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EVALUATION OF EARLY AGE SHRINKAGE CRACKING TENDENCY OF CONCRETE

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Abstract: This paper presents experimental work to investigate the early-age shrinkage cracking characteristics of concrete. Early-age shrinkage cracking is an ever-present concern in concrete technology which affects the long-term reliability and integrity of concrete structures. In this study, restrained and free ring tests were used to evaluate concrete cracking potential and creep characteristics. This study goes beyond the basic test data analysis and evaluates the rate of stress development under restrained shrinkage conditions. A test procedure addendum is also outlined to quantify the tensile creep behavior of concrete using a companion free shrinkage ring specimen. A separate study was carried out to evaluate the influence of curing on the rate of stress development under restrained conditions. Analysis of data showed that the time to cracking depends more on shrinkage rate than shrinkage magnitude. Thus, there is a strong correlation between stress rate and the time-to-cracking of the concrete ring specimen. Furthermore, cracking resistance under restrained conditions is found to depend on the combined effect of the shrinkage stress buildup, tensile strength development and tensile creep potential of concrete.
Keywords: Shrinkage, cracking, cracking potential, ring test, time-to-cracking, creep.

1 INTRODUCTION

Concrete undergoes volume changes due to moisture content changes that initiates when the concrete surface is exposed to an environment with a different relative humidity. Drying shrinkage is typically the main cause of cracking in most concrete structures. Cracking due to shrinkage occurs mainly because of restraint that prevents the concrete from contracting freely inducing internal tensile stresses. This is particularly true in the case of concrete overlays and slabs on grade where drying occurs from one face only and shrinkage is hindered by restraints (Bissonnette, Pierre, and Pigeon 1999). The magnitude of these induced stresses depends on factors including the degree of restraint, moisture gradients within the element, the concrete composition and proportions, etc. (Bissonnette, Pierre, and Pigeon 1999, Luković et al. 2016). In addition to these influencing factors, creep related stress relaxation parameters are critically needed for evaluating the cracking potential of concrete structures (Gao, Zhang, and Han 2013). The restrained ring test has become the most widely used to evaluate and quantify the shrinkage cracking potential of concrete mixtures (AASHTO 1999, ASTM 2009). Unfortunately, the usual ring test procedures do not provide *quantitative* information on concrete tensile stress and creep, which are required to evaluate the risk of cracking (See, Attiogbe, and Miltenberger 2003). To generate the necessary data, free shrinkage test can be performed in conjunction with the restrained ring tests, allowing to evaluate the creep characteristics of concrete. The present study is part of on-going research on the durability of concrete and shotcrete mixtures, and is particularly aimed at early age shrinkage cracking and tensile creep properties. is intended to improve the interpretation of the ring test results. In this study, the AASHTO PP34 ring configuration was used to quantify the restrained and free shrinkage behaviour of concrete mixtures. A simple approach based on the mechanical equilibrium between the steel and concrete rings was implemented for determining the stress development in the concrete ring specimens. Additionally, this paper presents a simple method for quantitatively predicting tensile creep with a combination of elastic modulus, free shrinkage and restrained shrinkage test data.

1.1 Research synopsis

The *restrained shrinkage ring test* is the most useful and economic test for characterizing the shrinkage cracking potential of concrete. The paper indicates how it can be used to *quantify* stress development and evaluate the tensile creep potential of concrete. The influence of curing on the rate of stress development under restrained conditions is also addressed.

2 EXPERIMENTAL PROGRAM

To obtain a better understanding of the restrained shrinkage phenomenon and quantify the tensile creep behavior of concrete, free and restrained tests were performed. A prepackaged repair concrete mixture with 10-mm aggregates was used for producing the test specimens (planetary mixer - cast horizontally). Approximately 5 kg/m^3 of naphthalene-based superplasticizer was used to obtain the desired workability with a slump in the range of 95 to 140 mm. The restrained shrinkage tests were carried out using the AASHTO PP34 (AASHTO 1999) ring test procedure shown in Fig. 1. For free drying shrinkage measurements, ring specimens similar to the AASTHO rings were cast, with the inner steel ring replaced with a core made of a very low stiffness material with respect to the concrete ring. The main goal is to measure free shrinkage on specimens having a geometry, size and surface-to-volume ratio such that they undergo the same conditions as the restrained rings. In the restrained ring test, compressive strain develops in the steel ring when the outer concrete ring shrinks. Four strain gages are installed on the interior face of the steel ring at mid-height. In the free ring test, however, the concrete specimen is not externally restrained and hence is allowed to shrink *"freely"*. DEMEC gages were installed on top of the free ring specimens for length change measurements of the free drying shrinkage.

The modulus of elasticity and splitting tensile strength were also determined in accordance with ASTM C469 (ASTM 2002) and C496 (ASTM 2004) test methods. The creep parameter was estimated by exploiting the data from the two types of ring tests, together with the modulus of elasticity test results. The two-investigated water-to-cement (w/c) ratios (0.45 and 0.60) were considered to cover fairly well the range from moderate to high water content mixtures. For each mixture, two moist curing periods, 3 and 7 days, were studied. The implemented test methods are briefly described in the following sections.

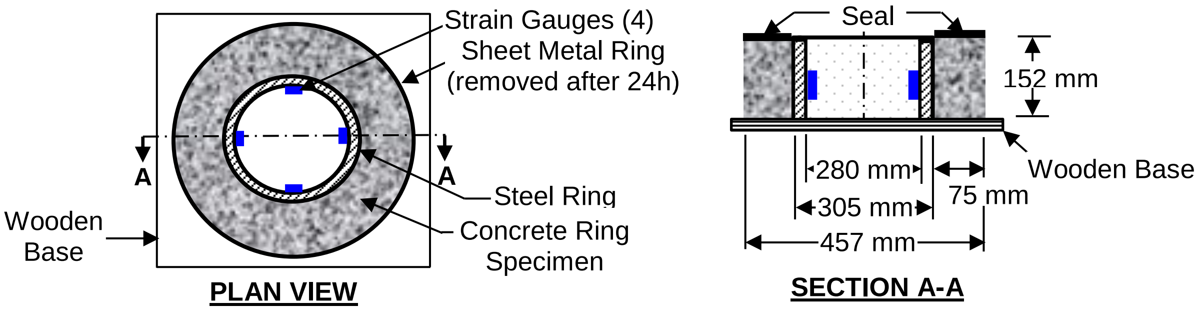


Fig. 1: Dimensions of restrained ring setup (AASHTO 1999)

2.1 Characterization test specimens

Twenty-one 100 x 200 mm (4 x 8 in.) cylinders were also prepared for each tested concrete mixture. Four cylinders per mixtures were tested in compression at 3, 7, and 28 days after casting to determine the modulus of elasticity and Poisson's ratio in accordance with ASTM C469. Three supplemental cylinders were used to determine the splitting tensile strength at 3, 7, and 28 days after casting in accordance with ASTM C496.

2.2 Free ring test specimens

At least two ring specimens were cast for each mixture to measure the free drying shrinkage simultaneously with restrained ring shrinkage to mimic the geometry, size and drying directions in the restrained rings. The free ring specimens were cast following AASHTO PP 34-99 test protocol with the exception of replacing the steel ring with a white polystyrene core with a very low stiffness. Validation of the test method was carried out in a separate study which will be published shortly, together with the detailed description of the test procedure.

2.3 Restrained ring test specimens

A total of fourteen (14) concrete ring specimens were prepared and tested in three series (however, only thirteen (13) concrete ring specimens were analysed in this paper). Each series consisted of at least two (2) ring specimens per mixture. Upon casting, the freshly placed concrete was consolidated in the mold. All specimens were left in their mold for the first 24 hours after casting and covered with wet burlap and plastic sheets. The exterior wall of the mold was removed after 24 h and the specimens were additionally moist cured for either 2 or 6 days. A specimen freshly cast ring test specimen is shown in Fig. 2 (a). After curing, the specimens were sealed on the top and bottom sides. Drying then occurred from the outer face only. The specimens were exposed to drying under standard conditions (21±1.7°C and 50 ± 4% R.H.) until cracking occurred. Fig. 2 (b) shows a typical crack that developed in the restrained ring specimen drying from the outer circumference. It should be mentioned that drying is not uniform within the concrete ring specimen because of the height (152 mm) and thickness (76mm) of the concrete ring.

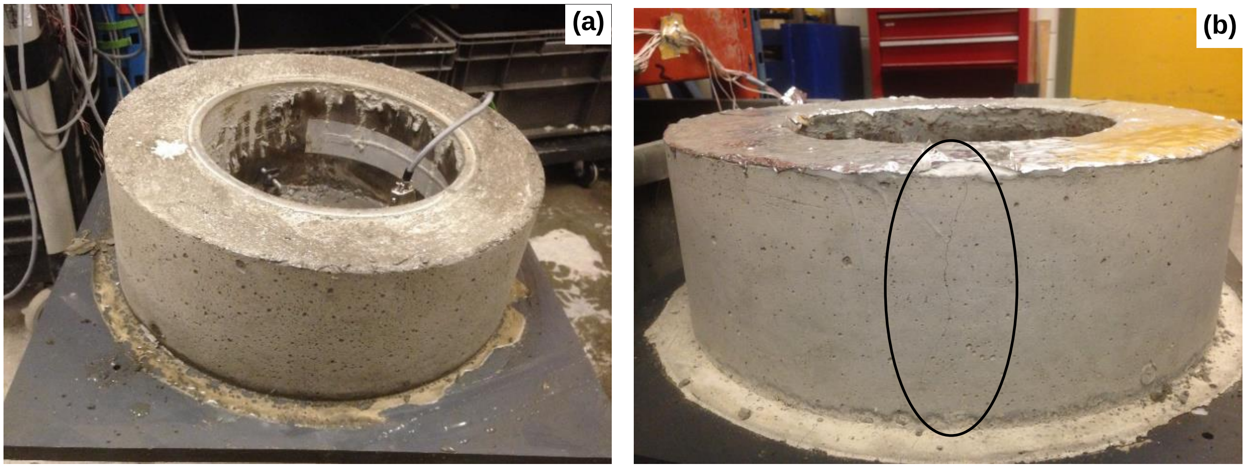


Fig. 2: Ring test specimen before and after casting

Drying from the circumference thus results in uniform shrinkage through the height of the specimen but not in the radial direction. This results in a non-uniform drying between the outer and inner radius of the concrete ring. Since shrinkage is faster at the outer drying surface where more rapid drying occurs, crack can initiate at a random position of from the outer circumference and propagates inside the ring. The non-uniform drying consequently results in the development of a complex stress distribution in the concrete which moreover changes in shape over time, making an estimation of the maximal residual stresses generated in the concrete very difficult without a complete knowledge of the developed drying gradient (Van Itterbeeck et al. 2010). In this paper, a simple approach based on the mechanical equilibrium between the steel and concrete rings for determining the average stress development in the concrete ring specimens, irrespective of the drying conditions is proposed. The average stress (σ_{c_avg}), development in the concrete can, in this case, be calculated using Eqs (1), presented below. A full derivation of this equation will be published shortly but is beyond the scope of this paper.

$$[1] \quad \sigma_{c\_avg}(t) = -\frac{1}{2}\frac{A_s}{A_c}\, E_s\, \varepsilon_s(t)\frac{R_{os}+R_{is}}{R_{os}}$$

where, A_s and A_c are the cross-sectional areas of steel and concrete ring, respectively, Es is the of elastic modulus of the steel ring (200 GPa), ε_s is the strain measured in the steel ring, R_{is} is the inner radius of steel ring, and R_{os} is the outer radius of steel ring. Since the geometrical and material properties are constant for a given ring setup, the induced tensile stress only is given by,

[2] $$\sigma_{c\_avg}(t) = -\,G\,\varepsilon_s(t) \qquad \text{(and } G = \frac{R_{os}+R_{is}}{2R_{os}}\,\frac{A_sE_s}{A_c}\text{)}$$

where G is a constant for the ring setup, synonymous with the term G derived by See et al. (See, Attiogbe, and Miltenberger 2004) for stress rate analysis in a thin ring specimen. For the ring setup used in this study, G= 31.55 GPa (4.58 × 10^6 psi). Based on the analysis carried out by See et al. (See, Attiogbe, and Miltenberger 2004), we can assume that the stress rate at time *t*, after initiation of drying in a thick ring, can be obtained as follows:

[3] $$S(t) = \frac{d\sigma_{cavg}(t)}{dt} = G\left|\frac{d\varepsilon_s}{dt}\right| = \frac{G\,|\alpha|}{2\sqrt{t}}$$

where $d\varepsilon_s/dt$ is the net steel strain rate at time *t*. Attiogbe et al. (Attiogbe, Weiss, and See 2004) found that the steel strain (ε_s) value shows a linear relationship with the square root of drying time up to the time-to-cracking. It can therefore be fitted using a linear regression as $\varepsilon_s(t) = \alpha\sqrt{t} + c$, where α is the slope of the line (or the strain rate) and *c* is a regression constant.

Similarly, analytical solution is developed for evaluating the creep strain in the AASHTO PP34 ring, derived from the solution proposed by See et al. (See, Attiogbe, and Miltenberger 2003) for the thinner-walled ASTM ring. It should be mentioned that thick concrete sections (as used in this study) show a different cracking behavior compared to thin sections (Weiss 1999). In fact, the average radial compressive stress in the steel ring is about 10% of the average concrete stress in the case of the thin ASTM ring specimen configuration, while it may reach as much as 25% in the thicker AASHTO ring configuration, according to See et al. (See, Attiogbe, and Miltenberger 2003), making the solutions proposed for the ASTM ring less accurate.

The analytical solution in Eqs (4) below can be used to evaluate the tensile creep coefficient (ϕ_c) in the concrete. Again, full derivation of the equation will be published shortly but is beyond the scope of this paper.

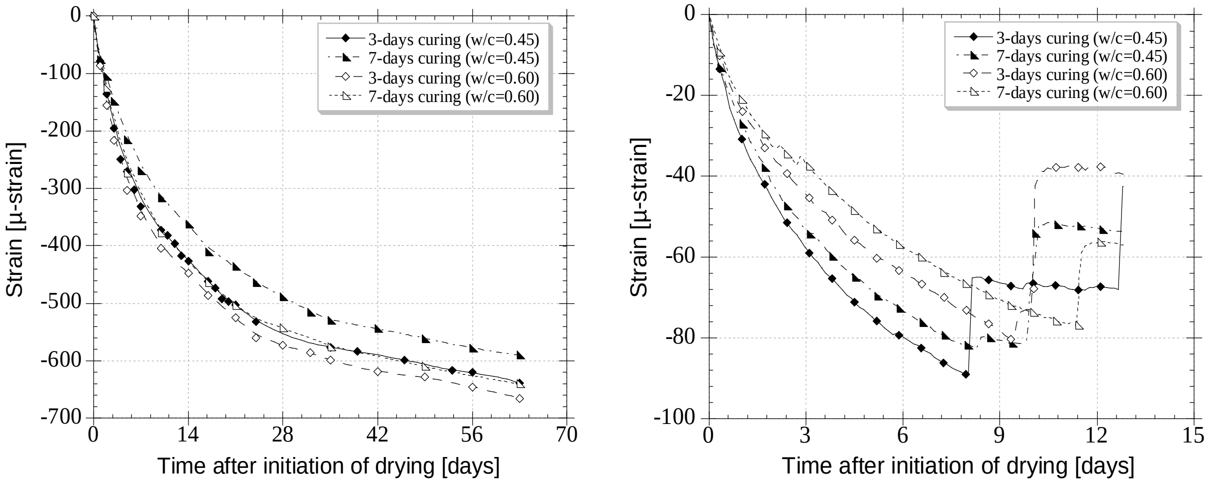
[4] $$\phi_c(t) = \frac{1}{G}E_c(t)\left[\frac{\varepsilon_{sh}(t)}{\varepsilon_s(t)} - 1\right] - 1$$

where, E_c is elastic modulus of concrete and ε_{sh} is the free shrinkage strain. The tensile creep can then be expressed in terms of tensile creep coefficient and elastic strains (ε_e) as:

[5] $$\varepsilon_{cr}(t) = \phi_c(t) * \varepsilon_e(t) \qquad \text{where } (\varepsilon_e(t) = \frac{\sigma_{c\_avg}(t)}{E_c(t)})$$

3 TEST RESULTS

The observed free drying shrinkage and restraining steel ring strains for the two concrete mixtures are presented in Fig. 3 ((a) and (b)). On each graph, the shrinkage as a function of drying time is shown for the two mixtures investigated. Each data point is an average of values recorded on at least two rings. As expected, a comparison of the free drying shrinkage and the corresponding strain measured in the restraining steel ring for both mixtures shows that the steel ring contraction is much less than the free drying shrinkage strain. Overall, the results in Fig. 3 show that the rate of drying is rapid. Shrinkage occurs at a very high rate at the beginning of the drying process and then evolves at a constantly decreasing rate. In the restrained specimen, the concrete shrinkage induces in the steel ring a compressive stress that grows at a decreasing rate until cracking, at what time a sudden drop is recorded in the strain gages, and a visible crack has developed in the restrained ring specimens. The evolution of the average tensile stress that developed in the restrained concrete specimen (σ_{c_avg}), which is calculated based on the data from the four strain gages located on the inner face of the steel ring using Eq. (2), is shown in Fig. 4 (a).The time interval between initiation of drying and cracking in the ring is referred to as the *time-to-cracking*. The rate of tensile stress buildup and time-to-cracking can be used to assess the resistance of a concrete mixture to restrained shrinkage cracking (ASTM 2014). It should be mentioned that in general, specimens cast from the same batch (and stored in the same environmental conditions) do not necessarily crack at the same time due to intrinsic concrete variability (properties, characteristics). This phenomenon is quite usual in restrained ring tests (Ideker, Fu, and Deboodt 2013). Fig. 4 (b) presents the relationship between the time-to-cracking parameter and the corresponding stress rate found experimentally for the range of concrete mixtures investigated in this study. The stress rate was estimated for each individual concrete ring specimen analysed in this paper.



(a) Free drying-shrinkage versus drying time **(b) Steel strain versus drying time**

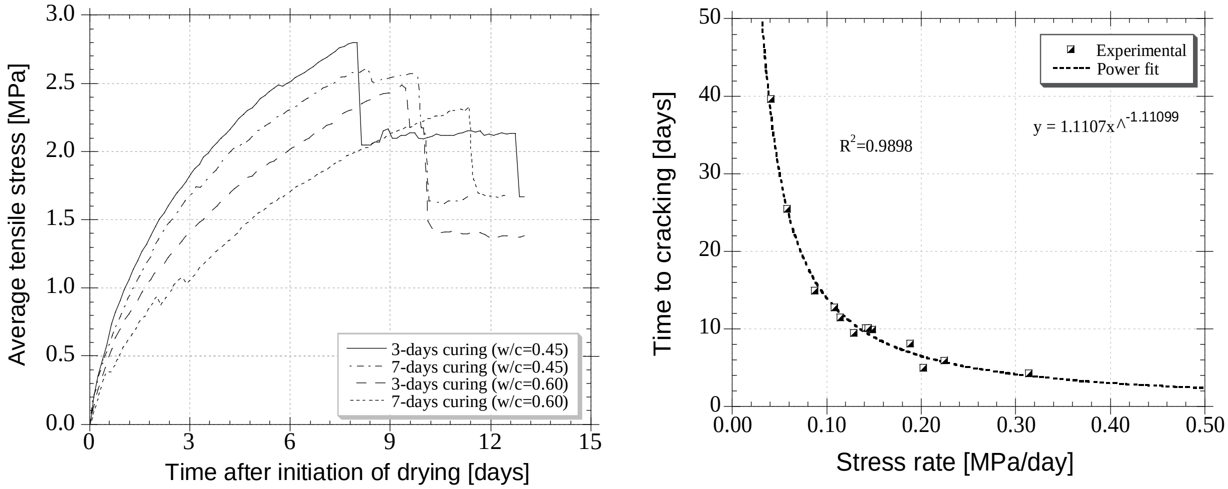
Fig. 3: Drying-shrinkage results of ring specimens

4 DISCUSSION OF RESULTS

4.1 Stress rate and shrinkage cracking of concrete

It can be observed from the experimental results that cracking occurs slightly earlier for the lower w/cm mixtures, as shown in Fig. 4 (a). This could be explained by the more significant contribution of autogenous shrinkage in these mixtures. Since autogenous shrinkage is higher when the w/cm is low, this increases the potential for early-age shrinkage cracking in low w/cm mixtures due to the resulting increase in stress rate. When concrete is drying, water evaporates and concrete will begin to shrink. In higher w/cm mixtures, drying is likely to take a longer time to reach a comparable magnitude, due to excess water available for evaporation in a coarser pore structure. This allows for some strength gain and relaxation due to creep, overall resulting in potentially extended time-to-cracking. Indeed, recent experimental evidence has shown that the potential for early-age cracking tends to increase with lower w/cm concretes (Meyer et al. 2006). In general, cracking in ring specimen depends on the tensile stress buildup rate. In fact, analysis of the time-to-cracking and the corresponding stress rate show that the higher the stress rate, the shorter the time it takes to crack simply due to inadequate strength developed.

Overall, the results indicate a strong relationship between the time-to-cracking and stress rate, with a statistical reliability (R^2) of 0.99 (Fig. 4 (b)). The results agree well with the findings from earlier investigations (Attiogbe, Weiss, and See 2004, Ideker, Fu, and Deboodt 2013), with the time-to-cracking increasing as the stress rate decreases. For example, 7-day cured specimens had slightly lower stress levels compared to 3-days cured specimen, hence cracked after a slightly longer drying period. In some cases, 7-day moist cured specimens survived up to almost 40 days, likely due to stress relaxation. This implies that prolonged moist curing has the potential of mitigating shrinkage cracking, since lowering the stress rate allows further strength development and increased creep relaxation. It is evident from the analysis that the *stress rate* provides a more fundamental way of evaluating the cracking potential of mixtures in the ring test experiment.



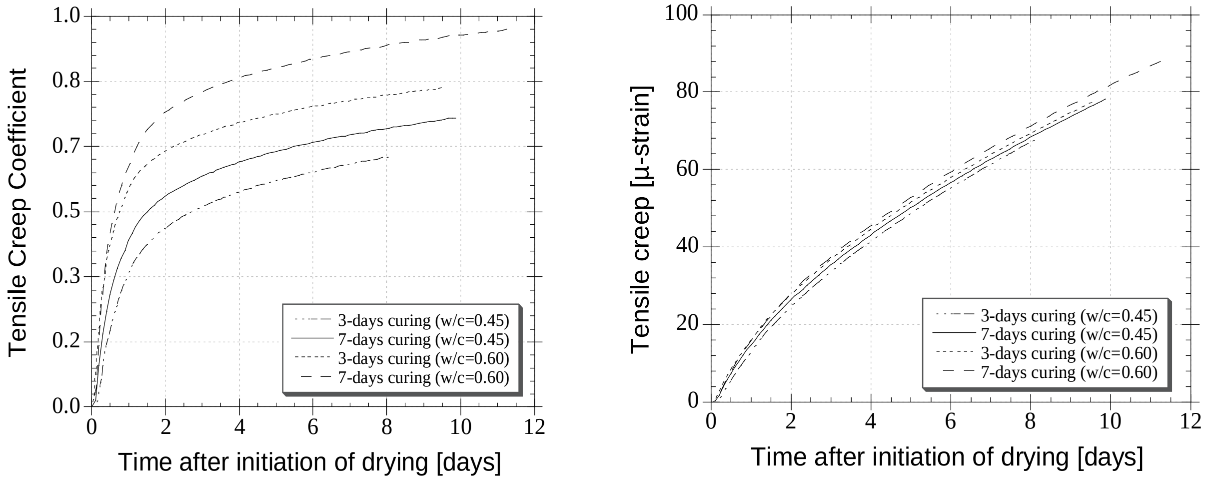
(a) Average tensile stress versus drying time

(b) Time-to-cracking versus stress rate

Fig. 4: Tensile stress development and stress rate in the restrained specimen

4.2 Creep behavior of concrete

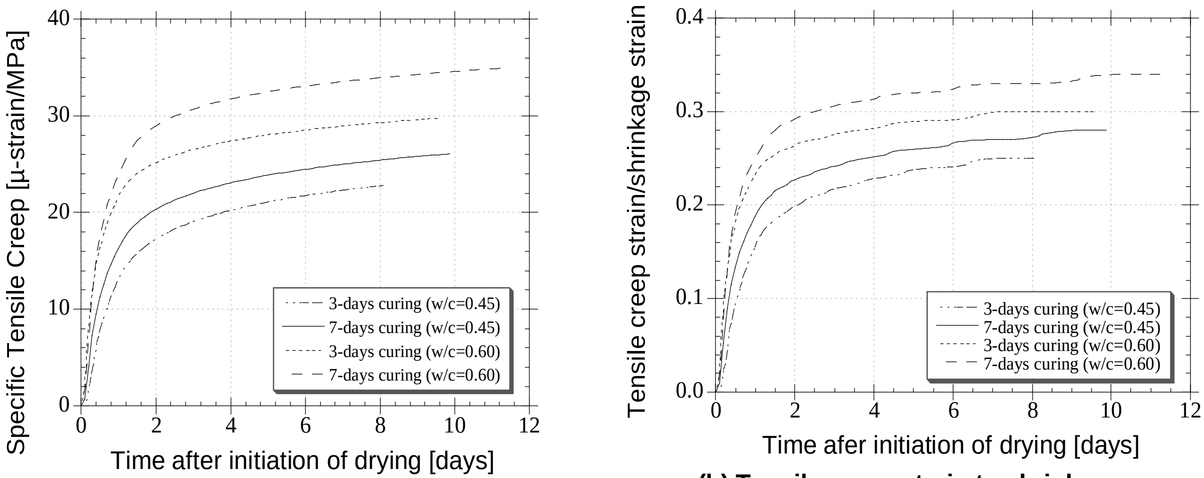
The creep parameters were calculated for the various concrete mixtures up to the age of cracking of the ring specimen. The experimental free shrinkage, steel ring strain and elastic modulus data were curve-fitted and exploited in the analysis, based on Eq. (4) to calculate creep coefficient. The free shrinkage and steel ring strains were fitted as functions of square root of time while the elastic modulus was fitted as functions of natural logarithm of time. Eq. (5) is then used to calculate the tensile creep strain. The calculated tensile creep coefficients and strains are presented in Fig. 5 (a) and (b), respectively. In general, the creep coefficient is found to increase with a corresponding increase in the concrete water content. At the time of cracking, the tensile creep coefficients calculated for the 0.45 w/cm mixture were 0.64 and 0.74 for the 3-day and 7-day moist curing durations respectively. For the 0.60 w/cm mixture, the tensile creep coefficients were 0.82 and 0.97 for 3-day and 7-day moist curing durations, respectively. The results indicate that specimens with higher tensile creep coefficients resisted longer to cracking. The estimated tensile creep strains developed at cracking for the 0.45 w/cm mixture represent approximately 20 % and 25 % of the drying shrinkage for 3-day and 7-day moist curing durations, respectively. For the 0.60 w/cm mixture,



(a) Tensile creep coefficient versus drying time

(b) Tensile creep strain versus drying time

Fig. 5: Calculation of tensile creep coefficients and strains from ring test analysis



(a) Specific tensile creep versus time drying time

(b) Tensile creep strain to shrinkage strain ratio versus drying time

Fig. 6: Calculation of specific tensile creep and tensile creep strain-to-shrinkage from ring test analysis

the generated tensile creep strains at cracking were about 22 % and 30 % of the drying shrinkage for 3-day and 7-day curing, respectively. These results suggest that tensile creep strain is a significant phenomenon in the outcome of restrained drying shrinkage and must be considered in the analysis and prediction of the risk of cracking. This was partially confirmed in the experiments of See et al. (See, Attiogbe, and Miltenberger 2003)

For the mixes analysed in this study the specific tensile creep (i.e. creep strain per unit stress) of the ring test specimens is calculated as a ratio between the tensile creep strain (see Eq. (5)) and the average tensile stress (see Eq. (2)).The calculated specific tensile creep data is presented in Fig. 6 (a). Lower specific creep values were recorded for the lower w/cm mixture in comparison with those obtained for the higher w/cm mixture. Similarly, the specific creep values recorded for the specimen moist cured for 3 days were lower than in the case where moist curing was carried out for 7 days. The tensile creep - shrinkage ratio (i.e. the ratio between the tensile creep strain (see Eq. (5)) and the free shrinkage strain) of the ring test specimens was also calculated. The calculated ratios of tensile creep to free shrinkage strains are presented in Fig. 6 (b). The results indicate ratios in the order of about approximately 0.25 and 0.28 at the time of cracking age for the 0.45 w/cm mixture and about 0.30 and 0.34 for the 0.60 w/cm mixture when moist cured for 3 days and 7 days, respectively. This implies that for the specimens and materials investigated, tensile creep relaxed can relax the shrinkage stress development by 25 % and 30 % when cured for 3 days and by 28 % and 34 % when cured for 7 days for 0.45 and 0.60 w/cm mixtures, respectively.

CONCLUSIONS

This research focused on using the combination of free and restrained shrinkage ring tests to evaluate the cracking sensitivity and creep properties of concrete. A simple procedure is outlined for estimating creep properties of the *thicker* AASHTO PP34 ring specimen using a free drying shrinkage ring and modulus of elasticity data. In addition, a data analysis procedure is proposed to evaluate the cracking potential of concrete using the stress rate of stress development in thick ring specimen. It was found that stress rate in the ring specimen can be a better way to evaluate the cracking potential of mixtures due to the material variability of concrete which influences the time-to-cracking. The results further show that moist curing can delay cracking of a concrete element under restrained shrinkage conditions. It should be mentioned that the study is still on going to quantify the influence of other important parameters on shrinkage cracking, such as the drying conditions, the surface-to-volume ratio, and the curing method.

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