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Tensile creep and early-age concrete cracking due to restrained shrinkage

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HIGHLIGHTS

- Tensile creep coefficients are deduced from the specimens under sustained tension.
- Creep coefficients are successfully exploited in analysing restrained ring test data.
- Tensile creep found to delay the shrinkage induced cracking.
- Increase in restraint reduces time to cracking when other parameters are kept same.
- Analytical equation is proposed allowing calculation of shrinkage induced stresses.

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ABSTRACT

Concrete structures are prone to cracking due to restraint provided to early age autogenous and drying shrinkage. In addition, the risk of early-age thermal cracking is increased by increasing the degree of restraint to early-age thermal contraction. At this early-age, tensile creep plays a key role in relaxing shrinkage induced tensile stresses and delaying the time to cracking. However, limited data are available concerning tensile creep of concrete and the magnitude and rate of development of the early-age shrinkage of concrete. As a consequence, restraint to shrinkage is often poorly modelled in structural design. In order to accurately quantify the early-age shrinkage and tensile creep of concrete, a comprehensive experimental program is being conducted at the UNSW Centre for Infrastructure Engineering and Safety. Tensile creep is measured on dog-bone shaped specimens subjected to constant sustained tensile stress, while shrinkage is measured on identical unloaded specimens. Restrained ring tests were also performed to validate the tensile creep coefficients calculated from dog-bone specimens. A simple analytical procedure to accurately predict the degree of restraint and the tensile stresses in concrete induced by shrinkage is described for the restrained ring specimens.

1. Introduction

Concrete structures can be subjected to internal or external restraint. Internal restraint exists when the concrete deformation is non-linear over the depth of a cross-section, i.e. when the shrinkage or temperature strain distribution is non-linear. Internal restraint is also provided by steel reinforcement embedded in the concrete. External restraint may be provided at the ends of member, or along the edges of a slab or wall, by the supports or by adjacent parts of the structure. Whether restraint is internal or external, shrinkage induced stresses are always produced in restrained concrete members. The development of tensile stress due to restrained shrinkage is slowed by tensile creep and therefore it is important to accurately quantify the early age tensile creep of concrete, as well as the early-age deformations due to cooling, autogenous shrinkage and drying shrinkage.

The understanding of stress relaxation and tensile creep behaviour is extremely important for accurate stress analysis of restrained concrete members and structures and for the prediction of early-age cracking of concrete. Due to the difficulties associated with measuring tensile creep, limited research has been undertaken to quantify the direct tensile creep characteristics of concrete at early-ages. Some researchers [1–4] have used uniaxially restrained shrinkage tests to indirectly measure the tensile creep of concrete. However, in a uniaxially restrained test, a higher degree of restraint is provided to concrete and cracking in concrete usually occurs within the first 5–6 days after casting [5] or sometimes even earlier [3]. Due to the short duration of the test,

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the tensile creep deduced from these experiments is only helpful in modelling very early-age deformation and cracking when a high degree of restraint is provided. However, concrete can be subjected to lower degrees of restraints and, in such cases, cracking might occur after a considerably longer period of time. To accurately model the time-dependent cracking that may occur in the weeks and months after casting and to quantify relaxation stresses, a knowledge of tensile creep over a longer period of time is essential. Tensile creep over a long period of time can be measured on concrete specimens subjected to direct tension at sustained stress levels typically less than 50% of the tensile strength of the concrete at the age of first loading. Limited experiments [6,7] have been reported in the literature of tensile creep tests involving direct sustained tensile stress applied to the concrete specimens. At the necessarily low stress levels in these tests, inaccuracies in the measured tensile creep can arise due to difficulties in isolating the autogenous and drying shrinkage in the concrete. The direct tension measurements can best be validated by conducting concurrent restrained shrinkage tests. The tensile creep data obtained in previously reported tensile creep tests involving specimens in direct tension have not been validated in this way. Therefore, there is still a gap in the literature and a dearth of guidance on the magnitude and development of tensile creep in concrete. Table 1 shows the experimental details of some previous studies of tensile creep in concrete.

Concrete cracking tendency under restrained conditions has been mainly evaluated by qualitative means through a variety of cracking tests, including bar test [12], the plate and slab test [13,14] and the ring tests [15,16]. The ring test consists of a concrete annulus that is cast around a steel ring. Asthe concrete ring dries, it shrinks. The steel ring restrains this shrinkage causing tensile stress to develop in the concrete. If these stresses are large enough, cracking may occur.

The purpose of this paper is firstly to measure tensile creep coefficients on dog-bone shaped specimens by application of sustained axial tension and secondly to use the restrained ring test in order to monitor the development of cracking in the concrete and to validate the tensile creep coefficients measured on the dog-bone shaped specimens. This kind of experimental program has not been undertaken previously. Furthermore, the restrained ring test was simulated numerically using the finite element program ANSYS and tensile creep coefficients measured on the dog-bone specimens were implemented in the analysis using the age-adjusted elastic modulus method. A numerical parametric study was also undertaken on restrained ring test specimens for different thicknesses of steel ring providing different degrees of restraint. The parametric study provided insight into the effect of the degree of restraint on the time to cracking.

2. Experimental program

A 32 MPa normal class concrete mix was used for all tests using General Purpose cement and a water-cement ratio of 0.55. Further tests are currently underway to determine the effects of varying the type of binder, the type and grade of aggregate and the water-cement ratio. The tests were carried out in a temperature-humidity control room at a constant temperature of 23 °C and a relative humidity of 50%.

Table 2
Mixture proportions of concrete.

Components	GP Cement	Sand	Gravel (10 mm Basalt)	Water
Mass (kg/m^3)	380	545	1265	210

Table 3
Mechanical characteristics of concrete.

Age (days)	Compressive strength (MPa)	Modulus of rupture (MPa)	Indirect tensile strength (MPa)	Elastic modulus (GPa)
0.75	13.18	2.57	1.20	18.35
1	15.28	3.11	1.40	20.35
2	21.55	3.785	2.10	22.05
3	24.64	4.03	2.54	22.7
7	32	4.56	2.94	27.78
28	37	4.84	3.47	28.58

2.1. Concrete mix

The mix proportions used in the experimental program are shown in Table 2. A sufficient number of cylinders and prisms were cast and tested to determine the evolution of compressive strength, tensile strength and elastic modulus, with tests performed at the ages of 0.75, 1, 2, 3, 7 and 28 days. Three specimens were tested in order to assess the statistical variation and this practice was repeated for each concrete batch.

Compressive strength, elastic modulus and indirect tensile strength tests were conducted on cylinders in accordance with AS 1012.9: 2014 [17] and AS 1012.10: 2000 [18] and the modulus of rupture tests were conducted on prisms in accordance with AS 1012.11: 2000 [19]. The evolution of concrete mechanical properties is presented in Table 3.

2.2. Test items and methods

2.2.1. Dog-bone test

In order to measure tensile creep on the dog-bone specimens, a creep rig capable of testing three specimens simultaneously under direct tension was designed. The dimensions of the dog-bone specimens were 200 × 300 × 35 mm and the loading arrangement is shown in Fig. 1.

The dog-bone specimens are fixed into the creep rig by means of two steel plates. These steel plates are connected to the specimens by two threaded bolts which are cast into the specimen at each end as shown in Fig. 1. To ensure even stress distribution in

Table 1
Some previous tensile creep experiments reported in the literature.

Authors	Test method	Creep type	Concrete w/c ratio	Loading age	Test duration
Altoubate & Lange [5]	Uniaxial restrained shrinkage test	Drying	0.4 & 0.5	0.5 day	6 days
Østergaard et al. [2]	Uniaxial restrained shrinkage test	Basic	0.4 & 0.5	1 day	4 days
Pane & Hansen [9]	Uniaxial restrained shrinkage test	Drying	0.35 & 0.45	1 day	6 days
Aly & Sanjayan [3]	Uniaxial restrained shrinkage test	Drying		1 day	0.9 days
Bissonnette & Pigeon [10]	Sustained tension	Drying	0.35 & 0.55	1 day	40 days
Briffaut et al. [8]	Sustained tension	Basic	0.57	2 days	3 days
Rossi et al. [5]	Sustained tension	Basic	0.54	7 days	40 days
Li et al. [11]	Sustained tension	Drying & Basic	0.5	3 days	120 days