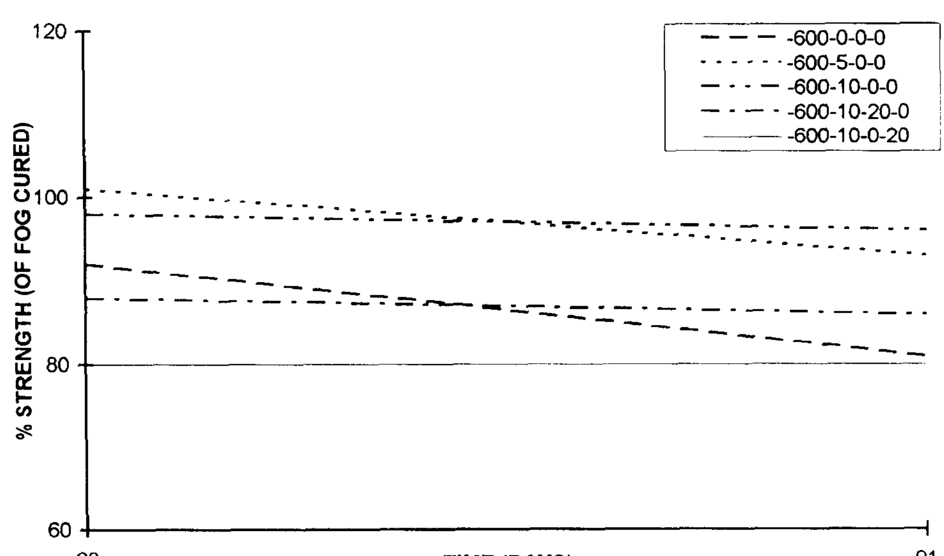

Fig. 3. Strength variation of 600-series concrete (after 3 days of fog curing).

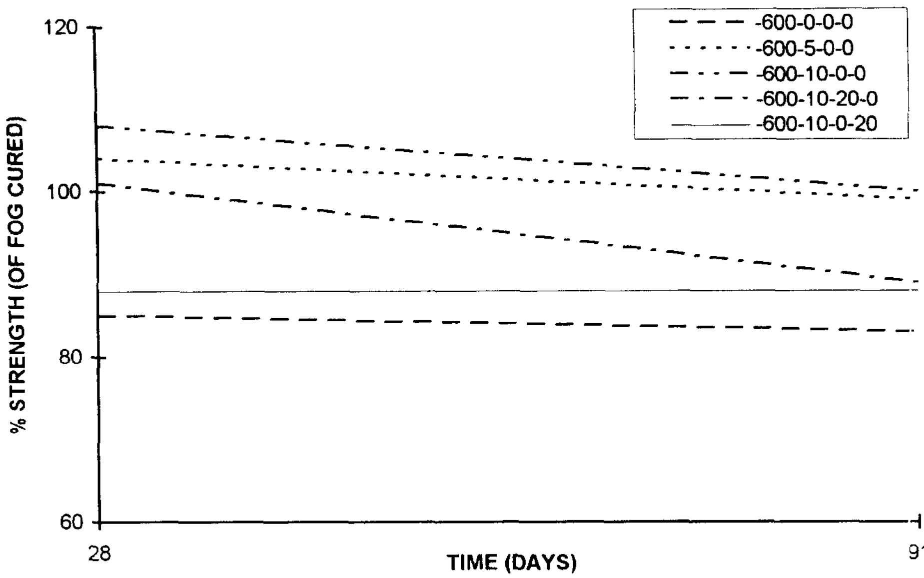

Fig. 4. Strength variation of 600-series concrete (after 7 days of fog curing).

values, discussion on the variation of *E* values due to the composition of concrete is not possible.

Water penetration into drying concretes

The water penetration test was performed by immersing the concrete cylinders for 24 h in a tub of water after 91 days of exposure in 2FE and 6FE regimes. Once the specimens were split in half in the indirect tensile test, readings were taken to determine as to how far the water had penetrated into the concrete. Several readings were taken on a specimen and the average values of water penetration are included in Table 7.

Again, in this paper, as the focus is on the effect of lack of curing on the strength and quality of concrete containing additional cementatious materials, the following discussion is centered more on 2FE curing. Figure 5 shows a generalized relationship between the strength of a concrete and the 24 h water penetration of the skin concrete. Parrott[18,19] has also reported that the 4 h water absorption measured after 6 months of drying was broadly related to the cube strength. According to him uniaxial water absorption after 4 h of wetting may be regarded as indicative of the capillary suction characteristics of a surface zone corresponding approximately to cover concrete.[18] In particular, as shown in Table 7, the addition of both 5 and 10% CSF in 550- and 600-series of concrete decreased the water penetration in the cover concrete as compared to the corresponding plain cement concretes. This decrease is 24 and 29% in 550-10 and 600-10 concretes as compared to the 550 and 600 concretes, respectively. This is certainly a respectable

Table 6. Modulus of elasticity at 28 days

		Modulus (GPa)	
Mix no.	*Mix designation*	*Fog cured*	*2 FE cured*
1	550-0-0-0	39.7	39.8
2	600-0-0-0	40.8	39.4
3	550-5-0-0	39.8	39.7
4	600-5-0-0	40.8	40.1
5	550-10-0-0	40.2	37.7
6	600-10-0-0	41.4	41.0
7	550-10-20-0	39.6	38.1
8	600-10-20-0	40.0	35.9
9	550-10-0-20	42.7	40.9
10	600-10-0-20	41.3	37.9

Table 7. Water penetration (mm) into drying concrete — 91 days

Mix designation	*2 FE cured*	*6 FE cured*
550-0-0-0	17	15
600-0-0-0	14	15
550-5-0-0	14	10
600-5-0-0	12	12
550-10-0-0	13	11
600-10-0-0	10	11
550-10-20-0	24	21
600-10-20-0	18	20
550-10-0-20	18	14
600-10-0-20	18	15

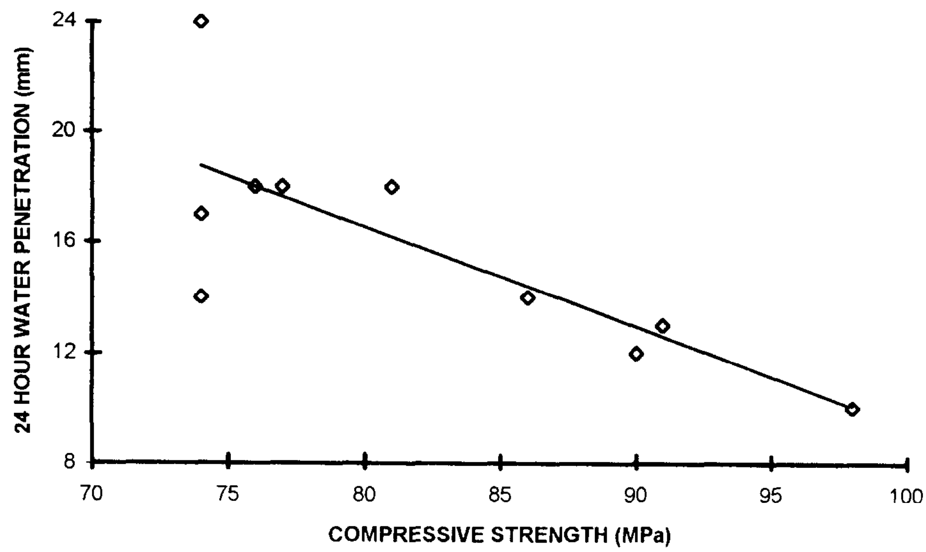

Fig. 5. Effect of drying on the skin concrete by water penetration.

improvement in the quality of the cover concrete as measured by depth of water penetration. However, further addition of 20% fly ash and GGBFS, in both 550 and 600-series concretes increased the depth of water penetration. In fact in these concretes (see mixes 7–10, Table 7) the addition of FA and slag has not only neutralized the improvement which CSF made but has further degraded the quality of cover concrete as regards depth of water penetration. There was, of course, a loss in strength in these concretes due to the addition of FA and GGBFS as alluded to earlier.

Drying shrinkage of concretes

The drying shrinkage of 550- and 600-series of concretes is included in Figs 6 and 7, respectively. The drying shrinkage of all the 10 mixes cast varies between 480 to 640 microstrain at 91 days. For high to very high strength concretes containing high quantities of cementitious contents, the above values of shrinkage strain are moderate and agree well with those reported by Hindy *et al.* for concretes of similar strength.[20]

As shown in Figs 6 and 7, the addition of 5 and 10% CSF in both 550- and 600-series has resulted in a substantial reduction in the drying shrinkage strains of the silica fume concretes (compare mixes 1, 3 and 5 in Fig. 6 and mixes 2, 4 and 6 in Fig. 7). These results are in agreement with those reported by Hindy *et al.*[20] and Burnell.[21] The lower values of the drying shrinkage of the concretes containing silica fume are attributed to the densification of the hydrated cementitious paste due to CSF and

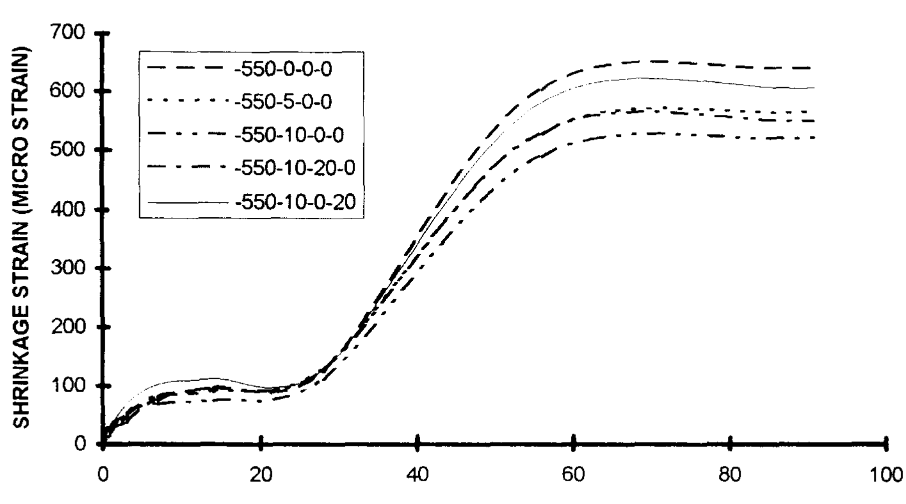

Fig. 6. Drying shrinkage on 550-series concrete.

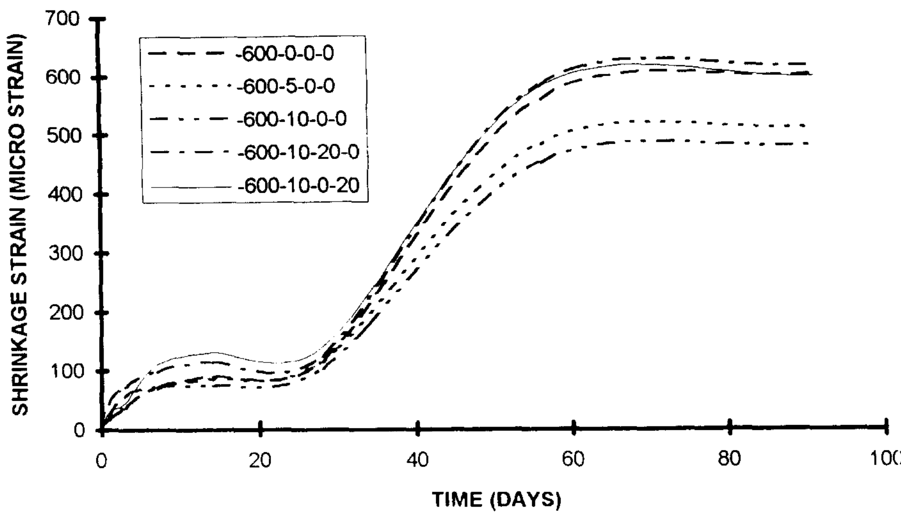

Fig. 7. Drying shrinkage on 600-series concrete.

the resultant slowing down of the water evaporation. Further addition of 20% FA and GGBFS has, however, increased the shrinkage of the concretes which were made with 10% CSF and the drying shrinkage of these triple blend concretes become similar to those of the plain concretes. The increase in shrinkage of the 600-series of concrete on the addition of FA and GGBFS are more pronounced (see Fig. 7 and compare mixes 6 with 8 and 10).

Nonetheless, shrinkage strains of the high strength concretes included in Figs 6 and 7 are typical of such high-strength and high-performance concretes.

CONCLUSIONS

In concretes with total cementitious contents of 550 and 600 kg, tested in this investigation, 5 and 10% CSF resulted in a substantial increase in the compressive strength of the corresponding plain cement concretes. The highest 91 day strength of 104 MPa was achieved with total cementitious contents of 550 kg with 10% CSF. A further 20% replacement of cement by FA decreased the compressive strength.

Irrespective of the composition of the concrete, those with and without CSF, FA and GGBFS, there was a decrease in strength in all the ten concretes tested at 91 days which were exposed to drying ambient conditions after initial curing of 3 days as compared to the continuously fog cured concretes. However, concretes made with silica fume registered the minimum loss in strength while those with 20% FA and CSF (triple blend) gave the maximum loss in strength.

The addition of 5 and 10% CSF in the concretes tested decreased the 24 h water penetration in the cover concrete as compared to the corresponding plain cement concretes. Further, 20% addition of both FA and GGBFS, however, increased the depth of water penetration in the concretes tested.

Addition of both 5 and 10% CSF in concretes resulted in a substantial reduction of drying shrinkage of the silica fume concretes. Further addition of 20% FA and GGBFS, however, increased the shrinkage of these concretes.

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