Influence of Exposure Conditions on the Efficacy of Internal Curing

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Abstract
Internal curing uses pre-wetted fine lightweight aggregate (LWA) to supply cementitious systems with water. This increases the hydration of cement and reduces the influence of self-desiccation resulting in concrete with increased compressive strength, reduced permeability, and reduced shrinkage potential (Shah et al., 1998; Henkensiefken et al., 2009a; Henkensiefken et al., 2009b). While these mixtures have shown great potential, there has been considerable debate on how internally cured samples should be conditioned during laboratory testing.

This paper explores the influence of sample storage on the properties of mixtures prepared with and without internal curing. Samples were prepared and cured in different exposure conditions including environments in which 1) moisture is supplied either via soaking or misting, 2) moisture is neutral, and 3) moisture loss is allowed. Experimental results show that when adequate external curing water is supplied, only limited benefits are seen from internal curing. The benefits of internal curing are more evident in systems that do not receive additional external curing water (sealed) and even more so when systems are exposed to external drying. Conditions where inadequate external curing water is supplied may be more representative of what would be experienced in the field.

Introduction

To counteract the effects of self-desiccation and to reduce the risk of early-age cracking in low water-to-cement ratio (*w/c*) concretes, the concept of internal curing (IC) has been developed (Shah et al., 1998). To use IC, a portion of the normal weight fine aggregate is replaced with pre-wetted lightweight aggregate (LWA). Internal curing supplies additional moisture within the concrete that allows enhanced hydration of cement and often produces increased compressive strength and reduced permeability(Henkensiefken et al., 2009b; Henkensiefken, 2008).

While IC has shown benefits(Henkensiefken et al., 2009b; Henkensiefken, 2008), there is debate on how these samples should be handled, stored, and cured after casting. In laboratory testing concrete cylinders are frequently water cured from the time of demolding until the time of testing. While this enables the cylinders to absorb additional water to enhance their strength development, it is unclear whether this is a fair or accurate representation of the behavior that can be expected in the field. Campbell and Tobin reported that for "nearly 500 samples of natural and lightweight concrete under simulated job conditions … all cores at comparable ages tested lower than cylinders." (Campbell & Tobin, 1967). This suggests that field curing does not provide the same level of water to the samples as laboratory curing. This is especially true for high strength concrete. Aitcin reported that high strength concrete in a sealed system was not as strong as the same concrete cured under water (Aïtcin et al., 1994). The difference between sealed and water cured concrete increased as the strength increased (and *w/c* decreased), presumably due to both self-desiccation and differences in achieved degrees of hydration. This paper explores the influence of different sample exposure conditions on the mechanical properties of internally cured mixtures. This study considers four possible moisture conditions: (1) additional curing water through submerging in saturated lime water, (2) additional curing water through misting, (3) sealed samples for moisture neutral conditions, and (4) partial loss of internal moisture through drying.

Research Program Overview

This testing program was developed to examine the influence of sample storage and curing conditions on the mechanical properties of internally cured cementitious mixtures. Conventional mortars and internally-cured mortars were prepared with two *w/c* (*w/c* = 0.30and *w/c* = 0.50). After being cured in four conditions (saturated lime water, moist curing, sealed, and drying), the samples were tested at 7 d, 28 d, and 91 d for compressive strength and elastic modulus. Samples were also tested at 7 d and 28 d for splitting tensile strength and internal relative humidity. A complete overview of the testing program can be found in Table 1.

Table 1- Testing Program Overview

Test Description	Test Method	Testing Ages
Internal Relative Humidity	i-button® RH sensors*	7 d, 28 d
Compressive Strength	ASTM C39	7 d, 28 d, 91 d
Spilt Tensile Strength	ASTM C496	7 d, 28 d
Elastic Modulus	ASTM C469	7 d, 28 d, 91 d

*Produced by Maxim[1]

Materials

Type I ordinary portland cement (ASTM C150)with a Blaine fineness of 476 m^2/kg, a specific gravity of 3.15, and an estimated Bogue composition of 52 % C_3S, 18 % C_2S, 8 % C_3A, and 9 % C_4AF by mass, with a Na_2O mass equivalent of 0.5 was used in the study. Both a normal weight and lightweight fine aggregate were used in this study. The normal weight sand used was natural river sand with a fineness modulus of 2.71, an apparent specific gravity of 2.58, and a water absorption of 1.8 %. The lightweight fine aggregate (LWA) was a rotary kiln expanded shale with a fineness modulus of 3.94 and an apparent specific gravity of 1.45. The LWA had a 24 h water absorption of 17.4 % by mass as determined by the paper towel test (Castro et al., 2010). The LWA releases 91.9 % of the absorbed moisture at a RH of 93 % (Castro et al., 2010). Mixture proportions were adjusted for aggregate moisture. A polycarboxylate-based high-range water-reducing admixture (HRWRA) was used at a rate of 0.8 g per 100 g of cement in all mixtures with *w/c* = 0.30.

Mixture Proportioning

Four mortar mixtures were prepared for this study. Two of the mixtures represent controls of conventional mortars with a *w/c* of 0.30 and 0.50. The other two mixtures were internally cured by replacing a portion of the normal weight fine aggregate with a pre-wetted lightweight fine aggregate. The volume of LWA used in these mixtures provided internal curing water to compensate for chemical shrinkage as computed using the procedures proposed by Bentz et al., (2005) and a chemical shrinkage of 6.4 ml per gram of cement. The mixture proportions, shown in Table 2 (in an oven dry condition), are designed to have equivalent paste volumes of 45 % (aggregate volume of 55 %, neglecting any entrapped air content).Each mixture is named based on its water cement ratio (30 = *w/c* 0.30 and 50= *w/c* 0.50) and whether it is a plain control (P) or internally cured (IC) mixture. The higher amount of internal curing water in the 0.30 mixture is

[1]Certain commercial equipment, instruments, or materials are identified in this paper in order to foster understanding. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology nor Purdue University, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

due to the fact that that mixture contains more cement since the paste volume was maintained constant.

Table 2- Mixture Proportions

Material	30-P	30-IC	50-P	50-IC
Cement (kg/m^3)	728	728	550	550
Water (kg/m^3)	218	218	275	275
Additional IC Water (kg/m^3)	0	46	0	41
Fine Agg. (kg/m^3), SSD	1444	1039	1444	1061
LWA (kg/m^3), Oven Dry	0	216	0	196
HRWRA (by weight of cement)	0.8 %	0.8 %	0 %	0 %
Paste Volume Fraction	45 %	45 %	45 %	45 %
NWA Volume Fraction	55 %	39.5 %	55 %	38 %
LWA Volume Fraction	0 %	15.5 %	0 %	14 %
FA Replacement (LWA/total agg)	0 %	28 %	0 %	25 %

Sample Preparation and Curing Conditions

The mortars in this study were prepared in accordance with ASTM C192-06. Prior to mixing, all aggregates were oven dried and allowed to cool for 24 h. The LWA was pre-wetted by soaking in water (mixing and IC water) for 24 h ± 1 h. After this period of soaking, the excess water was decanted from the aggregate and then used as the mixing water. The water, aggregate and cement were conditioned at room temperature (23 °C ± 1 °C) for a minimum of 24 h.

For each mixture, a total of 36 cylinders having dimensions 100 mm x 200 mm (diameter x height) and 32 cylinders having dimensions 100 mm x 25 mm were cast. Samples were demolded 24 h after casting and moved to their respective curing conditions. The larger cylinders (200 mm in height) were used for measuring elastic modulus and compressive strength. The smaller cylinders (25 mm in height) were used to measure internal relative humidity and split tensile strength.

Four curing conditions: 1) water curing, 2) moist curing, 3) sealed curing, and 4) drying were used for this study. Water-cured samples were submerged in saturated lime water. Moist cured samples were placed under misters in a moist room. Both water cured and moist cured represent moisture positive curing conditions (Figure 1). Sealed cured specimens were sealed in double plastic bags representing moisture neutral curing (Figure 1). Samples allowed to dry were placed in a chamber with 50 % ± 2 % RH representing moisture negative curing (Figure 1). All samples were held at 23 °C ± 1 °C.

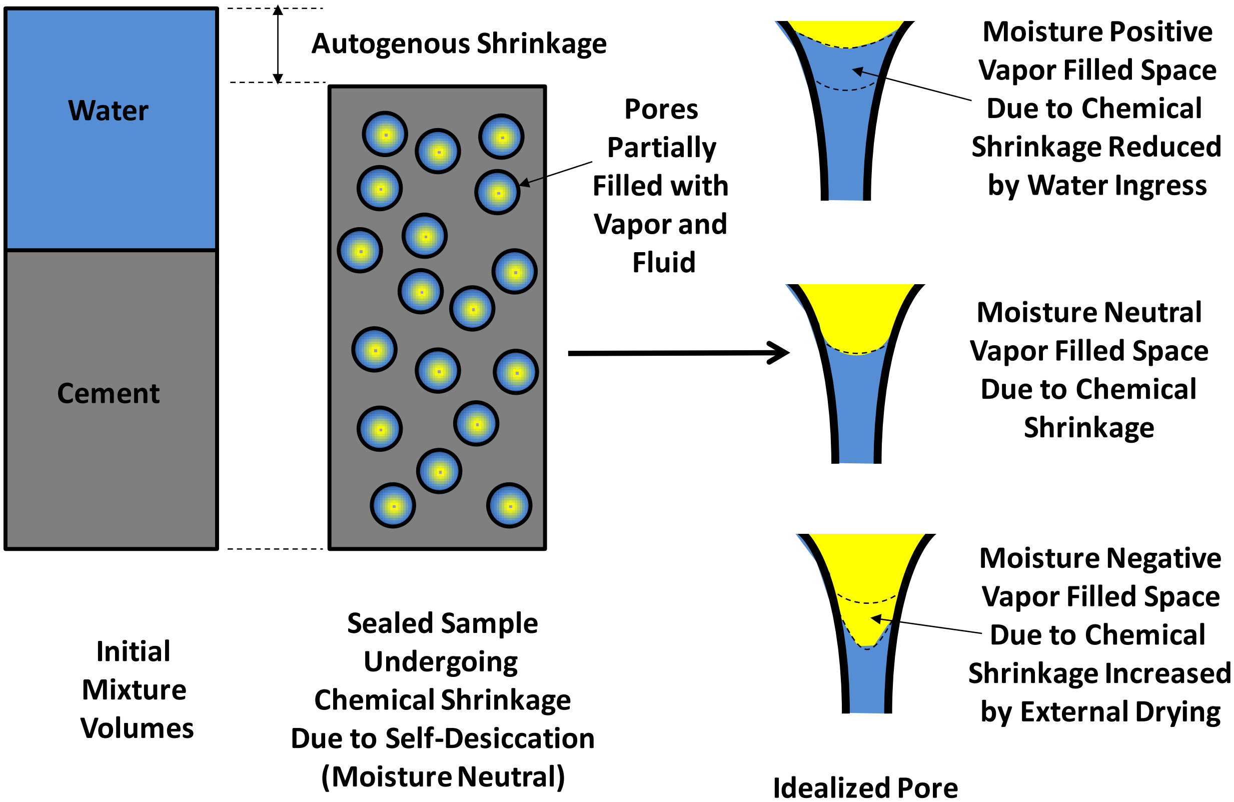
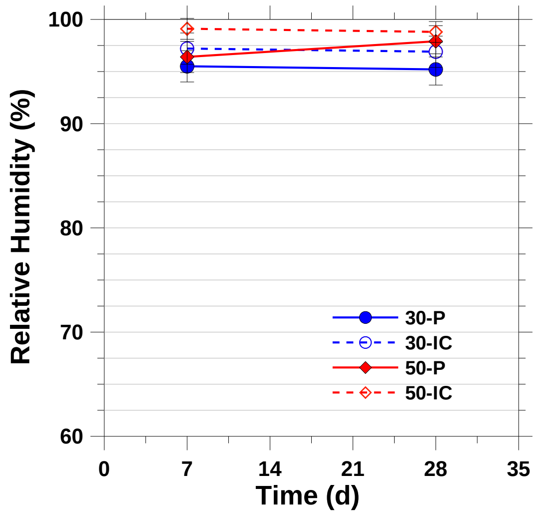


Figure 1 - Levels of moisture during curing. During moisture positive curing, external water fills voids. During moisture neutral conditions, water is consumed through the hydration process and vapor-filled voids form. During moisture negative conditions the vapor filled voids are formed as water is consumed through hydration and lost due to evaporation.

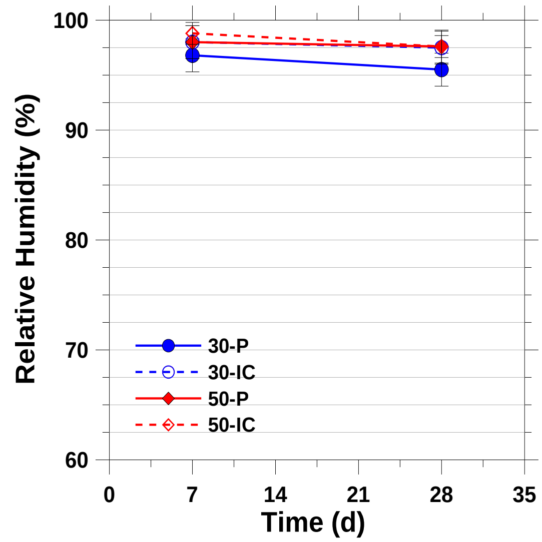
Experimental Results and Discussion

Internal Relative Humidity

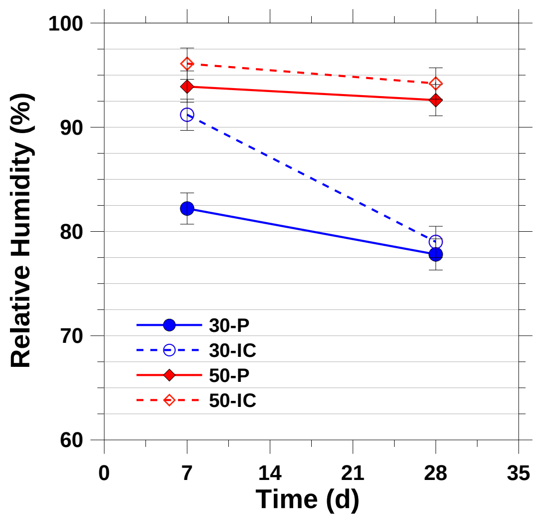
The internal relative humidity of the samples was measured using i-button®DS1923 temperature and humidity loggers at 7 d and 28 d (I-button sensors produced by Maxim. Complete sensor specifications can be found on the company website). A full cross-section of a 100 mm x 25 mm cylindrical mortar sample was crushed with a mortar and pestle. The sample was then sealed in a small plastic container (45 mm diameter, and a depth of 12.5 mm) along with an i-button sensor for 24 h. The relative humidity was recorded once the measurement had stabilized. These results were then calibrated with measurements for reference salts of potassium sulfate, potassium chloride, and sodium chloride (97 % RH, 84 % RH, and 75 % RH, respectively, at 23 °C). Experimental results can be seen in Figure 2.



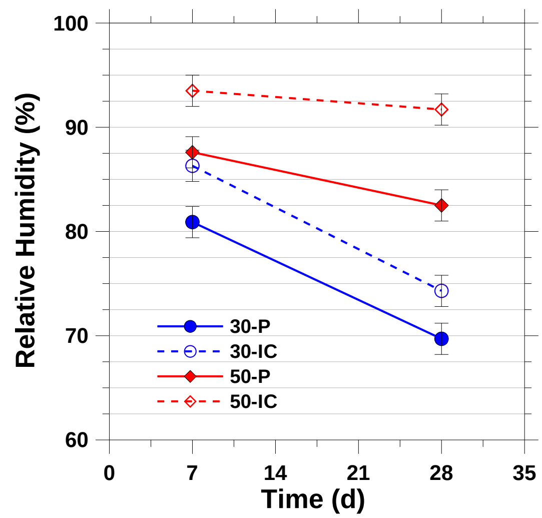
(a) Water Curing



(b) Moist Curing



(c) Sealed Curing



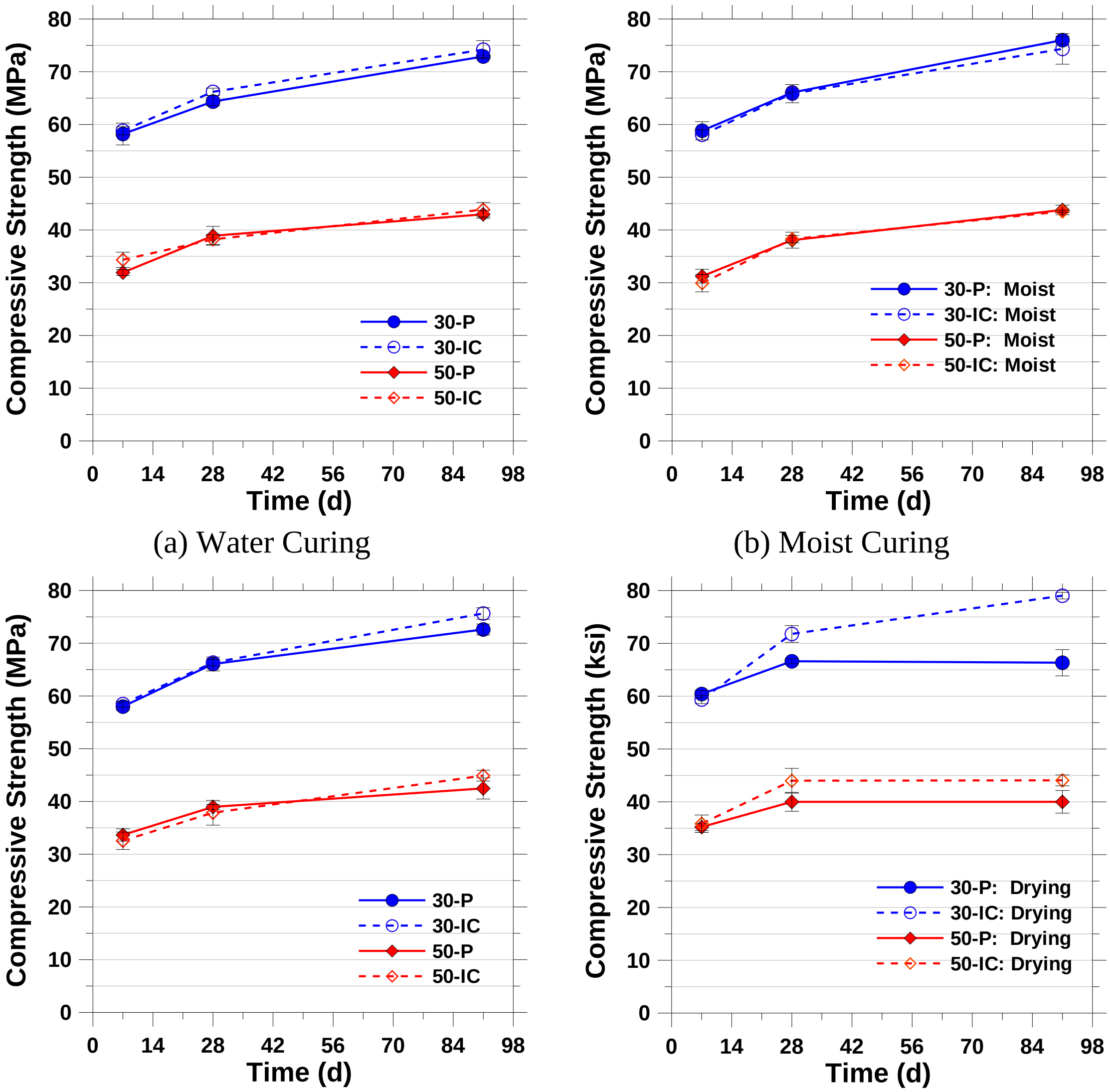
(d) Drying

Figure 2 - Internal relative humidity. All measurements are ± 1 %. (a) water curing, (b) moist curing, (c) sealed curing, and (d) drying. Error bars indicate ± one standard deviation in the testing results for three specimens.

When samples are water or moist cured, the difference between the internal relative humidity of plain or internally cured samples was not significant. This was anticipated as there is sufficient curing water being supplied to the samples. When the samples were sealed, there is a fixed amount of water available within the system. As the moisture is consumed/bound by hydration of the cement there is a drop in internal RH over time. Internally cured samples which were sealed had a higher internal RH than plain samples. The difference in RH between plain and internally cured samples is highest when samples are allowed to dry.

Compressive Strength

The compressive strength of the mortar samples was measured using the 100 mm x 200 mm cylinders in accordance to ASTM C39 at 7 d, 28 d, and 91 d. Experimental results can be seen in Figure 3.



(a) Water Curing (b) Moist Curing

(c) Sealed Curing (d) Drying

Figure 3 - Compressive strength experimental results. (a) water curing, (b) moist curing, (c) sealed curing, and (d) drying. Error bars indicate ± one standard deviation in the testing results for three specimens.

When samples were water or moist cured, the strengths of the plain and IC mixtures were within one standard deviation of each other. In both of these cases, there is a sufficient supply of curing water for these samples and there was no increase in strength associated with the inclusion of pre-wetted LWA for internal curing. However, when the supply of curing water is fixed (sealed) or is decreasing (drying), the benefits of IC are evident. For example, when the samples are sealed, there is little difference in the 7 d and 28 d compressive strength, but the additional IC water results in a higher compressive strength of the IC samples at 91 d. In the most severe curing condition tested, drying, the benefits of IC are seen even earlier as the internally cured *w/c* = 0.30 samples have an 8 % increase in strength at 28 d and 20 % at 91 d, compared with the plain samples. When considering w/c = 0.50, the internally cured samples exhibit an increase in strength of 9 % at both 28 d and 91 d. These increases in strength are observed in spite of the fact that the lightweight fine aggregate is generally weaker than the normal weight sand that it is replacing.

Split Tensile Strength

Splitting tensile strength was tested using the 100 mm x 25 mm cylinders in accordance with ASTM C496 at 7 d and 28 d. Experimental results can be seen in Figure 4.

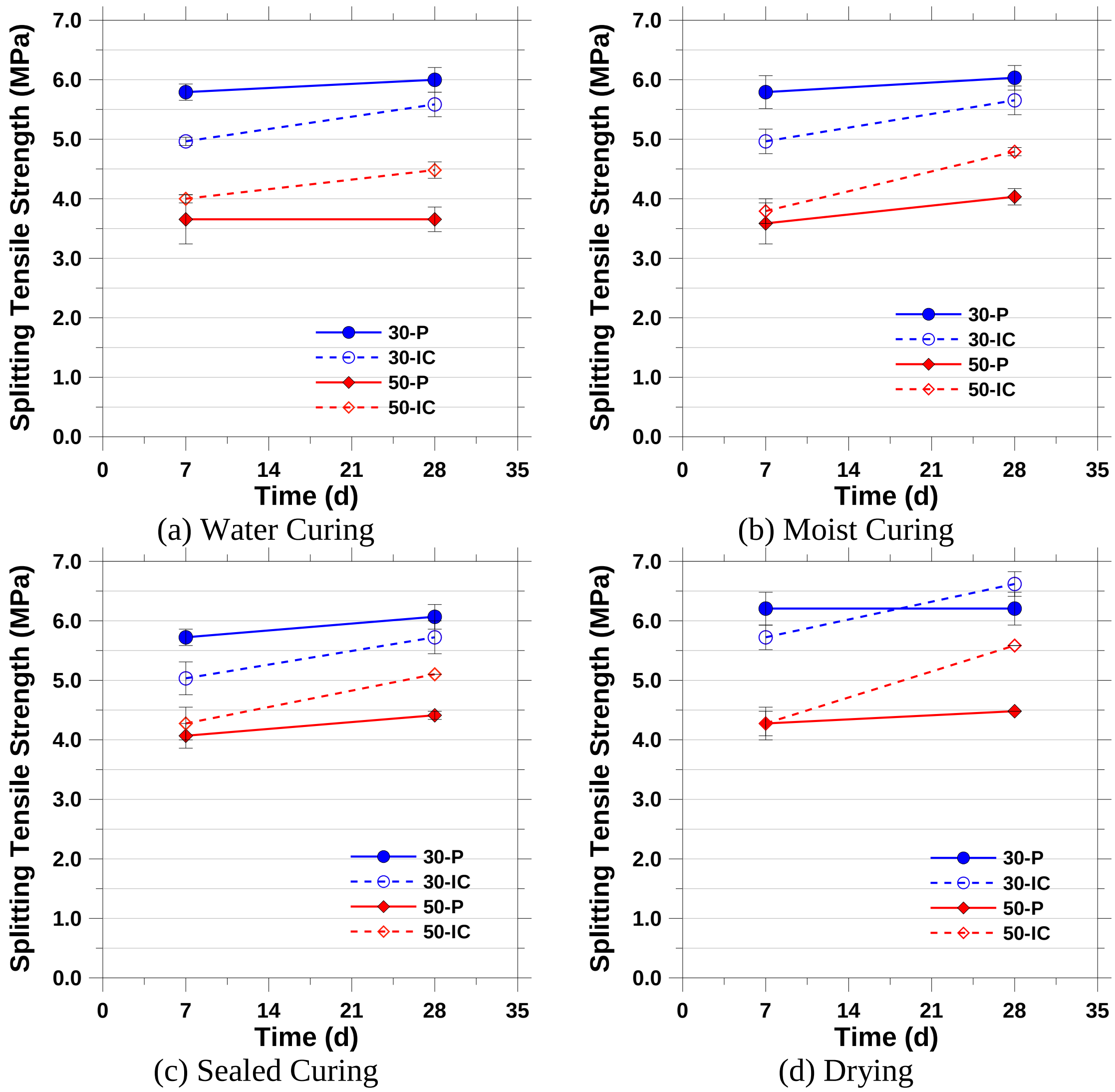


Figure 4 - Splitting tensile strength experimental results (a) water curing, (b) moist curing, (c) sealed curing, and (d) drying. Error bars indicate ± one standard deviation in the testing results for three specimens.

First, consider samples with a *w/c* = 0.30.For three of the four exposure conditions (water, moist, and sealed), the splitting tensile strengths of the internally cured samples were approximately 15 % lower than the strengths of the plain samples at 7 d. This reduction in tensile strength was only 6 % once the samples reached an age of 28 d. When samples were allowed to dry, the internally cured samples were 8 % weaker than the plain samples at 7 d, but continued to gain strength and were actually 8 % stronger than the plain samples at 28 d.

Now consider the *w/c* = 0.50. At 7 d there was no statistical difference between the splitting tensile strength of the conventional and IC samples under all four of the curing conditions. After 28 d, the internally cured samples were 20 % stronger when water, moist, or sealed cured. This increase in strength was 25 % when the samples were allowed to dry. Between 7 d and 28 d, there was not much of an increase in splitting tensile strength in any of the plain samples. During this time period there was continued strength development in the internally cured samples. This is the same trend seen in the *w/c* = 0.30 samples and can be attributed to the extra internal curing water promoting the continuing hydration of the cement.

Elastic Modulus

As a composite material, the elastic modulus of concrete is dependent on the properties of its constituents: paste and aggregate. There are many theories on how to calculate composite elastic modulus. Two of the simplest forms are the parallel and series models (Mindess et al., 2003). The parallel model assumes that there is a constant strain in each of the materials. This is considered to be an upper bound solution and can be calculated with equation 1. The series model assumes that there is a constant force in each of the materials. This is considered to be a lower bound solution and can be calculated with equation 2:

$$E_c = V_p E_p + V_a E_a \tag{1}$$

$$\frac{1}{E_c} = \frac{V_p}{E_p} + \frac{V_a}{E_a} \tag{2}$$

where E_c is the composite elastic modulus, V_p is the volume fraction of paste, E_p is the elastic modulus of the paste, V_a is the volume fraction of aggregate, and E_a is the elastic modulus of the aggregate. A graphical representation of these models can be seen in Figure 5.

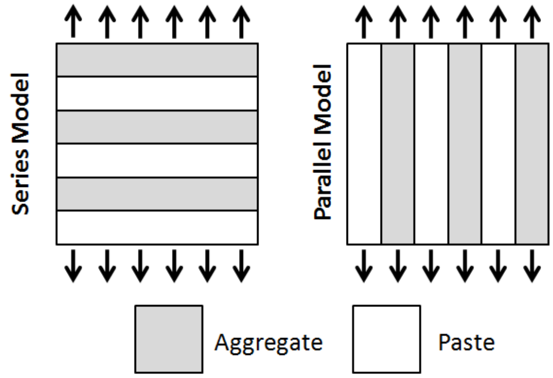


Figure 5. Series and parallel models for predicting elastic modulus (Mindess et al., 2003).

These models become more complicated when dealing with internally cured mortars. Under the correct external conditions, internally curing the concrete will be able to increase the hydration of the paste, resulting in a paste with a higher modulus of elasticity(Moon, 2006). Another factor to be considered when using internal curing is the replacement of normal weight aggregate (NWA) with lightweight aggregate (LWA). The porous nature of LWA results in a lower stiffness than when compared to NWA. The overall aggregate stiffness can be estimated using a law of mixtures as shown in equation 3:

$$E_a{}^* = (1 - V_r)E_{nwa} + V_r E_{lwa} \tag{3}$$

where $E_a{}^*$is the effective aggregate elastic modulus, V_r is the percentage of NWA replaced with LWA (full replacement of NWA with LWA results in V_r=1), E_{nwa} is the elastic modulus of the normal weight aggregate (e.g. an estimate of 50 GPa for granite), and E_{lwa} is the elastic modulus of the light weight aggregate (e.g., an estimate of 6 GPa to 11 GPa for LWA (Chen et al. 2003)). A theoretical representation of the effect of these factors on the composite modulus of elasticity can be seen in Figure 6.

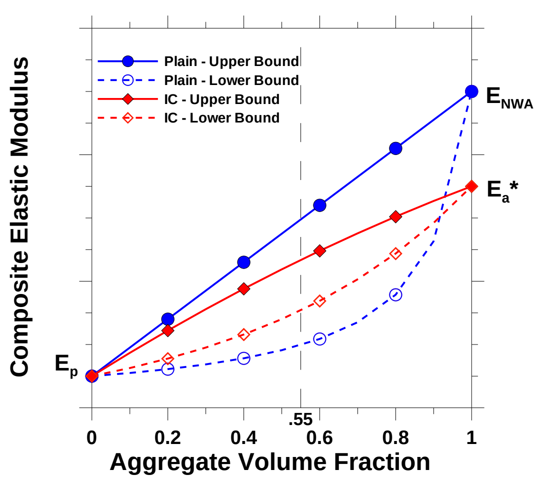


Figure 6 - The effect of internal curing on predicted modulus of elasticity.

In this study 100 mm x 200 mm cylinders were tested for elastic modulus in accordance with ASTM C469 at 7 d, 28 d, and 91 d. Experimental results can be found in Figure 7. Under all curing conditions, the plain samples had a higher modulus of elasticity than the internally cured samples, as expected. This can be attributed to the inclusion of the LWA that have a lower stiffness than the NWA. When specimens at either *w/c*are water or moist cured, the difference between the modulus of the plain samples and IC samples is consistent over time. When the *w/c* = 0.30 samples were sealed or exposed to drying, the difference between the moduli of the plain and IC samples decreased over time, but the IC samples are always lower. It is important to note that there was a larger difference in the moduli between plain and internally cured samples in *w/c* = 0.30 samples than in *w/c* = 0.50 samples. This implies that as *w/c* increases the aggregate stiffness has a smaller influence on the stiffness of the composite.

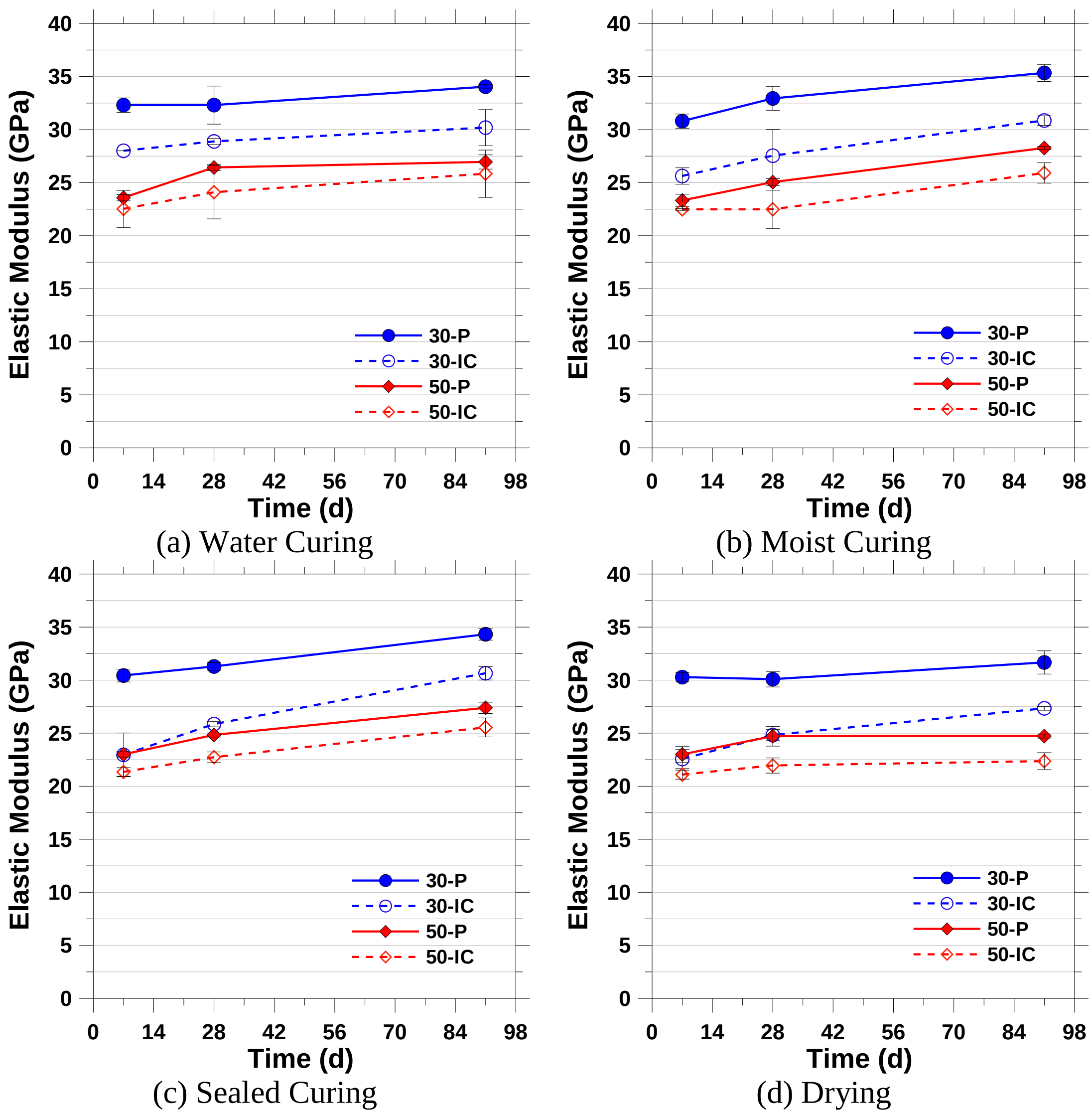


Figure 7 -Elastic modulus experimental results (a) water curing, (b) moist curing, (c) sealed curing, and (d) drying. Error bars indicate ± one standard deviation in the testing results for three specimens, and may be too small to be seen in some cases.

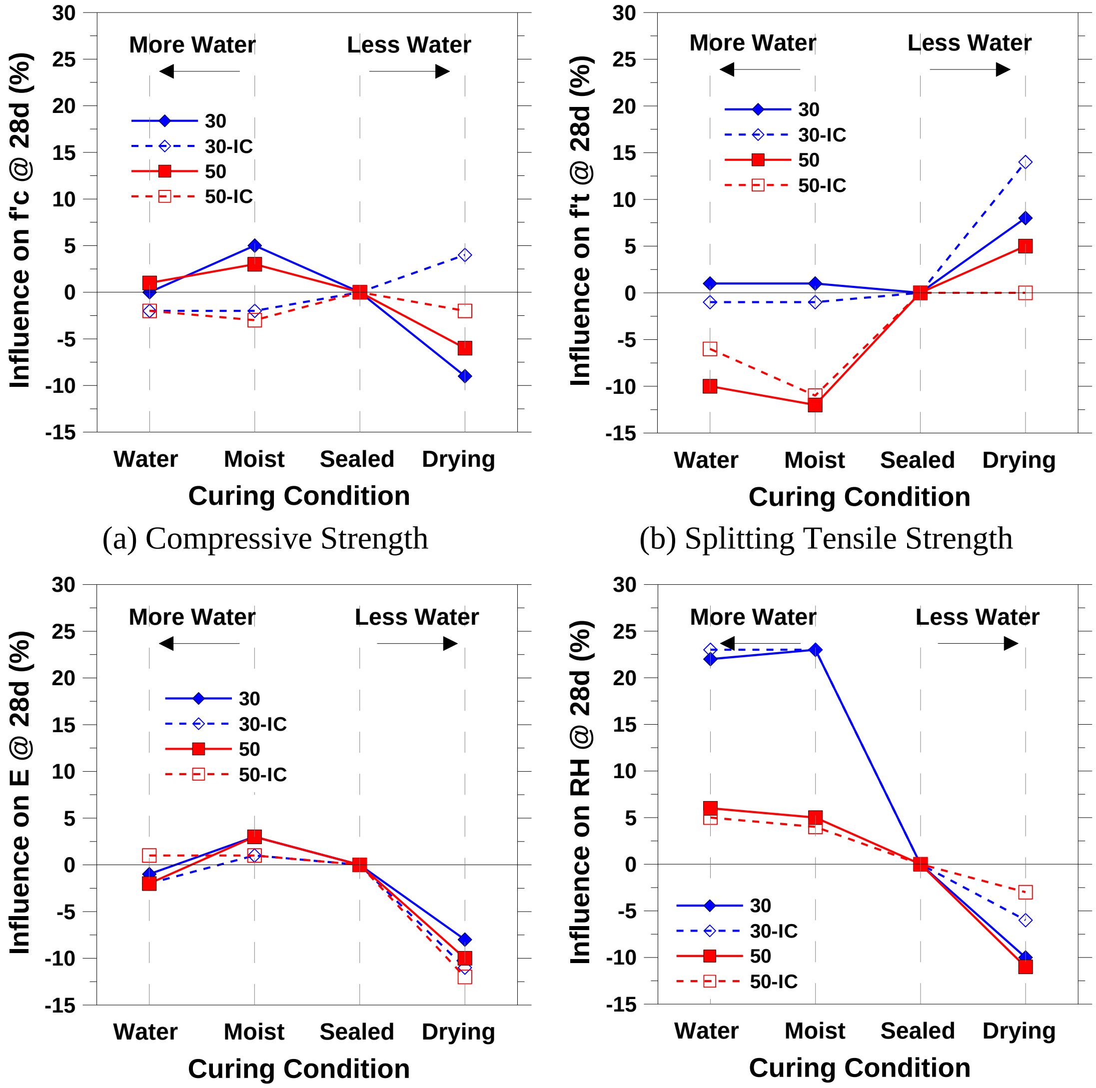
Influence of Sample Conditioning

Figure 8 illustrates the influence of curing environment on the 28 d properties of the samples. In this figure the results from the four different curing conditions were normalized to the sealed curing condition. For the compressive strength, when the conventional samples were moist cured, there was an increase in strength, while there was a decrease when it was allowed to dry. Internally cured samples did not experience a significant change in strength, implying the compressive strength of these samples is less dependent on the curing conditions.

Compared with sealed curing, water and moist curing conditions had no influence on splitting tensile strength of the *w/c* = 0.30 samples. The *w/c* = 0.50 samples, however, experienced a 10 % - 15 % reduction in splitting tensile strength when water or moist cured. Additionally, all of the samples experienced an increase in splitting tensile strength when they were allowed to dry. Although these results are counter-intuitive (poorer curing resulting in stronger concrete), this effect can be explained by the moisture content of the systems. Figure 2a illustrates that the internal relative humidity of a sample is proportional to the amount of moisture provided during curing (more curing water leads to increased internal RH). As the RH in concrete decreases, an under-pressure is developed in the pore system (Brooks & Neville, 1978). This internal pressure can work to help hold the sample together, initially providing a higher splitting tensile strength. Although this is seen in 28 d testing, this effect is likely to lead to retrogression of strength over time(Brooks & Neville, 1978). In general, poor curing of concrete will lead to a lower internal relative humidity. This will typically lead to increased autogenous shrinkage and a lower degree of hydration, resulting in a lower quality concrete.

For all of the samples tested, there was little variation in the elastic moduli of samples that were water, moist, or sealed cured. Conversely, there was a drop in elastic modulus of approximately 10% when samples were allowed to dry.

In summary, when samples are sealed there is no source of external curing water for the plain samples. Similarly, when the samples were exposed to drying, in addition to the lack of external curing water, some internal water was lost due to evaporation. Under these moisture neutral and moisture loss conditions, the benefits of internal curing are most prominent, resulting in samples with an increase in internal RH, compressive strength, and splitting tensile strength. In many cases, these benefits were small at early ages (7 d), but allowed for further development of long term strength (28 d and 91 d). The inclusion of LWA resulted in a reduction in elastic modulus relative to the plain specimens, under all exposure conditions. Unlike the water and moist curing, under moisture neutral and moisture loss conditions, the amount of this reduction decreased over time, but never reached zero when compared to the plain samples. Overall, the relative performance of internal curing improved as the amount of external curing water decreased.



(a) Compressive Strength (b) Splitting Tensile Strength

(c) Splitting Tensile Strength (d) Internal RH

Figure 8 - Influence of curing environment on the 28d properties of samples as compared to sealed curing. (a) compressive strength, (b) splitting tensile strength, (c) elastic modulus, and (d) internal relative humidity,

Conclusion

In laboratory testing, concrete cylinders are frequently exposed to an external source of water from the time of demolding until the time of the testing. While this enables the cylinders to absorb water to enhance strength development, it is unclear whether this truly represents the behavior that can be expected in the field. This paper explored the influence of various exposure conditions on the properties of internally cured concretes. When samples are water or moist cured, they absorb external water. As a result, the benefits of internal curing are not seen in these conditions. When samples were water or moist cured, both the conventional and internally cured samples had similar compressive strengths (±2%) and internal relative humidities (± 2 %). The inclusion of LWA in the internally cured mixtures resulted in a 7 % lower 28 d splitting tensile strength in the low *w/c* case and a 12 % lower elastic modulus. In the high water-to-cement ratio case (*w/c* = 0.50), the inclusion of LWA in the internally cured mixtures resulted in a 20 % higher 28 d splitting tensile strength and a 7 % lower elastic modulus.

It is recommended that internally cured samples be sealed for the curing period prior to laboratory testing. In low *w/c* mixtures (*w/c* = 0.30), the addition of external curing water did not have a significant influence on the mechanical properties of the internally cured mixtures when compared to sealed conditions, although it did impact internal relative humidity. When allowed to dry, the low *w/c* internally cured mixtures experienced moderate strength gains (5 %-15 %) and a decrease in elastic modulus of 10% relative to their sealed counterparts.

Bibliography

Aïtcin, P.-C., Miao, B., Cook, W.D. & Mitchell, D., 1994. The Effects of Size and Curing on Cylinder Compressive Strength of Normal and High-Strength Concretes. *ACI Materials Journal*, 91(4), pp.349-354.

ASTM, 2002. ASTM C469-02, Standard Test Method for Static Elastic Modulus and Poisson's Ratio of Concrete in Compression. *American Society of Testing and Materials*.

ASTM, 2006. ASTM C192-06, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. *American Society of Testing and Materials*.

ASTM, 2009. ASTM C39/C39M-09, Standard Test Method for Compressive Strength of Concrete Specimens. *American Society of Testing and Materials*.

ASTM, 2011. ASTM C150/C150M-11, Standard Specification for Portland Cement. *American Society of Testing and Materials*.

ASTM, 2011. ASTM C496/C496M-11, Standard Test Method for Splitting Tensile Strength of Cylinderical Concrete Specimens. *American Society of Testing and Materials*.

Bentz, D., Lura, P. & Roberts, J.W., 2005. Mixture Proportioning for Internal Curing. *Concrete International* , 27(2), pp.35-40.

Brooks, J.J. & Neville, A.M., 1978. A Comparison of Creep, Elasticity and Strength of Concret in Tension and Compression. *Magazine of Concrete Research*, 30(104).

Campbell, R.H. & Tobin, R.E., 1967. Core and Cylinder Strengths of Natural and Lightweight Concrete. *ACI Journal Proceedings*, 64(4), pp.190-95.

Castro, J., Keiser, L., Golias, M. & Weiss, J., 2010. Absorption and Desportion Properties of Fine Lightweight Aggregate for Application to Internally Cured Concrete Mixtures. *Submitted to Cement and Concrete Composites* .

Henkensiefken, R., 2008. *Internal Curing in Cementitous Materials*. MS Thesis. West Lafayette, IN: Purdue University.

Henkensiefken, R., Bentz, D., Nantung, T. & Jason, W., 2009a. Volume Change and Cracking in Internally Cured mixtures with Saturated Lightweight Aggregate Under Sealed and Unsealed Conditions. *Cement & Concrete Composites*, 31, pp.427-37.

Henkensiefken, R., Bentz, D., Nantung, T. & Jason, W., 2009. Volume Change and Cracking in Internally Cured mixtures with Saturated Lightweight Aggregate Under Sealed and Unsealed Conditions. *Cement & Concrete Composites*, 31, pp.427-37.

Henkensiefken, R., Castro, J., Bentz, D. & Weiss, J., 2009b. Water Absorbtion in Internally Cured Mortar Made with Water-Filled Lightweight Aggregate. *Cement and Concrete Research*, 39, pp.883-92.

Henkensiefken, R., Castro, J., Bentz, D. & Weiss, J., 2009c. Water Absorbtion in Internally Cured Mortar Made with Water-Filled Lightweight Aggregate. *Cement and Concrete Research*, 39, pp.883-92.

Mindess, S., Young, J.F. & Darwin, D., 2003. *Concrete*. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Moon, J.H., 2006. *Shrinakge, Residual Stress, and Cracking in Heterogeneous Materials*. PhD Thesis. West Lafayette, IN: Purdue University.

Shah, S., Weiss, J. & Yang, W., 1998. Shrinkage Cracking - Can it Be Prevented? *Concrete International* , 20(4), pp.51-55.