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Influence of Internal Curing on Concrete's Permeability in Simulated Field Conditions

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13. Abstract
The curing conditions stated in the AASHTO T358 standard require that concrete specimens remain fully saturated at all times in a moist room or cabinet prior to testing. These curing conditions obscure the true impact of internal curing. In order to assess the benefits of internal curing under more realistic condition, this study compared internally cured concrete's properties under the 100% relative humidity (RH) moist room curing condition for 28 days with its properties under a hybrid curing condition, which consists of 100% RH moist room curing for the first 7 days followed by a lab environment for the next 21 days. It was found that the hybrid curing condition produced a higher compressive strength than the 100% RH moist room curing condition, with the exceptions of the mixtures 50TI/50S/0ICA (w/cm of 0.35) and 50TI/50S/250ICA (w/cm of 0.45). The application of saturated fine internal curing aggregates (ICAs) reduced the compressive strength magnitude variation between the two different curing conditions. At the age of 56 days, the mixtures with ICAs had either equal or higher surface resistivity than those without ICAs for the hybrid curing condition. For w/cm of 0.35 and the hybrid

curing condition, the application of ICAs helped produce a lower apparent coefficient of chloride diffusion for mixtures with cementitious systems 100TI and 50TI/50S. For w/cm of 0.35, mixtures with ICAs also had a higher relative humidity than those without ICAs (except for mixtures with cementitious system 70TI/30C) at the age of 56 days. This shows that ICAs were able to continuously supply water to the surrounding matrix.

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Abstract

The curing conditions stated in the AASHTO T358 standard require that concrete specimens remain fully saturated at all times in a moist room or cabinet prior to testing. These curing conditions obscure the true impact of internal curing. In order to assess the benefits of internal curing under more realistic condition, this study compared internally cured concrete's properties under the 100% relative humidity (RH) moist room curing condition for 28 days with its properties under a hybrid curing condition, which consists of 100% RH moist room curing for the first 7 days followed by a lab environment for the next 21 days. It was found that the hybrid curing condition produced a higher compressive strength than the 100% RH moist room curing condition, with the exceptions of the mixtures 50TI/50S/0ICA (w/cm of 0.35) and 50TI/50S/250ICA (w/cm of 0.45). The application of saturated fine internal curing aggregates (ICAs) reduced the compressive strength magnitude variation between the two different curing conditions. At the age of 56 days, the mixtures with ICAs had either equal or higher surface resistivity than those without ICAs for the hybrid curing condition. For w/cm of 0.35 and the hybrid curing condition, the application of ICAs helped produce a lower apparent coefficient of chloride diffusion for mixtures with cementitious systems 100TI and 50TI/50S. For w/cm of 0.35, mixtures with ICAs also had a higher relative humidity than those without ICAs (except for mixtures with cementitious system 70TI/30C) at the age of 56 days. This shows that ICAs were able to continuously supply water to the surrounding matrix.

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Implementation Statement

When properly designed, the application of saturated fine internal curing aggregates (ICAs) could help continuously supply water to the surrounding matrix and produce a lower permeability in internally cured concrete.

Table of Contents

List of Tables

List of Figures

Introduction

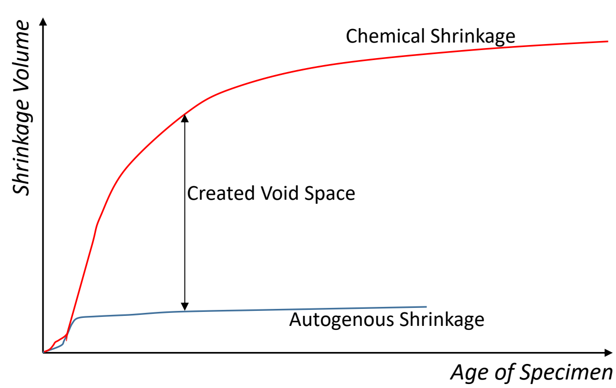
State highway agencies (SHAs) have started to implement more internally cured concrete (ICC) mixtures in the design and construction of pavements and structures. Coincidentally, the push for performance-based specifications on concrete's transport properties prompted research to understand the impact of internal curing on surface resistivity (see AASHTO T358). LTRC recently conducted a ruggedness study examining the impact of pre-wetted internal curing aggregates (ICAs) on resistivity, and the results showed that ICAs did not have a detrimental impact on resistivity at the 28- and 56-day test periods. However, the curing conditions established in the AASHTO T358 standard require that concrete remains fully saturated at all times in a moist room or cabinet prior to testing. These curing conditions can significantly obscure the true impact of internal curing and make it difficult to assess its benefits. As such, this study proposed to simulate the realistic condition by limiting the 100% relative humidity (RH) moist room curing conditions to the first 7 days followed by a lab environment for the next 21 days. Surface resistivity was measured until 56 days of age were reached. An additional test method, bulk diffusion (ASTM C1556), was employed to validate the surface resistivity results. Finally, internal RH was also measured to monitor concrete's degree of hydration over time.

Literature Review

It is well established that sufficient curing is of great importance to achieve the desired strength and durability of concrete. Once cement hydration initiates, the moisture within the concrete mixture is consumed and the internal relative humidity decreases [1]. If there is also water loss due to evaporation, the moisture would be depleted very quickly, and the hydration and maturity would be terminated at a very early age, resulting in lower strength, higher permeability, and higher shrinkage to the concrete.

Since the hydration products have a smaller volume than the reactants, as the hydration proceeds, there is a growing reduction in the total volume of the cement system. This is called chemical shrinkage, and it has been reported that the volume reduction could be up to 10% [2]. On the other side, there is also a bulk shrinkage, namely autogenous shrinkage. Per the definition, autogenous shrinkage is the bulk deformation of a closed, isothermal, cementitious material system not subjected to external forces [3, 4]. Initially, the volume of autogenous and chemical shrinkages are the same. With the time of set, the solidification of the matrix develops and keeps the bulk system from shrinking at the same rate as chemical shrinkage, which eventually causes autogenous and chemical shrinkages to diverge; see Figure 1. The difference between the autogenous and chemical shrinkages could be explained by the development of vapor-filled voids formed inside the paste [4]. As hydration proceeds, these voids grow and penetrate increasingly smaller pores. Once the shrinkage is restrained, stresses develop, leading to cracking in concrete [2, 5].

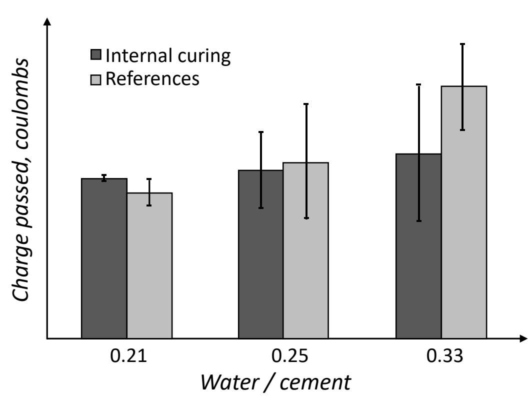
Figure 1. Chemical and autogenous shrinkage development during hydration [2]



In order to prolong cement hydration and reduce the risk of shrinkage cracking, internal curing has been developed by incorporating pre-saturated internal curing aggregates (ICAs) within the concrete mixture [6, 7]. Due to their highly porous and highly absorptive properties, the pre-saturated fine ICAs could serve as internal reservoirs to replenish the vapor-filled voids and reduce the underpressure in the pore fluid [2]. Hence, with the internal curing effects, cement hydration within the concrete mixtures is increased, while the capillary pores and their interconnectivity, as well as the risk of shrinkage cracking, are decreased [8]. Studies have shown that for a given strength of concrete, the permeability of concrete with ICAs could be lower than that of concrete containing conventional aggregates, as ICAs improved the interfacial transition zone and promoted a more unified microstructure [8, 9]. By comparing with mortar prepared with normal weight sand, Bentz found that the application of 31% fine ICAs could reduce the chloride penetration depths by at least 25% [10]. Another study showed that the mortars' water absorption was decreased by using ICAs for internal curing (IC) [11]. It is also reported that internal curing concrete mixtures could significantly reduce the warping in slabs on grade [12].

In order to further investigate the effect of internal curing on durability, Zhutovsky and Kovler compared the testing results for high performance concretes with water-to-cement ratios from 0.21 to 0.33 [7]. As shown in Figure 2 below, with the application of internal curing, the chloride diffusivity was reduced for a water-to-cement ratio of 0.33 and stayed approximately the same for a water-to-cement ratio of 0.25, but increased for a water-to-cement ratio of 0.21. It was also found that the effect of the water-to-cement ratio on the chloride penetration resistance is significant for the control mixtures, but minimal for the internally cured concretes.

Figure 2. Resistance to chloride penetration [7]



Previous studies have shown that replacing cement with supplementary cementitious materials (SCMs) such as fly ash and slag is an effective way to lower the carbon footprint, mitigate the alkali–silica reaction (ASR), and increase durability for concrete mixtures. However, due to the slower reaction rates for SCMs, it requires water to be present in the concrete for a longer time to ensure the proper development of the desired properties for the mixtures. Hence, the application of internal curing is more beneficial for mixtures with a large volume of SCMs [1, 13]. However, there is limited information on how the transport properties are influenced by IC under realistic field conditions for concrete mixtures with different SCMs.

Objective

The objectives of this study were to:

1. Assess the influence of internal curing on concrete's transport properties under more realistic curing condition.
2. Validate the results from surface resistivity with bulk diffusion testing.

Scope

To fulfill the objectives of this study, 12 mixtures were prepared to produce concrete samples with and without saturated fine ICAs. Two curing conditions (28 days at 100% relative humidity (RH) moist room vs 7 days at 100% RH moist room followed by a 21 day lab environment) were applied to assess the benefits of internal curing with saturated fine ICAs.

Methodology

One ICA source made from expanded shale and clay was used in this study. The ICAs were soaked for 72 hours prior to being used for concrete mixing. The centrifuge method was employed to provide moisture correction within the concrete mixture design. In order to evaluate the IC effect for different cementitious systems, Type I portland cement, Class C fly ash, and grade-100 ground granulated blast furnace slag were selected for the mix design, which also included a No. 57 coarse aggregate gradation and a 60/40 coarse-to-fine aggregate ratio. Finally, a superplasticizer was used to ensure workability. The experimental design is shown in Table 1.

Table 1. Experimental design

Factor	Levels	Description
Water/cementitious materials (w/cm)	2	0.35, 0.45
Total Cementitious Content	1	575 lbs/yd^3
ICA Dosage	2	0, 250 lbs/yd^3
Cementitious Systems and Designations	3	• 100% Type I cement (100TI) • 70% Type I cement and 30% Class C fly ash (70TI-30C) • 50% Type I cement and 50% slag (50TI-50S)
Superplasticizer Dosage	1	• 13 oz/cwt @ 0.35 w/cm • 5 oz/cwt @ 0.45 w/cm
Curing Conditions	2	• 7 days in 100% RH moist room followed by 21 days of lab environment (named as hybrid curing in this study) • 28 days in 100% RH moist room (named as 100% RM curing in this study)

To evaluate the influence of internal curing under more realistic condition, the curing period of freshly cast concrete was limited to 7 days in a 100% RH moist room, followed by standard laboratory conditions (i.e., ranging from 72°F and 30-50% RH) for all specimens. For comparison, another set of samples was exposed to a 100% RH moist room for 28 days to follow the curing conditions indicated on the standardized test methods for compressive strength, surface resistivity, and bulk diffusion. The applied testing program is detailed in Table 2.

Table 2. Applied testing program

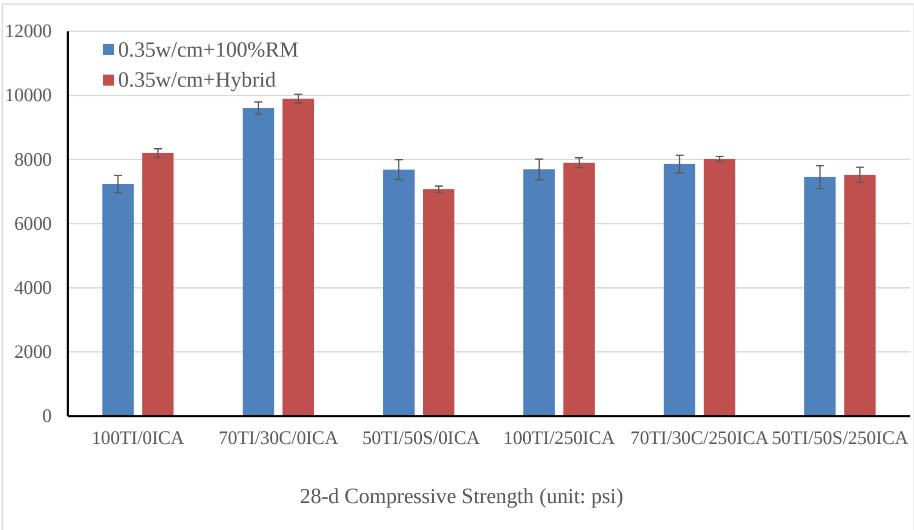
Test Method	Description		
	Concrete Age (days)	Initial Curing Conditions	Replicates
Slump (ASTM C143) [14]	0	N/A	1
Unit Weight (ASTM C138) [15]	0	N/A	1
Compressive Strength (ASTM C39) [16]	28	7 days 100% RM curing	3
		28 days 100% RM curing	3
Surface Resistivity (AASHTO T358) [17]	7, 14, 21, 28, 56	7 days 100% RM curing	3
		28 days 100% RM curing	3
Bulk Diffusion (ASTM C1556) [18]	28	7 days 100% RM curing	3
		28 days 100% RM curing	3
Internal RH Monitoring (ASTM F2170) [19]	7, 14, 21, 28, 56	7 days 100% RM curing	3

Discussion of Results

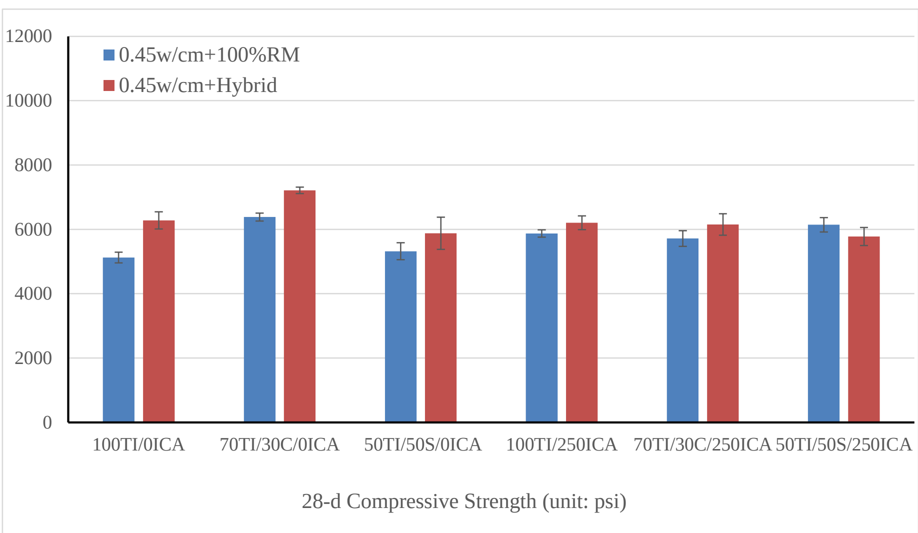
Compressive Strength

Figure 3. Compressive strength testing results

(a) 28-d compressive strength for 0.35 w/cm



(b) 28-d compressive strength for 0.45 w/cm



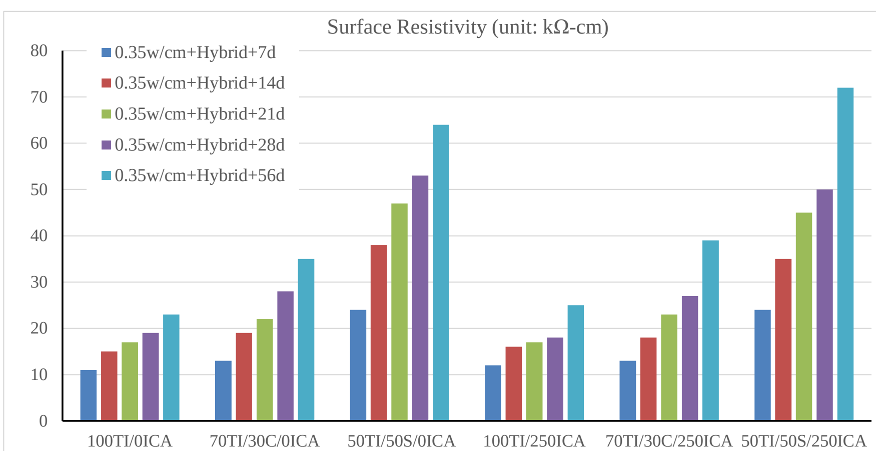
The compressive strength testing results are shown in Figure 3. Generally, the mixtures with water/cementitious materials (w/cm) of 0.35 showed a higher compressive strength than those with w/cm of 0.45. A comparison between the two different curing conditions shows that the hybrid curing condition (i.e., 21 days of lab environment after 7 days of 100% RH moist room curing) produced a slightly higher compressive strength than the 100% RH (i.e., 28 days of 100% RH moist room) curing condition, except for the mixtures 50TI/50S/0ICA (w/cm of 0.35) and 50TI/50S/250ICA (w/cm of 0.45). It also shows that the application of ICAs reduced the strength magnitude variation between the two different curing conditions (i.e., hybrid curing vs 100% RH curing).

Surface Resistivity

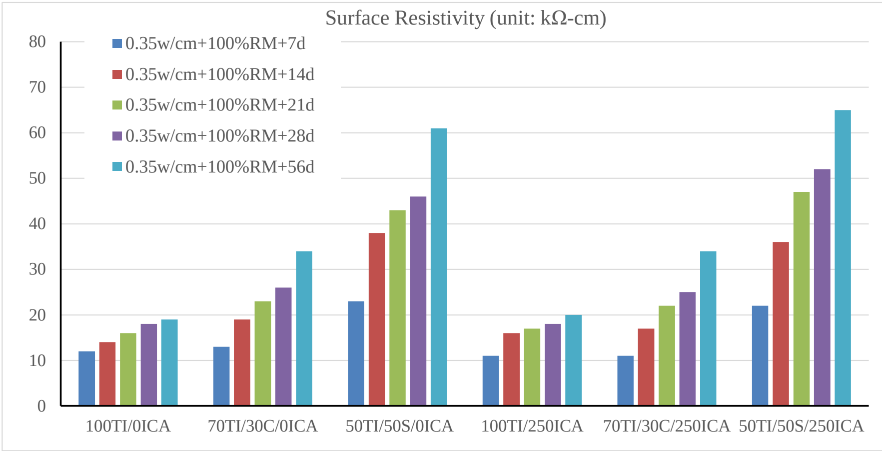
Figure 4 shows the surface resistivity testing results at the curing ages of 7, 14, 21, 28, and 56 days. The surface resistivity of all the mixtures increased for both curing conditions, and the mixtures with water/cementitious materials (w/cm) of 0.35 produced a higher surface resistivity than those with w/cm of 0.45. Overall, the mixture 50TI/50S/250ICA with w/cm of 0.35 produced the highest surface resistivity at the age of 56 days under the hybrid curing condition. For the hybrid curing condition, mixtures with ICAs had either equal or higher surface resistivity than those without ICAs at the age of 56 days.

Figure 4. Surface resistivity testing results

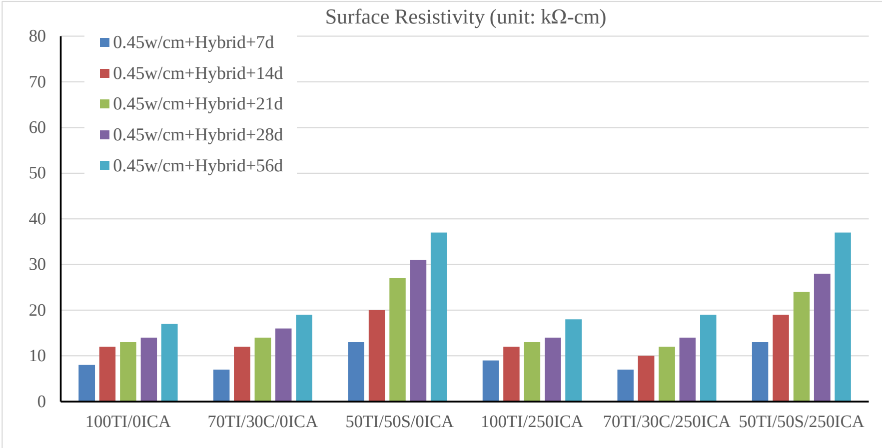
(a) Surface resistivity for 0.35 w/cm + hybrid curing



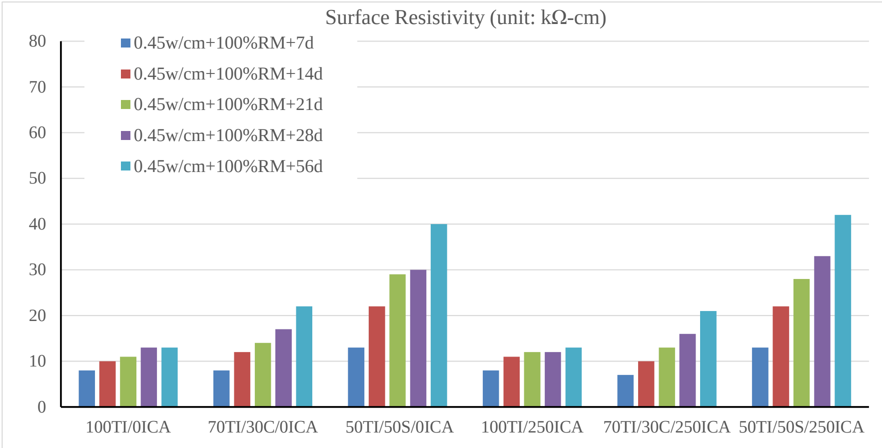
(b) Surface resistivity for 0.35 w/cm + 100% RH curing



(c) Surface resistivity for 0.45 w/cm + hybrid curing



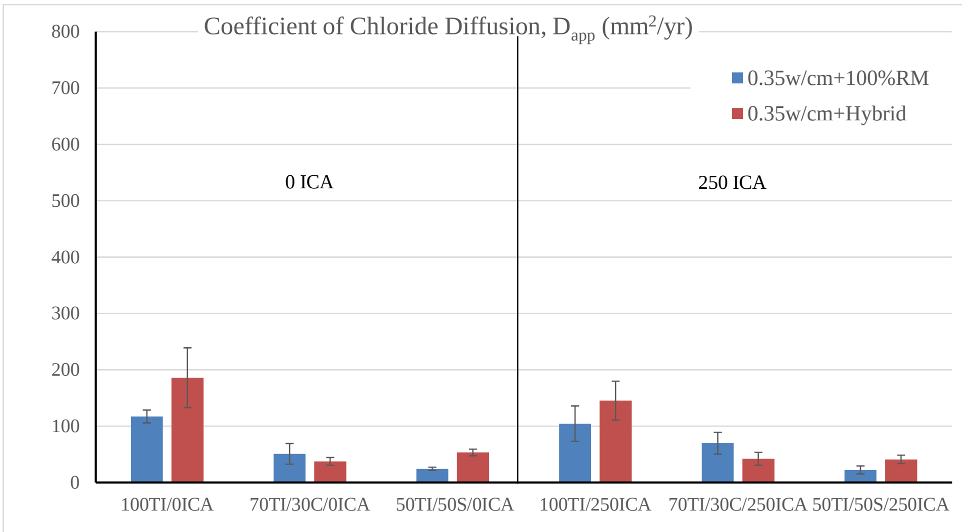
(d) Surface resistivity for 0.45 w/cm + 100% RH curing



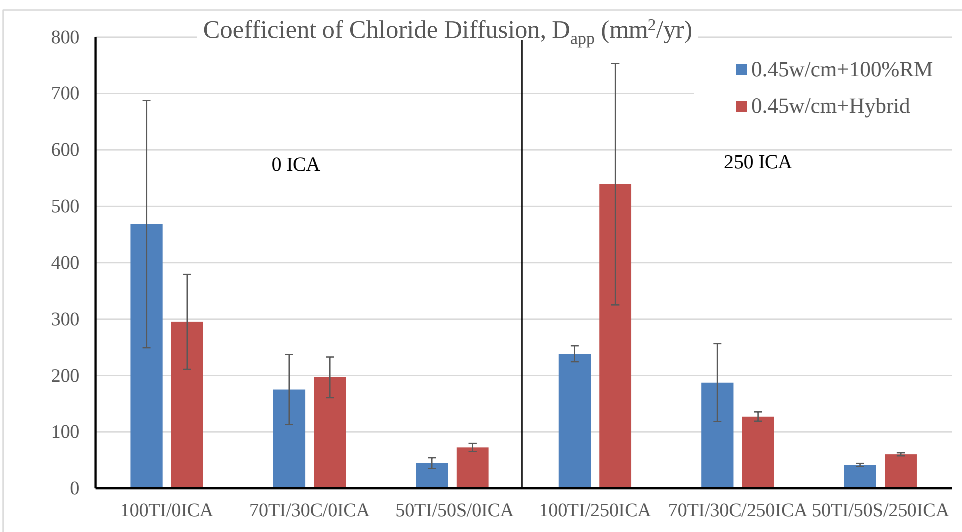
Bulk Diffusion

Figure 5. Apparent coefficient of chloride diffusion

(a) Mixtures with w/cm of 0.35



(b) Mixtures with w/cm of 0.45

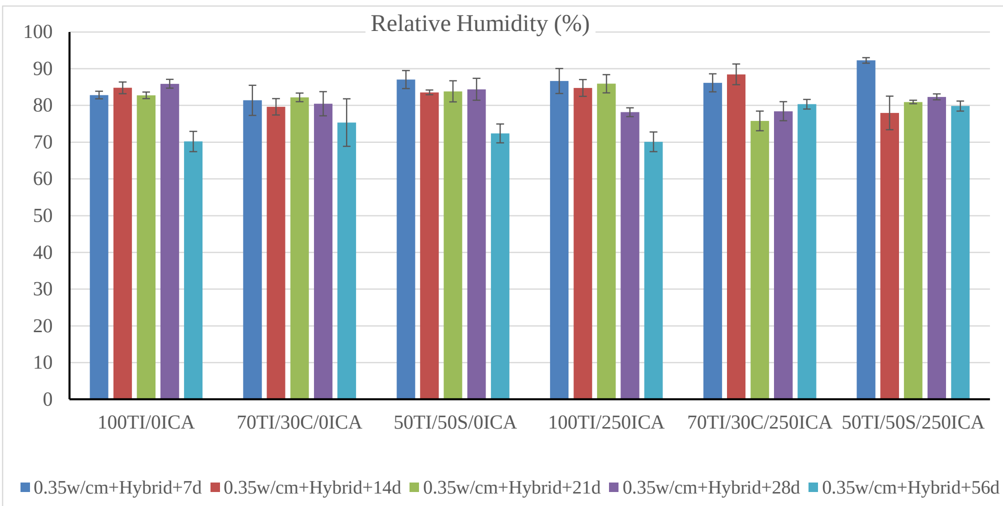


The apparent coefficient of chloride diffusion testing results are shown in Figure 5. The mixtures with w/cm of 0.45 had a much higher apparent coefficient of chloride diffusion than those with w/cm of 0.35, which matches the observation from surface resistivity testing. This is likely due to the higher porosity of the specimen with the higher water-to-cementitious materials ratio. From Figure 5(a), it can be observed that the application of ICAs produced a lower apparent coefficient of chloride diffusion for the 100TI and 50TI/50S mixtures. However, such trends are not observed in Figure 5(b) for the mixtures with 0.45 w/cm, which may be covered by the high deviation between the testing results.

Relative Humidity

Figure 6. Relative humidity testing results for specimens with hybrid curing

(a) Mixtures with a w/cm of 0.35



(b) Mixtures with a w/cm of 0.45

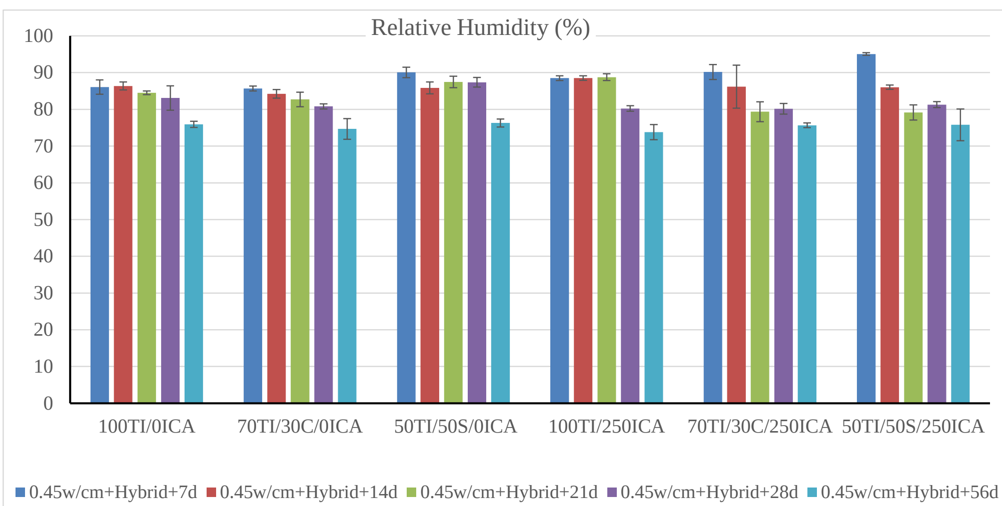


Figure 6 shows the relative humidity testing results for specimens under the hybrid curing condition. At the age of 7 days, the mixtures with ICAs had a higher relative humidity than those without ICAs (i.e., 100TI/0ICA vs 100TI/250ICA), indicating that ICAs were supplying water to the surrounding matrix. For w/cm of 0.35, the mixtures with ICAs also had a higher relative humidity than those without ICAs (except for mixtures with cementitious system 70TI/30C) at the age of 56 days. This shows that ICAs were able to continuously supply water to the surrounding matrix. However, for the mixtures with w/cm of 0.45, the relative humidity decreased to different levels at the curing age of 56 days. This is likely because the moisture loss was greater than the water supply from ICAs due to the higher porosity in the specimen with the higher water-to-cementitious materials ratio.

Conclusions

In order to investigate the influence of realistic curing condition on the properties of internally cured concrete, two different water-to-cementitious materials ratios and three different cementitious systems were applied to produce concrete samples in this study. A hybrid curing procedure with the first 7 days in a 100% RH moist room and 21 days in a lab environment was used to simulate field condition. Through the comparison of compressive strength, surface resistivity, bulk diffusion, and relative humidity tests, it was found that:

- The hybrid curing condition (i.e., 21 days of lab environment after 7 days of 100% RH curing) produced a higher compressive strength than the 100% RH curing condition, except for the mixtures 50TI/50S/0ICA (w/cm of 0.35) and 50TI/50S/250ICA (w/cm of 0.45). The application of saturated fine ICAs reduced the strength magnitude variation between the two different curing conditions (hybrid curing vs 100% RH curing).
- At the age of 56 days, the mixtures with saturated fine ICAs had either equal or higher surface resistivity than those without saturated fine ICAs for the hybrid curing condition.
- For w/cm of 0.35, the hybrid curing condition produced a higher apparent coefficient of chloride diffusion for the 100TI and 50TI/50S mixtures. However, the application of saturated fine ICAs was able to lower the apparent coefficient of chloride diffusion for these mixtures.
- At the age of 7 days, the mixtures with saturated fine ICAs had a higher relative humidity than those without saturated fine ICAs, indicating that saturated fine ICAs were able to supply water to the surrounding matrix. For w/cm of 0.35, the mixtures with saturated fine ICAs also had a higher relative humidity than those without saturated fine ICAs (except for mixtures with cementitious system 70TI/30C) at the age of 56 days, which shows that saturated fine ICAs were able to continuously supply water to the surrounding matrix.

Recommendations

The results of this study show that the application of saturated fine ICAs reduced the compressive strength magnitude variation between the 100% relative humidity (RH) moist room curing condition and the hybrid curing condition, and produced either equal or higher surface resistivity to the mixtures for the hybrid curing condition at the age of 56 days. For the combination of w/cm of 0.35 and the hybrid curing condition, the application of saturated fine ICAs also produced a lower apparent coefficient of chloride diffusion for mixtures with cementitious system 100TI and 50TI/50S. Hence, internal curing could be employed to reduce concrete's permeability when the mixtures are properly designed.

Acronyms, Abbreviations, and Symbols

Term	Description
AASHTO	American Association of State Highway and Transportation Officials
cm	centimeter(s)
DOTD	Louisiana Department of Transportation and Development
FHWA	Federal Highway Administration
ft.	foot (feet)
IC	Internal Curing
ICA	Internal Curing Aggregate
ICC	Internally Cured Concrete
in.	inch(es)
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
m	meter(s)
RH	Relative Humidity
SHA	State highway agencies

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Appendix

Table 3. Fresh properties of all mixtures

Mix design	w/cm	Air temperature (°F)	Concrete Temperature (°F)	Slump (inch)	Air Content (%)	Unit Weight (lbs/ft^3)
100TI/0ICA	0.35	76	76	8	2.6	147.44
100TI/0ICA	0.45	76	76	8	3.2	144.4
70TI/30C/0ICA	0.35	76	76	8.75	3.6	146.88
70TI/30C/0ICA	0.45	76	76	9.25	4.4	142.56
50TI/50S/0ICA	0.35	81	79	5	3.5	147.76
50TI/50S/0ICA	0.45	81	80	9.25	3.4	144.16
100TI/250ICA	0.35	77	77	8.5	2.25	142.67
100TI/250ICA	0.45	77	77	9.5	3	137.6
70TI/30C/250ICA	0.35	74	73	9.75	1.75	145.07
70TI/30C/250ICA	0.45	75	74	11	1.75	138.93
50TI/50S/250ICA	0.35	75	74	8.75	1.75	142.13
50TI/50S/250ICA	0.45	75	74	10.25	1.25	141.33

Notes:
100TI - 100% Type I cement
70TI-30C - 70% Type I cement and 30% Class C fly ash
50TI-50S - 50% Type I cement and 50% slag
0ICA – No internal curing aggregates (ICAs)
250ICA - ICA Dosage of 250 lbs/yd^3