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Quantifying Stress Development and Remaining Stress Capacity in Restrained, Internally Cured Mortars

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Concrete can develop tensile stress when it is restrained from shrinking freely. Standard tests, such as the restrained ring test (ASTM C1581), can be used to quantify how likely it is that a mixture will crack due to the stresses developed under constant temperature conditions. The standardized restrained ring test is a passive test where the residual stress that develops due to restraint can be quantified using strains measured on the inner steel ring. The residual stress can then be compared with the concrete's tensile strength to determine a mixture's propensity for cracking. A new dual-ring test method has been developed to characterize the early-age behavior of mixtures that expand and/or undergo a temperature change. A new testing approach uses this dual-ring test to quantify the remaining stress capacity (that is, the additional stress that can be applied before the concrete develops a through crack). The new testing procedure allows stress to develop under constant temperature conditions before rapidly reducing the temperature to induce cracking. To demonstrate this approach, a plain and three internally cured mortar mixtures were tested and the results of these tests are discussed.

Keywords: autogenous shrinkage; early age; internal curing; lightweight aggregate; mortar; residual stress; restrained shrinkage ring test; shrinkage; thermal cracking.

INTRODUCTION

Early-age cracking of concrete is a persistent problem for pavements and structures. Cracks can accelerate premature reinforcement corrosion and concrete deterioration,[1] resulting in higher maintenance costs and a reduced service life.[2] Although concretes with a lower water-cement ratio (*w/c*) offer higher strength and lower permeability, these mixtures may be particularly susceptible to early-age cracking. This early-age cracking may develop in concrete for a variety of reasons, with the restraint of the thermal and autogenous volume changes being significant contributors. Restraint of this volumetric change by surrounding elements generates stress inside the concrete that may lead to cracking.[3-5] Low *w/c* mixtures experience greater autogenous shrinkage, as well as external drying and thermal contraction.[6] Internal curing is a method in which an absorptive material is incorporated into the mixture that acts as an internal reservoir that will release water as the concrete demands. Internal curing can reduce or eliminate early-age autogenous shrinkage[7-10] and can also reduce the potential for early-age cracking due to plastic shrinkage[11] or drying shrinkage.[12]

The benefits of extending the service life of concrete structures by technologies such as internal curing have encouraged the development of tests that can be used to quantify improvements in the performance of concrete mixtures. One such test is the restrained ring test,[13-17] which has been used for nearly a century, but only recently (2004) has become standardized as ASTM C1581-04.[18] The restrained ring test is performed by casting an annulus of a cementitious mixture (paste, mortar, or concrete) around a steel ring. Residual tensile stress develops in the sample as it attempts to shrink but is restrained by the ring. A crack results if the stress that develops due to restraint (called "residual stress" by some) exceeds the developing tensile strength. The standard[18] suggests that the relative cracking potential of mixtures can be quantified by comparing the amount of time required to crack the samples. Shorter measured cracking times indicate a relatively higher cracking potential, whereas longer cracking times indicate a lower cracking potential. While ASTM C1581-04[18] describes a material behavior in terms of the age of cracking, the authors believe that describing the stress development, stress-to-strength ratio, or probability of cracking may be better indicators of cracking susceptibility.[19]

While the standard restrained ring test is a useful standardized test,[20] it is limited in at least three ways. First, it should be operated at a constant temperature because changing the temperature of a standard ring would significantly expand or shrink the restraining ring, thereby altering the degree of restraint and stress. This effect would make it difficult to isolate and study the behavior of the concrete under the changing temperature conditions that are commonly encountered in a field structure. The second limitation is that the standard restrained ring test is a passive test.[21,22] As a result, the test waits for the shrinkage of the specimen to generate enough stress to induce cracking. This provides useful time-to-cracking comparisons between multiple mixtures and can permit stress development to be calculated, but determining the probability of cracking[16] is more difficult.[23,24] Further, the passive behavior of the test may require considerable time to induce cracking. Third, the restrained ring test can only provide restraint against samples that shrink. Samples that exhibit net expansion typically come out of contact with the restraining ring and expand freely. This limitation becomes significant when studying expansive cements,[25] shrinkage-reducing admixtures,[26-28] and internal curing,[7,8,10,12,29] as these technologies often produce early-age expansion.

A dual-ring testing device[30] can be used to extend the applicability of the restrained ring test. The dual-ring device, as its name implies, incorporates a second restraining ring that is located on the outer face of the sample. This additional ring provides restraint against expansion and captures the restrained behavior of expansive samples. The dual ring used in this study can also be used to study the effects of

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restrained temperature change because its restraining rings are fabricated from a thermally stable alloy, Invar (that is, while the coefficient of thermal expansion of Invar is not

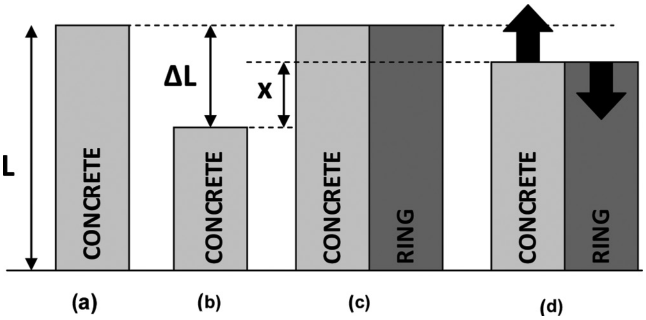

Fig. 1—Illustration of restraint: (a) initial length of unrestrained specimen; (b) length reduction of unrestrained specimen associated with shrinkage or temperature reduction; (c) conceptual illustration of initial length of concrete and restraining ring; and (d) resulting forces when ring restrains concrete movement, illustrating that ring also deforms.

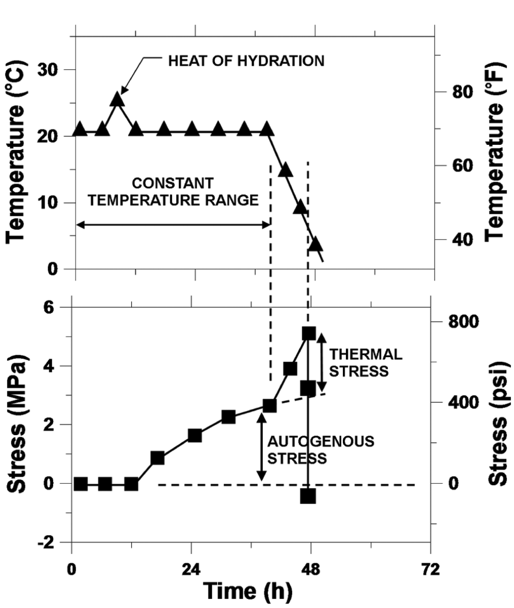

Fig. 2—Example of temperature reduction and resulting stress development.

zero, it is sufficiently low such that the volume change of the restraint does not impact the overall test results[31]).

This paper will focus on the development of a temperature-reduction technique using the dual-ring device made of Invar that quantifies the remaining stress that can be tolerated by a mixture before cracking would occur. This technique is significant because it provides a more complete understanding of the cracking propensity of a mixture compared with the standardized restrained ring test. This technique allows times to be identified when the concrete may be particularly sensitive to cracking. Further, the effects of sustained stress on cracking strength can be quantified. This paper shows the results of the temperature-drop technique used on one plain mortar mixture and three internally cured mortar mixtures.

RESEARCH SIGNIFICANCE

Concrete in the field inevitably experiences early-age autogenous, drying, and thermal volume changes that may induce cracking. The dual-ring test can assess the stress that develops when this volume change is restrained. By quantifying the temperature change required to cause cracking, the stress that would need to be applied to cause cracking (referred to as the remaining stress capacity) of a mixture can be determined. This is important when evaluating shrinkage-reducing technologies such as internal curing because it provides a quantitative measure of performance. This work quantifies potential benefits of internal curing, which may make concrete more robust in terms of reduced cracking potential at early ages.

Conceptual approach

Figure 1 illustrates the concept of restrained shrinkage. Figure 1(a) shows a sample of concrete with an original length L. If this sample were to shrink freely (that is, undergoing autogenous, drying, or thermal shrinkage), it would become smaller by an amount ΔL, as shown in Fig. 1(b). If this sample is restrained, the original concrete sample and restraining element (that is, the ring herein) are shown in Fig. 1(c). As the concrete tries to shrink (by an amount ΔL), its shrinkage is resisted by the restraining ring. This causes a deformation of the ring and reduces the concrete's deformation. The resulting residual stress $\sigma_{Residual}$ that develops in the concrete can be calculated by

$$\sigma_{Restraint} = -\left(\varepsilon_{FS} - \varepsilon_{RM}\right) E\left(t\right)_{Sample} \quad (1)$$

where ε_{FS} is the free shrinkage strain of the cementitious sample; ε_{RM} is the strain that develops in the restraining material; and $E(t)_{Sample}$ is the age-dependent modulus of the concrete. A negative value for strain indicates shrinkage and a positive value for stress indicates tension.

If the sample and restraining ring in Fig. 1(d) were further subjected to a temperature reduction, the sample would want to shrink further by an amount ΔL_T, causing the residual stress to increase and the ring to compress even further.

This approach can be applied to the dual-ring test. Initially, the temperature of the sample and ring is held constant and the strain that develops in the system due to autogenous shrinkage is measured. Then, the temperature of the dual ring is lowered (as shown in Fig. 2) to generate additional stress. The temperature-reduction (that is, temperature-drop) approach can be used on successive specimens of the same mixture design, causing cracking to occur at different ages. This results in a failure envelope. The stress that develops due to the reduction in temperature can be thought of as the difference between the stress that develops due to the restraint of autogenous shrinkage and the stress that is required to cause cracking (the remaining stress capacity). This remaining stress capacity can be computed at each age. Conceptually, this approach could also be used with a single Invar restraining ring when the cementitious materials do not expand and when only a temperature reduction is considered; however, this was not done in this study.

Figure 2 illustrates how temperature reduction of the dual-ring specimen may be used to induce cracking. In this example, the temperature control system was operated at a constant temperature until 39 hours, when the temperature was reduced at a constant rate until failure. Tensile residual stress in the specimen increases as the temperature decreases. Cracking is observed at 48 hours, as indicated by the sudden drop in residual stress. The magnitude of the temperature reduction required to induce cracking was 14.6°C (26.3°F). The stress (remaining stress capacity) may be calculated by subtracting the stress while operating at a constant temperature σ_S (called the "residual stress" by some) from the cracking stress σ_C. In this example, the stress that needed to be applied to cause failure was 3.1 MPa (450 psi). While the autogenous shrinkage does not stop during this time period, it shows dramatically due to the reduction in temperature-slowing hydration rates.

EXPERIMENTAL PROGRAM

Dual-ring device details

The dual-ring device consists of two instrumented concentric restraining rings that operate in an insulated chamber, as shown in Fig. 3. The specimen is cast between the inner and outer rings. After casting, a copper tube coil from the temperature control system is loosely placed on top of the rings and then the insulated chamber is closed. The temperature control system consists of a programmable 28 L (7.4 gal.) water-bath system that pumps an ethylene glycol-water mixture at 24 L/min (6.4 gal./min) through the copper coil loop inside the insulated chamber. Strain measurements are automatically recorded on the rings at 5-minute intervals. The data acquisition system is calibrated to negate the effects of temperature changes on the gauges.[30]

The restraining rings are operated inside an insulated chamber to improve temperature control. A minimum of 50 mm (2 in.) thick microporous insulation with a thermal conductivity of 0.019 W/m·K at 20°C (0.132 BTU/h·ft·°F at 68°F) (approximately half that of conventional glass-fiber insulation) surrounds the rings. The top portion of insulation is removable to provide access to the interior of the chamber.

The residual stress within the cementitious specimen is determined by using the strains measured with the dual ring and then applying basic principles of strain compatibility and force equilibrium.[14,32-34] Both rings were instrumented with four opposing CEA-00 series strain gauges[35] mounted at midheight. Figure 4 illustrates the inner and outer ring gauge locations, as indicated by the terms ε_{IN} and ε_{OUT}, respectively. The strains measured on the inner ring ε_{IN} and outer ring ε_{OUT} are reported as the average output of the four gauges on each ring. Converting these ring strains to specimen stress is dependent on the rings' geometry.

Figure 4 also presents the ring geometry, where R_{OC} and R_{IC} are the outer- and inner-face radii of the mortar specimen,

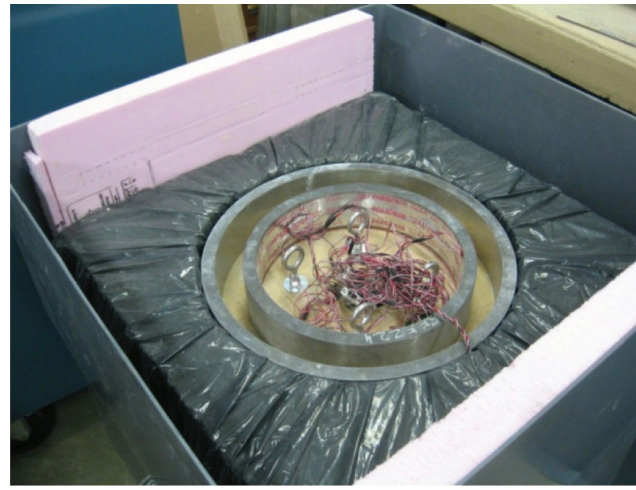

Fig. 3—Dual ring (top insulation removed).

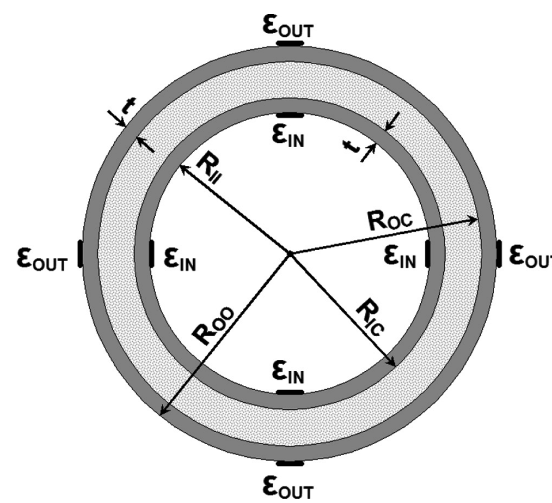

Fig. 4—Geometry of dual-ring test.

respectively; R_{OO} is the outer face of the outer restraining ring radius; R_{II} is the inner face of the inner restraining ring radius; and t is the thickness of each restraining ring. The dimensions are as follows: R_{OC} = 203 mm ± 3 mm (8.0 in. ± 0.12 in.), R_{IC} = 165 mm ± 3 mm (6.5 in. ± 0.12 in.), R_{OO} = 222 mm ± 3 mm (8.75 in. ± 0.12 in.), R_{II} = 146 mm ± 3 mm (5.75 in. ± 0.12 in.), t = 19 mm ± 3 mm (0.75 in. ± 0.12 in.), and the system is 76.2 mm ± 3 mm (3 in. ± 0.12 in.) tall. This geometry produces a degree of restraint of 72%, which is equivalent to that of the ASTM C1581-04 standard test[18] for a concrete with an elastic modulus of 32 GPa (4645 ksi).

The strains measured on the restraining rings can be used to calculate the circumferential residual stress in the sample at R_{IC}, $\sigma_\theta(R_{IC})$ by Eq. (2)[32]

$$\sigma_\theta\left(R_{IC}\right) = -\varepsilon_{in} E_{Invar}\left[\frac{R_{IC}^2 - R_{II}^2}{2R_{IC}^2}\right]\left[\frac{R_{OC}^2 + R_{IC}^2}{R_{OC}^2 - R_{IC}^2}\right] - \varepsilon_{out} E_{Invar}\left[\frac{R_{OO}^2 - R_{OC}^2}{2R_{OC}^2}\right]\left[\frac{2R_{OC}^2}{R_{OC}^2 - R_{IC}^2}\right] \quad (2)$$

where E_{Invar} is the elastic modulus of Invar, which is taken to be 141 GPa (20,450 ksi).[36] Inserting the dimensions used in this study results in a simplified expression for the circumfer-

Table 1—Saturated surface-dry (SSD) mixture proportions

	M-0 plain mortar	M-11	M-24	M-SAP
Material	Amount, kg/m^3 (lb/yd^3)	Amount, kg/m^3 (lb/yd^3)	Amount, kg/m^3 (lb/yd^3)	Amount, kg/m^3 (lb/yd^3)
Cement (Type I)	729 (1228)	728 (1228)	728 (1228)	707 (1192)
Water	218 (368)	218 (368)	218 (368)	212 (358)
Internal curing water*	0	19.46 (32.82)	38.82 (65.49)	12.44 (20.99)
Fine aggregate	1444 (2435)	1126 (1900)	810 (1366)	1440 (2429)
Fine lightweight aggregate	0	189 (318)	376 (635)	0
SAP	0	0	0	0.699 (2.55)
% of CS† replaced	0	50	100	33

*Water absorbed in SAP or LWA at set.
†CS is chemical shrinkage.

ential stress in the sample, as shown in Eq. (3). The residual stress can be determined using Eq. (3) in either MPa or psi, depending on the units of the elastic modulus.

$$\sigma_\theta\left(R_{IC}\right) = -0.53\varepsilon_{in}E_{Invar} - 0.58\varepsilon_{out}E_{Invar} \quad (3)$$

Mixture proportions

Four low *w/c* mortar mixtures were used in this study. Mixture proportions designated as M-0, M-11, M-24, and M-SAP are presented in Table 1.

Mixture M-0 was a plain mortar, while Mixtures M-11 and M-24 used internal curing using prewetted lightweight fine aggregate (fine LWA).[9,37] Mixture M-SAP was a mortar with a super-absorbent polymer (SAP) to provide internal curing water instead of prewetted lightweight aggregate.[8,38] All mixtures had a *w/c* of 0.30 and an aggregate volume of 55%. The internally cured Mixtures M-11 and M-24 had 11% and 23.7% of the total mixture volume comprised of fine LWA, respectively. It should be noted that the 23.7% fine LWA replacement value corresponds to the theoretical value of internal curing water that is required to compensate for the chemical shrinkage of this mixture.[39]

Materials

Type I ordinary portland cement was used (ASTM C150-05) with a Blaine fineness of 370 m^2/kg (1809 ft^2/lb) and an estimated Bogue phase composition of 56% C_3S, 16% C_2S, 12% C_3A, and 7% C_4AF by mass. Normalweight river sand was used with a fineness modulus of 2.71, an oven-dry specific gravity of 2.58, and a 24-hour absorption of 1.6%. The lightweight aggregate used in Mixtures M-11 and M-24 was a manufactured rotary kiln expanded shale. The lightweight aggregate had a fineness modulus of 4.3, an oven-dry specific gravity of 1.56, and a 24-hour absorption value of 10.5% by mass. A high-range water-reducing admixture (HRWRA) was added at a dosage of 1 g (0.04 oz) mass per 100 g (0.22 lb) of cement. Mixture water consisted of tap water conditioned to 23°C ± 1°C (73.4°F ± 1.8°F). The SAP was a powder-like substance with a specific gravity of 1.4 and an absorption of 18% by mass.

Mixing procedure

Aggregate for each mixture was batched in the oven-dry state. Fine LWA was prewetted for 24 hours ± 0.5 hours in the mixture water (including the water for prewetting the lightweight aggregate) while sealed in a container to prevent evaporation loss. Mixing was performed in accordance with ASTM C192-06.[40] First, the dry, fine, normalweight aggregate and the prewetted fine LWA were loaded into the "buttered" mixer. Where applicable, the mixing water was decanted from the fine LWA. The mixer was started and 50% of the remaining mixture water was added. The cement and remaining mixture water containing the HRWRA were then added. Dry SAP for Mixture M-SAP was added at this point. The mortar was mixed for 3 minutes, rested for 3 minutes while the sides of the mixer were scraped, and then mixed for a final 2 minutes.

Dual-ring testing protocol

The restraining rings were prepared by coating the surfaces that would make contact with the sample with form release and a layer of acetate sheet to minimize friction on the sample. The fresh mortar was then cast between the two rings in two layers. A handheld vibrator was used to consolidate each layer. The top of the sample was struck level with the top of the rings and then capped with a 3 mm (0.125 in.) thick sheet metal plate and temperature control coil. The top layers of insulation were then installed. Strain gauge data were automatically recorded at 5-minute intervals beginning immediately after the sample was sealed in the insulation chamber, which typically occurred approximately 30 minutes after water contacted the cement.

The temperature control system was operated at 23°C ± 0.2°C (73.4°F ± 0.4°F) for a minimum of 8 hours prior to casting to bring the rings and chamber to a consistent temperature. After casting, the system operated at 23°C ± 0.2°C (73.4°F ± 0.4°F) until the test ended due to the sample cracking or when a temperature reduction was desired. The temperature was reduced at a rate of 1°C/h (1.8°F/h) to a minimum temperature of –5°C ± 0.2°C (23°F ± 0.4°F). This rate was selected, as it provided a reasonably fast rate to minimize viscoelastic effects; however, the rate was slow enough that it permitted minimal thermal gradients.[41]

Split tensile, compressive strength, and elastic modulus tests

A series of 100 x 200 mm (3.9 x 7.8 in.) cylinders were cast for each of the three mortar mixtures to determine their early-age split tensile strength (ASTM C496/C496M-04), compressive strength (ASTM C39), and elastic modulus (ASTM C469-02e1).[42] The cylinders were cast according to ASTM C192-07.[43] Testing was performed at 1, 3, 5, and 7 days after mixing, using three samples at each age.

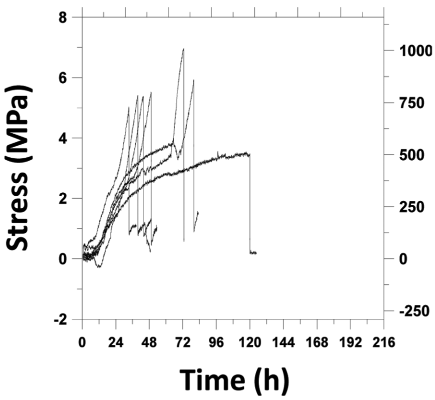

Fig. 5—Mixture M-0 stress development.

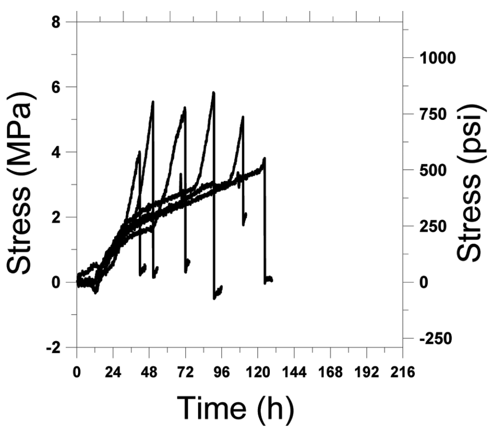

Fig. 6—Mixture M-11 stress development.

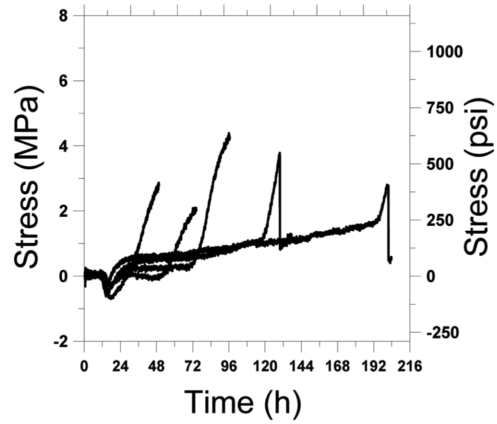

Fig. 7—Mixture M-24 stress development.

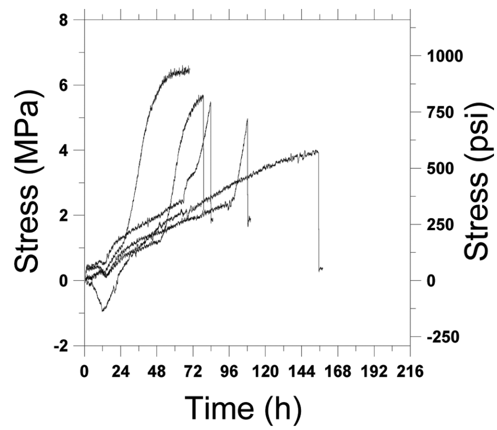

Fig. 8—Mixture M-SAP stress development.

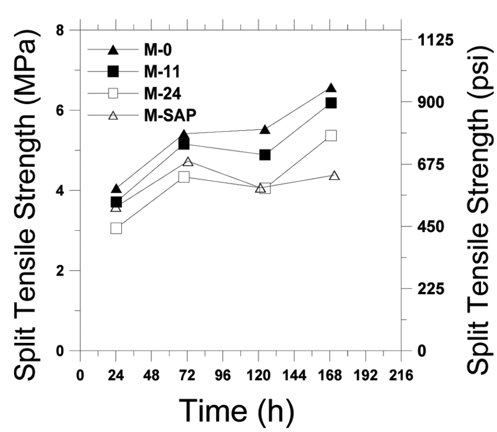

Fig. 9—Split tensile strength f_t'.

EXPERIMENTAL RESULTS

The temperature-drop approach was applied to the four mixture designs investigated in this study. Seven M-0 specimens were tested and their residual stress histories are presented in Fig. 5. The temperature was reduced to produce cracking at 33, 38, 43, 48, 72, and 79 hours. One M-0 specimen was allowed to crack without reducing temperature, which occurred at 120 hours.

Six M-11 specimens were tested and their stress histories are presented in Fig. 6. All M-11 specimens underwent temperature reductions and were forced to crack at 42, 50, 72, 89, 108, and 120 hours.

Five M-24 specimens were tested and their residual stress histories are presented in Fig. 7. All M-24 specimens underwent temperature reductions but cracking was only produced at 127 and 197 hours. The three earliest-aged specimens reached the lower temperature limit of the concrete (approximately –5°C [+23°F]) before freezing would occur, which could result in a complex volume change caused by ice formation. This was also approximately the lower end of the temperature that could be achieved with the water-bath system used; however, a larger bath or solid-state cooling can also be used.

Five M-SAP specimens were tested and their residual stress histories are presented in Fig. 8. Four M-SAP specimens underwent temperature reductions and cracking was produced at 77, 84, and 107 hours. One mixture underwent temperature reduction beginning at 24 hours but did not crack before reaching the previously described limit of the temperature control system. One mixture was allowed to crack without reducing temperature, which occurred at 155 hours.

The split tensile strength, modulus of elasticity, and compressive strength results for the four mixtures are presented in Fig. 9, 10, and 11, respectively. The average standard deviations for the values in these three plots are 0.47 MPa (69 psi), 1.5 GPa (218 ksi), and 1.01 MPa (153 psi), respectively. The autogenous shrinkage of the mixtures as evaluated using ASTM C1698-09 is shown in Fig. 12. It can be noticed that the internally cured mixtures show a slight expansion at early ages, which is presumably

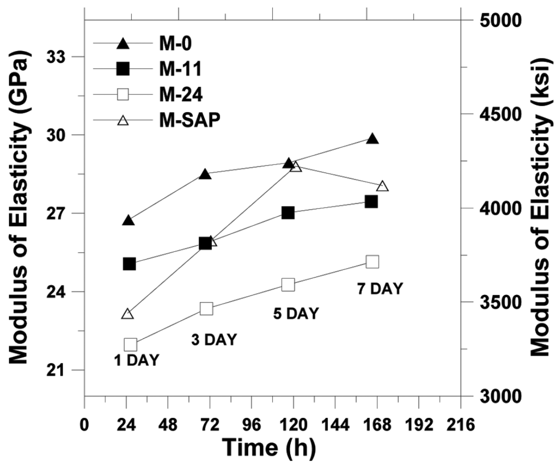

Fig. 10—Modulus of elasticity E.

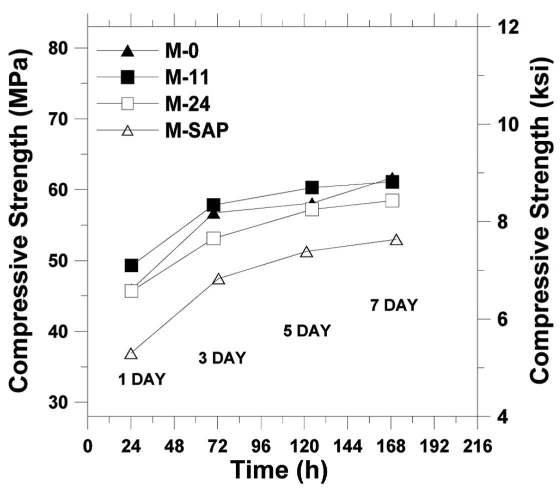

Fig. 11—Compressive strength f'_c.

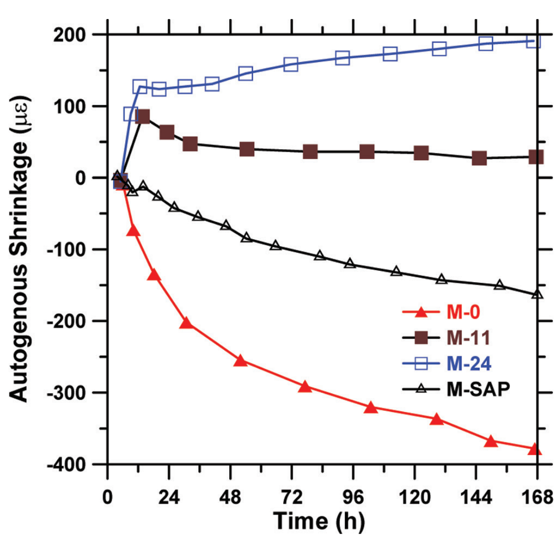

Fig. 12—Autogenous shrinkage.

due to the same factors responsible for swelling in conventional mixtures upon curing in water.

DISCUSSION

Internal curing reduces or eliminates the autogenous shrinkage from self-desiccation by supplying water from the pores of the fine LWA or the SAP particles. By reducing the autogenous shrinkage, the tensile stress that is induced when concrete is restrained can also be reduced or eliminated. Previous work[8,12,29] has shown that both the volume and dispersion of the internal curing water affects its ability to mitigate shrinkage. Because Mixture M-24 contains more curing water that is also distributed more evenly, it was expected to shrink the least and develop the least amount of residual stress out of all the mixtures.

Figures 9 and 11 show the tensile and compressive strength reductions, respectively. It should be noted that adding internal curing agents can lower the tensile strength, compressive strength, and elastic modulus. It is interesting to note that the use of SAP reduces the elastic modulus less than the use of LWA in sufficiently hardened systems. This may be explained by the fact that in this study (although it is not always done this way), the SAP is considered part of the paste and a 55% by volume of normalweight aggregate is maintained in the mortar, while the LWA system has a portion of the normalweight aggregate replaced with the more compliant LWA particles. It can be noticed that the compressive strength is reduced by the addition of SAP. Similar to the reduction typically observed with an increase in air content, this may be due to the dependence of strength on the size or volume of voids that appear in the paste fraction. The tensile strength appears to be most influenced by the volume of LWA. The fracture of LWA particles plays an important role in the overall fracture behavior of the mortar. This points to a subtle yet important distinction between the behaviors that can be expected from internal curing agents that replace a fraction of the aggregates (LWA) and internal curing agents that replace a portion of the paste volume fraction (SAP). This is an area where further research is needed.

The temperature-reduction approach can be used with the dual ring to show the potential benefits of internally cured mixtures. The benefits of reducing autogenous shrinkage through internal curing can be observed by comparing the residual stress histories in Fig. 5 through 8. Prior to any temperature reduction, the internally cured Mixtures M-11, M-24, and M-SAP develop less residual stress than the plain M-0 mixture. This can be attributed to the reduction in autogenous shrinkage, as shown in Fig. 12,[44] and the reduction in the elastic modulus of the concrete. Mixture M-24 has the highest level of internal curing and develops the least amount of residual stress due to autogenous shrinkage.

The temperature reduction that is required to induce cracking provides an indication of the thermal stress that would be required to produce cracking. Figure 13 summarizes the temperature reduction that was required to cause cracking in each mixture from the temperature-drop approach. The allowable thermal change is not constant over time and changes as the mixtures age. Every mixture could sustain greater amounts of thermal reduction prior to 96 hours. After 96 hours, the mixtures' resistance to thermal reduction decreased. This indicates that internal curing mixtures provided substantial reductions in early-age autogenous shrinkage, which can be quite useful in reducing the risk of cracking in early-age concrete when the concrete has a relatively low strength. Mixture M-24 (which has the greatest volume of internal curing water) required the greatest temperature change to induce cracking, as it was between two and two-and-a-half times greater than the plain M-0 mixture and, in many cases, cracking did not occur before the sample would have begun to freeze. This behavior indicates that the M-24 mixture design can sustain larger thermal swings during the first days after casting than any of the other mixtures. This can be important, as it is during these early ages that concrete in the field has a relatively low strength and is most susceptible to thermal changes induced by the heat of hydration or thermal gradients induced by formwork removal.

The total stress that was measured at the time of cracking for the four mixtures (as assessed using both the stress due to autogenous shrinkage and the temperature reduction) is presented in Fig. 14.

In comparison, the split tensile strengths are presented in Fig. 9. The observation that split tensile strength increases over time (which occurs in the unstressed state) can be contrasted with the stress that was required to cause cracking, as shown in Fig. 14, to provide a strong indication that microcracking may have occurred in the dual-ring samples as a result of their sustained state of residual stress. Because split tensile samples are cured in an unstressed state, they are not subjected to this damage. This discrepancy indicates that the split tensile cracking stresses of unstressed laboratory specimens may not provide a clear representation of the field performance of concrete, which is typically in a stressed state. This confirms earlier studies that suggest that cracking can occur at stresses that reach only 70% of the tensile strength, potentially due to damage development, creep rupture, moisture diffusion, or statistical variability.[45,46]

The cracking stress histories also show the effect of internal curing. Mixture M-24 (which had the largest amount of internal curing) cracked at later ages than M-0, M-11, and M-SAP, but it cracked at lower stresses. This reduced stress capacity may be attributed to either the lower split tensile cracking stresses, the longer duration that the specimen was stressed, or a combination of these two effects under sustained loading. This behavior indicates that the performance benefits of internal curing are more pronounced at earlier ages.

The temperature-reduction approach can also be used to determine the remaining stress capacity of a mixture, which represents the difference between the cracking capacity (total stress required to cause cracking) and the stress due to autogenous shrinkage (residual stress). Figure 15 presents the remaining stress capacity for the four mixtures. Mixture M-24 produces greater remaining stress capacity at later ages, indicating a greater ability to prevent cracking. Mixtures M-11 and M-SAP show an improvement over the plain Mixture M-0 at intermediate ages.

It is important to remember that while the temperature reduction can be used to cause cracking for several mixtures, a temperature reduction does not cause cracking in all mixtures. For example, at early ages, the M-24 and M-SAP mixtures do not crack before the temperature is reduced to approximately –5°C (+23°F), at which point the concrete begins to freeze. As such, these points are identified with arrows in Fig. 13 and 15.

CONCLUSIONS

This paper has described a new temperature-controlled dual-ring test specimen. The dual-ring test specimen has the ability to consider the restraint of a samples' expansion and the influence of a temperature change on the stress that develops in a concrete mixture. As such, the dual-ring device permits a temperature reduction to be used to assess the remaining stress capacity of a mixture as a method to better assess the resistance of a mixture to early-age cracking. An example is shown in this paper where the dual ring is used to quantify how internal curing may reduce the stress that develops due to the restraint of autogenous shrinkage and to compute the remaining stress capacity of the mixture. This test method can quantify the ability of a concrete to sustain temperature swings. The remaining stress capacity provides a clear indication of how much additional stress could be applied to the specimen either by the restraint of thermal movements or the application of mechanical loads. Specifically, in comparing a conventional (plain) mortar

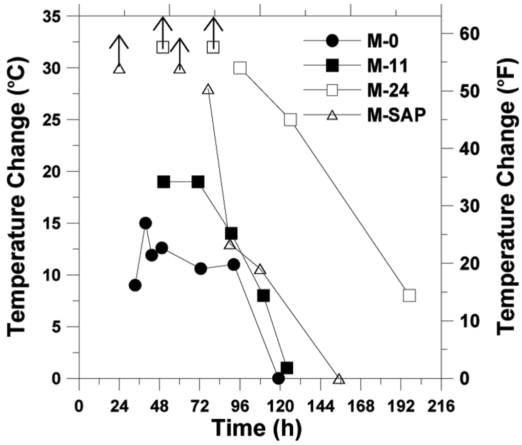

Fig. 13—Cracking temperature change: data points with arrows indicate that temperature reduction could not induce cracking of specimen.

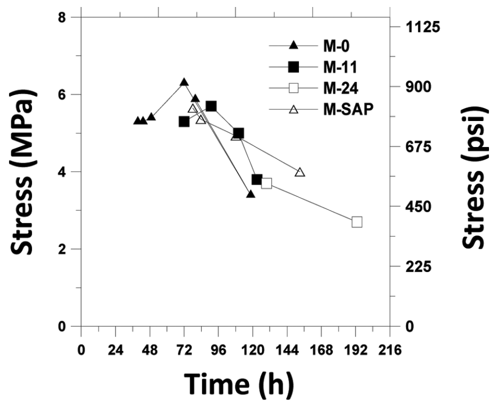

Fig. 14—Total stress at cracking.

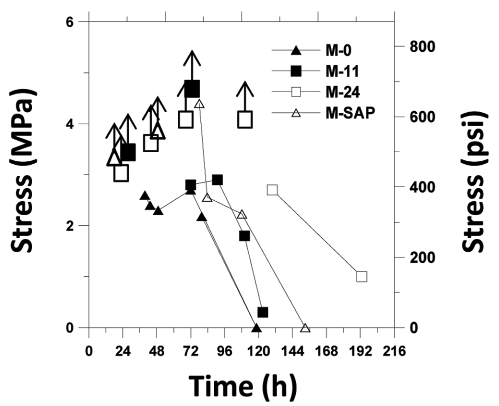

Fig. 15—Remaining stress capacity (data points with arrows indicate that temperature reduction could not induce cracking of specimen).

with an internally cured mortar (where internal curing water was supplied to replace 100% of its chemical shrinkage), it can be noticed that during the first 4 days, the plain system could undergo a temperature change of approximately 12°C (22°F), while the internally cured concrete could withstand a temperature change of over 30°C (54°F) before cracking. This shows that the internally cured system can experience a temperature swing that is at least 19°C (34°F) larger than that of an equivalent mixture without internal curing, quantitatively demonstrating that internal curing can improve concrete's robustness to resist early-age cracking.

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DISCLAIMER

Certain commercial equipment, instruments, or materials are identified in this report to foster understanding. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology or Purdue University, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose. The contents of this paper reflect the views of the authors and the accuracy of the data presented herein and do not necessarily reflect the official views or policies of the Indiana Department of Transportation, nor do the contents constitute a standard, specification, or regulation.

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