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TENSILE CREEP AT EARLY AGES OF ORDINARY, SILICA FUME AND FIBER REINFORCED CONCRETES

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ABSTRACT

The deformability of concrete in tension has never received much attention, although the capacity of concrete to deform in tension, especially its creep potential, could help to prevent shrinkage induced cracking, and thus improve the durability of thin repairs. This paper presents the results of an investigation aimed at understanding and characterizing the tensile creep of concrete. The influence of different parameters was studied: the water to cement ratio, the type of cement, the age at loading and the use of fibre reinforcement. The results indicate that, unlike drying shrinkage, tensile creep is significantly influenced by the water to cement ratio, the age of concrete at loading and the fibre reinforcement. Silica fume seems to enhance creep as well as drying shrinkage, but the effect is relatively small.

Introduction

Drying shrinkage is one of the major problems affecting the durability of thin concrete repairs [1, 2]. Shrinkage in the repair concrete is hindered by the bond with the old concrete. During the drying process, restrained shrinkage conditions are thus created. This phenomenon induces tensile stresses in the repair layer and these stresses can eventually exceed the tensile strength of the material and cause cracking and debonding.

When considering the strain balance in a concrete element in which shrinkage is partially or fully restrained, the components that can counteract the shrinkage strain (before cracking occurs) are the elastic strain and the creep strain. Since the elastic strain capacity in tension is very small (~ 100 to 200 μm/m), only the tensile creep component can play an important role in reducing the restrained shrinkage stresses. To be able to select the concrete mixtures that are best suited for thin repairs, information on the tensile creep capacity of concrete is thus necessary. A higher creep capacity, and, more precisely, a higher creep to shrinkage ratio, will improve the resistance of thin concrete repairs to cracking.

Unfortunately, if the creep of concrete in compression has been studied by a large number of investigators, experimental data on the creep of concrete in tension are very scarce [3]. The fact that, in the design of new concrete structures, the tensile properties of concrete are generally disregarded, as well as the difficulties related to the accurate measurement of these properties, probably explain why little attention has been paid to tensile creep.

Most of the work on tensile creep emphasizes the comparison with the behavior under uniaxial compression, either in terms of magnitude and rate, or in terms of the mechanisms involved [4, 5, 6, 7]. The results that are available tend to indicate that the tensile creep component is not negligible in the strain balance discussed previously, particularly when concrete is allowed to dry under load (drying creep). The influence of most basic parameters, such as the water to cement ratio or the characteristics of the cement, has hardly been investigated.

This paper presents the results of a series of experiments carried out using a uniaxial tensile creep test apparatus specially developed for this purpose. The parameters studied were the water to binder ratio, the type of binder, and the age at loading. The reinforcement with steel fibres was also investigated since the use of fibres can help to prevent the formation of large cracks in the repair layers, and fibre reinforced concretes are thus considered very good repair materials. Since the tensile stresses in the repair layer are due to shrinkage, the specimens were allowed to dry during the creep tests.

In addition to being necessary to analyze the stresses in the concretes used for thin repairs, a better knowledge of the tensile creep properties of concrete will be helpful in the solution of many other practical problems. The design of water-retaining structures, a better determination of cracking in the tensile zone of reinforced concrete elements, and a more precise evaluation of the stresses in prestressed beams are only a few examples.

Test program

There are two main variables related to the composition of concrete that can influence creep: the paste characteristics and the quantity of paste in the mixture. In this first series of tests on tensile creep (which are part of a more general research program), it was decided to evaluate the influence of the paste characteristics, and to prepare all mixtures at a constant paste volume.

The characteristics of a cement paste are basically a function of the water to cement ratio, of the length of the hydration period, and of the characteristics of the cement. To limit the number of tests in this first series, it was decided to prepare four basic concrete mixtures, and to investigate two

TABLE 1

Test program

Mix	Composition parameters						Testing parameters		
	w/c ratio		cement[1]		steel fibres		age on loading		sealed or unsealed
	0,55	0,35	type I	HSF	macro	micro	1d	7d	
C55	√		√				√	√	both
C35		√	√				√	√	unsealed
S55	√			√			√	√	unsealed
S35		√		√			√	√	unsealed
C55-M	√		√		√			√	unsealed
C55-μ	√		√			√		√	unsealed

[1] Type I and HSF refer to normal Portland cement (ASTM type I) and normal Portland cement with silica fume (7% by weight) respectively.

periods of curing. The two water to cement ratios that were selected (0,55 and 0,35) were considered to cover relatively well the range from normal quality concrete to high quality concrete. The cements selected were a normal Portland cement (ASTM Type I), and a silica fume cement (7% by weight). Silica fume was considered to modify very significantly the microstructural characteristics of the hydrated paste. The creep tests were started after 1 day and after 7 days of curing. These two values cover the practical range of curing periods in the field.

The effect of fibre reinforcement on tensile creep was studied with the use of two types of steel fibres: a typical 16 mm long twisted and chopped macrofibre, and a microfibre (3 mm in length and approximately 25 μm in diameter).

As previously mentioned, the creep tests were performed with unsealed specimens so as to obtain simultaneous drying shrinkage and creep (i.e., basic creep and "drying creep"). However, mixture C55 was prepared a second time, and an additional series of tests was performed with both sealed and unsealed specimens (after 1 and 7 days of curing).

The test program is summarized in Table 1 which also gives the code names of the six mixtures tested (the four basic mixtures plus the two with steel fibres).

Mixture composition and experimental procedures

Concrete mixtures

The composition of the six mixtures tested is presented in Table 2, together with the fresh concrete properties. For all mixtures, crushed limestone (nominal size: 10 mm) was used as coarse aggregate, and a granitic sand as fine aggregate. A superplasticizer (naphthalene based) was used in all mixtures with a water to cement ratio of 0,35, as well as in the mixtures containing steel fibres.

As previously mentioned, all mixtures were prepared with the same cement paste content (30% by volume). Slump values between 50 and 150 mm were thus considered acceptable for the purpose of these tests. It can be seen in Table 2 that the slump of all mixtures prepared is within these limits. It can also be seen in this table that the air content of the first five mixtures, which ranges between 2,4% and 3,1%, is normal. The air content of the mixture containing microfibres, at 8,8%, is relatively high. This is probably due to the so-called grid effect preventing bubbles from rising to the surface in the fresh mixtures. The same phenomenon has been observed in mortars [8].

Experimental procedures

For each mixture and test condition (i.e. curing period and type of creep test - basic creep and "drying creep"), the following specimens were prepared: three 50x50x700 mm prisms, and three 50x50x400 mm prisms. The 50x50x700 mm prisms were used for the creep tests, and the 50x50x400 mm prisms to measure drying shrinkage. These tests were performed at 23±2°C and 50±5% R.H. All specimens were removed from the molds 24 hours after casting and cured in lime saturated water until the beginning of the tests. Cylinders (100x200 mm) were also prepared for compressive strength and splitting tensile strength measurements. The results are presented in Table 3. All values in this table can be considered normal for non-air-entrained concretes prepared with an ordinary Portland cement and a silica fume cement. The values for the microfibre reinforced mixture are low, due to the high value of the air content.

The applied tensile stress varied with the age of the concrete at the beginning of the tests, but was the same for all mixtures. The applied stress was 0,77 MPa for the tests starting at 1 day, and 1,0 MPa for the tests starting after 7 days of curing.

TABLE 2

Concrete Mixture Compositions and Fresh Concrete Properties

Component / Property		Concrete mixture					
		C55[1]	C35	S55	S35	C55-M	C55-μ
Type I cement	(kg/m^3)	383	495	–	–	383	360
HSF cement	(kg/m^3)	–	–	380	494	–	–
Coarse aggregate	(kg/m^3)	1017	1010	1017	1005	993	933
Fine aggregate	(kg/m^3)	678	674	678	670	662	622
Macrofibres	(kg/m^3)	–	–	–	–	78	–
Microfibres	(kg/m^3)	–	–	–	–	–	73
Water	(kg/m^3)	211	173	209	173	211	198
Superplasticizer	(l/m^3)	–	3,46	–	3,96	0,77	0,72
Slump	(mm)	130	75	50	100	80	80
Air content	(%)	2,4	3,1	2,4	3,1	3,0	8,8

1 Mixture C55 has been batched twice; the composition and the fresh concrete properties were the same.

As for creep in compression, the stress/strength ratio obviously has a major influence on the value of the deformation due to tensile creep [9]. However, it was found by certain investigators that tensile creep (again as for creep in compression) is proportional to the applied stress up to approximately 50 or 60% of strength [5, 9]. Thus, at the stress/strength levels used in this study, specific creep (i.e. creep per unit of stress) can be used to compare the creep properties of the various mixtures. It should also be noted that, the specimens being loaded at early ages, the

TABLE 3

Mechanical Properties

Mixture	Compressive strength (MPa)			Splitting tensile strength (MPa)			Elastic modulus[2] (GPa)	
	1 d	7 d	28 d	1 d	7 d	28 d	1 d	7 d
C55[1]	9	23	39	1,3	2,9	4,4	17,7	26,7
C35	25	51	58	3,0	4,4	4,9	28,6	39,4
S55	11	35	53	1,6	3,7	4,8	20,6	34,7
S35	32	56	71	3,6	4,5	5,6	30,3	35,1
C55-M	–	30	39	–	3,5	4,8	–	37,7
C55-μ	–	20	27	–	2,9	3,7	–	24,5

1 Mixture C55 has been batched twice; the mechanical properties were the same.

2 Secant moduli were computed with the instantaneous strains measured on loading at the beginning of the tensile creep tests.

stress/strength ratio decreases with time because hydration continues during the first days of drying, and that the increase in strength is not necessarily the same for all mixtures. It would thus have been very difficult to load the specimens from all mixtures at the same stress/strength level.

Test apparatus

A dead-load lever arm system (4:1) on which 12 concrete specimens can be tested at the same time was built for the purpose of this project. The load is applied to the prismatic specimens (50x50x700 mm) through precision-made steel plates anchored at the ends of the specimens with threaded rods. These plates are placed and aligned in the PVC molds prior to casting. At both ends of the specimens, the load is transmitted through a hinge. The test set-up, shown in Figure 1, is placed in a temperature and relative humidity controlled room (23±2°C and 50±5% R.H.).

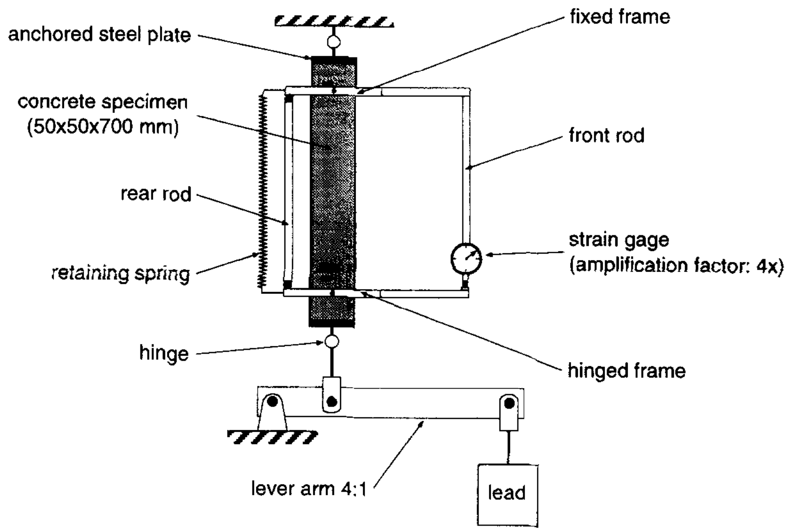
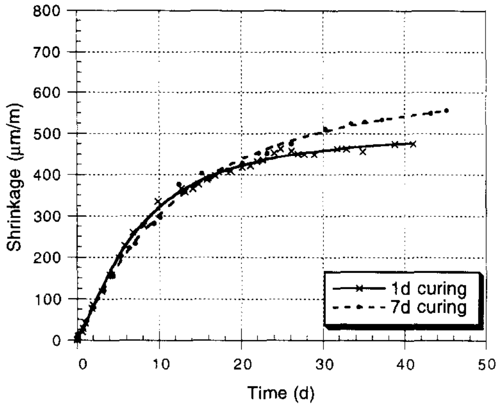


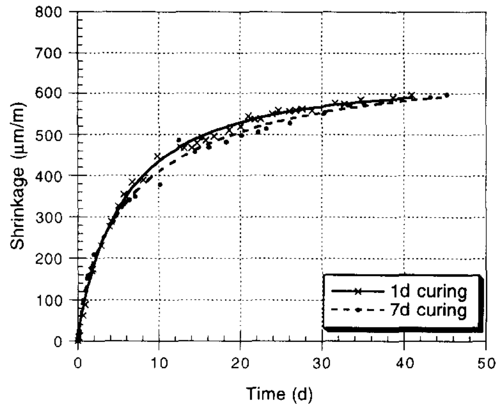
FIG. 1

Creep Test Apparatus and Strain Measurement Device

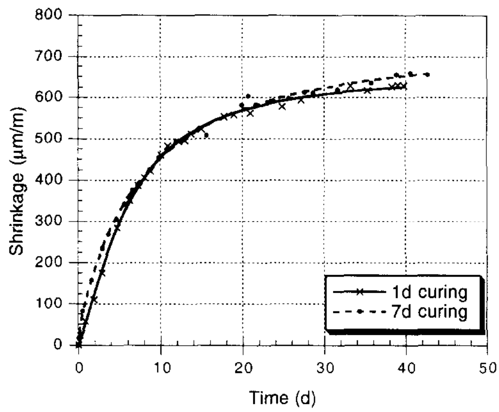
The strain measurement device, similar to those used to determine the static modulus of elasticity of concrete, is also shown in Figure 1. Two frames are attached to the concrete specimens, 508 mm apart (gage length). The upper frame is fixed, and the lower one is hinged, rotating around the rear rod (hinged at both ends) as the specimen deforms. The frames are attached to the specimens by means of brass plugs embedded in the concrete at the time of casting. For the rear and front rods, a special grade of stainless steel was used to avoid differential thermal strains between the measurement device and the concrete specimen. The thermal expansion coefficient of this steel ($9{,}9 \times 10^{-6}$/°C) is close to the usual values for concrete ($6\text{-}12 \times 10^{-6}$/°C). The dial gage is mounted on a lever arm (4:1), which means that the deformation that is measured represents four times the real deformation. The precision of this device is ±1 μm/m. Its performance was assessed through comparative shrinkage tests. The free shrinkage of three concrete specimens cast from the same batch was measured during 2 months with this device, and a standard extensometer was used to measure the free shrinkage of three other specimens of the same batch. The results showed very good agreement.



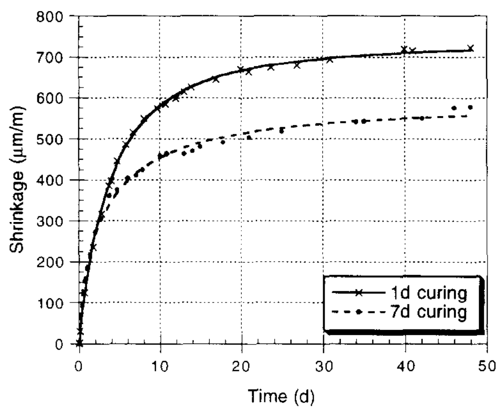
(a) Mixture C55



(b) Mixture C35



(c) Mixture S55



(d) Mixture S35

FIG. 2

Drying Shrinkage of the Basic Mixtures Stored at 50% R.H.

Test Results

The results of the tests performed on the four basic mixtures are presented in Figure 2 (drying shrinkage), and in Figure 3 (tensile creep). Figures 4 and 5 show the data for the two fibre reinforced mixtures, and Figures 6, 7, 8 and 9 that for the sealed and unsealed specimens of mixture C55. In Figures 3, 5, 8 and 9, the creep values are presented as specific creep, i.e. deformation at a given time under load divided by the value of the applied stress. Each curve on these figures represent the average result for three specimens. The detailed results for each group of three specimens generally show very little variation from one specimen to the other of the same group. This indicates that, in the tensile creep frame, the eccentricity of the loading is small. Since the strain measured on the loaded specimens included total creep and shrinkage, the creep component was determined by subtracting the shrinkage value from the strain measured under tensile stress.

Except for the additional series of tests with mixture C55 (on sealed and unsealed specimens), drying shrinkage and tensile creep measurements were only made up to approximately 45 days

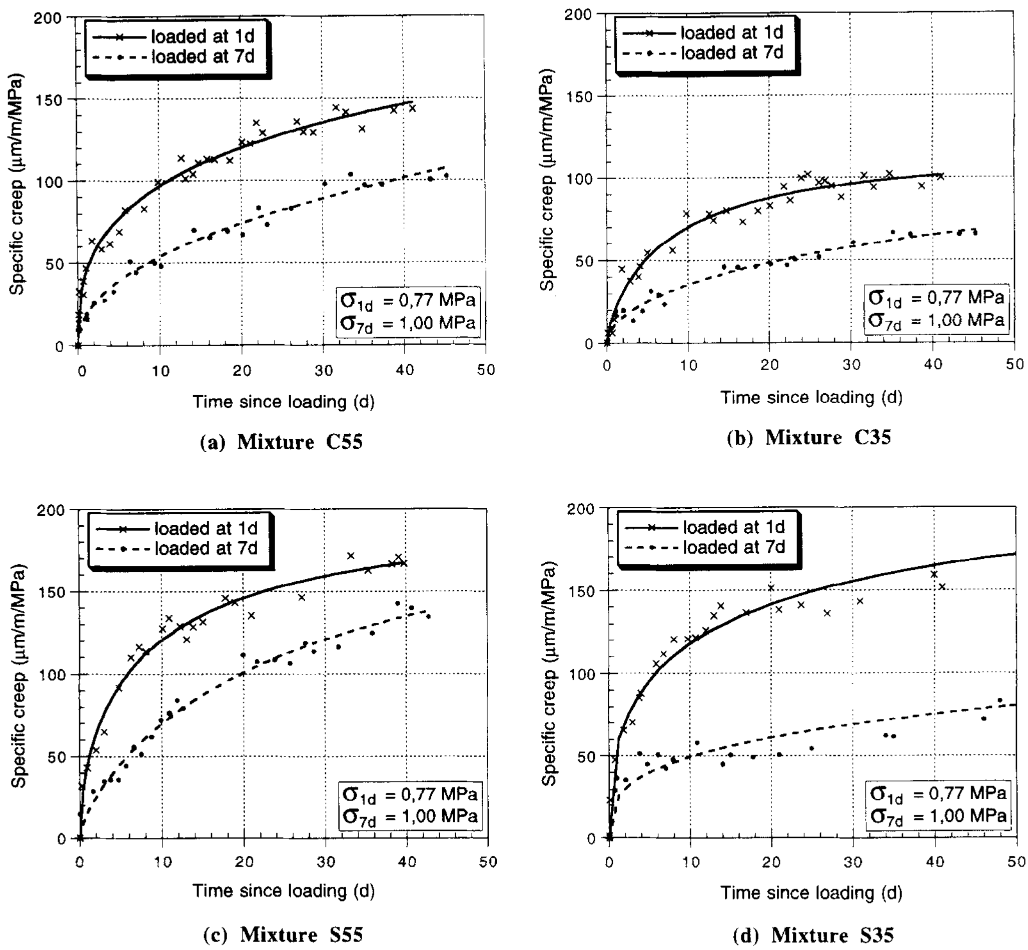


FIG. 3

Specific Total Tensile Creep of the Basic Mixtures Stored at 50% R.H.

after the beginning of the tests. This value was selected considering that most of the deformation due to shrinkage and creep in such 50x50 mm specimens occurs during this period, and in order to limit the time required for the tests, since only twelve specimens can be tested at the same time in the tensile creep frame. In the additional series of tests, the twelve specimens were loaded during more than one year.

For each of the six mixtures tested, the measured values of the drying shrinkage, which are of the order of 500 to 700 µm/m after 45 days, are normal for these types of concretes. The values of specific tensile creep (obtained at 50% R.H.) for all mixtures range from 60 to 200 µm/m/MPa after 45 days. Globally, these values are of the same order of magnitude as the values of creep in compression for normal concretes.

Discussion

The results from the drying shrinkage tests of the four basic mixtures and of the two fibre reinforced mixtures (Figures 2, 4, 6 and 7) indicate that none of the parameters tested (water to

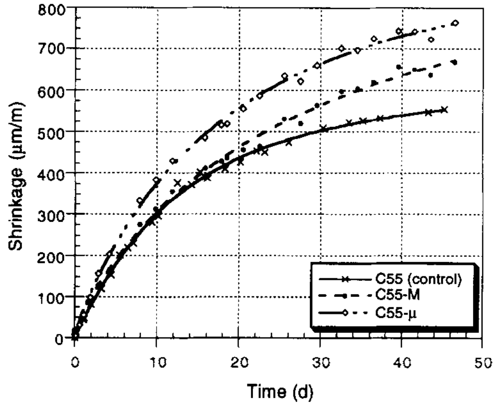


FIG. 4
Drying Shrinkage of Fibre Reinforced Concrete Mixtures Tested at 7 days (50% R.H.).

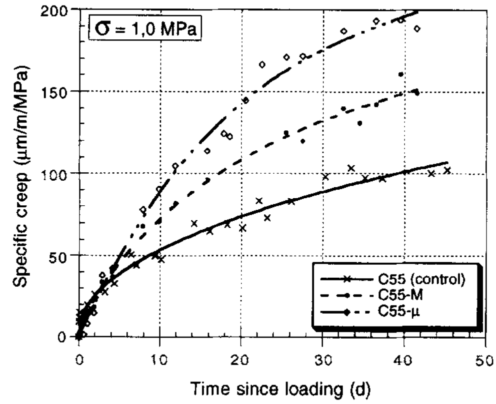


FIG. 5
Total Tensile Creep of Fibre Reinforced Concrete Mixtures Tested at 7 days (50% R.H.).

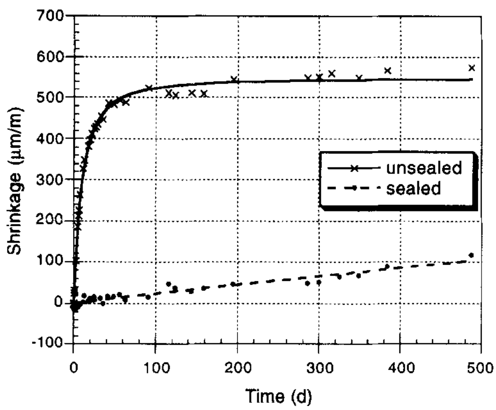


FIG. 6
Autogeneous and Drying Shrinkage of Mixture C55 Tested at 1 day (50% R.H.).

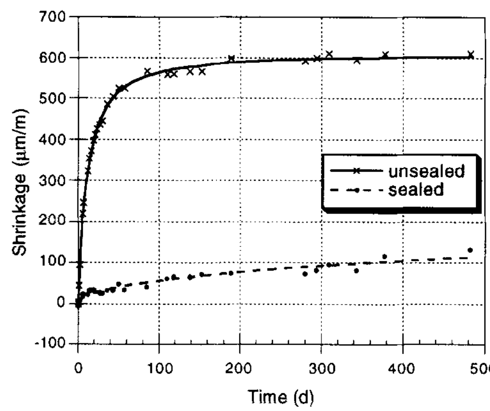


FIG. 7
Autogeneous and Drying Shrinkage of Mixture C55 Tested at 7 days (50% R.H.).

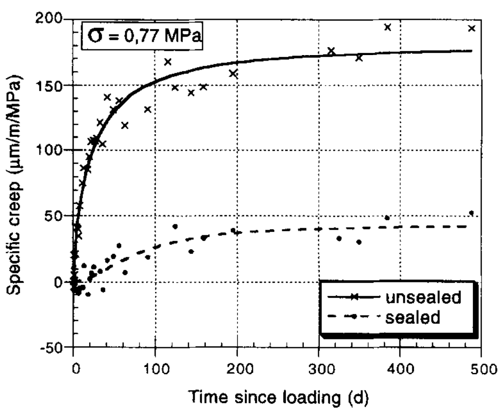


FIG. 8
Basic and Total Creep in Tension for Mixture C55 Loaded at 1 day (50% R.H.).

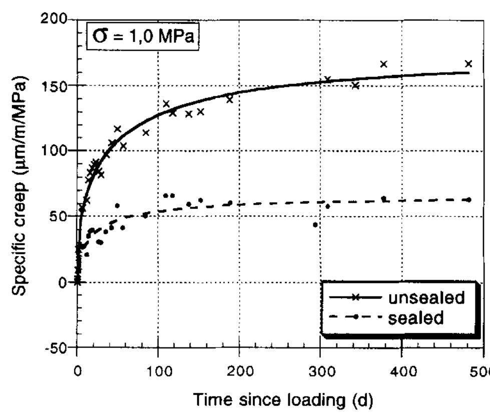


FIG. 9
Basic and Total Creep in Tension for Mixture C55 Loaded at 7 days (50% R.H.).

cement ratio, cement characteristics, age at loading, or the use of fibres) had a very significant influence. Except for the water to cement ratio, this is not in contradiction with most of the published data, particularly considering the constant paste volume of all of these mixtures, and also the fact that the measurements were generally only made up to 45 days [3, 10, 11]. The data in Figure 2 in fact show that the shrinkage is slightly larger at a water to cement ratio of 0,35 in the normal Portland cement mixtures. This phenomenon does not appear to be due to variations during the tests, since the data in Figures 6 and 7 (for mixture C55 prepared a second time) corresponds to that in Figure 2. It thus seems that, at a constant paste content, the water to cement ratio has little influence on the value of drying shrinkage, at least for the range of water to cement ratios and for the type of cements tested.

Contrary to the data for drying shrinkage, that for tensile creep of the four basic mixtures (Figure 3) show a significant influence of the water to cement ratio and of the age at loading. The influence of the age at loading appears to be quite significant for both types of cements and both values of the water to cement ratio. Except for the silica fume mixtures tested at 1 day, the decrease in creep with the decrease of the water to cement ratio is particularly clear. Such an influence of these two parameters has also been noted for creep in compression [9], which suggests that the phenomena involved are probably similar in tensile creep and in creep in compression.

The test results in Figure 3 generally show that the use of silica fume, even if it reduces the size of the capillary pores [12], tends to increase creep in tension. The higher value obtained for the silica fume mixture at a water to cement ratio of 0,35 and tested at 1 day is difficult to explain. However, it should be noted that the drying shrinkage of this mixture tested at 1 day is also significantly higher than that of the other basic mixtures (Figure 2).

In Figure 5, in addition to the creep data for the two fibre reinforced mixtures, that for the basic mixture prepared with the same cement at the same water to cement ratio (and tested after the same period of hydration - 7 days) is shown. It is clear in this figure that the use of fibres tends to increase creep in tension. For the microfibre reinforced concrete, part of this increase is probably due to the lower strength of this mixture which has an air content of 8,8%. But for the macrofibre reinforced mixture, which has an air content of only 3,0% and mechanical properties very similar to those of the reference mixture (C55), this increase has to be related to the influence of the fibres on the microstructure of the paste at the paste-fibre interface [13].

The basic creep values for mixture C55, together with the total creep values, are presented in Figures 8 and 9. The basic creep values were calculated in the same way as the total creep values, i.e. by subtracting the deformation measured on the unloaded (sealed) specimens from the strain measured under tensile stress. The basic tensile creep, similarly to the basic creep in compression, only represents a relatively small proportion of the total creep. Again, this tends to indicate that the phenomena involved are probably similar in tensile creep and in creep in compression.

As mentioned in the introduction, the study of the tensile creep properties of concrete was undertaken to obtain some of the information required to evaluate the stresses due to restrained shrinkage in thin repair layers. It was considered that creep could reduce significantly these stresses, and thus reduce the risk of significant cracking. Of course, considering the humidity gradient in the repair layers exposed to drying conditions, it is clear that the results obtained can not be used directly, since shrinkage (and thus the tensile stress and the tensile creep or relaxation under load) will also vary with the distance from the surface. Nevertheless, it is interesting to examine the results obtained in terms creep to shrinkage ratio, because the use of a concrete with a higher tensile creep capacity will only be useful if the drying shrinkage is not increased in the same proportion.

Table 4 gives the total creep to shrinkage ratio (after 14 and 28 days under load) for the four basic mixtures and for the fibre reinforced mixtures. From this table, it is clear that the main parameters that influence this ratio are the water to cement ratio and the age at which the tests are started. The largest values correspond to basic mixtures having a water to cement ratio of 0,55 and tested at 1 day, and to the fibre reinforced mixtures. It should not be inferred from these results that one day is an adequate curing period for thin repairs, or that 0,55 is an adequate water to cement ratio. Obviously, other phenomena, such as frost and deicer salt scaling resistance, or corrosion of the reinforcement, have to be taken into account. But these values also indicate that extremely dense repair materials are not necessarily the best. As pointed out in recent publications [1, 2, 14], the compatibility of the repair material with the concrete of the repaired structure is a very important consideration for durable repairs. The results in Table 4 further show that the total creep to shrinkage ratio does not decrease with time.

TABLE 4

Specific Total Creep to Shrinkage Ratio

Mix	1d concrete		7d concrete	
	days under load		days under load	
	14 d	28 d	14 d	28 d
C55	0,29	0,29	0,17	0,17
C35	0,16	0,17	0,09	0,10
S55	0,26	0,26	0,16	0,19
S35	0,21	0,22	0,11	0,13
C55-M	–	–	0,23	0,24
C55-μ	–	–	0,25	0,26

Conclusion

The test results presented in this paper indicate that creep in tension is a very significant phenomenon, that could play an important role in reducing the stresses due to restrained shrinkage in thin repair layers. Although most creep tests were only performed for a relatively short period of time (45 days), the results show that tensile creep increases with the water to cement ratio, decreases with the age at loading, and is little influenced by the use of silica fume. The results further show that the creep to shrinkage ratio varies in the same way.

Further research will be necessary, particularly to analyze the influence of the stress level, since the tensile stresses due to restrained shrinkage can be quite high, high enough, in fact, to cause cracking in most cases. Further research will also be necessary to better evaluate the influence of fibres. Fibre reinforced concrete is frequently used for repairs, since fibres prevent the formation of large cracks, and the results presented indicate that fibres also tend to increase creep in tension.

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References

[1] Saucier, F. and Pigeon, M., Durability of New-to-Old Concrete Bondings, Proceedings of the ACI International Conference on Evaluation and Rehabilitation of Concrete Structures and Innovations in Design, Hong-Kong, pp. 689-705, 1991.

[2] Pigeon, M. and Saucier, F., Durability of Repaired Concrete Structures, Proceedings of the International Conference on Advances in Concrete Technology, Athens, pp. 741-773, 1992.
[3] Neville, A.M., Properties of Concrete (3rd edn.), Longman Scientific & Technical, Essex, England, 1990.
[4] Brooks, J.J. and Neville, A.M., Mag. Concr. Res., 29 (100), 131-141 (1977).
[5] Illston, J.M., Mag. Concr. Res., 17 (51), 77-84 (1965).
[6] Domone, P.L., Mag. Concr. Res., 26 (88), 144-152 (1974).
[7] Ward, M.A. and Cook, D.J., Mag. Concr. Res., 21 (68), 151-158 (1969).
[8] Boisvert, J., Pleau, R. and Pigeon, M., Propriétés mécaniques de mortiers renforcés de micro-fibres d'acier et de carbone , Proceedings of the Colloque Les Bétons Renforcés de Fibres Métalliques, Béthune (France), pp. 229-236, 1994.
[9] Neville, A.M., Dilger, W.H. and Brooks, J.J., Creep of Plain and Structural Concrete, Construction Press, London and New-York, 1983.
[10] Khayat, K. and Aïctin, P.-C., Silica Fume in Concrete - An Overview, Proceedings of the Canmet/ACI International Workshop on the Use of Silica Fume in Concrete, Washington, pp. 1-46, 1991.
[11] Tatnall, P.C., Steel Fiber Reinforced Concrete - A State-of-the-Art Report, Proceedings of the First Canadian University-Industry Workshop on Fibre Reinforced Concrete, Québec (Canada), pp. 73-88, 1991.
[12] Sellevold, E.J., Bager, D.H., Klitgaard Jensen, E. and Knudsen, T., Silica Fume Cement Pastes: Hydration and Pore Structure, Report BML 82.610, The Norwegian Institute of Technology, Trondheim (Norway), 1982.
[13] Hornain, H., Aspects microstructuraux des bétons renforcés de fibres métalliques, Proceedings of the Colloque Les Bétons Renforcés de Fibres Métalliques, Béthune (France), pp. 9-19, 1994.
[14] Shrader, E.K., Mistakes, Misconceptions and Controversial Issues Concerning Concrete and Concrete Repairs, Concrete International, 14 (11), 54-59 (1992).