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Performance evaluation of curing compounds using durability parameters

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HIGHLIGHTS

- Effectiveness of five curing compounds at 25 °C and 45 °C was evaluated using three durability index tests and compressive strength test.
- Durability parameters were found to be more sensitive than compressive strength.
- Oxygen permeability index (OPI) test showed most consistent results.

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ABSTRACT

With the world facing a huge shortage of water and labourer, the use of curing compounds in place of conventional and prolonged wet curing is inevitable. However, hot weather conditions and the quality control issues in many countries necessitate diligence in the selection of curing compounds. However, the ASTM C156 standard (water loss test) – the only standard method available – exhibits large variability in results and cannot be used to reliably assess the effectiveness and qualify curing compounds. Also, the compressive strength test is not sensitive enough to assess the quality of curing compounds. Given this scenario, there is a need for an alternate test method to assess the effectiveness of curing compounds. This paper presents an experimental investigation on the suitability of tests on various durability parameters to assess the effectiveness of curing compounds. The oxygen permeability index (OPI), water sorptivity index (WSI), non-steady-state migration coefficient for chloride penetration (D_{nssm}), total porosity, and compressive strength were used as test parameters. These parameters of mortar specimens prepared using Ordinary Portland Cement and cured using wet curing, air drying, and five curing compounds were evaluated. The mortar specimens were kept in the following two controlled environments: (i) mild (25 °C, 65% RH) and (ii) hot (45 °C, 55% RH). The study found that the OPI, WSI, and D_{nssm} are suitable and more sensitive than the compressive strength in assessing the effectiveness of curing compounds. Amongst these three, OPI test showed more consistent results and can be recommended as a test for qualifying curing compounds.

1. Introduction

Curing compounds are membrane-forming chemicals that help in preventing the loss of water from the surface of concrete and thus, facilitate curing of concrete during the early stages of the hydration process [1]. The use of curing compounds not only eliminates the need for additional potable water and frequent supervision for the entire period of curing but also provides a viable solution where the conventional wet curing methods become impractical. Some of the examples are high-rise buildings, tunnel linings, and large pavement slabs. However, despite their relevance in the fast-paced construction industry of present times, which is struggling to meet its water requirements, there have been very limited attempts to investigate performance of curing compounds and the factors affecting it.

ASTM C156 provides a water loss test for the qualification of curing compounds [2]. Although ASTM C156 appears to be a fairly simple test, it has met with acute criticism worldwide because of its extremely low precision. ASTM C156 itself has reported a single-operator standard deviation of 0.13 kg/m^2 and a multi-laboratory standard deviation of 0.30 kg/m^2. Considering the limit of 0.55 kg/m^2 on water loss prescribed by ASTM C309 [3], these standard deviation values would reach to a minimum of 24 and 55% respectively. With this level of precision, it would be impossible to decide whether to pass or fail a particular curing compound

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let alone differentiating between the performances of different curing compounds [4].

Conventionally, the influence of curing on the quality of concrete in the field has been evaluated by its effect on the compressive strength of concrete and have also been studied well [5–10]. However, it has been observed that the properties of the cover concrete or the near-surface concrete can vary substantially from those of the interior concrete. These variations in the properties of concrete can extend to more than 40 mm beneath the surface, out of which the outer 20 mm exhibits the major variations [11]. These variations can result from the segregation of concrete as a result of bleeding, over working of the concrete by excessive consolidation/finishing, and the loss of water due to poor curing practices. It was observed in the studies on cement paste and mortar that drying due to poor curing practices can adversely affect the porosity, diffusivity, and water sorptivity up to a depth of 50 mm [12,13].

As the effect of curing extends only to the near-surface region, the use of a bulk property such as compressive strength appears to be an ineffective way of evaluating the curing efficiency. In fact, Fattuhi, in a study on 16 different curing compounds, found that although the water retention efficiencies of curing compounds with respect to air-dried specimens varied widely between 25% and 89%, the resultant 28-day compressive strength for all the cases were above 80% of that of the water cured specimens [14]. This practice also results in the underestimation of the role that curing plays in enhancing the durability of RC structures. Also, transport parameters have been observed to yield much better sensitivity to the effects of curing than compressive and flexural strength [15–17]. These parameters include air permeability, water sorptivity, resistance to carbonation, and chloride permeability.

Studies have shown the benefits of adopting wet curing during the early age on the durability of concrete. Seven days of wet curing has been observed to reduce the water absorption of concrete exposed to harsh environment for 360 days by 22% [18]. Through a study on Ground Granulated Blast Furnace Slag (GGBFS) concrete cured in simulated arid climate, Austin et al. have shown that the lack of wet curing could significantly increase the air permeability and water sorptivity [19]. Similarly, the water sorptivity of fly ash concretes has been observed to demonstrate greater sensitivity to deficient curing in arid climates than that of Ordinary Portland Cement (OPC) concretes [15,20]. Zhang et al. reported that the influence of curing on the chloride resistance of OPC concretes increases with increase in the water-to-cement ratio [21]. The findings of a limited number of studies on curing compounds generally highlight their inferior performance in comparison to wet curing and in some cases, marginal or even no improvement over air curing [17,19,21,22]. However, their potential in reducing the differences between the transport properties of near-surface concrete and the interior concrete has also been realized [23,24]. Curing compounds also help in mitigating plastic and drying shrinkage, although wide variations exist in the performance [25,26].

Tests on transport properties, also commonly referred to as durability tests, can serve as a rational and effective approach to characterize curing methods. However, the lack of standardization and the use of different test methods across the world render it very difficult to conclusively assess the sensitivity of these tests to curing from the existing literature. Moreover, contradictions between the results of different test methods have also been observed [27,28]. For instance, Tan and Gjorv concluded that elevated temperatures reduced the chloride resistance of concrete; however, the resistance to water penetration showed no corresponding variation with temperature [27]. In general, water sorptivity appears to be the most widely used parameter for evaluating curing efficiencies and has been observed to demonstrate great sensitivity to curing [23,29]. However, instance where surface tests such as water sorptivity, air permeability, pull-off strength, and accelerated carbonation test showed limited sensitivity to curing has also been reported [28]. Taking into account the above mentioned gaps and contradictions present in the existing literature, this study focuses on the following two objectives: (1) to evaluate and compare the performance of curing compounds (CC) with respect to conventional curing methods in different exposure conditions, and (2) to investigate the suitability of durability index (DI) tests as a screening test in evaluating the effectiveness of curing methods. The primary intention of the paper is to investigate and propose the possibility of durability index test as a screening test for curing compounds and not to investigate the chemical actions of various curing compounds. Mortar is used in this study instead of concrete because the use of concrete could complicate the analysis by the variability introduced by the use of coarse aggregates. The use of mortar facilitates more sensitivity and easier assessment of curing efficiencies of curing compounds. This is important for producing reproducible results across different laboratories and eventual standardization. This may be the reason why the ASTM C156 also suggests using mortar (instead of concrete). However, to evaluate the actual impact of a curing method on the properties of a specific concrete at site, it is imperative to conduct tests on that specific concrete and is a subject of further study.

2. Experimental procedure

2.1. Materials

Cement mortar was used in this study with a cement-to-sand ratio of 1:2.75 and a water-to-cement ratio of 0.5. A water-to-cement ratio of 0.5 was chosen to avoid self-desiccation in cement paste. It is well known that a w/c of 0.42 to 0.44 is needed for complete hydration of cement [30]. A w/c less than that can lead to self desiccation of cement paste. In such case, the use of wet curing would provide external water to the cement and help in cement hydration over and above what could be possible with the mixed water. This gives an undue advantage to wet curing when the curing efficiencies are evaluated over other methods where no such additional water is involved. To avoid such biased comparison, a rounded value of 0.5 was chosen which is above the limiting value of 0.42 to 0.44. However, in practice the use of low w/c is becoming common and is also recommended for strength as well as durability. In such cases, the use of curing compounds in isolation might not give the best possible results.

Five curing compounds, procured from three manufacturers, were used in this study. The specifications of these curing compounds and the abbreviations that are used for them in this study are presented in Table 1. Out of the five curing compounds, the curing compounds WX-1 and WX-2 were wax emulsions; RW was a resin emulsion; and RS-1 and RS-2 were resin-based compounds in organic solvents.

As per the manufacturers' data sheets, the curing compounds that were used in this study conform to ASTM C309 [3]. The curing compounds WX-1, RW, and RS-1 formed a white membrane. On the other hand, the curing compound WX-2 was white initially, but formed a translucent film upon drying. The curing compound RS-2 was aluminized and was silver-grey in colour, but left a clear film on drying. Curing compounds were applied on mortar specimens at a rate of 5–6 m^2/L (or 167–200 mL/m^2) as recommended by the manufacturers and ASTM C309 [3]. The solids content (non-volatile matter) of curing compounds was measured in the laboratory. The curing compound was spread on a glass slide as per the recommended coverage rate of 5–6 m^2/l and was left for drying in air at 25 °C and 65% RH for 24 h. The solids content is

Table 1
Details of curing compounds.

Curing compound	Generic type	Classification as per ASTM C309		Solids content, % (non-volatile matter)
		Based on colour	Based on composition	
WX-1	Wax in Water (Wax Emulsion)	Type 2	Class A	6
WX-2	Wax in Water (Wax Emulsion)	Type 1-D	Class A	25
RW	Resin in Water (Resin Emulsion)	Type 2	Class B	37
RS-1	Acrylic Resin in Organic Solvent	Type 2	Class B	40
RS-2	Acrylic Resin in Organic Solvent (Aluminised)	Type 1	Class B	50

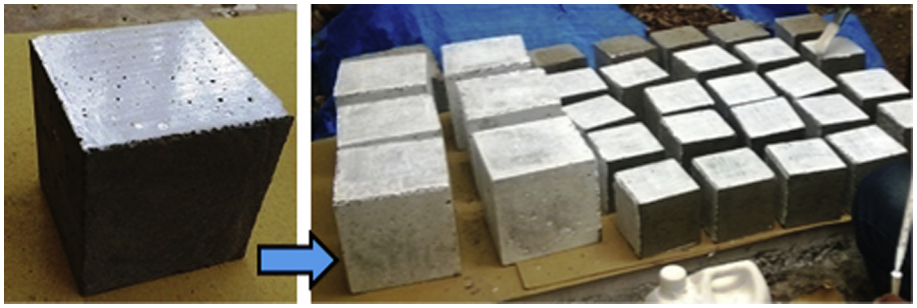

Fig. 1. Application of curing compound on the cube specimens.

provided in Table 1. The solids content presented here represents the percentage mass left after 24 h of drying with respect to the initial mass of curing compound.

2.1.1. Curing methods

Broadly, four types of curing methods were adopted in this study: (1) air drying, (2) curing compound, (3) 7 days of wet curing, and (4) continuous wet curing. Amongst the chosen curing methods, air curing and continuous wet curing represent the extremities of curing quality. As the most common practice on site is to adopt "7 days of wet curing", so "7 days of wet curing" was also studied. Under the method – curing compound, five types of curing compounds were used. Two sets of specimens were cast for each curing method/curing compound. One set of specimens was subjected the exposure conditions – (1) 25 °C, 65% RH and the another to the exposure conditions – (2) 45 °C, 55% RH (refer Section 2.1.2 (see Fig. 3)).

After casting, the moulded specimens were stored in a laboratory for 24 h. The temperature of the laboratory varied from 25 °C (minimum) to 35 °C (maximum) in 24 h. After 24 h, the specimens were extracted from the moulds and each set of specimens was then cured using one of the above mentioned curing methods. The following procedure was followed for each curing method.

1. *Air drying (Air):* The specimens were stored directly in the environmental chambers after demoulding.
2. *Curing compound (CC):* The cube specimens were cleaned with a cotton cloth to remove laitance or loose material from the surface of the specimens before applying the curing compound on them. The curing compound was applied on all the six face of the cubes using a paint brush (size – 25 mm). The brush was saturated with curing compound before starting the application to avoid the loss of curing compound through absorption by the paint brush. The excess curing compound was also carefully removed from the brush prior to the application. The surfaces were painted with curing compound in a horizontal position, as uniformly as possible, without dripping the curing compound at the edges (Fig. 1). After drying of the curing compound

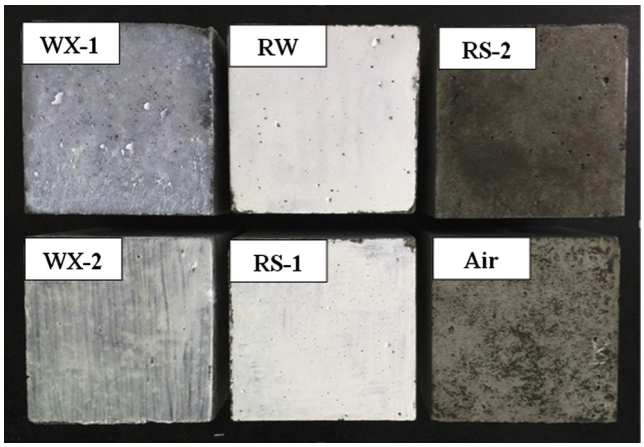

Fig. 2. The cube specimens after the application of curing compounds.

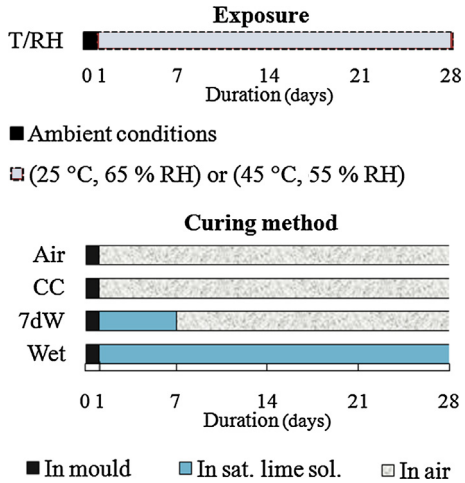

Fig. 3. Exposure conditions for each curing regime.

layer on the last painted face, the cube was turned over and the next face was painted. This procedure was followed for all the faces of the cube specimens. The application rate was maintained in the range of 5 to 6 m^2/L. Finally, the specimens were transported to the environmental chambers. The cube surfaces painted with curing compounds are shown in Fig. 2.

3. 7 days *wet curing (7dW):* The specimens were kept immersed in saturated lime solution in a closed container for 6 days after demoulding. They were taken out of the container at the age of 7 days and were stored in air until tested. The specimens were stored in the appropriate environmental chamber (one at 25 °C and another at 45 °C), both during and after the water bath period.
4. *Continuous wet curing (Wet):* The specimens were kept immersed in saturated lime solution in a closed container until they were tested. The specimens were stored in the appropriate environmental chamber (one at 25 °C and another at 45 °C) throughout the curing period.

2.1.2. Exposure conditions

Two types of exposure conditions were chosen for this study: (1) Temperature (T) of 25 ± 2 °C with relative humidity (RH) of 65 ± 10% and (2) Temperature of 45 ± 2 °C with relative humidity of 55 ± 15%. The description of curing regimes with the imposed exposure conditions is presented in Fig. 3. The effects of wind and solar radiation were not included in this study. Environmental chambers were used to maintain the mentioned controlled exposure conditions.

2.2. Testing

Compressive strength was evaluated on cube specimens of size 100 mm at the age of 3, 7, 14, and 28 days. Each compressive strength result constitutes an average of three strength tests. Three durability index (DI) tests were adopted in this study, namely, Oxygen Permeability [31], Water Sorptivity [32], and Rapid Chloride Migration Test (RCMT) [33]. Apart from these tests, water-penetrable porosity was also measured using vacuum saturation technique [32]. In case of the above mentioned four tests, four specimen replicas were tested for each result.

2.2.1. Preparation of slice specimens for durability tests

Cubes of size 150 mm were cast for durability tests. After the age of 28 days, cores of 70-mm diameter (or of 100-mm diameter for RCMT) were extracted from each of the cube specimens. Cores from the cube specimens were used instead of standard cylinder specimens for RCMT to avoid the variations introduced as a result of differences in the specimen geometry. This also facilitates valid comparison between the results of different test methods for assessing the effectiveness of the adopted curing methods. To minimize the effect of variations in the surface finish on the curing efficiency, coring was performed in the direction that is perpendicular to that of casting, i.e., across the moulded faces and thereby avoiding the cast face. In the field conditions, this is applicable to the case of formed surfaces. Then, slices of 30 mm were extracted from 5 to 35 mm and 40 to 70 mm depths from either side of the cores. The outward surface of the slices was carefully marked as the test surface after the slicing operation as shown in Fig. 4.

2.2.2. Description of test methods

(a) Oxygen permeability test [31]

Slices of diameter 70-mm and thickness 30-mm were dried in an oven for 7 days at 50 °C. After this preconditioning, the specimens were kept in a falling head permeameter as per the standard [31] and an initial pressure of 100 ± 5 kPa of oxygen gas was applied on the test face of the specimen. From the start time, the decay in pressure was recorded at an interval of 15 minutes for a period of 6 h or until the cumulative drop in pressure reached 50 ± 2.5 kPa, whichever occurred first. The coefficient of permeability (K) was calculated from this data using D'arcy law. A graph was plotted between $\ln\left(\frac{P}{P_o}\right)$ and t and using the slope of the best fit line of this curve and Darcy's law, k was calculated. Finally, OPI was computed as the negative logarithm (common) of the average of coefficients of permeability of at least 4 specimens as per Eq. (1) [31].

$$OPI = -\log_{10}\left[\frac{(k_1 + k_2 + k_3 + k_4)}{4}\right] \quad (1)$$

(b) Water sorptivity test [32]

Water Sorptivity test was performed on the same specimens that were tested for OPI. Initially, the dry mass of the specimen was recorded. Then, the specimen was placed on narrow plastic supports with the test surface dipped into saturated lime solution up to a depth of 2 mm from its surface. Mass of the specimen was recorded at 3, 5, 7, 9, 12, 16, 20, and 25 min from the time it was placed in the lime solution. The submerged surface of the specimen was wiped clean with a paper towel before weighing. After the completion of the test, the specimen was saturated with lime solution using vacuum saturation method as described in next section

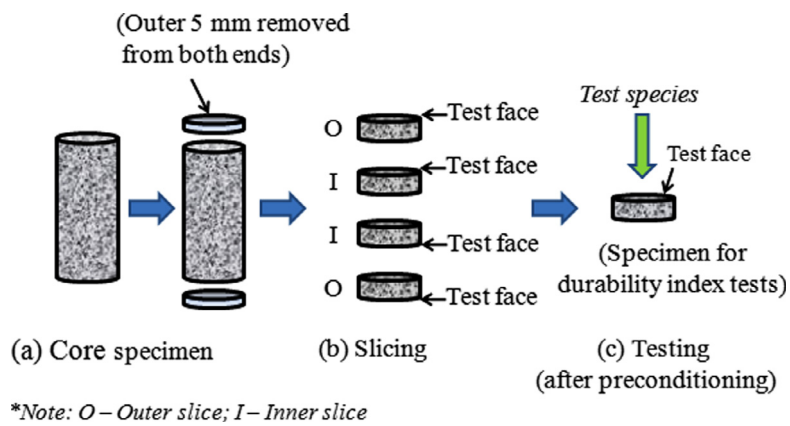

Fig. 4. Preparation of test specimens for durability tests.

to measure its water absorption capacity. Finally, the sorptivity was calculated using Eq. (2) [32].

$$S = \frac{\Delta M_t}{t^{1/2}} \cdot \frac{d}{(M_{sat} - M_{dry})} \quad (2)$$

where

S is the sorptivity in m/s$^{1/2}$
ΔM_t is the mass of water absorbed at time 't' in kg
t is the time in s
d is the specimen thickness in m
M_{sat} is the saturated mass in kg
M_{dry} is the initial mass in kg

$\frac{\Delta M_t}{t^{1/2}}$ is the slope of best fit line for mass of water absorbed versus square root of time graph.

(c) Water penetrable porosity test [32]

After being tested for oxygen permeability and water sorptivity, the 70-mm diameter and 30-mm thick slices were kept in a vacuum desiccator. A vacuum of greater than 70 kPa was maintained in the desiccators for about 3 h. Then, the desiccator was filled with saturated calcium hydroxide solution to submerge the specimens completely. Vacuum of greater than 70 kPa was maintained for another hour. At the end of one hour, the pressure inside the desiccators was allowed to rise to atmospheric pressure. The specimens were stored in the desiccator for another 18 h in submerged condition. Then, the specimens were taken out of the desiccator and their mass was measured immediately (in saturated surface dry [SSD] condition). Using the dry mass, SSD mass, and the dimensions of the specimen, the water-penetrable porosity was calculated.

(d) Rapid chloride migration test [33]

Lime saturated specimens of diameter 100 mm and thickness 50 mm were used in this test. A solution of 10% NaCl (by mass) was used as the catholyte and a solution of 0.3 N NaOH was used as the anolyte. The cathode and anode were made of stainless-steel mesh. To start the test, an initial potential of 30 V was applied across the specimen and the resulting current was measured. On the basis of the obtained value of the current, the final voltage was selected from NT Build 492 [33]. Initial current was measured after applying the final voltage across the specimen. Temperature of the anolyte was also recorded. Final current and temperature were measured at the end of the test duration. Then, the specimens were extracted from the sleeves and were split into two halves in longitudinal direction. The split face was sprayed with 0.1 M silver nitrate solution which on reacting with chlorides forms a white precipitate of silver chloride. The depth of silver chloride from the incident face was measured at every 10 mm to obtain the penetration depth of chlorides (see Fig. 4). However, the outer 10 mm at both the edges were not included in this measurement to avoid edge effects.

Non-steady-state migration coefficient (D_{nssm}) was calculated using the following simplified equation (Eq. (3)) [33].

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)Lx_d}{(U-2)}}\right) \quad (3)$$

where

D_{nssm} is non-steady-state migration coefficient in 10^{-12} m^2/s
T is average temperature of anolyte during the test in °C
L is specimen thickness in mm
U is applied potential in V
t is time in h
x_d is average penetration depth of chlorides in mm

3. Results and discussions

3.1. Compressive strength

Table 2 presents the compressive strength of mortar specimens up to 28 days under each curing regime at both the temperatures. For the ease of comparison and interpretation, the *relative strength* is defined as the percentage compressive strength achieved under each curing regime with respect to the compressive strength of continuously wet-cured specimens at the same age. This *relative strength* for various cases is presented in Fig. 5. Compressive strength results for the exposure conditions of 25 °C and 65% RH suggests that the influence of the quality of curing is apparent throughout the exposure period from as early as 3 days to the later age of 28 days. However, the distinction between the performances of curing methods is clearer from the age of 14 days onwards.

Table 2
Compressive strength of mortar cube specimens (in MPa).

Curing method	Exposure: 25 °C/65% RH				Exposure: 45 °C/55% RH			
	Age (days)				Age (days)			
	3	7	14	28	3	7	14	28
Air	15.8 (1.2)	21.7 (2.0)	23 (0.2)	26.4 (4.0)	22.1 (0.8)	26.5 (1.3)	27.1 (1.8)	23.9 (1.3)
WX-1	13.7 (0.9)	19.4 (1.2)	23.6 (0.6)	24.0 (0.4)	19.6 (1.0)	21.0 (1.2)	22.1 (1.2)	23.2 (0.5)
WX-2	17.2 (1)	25.1 (0.8)	29.1 (1.2)	32.3 (0.1)	23.9 (2)	30.6 (0.7)	33.5 (1)	29.8 (0.3)
RW	15.8 (1.6)	25.2 (5.6)	22.8 (2.2)	24.8 (1.4)	20.7 (0.2)	25.8 (5.5)	24.8 (4.6)	22.6 (1.4)
RS-1	15.7 (0.8)	20.5 (4.1)	24.4 (0.4)	27.7 (0.6)	18.6 (0.9)	22.1 (1.8)	23.4 (0.3)	20.8 (1.4)
RS-2	18 (0.4)	22 (1.4)	25.8 (2.2)	29.2 (1.7)	21.5 (0.8)	23.9 (0.4)	24.8 (2.3)	26.5 (0.3)
7dW	15.2 (0.7)	25.6 (0.5)	36.9 (2.5)	35.5 (1.9)	22.5 (0.7)	35.0 (3.4)	45.8 (1.8)	43.2 (4.4)
Wet	18.9 (1.3)	28.4 (1.5)	34.9 (0.8)	45.4 (1.9)	22.5 (0.7)	35.0 (3.4)	39.6 (1.4)	42.4 (2)

Note: Values in the parentheses represent standard deviation.

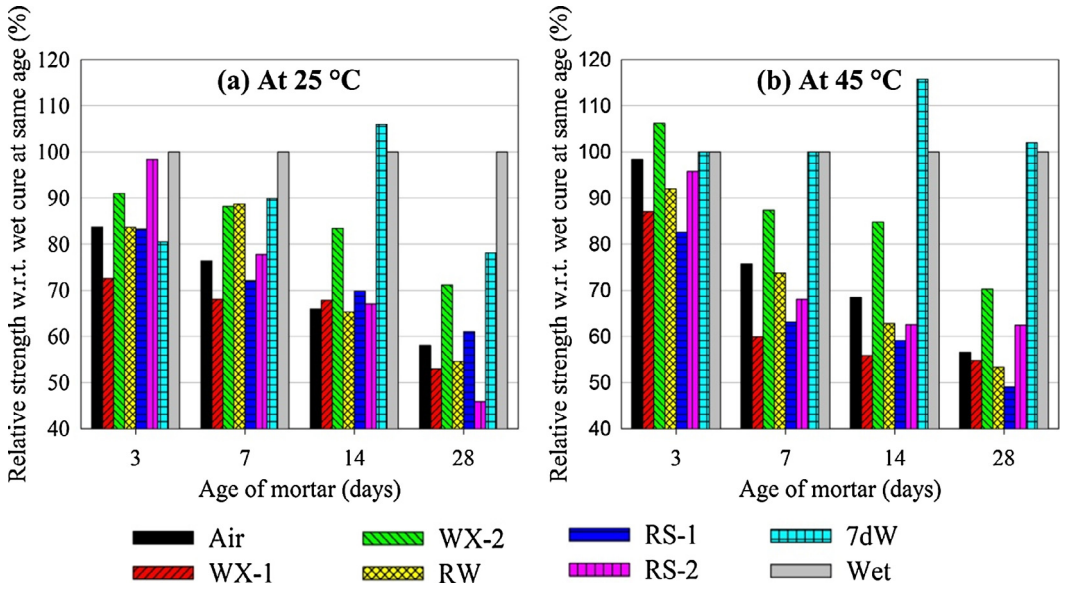

Fig. 5. Percentage compressive strength of mortar cured under different curing regimes relative to the strength of the continuously wet-cured mortar at same temperature and age.

At 25 °C and 65% RH, wet curing (Wet) leads to the highest compressive strength at 28 days as expected (Fig. 5(a)). The loss in compressive strength due to deficient curing, throughout the period of 28 days, is prominently visible in the case of air drying (Air). On the other hand, curing compound WX-2 results in a relative compressive strength of 71% with respect to that of wet-cured specimens at 28 days, which is only about 7% less than that of 7-day wet curing. However, none of the other curing compounds leads to any significant improvement over air curing. In the case of curing compounds, the rate of gain of compressive strength reduces substantially after 3 days, suggesting the unavailability of sufficient water in the pores for hydration to progress.

The exposure to a high ambient temperature of 45 °C results in a higher rate of strength gain compared to at the temperature of 25 °C. Consequently, higher strength is achieved during the early ages, i.e., 3 to 14 days, as compared to the standard laboratory exposure for all the curing methods. However, this trend reverses subsequently before 28 days. Only in the case of 7-day wet curing, the 28 day-strength at 45 °C remains higher than that at 25 °C. At this temperature the effect of curing is not apparent at the age of 3 days; however, it is clear from 7 days onwards (Fig. 5 (b)).

At 45 °C, the mortar cured with 28-day wet curing (Wet) and the mortar cured with 7-day wet curing achieve similar strengths at 28 days, which are higher than the strengths achieved under all the other curing methods. It must be noted that due to high rate of strength gain, both continuously wet-cured and 7-day wet-cured mortar, achieve more than 75% of the 28-day strength by 7 days. Hence, the gain in strength afterwards is not substantial which explains the similarity in their strengths at the age of 28 days. Moreover, the specimens for 7-day wet curing and continuous wet curing at 45 °C were cast in the same batch, so the strength results up to the age of 7 days are same for both the regimes. These results suggest that wet curing in the early ages eliminates the need for prolonged curing periods in the case of high ambient temperatures.

The trend followed by compressive strength of 7-day wet cured specimens is such that it exceeds the compressive strength of continuously wet cured specimens at the age of 14 days in both the exposure regimes. Then, at the age of 28 days, the compressive strength of 7-day cured specimens is either close to (for curing at 45 °C) or lower than (for curing at 25 °C) that of continuously wet cured specimens. The observed higher strength of the 7-day wet cured specimens than that of continuously wet cured specimens at the age of 14 days could be attributed to the difference in moisture conditions of both types of specimens.

Drying has been shown to result in higher compressive strength in the literature [34,35]. Popovics [35] explained that concrete specimens soaked in water are likely to have a moisture concentration gradient across the cross-section that results in swelling of the exterior *"wet"* concrete. This swelling is restraint by the interior *"dry"* concrete resulting in a state of self-equilibrating residual stress in the specimen. The wet exterior is subjected to biaxial compression and the dry interior to biaxial tension. This state of residual stress in a wet specimen leads to a reduction in the compressive strength of the specimen. The exact opposite occurs when the specimens are allowed to dry, i.e., exterior will shrink due to drying and vice versa. Another explanation proposed for this behavior is that drying reduces the interlayer spacing of the C-S-H gel and hence increases the Van der Waal forces between the layers [34]. This increased interlayer bonding leads to an increase in the compressive strength.

In the present case, drying of 7-day wet cured specimens from 7th day to 14th day in air storage could have led to the compressive strength exceeding that of continuously wet cured specimens at 14 days. However, later on, due to lack of sufficient water for further hydration, there is no improvement in the strength of 7-day wet cured specimens between 14 and 28 days. On the other hand, continuously wet cured specimens, owing to the availability of sufficient water, keep hydrating throughout and gain strength close to or more than 7-day wet cured specimens at the age of 28 days.

In the case of curing compounds, as in the case of 25 °C, the rate of strength gain decreases significantly after the age of 3 days at 45 °C also. Only the curing compound WX-2 results in an improvement in strength, of about 13%, over that achieved under air curing. However, while it results in a loss in strength of less than 10% at 25 °C with respect to 7-day wet curing, this loss escalates to more than 30% at 45 °C. Overall, it is apparent that the adopted curing compounds result either in no or, at best, a meagre improvement in compressive strength over air curing. Further, retrogression in strength was also observed after 14 days at 45 °C with air curing,

7-day wet curing, and curing compounds WX-2, RW, and RS-1. This retrogression of strength could have occurred due to differential drying shrinkage as a result of excessive loss of water from the surface of mortar specimens.

3.2. Transport properties of mortar in the near-surface region

3.2.1. Water-penetrable porosity

The porosity results are presented in Fig. 6(a). Air drying (Air) and wet curing lead to similar porosities, when cured at 25 °C. The porosity of 7-day wet-cured mortar at this temperature also lies very close to them. All the curing compounds result in higher porosity than air drying (Air). This is contrary to the general expectations. However, a rise in the porosity values is seen, in general, with the increase in the curing temperature from 25 °C to 45 °C as expected [36]. Decrement in the porosity is seen only in the case of 7-day wet curing at 45 °C. Otherwise, porosity results at 45 °C follow a trend similar to that at 25 °C.

The possible reason behind the observed trends in the porosity results could be partial pore filling. Wet cured specimens, owing to greater hydration, could have finer pores than the rest of the specimens. Fine porosity of the wet cured specimens could lead to a greater depth of penetration of water due to capillary suction than the rest of the specimens. Therefore, although the total amount of porosity in the case of wet cured specimens might be lower, a greater depth of penetration would lead to similar porosity result as other specimens. Similarly, the anomalous porosity in the case of 7-day wet cured specimens at 45 °C could also be a result of partial pore filling and may not represent the actual porosity.

3.2.2. Oxygen permeability index (OPI – log scale)

Fig. 6(b) shows the OPI results. It must be emphasized here that a higher value of OPI indicates superior performance and vice versa (OPI = −log K, *'K' is Coefficient of permeability*). OPI results at 25 °C indicate a large improvement in the OPI from 9.4 (Air) to 10.2 (Wet) with 28 days of wet curing. 7-day wet curing results in a very similar OPI to wet curing. On the other hand, only the curing compound WX-2 leads to a noticeable improvement — although not very substantial — in OPI over air drying (Air) with an OPI of 9.7. OPI results of all the other curing compounds remain close to or even worse (WX-1) than that of air drying (Air).

Increase in the curing temperature from 25 °C to 45 °C seems to improve OPI in the case of wet curing (Wet and 7dW). However, it seems to reduce the OPI in the case of curing compounds. In this case, none of the curing compounds leads to any improvement over air drying (Air), including curing compound WX-2. It implies that curing compound WX-2 may help in curing at 25 °C, but it may not be as effective at 45 °C. Furthermore, the superior performance of 7-day wet-cured *mortar* suggests that even a mortar achieving a *"poor"* OPI under deficient curing can achieve a *"very good"* OPI with only 7 days of proper curing. This is based on the qualitative classification for the durability potential of *concrete* (OPI > 10 implies very good performance; OPI < 9.5 implies poor performance) [29].

3.2.3. Water sorptivity index (WSI)

Higher value of WSI is indicative of deeper penetration of water into mortar and thus an inferior performance. Therefore, WSI results, as shown in Fig. 6(c), in line with OPI results, also suggest a superior performance by both the methods of wet curing over other curing methods. However, certain differences between the trends followed by OPI and WSI results can be easily noticed. First, 7-day wet curing exhibit better WSI than 28-day wet curing at both the temperatures. Second, the curing compound WX-2 yields a WSI similar to 7-day wet curing, which is also better than 28-day wet curing at 25 °C.

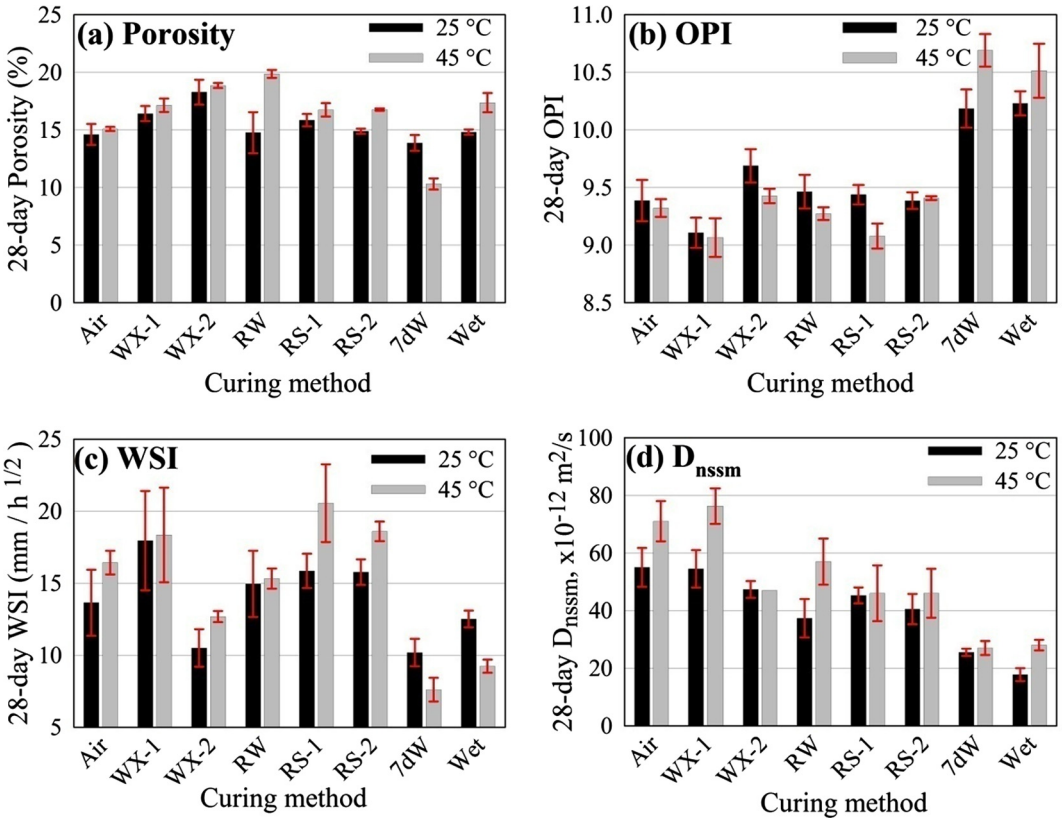

Fig. 6. Effect of laboratory curing on the properties of near-surface mortar (outer slices).

3.2.4. Non-steady-state migration coefficient for chloride penetration (D_{nssm})

The effect of lab curing on D_{nssm} of OPC mortar is shown in Fig. 6 (d). It should be noted that larger value of D_{nssm} signifies inferior performance of mortar. From Fig. 6(d), it is apparent that D_{nssm} increases significantly in the absence of wet curing. 28-day wet curing results in the lowest value of D_{nssm} at 25 °C, followed by 7-day wet curing. Curing compounds lead to improvement over air curing at 25 °C, although that is only a minor improvement. Increase in curing temperature seems to degrade the performance of OPC mortar to resist chloride penetration, in general. At 45 °C, 28-day wet curing and 7-day wet curing both result in similar D_{nssm}. All the curing compounds except WX-1 result in superior D_{nssm} than that of air curing.

Migration results differ with OPI and WSI results in certain aspects. First, curing compounds, in general, lead to better D_{nssm} than air drying (Air) at both the temperatures as opposed to their OPI and WSI, which were similar to or worse than those of air-dried (Air) mortar. Second, curing compound WX-2 does not stand out well in migration results, compared to what is seen from other test results. Finally, the increase in curing temperature seems to reduce the performance of all the curing methods in migration results uniformly; however, in OPI and WSI results, wet curing and the rest of the curing methods exhibit opposite trends.

It is interesting to note that in case of wax-based curing compounds, the difference in the solids content of the two curing compounds seems to have influenced their efficiency (Table 1). However, the resin-based curing compounds, despite having higher solids content, could not demonstrate better performance than WX-2. In short, it appears that the solids content alone cannot be used as a performance-deciding factor.

3.3. Transport properties of mortar in the inner region

Fig. 7 shows the effect of curing on the porosity, OPI, and WSI of the inner mortar compared to the near-surface mortar.

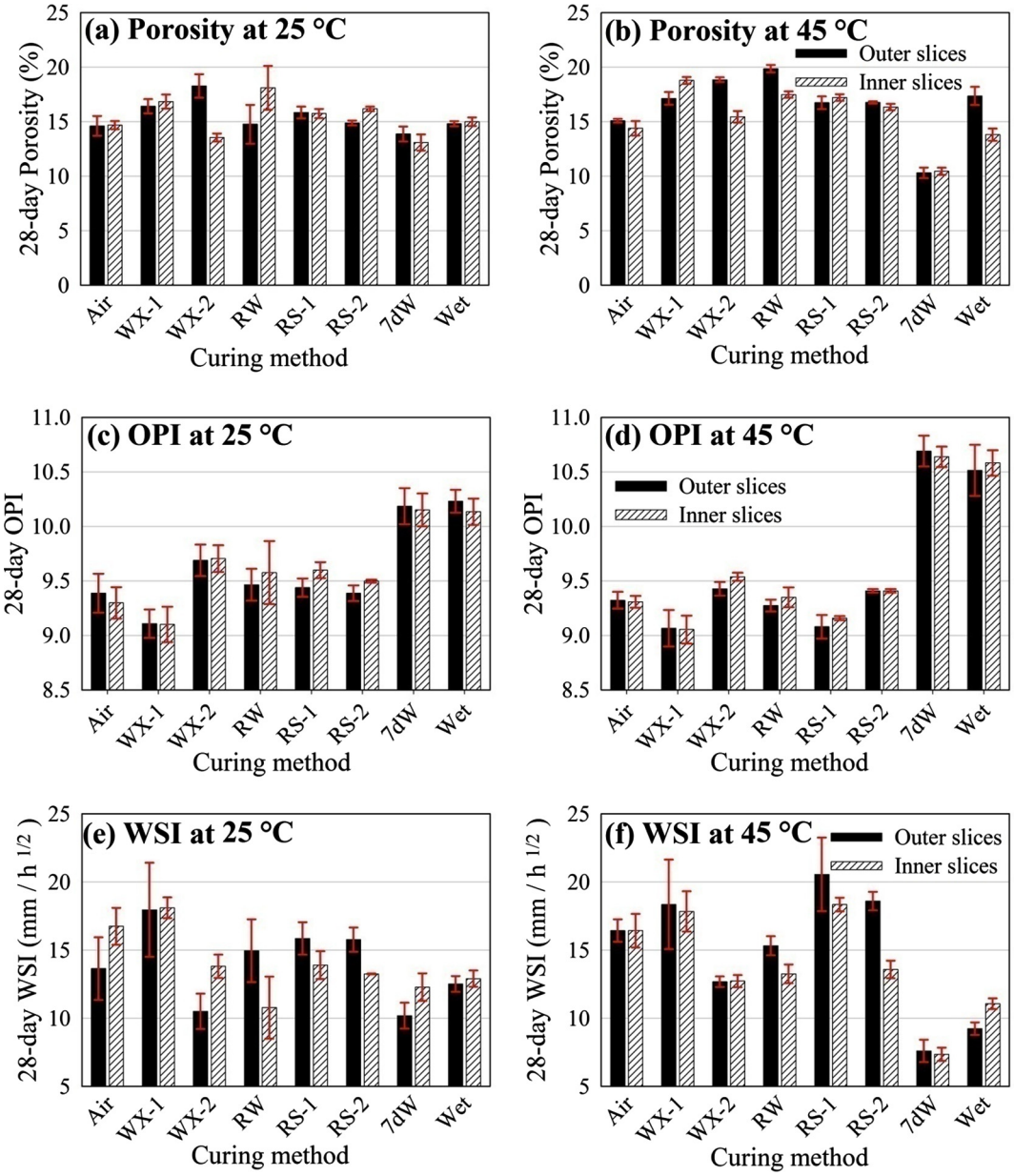

Fig. 7. Effect of laboratory curing on properties of the near-surface and inner mortar (outer and inner slices) at 25 °C and 45 °C.

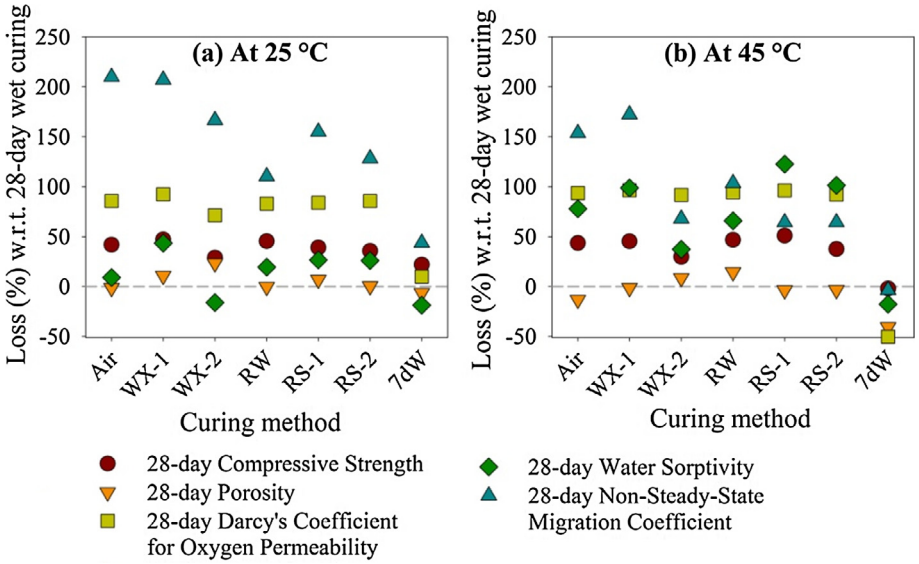

Fig. 8. Percentage loss in 28-day index values/properties for various curing methods relative to those of 28-day wet curing.

It can be inferred from the results that the inner slices do not show any significant improvement in performance as compared to the outer slices in any of the cases. While this was expected of wet-cured specimens owing to the availability of sufficient water to both outer and inner slices, some improvement in the quality of mortar with depth was expected in other cases. However, it is well known that high surface-area-to-volume ratio of the cube specimens can lead to high rate of water-loss from the surface. Owing to the high initial porosity of mortar, moisture from the core may rise towards the surface easily to maintain a uniform hygral state throughout the specimen. In this way, the continuous loss of water from the surface would have eventually led to depletion of moisture from the core of the specimen at early ages, leading to similar degrees of hydration and therefore, similar results for near-surface and inner mortar.

3.4. Sensitivities of test methods to detect differences in the effectiveness of curing methods

To facilitate comparison between the results of test methods used in this study, all the 28-day results are presented in terms of percentage decrement/loss in the test parameters with respect to the results of 28-day wet cured mortar in Fig. 8.

In general, Darcy's coefficient of permeability (from OPI test), WSI, and compressive strength follow trends similar to each other at both the temperatures. Contrary to this, non-steady-state migration coefficient shows distinctly different behaviour in certain cases. For example, the curing compound RW at 25 °C and the curing compounds RS-1 and RS-2 at 25 and 45 °C result in lower loss in the performance than curing compound WX-2. Moreover, porosity does not seem to show significant variations with the change in curing methods.

Compressive strength exhibits a maximum variation of 20 to 40% at 25 and 45 °C respectively due to change in curing method. On the other hand, Oxygen permeability shows a variation of 76 and 166% at 25 and 45 °C respectively. Similarly, migration coefficient exhibits a variation of 112% and 158% at the two temperatures. On the other hand, WSI exhibits a variation of mere 28% at 25 °C compared to a variation of 96% at 45 °C. Both WSI and migration coefficient also demonstrate large variability in the results.

In conclusion, OPI seems to give clear indication of large variations in the quality of curing with high degree of reliability. This is in agreement with the literature [37]. On the other hand, WSI results show the intermediate variations with much more prominence, which in some cases can lead to exaggerated view of the apparent performance. Chloride migration coefficient seems to identify large differences in the quality of curing with high sensitivity; however, high variability observed in the data could limit its use for the intermediate cases. Further, water penetrable porosity shows very low sensitivity to curing.

4. Conclusions and limitations

An experimental program was followed to evaluate the influence of various curing methods on the strength and durability characteristics of OPC mortar (with w/c of 0.5) at 25 and 45 °C exposure temperature. The curing methods that were adopted in this study included five curing compounds, two durations of wet curing (i.e., 7 and 28 days), and air drying. The two exposure conditions (i) 25 °C at 65% RH and (ii) 45 °C at 55% RH were used. The performance of curing compounds was evaluated using compressive strength, porosity, oxygen permeability index (OPI), water sorptivity index (WSI), and non-steady-state migration coefficient (D_{nssm}) for chloride penetration. The following conclusions are drawn from this study.

4.1. Performance of curing compounds with respect to conventional curing methods

One wax-based curing compound exhibit better performance than air curing. The other wax-based and three resin-based compounds exhibit very poor performance to the extent that performance of these four compounds could not be even differentiated from that of air drying (no curing). Both strength and durability performance depreciate immensely in the absence of wet curing. Wet curing, until the age of 7 days, seems to be more than satisfactory in achieving the potential of OPC mortar, which should translate to OPC concretes as well. The increase in the curing temperature from 25 to 45 °C, in general, seems to downgrade both the transport characteristics and compressive strength as expected. However, in the case of 7-day wet curing and continuous-wet curing, perhaps due to a greater degree of hydration during the first 7 days at 45 °C compared to that at 25 °C, this trend seems to reverse for most of the characteristics.

4.2. Sensitivity of test methods to curing

A comparison of all the test results indicates the durability parameters have greater 'sensitivity to curing' than the compressive strength. In particular, OPI test exhibits high sensitivity and generate consistent results with low variability; hence, can be recommended as a qualifying test for curing compounds. Although WSI and D_{nssm} also demonstrate high percentage changes in the results with the changes in curing quality in some cases, the lack of consistency and large variations in the results reduce their overall reliability. On the other hand, the total porosity test completely fails to detect changes in the curing quality. Also, the observed subtle differences in the trends of different durability tests indicate that curing may affect the transport properties to different degrees and in different ways. The influence of curing with depth could not be detected possibly because of the high surface-to-volume ratio and large initial porosity of the mortar specimens. These conclusions are drawn from studies under laboratory controlled conditions. Similar studies on field-cured specimens should be conducted, which would further help in developing guidelines for the selection of curing compounds.

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