PERFORMANCE EVALUATION OF CURING COMPOUNDS USING STRENGTH AND DURABILITY PARAMETERS OF CONCRETE

A THESIS

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **"Performance evaluation of curing compounds using strength and durability parameters of concrete"**, submitted by **Saarthak Surana**, to the Indian Institute of Technology Madras, Chennai for the award of the degree of Master of Science, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

Curing compounds can provide a sustainable alternative to the conventional wet methods of curing. However, insufficient knowledge about their performance limits their usage in the industry. Most importantly, the effect of curing on the transport properties of concrete, which affect the durability of concrete, rather than on only strength need to be studied extensively to be able to move towards durable construction. Taking this into account, this work focuses on the comparative study of the influence of curing compounds on the strength and durability of cementitious systems in different exposure conditions and the suitability of durability index tests used for this purpose.

The study was divided into two parts on the basis of type of exposure conditions: (i) laboratory exposure and (ii) field exposure. In laboratory exposure study, specimens made with ordinary Portland cement mortar were cured at two levels of temperature prevalent in India: (a) 25 °C and (b) 45 °C. In field exposure study, reinforced-concrete slab specimens were cured under natural environmental conditions of Chennai, India. In addition to compressive strength test, different durability index tests: oxygen permeability, water sorptivity, rapid chloride migration, and surface resistivity test, were performed on the specimens cured using different curing methods in both of these studies.

The curing compounds used in this work exhibited very limited performance in water retention. Hence, they were found to be inferior to wet curing in both strength and durability aspects by a considerable amount, especially at 45 °C. In general, durability tests were found sensitive to large variations in curing quality, in controlled exposure conditions. However, smaller variations could not be observed in all the tests. In the case of field study, large variations and inconsistencies were observed in the results. Durability tests were found to have a limited sensitivity in field conditions.

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ABRREVIATIONS

7dH	7-day Wet Hessian Curing
7dW	7-day Wet Curing
Air	Air Curing
CC	Curing Compound
C-S-H	Calcium Silicate Hydrate
DI	Durability Index
OPC	Ordinary Portland Cement
OPI	Oxygen Permeability Index
RCMT	Rapid Chloride Migration Test
RCPT	Rapid Chloride Permeability Test
RH	Relative Humidity
RS	Resin- and Solvent-based curing compound
RW	Resin- and Water-based curing compound
SCM	Supplementary Cementitious Material
T	Temperature
w/c	Water-to-cement ratio
WX	Wax-based curing compound

1. INTRODUCTION

1.1 PROBLEM STATEMENT

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 (ASTM C309 2011). 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 such as in the case of 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 their performance and the factors affecting it. This is obvious from the sparse literature available on this subject. Further, currently the only standardized test method available for evaluating the efficiency of curing compounds is ASTM C156 (2011). However, this test method suffers from such a large variability (ASTM C156 2011) in its results that it cannot be relied upon for the selection or rejection of curing compounds (Senbetta 1988).

The performance of curing methods has conventionally been assessed by its effect on the compressive strength of concrete. However, the effect of curing is known to extend only up to a few centimetres from the surface, which constitutes the cover zone of the Reinforced Concrete (RC) (Senbetta and Scholer 1984; Patel et al. 1985; Parrott 1992). As the cover zone is of utmost concern in ensuring the durability of concrete, there is a need to evaluate the effect of curing on the transport properties of concrete rather than on the compressive strength. Moreover, the majority of research on this subject focuses on curing under standard laboratory condition—which are starkly different from the field conditions.

Therefore, to be of actual practical significance, the effect of curing must be studied by taking into account the different exposure conditions prevalent in the region. To achieve this, test methods that are sensitive enough to reliably assess the performance of curing methods both in the lab and the field should be identified. This would also serve as an approach for the performance evaluation and acceptance of curing compounds.

1.2 OBJECTIVES AND SCOPE OF THE STUDY

The two objectives of this study are presented below. The respective scope is also presented in bulleted list.

1. To evaluate and compare the performance of curing compounds (CC) with respect to conventional curing methods in different exposure conditions.

   - Curing methods
     - Five commercially-available curing compounds
     - Wet curing for 7 and 28 days
     - Air curing
   - Cementitious systems:
     - OPC mortar
     - Concrete

2. To assess the suitability of durability indicator tests in evaluating the effectiveness of curing methods in laboratory and field conditions.

   - Durability parameters:
     - Oxygen permeability index
     - Water sorptivity index
     - Non-steady-state chloride migration coefficient
     - Surface resistivity
   - Exposure conditions:
     - Laboratory exposure: 25 ± 2 °C, 65 ± 10 % RH and 45 ± 2 °C, 55 ± 15 % RH, without the effects of wind and sunlight
     - Field exposure: Temperature: average monthly minimum – 21 °C to 27 °C, average monthly maximum- 29°C to 37 °C; and average monthly RH –

approximately 50 % to 90 % in the period of exposure. [hot and humid weather conditions of IIT Madras campus in Chennai (Tamil Nadu, India)]

1.3 RESEARCH HYPOTHESIS

The hypotheses based on which Objective 1 is framed are as follows:

- Performance of curing compounds lies between that of air curing and 28-day wet curing.
- Performance of curing compounds depreciates in harsh exposure conditions compared to standard lab conditions.

The hypothesis based on which Objective 2 is framed is as follows:

- Durability parameters provide higher sensitivity to curing than compressive strength in lab as well as field conditions.

1.4 RESEARCH METHODOLOGY

Two separate test programs were adopted to achieve the objectives of this study. Test Program-1 dealt with curing of mortar specimens exposed in the controlled environment of the laboratory and testing their strength and durability parameters. On the other hand, Test Program 2 comprised of curing of concrete specimens in the field conditions of Chennai and testing of the specimens extracted from them to assess their strength and durability characteristics. Figure 1.1 illustrates the overall experimental methodology adopted for this study.

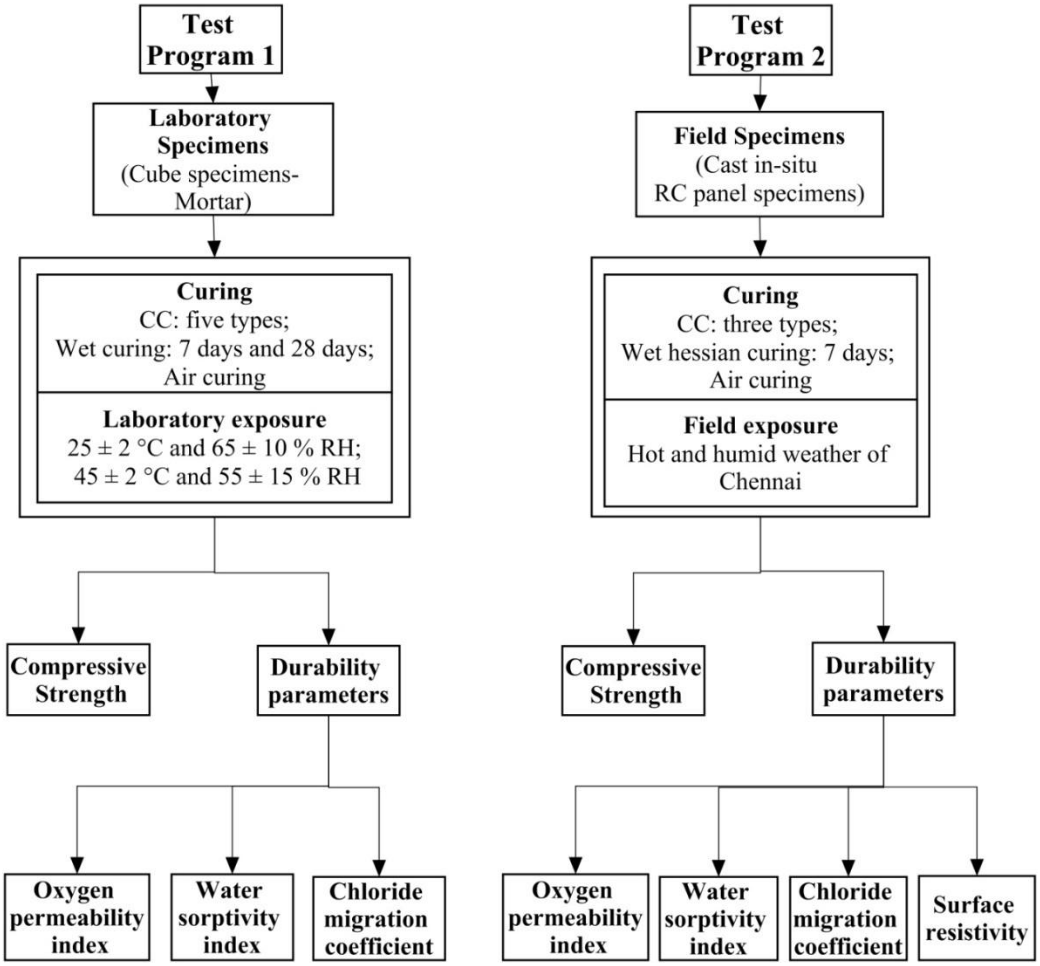


Figure 1.1 The methodology that was followed for this study

1.5 THESIS ORGANIZATION

This thesis is divided into six chapters, including the present one that introduces the research problem that this thesis work attempts to address, and presents an overview of the overall scheme of the investigation carried out for that.

Chapter 2 presents a detailed description of the properties, application procedure, and the available specifications for the use of curing compounds; and a critical review of the available literature pertaining to the influence of curing on the compressive strength and the durability characteristics of concrete. This chapter highlights the contradictions and research gaps existing in this area.

Chapter 3 consists of the details of the materials and methods that were adopted in the experimental program.

Chapter 4 presents the results and discussion of the experimental investigation of the influence of laboratory curing on the water loss, compressive strength, and the durability characteristics of mortar.

Chapter 5 presents the results and discussion of the experimental investigation of the influence of field curing on the compressive strength and durability characteristics of concrete.

Chapter 6 summarizes the conclusions drawn from this study and the scope for future research. It also includes the limitations associated with this study and recommendations to improve the performance of curing compounds.

2. LITERATURE REVIEW

2.1 INTRODUCTION

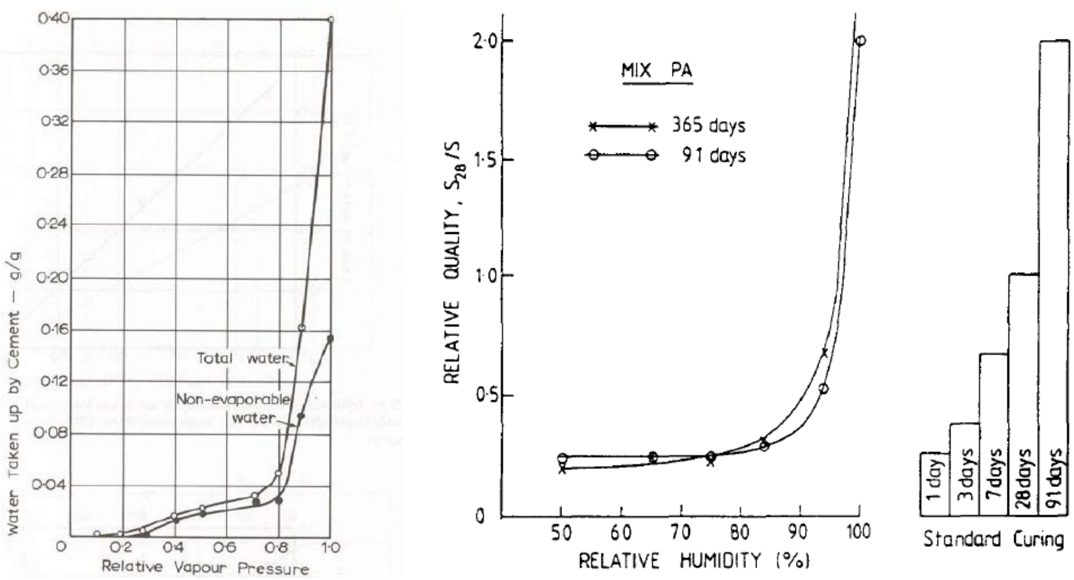
The curing of concrete has been a subject of interest and study, perhaps, since the very existence of concrete. The importance of curing is well known and well appreciated among researchers and practitioners alike. In the recent past, the understanding of the extent to which different properties of concrete are influenced by curing has evolved leading to a shift in the focus from strength-related aspects to durability-related aspects. Moreover, with the world facing a huge water crisis, alternative curing techniques are increasingly becoming more relevant. This chapter presents an overview of the major aspects of curing with a greater emphasis on curing compounds; however, it is restricted to curing at ambient temperatures only. Accelerated methods of curing are not discussed with in this chapter. Also, the major transport mechanisms affecting the durability of concrete are discussed briefly in this chapter. As the maintenance of proper temperature is an integral part of the curing process, its effect on the properties and microstructure is also discussed. Further, a detailed review of the influence of curing on the strength and durability of concrete is presented and finally, the chapter concludes with an overview of the current research needs in this area.

2.2 CURING AND ITS IMPORTANCE

Curing encompasses any measures taken to facilitate the hydration of cement by preventing the loss of water from concrete or by providing additional water, if need be, while maintaining suitable temperature to achieve the desired rate of hydration (ACI 116R 2000; IS 456 2000). Hydraulic cement, as the name suggests, needs water for the chemical reaction (hydration reaction) that results in a solid mass—which forms the basis for most of the construction materials used today, such as, concrete, masonry etc. Ordinary Portland cement in ideal conditions requires minimum water content of approximately 0.42 to 0.44 relative to the mass of cement for full hydration of cement

(Neville 1995). However, this can only be achieved if the capillary pores are sufficiently saturated with water.

Powers, in one of his most cited works, studied the hydration behavior of cement that was exposed to different water-vapour pressures for six months (Neville 1995). Through this experiment, he demonstrated that the rate of hydration of cement diminishes significantly when the relative vapour pressure in the surrounding environment goes below 0.8 (Figure 2.1(a)).



(a) (b)

Figure 2.1. Importance of degree of pore-saturation in the hydration of cement illustrated in terms of (a) water taken up by cement at different RH (adapted from Neville, 1996) and (b) sorptivity achieved by concrete at different RH (adapted from Ho et al., 1989)

This implies that hydration is heavily impeded when the relative humidity in the capillary pores of hydrating cement paste goes below 80 %. In continuation of Powers' study, Ho et al. (1989) studied the water sorptivity (defined in Section 2.6.3) of a range of concretes incorporating various combinations of mineral and chemical admixtures exposed to different RH environments. They showed that concrete maturing under an external relative humidity of 94 %, i.e., only 6 % below the air saturation level, will require a year to achieve the same sorptivity values as of a concrete cured for only 7 days under 100 % relative humidity (Figure 2.1(b)). This clearly emphasizes the importance of keeping the concrete saturated in its early ages.

Chemical reactions with positive activation energy accelerate with an increase in temperature and vice versa (Atkins and Paula 2009). Hydration of cement, being no exception, is also greatly influenced by temperature. In fact, the temperature of concrete during its early age plays a significant role in the development of its short-term and long-term properties. Low temperature during early age of concrete can delay its setting and hardening process, thereby hindering the subsequent construction processes, such as formwork removal, finishing work etc. Further, if the temperature of concrete is allowed to fall below freezing point before it gains sufficient strength, expansion of water during freezing can lead to premature cracking in the concrete. Hence, ACI 306R recommends a minimum compressive strength of 3.5 MPa before the concrete is allowed to freeze to avoid frost damage (ACI 306R 2010).

On the other hand, high temperature can reduce the time to setting and hardening substantially and thus, can facilitate faster construction. This property of concrete is especially utilized in the manufacture of precast concrete elements. However, high temperature can adversely affect the homogeneity of microstructure of the hydrated cement paste, which can hamper the long-term properties of concrete (refer to Section 2.7). High ambient temperatures coupled with other environmental factors: relative humidity, wind, and sunlight increase the moisture loss from concrete due to increased evaporation, thereby hampering the hydration process. Moreover, in such situations, the risk of plastic shrinkage cracking increases, if rapid evaporation from the concrete surface is not prevented. Additionally, large variations of temperature in a diurnal cycle can also result in large thermal gradient in the concrete, leading to thermal shrinkage cracking. It is evident from the preceding discussion that control of temperature during the curing period is imperative to the development of desirable properties.

2.3 EVAPORATION FROM FRESH CONCRETE

Evaporation involves phase change of water as a consequence of heat absorption, which is assisted by convective transport. Evaporation depends on the temperature of water and surrounding air, relative humidity of surrounding air, wind velocity, and sunlight. In the case of concrete, the temperature of concrete surface is assumed as the temperature of water. Evaporation behaviour of a fresh concrete surface is distinct from that of free water surface under constant ambient conditions. The rate of evaporation from the surface of free water remains constant with time under constant ambient conditions. However, the case of concrete is different as the temperature of concrete does not remain same even under constant ambient conditions in the early stages of hydration. In fact, there is an increase in the temperature of concrete depending upon the stage of hydration and hence, the rate of evaporation also varies accordingly with time (McCarter and Ben-Saleh 2001; Wang et al. 1994) as shown in Figure 2.2 (a). Further, the rate of evaporation from concrete is also affected by its water-vapour diffusivity after the free water on the concrete surface due to bleeding has evaporated.

Hot weather conditions are characterized by high rates of evaporation, necessitating diligence in the selection and execution of chosen curing method for adequate length of time to avoid any damage to concrete. Weather conditions can be evaluated using Menzel formula or modified NRMCA chart (ACI 305.1 2006) in terms of rate of evaporation (see Figure 2.3). The rate of evaporation which is calculated using these methods represents the rate of evaporation from a free water surface that is protected from sunlight and when the temperature, relative humidity, and wind velocity measurements are taken at the specified locations. Thus, these values cannot be used as the actual rate of evaporation from the concrete surface; however, these are useful in the assessment of potential severity of ambient environmental conditions to evaporation (ACI 308R 2001).

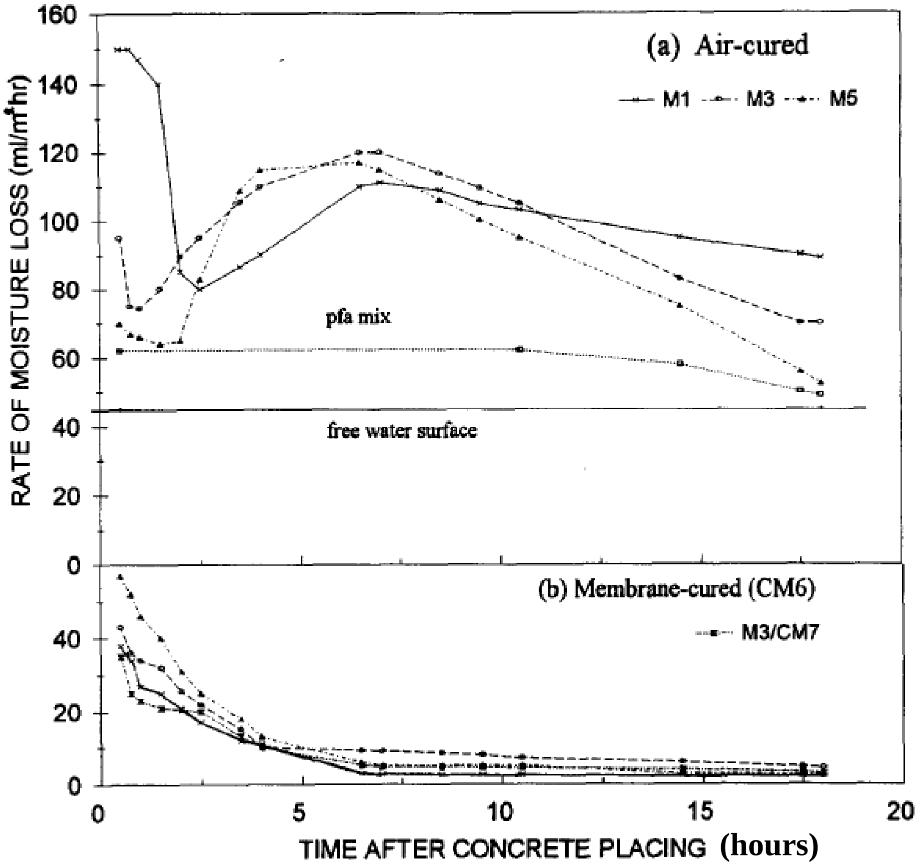


Figure 2.2. Evaporation behaviour of fresh concrete with time (in hours): M1, M2, and M3 are different OPC concretes with the same total water content (adapted from Wang et al., 1994)

Additionally, the accuracy of these estimates depends largely on the similarity between the field conditions in which the parameters are recorded on the site and the test conditions used in the preparation of nomograph. For example, the geometry of the space in the immediate proximity of the point of measurement affects the flow characteristics and velocity distribution of air, which can result in an erroneous estimation of evaporation rates. ACI 305.1 recommends the use of evaporation control measures for weather conditions with rates of evaporation equal to and above 1 kg/m^2/hr to avoid plastic shrinkage cracking (ACI 305.1 2006). However, this value of critical evaporation rate may not be applicable to concretes incorporating SCMs, in which case surface drying can start at a much lower evaporation rate and hence, a lower value of critical rate must be resorted to.

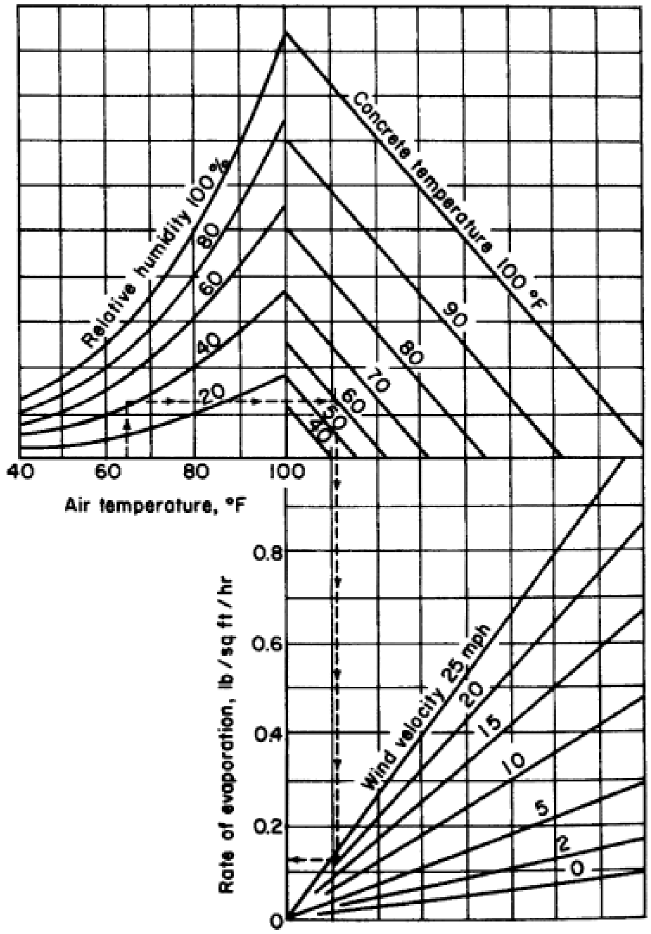


Figure 2.3. NRMCA nomograph for the estimation of evaporation (adapted from ACI 305.1, 2006)

2.4 CURING METHODS

Curing methods can be broadly classified into (1) wet methods and (2) membrane methods. Wet methods involve supplying additional water (or moisture) to either the concrete surface directly or to the air in the immediate vicinity of the concrete surface. Membrane methods, on the other hand, restrict the loss of premixed water from the concrete by means of an impervious membrane laid over the concrete surface.

2.4.1 Wet methods

Wet curing methods can be adopted in the form of ponding, sprinkling, wet blankets or fogging (ACI 308R 2001).

- In *Ponding*, horizontal surfaces are flooded with water by creating ponds with the help of temporary abutments or bunds that are made with lean mortar or plain sand.
- *Water sprinkling* involves intermittent or continuous sprinkling of water with the help of mechanical sprinklers or manually-operated water hoses.
- *Wet blanket* method utilizes the property of absorbent materials to absorb and retain water for a long period of time. Materials such as hessian cloth (or burlap), straw, and sand are commonly used for this purpose. These materials are spread over the surface of concrete and are kept continuously wet by intermittent sprinkling. Plastic sheets are also used sometimes in conjunction with hessian cloth to prevent evaporation of water from it. Multiple layers of hessian cloth are used to enhance its water-retention capacity. Similarly, the thickness of sand or straw cover is increased to prolong the water retention.
- *Fogging*, on the other hand, comprises of saturating the surrounding air by spraying a fine mist from an atomizer nozzle.

The water used for curing must not contain any substance that is detrimental to concrete in any way. Water of potable quality is considered acceptable for the purpose of curing concrete (IS 456 2000).

2.4.2 Membrane methods

Plastic sheets, curing paper, and membrane-forming curing compounds constitute this category (ACI 308R 2001) .

- ASTM C171 specifies the use of transparent and white opaque *plastic films* with a minimum nominal thickness of 100 microns for the purpose of curing concrete (ASTM C171 2016); however, dark-coloured plastic films are also common in practice.
- C*uring papers* can also be used for this purpose. Curing papers are made of two sheets of craft paper bonded together with bituminous materials and reinforced both ways with fibers. ASTM C171 limits the water vapour transmission rate of these sheet materials to a maximum of 0.01 kg/m^2 in 24 h.

- *Curing compounds* are externally-applied liquid chemical compounds which form inert membrane on drying (ASTM C309 2011). ASTM C309 (2011) specifies a water loss of not more than 0.55 kg/m^2 in 72 h for curing compounds. Curing compounds find application particularly in situations that pose constraints to the use of conventional methods of wet curing in terms of either economy or feasibility. Some of the examples are large pavement slabs, high-rise buildings, and tunnel linings.

Next section explains the criteria to be considered while selecting a curing method. Table 2.1 summarizes the advantages and disadvantages of the most common practical curing methods to be considered during the selection process.

2.4.3 Selection of curing method

Curing is necessitated when the rate of evaporation exceeds the rate of bleeding to avoid early drying of the concrete. The time when this happens can vary depending on the composition of concrete, geometry of the member, and the weather conditions. This can happen before initial setting, after final setting, or in between initial and final setting of concrete. Hence, the curing measures taken before the initial setting are referred to as 'initial curing'. Curing measures taken after final setting are referred to as 'final curing' and those taken between initial and final setting are called 'intermediate curing' (ACI 308R 2001). Different methods may have to be adopted for initial or final curing to avoid marring the surface as well as to prevent loss of water in the most efficient way. Other factors that need to be considered in the selection of a curing method are: (1) type of member—horizontal, vertical, or inclined; (2) quantity of water required; labour and cost involved; (3) degree of supervision needed; (4) weather conditions. All of these factors must be weighed with the respective efficiencies of curing methods to achieve the design performance in an optimal way.

Table 2.1. Comparison of different practical curing methods

Curing method	Ponding	**Stage of curing**	Final	**Type of member**	Horizontal
Merits			**Demerits**		
• Helps in lowering the temperature of the concrete by evaporation of water • Considered as the most effective way			• Large quantities of water are required • Abutment/ bunds are required to be made for creating the pond • Supervision necessary throughout the period of curing		
Curing method	Water sprinkling / Wet blanket	**Stage of curing**	Final	**Type of member**	Any inclination
Merits			**Demerits**		
• Absorbent material retains water for long durations—relatively lower amount of water needed • Helps in lowering the temperature of the concrete by evaporation of water			• Additional water is required • More labour is required for periodic sprinkling of water • Danger of wet-dry cycles, if the gap between intermittent sprinklings is too large • Hessian can absorb water from concrete on drying • Supervision is necessary		
Curing method	Fogging	**Stage of curing**	Initial, intermediate	**Type of member**	Any inclination
Merits			**Demerits**		
• Facilitate delayed finishing			• Additional instrumentation is required, which increases the cost • Difficult to keep air saturated in a windy climate		
Curing method	Plastic film/ Curing paper	**Stage of curing**	Initial, intermediate, final	**Type of member**	Any inclination
Merits			**Demerits**		
• No additional water is required			• Requires substantial overlapping to avoid evaporation through the edges • Difficult to keep intact in a windy climate • Can increase the temperature of the concrete due to its insulating property		
Curing method	Curing compound	**Stage of curing**	Intermediate, final	**Type of member**	Any inclination
Merits			**Demerits**		
• No additional water is required • No post-application supervision is required • White or aluminized CC helps in avoiding solar heat gain			• Requires skilled labour • Performance sensitive to the quality of application • Removal may require abrasion of the surface; tedious particularly in the case of tinned surfaces		

2.5 CURING COMPOUNDS

2.5.1 Properties and specifications

Curing compounds are available in a wide range of commercial products, both for general and special purposes. Membrane-forming curing compounds for general purpose are classified on the basis of their transparency and composition in ASTM C309 (2011). Type 1 refers to curing compounds forming clear or transparent film. Type 1D refers to curing compounds containing a fugitive dye, which leaves a clear or translucent film on drying. The fugitive dye helps to ascertain uniformity of coverage visually while applying curing compound and subsequently turns clear or translucent and thus, does not interfere with the aesthetics. Type 2 curing compounds form a white film which reflects the solar radiations and consequently helps in controlling the temperature of concrete by reducing the solar heat gain.

ASTM C309 (2011) also provides a broad classification based on the composition. It divides the curing compounds into two categories: with or without resin based compounds. Wax based curing compounds fall in the first category, Class A, and resin based curing compounds fall in the second category, Class B. However, the point of such a broad and vague classification is not clear as a wide variation in the performance is observed for both the classes of curing compound in the literature reviewed for this study.

Currently, most of the curing compounds are composed of wax, acrylic resin, hydrocarbon resin, styrene butadiene latex etc. Aluminized resin-based curing compounds are also commercially available; however, these are not specified in ASTM C309. Aluminized curing compounds can help in reducing the thermal gain by reflecting solar radiation. Minnesota Department of Transportation specifies the use of 100 % poly-alpha-methyl styrene in a total solids content of 42 %, which was found very effective in the other parts of US (Vandenbossche 2001). However, earlier, linseed oil emulsion based curing compound was specified for extreme weather in these specifications.

In some cases, silicate-based compounds have also been considered as curing compounds (Al-Khaiat and Fattuhi 2001; Fattuhi 1986; Xue et al. 2015) even though ASTM C309 (2011) clearly excludes them from the category of curing compounds. The reason behind this exclusion is that inorganic silicates, the most common is sodium silicate, do not form an inert membrane over the concrete surface; but rather react with the calcium hydroxide present in the concrete to form a type of calcium silicate gel. Hence, the application of sodium silicate may increase the surface hardness, but its ability to facilitate the process of curing is not well founded.

Some variants of curing compounds also exhibit additional features and can act as de-bonding agents, primer coat for paint etc. Furthermore, ASTM C1315 (2011) also specifies the use and properties of curing compounds to be used as a long-term sealing membrane in deleterious environments, which include acidic and alkaline environments in addition to UV exposure (ASTM C1315 2011). A comparison between the specifications under ASTM C309 (2011) and ASTM C1315 (2011) is presented in Table 2.2.

ASTM C309 restricts the water loss through a curing compound to 0.55 kg/m^2 in 72 h when tested in accordance with ASTM C156 (2011). ASTM C156 (2011) describes a standard test method for water loss through curing compounds. It is essentially a water vapour transpiration test in which the water loss of a mortar slab specimen (applied with curing compound and stored at a temperature of 37.8 ± 1.1 °C (100 ± 2 °F), relative humidity of 32 ± 2 %, and a wind velocity sufficient to generate an evaporation rate of 2.0 to 3.4 g/h) is measured after 72 hours.

Although ASTM C156 (2011) 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, 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 let alone differentiating between the performances of different curing compounds. Despite the severity of its ineffectiveness and need for a sensitive qualification test, there has been disparagingly few well documented attempts to improve upon the existing performance of this test method.

Table 2.2. Comparison between the standard specifications for general- (ASTM C309) and special-purpose (ASTM C1315) curing compounds

Characteristics	**ASTM C309 (2011)**	**ASTM C1315 (2011)**
Functional requirements	Curing	Curing, acid resistance, alkali resistance, adhesion promotion, resistance to UV degradation
Transparency	Type 1 (Clear or translucent)	Type I (Clear or translucent)
	Type 1-D (Clear or translucent with fugitive dye)	Type II (White pigmented)
	Type 2 (White pigmented)	
Yellowing	-	Class A (Non-yellowing)
	-	Class B (Moderate yellowing)
	-	Class C (No restrictions on yellowing or darkening)
Composition	Class A (No restrictions)	-
	Class B (Resin based)	-
Application rate	5.0 m2/L	Type I: 7.4 m2/L
		Type II: 5.0 m2/L
Water loss (as per ASTM C156)	< 0.55 kg/m2 in 72 h	< 0.40 kg/m2 in 72 h
Drying time	Not more than 4 h	Not more than 4 h
Reflectance (white pigmented)	60 % (minimum)	65 % (minimum)
Shelf-life	6 months (minimum)	6 months (minimum)
Solid content	-	25 % or more (excluding pigment solids)

So as to mention one of those studies, Audenaert and Schutter conducted a round robin study for developing a water loss test for curing compounds (Audenaert and Schutter 2002). In their study, they could establish a correlation between the evaporation efficiency at the end of 7 days with 28th day compressive strength; however, they have not discussed about the precision of the test method. Other standard test methods used for this purpose include AASHTO T 155 (2013) and BS 7542 (1992) which are essentially identical to ASTM C156 (2011). Other properties, which are required to be complied with, in ASTM C309 (2011) are reflectance, drying time, long-term settling, and Volatile Organic Compound (VOC) content.

2.5.2 Application process

Other than the composition, the performance of a curing compound is dictated largely by the diligence exercised in its application. Curing compounds can be applied by spraying, brush-painting, or roller-painting. Spraying is the preferred choice for horizontal surfaces because the curing compounds are applied before the concrete has finally set. On the other hand, both spraying and painting can be used for formed surfaces. While spraying should be the preferred choice for large surfaces, intricacies involved in the spraying operations must be properly taken care of to achieve a uniform coverage rate. Various factors that need to be considered are: type of nozzle used, air pressure used, height of the nozzle from the surface, spacing between the nozzles, speed of traverse of the nozzle over the concrete surface, and time of start of the application. Another important aspect of application is sampling of the curing compound. Curing compound solids have a high tendency to settle. So, curing compounds must be vigorously stirred before using them (ACI 308R 2001).

Generally, atomizer nozzles generate three types of spray patterns: flat fan, full cone, and hollow cone type spray patterns. In flat fan spraying, the curing compound is sprayed in a nearly flat cone generating a narrow strip on the applied surface, whereas the full or hollow cone spraying results in solid or hollow circular patterns on the applied surface. However, as curing compounds are generally applied on large surfaces over which nozzles are moved from one end to another, the flat fan type nozzle is preferred. Compressed air is used to atomize the curing compound. High pressure generates fine spray with small diameter droplets, which would enhance the uniformity of coverage; however, fine droplets would also suffer greater evaporation and greater drift due to wind resulting in the loss of curing compound. Hence, the amount of pressure needs to be optimized as per the prevailing weather conditions and adequate protection should be provided from wind by using windshields or wind barriers. Moreover, if the nozzles are not cleaned at regular intervals, the curing compound can cause clogging of the nozzles, which would reduce the application rate substantially (Vandenbossche 2001).

If multiple nozzles are used at the same time, the spacing of the nozzles and the height of the boom should be adjusted so as to achieve an overlap of at least 30 % between adjacent sprays (Vandenbossche 2001). This is because the coverage rate is not uniform across the width even in the case of a single nozzle due to various factors such as nozzle design, capacity, pressure used, and wind etc. Hence, overlapping is required to have a uniform coverage. A typical arrangement is shown in Figure 2.4. Finally, the cart speed is governed by the rate of application. Application can be done in multiple passes to get uniform coverage; however, the downside of this is that the cumulative increase in the loss of curing compound to air with the increase in the number of passes.

The application of curing compound should be initiated immediately following the disappearance of the bleed water sheen from the surface of concrete (ACI 308R 2001; Wang 2003). Applying curing compound before the termination of bleeding and evaporation of bleed water can interfere with membrane formation and can also induce cracking in the film (ACI 308R 2001). On the other hand, delay in the application can increase the loss of water from the concrete. Moreover, application on the dry surface can cause absorption of curing compound into the concrete resulting in excessive number of pin holes in the membrane. Contrary to this general notion about the time of application, findings of Wang et al. suggest that the curing compound should be applied as soon as possible after the placing of concrete to minimize even the loss of bleed water to the environment (Wang et al. 1994). However, besides the performance issues, this may not be possible in field conditions where surface gradients are common for the purpose of providing drainage and thus, can result in the draining of applied curing compound along with the bleed water.

Figure 2.4. Spraying of curing compound using a paver machine (adapted from: "Poly-Alphamethylstyrene Concrete Curing Compound", 2016)

2.6 TRANSPORT MECHANISMS

Transport of deleterious substances into concrete can lead to deterioration of concrete, for example, by sulphate attack or chloride-induced/carbonation-induced corrosion of embedded steel. These substances enter into concrete through a combination of transport mechanisms; however, for the ease of study, transport mechanisms are generally studied individually. This section describes fundamental transport mechanisms that are most important in the context of concrete.

2.6.1 Diffusion

Diffusion is the process in which net movement of matter occurs from the region of high concentration to the region of low concentration. This is attributed to the random motion of the particle species, also known as Brownian motion, which results from their thermal energy. As the probability of particles moving from a region of high concentration to a region of low concentration is higher than the probability of particles moving in the opposite direction, due to the number of particles present at each side, net movement of mass occurs. Diffusion is easier in gases and liquids than solids due to the limited movement of atoms/molecules possible in the solids.

Diffusion is mathematically described by Fick's laws. Fick's first law states that the time rate of transfer of mass per unit area (flux) at any point in a steady state is directly proportional to its concentration gradient at that point. Fick's first law can be represented in one-dimension using Equation (2.1) (Kropp and Alexander 2007).

$$J(x) = -D\frac{\partial c}{\partial x} \tag{2.1}$$

where

$J(x)$ is the mass flux ($\frac{1}{A}\frac{\partial m}{\partial t}$) at any point '$x$' in x direction (g/m^2.s)

D is the diffusion coefficient (m^2/s)

c is the concentration (g/m^3)

Diffusion coefficient, D, also known as diffusivity, is specific to the diffusion of a particular species in a specific fluid. It depends on the fluid present in the pores and the pore structure of the porous medium. Diffusibility, on the other hand, represents the property of the medium to allow diffusion through it and thus, is solely an intrinsic material property.

In the case of non-steady state diffusion, concentration at a point changes with time (t) and this is described by Fick's second law of diffusion (Equation (2.2)), which can be derived from the Fick's first law and conservation of mass (Kropp and Alexander 2007).

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial c}{\partial x}\right) \tag{2.2}$$

It should be noted that if any portion of the diffusing species is getting consumed in the porous medium through physical or chemical phenomena, it should be accounted in the above equation as sink. Examples of these phenomena in concrete include binding of chlorides and reaction of carbon dioxide with hydrated cement paste.

In the context of concrete, diffusivity can be measured by gas diffusion, water vapour diffusion, and ionic diffusion tests. Gas diffusion test involves detection of traces of a gas at the other side after it has diffused through the dried specimen from original side. Water vapour diffusion can be determined using transmission of water vapour through the dried specimen or transpiration from saturated specimen (Basheer et al. 2001). In case of ionic diffusion, the test durations are very long and specimen is immersed or ponded in water having ionic species after saturation. So, the concrete is subjected to the test only after attaining sufficient maturity to avoid any significant changes in the microstructure during the test period. To maintain electrical neutrality in the specimen and the solution, oppositely charged ions must diffuse equally; however, that does not happen due to the difference in the mobility of different ionic species. This disturbs the electrical neutrality and consequently, results in an electric field between the specimen and the solution. Movement of ions under this electric field is known as electromigration (refer to Section 2.6.4), which should also be accounted for in the diffusion tests (Kropp and Alexander 2007).

2.6.2 Permeation

Permeation is defined as the process in which a fluid flows through a porous medium saturated with the permeating fluid under a pressure differential. D’Arcy in his experimental investigations on the flow of water in soils found out that for laminar flow of a fluid through a porous medium, the rate of flow is directly proportional to the pressure gradient. This was later derived using Navier-Stokes theorem. The constitutive relationship from D’Arcy’s law is presented below in Equation (2.3) (Kropp and Alexander 2007).

$$\frac{\partial V}{\partial t} = -KA\frac{\partial h}{\partial x} \tag{2.3}$$

where

V is the volume of the fluid discharged (m^3) in time t (s)

K is the coefficient of permeability (m/s)

A is the area of cross-section of flow (m^2)

h is the pressure head (m) and $\frac{\partial h}{\partial x}$ represents the pressure gradient in m/m.

Permeability can also be calculated using Hagen-Poisueilli's law for Newtonian compressible fluids under laminar flow in cylindrical pipes with constant cross-section (Equation (2.4)) (Kropp and Alexander 2007):

$$K = \eta\frac{Ql}{tA}.\frac{P_2}{(P_2^2 - P_1^2)} \tag{2.4}$$

where

η is the dynamic viscosity of the fluid (N.s/m^2)

Q is volumetric discharge (m^3)

l is the length of penetration (m)

P_1 is the pressure at the entry of the specimen (N/m^2)

P_2 is the pressure at the exit of the specimen (N/m^2)

K, the coefficient of permeability is also called hydraulic conductivity in geotechnical literature where the permeating fluid is water. Coefficient of permeability or simply *'permeability'* denotes the ease with which the given fluid penetrates the medium under pressure differential. As it depends on both the properties of medium and the permeating fluid, it is also known as extrinsic permeability. On the other hand, intrinsic permeability depends only on the properties of the medium. The relationship between these two is shown below in Equation (2.5) (Kropp and Alexander 2007):

$$K = K_i \frac{\eta}{\rho g} \tag{2.5}$$

where

K is the coefficient of permeability (m/s)

K_i is the intrinsic permeability (m^2)

η is the dynamic viscosity of the fluid ($N.s/m^2$)

ρ is the density of the fluid (kg/m^3)

g is the acceleration due to gravity (m/s^2)

Theoretically, intrinsic permeability should be constant for a medium irrespective of whether a gas or a liquid is used to measure it. However, the phenomenon of gas slippage in the case of gases introduces differences in the measured permeability for different fluids. Contrary to the flow of liquids, when a gas is flowing along a wall, the layer near the wall surface has a finite velocity in the direction of the flow. Consequently, the amount of gas flowing through a capillary will be greater than that calculated using Poiseuilli's equation and hence, the measured permeability will be greater. It follows that this effect gets more pronounced as the radii of the capillaries decrease and the mean free path of the gas molecules increases. For example, in the case of a highly porous medium at low pressures or when the gas permeates through fine pores at given pressure having comparable or smaller pore sizes as mean free path of the gas. However, intrinsic permeability can still be calculated by using Klinkenberg’s correction (Klinkenberg 1941). Klinkenberg found out that if the measured permeability is extrapolated to infinite pressure, it is possible to get intrinsic permeability devoid of any effect of the fluid involved (Klinkenberg 1941).

However, using very high pressures can alter the microstructure of concrete and introduce turbulence in the flow. A gas is chosen such that it does not change the microstructure while testing (Basheer 2001). Permeability depends on the porosity, pore size distribution, pore shape, tortuosity, and pore saturation or moisture content of the concrete (Abbas et al. 1999). Drying of specimens is done to avoid variability in permeability results due to non-uniform moisture contents in the specimens; however, drying may introduce micro-cracking in the specimen (Kropp and Alexander 2007).

As in the case of highly dense concrete, it is difficult to get a through penetration of fluid in a short time, in-flow methods are relied upon instead. Falling head methods are preferred to steady head methods as the change in pressure can be measured more accurately than the change in discharge (Alexander et al. 1999). The description and comparison of various types of falling head permeameter used for concrete can be found elsewhere (Basheer 2001).

The study of permeation in context to concrete bears importance not only in the case of water retaining structures but more so from the fact that permeability has a strong correlation with diffusivity, which is much more difficult to measure (Lawrence (1984) as reported by Neville (1996)). A manifestation of this is seen as the close correlation between gas permeability and depth of carbonation as shown in Figure 2.5.

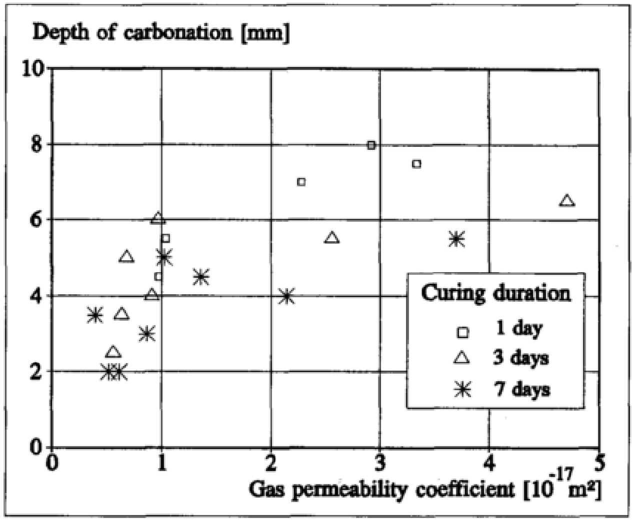


Figure 2.5. The relationship of gas permeability with carbonation (adapted from Dinku and Reinhardt, 1997)

2.6.3 Absorption

Absorption is the process in which a wetting liquid in contact with the surface of a porous medium is carried into it through the capillaries as a result of liquid’s surface tension. The pressure across the liquid-gas interface is known as capillary pressure and is described through Young-Laplace equation (Equation (2.6)) (Kropp and Alexander 2007):

$$P_{cap} = \frac{2\sigma \cos\theta}{r} \tag{2.6}$$

where

σ is the surface tension of the liquid (N/m)

θ is the contact angle at the liquid-solid interface

r is the radius of the capillary (m)

The Equation (2.6) in conjunction with Hagen-Poisseuille equation can be used to arrive at the depth of penetration in a capillary as a function of time in the form of Equation (2.7) (Kropp and Alexander 2007), mentioned below:

$$z(t) = \sqrt{\left(\frac{2\sigma\cos\theta}{r} + P_a\right) \cdot \frac{r^2}{4\eta}} \cdot \sqrt{t} \tag{2.7}$$

where

$z(t)$ is the depth of penetration at time t (m)

P_a is the external pressure (N/m)

η is the dynamic viscosity of the liquid (Ns/m^2)

For the ease of measurement, this equation can also be described in terms of mass gain (Kropp and Alexander 2007):

$$m(t) = S\sqrt{t} \tag{2.8}$$

where S is termed as Sorptivity, which signifies the rate of liquid uptake by the porous medium.

In other words, it indicates the medium’s ability to allow or disallow penetration of liquid into it by capillary suction. However, concrete, due to its complex distribution, shape, size, and interconnectivity of pores, does not adhere to this relationship in its exact form. The relationship has been found to be of the form described below (Kropp and Alexander 2007):

$$m(t) = A + St^n \tag{2.9}$$

where

A is the initial absorption

$n < 0.5$

A number of test methods have been developed in the past for measuring sorptivity of concrete both in the laboratory and in situ, for example, Initial Surface Absorption Test (ISAT) as per BS 1881-208 (1996), water sorptivity test as per ASTM C1585 (2013), Autoclam sorptivity test (Basheer 1991), Figg water permeability test (Figg 1973) etc. Modified versions of these test methods have also been proposed to help in maintaining unidirectional flow through the test. However, the application of in-situ tests is still limited by the constraints of specimen conditioning (drying) in the field (Basheer 2001).

2.6.4 Migration (or Electro-migration)

As explained earlier in Section 2.6.1, migration is the movement of ions through a porous medium under an electrical field. As it is almost inevitable to have migration effects in ionic diffusion tests and vice versa, ionic transport test should always account for both the effects. Nernst-Planck equation describes transport by combination of ionic diffusion, migration, and bulk flow of the solvent (advection). Nernst-Planck equation for unidirectional transport is presented below (Equation (2.10)) (Kropp and Alexander 2007):

$$J(x) = D\left(\frac{\partial c}{\partial x} + \frac{zFc}{RT}\frac{\partial \varphi}{\partial x}\right) + cv \tag{2.10}$$

where

$J(x)$ is the mass flux $(\frac{1}{A}\frac{\partial m}{\partial t})$ at any location *'x'* (g/m^2.s)

D is diffusion coefficient (m^2/s)

c is concentration (g/m^3)

z is charge of the ion

F is Faraday constant (J/V.mol)

R is gas constant (J/mol.K)

T is temperature (K)

$\frac{\partial \varphi}{\partial x}$ is electrical potential gradient (V/m)

v is velocity of flow (m/s)

This equation can also be used in situations where electric field is used to accelerate transport of ions, which is often the case because of the long durations required in the diffusion tests. Appropriate signs (+/-) should be ascribed to each term in the Equation (2.10) depending on the direction of the driving force. Furthermore, the flow term can be dropped if the specimens are saturated with the solvent (in the case of concrete, saturated with lime solution or water).

2.7 INFLUENCE OF TEMPERATURE ON THE MICROSTRUCTURE-DEVELOPMENT OF CONCRETE

The increase in the temperature of concrete not only accelerates the hydration reactions but it also changes the way microstructure of the hydrated cement paste evolves. Verbeck & Helmuth suggested that as hydration products appear more rapidly at higher temperatures, they increasingly tend to remain near the cement grain instead of filling the open interstitial spaces, owing to their low solubility and diffusivity in the pore solution

(Neville 1995; Verbeck and Helmuth 1968). Furthermore, due to limited space available between the cement grain and the already formed C-S-H gel, the subsequent hydration results in denser C-S-H shells around the cement grains. These dense hydration shells subsequently hinder the diffusion of water through them, ultimately limiting further hydration. As the hydration products are not able to fill the interstitial spaces effectively, this process results in a coarser, non-uniform microstructure with higher porosity.

Back Scattered Electron (BSE) study of cement paste hydrated at 5, 20 and 50 °C confirmed this explanation (Kjellsen et al. 1991). Figure 2.6 and Figure 2.7 show the BSE images of cement paste hydrated at 50 and 5 °C respectively. It should be noted that in these images the level of brightness of different phases corresponds to their density. Hydration shells depicted in light grey colour can be easily seen around the cement grains in Figure 2.6 (cement grains are the bright spots) in the case of hydration at 50 °C but are not apparent in the case of hydration at 5 °C (see Figure 2.7). Also, higher amounts of large pores can be seen in the C-S-H matrix in the case of 50 °C than in the other case of 5 °C.

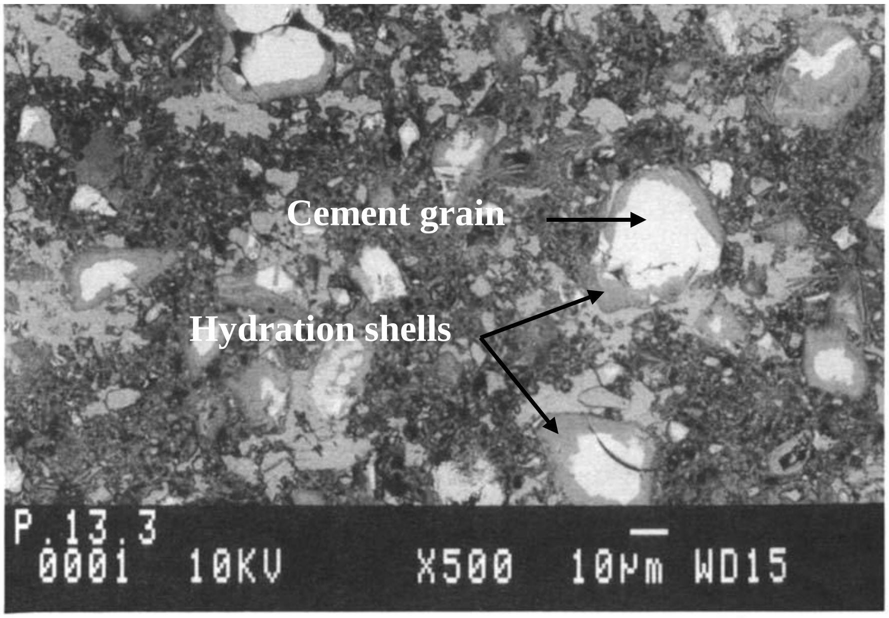


Figure 2.6. Backscattered electron image of cement paste hydrated at 50 °C to degree of hydration of 71 % clearly shows hydration shells around cement grains and the presence of larger pores in the paste matrix (adapted from Kjellsen et al., 1991)

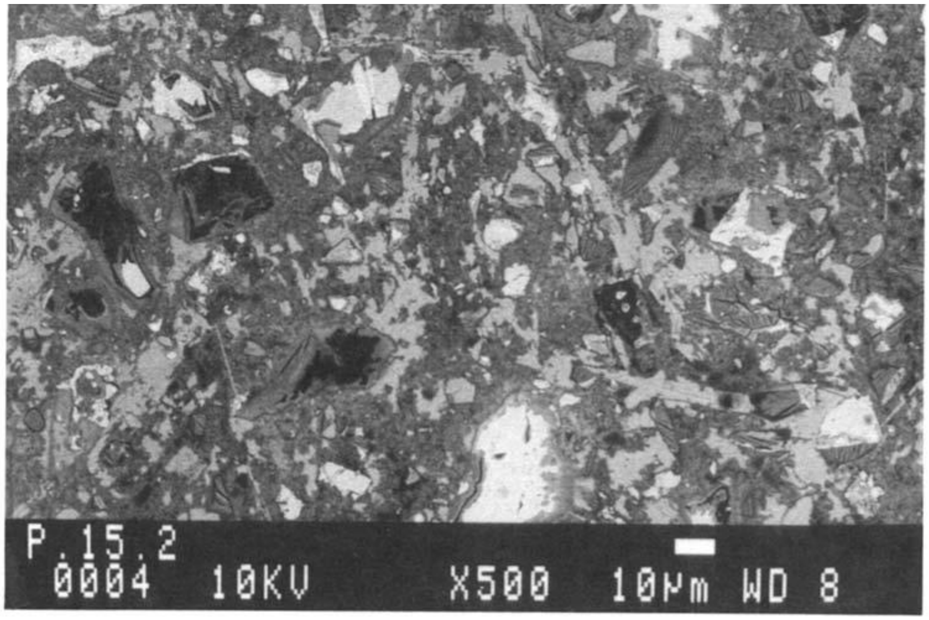


Figure 2.7. Backscattered electron image of cement paste hydrated at 5 °C to degree of hydration of 73 % showing uniformly distributed C-S-H (adapted from Kjellsen et al., 1991)

At similar degrees of hydration, higher temperature of hydration results in more higher-density C-S-H gel in the form of hydration shells. While hydration at lower temperature results in larger quantity of lower density C-S-H gel that is more uniformly distributed in space (Kjellsen et al. 1990a). It was also found in these studies that early curing temperature (up to 30 % hydration) and prolonged curing temperature (up to 70 % hydration) have different effects on the morphology of different phases of hydrated paste, in accordance to their time of appearance (Kjellsen et al. 1991). For example, as most part of calcium hydroxide appears early due to rapid hydration of C_3S, its morphology gets affected by early curing temperature, and not much by the prolonged curing temperature. On the other hand, in the case of C-S-H, prolonged temperature influences the morphology the most. As far as the mechanical strength of a material is concerned, it is dictated by its weakest constituent, not by the amount of strongest constituent. Therefore, it is expected that at similar degree of hydration, concrete hydrated at higher temperature shall yield larger porosity and so, shall yield lower strength.

2.8 INFLUENCE OF CURING ON THE POROSITY OF CONCRETE

The volume of capillary porosity in the hydrated cement paste decreases with the increase in the degree of hydration. Although the gel porosity increases with the degree of hydration, as there is a net reduction in the final volume of the hydrated paste, total porosity follows a diminishing trend with the progress of hydration. As the quality of curing affects the degree of hydration, it also influences the porosity of the cover zone. For instance, wet curing can result in much better porosity values for concrete—as much as 19 - 22 % lower—than air curing in harsh field conditions (Alsayed and Amjad 1994). On the other hand, the effect of curing on porosity may not be reflected in absorption tests using cold water saturation due to their reported lower sensitivity to curing (Nolan et al. 1997).

Pore-size distribution of the hydrated cement paste changes with different curing temperatures. Goto and Roy (1981) reported an increase in the amount of large-sized pores in the range of 750 Å to 7,500 Å with an increase in the curing temperature from 27 °C to 60 °C as measured by Mercury Intrusion Porosimetry (MIP). Another study found this size range to be 200 – 1,200 Å for a curing temperature of 50 °C (Kjellsen et al. 1990b). In the same study, much more significant differences were encountered between the porosity values of cement pastes cured at different temperatures using BSE images, the additional porosity was in the size range of 2,500 to 12,500 Å. As the permeability is reportedly more influenced by the amount of larger pores, higher temperature during hydration can lead to increased permeability of concrete.

2.9 INFLUENCE OF CURING ON THE COMPRESSIVE STRENGTH OF CONCRETE

Besides the importance of compressive strength in the structural design of concrete structures, the ease of testing concrete under compression as compared to under tension or flexure also makes compressive strength the first choice for the classification of different concretes and their quality control. The extent of such wide use can be appreciated from the fact that even the elastic modulus and flexural strength of concrete are also represented empirically in terms of its compressive strength. Consequently, the influence of curing on the quality of concrete has also been conventionally evaluated by its effect on the compressive strength of concrete. The influence of curing on the compressive strength of concrete has been a subject of study for at least seven decades now.

Most of the literature in the past has been focused on studying the effect of different durations and modes of wet curing on the compressive strength of concrete. It is now well known that prolonged and continuous wet curing improves compressive strength (Figure 2.8). Studies have reported a gain in compressive strength of 33 % at the age of 28 days (Padmanabhan and Gettu 2016) and 20 % (Ozer and Ozkul 2004) at the age of 6 months for 150 mm sized concrete cubes continuously wet cured over that of air cured in standard conditions. However, this gain or loss due to the differences in curing regimes adopted depends on various factors such as type and quantity of binder used, water-to-cement ratio, size and shape of the specimen, and the exposure conditions.

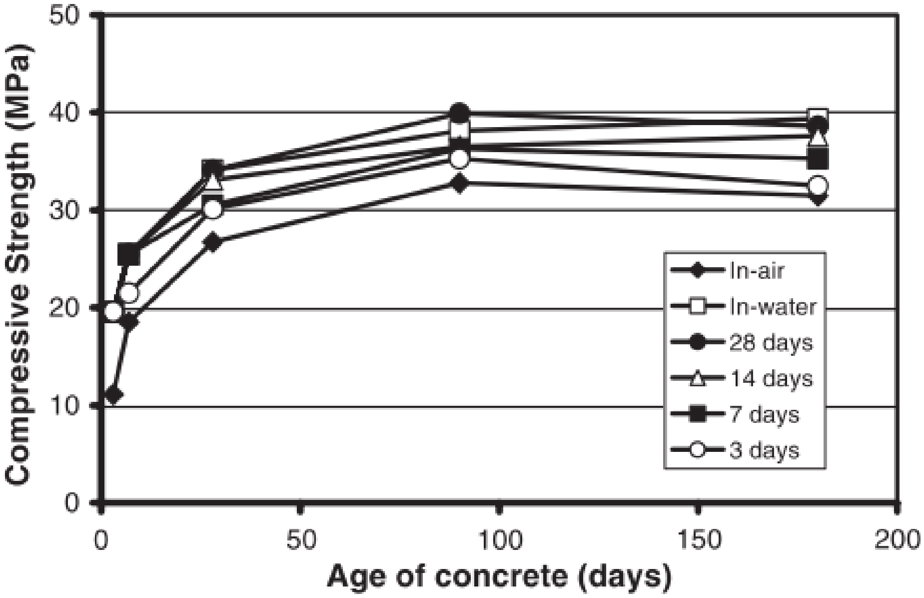


Figure 2.8. Effect of different durations of wet curing on the compressive strength of concrete (adapted from Ozer and Ozkul, 2004)

The compressive strength of concretes containing supplementary cementitious materials demonstrates higher sensitivity towards poor curing conditions, perhaps, due to their slower rate of hydration (Zhang et al. 1999; Ozer and Ozkul 2004). Ramezanianpour and Malhotra (1995) reported a loss in compressive strength of about 38 to 50 % at 180 days for concretes containing slag or fly ash at various levels of replacements, if air curing was adopted instead of continuous moist curing. Compressive strength results from another extensive investigation on 48 concretes incorporating silica fume with various levels of replacements, binder content, and water-to-cement ratios showed an average loss of 13 % at 28 days for silica fume concretes as compared to only a 5 % loss for control concretes due to poor curing conditions (Atiş et al. 2005). However, the contrary has also been reported for concrete containing silica fume (Tan and Gjorv 1996).

Water-to-cement ratio also significantly affects the sensitivity of concrete towards curing. Increase in the water-to-cement ratio increases the degree of influence that curing has on the strength of concrete (Zhang et al. 1999; Atiş et al. 2005). Concretes with high w/c are highly susceptible to water-loss due to evaporation owing to their high initial porosity. Another factor is the surface-area-to-volume ratio, that is, the size and shape of the specimens used. The percentage volume that gets affected by drying shrinkage as a result of poor curing increases with the reduction in the specimen size. Hence, smaller specimens exhibit higher reduction in strength due to poor curing. Soroka and Baum (1994) observed an increase in strength of 100 % at 28 days by increasing the period of wet curing from zero to seven days for 70 mm-cubes as opposed to a mere 10 % in the case of 250 mm-cubes. Therefore, the impact of curing practices on the strength of concrete in actual structures could appear greatly exaggerated, if the conventional small-sized laboratory specimens are used. Another consequence of this is that the relative influence of curing will vary with the type and the size of the member. Consequently, the practice, in the recent past, has been changing from using conventional laboratory specimens to using large specimens having a surface-area-to-volume ratio close to members in actual structures.

Besides the influence of composition (materials) and geometry (structural design) of concrete members on the selection of the curing method, early internal temperature (curing temperature) and micro-environmental conditions also play a deciding role in ensuring the required strength performance. Elevated curing temperatures accelerate the development of strength and thus, help in achieving high early strength. This reduces the formwork turn-over time. However, elevated curing temperatures can also lead to inferior long-term strength (Kim et al. 1998; Tan and Gjorv 1996) as shown in Figure 2.9. Elevated curing temperature can result from increase in temperature by artificial means (steam curing, heating coils), heat of hydration (semi-adiabatic conditions in mass-concreting or in thick sections), and/or hot weather conditions.

Appropriate curing measures are crucial in hot weather conditions, not only due to high ambient temperatures but also because the high temperature conditions are often accompanied by low relative humidity, high wind, and direct solar radiation. All of these factors acting in tandem accentuate the severity of evaporation losses, contributing further to the adverse effects of high curing temperatures on strength.

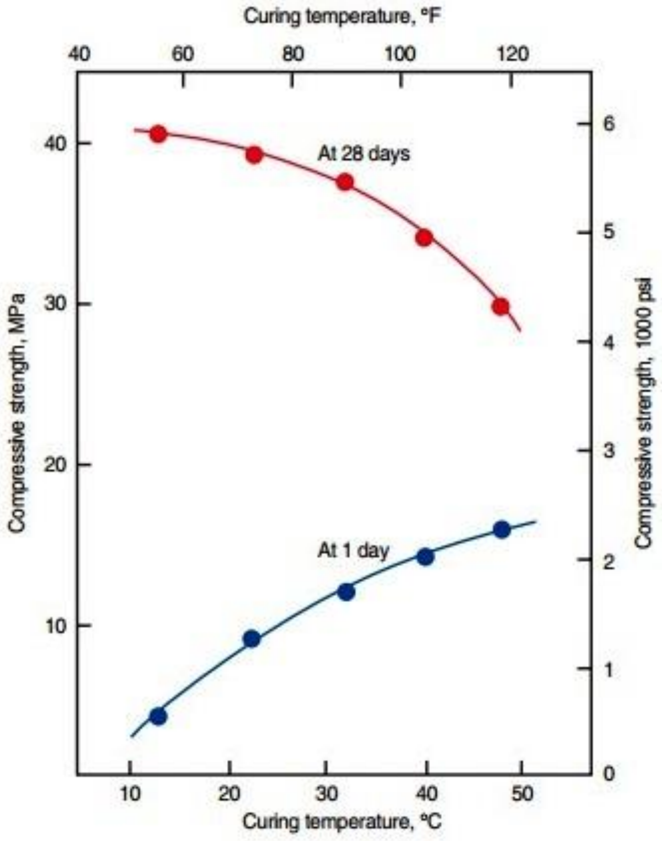


Figure 2.9. Effect of curing temperature on the early (1-day) and long-term (28-day) strength of concrete (adapted from Verbeck and Helmuth, 1968; source: “Chapter 12-Curing Concrete”, n.d.)

Consequently, the major portion of research on the efficiency of different curing methods, both under lab and field conditions, in the last five decades happened in the Middle East—where environmental conditions are mostly hot and dry. Moreover, these regions also suffer from severe scarcity of potable water, necessitating the use of alternative curing methods such as plastic sheeting, curing compounds etc. Taryal et al. (1986) found intermittent sprinkling of water twice a day for seven days with plastic covering yielding in a 224th day compressive strength higher than uncured concrete by 25 % in hot and dry field conditions. Another study on RC slabs exposed to similar field conditions reported the loss in strength for uncured concrete as compared to seven days wet curing with or without burlap to be about 42 % at 360th day (Alsayed and Amjad 1994). Contrary to this, a long-term study in an arid region found no apparent benefit of using wet curing on the 1800th day compressive strength, even though the gain in the 28th day strength for 28-day wet cured specimens was 51 % over uncured cube specimens (Al-Khaiat and Fattuhi 2001). The long-term strength gain of uncured specimens was attributed to the carbonation of specimens over a long duration of 1800 days, overcoming even the effects of drying shrinkage.

Studies on curing compounds, however, have shown a wide variation in their performance. In fact, Fattuhi (1986), 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. Amongst the 16 curing compounds studied, hydrocarbon-resin-based compound exhibited best results. Xue et al. (2015) reported the efficiencies of curing compounds in the range: 88.5 % (Paraffin-based) to 97.5 % (Acrylic-based). On the other hand, Padmanabhan and Gettu (2016) reported the efficiencies from 72 % to 86 % even for curing compound application rates up to 5 times higher than usual. 86 % efficiency was achieved for wax-based compound in hot and moist ambient conditions of Chennai. Fattuhi (1986) also reported depreciation in the efficiencies of curing compounds in harsh conditions (60 °C, 30 % RH). However, Wasserman and Bentur (2013) reported improvement in the performance in the harsh conditions (at 30 °C, 40 % RH)—contrary to all the above mentioned. They ascribed the findings to a possible improvement in the coalescence of curing compound at high temperature and low humidity conditions.

2.10 INFLUENCE OF CURING ON THE DURABILITY CHARACTERISTICS OF CONCRETE

In the recent past, great amounts of effort and resources have been expended in the repair and even the replacement of a large number of existing RC structures, which were once considered durable. The one issue which has surpassed the boundaries of region (and so the type of materials used) and has affected the durability of RC structures all over the world is the corrosion of reinforcing steel. Reinforcing steel is protected from the effects of a deleterious environment, and thereby from corrosion, by the cover concrete. Hence, the properties of cover concrete are of utmost significance in achieving the potential durability of RC structures.

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 (Parrott 1992). These variations 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 has been 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 (Figure 2.10) up to a depth of 50 mm (Senbetta and Scholer 1984; Patel et al. 1985).

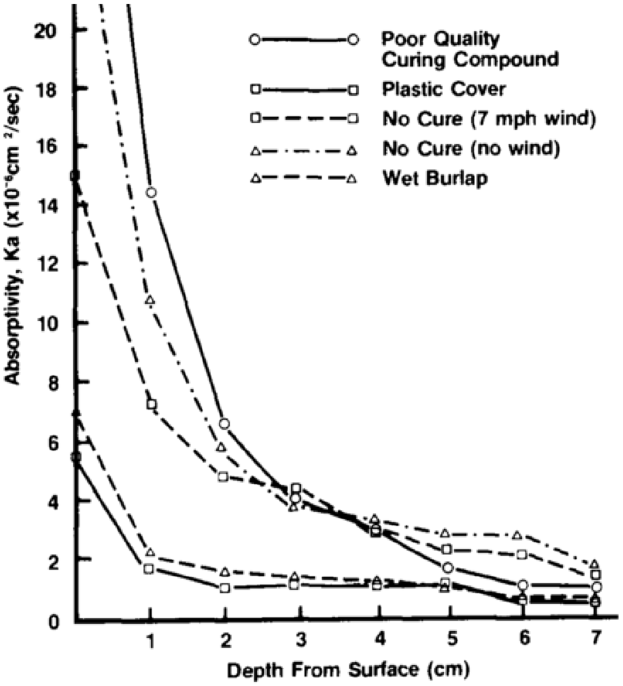


Figure 2.10. Influence of curing on the gradient of sorptivity from the surface of mortar specimens cured at 22 % RH for five days (adapted from Senbetta and Scholer, 1984)

In view of the aforementioned observations that 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. 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 (Bentur and Jaegermann 1992; Ramezanianpour and Malhotra 1995; Wasserman and Bentur 2013). These parameters include air permeability, water sorptivity, resistance to carbonation, and chloride permeability. To cite an example, Figure 2.11 shows capillary absorption varying up to 50 % for a change of 15 % in the compressive strength, while air permeability shows a variation of 150 % for a change of 30 % in strength. Additionally, Figure 2.12 shows that a reduction of mere 20 % in strength can bring down the service life of a concrete structure subjected to carbonation by about 80 %. These examples emphasize the ineffectiveness of strength as a parameter to assess the efficacy of curing in achieving designed service life.

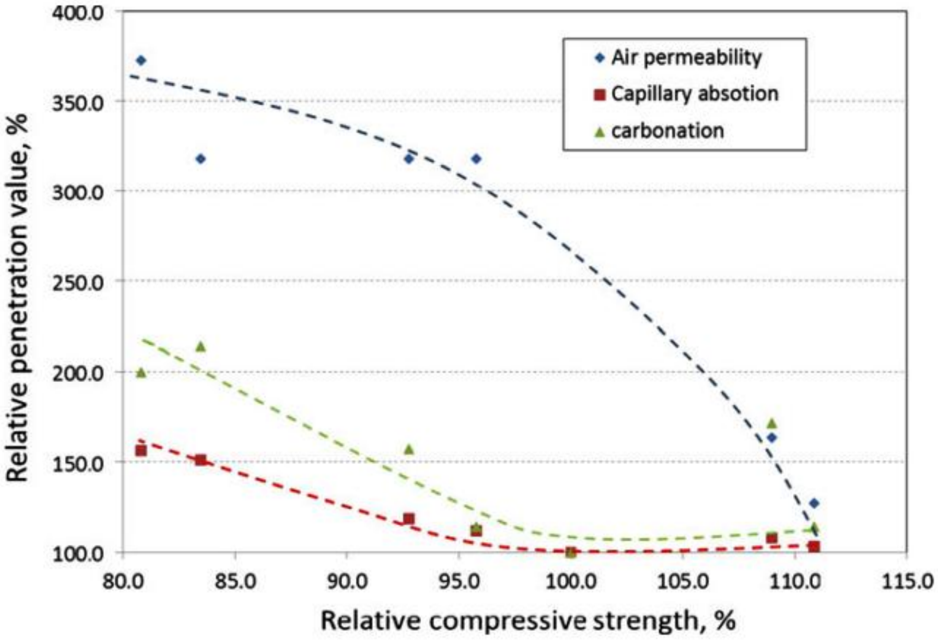


Figure 2.11. Comparison between sensitivity of durability parameters and compressive strength to curing conditions, relative to 7-day wet curing in standard conditions (adapted from Wasserman and Bentur, 2013)

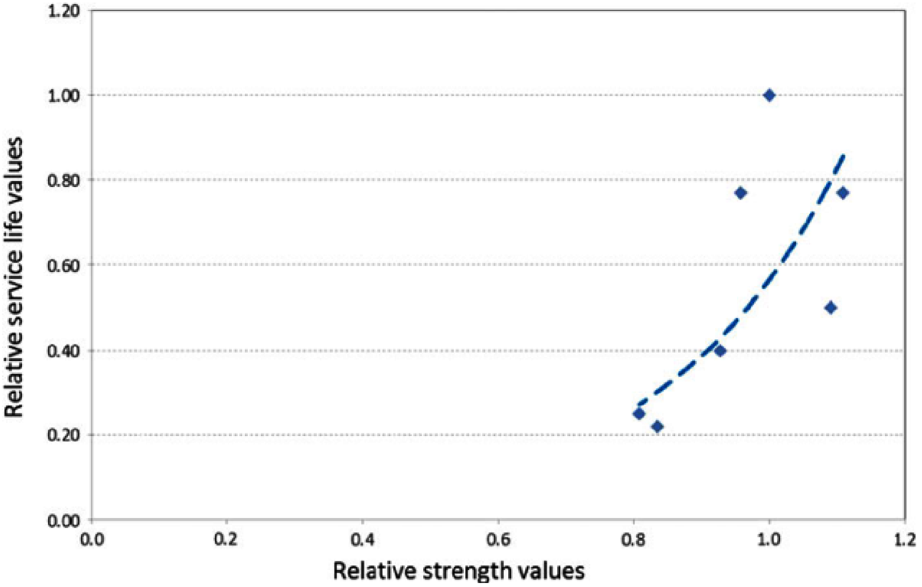


Figure 2.12. The relationship of compressive strength with the service life values for concrete exposed to carbonation, relative to 7-day wet curing in standard conditions (adapted from Wasserman and Bentur, 2013)

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 % (Alsayed and Amjad 1994). Through a study on Ground Granulated Blast Furnace Slag (GGBFS) concrete cured in simulated arid climate, Austin et al. (1993) have shown that the lack of wet curing could significantly diminish the air permeability and water sorptivity. 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 (Bentur and Jaegermann 1992; Saricimen et al. 1995). Zhang et al. (1999) reported that the influence of curing on the chloride resistance of OPC concretes increases with increase in the water-to-cement ratio. 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 (Austin et al. 1993; Zhang et al. 1999; du Preez and Alexander 2004; Wasserman and Bentur 2013). However, their potential in reducing the differences between the transport properties of near-surface concrete and the interior concrete has also been realized (Wang et al. 2006; Xue et al. 2015). Curing compounds also help in mitigating plastic and drying shrinkage, although wide variations exist in the performance (Al-Gahtani 2010; Sirajuddin 2015).

Tests on transport properties 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 (Tan and Gjorv 1996; Nolan et al. 1997). For instance, Tan and Gjorv (1996) concluded that elevated temperatures reduced the chloride resistance of concrete; however, the resistance to water penetration showed no corresponding variation with temperature. In general, sorptivity appears to be the most widely used parameter for evaluating curing efficiencies and has been observed to demonstrate great sensitivity to curing (Wang et al. 2006). However, instances where surface tests such as water sorptivity, air permeability, pull-off strength, and accelerated carbonation test showed limited sensitivity to curing have also been reported (Nolan et al. 1997).

2.11 SUMMARY OF CURRENT RESEARCH NEEDS

With the challenge of achieving rapid growth in infrastructure development for its increasing population, India and the world as a whole are facing another huge challenge of a growing water-crisis. Construction industry, which consumes a large portion of potable water in the construction processes, needs to adopt more sustainable alternatives to reduce its water footprint. One such alternative is the use of curing compounds instead of conventional wet curing. Curing compounds eliminate the requirement of additional water for curing concrete. The use of curing compounds in the industry is increasing rapidly; however, the lack of adequate knowledge about their performance and behavior limits their effective usage. The limited availability of literature in this area clearly shows this lack of attention received by curing compounds from the research community. The various aspects of curing compounds and curing, in general, that need to be investigated further are described in this section.

2.11.1 Water loss test for curing compounds as per ASTM C156 (2011)

Water loss test for the qualification of curing compound as per ASTM C 156 lacks sufficient precision to be of any value for the intended purpose of selecting curing compounds. However, as it presents a simple way to assess the performance of curing compounds, it would be better to identify and rectify the deficiencies present in this test method rather than simply rejecting it without enough investigation. Thus, a thorough study is required to improve the precision of this test method.

2.11.2 Aspects related to handling, application, and mechanism of membrane formation

As discussed in this chapter, the performance of a curing compound depends on the way it is handled and applied in the field. There is a severe lack of studies on this aspect. Moreover, an improvement in the understanding of the mechanism of film formation will immensely help in refining application technology and making an informed choice about the selection of curing compounds.

However, the above-mentioned research gaps have not been addressed in this study. The current study focuses on the issues presented below.

2.11.3 Performance of curing compounds in different exposure conditions

There is a lack of information on the influence of individual environmental factors on the performance of curing compounds. Hence, the performance and behaviour of curing compounds in different controlled exposure conditions needs to be explored further.

2.11.4 Effect of curing on the durability characteristics of concrete

Durability of concrete depends on its resistance to penetration of aggressive agents through various transport processes. The effect of curing on the various transport characteristics of concrete needs to be better understood.

2.11.5 Sensitivity of durability tests

Sensitive test methods are required to detect changes in the properties of cover concrete because of aspects including, but not limited to curing, to predict the long-term performance of concrete. There is a need to select and standardize test methods that are sensitive to factors affecting the durability of concrete to develop a unified approach that facilitates valid comparison between different studies and addresses the various contradictions present in the existing literature.

2.11.6 Performance of concrete in field conditions

The performance of concrete in the field as opposed to that in the lab is characterized by uncertainty introduced by the lack of control on various construction activities and exposure conditions. Hence, the performance of concrete in the field can be substantially different from that predicted from the laboratory tests. However, there have been only a few attempts to study concrete in the field conditions. Therefore, to assess the performance of field concrete, there is a need to study the nuances of field concrete and develop a suitable testing approach.

3. METHODOLOGY

3.1 INTRODUCTION

The details of the materials and methods adopted in the experimental program of this study are presented in this chapter. The properties of materials that are used in this study are discussed first, which is followed by the adopted specimen design and curing conditions for the lab and the field study. Then, all the test methods are explained in detail.

3.2 MATERIALS

3.2.1 Cement

Ordinary Portland Cement (OPC) of grade 53, conforming to IS 12269 (2013), was used to prepare mortar and concrete mixtures. The specific gravity and fineness of OPC was 3.15 as per IS 4031-11 (1988) and 310 (m^2/kg) as per ASTM C204 (2011), respectively. Further, the oxide composition of the cement determined using X-Ray Fluorescence Spectroscopy is presented in Table 3.1.

3.2.2 Aggregate

Graded crushed-granite aggregate of maximum nominal sizes 10 and 20 mm were used as the coarse aggregate and river sand (maximum nominal size: 4.75 mm) conforming to Zone 1 as per IS 383 (1970) was used as the fine aggregate. The physical properties of the aggregates, measured as per IS 2386-3 (1963), are listed in Table 3.2. The particle size distribution of these aggregates was determined using sieve analysis as per IS 2386-1 (1963) and is presented in Figure 3.1.

Table 3.1. Oxide composition of OPC (adapted from Bahurudeen, 2014)

Oxide composition	Amount (%)
CaO	60.36
SiO_2	20.68
Fe_2O_3	5.44
Al_2O_3	4.12
SO_3	2.46
MgO	0.83
K_2O	0.27
Na_2O	0.23
Others	5.61

Table 3.2. Physical properties of aggregates

Type of aggregate	**Specific gravity**	**Water absorption capacity (%)**
Fine aggregate (River sand)	2.64	0.71
Coarse aggregate (10 mm)	2.78	0.43
Coarse aggregate (20 mm)	2.82	0.41

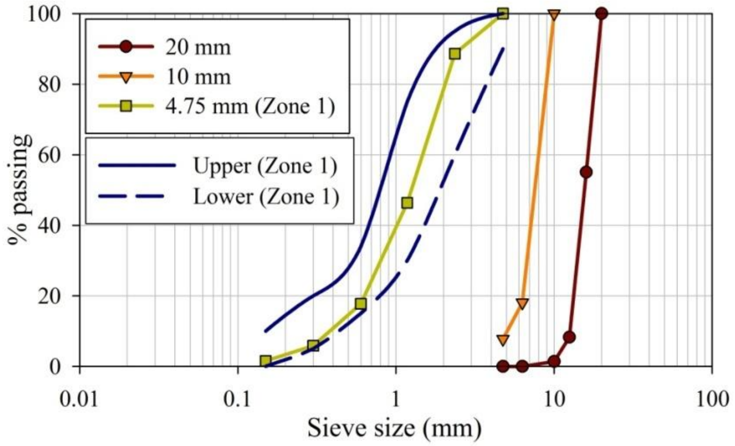


Figure 3.1. Particle size distribution of aggregates

3.2.3 Curing compounds

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 3.3. 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.

Commercially, wax emulsions are often referred to as wax-based compounds or water-based compounds. However, both these terms refer to fundamentally different components of a curing compound, i.e., membrane-forming solid component in the former and the dispersion medium in the latter. Terms like these are increasingly being used to emphasize that a manufacturer has gone beyond just complying with the Volatile Organic Compound (VOC) content restrictions by using water in the place of organic solvents, thereby eliminating the use of hazardous chemicals. In short, it serves in promoting more environment-friendly products. However, this terminology is technically ambiguous and often misleading as it hides the very nature of the membrane-forming solids that dictate most of the properties of a curing compound. **Hence, this practice is not followed in this study; instead, the curing compounds are designated on the basis of their membrane-forming component followed by the dispersion medium.**

As per the manufacturers' data sheets, the curing compounds that were used in this study conform to ASTM C309 (2011). Manufacturers' data sheets claim that these compounds restrict water loss to less than 0.55 kg/m^2 in 72 hours, if tested as per ASTM C156 (2011). As per the data sheets, the drying time for these curing compounds was less than 3 hours. The curing compounds WX-1, RW, and RS-1 formed a white membrane with a reflectance of greater than 60 % (as per the data sheet). 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 so, was silver-gray in colour, but left a clear film on drying. 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 hours. The solids content is provided in Table 3.3. The solid content presented here represents the percentage mass left after 24 hours of drying with respect to the initial mass of curing compound.

Table 3.3. Details of the 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

Infra red spectra were generated for the curing compounds using Fourier Transform Infra Red (FTIR) spectroscopy. The results are shown in Figure 3.2. The curing compounds WX-1, WX-2, and RW exhibit a broad peak in the region 3300 – 3400 cm^{-1} which indicates the presence of O-H group (broad peak - hydrogen bonding). This is due to the presence of water in these curing compounds. All the curing compounds exhibit peaks related to SP^3 C-H (2800 – 3000 cm^{-1}: stretch and 1400 – 1500 cm^{-1}: bend), which is expected from organic compounds. WX-1 and WX-2 show a peak at 1636 cm^{-1} that indicates the presence of C=C of alkenes. The peaks close to 720 cm^{-1} suggests the presence of cis-disubstituted alkene. The spectra of these two curing compounds show that they seem to contain aliphatic hydrocarbons with the presence of unsaturation, which does not confirm the presence of Paraffin wax (Paraffin wax consists of aliphatic saturated hydrocarbon, although the definition of wax is quite broad and may include ester, naphthalene etc). However, the presence of C=O stretch at ~1730 cm^{-1}, C-O at ~1150 cm^{-1}, C=C conjugation at 1600 cm^{-1}, and cis-disubstituted C=C bend at ~700 cm^{-1} indicate that curing compound RS-1 and RS-2 are based on acrylic ester (Acrylic ester : $R_1HC=CR_2COOR_3$).

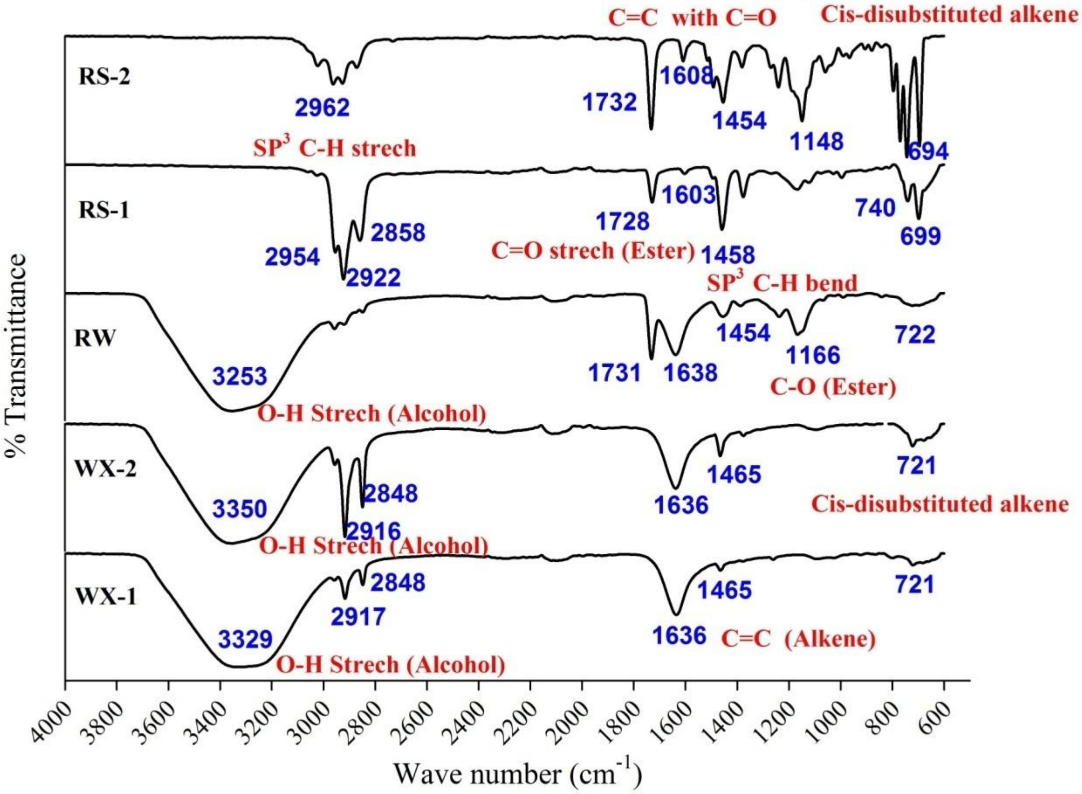


Figure 3.2. Infra-red spectra of the curing compounds

The curing compounds WX-1, WX-2, and RS-2 were of low viscosity, while the curing compounds RW and RS-1 were of relatively higher viscosity. Because of the low viscosity, the curing compounds WX-1 and WX-2 resulted in a patchy film. On the other hand, the curing compounds RW, RS-1, and RS-2 formed a uniform film. However, the curing compound RW had a tendency to dry quickly and so, posed issues of nozzle-clogging frequently. This issue makes it impractical for use in large-scale spray based applications.

All the curing compounds were applied at a rate of 5 - 6 m^2/L (or 167 - 200 mL/m^2) as recommended by the manufacturers and ASTM C309 (2011).

3.3 TEST PROGRAM-1: LAB STUDY

3.3.1 Mixture proportion: Mortar

A mixture proportion of 1 : 2.75 : 0.5 (cement : sand : water/cement) by mass was adopted for the mortar that was used in this study.

3.3.2 Mixing method: Mortar

A 30-30-30-90-60 (seconds) timing pattern as per ASTM C305 (2014) was used for mixing mortar in a mechanized mortar mixer. Initially, all the mixing water was placed in the bowl. In the first 30 seconds, cement was added to the water and mixed at a Slow speed (140 ± 5 rpm). Then, sand was added to the mixer in the next 30 s while the mixer was being operated at the slow speed. Subsequently, all the constituents were mixed together for 30 s at a Medium speed (285 ± 10 rpm). This was followed by a rest period of 90 s and a final mixing for 60 s with the medium mixing speed.

3.3.3 Specimens

Cube specimens of size 100 mm and 150 mm were cast for compressive strength tests and durability tests, respectively.

3.3.4 Curing and Exposure Conditions

3.3.4.1 Curing

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 (see Table 3.4). Two sets of specimens were cast for each curing method/curing compound. Each set of specimens was subjected to two different exposure conditions – (1) 25 °C, 65 % RH and (2) 45 °C, 55 % RH (refer Section 3.3.4.2 (see Figure 3.5)).

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

Table 3.4. Description of the curing methods that were used in the laboratory study

Curing method		**Description**
Air		Air curing
Wet		Continuous wet curing
7dW		Wet curing until 7 days, then in air
Curing Compounds (CC)	WX-1	Wax based CC
	WX-2	Wax based CC
	RW	Resin emulsion based CC
	RS-1	Resin-solvent based CC
	RS-2	Resin-solvent based CC

Air curing (Air): The specimens were stored directly in the environmental chambers that were maintained at one of the above mentioned exposure condition, after demoulding.

Continuous wet curing (Wet): The specimens in this case were stored in a closed container filled with saturated lime solution until tested. The container was then placed in the respective environmental chamber that was maintained at one of the above mentioned exposure condition.

7 days *wet curing (7dW):* The specimens were kept in a closed container filled with saturated lime solution 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 kept in the environmental chamber throughout the period of exposure, both while under wet curing, i.e., in the closed container, and afterwards.

Curing compounds (CC): All the five curing compounds mentioned in Table 3.3 (Section 3.2.3) were used in the laboratory study. After demoulding, 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 - 1”). 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.

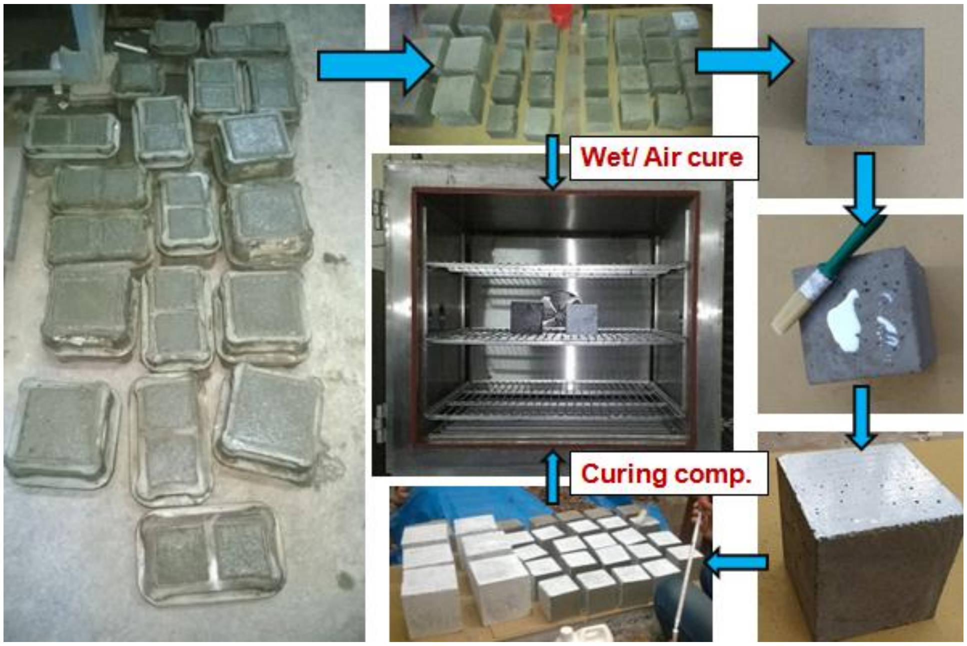


Figure 3.3. Application of curing compound on the cube specimens

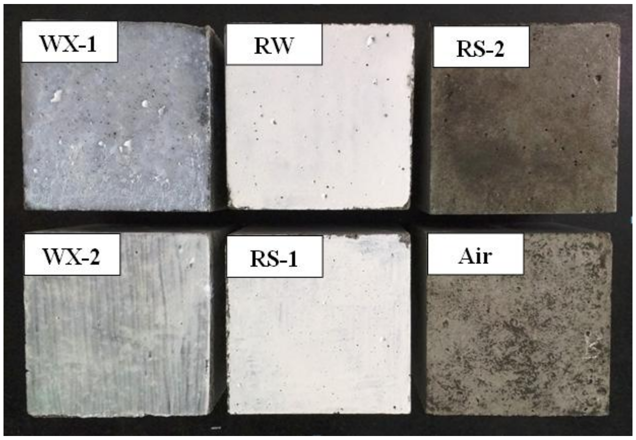


Figure 3.4. The cube specimens after the application of curing compounds

The surfaces were painted with curing compound in a horizontal position, as uniformly as possible, without dripping the curing compound at the edges (see Figure 3.3). After drying of the curing compound 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 - 6 m^2/L. Finally, the specimens were transported to the environmental chambers. The cube surfaces painted with curing compounds are shown in Figure 3.4.

3.3.4.2 Exposure Conditions

Two types of exposure conditions were chosen for this study: (1) Temperature of 25 ± 2 °C with relative humidity 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 Figure 3.5. The effects of wind and solar radiation were not included in this study. Environmental chambers were used to maintain the mentioned controlled exposure conditions throughout the exposure period.

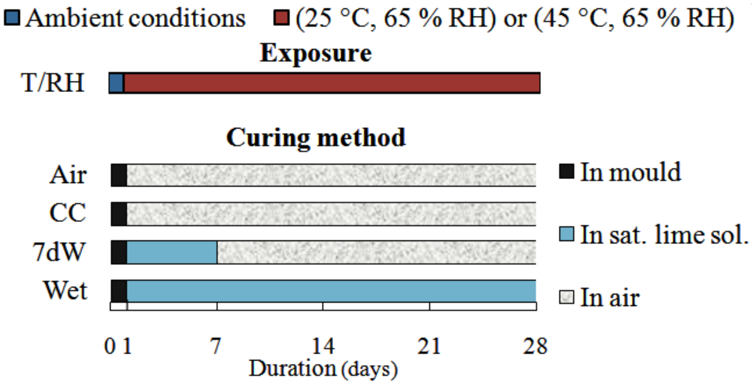


Figure 3.5. Exposure conditions for each curing regime

3.4 TEST PROGRAM-2: FIELD STUDY

3.4.1 Mixture proportions: Concrete

An M35 grade OPC concrete with a mixture proportion as per Table 3.5 was used in this study. The measured slump of the concrete was in the range of 40 to 90 mm.

Table 3.5. Mixture proportion of the concrete that was used in the field study

Ingredient		Quantity per m^3
OPC content		340 kg
Coarse aggregate (SSD)	20 mm	692 kg
	10 mm	461 kg
Fine aggregate (River sand - SSD)	4.75 mm	720 kg
Water-to-cement ratio		0.55
Note: SSD – Saturated and Surface-Dry		

3.4.2 Mixing method: Concrete

Concrete mixtures were prepared in a 300-kg pan mixer. The moisture content of sand was measured using microwave oven to adjust for the water content. The mixing procedure used was as follows. First, all the aggregate were mixed for two minutes without the addition of water. They were further mixed for two minutes after adding onethird of the total water followed by a rest period of 4 minutes, the rest period is to ensure that aggregate absorb water before the addition of cement. Then, the cement was added and mixed for one minute. Finally, the remaining two-thirds of the water was added and final mixing was done for further two minutes. Initial slump was determined for each batch of concrete. Concrete was transported manually to the location of casting in wheel barrows.

3.4.3 Specimens

To simulate the field conditions, relatively large specimens with close to practical surface-to-volume ratio were used in this study and smaller specimens were in turn extracted from them for laboratory testing. 1200 mm square and 200 mm thick reinforced concrete slab specimens were cast in an outdoor location near the concrete testing laboratory in the IIT Madras campus, Chennai. The slab specimens were doubly reinforced with 8 mm-diameter bars spaced 150 mm centre-to-centre in both the orthogonal directions as shown in Figure 3.6.

Although the slab specimens were 1200 mm x 1200 mm in size, the test specimens were extracted from only the inner region (900 mm x 900 mm) of the slab specimens that excludes a strip of 150 mm from the edges of the slabs. The outer 150 mm wide portion of the slab was excluded from non-destructive testing or specimen extraction to avoid any possible variations in the properties of concrete arising due to the *edge effects*. The wall effect near the formed faces and the additional loss of water and heat to the atmosphere from the vertical edges constitute these edge effects.

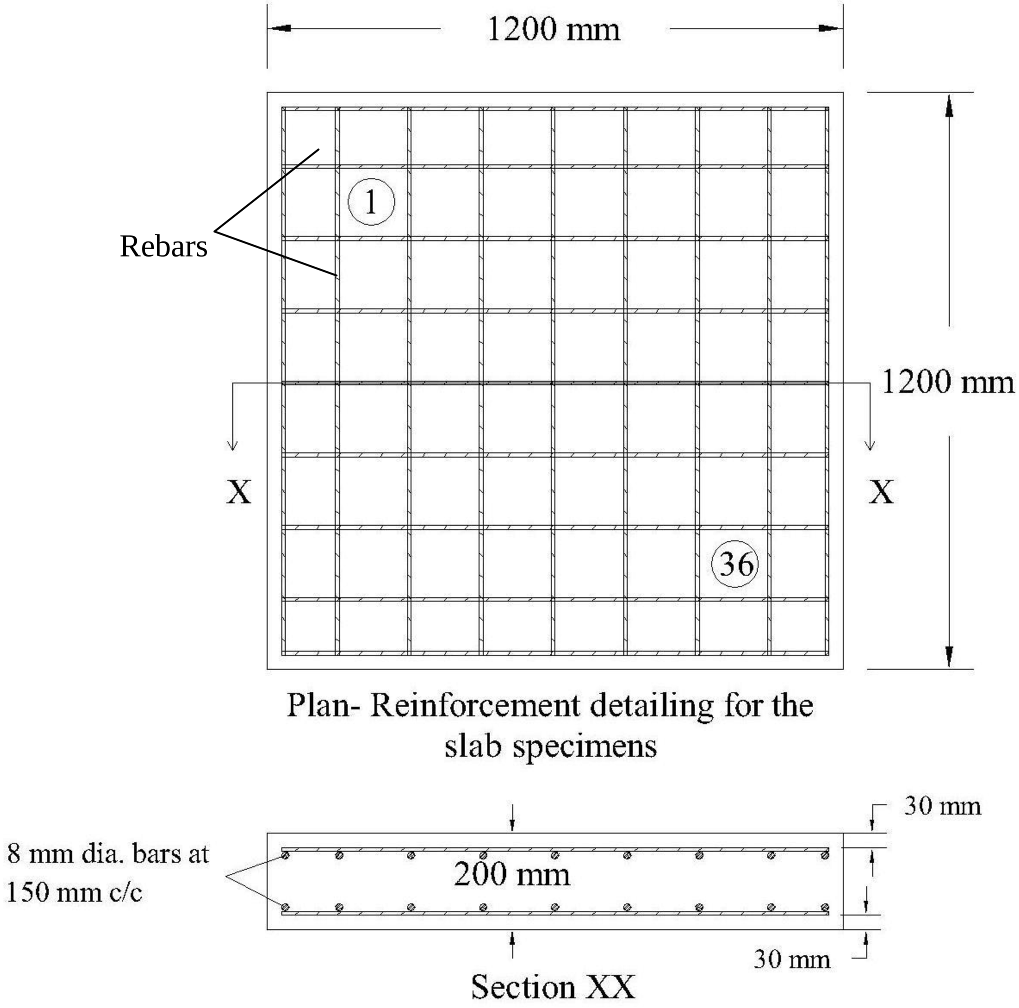


Figure 3.6. Reinforcement detailing of the slab specimens

A total of five slab specimens were cast in situ, one for each type of curing method that was adopted in this study. Figure 3.7 illustrates the various steps involved in the preparation of slab specimens and Figure 3.8 illustrates the extraction of test specimens from them. The slab specimens were cast on an elevated wooden platform using wooden formwork. These platforms were covered with a double layered plastic sheet before placing the formwork on it. The reinforcement was arranged and tied in place as per Figure 3.6.

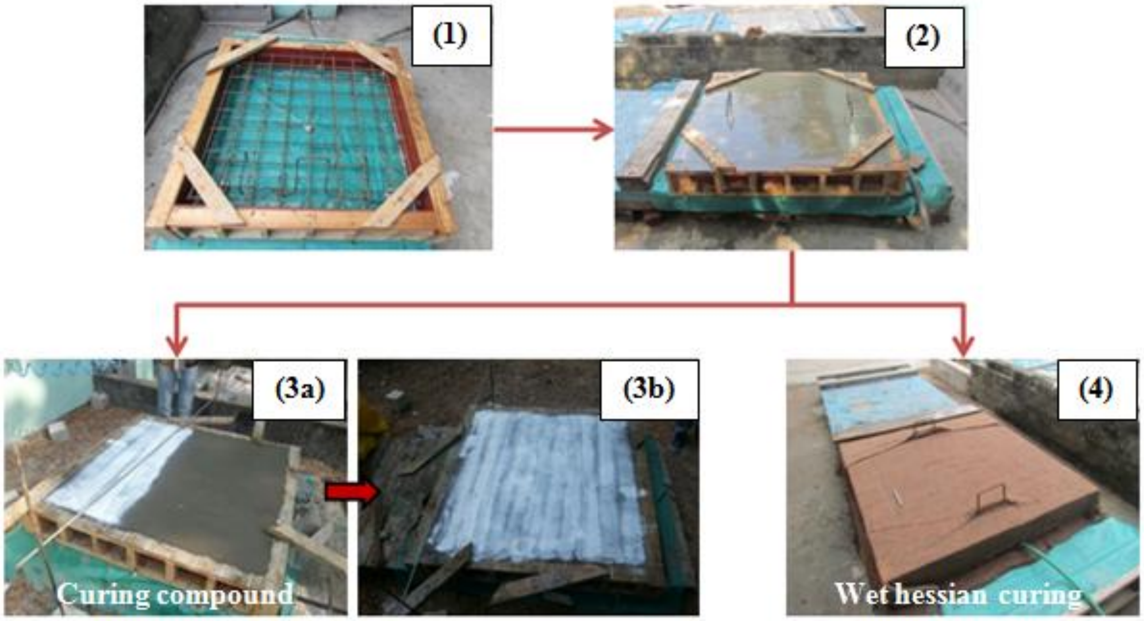


Figure 3.7. Preparation of panel specimens: (1) Mould and reinforcement fixing, (2) Concrete casting in the moulds, (3, 4) Curing of slab specimens

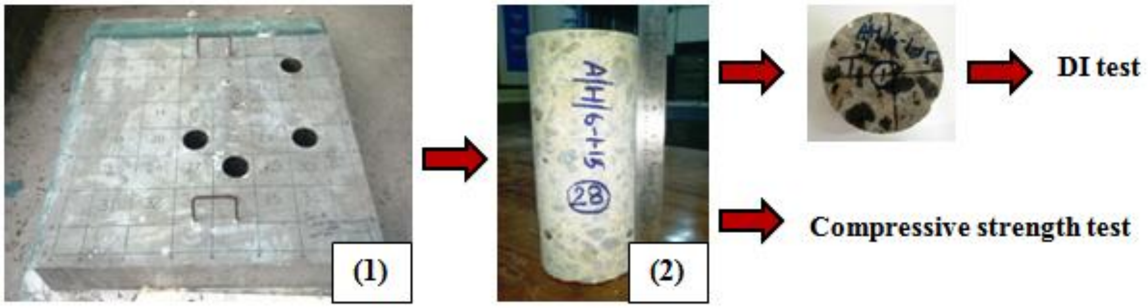


Figure 3.8. Extraction of test specimens: (1) Extraction of cores from slab specimens, and (2) Extracted core specimens were then used for strength test or were sliced to obtain disc specimens for DI tests

The concrete was mixed in the laboratory as discussed in Section 3.4.2 and was transported to the site in wheel barrows. Compaction of concrete was done using a poker vibrator (25 mm). After compaction, initial leveling was achieved using an aluminum straight edge. The final finishing of the surface was done using a steel trowel as soon as the bleed water sheen disappeared from the surface. Finally, the formwork was removed from the slab specimens after 24 hours of casting.

3.4.4 Curing and Exposure Conditions

3.4.4.1 Curing

The slab specimens were subjected to the five curing methods that are mentioned in Table 3.6.

Table 3.6. Description of the curing methods that were used in the field study

Curing method	Description
7dH	Wet hessian cloth until the age of 7 days, then in air
Air	Air curing
WX-1	Wax emulsion-based CC
RS-1	Resin-solvent-based CC
RW	Resin emulsion-based CC

The first slab was cured using two layers of wet hessian cloth for 6 days after demoulding, i.e., until the age of 7 days, after which it was exposed to air. Hessian cloth was kept continuously wet by sprinkling water intermittently. The second slab was left exposed to air after casting without any deliberate curing measures, referred here as air cured. The next three slabs were cured using different curing compounds.

The chosen curing compound was sprayed immediately after the disappearance of bleed water sheen from the concrete surface by using a compressed air assisted spraying gun. To ensure uniformity in the application rate, the whole area was divided into strips of 100 mm width. The height of the spray nozzle was also kept fixed at about 200 mm using a duly-supported horizontal bar. The time of traverse of the spray nozzle, from one end to the other end forming a strip, was adjusted in such a way as to maintain the rate of application in the range of 5 to 6 m^2/L throughout the strip. An overlap of 2 to 3 cm was also maintained between each adjacent strip. Furthermore, standard laboratory specimens (concrete) were also cast in the laboratory along with the slab specimens and were moist cured until the age of testing (referred to as *lab-cured* specimens with the legend: 28d-Lab in Chapter 5).

3.4.4.2 Exposure Conditions

All of the five slab specimens were stored in an open space and thus, were exposed to the uncontrolled ambient environment of Chennai. The monthly average temperature and precipitation data for Chennai during the period of exposure is plotted in Figure 3.9.

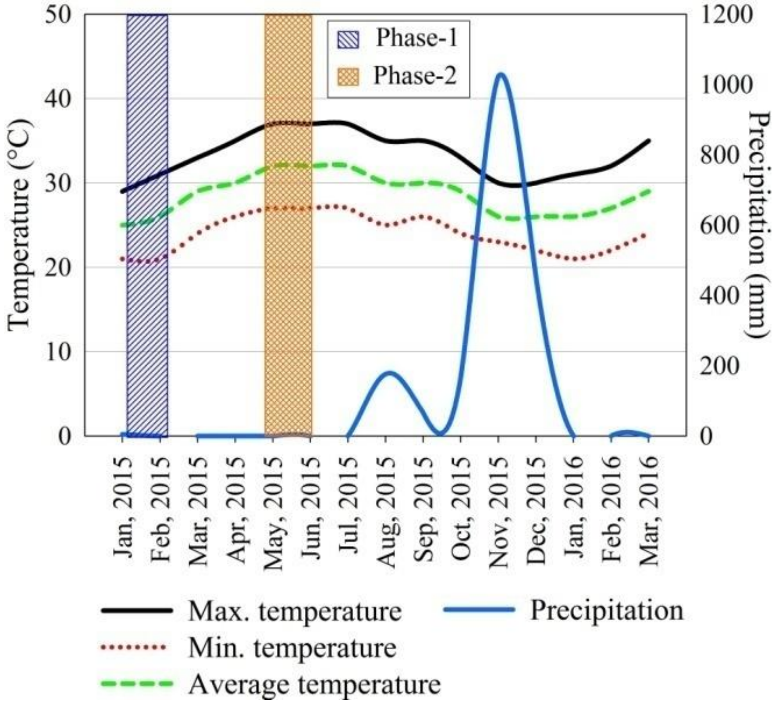


Figure 3.9. Average monthly temperature and precipitation data for the exposure period of the slab specimens ("Chennai weather" n.d.)

Due to the physical constraints involved in the casting and testing of such relatively large specimens, the specimens were cast in two phases: Phase-1 and Phase-2. Phase-1 comprised of slabs cured with wet hessian cloth curing and air curing, whereas Phase-2 consisted of the three slabs cured using curing compounds. The two hatched portions in the Figure 3.5 approximately mark the two phases in which the slabs were cast. The exact date of casting and the period of exposure for each slab are presented in Table 3.7.

It can be observed from Figure 3.9 that there was a difference in average temperature of about 7 °C between the exposure periods (28 days) of the slabs cast in Phase-1 and Phase-2. However, the temperature presented here represents only the temperature of the ambient air, not of the concrete itself. So, considering the increased amount and intensity of the directly incident solar radiations that the Phase-2 slabs were exposed to (which was during the summer), the actual magnitude of this difference between the internal temperature of the concrete slabs could have been well beyond 10 °C. Also, there was no significant precipitation during the 28 days exposure period of any slab. However, large amounts of precipitation were received later, in the months of November and December, seen as the higher of the two blue peaks in Figure 3.9.

Table 3.7. Schedule of casting and exposure for the slab specimens

Phase	Slab	Casting date	7 days	28 days
Phase-1	7dH	6-Jan-15	13-Jan-15	3-Feb-15
	Air	12-Jan-15	19-Jan-15	9-Feb-15
Phase-2	WX-1	24-Apr-15	1-May-15	22-May-15
	RS-1	28-Apr-15	5-May-15	26-May-15
	RW	15-May-15	25-May-15	15-Jun-15

3.5 COMPRESSIVE STRENGTH TEST

For the lab study, the compressive strength tests were performed on 100 mm mortar cube specimens at the age of 3, 7, 14, and 28 days. While for the field study, compressive strength was evaluated on the cylindrical core specimens of size 100 mm (diameter) x 200 mm (length) extracted from the slab specimens. Compressive strength tests were performed using a 3 MN Controls testing system (Figure 3.10).

Load was applied on the mortar cubes at a rate of 900 N/s (ASTM C109/C109M 2007) until failure. The mortar cubes were removed from their respective environmental chambers on the day of testing and were allowed to reach room temperature before testing. The concrete cubes and cores were tested at a rate of 2280 N/(m^2.s) (i.e., 140 kgf/cm^2/min as per IS 516 1959). Also, the concrete specimens were tested in a saturated surface dry (SSD) condition. The core specimens were saturated in the moist room for 48 hours after their end surfaces were capped with sulphur mortar (IS 516 1959). Furthermore, the mass of each specimen was measured before the compression testing.

Figure 3.10. Compression testing of cube specimen

3.6 PREPARATION AND CONDITIONING OF TEST SPECIMENS FOR DURABILITY TESTS

3.6.1 Methods

Cylindrical slices were extracted from the primary specimens (cube and slab specimens) for durability tests. The preparation of these test specimens comprised of the extraction of cores from the cube/slab specimens followed by the application of epoxy coating on the cores, and finally, the slicing of the cores. Cylindrical cores were extracted using a water-cooled diamond impregnated core-cutting machine (see Figure 3.11(a)). The core barrel (70 or 100 mm nominal diameter) was first centred on the specimen to be cored and the machine was fastened firmly to a rigid base with the help of anchors. The end surfaces of the cores can get damaged due to large splitting forces arising from the high speed of advancing of the core barrel during the process of coring. Therefore, slower speeds of vertical movement than usual were resorted to while starting and near the end of the core.

The extracted cores, after thorough cleaning with plain water, were kept exposed to the ambient air for drying the surface before applying the epoxy coating. Two-component epoxy was used for this purpose. It was uniformly applied on the lateral surface of the cores with a paint brush and was left undisturbed for a curing period of 24 hours in air. Epoxy coating effectively seals the lateral surface so that there is no movement of fluids from the lateral surface of the specimen during the test and thus, the penetration of fluids in the course of a test is unidirectional.

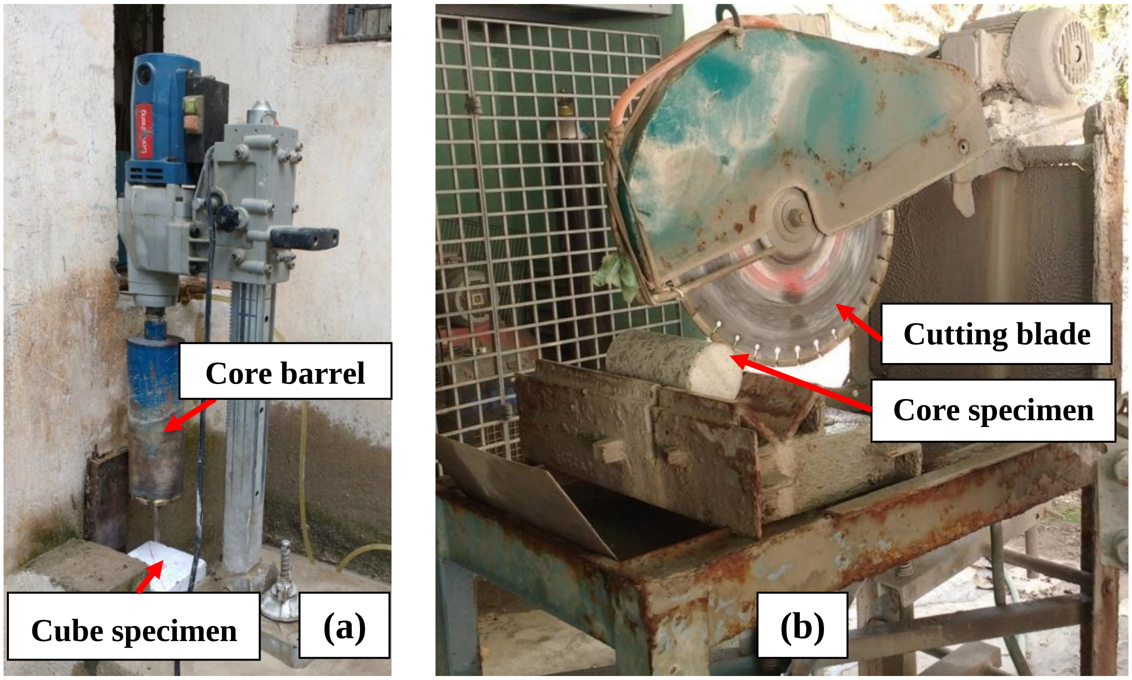


Figure 3.11. (a) Extraction of core using water-cooled core-cutting machine and (b) Slicing of extracted cores using a water-cooled cutting wheel

Finally, the cores were sliced using a water-cooled diamond impregnated cutting/sawing machine (see Figure 3.11(b)). The outer 5 mm portion of the end faces of the cores were removed by grinding against the face of the cutting wheel. Removal of this 5 mm portion was necessary to ensure a plain, smooth, and clean surface devoid of any surface undulations, laitance, and curing compound coating. It also ensures uniform surface area for all the slices as the coring operations often damages the edges of the cores and compensates for any inadvertent inclination of the surface of the slice to its length introduced while coring.

This was followed by moisture conditioning of the specimens. The test specimens for OPI and water sorptivity tests were subjected to drying and the specimens for RCMT were subjected to lime-water saturation. Specimens were dried in an oven at a temperature of 50 °C for 7 days. After 7 days, they were gradually cooled before taking out of the oven to avoid surface-cracking due to a thermal shock. In the case of lime-water saturation, the specimens were kept in a vacuum desiccator (Figure 3.12) for 3 hours at a vacuum pressure of 90 kPa. This was followed by introducing a saturated lime solution into the desiccator carefully without releasing air into the desiccator. When the specimens were completely submerged into the saturated lime solution, the desiccator was reconnected to the vacuum pump to remove any air that entered in the process of filling the desiccator with lime solution. The vacuum pump was disconnected after an hour and the specimens were kept in the solution for another 18 hours before commencing the tests.

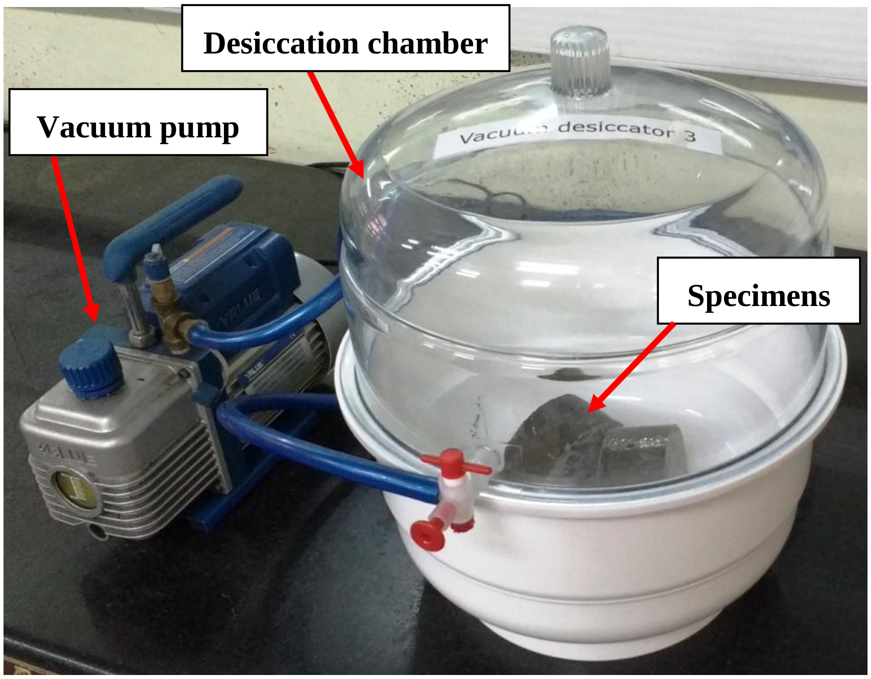


Figure 3.12. Saturation of specimens using vacuum desiccator

3.6.2 Test Program-1 (Laboratory Study)

Cubes of size 150 mm were cast for durability tests in the laboratory study. After the age of 28 days, cores of 70 mm diameter (or 100 mm diameter for rapid chloride migration test) were extracted from each of the cubes (Figure 3.13). Cores from the cube specimens were used instead of standard cylinder specimens for chloride migration test 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 done in the direction perpendicular to that of casting, i.e., across the moulded faces and thereby, avoiding the cast face. In 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 were carefully marked as the test surface after the cutting operation as shown in Figure 3.13.

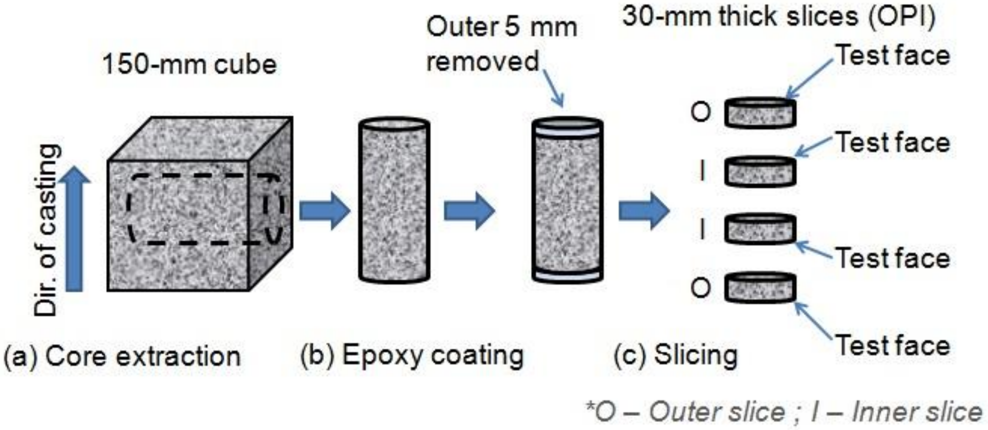


Figure 3.13. Preparation of test specimens for durability index tests for the lab study (Note: figure is not drawn to scale)

3.6.3 Test Program-2 (Field Study)

A similar procedure was followed for the preparation of specimen in the field study as described in Section 3.6.2. However, cores were extracted from the slab specimens in the direction of casting as opposed to the lateral direction in the lab study as shown in Figure 3.14.

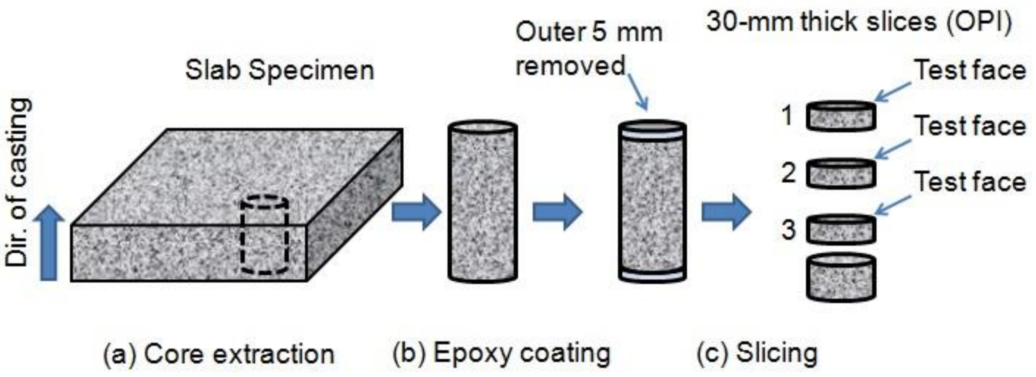


Figure 3.14. Preparation of test specimens for durability index tests for the field study (Note: figure is not drawn to scale)

3.7 OXYGEN PERMEABILITY TEST

Oxygen permeability test is a falling head gas permeability test. It was originally developed by Ballim (Ballim 1991). This test is one of the three tests, which form the basis of South African durability specifications for durability design and performance assessment of concrete structures (Alexander et al. 2008). Several laboratory and field investigations carried out using these tests over the past two decades in South Africa have shown promising output (Alexander et al. 2011; Beushausen and Alexander 2008; Nganga et al. 2013; du Preez and Alexander 2004). It has been found that Oxygen Permeability Index (OPI), which is defined as the negative logarithm of the coefficient of permeability, exhibits high sensitivity towards the effects of curing and compaction methods on concrete. Therefore, OPI can be used to compare the effects of different curing and compaction methods (Alexander et al. 1999). OPI has also demonstrated good correlation with the diffusion coefficient for carbonation and thus can be used in service life prediction of structures prone to carbonation-induced corrosion (Salvoldi et al. 2015).

The schematic in Figure 3.15 illustrates the salient features of a typical OPI test setup. The standard procedure for OPI test as per Concrete Durability Index Testing Manual (Alexander et al. 2009) was followed in the present study. Cylindrical specimens sized 70 ± 2 mm in diameter and 30 ± 2 mm in thickness were used. Drying as described in the Section 3.6 was followed for preconditioning of the specimens. Diameter and thickness of each specimen were measured at four equidistant locations. The specimen was fitted into a flexible rubber collar that in turn was fitted into a steel sleeve. Foam tape was also wrapped around the specimen before inserting it into the rubber collar to facilitate air-tightness. This assembly was then placed into the permeability cell (permeameter). The specimen assembly was fixed into position by tightening the top cover plate over it (Figure 3.16). As the rubber collar is longer than the steel sleeve containing it, the compression of the collar due to tightening of the top and bottom plates against the specimen assembly leads to an airtight arrangement around the specimen. It was ensured that the concrete surface to be tested was placed facing the inlet side. After placing the specimen in position, the pressure chamber was purged with oxygen for 5 seconds by opening both the inlet and outlet valves together. This helps in replacing the existing air in the chamber containing other elements with oxygen. Then, the outlet valve was closed and the pressure in the cell was allowed to increase. The inlet valve was closed when the pressure reached to a stable value of 100 ± 5 kPa. This time was marked as the start time of the test. From the start time, the decay in pressure was recorded at an interval of 15 minutes for a period of 6 hours 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 according to Equation (3.1).

$$k = \frac{\omega V g d}{R A \theta t} . \ln\left(\frac{P}{P_o}\right) \tag{3.1}$$

where

k is the coefficient of permeability in m/s

ω is the molecular mass of oxygen in kg/mol

V is the volume in m^3

g is the acceleration due to gravity in m/s^2

d is the thickness of the specimen in m

R is the gas constant in N.m/K.mol

A is the area of cross section in m^2

Θ is the absolute temperature in K

t is the time in s

P is the pressure at time t in kPa

P_o is the initial pressure in kPa

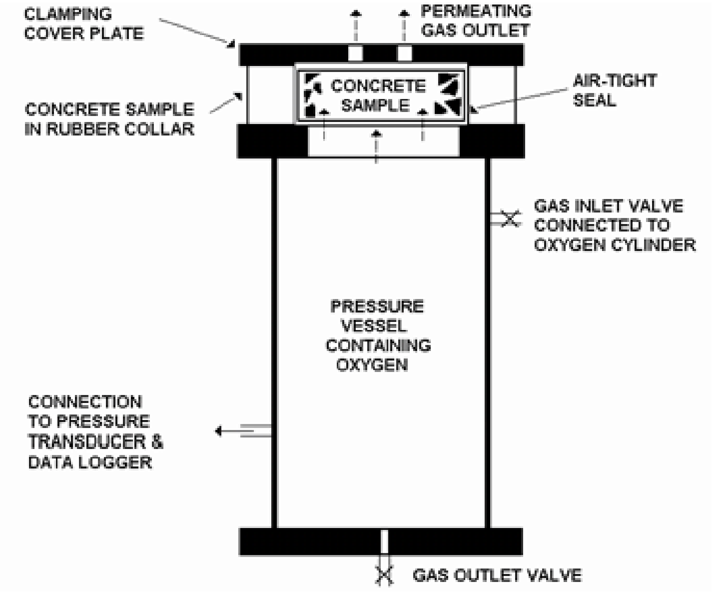


Figure 3.15. Schematic of the OPI test setup (adapted from Alexander et al., 1999)

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 Equation (3.1), 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 Equation (3.2).

$$OPI = -\log_{10}\left[\frac{(k_1 + k_2 + k_3 + k_4)}{4}\right] \tag{3.2}$$

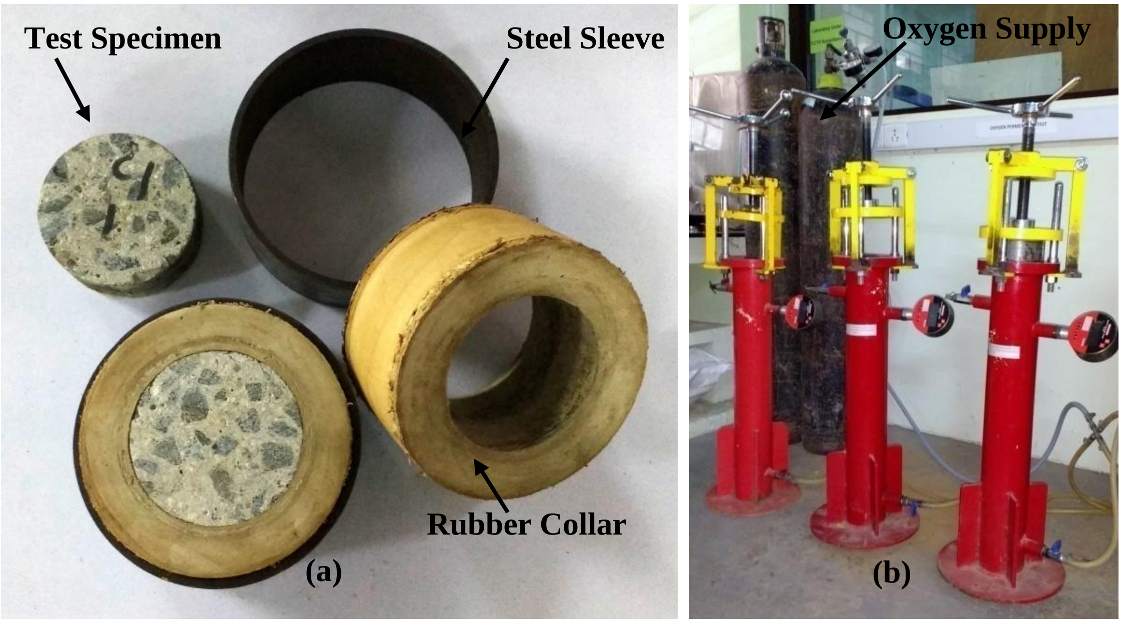


Figure 3.16. (a) Various components of the specimen assembly (b) Permeability cells for OPI testing

3.8 WATER SORPTIVITY TEST

Water Sorptivity test, like oxygen permeability test, is a part of South African durability specifications (Alexander et al. 2008). This test method offers several merits over other surface absorption tests such as ASTM C1585 (2013) or Initial Surface Absorption Test (ISAT) as per BS 1881-208 (1996). The procedure followed in this test is similar to that described in ASTM C1585 (2013). However, water sorptivity test requires a smaller duration of testing, i.e., 25 minutes rather than 8 days required for the ASTM C1585 (2013) method. Moreover, the ease of handling and minimal instrumentation required for testing are added advantages over methods like ISAT or Figg permeability test (Figg

1973). Also, the duration of specimen conditioning required for sorptivity test is only 7 days as compared to 18 days required in the ASTM C1585 (2013) method. However, the resulting moisture distribution in the ASTM C1585 (2013) method appears to depict the actual field conditions in a more realistic way than the South African method. Therefore, the method of specimen conditioning is a debatable issue. In any case, studies have shown that the water sorptivity test exhibit high sensitivity to changes in surface properties of concrete such as those resulting from deficient curing (Alexander et al. 1999).

In general, *Sorptivity*, S, is defined in terms of the height of rise of the wetting front with time. However, the measurement of the depth of penetration of the wetting front involves breaking the specimen for every reading. So, instead of that, the increase in the mass of the specimen is measured. As per the South African specifications, sorptivity is calculated using Equation (3.3).

$$S = \frac{\Delta M_t}{t^{1/2}} \cdot \frac{d}{(M_{sat} - M_{dry})} \qquad (3.3)$$

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.

The relationship of the mass of water absorbed and the height of rise of the wetting front depends on the overall pore-structure of concrete. However, to obtain the rate of rise of water front, the Equation (3.3) assumes the height of capillary rise to be inversely proportional to the amount of porosity. The underlying assumption here is that as the total porosity increases the average size of the capillary (connected pores) also increases which may not always be true for a material like concrete with a complex pore-structure. Moreover, this assumption cannot be used with certainty especially when comparing concrete incorporating different types of binders and fillers. Therefore, it would be better to use the slope of sorptivity curve i.e., $\frac{\Delta M_t}{t^{1/2}}$, as an indicator of sorptivity. However, in the present study, the focus is on the comparison between the effects of different curing methods on OPC concrete/mortar and not between different types/grades of concrete. In which case, the comparison using sorptivity $'S'$ is also acceptable. Therefore, both sorptivity and slope of sorptivity curve are used to study the surface absorption characteristics of mortar and concrete. The procedure for sorptivity test is described in the following text.

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 as shown in Figure 3.17 and Figure 3.18.

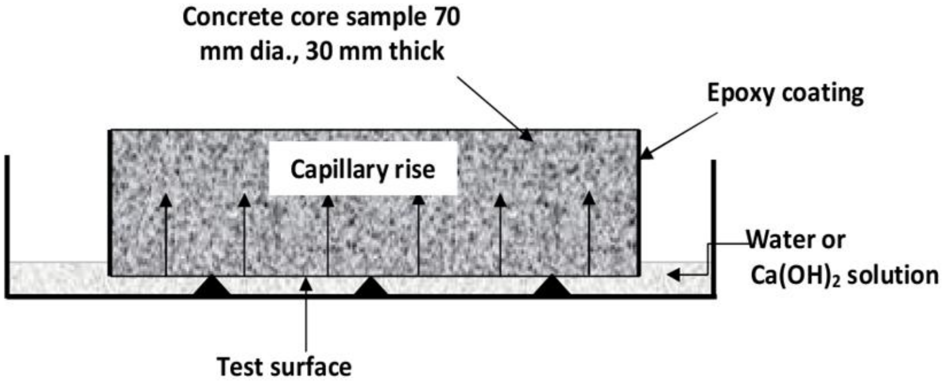


Figure 3.17. Schematic of sorptivity test (adapted from Alexander et al., 1999)

Figure 3.18. Sorptivity test on concrete specimens

Mass of the specimen was recorded at 3, 5, 7, 9, 12, 16, 20, and 25 minutes 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 Section 3.6 to measure its water absorption capacity. Finally, the sorptivity was calculated using Equation (3.3).

3.9 RAPID CHLORIDE MIGRATION TEST (RCMT)

Rapid Chloride Migration Test (RCMT) is an electrically accelerated method to measure the non-steady state migration coefficient for chloride penetration (D_{nssm}). Proposed by Tang and Nilsson as the *CTH* method (Tang and Nilsson 1992), RCMT is a standardized Nordic test method (NT Build 492 1999). It offers a range of advantages over the most commonly used accelerated test, Rapid Chloride Permeability Test (RCPT) (ASTM C1202 2012). The issues of rise in temperature due to high applied potential (60 V) in RCPT is resolved by using lower values of potential (10-60 V) in RCMT depending on the quality of concrete. Furthermore, during the course of testing, chloride ions from catholyte solution penetrate into the concrete specimen resulting in a reduction in chloride ion concentration of the catholyte solution. However, the use of large reservoir for catholyte solution in RCMT lowers the net reduction in the concentration of the chloride ions. Also, the specimen is kept in an inclined position in RCMT to facilitate the escape of bubbles formed at the electrodes. Most importantly, RCMT provides a means for further quantitative analysis such as service life prediction by yielding D_{nssm}, whereas RCPT can only provide a qualitative indication of the electrical conductivity of concrete. The procedure followed for RCMT in this study is as follows.

Lime saturated specimens of diameter 100 mm and thickness 50 mm were used in this test as per NT Build 492 (1999). The diameter and thickness of each specimen were measured before testing. The specimens were fitted tightly into PVC pipe sleeves with the test face aligned towards the cathode as shown in Figure 3.19. The edges of the specimen in contact with the pipe were sealed with double coat of a silicone caulking gel to ensure water-tightness of the specimen assembly. 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. The test setup is shown in Figure 3.20.

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 (1999). 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 Figure 3.21). 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.

$$D_{nssm} = \frac{0.0239\ (273 + T)L}{(U - 2)t}\left(x_d - 0.0238\sqrt{\frac{(273 + T)Lx_d}{(U - 2)}}\right) \tag{3.4}$$

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

In this calculation, (U-2) is used instead of U to account for the potential drop at the electrode and electrolyte interface (McGrath and Hooton 1996).

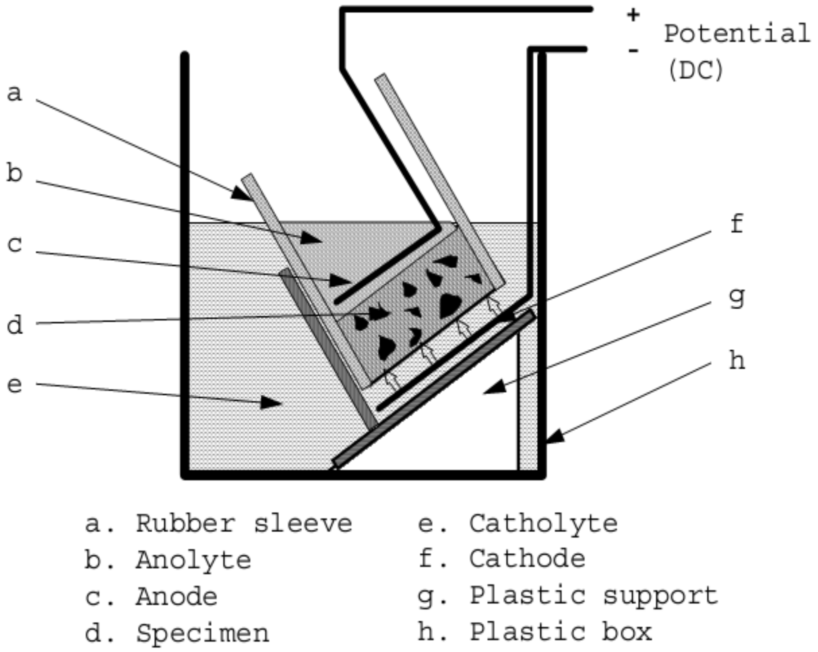


Figure 3.19. Schematic of Rapid Chloride Migration Test (adapted from NT Build 492, 1999)

Figure 3.20. RCMT test setup that was used in this study

Figure 3.21. Penetration of chlorides into concrete seen as a white precipitate of AgCl on the split face of the specimen

The quality of concrete can be classified on the basis of the following three durability indicators: OPI, WSI, and D_{nssm}, as shown in Table 3.8.

Table 3.8. Classification of concrete quality based on durability indices: OPI, WSI, and Non-steady-state migration coefficient (Alexander et al. 1999; Bjegović et al. 2015)

Oxygen Permeability Index (OPI)	Water Sorptivity Index (WSI, mm/√hr)	Non-Steady-State Migration Coefficient, D_{nssm} (x 10^{-12} m^2/s)	Concrete Quality
> 10.0	< 6	< 2	Very good
10.0 - 9.5	6 - 10	2 - 8	Good
		8 - 16	Normal
9.5 - 9.0	10 – 15	> 16	Poor
< 9.0	> 15		Very poor

3.10 REBAR DETECTION AND COVER DEPTH MEASUREMENT USING COVER METER

Rebar Locator or Cover Meter is a portable device used for metal detection in concrete structures. This device can detect the presence and even ascertain the exact position of steel reinforcement bars, conduits, embedded metallic parts, electrical cables etc inside concrete. It can also measure the depth of embedment of the metallic parts. Most commonly, it is used in the determination of the location of rebars embedded in concrete and measurement of their cover depths. The knowledge of the location of embedded rebars is essential, especially, while extracting cores or executing non-destructive tests such as ultrasonic pulse velocity test, surface resistivity etc. On the other hand, cover depth measurements are used for compliance testing of the built structure for quality control purposes and for supplementing other condition monitoring tests in cases where the information is not available.

A number of variants of cover meters are available commercially. The basic models measure the cover depth of top two layers of reinforcement only, while more sophisticated versions can also measure bar size, locate multiple layers of reinforcement, and present the data in the form of 2 D and 3 D scans. The less sophisticated versions are generally based on the principle of Electromagnetic Induction, whereas the more sophisticated versions utilize the principle of Ground Penetrating Radar (GPR). The electromagnetic cover meters are based on Pulse Induction Technique in which electrical pulses are sent to a single or multi-core circuit. These pulses induce eddy currents in the nearby rebar and the magnetic field generated by these eddy currents prolongs the decaying of the pulse. This is processed to generate an output in terms of the presence, size, and/or cover of rebar. A lab study comprising commonly available cover meters found the accuracy of measurement to be 10 % for cover depth up to 40 mm (Luco 2005). The accuracy was found to decrease for larger covers and smaller diameter rebars. The influence of temperature, moisture, and w/c of concrete was found to be insignificant. On the other hand, field measurements on bridge structures were found to have a high variability in another study, which highlights the need for proper calibration of the instruments and user guidelines for conducting this type of survey (Nganga et al. 2013). As the electromagnetic measurements can especially get affected by the type of steel used, calibration of the instrument is recommended each time a change in the type of steel is expected. Various methods for calibration are described in BS 1881-204 (1988)

In the present study, a basic version of cover meter, conforming to BS 1881-204 (1988) is used which takes the rebar diameter as input and provides the cover depth accordingly. The device consists of a sensor unit, which is connected to a display console unit (see Figure 3.22).

Figure 3.22. (a) Cover meter and its components and (b) rebar detection on field specimen using cover meter

It also comes with a plastic spacer unit, which is used in situations where the cover depth lies below 12.7 mm (0.5’) and cannot be accurately detected by the sensor. The location of rebars on the slab specimens was found out by sliding the sensor in the lateral direction to the expected direction of rebars. A grid was marked on the slabs. Then, cover depth of rebars in both the top layers was measured between every set of grid points. This grid also facilitated extraction of core specimens.

3.11 Surface Moisture Measurement using Moisture Meter

A portable moisture meter (Figure 3.23) was used for measuring the surface moisture of the slab specimens to facilitate valid interpretation of surface resistivity results. The instrument uses a capacitive contact sensor which detects the percentage of surface moisture present in the concrete. This instrument measures the dielectric constant of the concrete. Because the dielectric constant of concrete is influenced by the degree of saturation, the output is generated in terms of the moisture content after proper calibration. This instrument is believed to have a detection range of 1” from the surface.

Two measurements were taken from the central portion of each grid box (marked using cover meter) of the slab specimens to avoid possible interference by rebars in the measurement.

Figure 3.23. Hand-held surface moisture meter used in this study

3.12 SURFACE RESISTIVITY MEASUREMENT USING WENNER FOUR PROBE METHOD

Wenner Four Probe method offers a non-destructive way of measuring resistivity of cover concrete. This method features four probes, the outer two of which supply alternating current to the concrete in contact and the inner two measure the resulting potential drop (Figure 3.24). By using Ohm's law for a homogenous material with semi-infinite extent and point electrodes, the surface resistivity can be calculated with the help of Equation (3.5). However, Equation (3.5) can be also be used in the case of concrete with acceptable tolerance (Polder et al. 2001).

$$\rho = 2\pi a R \tag{3.5}$$

where

ρ is the surface resistivity of concrete

R is the resistance (V/I)

a is the probe spacing

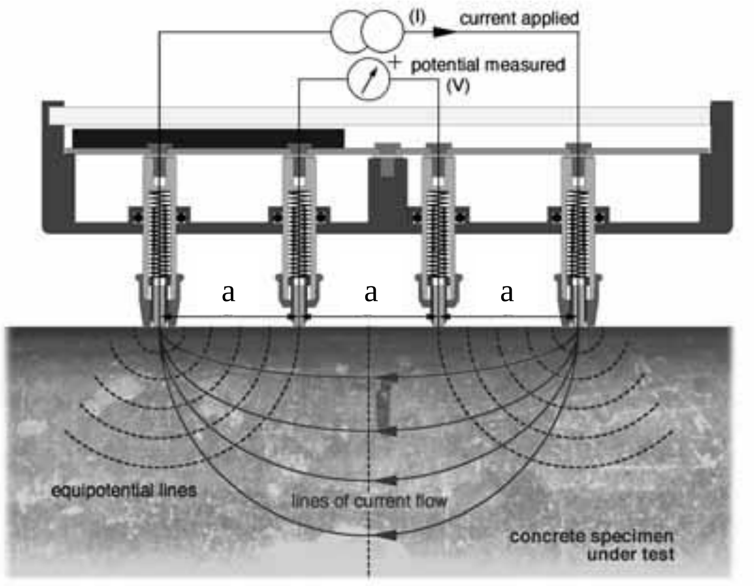


Figure 3.24. Schematic of Four Probe Resistivity method (adapted from Proseq Asia Pvt. Ltd. (2011))

The instrument used in the present study (Figure 3.25) uses a range of current values (10 µA-200 µA) depending on the quality of concrete to maximize the resolution of the measurement. The measurements were taken along the two diagonals of each grid box in order to avoid influence of rebars on the results. Also, the probes were soaked in water to facilitate contact with the concrete.

Figure 3.25. Surface resistivity instrument used in this study with the calibration strip

3.13 SUMMARY

In the present study, OPC is used for making cementitious mixtures. Compressive strength, oxygen permeability, water sorptivity, chloride migration, and electrical resistivity tests are used to study the effect of five curing compounds on the strength and durability characteristics of cementitious systems. The materials and methods that were used in the course of this study were described in this chapter.

4. INFLUENCE OF LABORATORY CURING ON STRENGTH AND DURABILITY OF MORTAR

4.1 INTRODUCTION

A major part of India experiences hot weather conditions for a substantial period in a year, often exceeding six months in most of the regions. In such a country, concreting in hot weather conditions is inevitable. As discussed in Section 2.9, the influence of hot weather on the strength of concrete has been studied well in the past. These studies have mostly been focused on wet curing. However, the increasing need to have alternative curing methods such as curing compounds entails investigation of their performance also in such conditions. Moreover, as is now widely accepted that the influence of curing on durability is much more significant than on strength, its performance should also be evaluated in the context of durability. This experimental program is an attempt to study the influence of curing on both strength as well as durability.

This program restricts itself to the performance evaluation of five curing compounds and conventional wet curing at two different temperatures and RH conditions, one mild: 25 °C, 65 % RH and the other harsh: 45 °C, 55 % RH, controlled in the laboratory. As the intention is to study the performance of curing methods, mortar is used in this study instead of concrete to limit variability in the results that may arise due to the presence of coarse aggregates. Further, a study of the difference in the influence of curing on the surface region of concrete structural elements and the inner region is also attempted along with the comparison of the suitability of various test methods used in this study.

4.2 INFLUENCE OF LABORATORY CURING ON THE WATER LOSS FROM MORTAR

Water lost by the cube specimens, cast for compressive strength test, during the exposure period of 28 days is computed using Equation (4.1).

$$M_{wl}, \% = \frac{(M_{i,av} - M_t)}{M_d} \times 100 \qquad (4.1)$$

where,

M_{wl} = Percentage water loss with respect to the original water-content

$M_{i,av}$ = Initial mass of cube specimen in g (taken as an average value of 2259. 3 g)

M_t = Mass of the cube specimen at the age 't' days in g

M_d = Initial water content of a cube specimen as per mixture design in g (= 276.2 g)

An average value of initial mass is used for $M_{i,av,}$ which was measured on a set of three cubes cast separately for this purpose. The mass was measured right after initial leveling of the top surface, while the mortar was still in the fresh state. It is important to mention here that water loss as calculated using Equation (4.1) represents the total water lost from the cube specimens that also includes the water loss due to bleeding and evaporation before the start of curing process. Also, the mass of curing compound applied on the cube specimens is neglected in these calculations. The water loss at the age of 3, 7, 14, and 28 days is calculated for all the curing regimes and the results are presented in Figure 4.1. Each result represents an average of the observations on three replicate cube specimens.

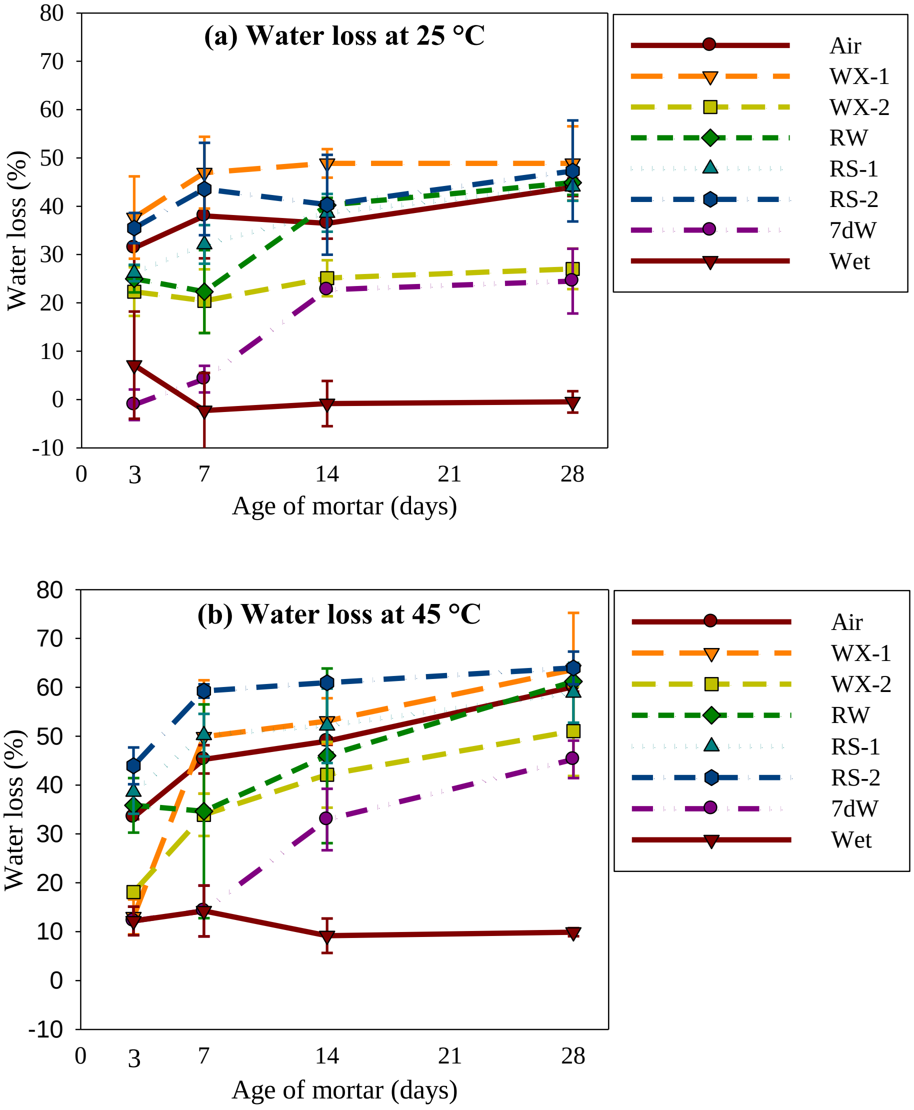


Figure 4.1. Water loss from mortar cube specimens during 28 days exposure, under different curing regimes

Further, to assess the influence of temperature on the performance of curing compounds, it is important to separate the influence of temperature on the evaporation of water from the water loss results. Therefore, the water loss results are normalized with respect to the water loss capacity of mortar at the respective curing temperature to obtain the water retention capacity of each curing method used in this study. The water-loss capacity of the mortar at any age is taken as the water loss from the mortar under air curing at that age. Water-retention capacity or water retention of a curing method at any age is defined here as the percentage reduction in the water loss at any age relative to the water loss under air curing at the same age (see Equation (4.2)). The results calculated as per Equation (4.2) are presented in Figure 4.2.

$$Water\ retention, \% = \frac{\left(M_{wl,\ AC} - M_{wl}\right)}{M_{wl,\ AC}} \times 100 \tag{4.2}$$

where

M_{wl} = Percentage water loss of any cube specimen

$M_{wl,AC}$= Average percentage water loss of cube specimens under *air curing*

Figure 4.1(a) shows water loss results at the temperature of 25 °C. It can be seen in this figure that wet-cured mortar exhibit negative water loss after 3 days. This implies that specimens have absorbed additional water because of being stored in the submerged condition. Moreover, the water loss from wet-cured mortar remains nearly constant at zero level throughout the period of 28 days as expected. On the other hand, air-cured mortar exhibit an average water loss of about 40 % with respect to wet-cured mortar. Most of this water loss seems to occur in the first 3 days. It can be anticipated that water loss due to bleeding would have contributed a major portion to this value. The water loss does not seem to increase significantly beyond 3 days. In general, large scatter is encountered in all the results.

In the case of curing compounds, mortar cured with WX-1 and RS-2 exhibit greater water loss values than air cured mortar throughout the exposure period. Water loss results of mortar cured with curing compound RS-1 remain very close to air-cured mortar whereas that cured with curing compound RW demonstrates 10-15 % lower water loss than air-cured mortar up to 7 days. However, beyond 7 days, it also shows a performance similar to that of air-cured mortar. These curing compounds result in an average water loss of 40-50 % at 28 days. On the other hand, mortar cured with curing compound WX-2 exhibits an average water loss of 25 % at 28 days which is 20-25 % lower than all the other curing compounds. Further, the mortar cured under 7-day wet curing lose water rapidly between 7 and 14 days, ultimately reaching close to the water loss results of that cured with curing compound WX-2. Additionally, the differences between the performances of different curing methods are clear only after 14 days.

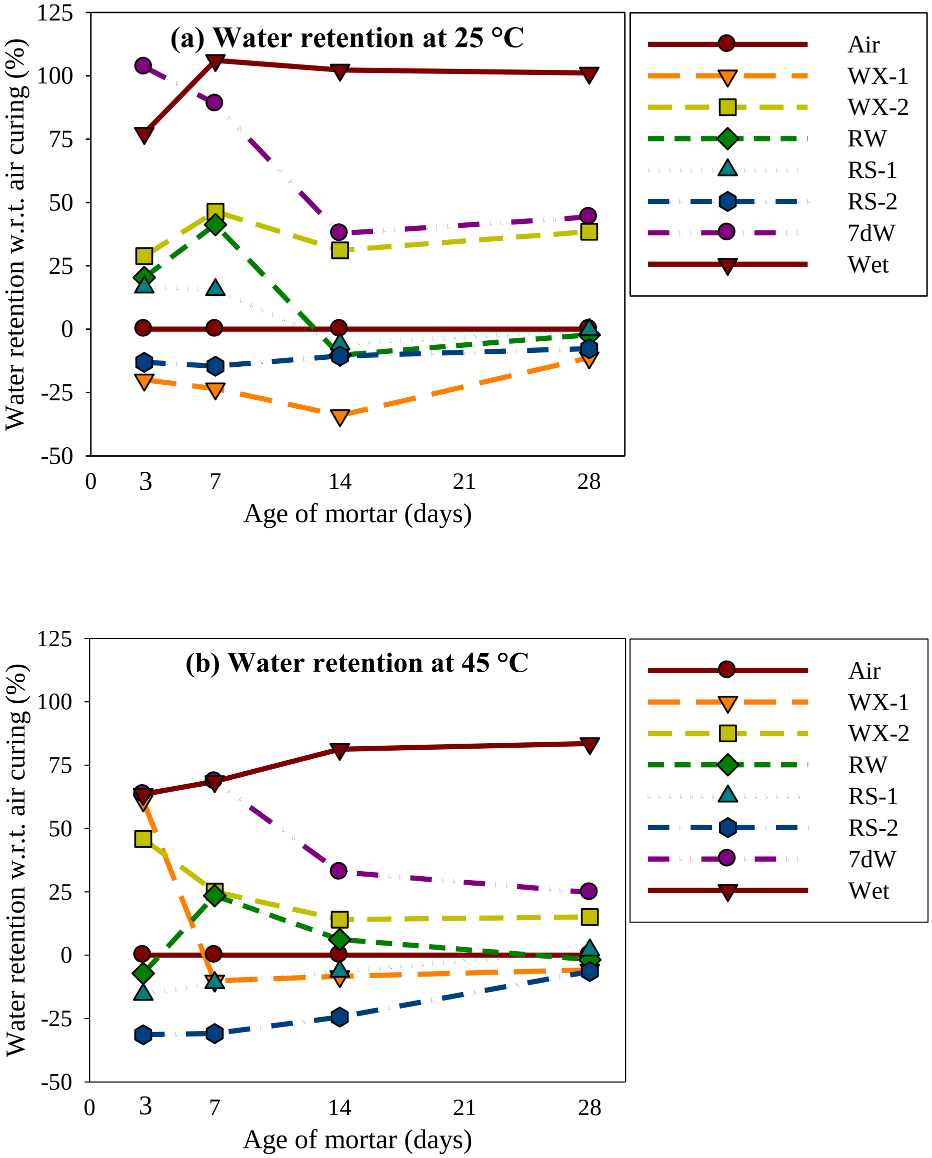


Figure 4.2. Water retention in mortar cube specimens under different curing regimes relative to that under air curing at the same age

Water loss results at 45 °C are presented in Figure 4.1(b). At this temperature also, wet-cured mortar shows a nearly constant water loss throughout the exposure period. However, in this case, the water loss is increased to about 10 %. This can be attributed to the loss of water from the wet specimens while they were kept in open air for lowering their temperature to the ambient temperature level, prior to testing. In retrospect, this could have been avoided if the specimens were kept submerged in lime water until they reached the ambient temperature level. Also, unlike the case of 25 °C, where the difference between the water loss results of the air-cured mortar and wet-cured mortar remains nearly constant at 40 % throughout 28 days, it increases from 20 % at 3 days to 50 % at 28 days in this case. In general, the water loss appears to increase throughout the period of 28 days; however, the rate is highest up to 7 days. Large scatter in the data is observed in the case of curing at 45 °C also. As far as the performance of curing compounds is concerned, the curing compounds WX-1 and WX-2 show performance similar to that of wet curing at the age of 3 days; however, their performance recede rapidly later. Mortar cured with curing compounds WX-1, RW, RS-1, and RS-2 demonstrate similar to or poorer water loss results than that of air-cured mortar. Only the curing compound WX-2 shows a minor improvement in inhibiting water loss. As compared to its performance of curing compound WX-2 at 25 °C, the performance at 45 °C declines by about 20 % in terms of water lost. Further, the distinction between the performances of different curing methods is rather difficult at this temperature owing to the large scatter in the data and poor performance of most of the curing methods.

Results indicate that most of the curing compounds in this study do not help in preventing water loss. Only the curing compound WX-2 retains water throughout the 28 days at 25 °C. However, its water-retention capacity decreases substantially at 45 °C (Figure 4.2(b)). Although the amount of water lost at 7 days by the mortar cured with curing compound WX-2 is lower than the mortar cured under air curing, the rate of water-loss (which is the slope of the curve in Figure 4.1 (b)) seems to be nearly same for both the cases after 3 days. As the function of curing compound is essentially to prevent the loss of water by reducing the rate of water loss through it, this indicates that curing compound WX-2 performs effectively only in the early ages, when subjected to high temperatures. Similarly, all the other curing compounds also demonstrate ineffectiveness in water-retention at this temperature (45 °C) and result in greater water loss as compared to that at 25 °C (Figure 4.2). This is in agreement with the observations of Fattuhi (1986) and contradicts Wasserman and Bentur (2013) who observed an improvement in the performance of curing compounds with the increase in the harshness of the ambient environment.

These results also suggests that the effectiveness of a curing compound up to 3 days (as is tested according to ASTM C156 (2011) may not reflect on its performance beyond 3 days. Furthermore, the large scatter encountered in the individual results of water loss renders the comparison between the performances of different curing compounds difficult at early ages. Hence, it is expected that the differentiation between the water-retention efficiencies of different curing compounds would be more reliable if it is based on results obtained over longer duration. Additionally, the inevitability of the use of pozzolans in concrete in the present times—which often require longer durations of curing than OPC—seems to justify the use of longer test durations. Moreover, it is also worth noting that if proper curing measures are not taken care of, water loss can reach well beyond 50 % at 28 days, limiting the achieved degree of hydration to even less than 50 % of the potential degree of hydration.

4.3 INFLUENCE OF LABORATORY CURING ON THE COMPRESSIVE STRENGTH OF MORTAR

Figure 4.3 shows the evolution of compressive strength of mortar specimens up to 28 days under each curing regime at both the temperatures. Each data point constitutes an average of test observations on three specimens. For the ease of comparison and interpretation, the percentage compressive strengths achieved under each curing regime with respect to the compressive strength of continuously wet-cured specimens at the same age are also presented in Figure 4.4. Compressive strength results of mortar specimens cured under standard laboratory 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 (see Figure 4.4(a)). However, the distinction between the performances of curing methods is clearer from the age of 14 days onwards.

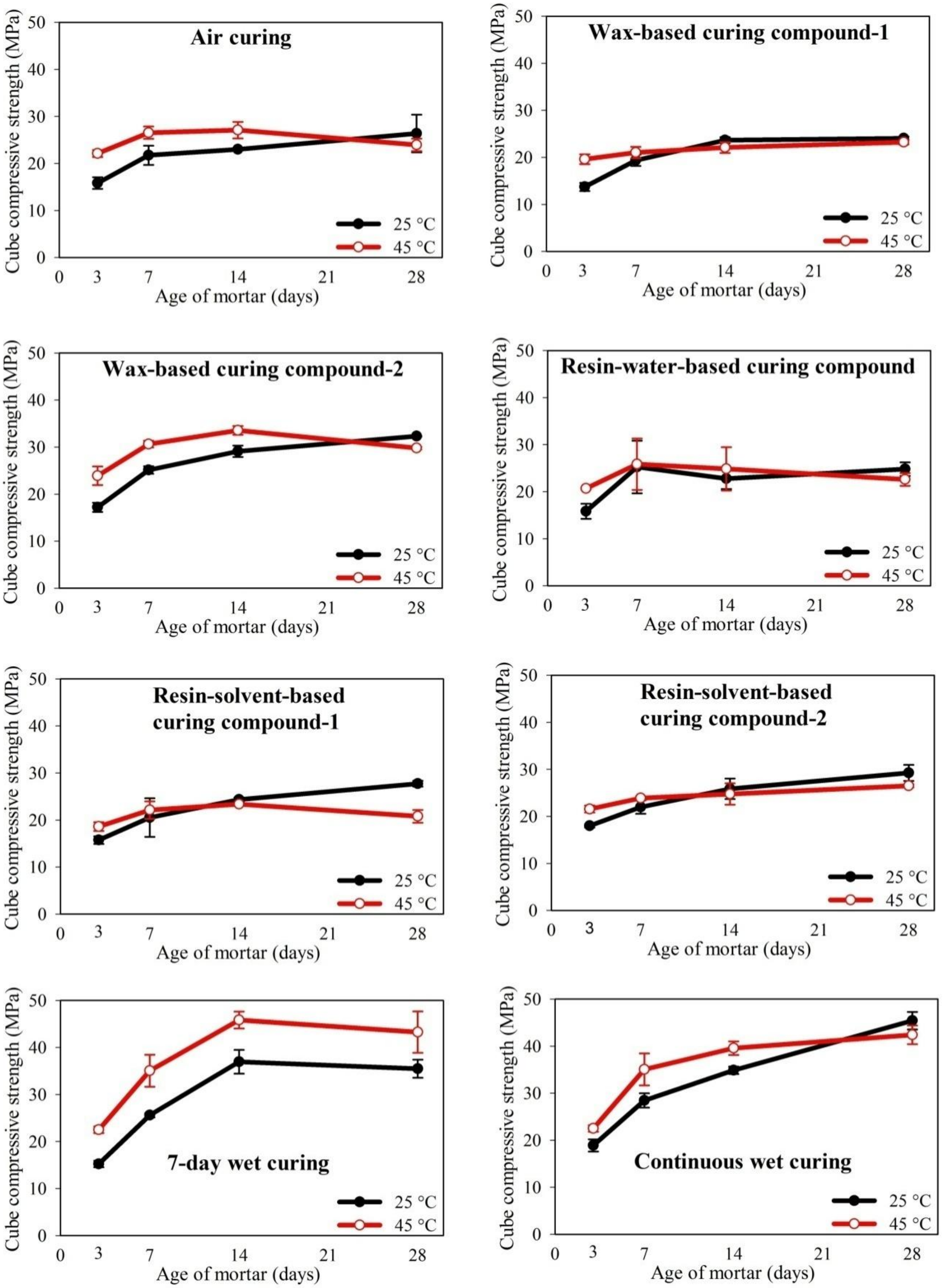


Figure 4.3. Evolution of compressive strength of mortars cured under different curing regimes

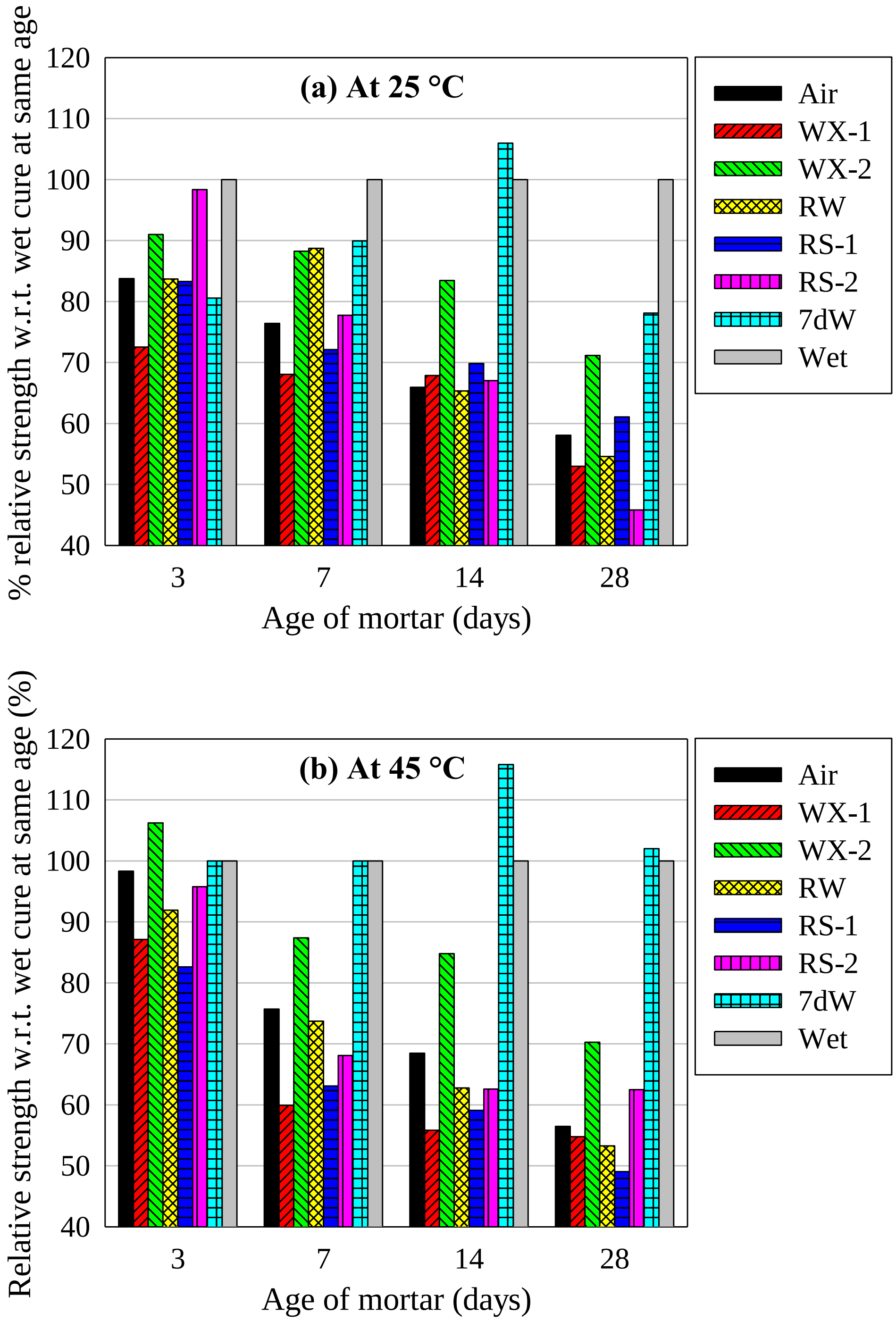


Figure 4.4. Percentage compressive strength of mortar cured under different curing regimes relative to the strength of the continuously wet-cured mortar at same temperature and age

At the temperature of 25 °C and relative humidity (RH) of 65 %, wet curing (Wet) leads to the highest compressive strength at 28 days amongst the curing methods used in this study as expected (see see Figure 4.4(a)). The loss in compressive strength due to deficient curing, throughout the period of 28 days, is prominently visible in the case of air curing (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 owing to the unavailability of sufficient water in the pores to maintain the rate of reaction as seen in the water loss results (Figure 4.1(a), Section 4.2).

The exposure to a high ambient temperature of 45 °C with an RH of 55 % results in a higher rate of strength gain than at the temperature of 25 °C (Figure 4.3). 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 (Figure 4.4(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 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 as opposed to those wet cured at 25 °C, so the strength results for curing at 45 °C up to the age of 7 days are same for both the regimes—7dW and Wet. Casting from different batches of mortar could be one of the reasons for the observed variability in the results of 7dW and Wet at 25 °C. Also, as the castings were done on different days, difference in ambient temperature conditions in which the castings were done could also have increased the variability in the results.

Moreover, 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 (Bartlett and Macgregor 1994; Popovics 1986). Popovics (1986) 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 (Bartlett and Macgregor 1994). 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 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, 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, the strength is about 30 % lower than that of wet-cured mortar at the age of 28 days. The air-cured mortar registers a loss in compressive strength of 43.5 % at 28 days with respect to that of wet-cured mortar. Thus, the loss in strength with respect to wet curing in the case of air curing and curing compound WX-2 at the age of 28 days remains nearly same at both the temperatures. Further, mortar cured under air curing, 7-day wet curing, and curing compounds WX-2, RW, and RS-1 exhibit retrogression in strength after 14 days at 45 °C. This could be due to differential drying shrinkage as a result of excessive loss of water from the surface of mortar specimens.

In general, the compressive strength results are found to be in agreement with water-loss results. For example, both 7 days wet-cured mortar and mortar cured with curing compound WX-2 show similar water loss as well as compressive strength at the age of 28 days at 25 °C. The only difference is that 7-day wet-cured mortar starts losing water after 7 days, but mortar cured with curing compound WX-2 loses most of the water in the first 3 days. On the contrary, although the total water loss at 45 °C for these two differ only by 5-10 %, their respective strengths differ by a large margin of 30 %. This indicates the importance of pore saturation in the early ages of cement hydration to achieve long-term strength, especially in hot weather conditions. Furthermore, as seen in the results, wet curing in the early ages eliminates the need for prolonged curing periods in the case of high ambient temperatures.

4.4 INFLUENCE OF LABORATORY CURING ON THE DURABILITY INDEX VALUES OF MORTAR IN THE NEAR-SURFACE REGION

4.4.1 Water-Penetrable Porosity

Porosity of mortar specimens (70-mm dia. and 30-mm thick) was measured using water absorption by vacuum saturation technique as explained in Section 3.8. Four specimens were tested for each durability test result. The results are presented in Figure 4.5. Air curing and wet curing lead to similar porosities (that is, 14.6 and 14.8 % respectively) when cured at 25 °C. The porosity of 7-day wet-cured mortar at this temperature also lies very close to them with a value of 13.9 %. Moreover, curing compound WX-2—which results in lower water loss than air curing (Section 4.2)—leads to a porosity of 18.3 % which is higher than that achieved under air curing. Similarly, all the other curing compounds also result in higher porosity than air curing. This is contrary to the general expectations (see Section 2.8) as well as the observed water loss behaviour of these curing methods (see Section 4.2). However, a rise in the porosity values is seen, in general, with the increase in the curing temperature to 45 °C as expected. 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.

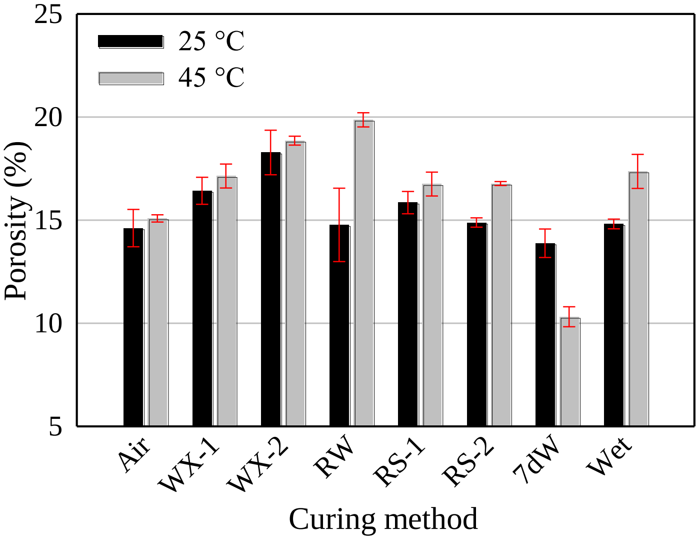


Figure 4.5. Effect of laboratory curing on the porosity of near-surface mortar (outer slices)

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.

4.4.2 Oxygen Permeability Index (OPI)

Figure 4.6 shows the OPI results of mortar specimens, lab-cured at 25 and 45 °C. It must be emphasized here that a higher value of OPI indicates superior performance and vice versa (OPI = - log K as per Equation (3.2), Section 3.7). 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 curing 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 curing.

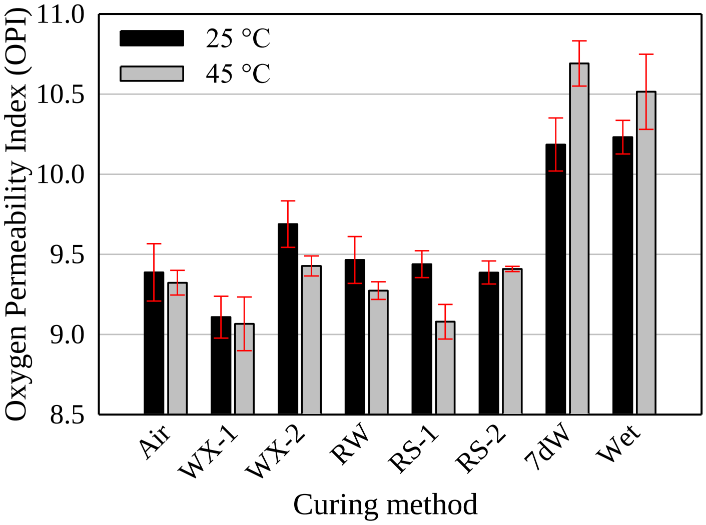


Figure 4.6. Effect of laboratory curing on the OPI of near-surface mortar (outer slices)

Increase in the curing temperature from 25 °C to 45 °C seems to improve OPI in the case of wet curing (Wet and 7dW), as seen in Figure 4.6. 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 curing, including curing compound WX-2. It implies that curing compound WX-2 may help in curing at 25 °C, but it is not 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) as per Alexander et al. (1999).

4.4.3 Water Sorptivity

Higher value of water sorptivity is indicative of deeper penetration of water into mortar and thus an inferior performance. Therefore, sorptivity results (see Figure 4.7), 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 sorptivity results can be easily noticed. First, 7-day wet curing exhibit better sorptivity than 28-day wet curing at both the temperatures. Second, the curing compound WX-2 yields a sorptivity similar to 7-day wet curing and better than 28-day wet curing at 25 °C. Therefore, the trend followed by sorptivity results at 25 °C is, in decreasing order of superiority, 7dW (10.2), WX-2 (10.5), and Wet (12.5).

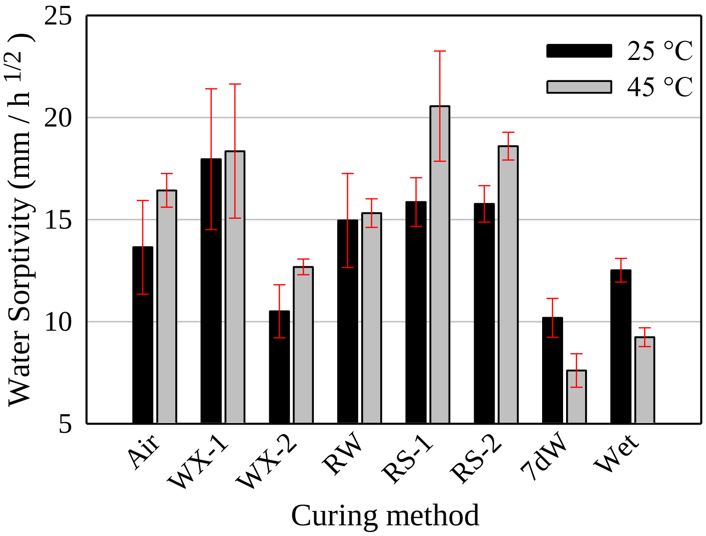


Figure 4.7. Effect of curing on the sorptivity of near-surface mortar (outer slices)

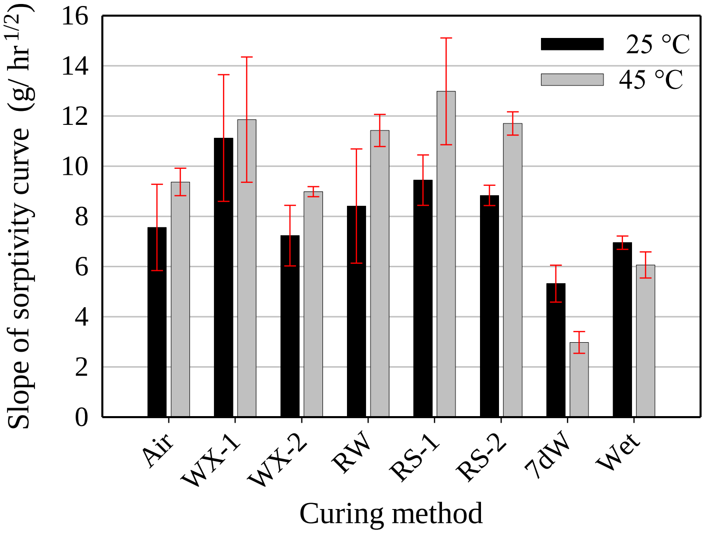


Figure 4.8. Effect of curing on the slope of sorptivity-curve values of near-surface mortar (outer slices)

However, slope-of-sorptivity-curve results (see Figure 4.8) present a different picture. In this case the trend at 25 °C is, in decreasing order of superiority, 7dW (5.3), Wet (6.9), and WX-2 (7.2). The reason behind this variation between sorptivity and slope-of-sorptivity-curve results is the unusual porosity values of mortar cured using curing compound WX-2 (see Figure 4.5). This is because of the fact that the value of sorptivity (as defined in Equation (3.3), see Section 3.8) decreases with the increase in porosity. However, all the other curing compounds exhibit performances even poorer than air curing at both the temperatures.

4.4.4 Non-Steady-State Migration Coefficient for Chloride Penetration (D_{nssm})

The effect of lab curing on D_{nssm} of OPC mortar is shown in Figure 4.9. It should be noted that larger value of D_{nssm} signifies inferior performance of mortar. From Figure 4.9, 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.

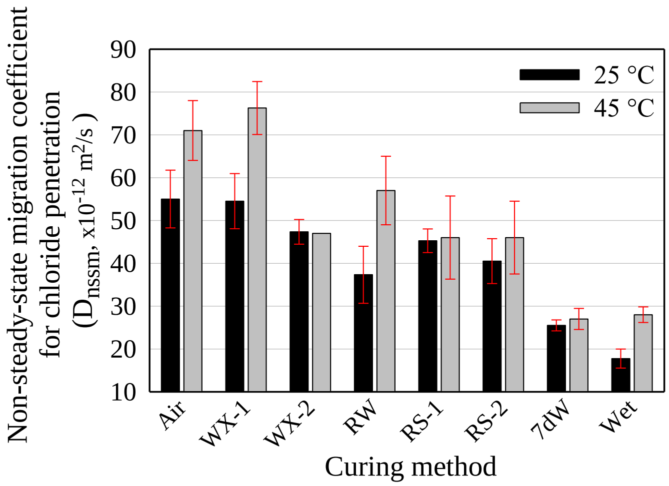


Figure 4.9. Effect of laboratory curing on the non-steady-state migration coefficient for chloride penetration of near-surface mortar (outer slices)

Migration results differ with OPI and sorptivity results in certain aspects. First, curing compounds, in general, lead to better D_{nssm} than air curing at both the temperatures as opposed to their OPI and sorptivity, which were similar to or worse than those of air-cured 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.

4.5 Influence of Laboratory Curing on the Durability Index Values of Mortar in the Inner Region

Figure 4.10, Figure 4.11, Figure 4.12, and Figure 4.13 shows the effect of curing on the porosity, OPI, WSI, and slope of sorptivity curve of the inner mortar compared the near-surface mortar, respectively. It can be inferred from these figures 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 due to the difference between the availability of water near the surface region and the core. However, we know 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 hygrostatic equilibrium in the specimen. In this way, the continuous loss of water from the surface would eventually lead 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.

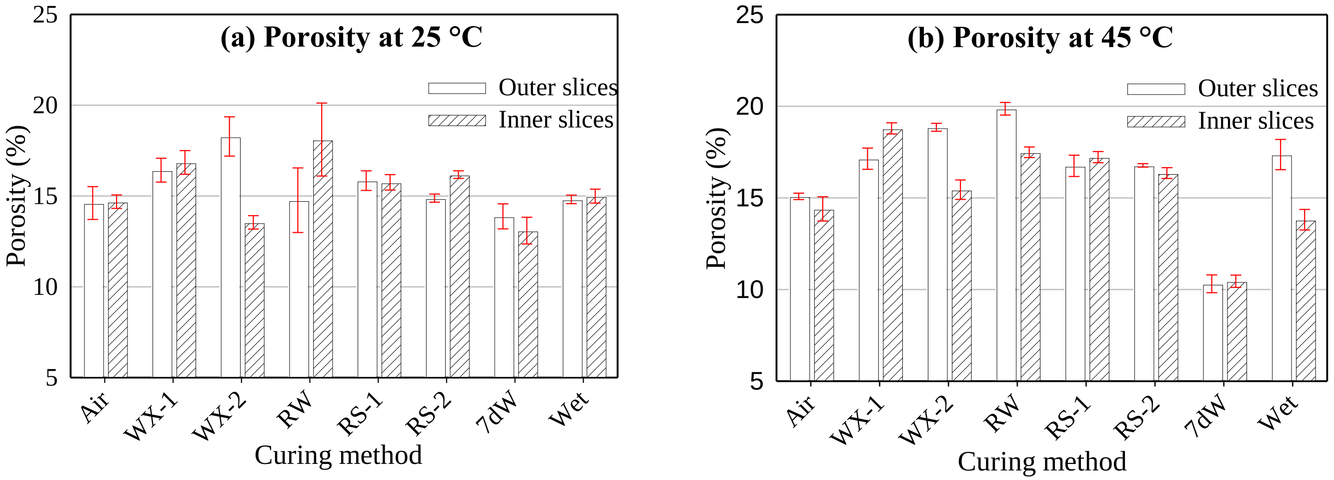


Figure 4.10. Effect of laboratory curing on porosity of the near-surface and inner mortar (outer and inner slices) at 25 °C and 45 °C

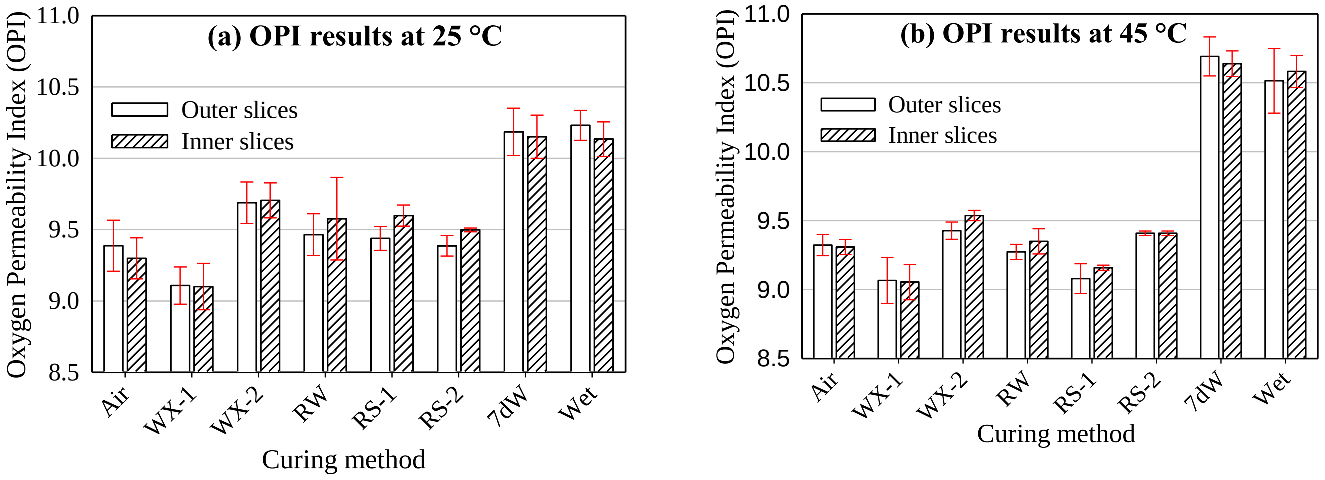


Figure 4.11. Effect of curing on OPI of the near-surface and inner mortar (outer and inner slices) at 25 °C and 45 °C

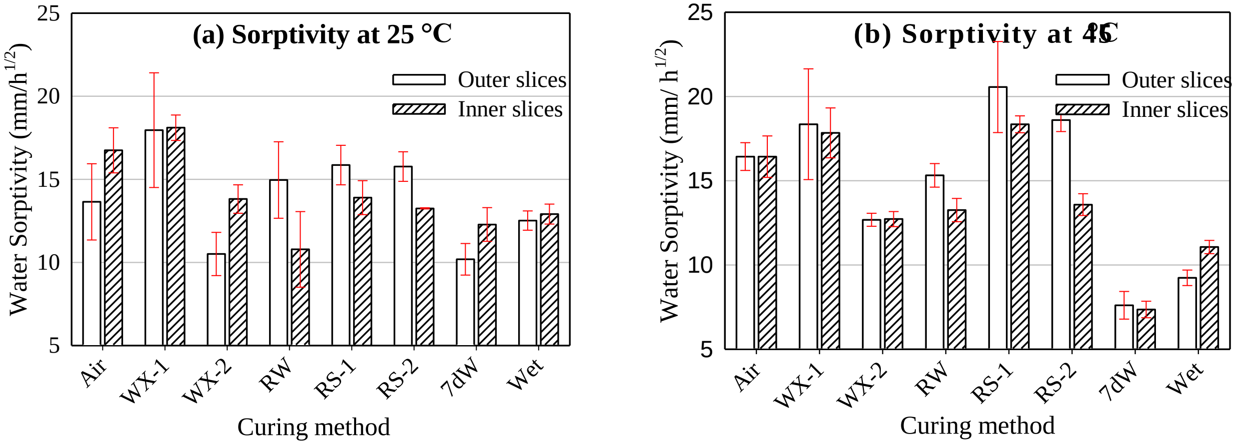


Figure 4.12. Effect of curing on sorptivity of the near-surface and inner mortar (outer and inner slices) at 25 °C and 45 °C

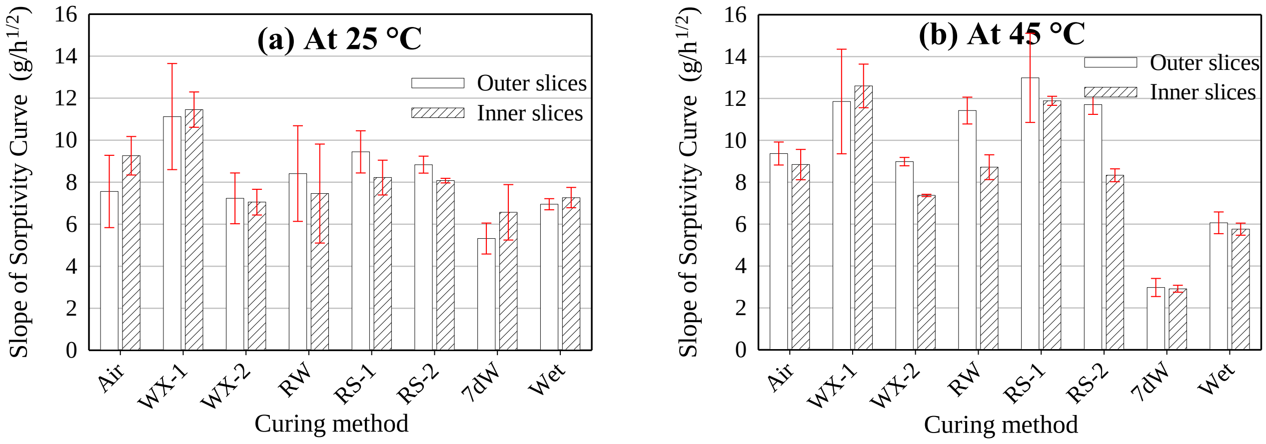


Figure 4.13. Effect of curing on slope-of-sorptivity-curve of the near-surface and inner mortar (outer and inner slices) at 25 °C and 45 °C

4.6 COMPARISON BETWEEN THE 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 Figure 4.14. This comparison cannot be termed valid unless the standard deviation observed in the results is also taken into account. Thus, the values of coefficient of variation for all the results are also presented in Table 4.1.

In general, Darcy's coefficient of permeability (from OPI test), sorptivity, and compressive strength follow trends similar to each other at both the temperatures. Contrary to this, non-steady-state migration coefficient shows distinctly different behavior 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. Further, to be able to analyze these trends closely, the three curing methods that span the entire spectrum of the practical curing methods presented in this study, namely, air curing, curing compound WX-2, and 7-day wet curing are focused henceforth (see Table 4.2).

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, sorptivity exhibits a variation of mere 28 % at 25 ° C compared to a variation of 96 % at 45 °C. Both sorptivity and migration coefficient also demonstrate very large variability in the results as shown in Table 4.1.

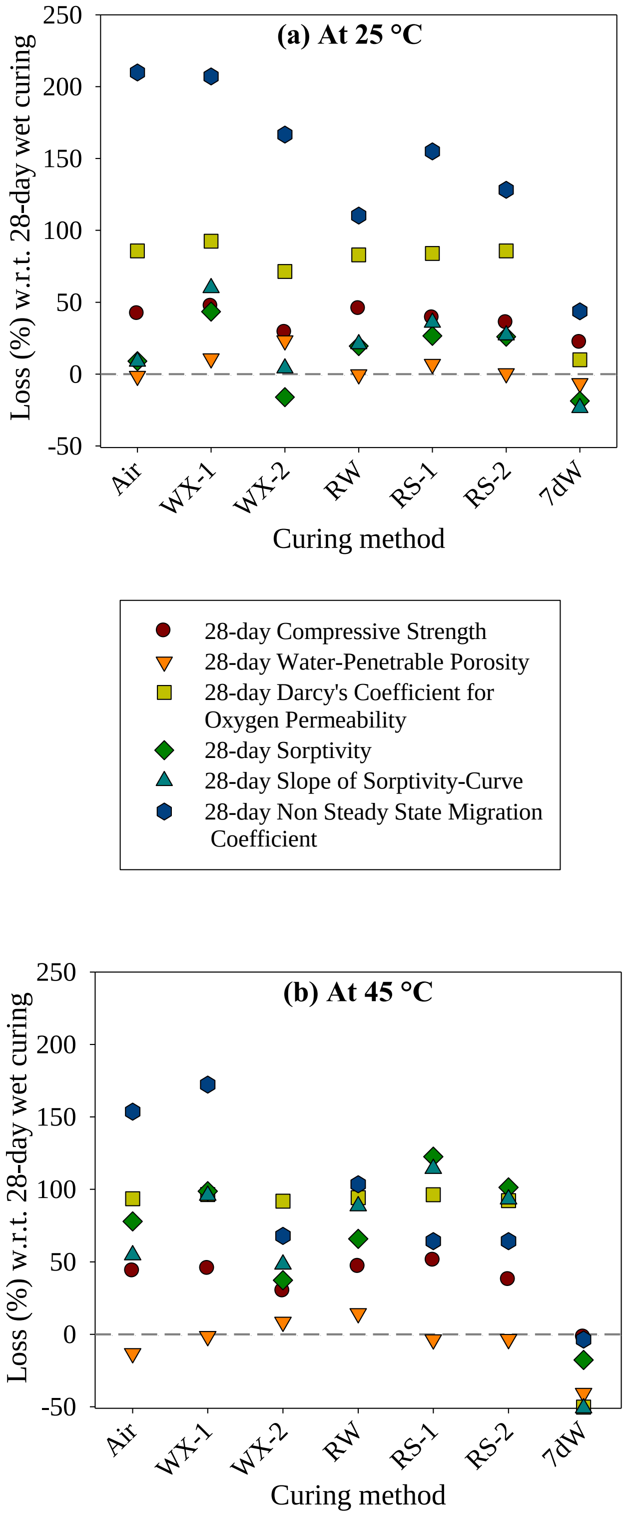


Figure 4.14. Percentage loss in 28-day index values/properties for various curing methods relative to those of 28-day wet curing

Table 4.1. Coefficient of variation (%) observed for different test results of OPC mortar at the age of 28 days

Test parameter	Tem.	Air	WX-1	WX-2	RW	RS-1	RS-2	7dW	Wet
Compressive strength	25 °C	15	1	0	6	2	6	5	4
	45 °C	6	2	1	6	7	1	10	5
Porosity	25 °C	6	4	6	12	3	2	5	2
	45 °C	1	3	1	2	3	1	5	5
OPI	25 °C	2	1	1	2	1	1	2	1
	45 °C	1	2	1	1	1	0	1	2
WSI	25 °C	17	19	12	15	7	6	9	5
	45 °C	5	18	3	5	13	4	11	5
Slope-of-sorptivity curve	25 °C	23	23	17	27	11	5	14	4
	45 °C	6	21	2	6	16	4	15	9
D_{nssm}	25 °C	12	12	6	18	6	13	5	12
	45 °C	10	8	0	14	21	18	9	7

Table 4.2. Percentage loss of index values for select curing methods

Curing method	25 °C				45 °C			
	Comp. Strength	OPI	WSI	D_{nssm}	Comp. Strength	OPI	WSI	D_{nssm}
Air	42	86	9	210	44	94	78	154
WX-2	29	71	-16	167	30	92	37	68
7dW	22	10	-19	44	-2	-18	-18	-4

In conclusion, OPI seems to give clear indication of large variations in the quality of curing with high degree of reliability. On the other hand, sorptivity 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, contrary to the expectations, show low sensitivity to curing.

4.7 SUMMARY

An experimental program was followed to evaluate the influence of various curing methods on the strength and durability characteristics of OPC mortar at two different controlled exposure conditions. The curing methods that were adopted in this study included five curing compounds and two durations of wet curing. The two exposure conditions that were used were 25 °C, 65 % RH and 45 °C, 55 % RH. Various test results indicate sub-par performance of curing compounds to the extent that performance of most of these could not be even differentiated from that of air curing. Performance, both strength and durability, depreciates 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 penetration 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.

A comparison of the results of all the test methods used in this study indicates greater sensitivity of OPI test over all the other test methods used. Although sorptivity and chloride migration coefficient also demonstrate high percentage change in the results with the change in curing quality in some cases, the lack of consistency and large variations in the results reduces their overall reliability. On the other hand, total porosity test completely fails to detect changes in the curing quality. However, the water retention results, despite of the limitations of the test method (which was not as per ASTM C156), could give a fair idea about the water retention capacities of various curing compounds. As far as influence of curing with depth is concerned, that could not be detected possibly because of the high surface-to-volume ratio and large initial porosity of the mortar.

5. INFLUENCE OF FIELD CURING ON STRENGTH AND DURABILITY OF CONCRETE

5.1 INTRODUCTION

Exposure conditions in the field are different from the laboratory conditions in which test specimens are stored. Unique to the specific geographical location, exposure conditions at a site are characterized by diurnal as well as seasonal variations in the temperature, relative humidity, wind, sunlight, rainfall etc. All these factors need to be considered while selecting a curing method for a specific site. Thus, it is essential that the performance of curing methods be tested in the specific field conditions to establish a rational basis for their selection. To enable that, it is essential to identify test methods which can efficiently evaluate the effectiveness of a curing method in the field conditions. This experimental program aims to contribute towards the same.

In this study, large-sized Reinforced Concrete (RC) specimens were cast in-situ and cured in the hot and humid weather conditions of Chennai using five curing methods, which included 7-day wet-hessian curing (7dH), three types of curing compounds (WX-1, RS-1, and RW), and air curing (Air). These specimens were tested for compressive strength and durability characteristics, namely, oxygen permeability, sorptivity, rapid chloride migration, and surface resistivity. The individual results of each test and their comparison are presented in this chapter.

5.2 INFLUENCE OF FIELD CURING ON THE COMPRESSIVE STRENGTH OF CONCRETE

Each compressive strength result in this study represents an average of the test observations on four replicate or representative specimens. Compressive strength of slab specimens was evaluated by testing the cylindrical cores extracted from the slab specimens at the age of 7 days, 28 days, and between 299 and 425 days. The core strengths were modified using correction factors prescribed by IS 516 (1959) in case the length/diameter ratio deviated from 2. The corrected core strengths were multiplied by a factor of 1.25 (BS 1881 1983; Neville 1995) to obtain *equivalent cube strength*. The results are presented in terms of the calculated *equivalent cube strength* at the age of testing in Figure 5.1. The exact age of concrete at the time of testing along with the obtained compressive strength can be found in Table 5.1. It should be noted here that the age at the time of testing includes the duration of specimen saturation (48 hours as per IS 516 (1959)) before testing.

It can be seen in Figure 5.1 that the type of curing method does not seem to influence compressive strength during the age of 9 to 12 days significantly. However, concrete cured with curing compound RS-1 yields the highest strength in this age range, surpassing even the concrete cured with 7-day wet-hessian curing (7dH). On the other hand, none of the concretes cured with curing compounds demonstrate significant improvement in compressive strength over that of air-cured concrete during the age of 31 to 38 days. The air-cured concrete (Air) exhibits 20 % lower compressive strength than 7-day wet-hessian-cured concrete, although the scatter in the data is very large. From the compressive strength results, these curing compounds seem to be ineffective.

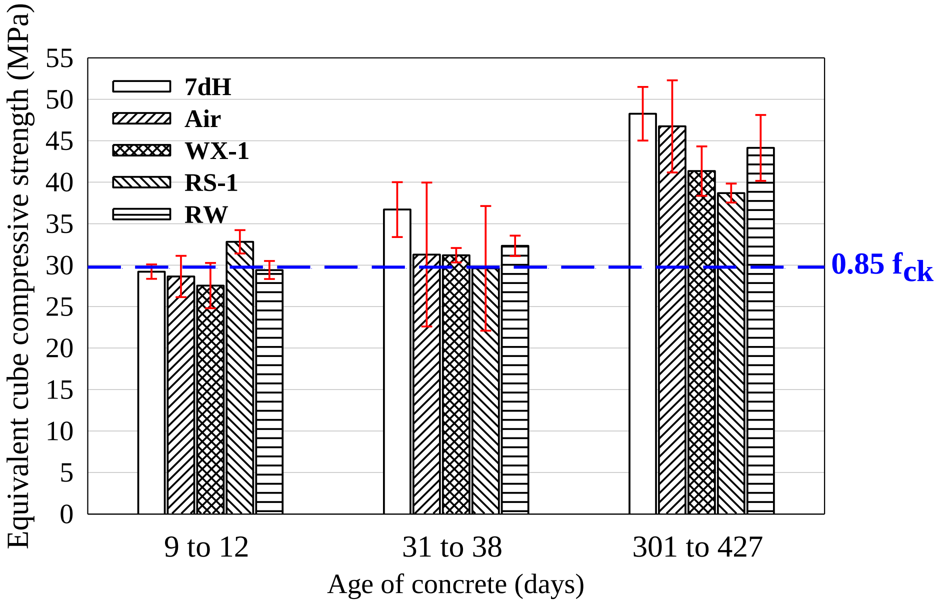


Figure 5.1. Effect of curing on the compressive strength of field-cured concrete specimens

Table 5.1. Compressive strength of cores extracted from slab specimens at different ages, in terms of equivalent cube strength

Curing Method	Age-1 (days)	Compressive strength (MPa)	Age-2 (days)	Compressive strength (MPa)	Age-3 (days)	Compressive strength (MPa)
7dH	12	29.2 (0.9)	36	36.7 (3.3)	426	48.3 (3.2)
Air	9	28.6 (2.5)	38	31.3 (8.7)	427	46.7 (5.6)
WX-1	10	27.5 (2.7)	31	31.2 (0.9)	325	41.3 (3.0)
RS-1	9	32.8 (1.4)	31	29.6 (7.5)	321	38.7 (1.1)
RW	9	29.4 (1.1)	31	32.3 (1.2)	301	44.1 (4.0)
Note: Values in the parentheses represent standard deviation						

In terms of percentage increase in the compressive strength at this age (31-38 days), the slab cured with 7-day wet-hessian gains 26 % strength with respect to strength at 9-12 days whereas all the other slabs exhibit a maximum gain of only 13 % in this period. However, in the long term (that is, 301-427 days), air-cured slab registers a strength gain of 49 % with respect to its strength at 31-38 days when all the other slabs gain strength in the range of 31-37 % including wet-hessian-cured slab. The high strength gain in OPC concrete after 28 days can be attributed to the excessive amount of precipitation received in the months of November and December (see Figure 3.9). Also, the degree of hydration achieved within the first 28 days in the field using practical curing methods cannot be at par with the degree of hydration of laboratory-cured concrete. Therefore, such high gain of strength can be expected after 28 days.

Overall, in the long term, air cured concrete (cast during Phase-1) exhibits similar compressive strengths as wet-hessian-cured concrete, and the three curing-compound-cured concretes (cast during Phase-2) exhibit lower compressive strengths than even the air-cured concrete. Also, the slab cured with curing compound

RS-1 that showed the highest strength during the age of 9 to 12 days, yields the lowest strength in the long term. From these trends, it is apparent that in this study the concretes cured with curing compounds exhibit higher early strength and lower long term strength than wet-cured concrete. This is typical of concrete exposed to high curing temperatures, which is also the case with these concretes (they were cast in Phase-2, see Section 3.4.4.2). In short, air-cured specimen exhibits strength similar to wet-hessian-cured specimen after a spell of heavy precipitation. However, specimens cured with curing compounds—which are seemingly ineffective—exhibit strength inferior to air-cured specimen and hence, do not seem to have benefited by the precipitation as much as air-cured specimens.

It should be noted here that from the compressive strength results up to the age of 31-38 days, curing compound seem to be ineffective in water-retention before the period of precipitation. Owing to their ineffectiveness during the early period, they cannot be expected to prevent the ingress of water into the concrete during the precipitation. Thus, the concrete slabs cured with curing compounds are also expected to show long-term strength gain. However, this is contrary to what is seen in the long-term results. Hence, it seems that curing temperature could have a more significant influence on the long-term compressive strength than the curing method used itself. Interestingly, all the concretes irrespective of the adopted curing method cleared the acceptance criteria of IS 456 (2000) by achieving a mean strength not less than 0.85 f_{ck}. This also highlights the relatively lower impact of curing on the compressive strength of concrete.

5.3 INFLUENCE OF FIELD CURING ON THE DURABILITY INDEX VALUES OF THE NEAR-SURFACE CONCRETE AT 28 DAYS

The results of the porosity, oxygen permeability index (OPI), water sorptivity, and rapid chloride penetration tests (RCMT) at the age of 28 days on both laboratory- and field-cured concretes are presented in this section. Laboratory- or lab-cured concrete refers to standard laboratory concrete specimens cured in the mist room for 28 days. Each result presented in this section is averaged on the test observations of four specimens.

The objective of this study is to evaluate the effect of curing on the durability characteristics of concrete. Thus, it is essential that the concrete tested belongs to the concrete in the near-surface region. Therefore, the concrete slices were extracted from the depth of 5 mm to 35 mm (and 5 mm to 55 mm for RCMT) from the surface. Nevertheless, to evaluate the effect of curing on concrete with increasing depth from the surface, test results for the slices beyond first 35 mm (or 55 mm for RCMT) are also presented in the Section 5.4.

5.3.1 Total Water-Penetrable Porosity

As shown in Figure 5.2, 28-day porosity of lab-cured specimens lies in the range of 10.5 to 11 %, whereas porosity of field-cured specimens falls in the range of 6.5 to 7.5 % and 8 to 10 % for the specimens that were cast in Phase-1 and Phase-2 respectively. The lab-cured concrete, despite being wet-cured for 28 days, yields the highest porosity. Also, there is no significant difference between the porosities of 7-day wet-hessian-cured concrete (7dH) and air-cured concrete (Air) even though the difference between the quality of curing that was adopted for them was drastic. Further, despite the fact that curing compounds are expected to help in retaining water in concrete to enhance cement hydration and consequently, reduce the capillary porosity, concrete specimens that were cured with curing compounds (WX-1, RS-1, and RW) yield 1-3 % higher porosities than air-cured concrete.

Overall, these trends suggest that factors other than curing could also have influenced the results. For example, the possible difference in the amount of water lost due to bleeding and the temperature of exposure can explain these trends. For instance, laboratory specimens (150 mm) were 8 times smaller than the slab specimens (1200 mm). Hence, the lateral restraint from the mould faces against settling of concrete would have been greater in the case of lab specimens than the slab specimens, thereby resulting in a lower amount of bleed water. Therefore, it is possible that because of the higher initial water content, the porosity of the lab specimens at 28 days is higher than the field specimens despite superior curing. In the case of Phase-2 slabs, higher early temperature as compared to Phase-1 slabs could have reduced the bleeding by accelerating the setting process, resulting in higher initial water content and finally, in higher porosity than

Phase-1 slabs at 28 days. Moreover, an increase in the ambient temperature during hydration itself leads to an increase in the total porosity at the same degree of hydration (as discussed in Section 2.7).

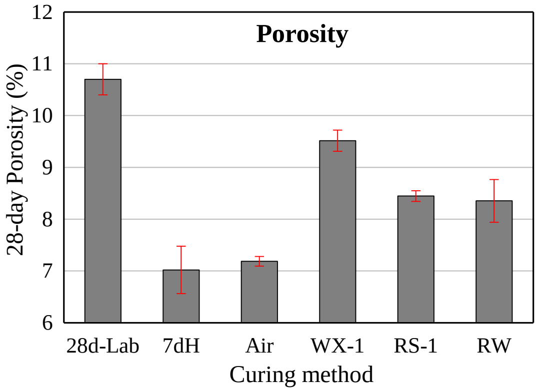


Figure 5.2. Effect of curing on the 28-day porosity of field-cured concrete

5.3.2 Oxygen Permeability Index (OPI)

Figure 5.3 shows 28-day OPI results of concrete specimens that were cured under various curing regimes. OPI results do not seem to follow the trends seen in the porosity results (Section 5.3.1). The wet-hessian-cured concrete shows slightly superior OPI value of 9.8 than the air-cured concrete with an OPI of 9.4, and the concrete that was cured with curing compound WX-1 shows an OPI of 9.5. As per the durability classification of concrete, it implies that insufficient curing leads to poor concrete. However, the OPI values of concretes that were cured with the curing compounds RS-1 and RW (10.2 and 10.0, respectively) surprisingly exceed that of the wet-hessian-cured concrete. Also, the lab-cured concrete, which has the highest total porosity, yields a superior OPI value of 10.1—which is higher than that for most of the other curing methods (except RS-1). It must be recalled here that coring of the lab specimens was also performed in the direction of casting as in the case of slab specimens. Therefore, the possibility of bleed channels adversely affecting the OPI results exists in the case of lab specimens as well.

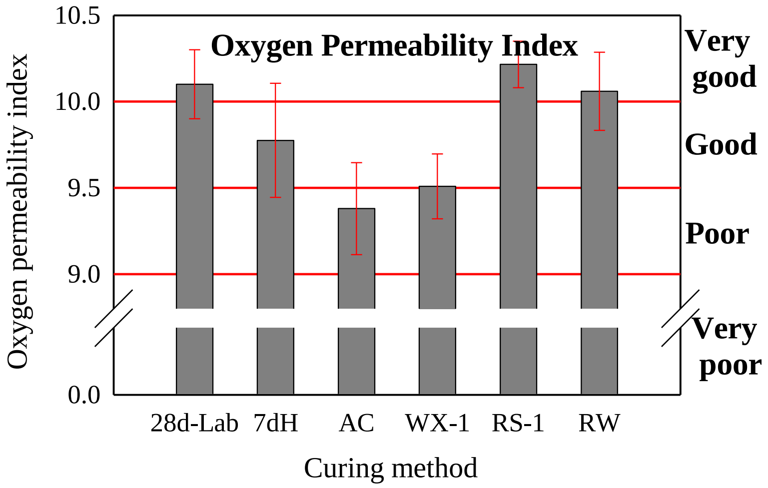


Figure 5.3. Effect of curing on the 28-day OPI of field-cured concrete

5.3.3 Water Sorptivity Index (WSI)

28-day Water Sorptivity Index results, like OPI results, also exhibit unusual variations. As shown in Figure 5.4, concrete cured with the curing compounds RS-1 and RW achieve superior water sorptivity than both the lab-cured concrete and the 7-day wet-hessian-cured concrete. On the other hand, the performance of the concrete cured with the curing compound WX-1 lies close to that of the air-cured concrete. Besides, even the 7-day wet-hessian-cured concrete (WSI = 11.4) does not demonstrate significant improvement over the air-cured concrete (WSI = 13.5). The slope-of-sorptivity-curve results resemble sorptivity-index results in some aspects, but differ in others (Figure 5.5) due to the differences in their total porosity. For instance, curing compound RW exhibits superior performance in the slope-of-sorptivity-curve results than all the other curing methods like in the sorptivity-index results. However, slope-of-sorptivity-curve results for curing compound RS-1 and lab curing are significantly inferior to that of wet-hessian curing, in contrast with the sorptivity-index results.

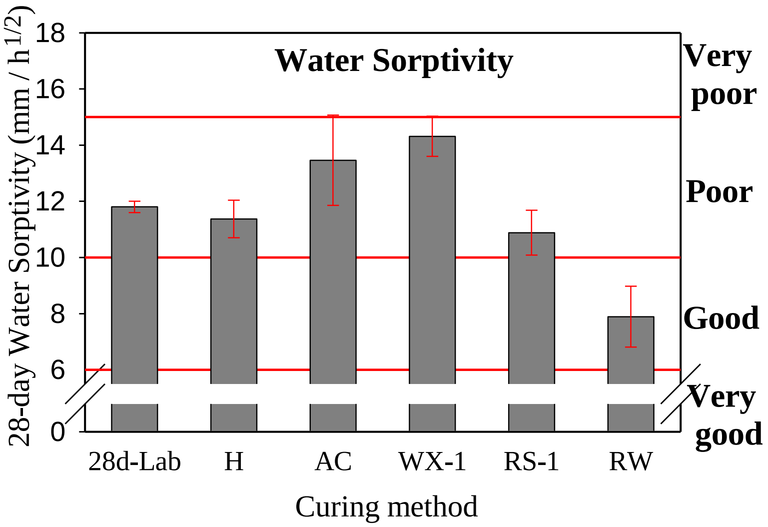


Figure 5.4. Effect of curing on the 28-day sorptivity results of field-cured concrete

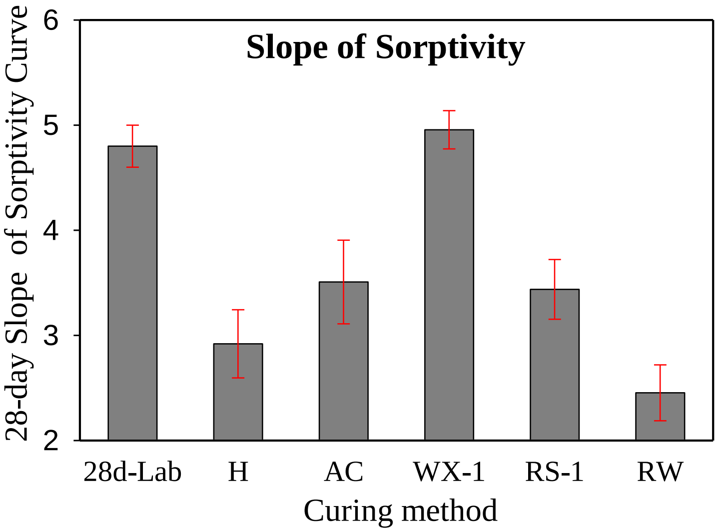


Figure 5.5. Effect of curing on the 28-day slope of sorptivity-curve results of field-cured concrete

5.3.4 Non-Steady-State Migration Coefficient (D_{nssm}) for Chloride Penetration

Rapid chloride migration test results bear a clear contrast with OPI and WSI results as far as the performance of curing compounds is concerned. The values of 28-day D_{nssm} for concretes that were cured with curing compounds, as presented in Figure 5.6, are found to be inferior to that of concretes that were cured with 7-day wet-hessian curing. The performance of curing-compound-cured concretes can be expected to be even worse compared to what is presented here, in view of the fact that the chlorides penetrated through the entire depth of the specimens in the course of testing. This was also observed in the case of air-cured specimens. It is essential to note here that for the specimen in which chlorides penetrated through the entire depth, D_{nssm} was computed using the average depth of the specimen. Also, as the exact time for the chlorides to reach the other end is unknown, the entire duration of the test is used in the calculation, instead. This is not only incorrect but also results in a less conservative value of the migration coefficient. Possibly, for this reason, the difference between the values of migration coefficient for wet-hessian-cured concrete and air-cured concrete appears to be smaller than expected.

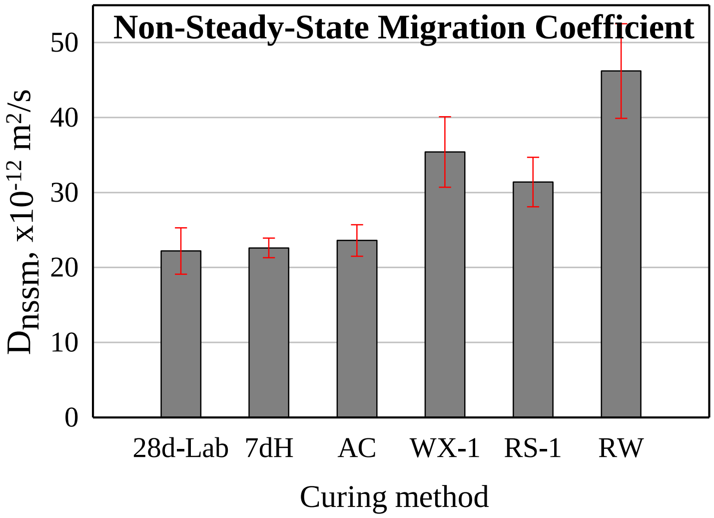


Figure 5.6. Effect of curing on the 28-day non-steady-state migration coefficient (D_{nssm}) of field-cured concrete

5.4 INFLUENCE OF FIELD CURING ON THE DURABILITY CHARACTERISTICS OF CONCRETE WITH INCREASING DEPTH FROM THE SURFACE

In the absence of proper curing, concrete loses its mix water to the surrounding air from the exposed surface during the early age of hydration. The severity of water loss varies with the depth from the surface, the surface being the most severely affected region. This difference in the availability of water at different depths can result in differences in the degree of hydration achieved. Consequently, the pore structure of concrete is also expected to vary with the depth. Therefore, it is relevant to investigate and compare the extent to which curing influences the properties of concrete in the near-surface region and in the inner region, respectively. For this reason, specimens from different depths were extracted from the wet-hessian-cured slab and air-cured slab, and durability tests were performed on them.

In such a case, it is expected that the gradient of durability index values for air-cured specimens will be found steeper than that for wet-hessian-cured specimens, with the wet-hessian-cured specimens achieving superior durability index values than the air-cured specimens. However, test results shown in Table 5.2 and Figure 5.7 do not follow this expected trend. In fact, the large scatter in the individual results as compared to the slight change in the index values due to curing renders any emerging trend unreliable.

From the visual inspection of the test specimens, it was observed that the amount of coarse aggregates present in the test specimens varied significantly (see Figure 5.8) and hence, could have led to the observed behavior. So, to substantiate this possibility, the percentage area of mortar available on the surface of each specimen was computed using Image Analysis technique. Coarse aggregates visible on the surface of the specimens were coloured using a colour marker to enhance the contrast between the coarse aggregates and the mortar regions. Then, the test faces of all the specimens were scanned using a document scanning machine and those images were analysed using the software Image Pro Premier 9.1®.

Table 5.2. Variation of 28-day non-steady state migration coefficient (D_{nssm}) of 7-day wet-hessian-cured and air-cured concrete with depth from the surface

Curing	Depth from the surface (mm)	D_{nssm}, x 10^{-12} m^2/s (RCMT)	
		Average	St. dev.
7dH	5 to 55	22.6	1.3
	60 to110	24.5	2.1
	115 to 165	23.7	1.6
Air	5 to 55	23.6	2.1
	60 to 110	23.5	1.4
	115 to 165	23.5	1.7

Figure 5.9 shows a typical image that was used in the analysis and the different areas demarcated by the software. The percentage area of mortar with respect to the total area of the specimen was then computed with the help of this data for all the specimens.

Slope-of-sortivity curve, water sorptivity, and OPI results are plotted against the percentage area of mortar present on the surface of the specimens in Figure 5.10, Figure 5.11, and Figure 5.12 respectively. It can be observed from these figures that none of the results appear to bear any correlation with the percentage area of mortar. Hence, the possibility that the relative amount of coarse aggregates present in the specimens influenced the durability index results over and above other factors cannot be substantiated through these results.

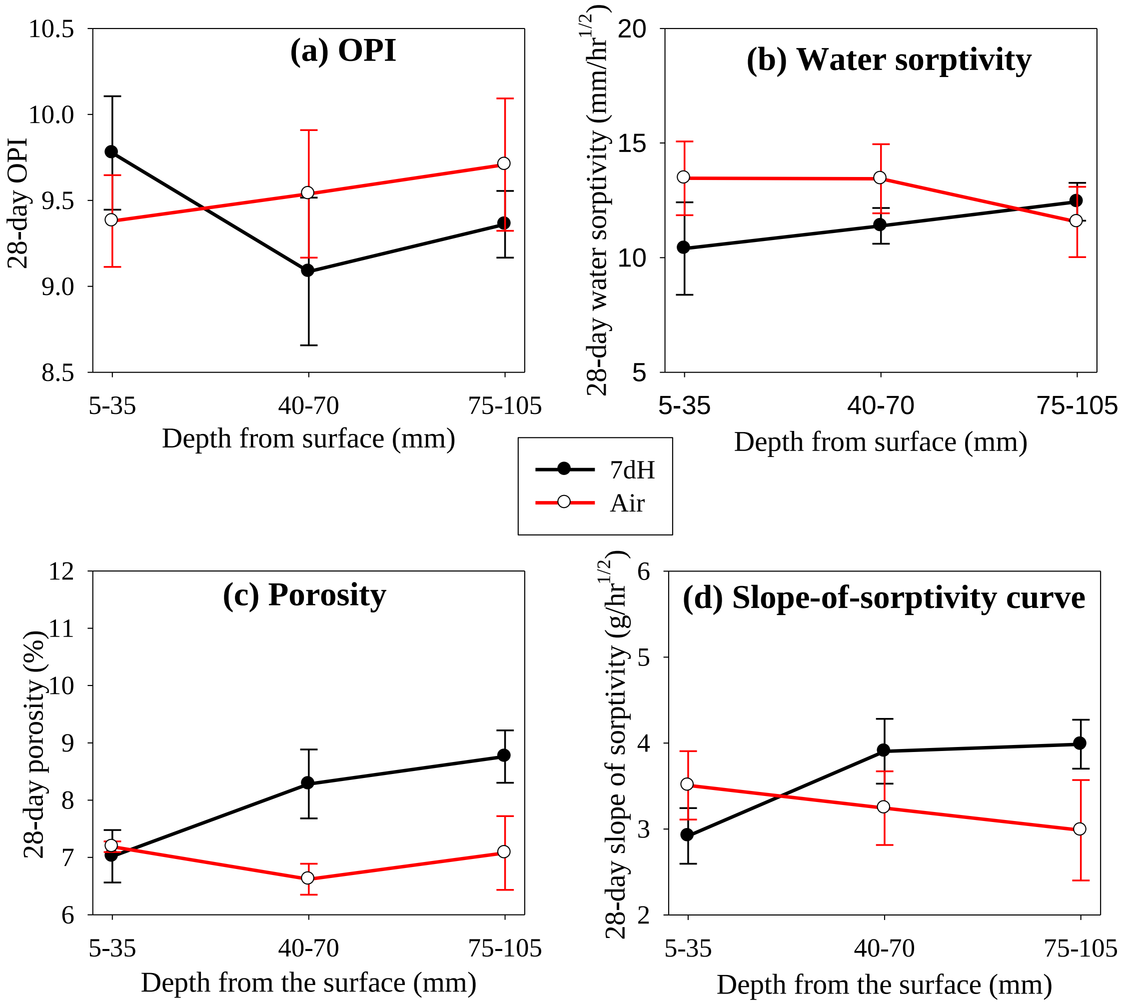


Figure 5.7. Variation of durability index values of 7-day wet-hessian-cured and air-cured concrete with depth from the surface

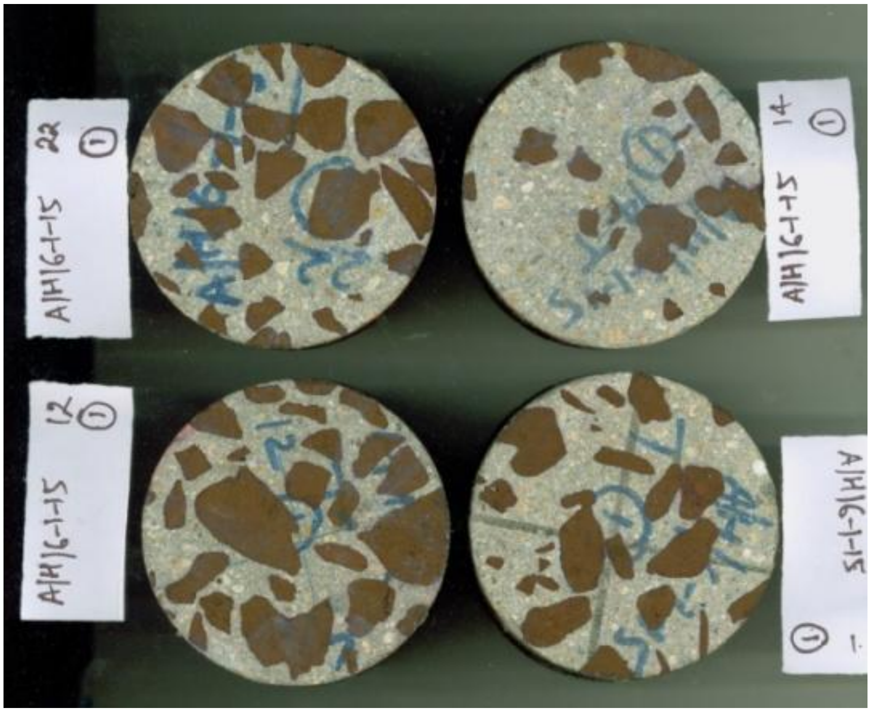
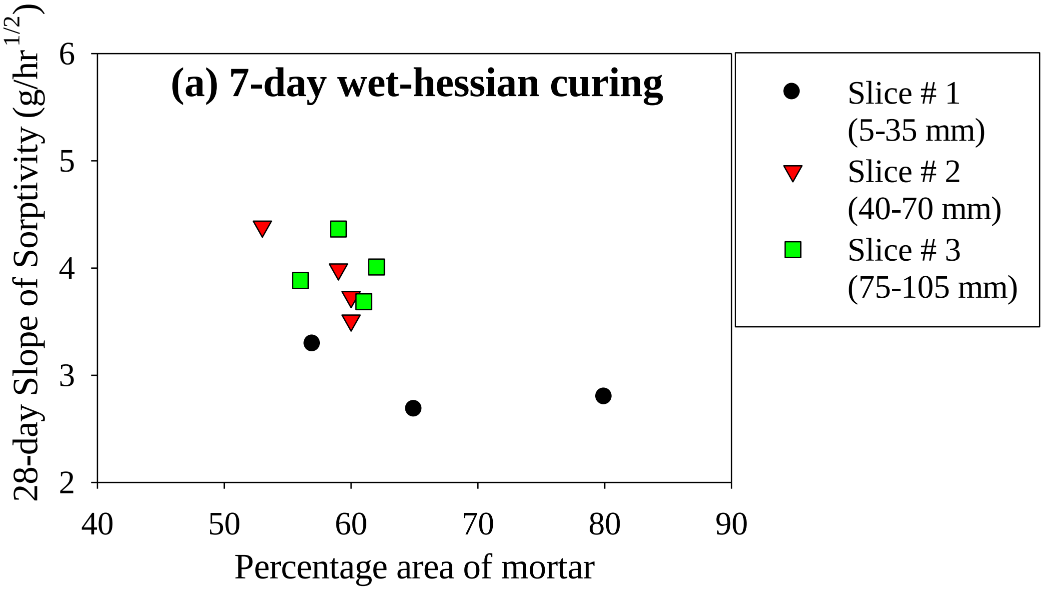


Figure 5.8. Image of sorptivity specimens (7dH) showing the differences in the amount of coarse aggregates present on their surfaces

Figure 5.9. Image analysis of a 70-mm diameter specimen (used for OPI/sorptivity test) (a) a typical image that was used for the analysis and (b) different regions demarcated in the image by Image Pro Premier 9.1$^{®}$ software



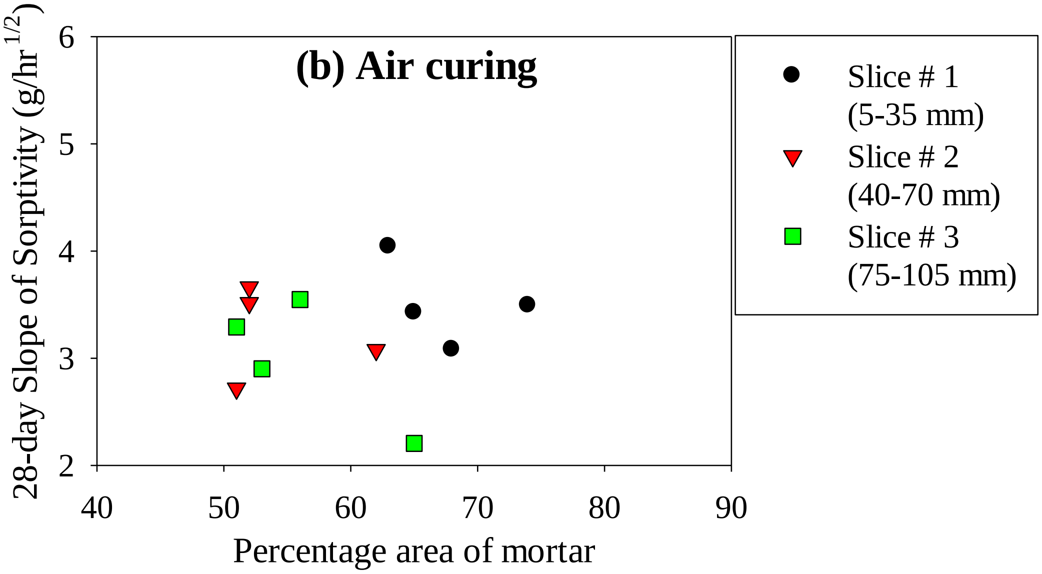
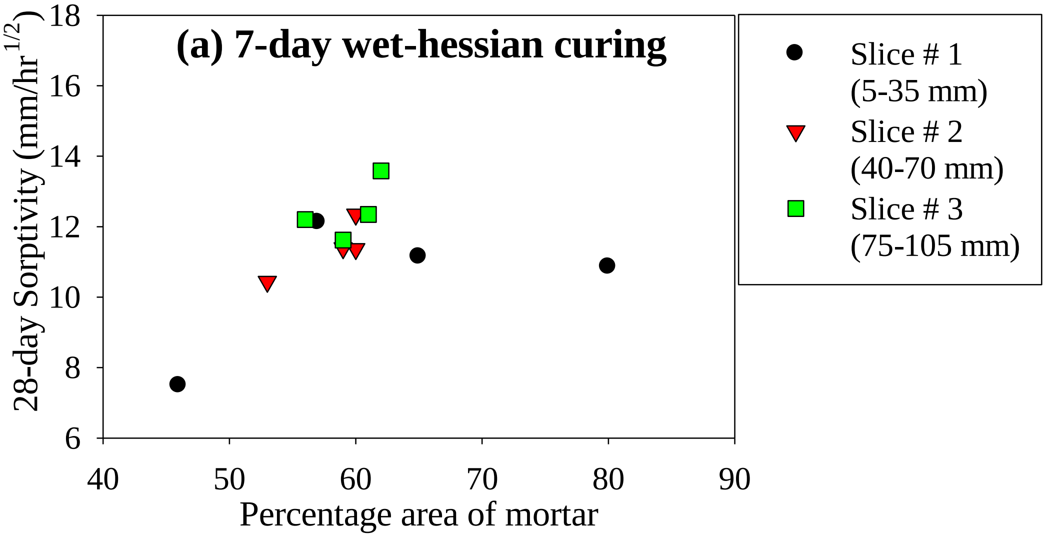


Figure 5.10. Effect of percentage area of mortar on slope of sorptivity curve in case of (a) 7-day wet-hessian curing and (b) Air curing



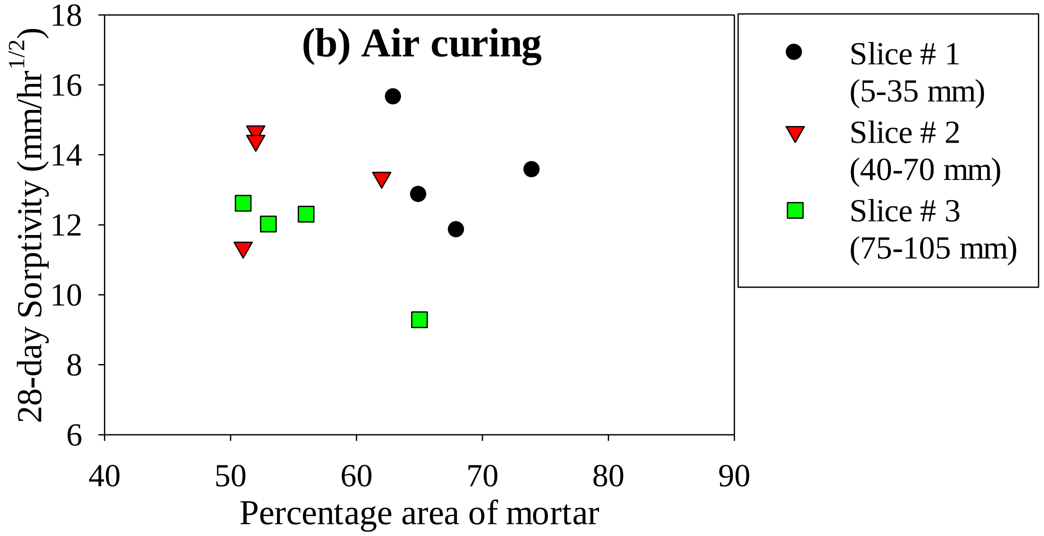


Figure 5.11. Effect of percentage area of mortar on sorptivity in case of (a) 7-day wet-hessian curing and (b) Air curing

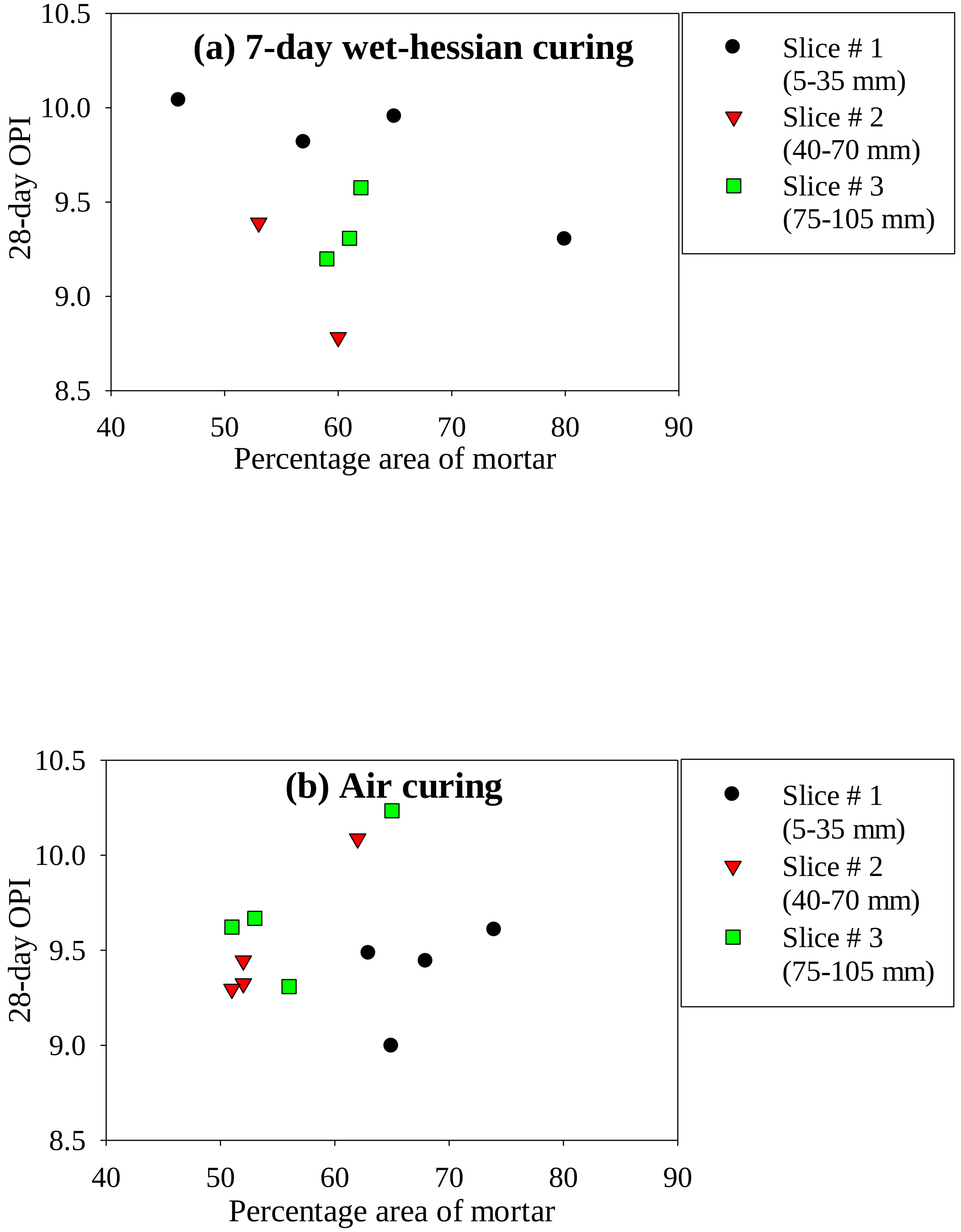


Figure 5.12. Effect of percentage area of mortar on OPI in case of
(a) 7-day wet-hessian curing and (b) Air curing

5.5 Influence of Field Curing on the Surface Resistivity of Concrete

Figure 5.13 illustrates the relationship between surface resistivity (using Wenner Probe) (Section 3.12) and surface moisture content of the concrete specimens that were cured using different curing methods in the field, at the age of 7 days and 28 days. For each case, measurements were taken at 26 to 36 locations on the slab specimens. At each location, two measurements were taken in diagonally opposite directions. The average of these two measurements at each location is shown in the form of coloured markers, whereas the average values for each slab are shown in the inset graph with filled and unfilled markers representing the age of 7 days and 28 days respectively. It is clear from this figure that both surface resistivity and surface moisture results exhibit excessively large amount of scatter. Consequently, neither the influence of curing nor the influence of surface moisture on the surface resistivity could be detected from this data.

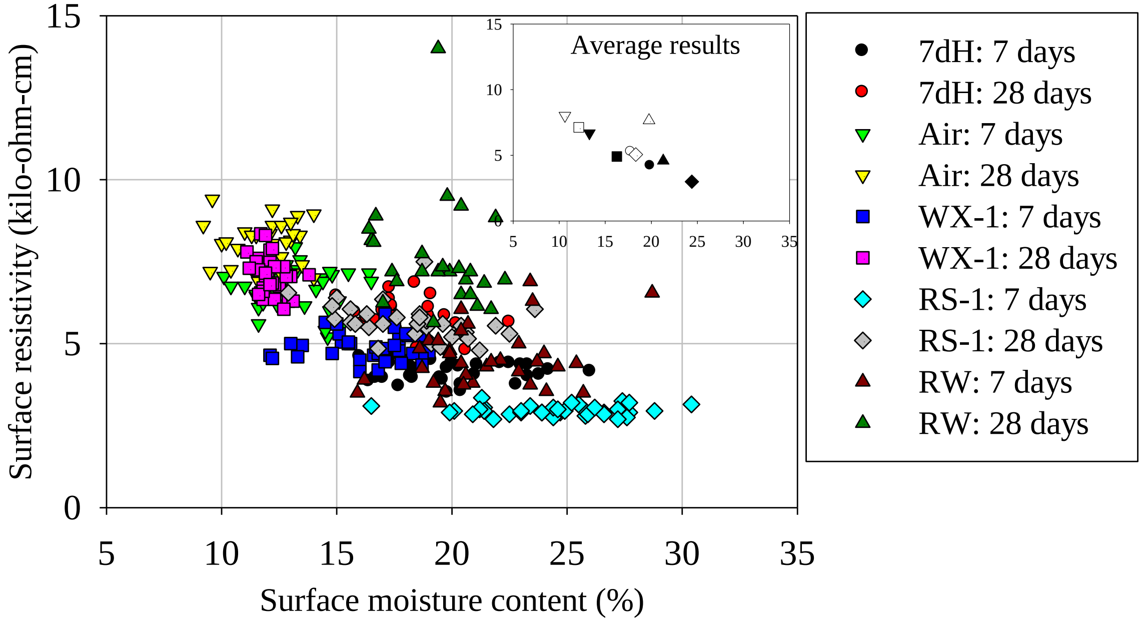


Figure 5.13. The relationship of surface resistivity with surface moisture content of concretes which were field-cured using different curing methods

5.6 SUITABILITY OF TEST METHODS TO DETECT VARIATIONS IN CURING

In this study, compressive strength, porosity, oxygen permeability, water sorptivity, rapid chloride migration, and surface resistivity test are used to detect the variations in the quality of curing. At the age of 28 days, compressive strength demonstrates variations according to the adopted curing method although with only minor changes. However, these variations are over shadowed by the large scatter involved in some of the results (see Table 5.3). OPI and WSI also show large scatter that surpasses the variations arising from the differences in the adopted curing method. Moreover, porosity, OPI, and WSI exhibit several contrasts in the trends between themselves and also with D_{nssm}. Even D_{nssm} could not detect the difference between 7-day wet-hessian curing and air curing. Surface resistivity also shows inordinately large scatter. These observations suggest that it would be difficult to study the influence of curing on concrete that is cast and cured in site conditions with these test methods. However, further studies are required on different types of concrete and under different field conditions to validate these observations and take measures to improve these test methods. Even amidst these shortcomings, it is clear that the use of compressive strength alone as a performance test for curing can severely undermine the impact that curing has on the durability of the concrete structures.

Table 5.3. Coefficient of variation (%) for results of different tests on field-cured concrete at the age of 28 days

Test parameter	7dH	Air	WX-1	RS-1	RW
Compressive Strength	9	28	3	25	4
Porosity	7	1	3	1	8
OPI	3	3	2	1	2
WSI	6	12	15	7	16
Slope-of-Sorptivity Curve	11	11	13	8	21
D_{nssm}	6	9	13	10	14
Surface Resistivity	37	8	8	21	37

5.7 SUMMARY

Specimens extracted from field-cured OPC concrete slab specimens were tested for their strength and durability performance. Durability tests that were adopted in this study included porosity, oxygen permeability, water sorptivity, rapid chloride migration, and surface resistivity test. In general, the test results failed to show the influence of deficient curing in a reliable way. Further studies are imperative to enable the effective use of these methods in testing the field-cured concrete.

6. CONCLUSIONS AND SCOPE FOR FUTURE STUDIES

6.1 INTRODUCTION

The aim of this study was to investigate the potential of curing compounds as an alternative to the conventional wet curing methods and to assess the suitability of different test methods in evaluating the efficiency of practical curing methods. Two experimental test programs were followed to achieve this aim. In Test program 1, OPC mortar specimens were cured under different curing regimes in laboratory controlled conditions. In Test program 2, OPC concrete specimens were cured using different practical curing methods under field conditions of Chennai. Test results from both of these studies are discussed in Chapter 4 and Chapter 5. The major conclusions drawn in the light of these results and their limitations are presented in this chapter. The scope of further study is also presented.

6.2 CONCLUSIONS

The salient conclusions drawn from the current study are described in this section.

6.2.1 Performance of curing compounds with respect to conventional curing methods in different exposure conditions

6.2.1.1 Lab exposure

- Four out of five curing compounds used in this study demonstrated performance similar to or even worse than air curing. Only the wax-based curing compound WX-2 showed improvement in performance over air curing. This implies that four out of five curing compounds failed to exhibit water-retention characteristics.
- Increase in curing temperature from 25 °C to 45 °C leads to a reduction in the performance of mortar cured with curing compounds.

- Wet curing – In the case of OPC mortars, a wet curing period of 7 days appears to be sufficient to achieve a performance equivalent to that from laboratory curing period of 28 days.

6.2.1.2 Field exposure

- Early curing temperature, that is, the temperature in the first 28 days can have a larger influence on long-term strength of concrete than the curing method employed to cure the concrete.
- In view of the large inconsistencies in the results, further studies are imperative to confirm the findings of this study.

6.2.2 Suitability of test methods in evaluating the performance of curing methods

6.2.2.1 Water retention test

- Water retention test can serve as a useful qualification test; however, large scatter in the data at the age of 3 days could pose difficulties in the interpretation of results. Thus, it is recommended to increase the test duration from 3 days to at least 7 days to obtain more reliable data.

6.2.2.2 Compressive strength test

- Compressive strength test shows fair sensitivity to curing for specimens with high surface-area-to-volume ratio, not in the case of realistic specimens.

6.2.2.3 Durability tests

- In the case of lab exposure, durability tests exhibit high sensitivity to large changes in the performance caused by curing; however, their sensitivity is low in the case of smaller changes in the performance. This is due to the large variability in the test results.
- In general, durability tests exhibit higher sensitivity compared to compressive strength tests.

- OPI test demonstrates high sensitivity to curing with low variability compared to all the other test methods in the laboratory conditions.
- Subtle differences in the trends of different durability tests indicate that curing may affect the transport properties to different degrees and in different ways.
- In the case of field exposure, large variability and inconsistencies in the results due to the complex interaction of several factors in the field lead to low sensitivity to curing in such situations.

From the above observations, it can be concluded that compressive strength alone is not a sufficient to evaluate the performance of curing methods. It should at best be used in conjunction with durability tests. Moreover, this study has also accentuated the dichotomy that still exists between the laboratory and field testing experiences. Further studies are imperative to resolve this confronting issue that stand in the way of successful implementation of performance specifications for durability of concrete structures.

6.3 LIMITATIONS

The various limitations of this study are presented below.

- The specimens used in Test program-1 were standard lab specimens and hence, had higher surface-area-to-volume ratio than what is realistic.
- The specimens in Test program-2 were cast in two different phases. These phases had slightly different weather conditions, which could complicate the comparison of results from these specimens.
- The curing compound membrane was not removed prior to measuring moisture content and surface resistivity of the field specimens that could have introduced additional errors in the data.

6.4 RECOMMENDATIONS FOR IMPROVING THE PERFORMANCE OF CURING COMPOUNDS

From the literature reviewed and test observations of this study, some recommendations that have the potential to improve the performance of curing compounds are stated here.

- The dosage of curing compounds should be increased depending on the initial efficiency.
- For a surface with poor or tinned finish, the dosage should be increased to account for the increase in the surface area due to increased undulations in the surface.
- Application should preferably be done in multiple coats to maximize uniformity in the application rate, especially in the regions where the individual strips of applied curing compounds overlap. The multiple coats should be done in mutually-transverse directions.
- Spray hoods or wind barriers should invariably be used while spraying the curing compounds in the field to prevent the loss of curing compound through drift by wind.
- While using pressurized-air assisted spraying guns, the air pressure and the height of nozzle must be regulated such as to avoid the formation of large droplets as well as air bubbles in the curing compound layer.

6.5 SCOPE FOR FUTURE STUDIES

- Water-retention test is required to be developed for Indian conditions.
- The sensitivity of durability tests should also be investigated on large specimens with realistic surface-area-to-volume ratio under controlled conditions.
- Microstructural studies are needed to study the behaviour of curing compounds in relation with concrete to develop more efficient curing compounds.
- Parametric studies are required in different field conditions to understand the factors influencing durability index test results.
- Other durability characteristics like shrinkage, carbonation etc. needs to be studied in the context of curing compounds.

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