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STRENGTH, SHRINKAGE AND CREEP OF CONCRETE IN TENSION AND COMPRESSION

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ABSTRACT

Strength, shrinkage and creep of concrete in tension and compression have been determined and the relationship between those properties was studied. Direct tensile tests were applied to measure those properties in tension. The relationship of creep in tension and compression was determined based on the measurement of creep at similar stress and similar stress/strength ratio. It is found that concrete deforms more in tension than in compression. Except for concrete with a higher water/cement ratio, the use of pulverised fuel ash, ground granulated blast furnace slag, superplasticizer and shrinkage reducing admixture has no effect on strength. However, they affect creep and shrinkage of concrete.

Keywords: direct tensile, tensile strength, tensile creep, compressive creep, shrinkage.

INTRODUCTION

The presence of cracks in concrete indicates a potential problem in the structure. Although concrete may still be capable to serve as load-bearing function in the structure, the presence of cracks could facilitate the ingress of aggressive agents leading to deterioration and ultimately failure of concrete. There are several sources of cracking in concrete. One of them is due to development of tensile stress in the restrained shrinkage condition. This type of cracking can propagate continuously on the condition that concrete still shows shrinkage. However, there is other factor that should be considered and has beneficial effect in reducing the possibility of cracking to occur and propagate i.e. creep. While shrinkage generates tensile stress, creep will relieve it and may prevent cracking. The competition between shrinkage and creep determines the magnitude of development of tensile stress. Whether cracking is likely to occur or not depends on this magnitude of development of tensile stress in comparison with the tensile capacity of concrete [1].

The data of tensile properties are necessary to enable prediction of the cracking behaviour of restrained shrinkage in concrete. Tensile strength may be used as a key parameter to determine the limit of stress at which concrete is considered to crack. Tensile strength is affected by the method of test application [2]. To choose the best method suitable for evaluating the cracking of concrete under restrained shrinkage condition, one should understand the nature of tensile stress developed in such condition. In a structure where the ends of concrete elements are fixed in such a way to form external restraint, tensile stress due to restrained shrinkage may be regarded similar to that occurring in direct tensile test i.e. the stress is distributed across the area of concrete element. For concrete element subjected to tensile stress due to differential shrinkage between new and old structure in concrete overlays, the flexural strength may be more appropriate. From practical point of view, any methods of test may be used regardless the possible differences in the nature of stress, if the relationship between tensile strength determined from various test methods and between tensile and compressive strength could be established.

The role of creep to reduce induced tensile stress in restrained shrinkage has been recognised and included in methods to predict shrinkage cracking. Predictions based on the Effective Modulus Method, Trost-Bazant Method, Rate of Creep Method and Improved Dischinger Method as described in [3] may be adopted for the calculation of induced tensile stress in the restrained shrinkage of concrete. However, the proposed methods are originally derived from the compressive creep data. Tensile creep is assumed to have similar behaviour to compressive creep. This assumption, although inaccurate, is understandable due to the lack of data and models for tensile creep.

This research provides data on the behaviour of concrete under direct tension test which includes strength and creep and their relationship with the

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compressive ones. The relationships between tensile and compressive creep were determined on the basis of application of load at similar stress and similar stress/strength ratio. The influences of water/cement ratio, pulverised fuel ash (pfa), ground granulated blast furnace slag (ggbs), superplasticizer and shrinkage reducing admixture on strength, creep and shrinkage were investigated. All laboratory tests were done at the School of Civil Engineering, Leeds University, UK.

EXPERIMENTAL INVESTIGATION

Materials and Mixes

Six mixes have been used in the research. Details of the mixes are given in Table 1. The first, acting as control concrete, referred as c1dry, was in the mass proportion of 1:2:3 (cement: fine aggregate: coarse aggregate) with water/cement ratio of 0.47. The c2dry had the same proportion as above but the water cement/ratio was increased to 0.52. The pfa30dry and ggbs30dry were made by replacing 30% cement (by weight) of the c1 with pulverised fuel ash and ground granulated blast furnace slag, respectively. Finally, 0.6% volume of superplasticizer and 1.5% of shrinkage reducing admixture by weight of cement were added into the c1 to make up the sp06dry and sra15dry.

Table 1. Proportion of the mixes.

No	Mix	Proportion	w/c	Admixture
1	c1dry	1 : 2 : 3	0.47	N/A
2	c2dry	1 : 2 : 3	0.52	N/A
3	pfa30dry	1 : 2 : 3	0.47	30% of opc replaced with pfa
4	sp06dry	1 : 2 : 3	0.47	0.6% volume of superplasticizer by weight of cement
5	sra15dry	1 : 2 : 3	0.47	1.5% of shrinkage reducing admixture by weight of cement
6	ggbs30dry	1 : 2 : 3	0.47	30% of opc replaced with ggbs

Specimens

For compressive strength and flexural strength tests two cubes of 100 mm and prismatic of 100 x 100 x 500 mm specimens complying with BS 1881: Part 116: 1983 [4] and BS 1881: Part 118: 1983 [5], respectively, were used for every mix. The bobbin-shaped specimens as developed earlier by Brooks et al [6] were adopted for testing of direct tensile strength, creep in tension and creep in compression at low stress. It is a cylinder with diameter of 76 mm and length of 265 mm and with the ends of specimen has wider diameter to form truncated cones. Figure 1 gives an example of the bobbin-shaped specimen. For testing of compressive creep at high stress level, cylinders with diameter of 76 mm and length of 265 mm were used. Specimens for measuring shrinkage were similar to those used for creep tests. Table 2 presents the type and number of specimens required for every set of test in every mix.

Figure 1. An example of bobbin shaped specimen where it was cast in the bobbin-shaped mould (left) and after concrete hardened the middle sections of the mould were removed leaving the specimen with end caps (second from right).

Table 2. The number of specimens required for every set of experiment in every mix.

Test	Specimen	Quantity
Compressive strength	Cube	2
Flexural Strength	Prism	2
Direct tensile strength	Bobbin	2
Tensile creep	Bobbin	6*
Compressive creep at low stress level	Bobbin	6*
Compressive creep at high stress level	Cylinder	4*

* including those for measuring the concurrence shrinkage.

Strength tests

The cube compressive strength and prismatic flexural strength tests were carried out in accordance with the requirements of the relevant British standards. For direct tensile strength test, the Instron machine was used and a stress rate of 0.06 MPa/sec was applied. This stress rate was equal to that applied for measuring flexural strength. All specimens were tested at the age of 14 days after undergoing curing at 20^{o}C and 100% RH. The required strength for the assessment of shrinkage cracking of concrete was determined at the age corresponding to the time when shrinkage was started. It is common in practice to stop curing of concrete (and so concrete start to shrink) after 14 days of age. Other investigator [1] considered 7 days in addition to 14 days for such purpose.

Tensile and compressive creep tests at low stress level

The frame consists of four steel bars of 20 mm diameter and 760 mm long with two steel end plates of 240 mm wide and 20 mm thick. The apparatus for measuring compressive creep (Fig. 2) at low stress level is similar to that used for the measurement of tensile creep (Fig. 3) but without semi-universal joint, instead a 25 mm diameter ball is used to transfer the load concentrically to the specimen.

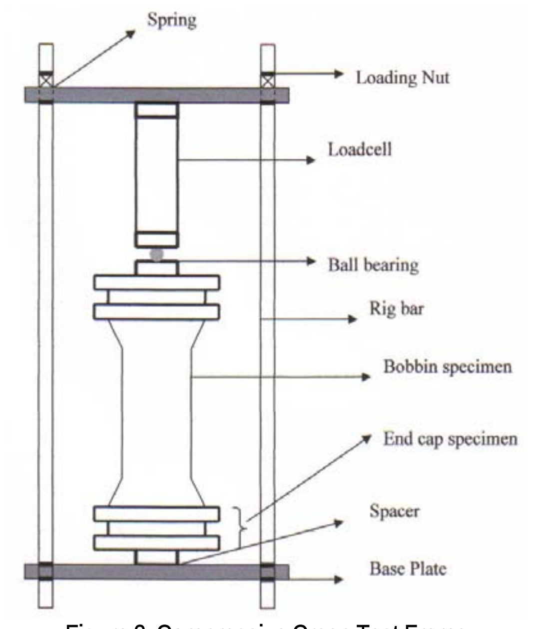

Figure 2. Compressive Creep Test Frame

Figure 4. Arrangement of LVDTs on The Specimen

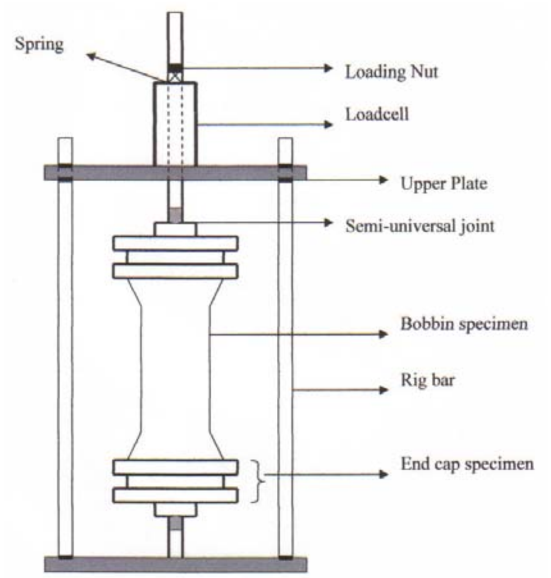

Figure 3. Tensile Creep Test Frame

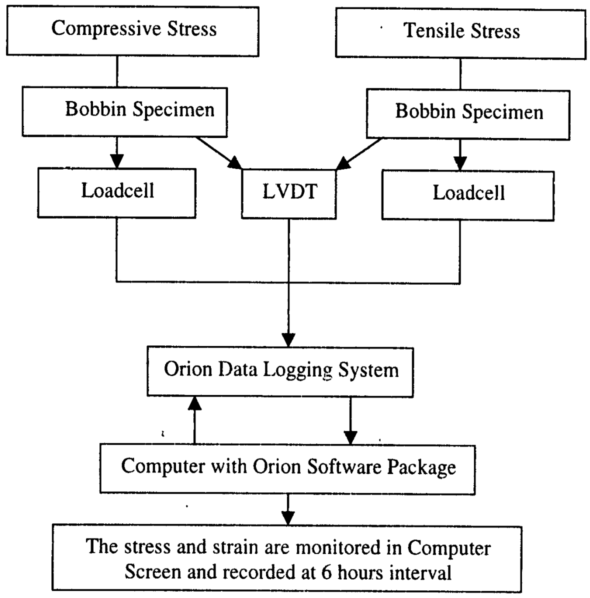

Figure 5. The Scheme of Data Acquisition System

The load was measured using load cells made of hollow tubes of aluminium alloy of an external diameter of 42 mm and wall thickness of 2 mm with the flange of external diameter of 75 mm at the ends. The deformation of specimens was measured by Linear Variable Displacement Transducer (LVDT). Two LVDTs were installed on every test specimen. A special pair of ring clamps were used to fix the LVDTs at a gauge length of 100 mm. The arrangement of LVDTs on the specimen is shown in Figure 4. Data acquisition system was used to record loads and strains continuously every 6 hours. The test was ended when failure of concrete occurred in the concurrence restrained shrinkage test as described elsewhere [7]. The system is illustrated in Figure 5.

Compressive creep test at high stress level

The compressive creep (high stress) test apparatus was a frame consisting of 25 mm diameter bars 1000 mm long with two end plates each 27 mm thick. One end plate is fixed while the other is movable. Figure 6 illustrates the loading frame together with the arrangement of specimens. The stress applied to the specimens is measured using a steel tube dynamometer 296 mm long, 76 mm internal diameter and 3 mm wall thickness. On the surface of dynamometer Demec points having a gauge length of 200 mm were placed at intervals of 90°. The dynamometer was calibrated up to a load of 180 kN in an Avery Denison universal testing machine. Figure 7 gives an example of result of the dynamometer calibration.

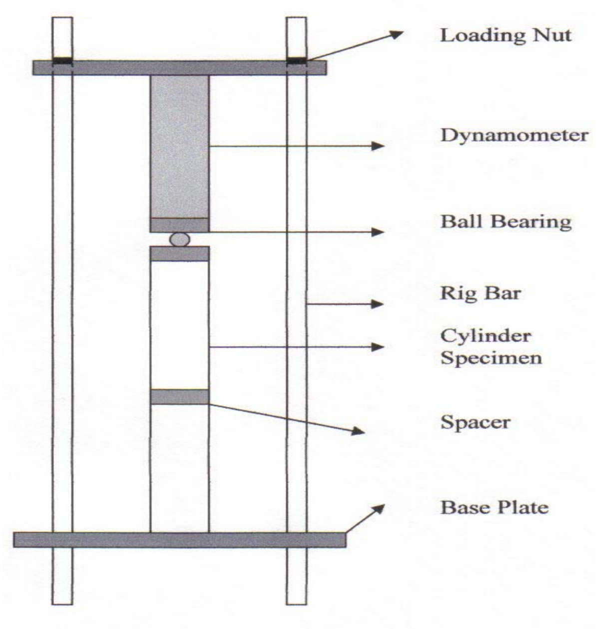

Figure 6. Compressive Creep Loading Frame (High Stress Level)

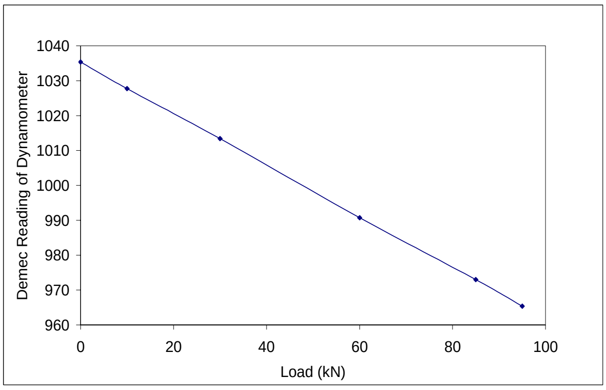

Figure 7. Example of The Result of Dynamometer Calibration.

The load for this creep test was equal to a stress at 30% of the compressive strength of the specimen. This level of stress was applied due to the following reasons: firstly, at this level of stress concrete is considered still at elastic state and secondly, at elastic state creep is proportional to the stress. In turn, specific creep, i.e. creep per unit of stress obtained would represent true creep consistently. The load was converted to a targeted loading strain of the dynamometer using the calibration graph. During the creep test two companion specimens for the control load-free strains (shrinkage) were also measured. Deformations of concrete (both creep and shrinkage) were monitored by Demec gauge at a gauge length of 200 mm. Demec readings were taken every 12 hours for the first day, and after that period they were taken continuously every 24 hours. The test was stopped at the same time as that of tensile creep test.

TEST RESULTS AND DISCUSSION

Strength

The 14-day compressive, direct tensile and flexural strengths for all the mixes are tabulated in Table 3. The results show that, for all types of tensile test, concrete with the higher w/c ratio has a lower tensile strength. The addition of cement replacement materials or chemical admixtures slightly reduces the flexural strength, but hardly affects the direct tensile strength.

Table 3. Strength in Compression, Direct Tension and Flexure.

Mix	Compressive Strength (MPa)	Direct Tensile Strength (MPa)	Flexural Strength (MPa)
c1	55.35	3.31	5.78
c2	45.10	2.71	4.47
pfa30	41.00	3.31	4.61
sp06	50.58	3.30	4.86
sra15	48.00	3.22	4.84
ggbs30	51.35	3.21	5.10

Table 4. Relationship Between Compressive, Direct Tensile and Flexural Strength.

Mix	Ratio (x100 %)		
	Tensile/Compressive	Flexural/Compressive	Tensile/Flexural
c1	5.98	10.44	57.27
c2	6.00	9.91	60.63
pfa30	8.07	11.24	71.80
sp06	6.50	9.61	67.90
sra15	6.71	10.08	66.53
ggbs30	6.25	9.93	62.94

The relation of compressive, direct tensile and flexural strength is listed in Table 4. The relations established in this table were calculated from the values of various strengths given in Table 3. Generally concrete with lower compressive strength tends to have higher ratio of direct tensile to compressive strength, but the relation is not consistent for the ratio of flexural to compressive strength. The direct tensile and flexural strength are about 5.9%-8.1% and 9.9%-11.2%, respectively, of compressive strength. The values are similar to that observed by other investigator [8].

The tensile strength of concrete determined from flexural strength test is higher than that obtained from direct tensile test. The direct tensile strength is about 57%-72% of flexural strength. Some investigators [2,,9,10,11] suggested lower value, but recently Wee et al [8] found similar value. Raphael [12] explained the flexural strength is higher compared to the direct tensile strength because it is measured by equation derived from elastic theory. The actual failure mode of concrete is not elastic mode as shown by non-linearity of stress-strain curve near failure. To account for the non-linearity of stress-strain relationship in the calculation of measured flexural strength, he replaced the curvilinear tensile stress-strain diagram by a simple rectangular stress diagram with the same dimensional constraints proposed by Whitney. In this way, he showed that the flexural strength was about 75% of that calculated from equation derived from elastic theory. His finding implies that tensile strength measured from flexural test is 25% higher than that measured from direct tensile test.

Tensile Creep

The total tensile creep determined on the drying specimens is presented in Figure 8. Concrete having water/cement ratio of 0.47 with no addition of mineral or chemical admixtures is referred as a control concrete (c1). The effects of water/cement ratio, addition of pfa, ggbs, superplasticizer and shrinkage reducing admixture are analysed by comparing the total tensile creep of c1 concrete with that of c2, pfa30, ggbs30, sp06 and sra15 concrete, respectively. From the figure it is seen that shrinkage reducing admixture has no effect on the total tensile creep. This result confirms what previously has been shown by Jiang [1]. The additions of pfa, ggbs, and superplasticizer increase the total tensile creep, with the superplasticizer giving the most significant effect in increasing total tensile creep. Increasing water/cement ratio also causes an increase in the total tensile creep.

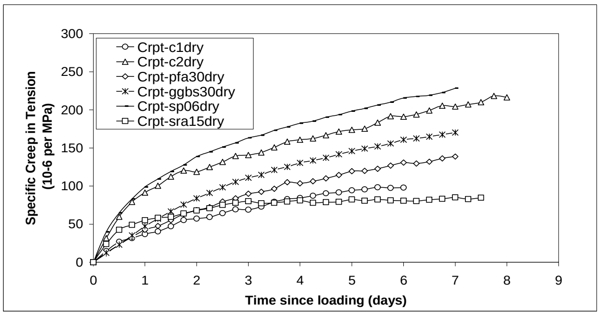

Figure 8. Total Tensile Creep of Concrete Determined on Drying Specimens

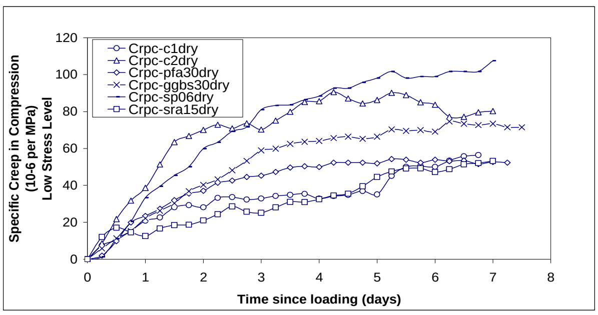

Figure 9. Total Compressive Creep (Low Stress) of Concrete Determined on Drying Specimens.

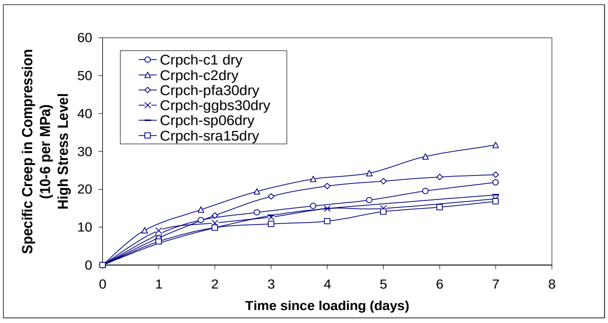

Figure 10. Total Compressive Creep (High Stress) Determined on Drying Specimens

The effect of superplasticizer on the increase in tensile creep may not be due to the effect of chemical composition of the material, but due to the consequence of using superplasticizer for enhancing workability. As superplasticizer is used in the mix without changing the water/cement ratio, it makes the fresh concrete flow. At this stage the water content in the mix tends to move upward during compaction while the aggregates settle in the bottom. Some of the water may be trapped causing flaw in the concrete. Ward and Cook [13] suggested that mechanism of tensile creep is related to the opening of microcracks. Under tensile stress the weakest part of the concrete i.e. the flaw, will propagate. As a result concrete extends at direction of the tensile stress and it measures up the strain (creep) of concrete. The opening of microcracks may also explain the higher tensile creep of concrete with higher water/cement ratio.

Compressive Creep

The total compressive creep observed on the drying specimens under low level of sustained stress is given in Figure 9. Except for concrete with shrinkage reducing admixture the increase in water/cement ratio, the use of pfa, ggbs and superplasticizer increase the total compressive creep. This observation is similar to that for total tensile creep and in fact, those mixes tend to behave in similar way also. For example, at later time concrete with the superplasticizer shows the highest magnitude of compressive creep.

The total compressive creep determined under high level of sustained stress is presented in Figure 10. As for tensile creep and compressive creep under low stress level, water/cement ratio shows significant effect in increasing the total compressive creep while the use of pfa slightly increases the total compressive creep. The other mixes seem to have little effect.

Relationship Between Tensile and Compressive Creep

The relationship between tensile and compressive creep found in the literatures is very limited and not always in agreement. In 1939 Glanville and Thomas [14] observed a similarity between total tensile and compressive creep. However, two years earlier Davis et al [15] showed that tensile creep is higher than compressive creep. Later other investigators [9,16] confirmed the finding of Davis et al. Most recently, Li et al [17] pointed out that tensile creep could be four times higher than compressive creep. The relation between tensile and compressive creep based on the same applied stress as observed in the current research is presented in Figure 11. The relationship is:

$$c_{cl} = 0.5\, c_t \tag{1}$$

where c_{cl} and c_t are the specific creep in compression (low stress) and in tension respectively. The relationship is only a tentative suggestion due to the limited data of the current research. It is convenient to include instantaneous strain in the relation since the instantaneous strain due to application of load and the subsequent creep could not easily be separated from one another. The relationship between creep function i.e. elastic-plus-creep per unit stress in tension and compression shown in Figure 12 is:

$$\Phi_{cl} = 0.65\Phi_t \tag{2}$$

where Φ_{cl} and Φ_t are the respective tensile and compressive creep function.

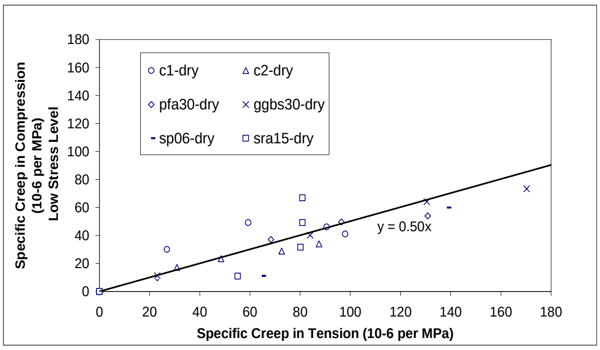

Figure 11. Relationship Between Specific Creep in Tension and Compression Based on Equal Applied Stress.

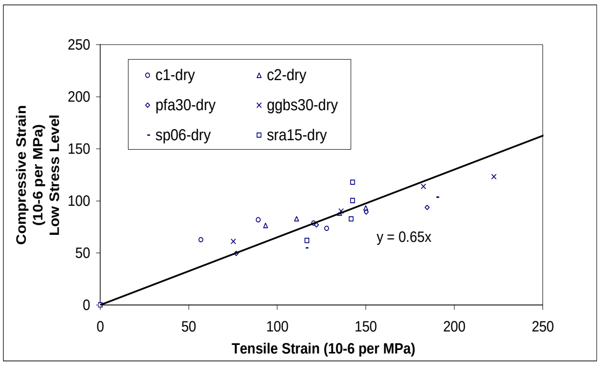

Figure 12. Relationship Between Creep Function in Tension and Compression Based on Equal Applied Stress.

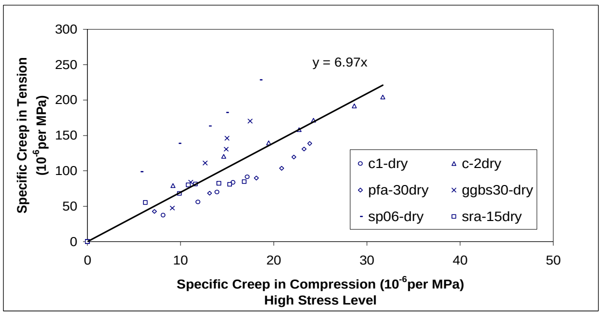

Figure 13. Relationship Between Specific Creep in Tension and Compression Based on Equal Applied Stress/Strength Ratio.

When the relation is based on the similar stress/strength ratio, the tensile creep is much bigger compared to the compressive creep as shown in Figure 13. On average tensile creep is about six times of the compressive creep. The relationship is:

$$c_t = 6.97 c_{ch} \tag{3}$$

where c_{ch} is the specific compressive creep due to a high stress level. When the elastic strain is included in the relation as given in Figure 14, the equations become:

$$\Phi_t = 3.68\Phi_{ch} \tag{4}$$

where Φ_{ch} is the compressive creep function (high stress)

It is clear that the relation between tensile and compressive creep must take into account the stress level at which the creep is determined. It is due to the fact that the magnitude of compressive creep determined under low stress level is different than that determined under high stress level. Figures 15 and 16 correlate the two creeps in the following equations:

$$c_{cl} = 3.11 c_{ch} \tag{5}$$

$$\Phi_{cl} = 1.96\Phi_{ch} \tag{6}$$

The higher compressive creep under low stress compared to that under high stress level may be explained as follows. An external load will squeeze some of the interlayer water out into areas of unhindered adsorption. Disjoining pressure between the surfaces decreases and causes a decrease in the volume of the paste as the spacing of the particles in the gel is reduced. The change in the volume corresponds to creep. With high compressive stress there is enough energy to press together the surface of crystallized layered silicate material to form a formation of new bonds between surfaces as suggested by Powers [18]. Higher stress will not cause significant additional creep. As a result the computed creep per unit stress (specific creep) is low. On the other hand with low compressive creep there is only small energy to squeeze the water unable to cause the surfaces to form the new bonds. As the stress is low the changing in the volume will measure up high specific creep.

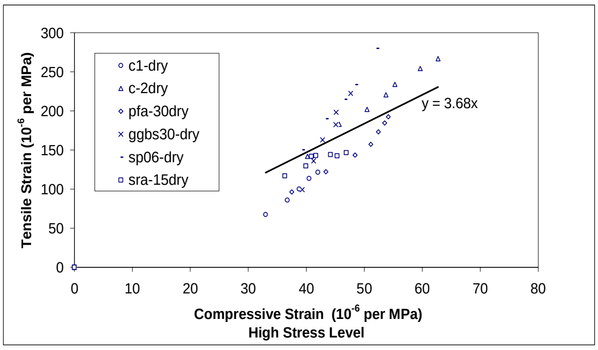

Figure 14. Relationship Between Creep Function in Tension and Compression Based on Equal Applied Stress/Strength Ratio.

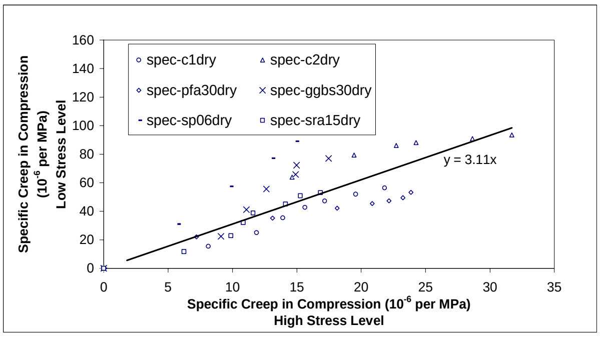

Figure 15. Relationship Between Specific Creep in Tension Determined From Low Applied Stress and High Applied Stress Level.

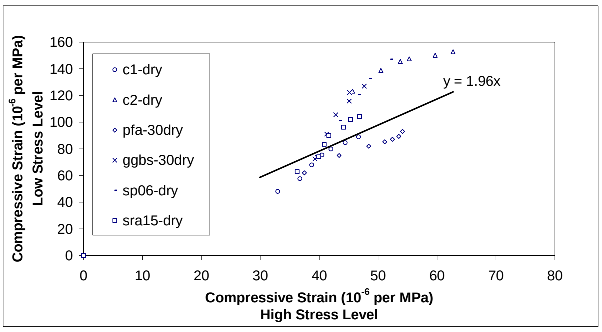

Figure 16. Relationship Between Creep Function in Tension Determined From Low Applied Stress and High Applied Stress Level.

Drying Shrinkage

The deformation of concrete measured on the unloaded specimens under drying condition is given in Figure 17. The figure demonstrates that water/cement ratio has a considerable effect on the drying shrinkage. Concrete with the highest water/cement ratio shows the highest shrinkage; it is almost twice that of the drying shrinkage of the control concrete. The inclusion of pfa, ggbs and superplasticizer without changing the water/cement ratio does not affect the drying shrinkage. This finding is similar to that noted by Fattuhi and Al-Khaiat [19] and Brooks [20]. On the other hand Chern and Chan [21] pointed out that there is an increase in the drying shrinkage of concrete due to the addition of ggbs. The use of the shrinkage reducing admixture in the concrete effectively reduces the drying shrinkage; concrete with the shrinkage reducing admixture only shrinks at a magnitude of 35 microstrains after 4.5 days while the corresponding control concrete c1 shrinks at about 108 microstrains. The reduction of the drying shrinkage in concrete containing shrinkage reducing admixture is caused by the ability of the admixture to chemically reduce the capillary tension in the pores water which develops within concrete as it dries.

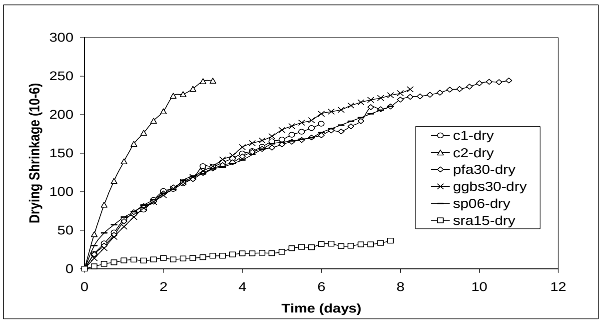

Figure 17. Drying Shrinkage of All Mixes Observed in The Current Research

SUMMARY AND CONCLUSIONS

The main conclusions deducted from the current experimental work are as follows:

a. Tensile strength determined from direct tensile test is lower than that of flexural strength and this finding is in agreement with the finding of previous investigators [2,9,10,11]. Addition of concrete with pfa, ggbs, superplasticizer and shrinkage reducing admixture will not affect (either increase or decrease) the tensile strength as long as the water/binder ratio is kept constant.
b. Tensile creep may be related with the compressive creep based on the measurement of creep at equal stress or stress/strength ratio. On the basis of equal stress, tensile creep seems to behave similarly with that of compressive creep as can be seen in the trends of the two creeps. However, if they are compared in term of their magnitude of creep, it is found that tensile creep is about twice that of the compressive creep. If comparison is based on a similar stress/strength ratio tensile creep is about seven times of the compressive creep.
c. An increase in water/cement ratio significantly increases drying shrinkage. On the other hand, the use of a shrinkage reducing admixture effecttively reduces the drying shrinkage of concrete.

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