ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

ASSESSMENT OF THE EFFECTIVENESS OF DIFFERENT CURING PRACTICES IN ADDIS ABABA

A thesis submitted to the School of Graduate Studies of the Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
(Construction Technology and Management)

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September 2014

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DECLARATION

I, Samson Walelign the researcher declare that this research is my original work. The findings presented in this paper are not found in any other previous research works.

Samson Walelign

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Addis Ababa Institute of Technology
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September 2014

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ABSTRACT

Curing is defined as a process of maintaining adequate moisture and favorable temperature in concrete for the hydration reaction to continue. The main advantage of curing is to keep the internal humidity of concrete to the desired level. Different researches showed that if the internal humidity of concrete is below 80% the rate of hydration will be reduced and if it goes below 30% the reaction will even cease. Therefore curing is the most significant process in order to keep the internal relative humidity to the required amount because it is through hydration reaction concrete develops the desired properties, which are mechanical properties and durability.

This research work has two objectives. The first one is assessing the current curing practices and to study the awareness given to curing. And the second objective is assessing the effectiveness of current curing practices in Addis Ababa.

To meet the above mentioned objectives questionnaire was used for the first objective and experimental study was also conducted for the second objective. For the experimental study, tests were conducted in two phases. In both phases tests were conducted in rich mortar mixture with cement to sand ratio of 1 to 2.5.

In the first phase water absorption and compressive strength tests were conducted to correlate compressive strength and absorption test results. The objective of the first phase was to check the acceptability of compressive strength test for measuring the effectiveness of current curing practices. And the objective of the second phase was to assess the effectiveness of current curing practices by conducting compressive strength test on mortar samples, which were subjected to different curing practices.

In ACI 308R-01, there are methods for assessing the effectiveness of curing. These are tests by monitoring the quantitative changes on the immediate environment, by monitoring the environmental conditions, by monitoring the moisture and temperature of concrete and by measuring the physical properties, etc… From the above mentioned tests we can understand that monitoring curing effectiveness is all about checking whether there is adequate moisture so that the hydration reaction will continue.

In assessing the effectiveness of current curing practices the 70% criteria from ACI 308R-01, which says "at time of termination of curing the concrete has to develop 70% of the specified strength", was used.

It is the researcher opinion that two terms „adequacy‟ and „effectiveness‟ of curing has to be seen separately. Adequacy of curing is all about efficiency of curing for the development of the desired properties. Assessing the adequacy of curing for the development of the desired properties of concrete by conducting tests on mortar specimens may not be good enough unless there is a developed correlation between compressive strength and absorption capacity of mortar and concrete specimens. Because the adequacy of curing is a function of exposure condition, mixture proportion and properties under question. But there are researches which correlate properties of mortar and concrete. One finding showed that there is a clear relationship between compressive strength of mortar and concrete. A given curing method can be adequate for the desired compressive strength but it may not be adequate if durability is desired. But when we say curing effectiveness it is the ability of the curing method in creating suitable condition for the paste phase to have “complete‟ hydration so that the pore size and pore distribution will be minimum. In this research the compressive strength of standard laboratory cured samples are assumed to be the full potential of the mixture. Therefore, if the field curing doesn‟t allow the development of at least 70% compressive strength of the standard laboratory cured samples at time of termination or 85% at 28^{th} day, the curing is considered to be ineffective. Effectiveness of curing is related with ability of curing to create a suitable condition in order to have “complete” hydration of the paste phase.

Results from questionnaire survey showed that water sprinkling twice a day for 7 days with and without burlap is mostly practiced curing method.

Another finding from the questionnaire survey showed that most of the practitioners are aware of the benefits of curing and consequences of lack of it. But when we see on the implementation it was found poor.

From the experimental study; current curing practices were found to be very poor in creating suitable condition for the hydration of cement so that the desired properties can develop. Based on the 70% criteria the current curing practices were found ineffective for mixtures with a w/c less than 0.5.

Although water-cement ratio of 0.5 is greater than required for “complete” hydration, but sealed curing is found ineffective. One major reason is late application of curing.

Key Words: Curing, Curing Affected Zone, Curing Effectiveness, Mortar, Compressive Strength, Water Absorption,

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ABBREVIATIONS

AASHTO	American Association of State Highway Transport Officials
ACI	American Concrete Institute
ASTM	American Standard for Testing of Materials
BS	British Standard
EBCS	Ethiopian Building Code Standard

CHAPTER ONE -- INTRODUCTION

1.1 BACKGROUND INFORMATION

Curing of concrete plays a major role in developing the microstructure and pore structure of concrete. Curing of concrete means maintaining moisture and favorable temperature inside the body of concrete during the early ages and beyond, in order to develop the desired properties in terms of strength and durability. A good curing practice involves keeping the concrete damp until the concrete is strong enough to do its job. However, good curing practices are not always religiously followed in most of the cases, leading to a weak concrete. (www.allbusiness.com)

Researchers showed that in average 25% of water per weight of cement is required to chemically combine with cement and approximately 20% by weight of cement is also required to fill the gel pores; totally about 44% by weight of cement is required for "complete" hydration (ACI 308R-01). Some concrete mixes have an initial w/c greater than the specified ratio and some have below this amount. For complete hydration we have to maintain the amount of water required to chemically combine with cement and to fill the gel pores. For those concrete mixes with a w/c greater than 0.44 external supply of water is essential to maintain the water to the desired level and for those mixes with a w/c greater than 0.44 prevention of the initial water from evaporation can be sufficient for the development of the desired properties.

The one significant variable which directly affects permeability and the ultimate strength properties of concrete is curing. One form of prolonged moist curing is to apply moist burlap to the concrete surface continually keeping it moist. Research shows that concrete continuously moist cured for a period of 28 days resulted in compressive strengths exceeding 31.03 MPa. Yet, the same concrete air-dried for the same period achieved only 17.58 MPa. Furthermore, the compressive strengths at 180 days were actually lower for the air-dried concrete, where the continuously moisture cured concrete achieved an ultimate compressive strength of over 39.64 MPa. (www.moxie-intl.com)

1.2 STATEMENT OF THE PROBLEM

It is already known that curing is the most significant process for the development of the desired properties of concrete such as mechanical and durability. Lack of adequate curing may cause cracks on the structure which may decrease the service life of the structure and potentially decrease its structural capacity.

For compliance criteria and quality control for the concrete produced in the site, samples are taken to laboratory and moist cured entire time so that they can fully develop the desired properties. But when we see the actual condition in the site regarding curing it is completely different. The adequacy of the current curing practices for the development of the desired properties of concrete is not explored or not known.

Therefore, this research is aimed at to explore the adequacy of the current curing practices in the construction industry in Addis Ababa.

1.3. OBJECTIVE OF THE STUDY

The objective of this research is to assess the current curing practices, the awareness about curing and to explore the adequacy or effectiveness of curing practices in Addis Ababa.

1.4. DELIVERABLE

The deliverable of the research is:

- Showing the status of our curing practices regarding their effectiveness and

For those curing methods which are ineffective:

- To show how we can increase the effectiveness of the current practices
- To also recommended other curing practices that can be easily applied effectively

1.5. SCOPE AND LIMITATIONS

The research on the effectiveness of current curing practices was studied by preparing mortar cubes and by exposing the samples to actual environmental condition on selected construction site. Due to time and budget constraints the research cannot be done throughout the season/year. Therefore, the effectiveness of curing practices was assessed for a specific season, which is from December – February. On this season the humidity is relatively low and the temperature is also relatively high

The other limitation of this research is effectiveness of curing is studied only on w/c of 0.3, 0.4 and 0.5 by considering the future concrete production development in Addis Ababa, Ethiopia.

In Ethiopia there are three different types of cement produced, OPC, PPC and Portland Limestone Cement (PLC). But due to budget constraint the study was only conducted by using Portland Pozzolana Cement (PPC) which is produced and consumed in high amount in the construction industry.

1.6. MATERIALS AND METHODOLOGY

1.6.1. Materials

To achieve the objective of the research different materials will be used. The following are the main ones:

- Cement
- Sand
- Aggregate
- Water
- Burlap Cloth
- Plastic sheets (Polyethylene)
- Humidity Measuring Equipment

1.6.2. Methodology:

For the objectivity of the research the following are the methodologies followed.

1) Preparation of questionnaire

Questionnaire was prepared in order to gather information about the current curing practices used at the construction industry in Addis Ababa.

2) Questionnaire distribution

First pilot samples were distributed to collect the data which will help to determine the curing method and duration for the experimental study. And then from the total population representative number of samples was determined using sampling sheet, by determining level of confidence and margin of error. The questionnaire was distributed for Practicing Engineers in the construction industry.

3) Identification of dependent and Independent Variables

For the experimental study dependent and independent variables were identified (the variables can be found on chapter 3)

4) Preparation of constituent materials

The samples prepared for the experimental study were mortar specimens. The constituent materials such as cement and river sand for mortar samples were prepared.

5) Site selection

One construction site found at Akaki-Kality Sub-City was selected for the samples to be exposed to actual environmental condition and cured for the same curing practice used in the construction industry.

6) Sample preparation

Mortar samples with three different types of water-cement ratio but with the same constituent materials were prepared.

7) Curing of the specimen

Mortar specimens are cured with 3 different curing methods and durations. Some of the samples are also left air dried. For the control test, three specimens from each w/c were cured on the laboratory with pounding.

8) Data recording

Data about the climatic condition were recorded, such as, Relative Humidity, Wind Speed and Temperature.

9) Testing of mortar samples

After complete curing the samples were left on air until 28 days and tested for compressive strength and absorption (after immersing the samples in water for about 24 hours)

10) Analysis of the results

The test data was then analyzed. Standard deviation and variance were determined for compressive strength and absorption results.

11) Conclusion and recommendation

Finally conclusion and recommendation were drawn based on the findings found through questionnaire and experimental study.

CHAPTER TWO --- LITERATURE REVIEW

2.1. INTRODUCTION

It has long been recognized that adequate curing is essential to obtain the desired strength and durability properties of concrete. Proper curing of concrete is one of the most important requirements for optimum performance in any environment or application. (Meeks, K. W., Carino, N. J., 1999)

Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration. It may be either after it has been placed in position (or during the manufacture of concrete products), thereby providing time for the hydration of the cement to occur. Since the hydration of cement does take time – days, and even weeks rather than hours – curing must be undertaken for a reasonable period of time. For example American Concrete Institute (ACI) Committee 301 recommends a minimum curing period corresponding to concrete attaining 70% of the specified compressive strength, if the concrete is to achieve its potential strength and durability. Curing may also encompass the control of temperature since this affects the rate at which cement hydrates. The curing period may depend on the properties required of the concrete, the purpose for which it is to be used, and the ambient conditions, i.e. the temperature and relative humidity of the surrounding atmosphere.

In this chapter starting from definition of curing, the significance, methods, requirements of curing, properties of concrete influenced by curing and other issues related to curing will be discussed from different literatures.

2.2. DEFINITION OF CURING

Different scholars in the field of concrete define curing in different ways. In this part some of the definitions of curing defined by different people and organizations will be discussed.

ACI 308 R:

> *"The term "curing" is frequently used to describe the process by which hydraulic-cement concrete matures and develops hardened properties over time as a result of the* ***continued hydration*** *of the cement in the presence of sufficient water and heat. While all concrete cures to varying levels of maturity with time, the rate at which this development takes place depends on the natural environment surrounding the concrete and on the measures taken to modify this environment by limiting the loss of water, heat, or both, from the concrete, or by externally providing moisture and heat. The term "curing" is also used to describe the action taken to maintain moisture and temperature conditions in a freshly placed cementitious mixture to* ***allow hydraulic-cement hydration*** *and, if applicable, pozzolanic reactions to occur so that the* ***potential properties*** *of the mixture may develop"*

Kosmatka, et al. (2003):

> *"Curing is the maintenance* ***of a satisfactory moisture content and temperature*** *in concrete for a period of time immediately following placing and finishing so that the* ***desired properties*** *may develop."*

ACI 308.1-98:

> *"Maintenance of a satisfactory moisture content and temperature in concrete during its early stages so that* ***desired properties*** *may develop."*

Neville (1996):

> *"Curing is the name given to procedures used for* ***promoting the hydration of cement****, and consists of a control of temperature and of the moisture movement from and into the concrete. [...] More specifically, the object of curing is to keep concrete saturated, or as nearly saturated as possible, until the originally water-filled space in the fresh cement paste has been filled to the desired extent by the products of hydration of cement."*

Mindess (2003):

> *"Concrete must be properly cured if its optimum* ***properties are to be developed****. And adequate supply of moisture is necessary to ensure that hydration is sufficient to reduce the porosity to a level such that the* ***desired strength and durability*** *can be attained and to minimize volume changes in the concrete due to shrinkage."*

Shetty (1982):

> *"Curing can be described as keeping the concrete moist and warm enough so that the* ***hydration of cement can continue****. More elaborately, it can be described as the process of maintaining satisfactory moisture content and a favorable temperature in concrete during the period immediately following placement, so that* ***hydration*** *of cement may continue until the* ***desired properties*** *are developed to a sufficient degree to meet the requirement of service."*

BS-8110:

> *"Curing is the process of preventing the loss of moisture from the concrete whilst maintaining a satisfactory temperature regime. The curing regime should prevent the development of high temperature gradients within the concrete."*

In the definitions of curing discussed above they all agreed that curing is the most important process for the development of the desired properties of concrete, such as strength and durability as mentioned by Mindess. And some of them tried to show the significance of curing related to hydration, which is responsible for the required properties of concrete through a reaction between cement and water.

As we can see the definitions for curing from different literatures it is discussed in different ways but when it is generalized we can say that the objectives of curing are to maintain moisture and temperature conditions in concrete. Maintaining moisture and temperature can be done in either of the two ways, by preventing the loss of moisture or by supplying additional moisture in concrete for a sufficient period of time.

In general there are three basic and common points mentioned about curing.

1) Curing maintain satisfactory moisture and temperature in concrete so that hydration of hydraulic cement can continue
2) Curing prevents moisture loss from concrete.
3) Curing allows hydration reaction so that desired properties, such as strength and durability, can develop

2.3. THE SIGNIFICANCE AND IMPORTANCE OF CURING

Proper curing allows the cementitious material within the concrete to properly hydrate. Hydration refers to the chemical and physical changes that take place when Portland cement reacts with water or participates in a pozzolanic reaction. Both at depth and near the surface curing has a significant influence on the properties of hardened concrete such as strength, permeability, abrasion resistance, volume stability, and resistance to freezing and thawing, and deicing chemicals. (ACI 308R-01)

Poor curing practices adversely affect the desirable properties concrete. Proper curing of concrete is essential to obtain maximum durability especially if the concrete is exposed to severe conditions where the surface will be subjected to excessive wear, aggressive solutions, or severe environmental conditions (such as cyclic freezing and thawing). Likewise, proper curing is necessary to assure that design strengths are attained. (Meeks, K. W., Carino, N. J., 1999)

When Portland cement is mixed with water, a chemical reaction called hydration, the chemical reaction of components tri- and di-calcium silicate, tri calcium aluminates and tetra calcium-alumino ferrate with water, takes place. The extent to which this reaction is completed influences the strength and durability of the concrete. Freshly mixed concrete normally contains more water than is required for hydration of the cement; however, excessive loss of water by evaporation can delay or prevent adequate hydration. The surface is particularly susceptible to insufficient hydration because it dries first. But with proper curing the concrete becomes stronger, more impermeable, and more resistant to stress, abrasion, and freezing and thawing. The improvement is rapid at early ages but continues more slowly thereafter for an indefinite period. (Kosmatka, S. et al., 2002)

Hydration is the basic chemical reaction that takes place between cement and water in order to produce a solid phase “cement gel”. But this will happen only in the presence of sufficient water for the reaction. Initially the amount of water used during mixing can be used in the initial hydration reaction but further the amount of water required for “complete” hydration reaction can be dropped due to environmental conditions such as high temperature, low relative humidity and wind effect.

Therefore, the water has to be either replaced if it is lost due to evaporation or it should be protected from evaporation at the initial stage. And replacing the evaporated water or initially preventing loss of water from the surface of concrete are both methods of curing which will be discussed later.

Hydration increases the amount of solid phase of the paste as water is consumed by chemical reactions. In addition, some of the water is absorbed onto the surfaces of the solids in the cement gel. If the supply of water is insufficient to keep these surfaces saturated, the relative humidity in the paste will decrease (self-desiccation). When the relative humidity drops below 80 %, the hydration rate slows down and it becomes negligible when the internal relative humidity drops to 30 %. Self-desiccation will not occur if the initial water/cement ratio of the paste is sufficiently high and the mix water is prevented from evaporating (sealed condition). (Mindess, S. et al., 2003)

In order to achieve full potential strength and to reduce the amount of drying shrinkage and moisture movement to the lowest possible levels it is necessary to carry out the 'curing' process. This connotes a method whereby the amount of water in the newly placed concrete, which is always higher than that required to fully hydrate the cement present, will be retained over a period of at least several days.

Significance of maintaining moisture

The amount of mixing water in the concrete at the time of placement is normally more than must be retained for curing. However, excessive loss of water by evaporation may reduce the amount of retained water below the necessary amount which is required for the development of desired properties. The potentially harmful effects of evaporation shall be prevented either through external supply of water or by sealing the surface of concrete which is subjected to evaporation.

Significance of maintaining temperature

The rate of cement hydration varies with temperature, proceedings slowly at cooler temperatures down to -10 C^o and more rapidly at warmer temperature up to somewhat below 100 C^o. Concrete temperatures below 10 C^o are unfavorable for the development of early strength. Below 5 C^o the development of early strength is greatly retarded and at 0 C^o little strength develops. There is some evidence that curing for shorter time at a higher temperature will not be as beneficial as longer curing at a lower temperature in terms of final strength. (ACI 308-80)

Higher curing temperatures promote an early strength gain in concrete but may decrease its later age strength. Effect of curing temperature on compressive strength development is presented in Fig. 2.1. One-day strength increases with increasing curing temperature but 28 days strength decreases with increasing curing temperature. (ACI 308-80)

The rate of strength development at early ages of concrete made with supersulfated cement is significantly reduced at lower temperatures. Supersulfated cement concrete is seriously affected by inadequate curing and the surface has to be kept moist for at least 4 days. (British Standard 8110, 1985)

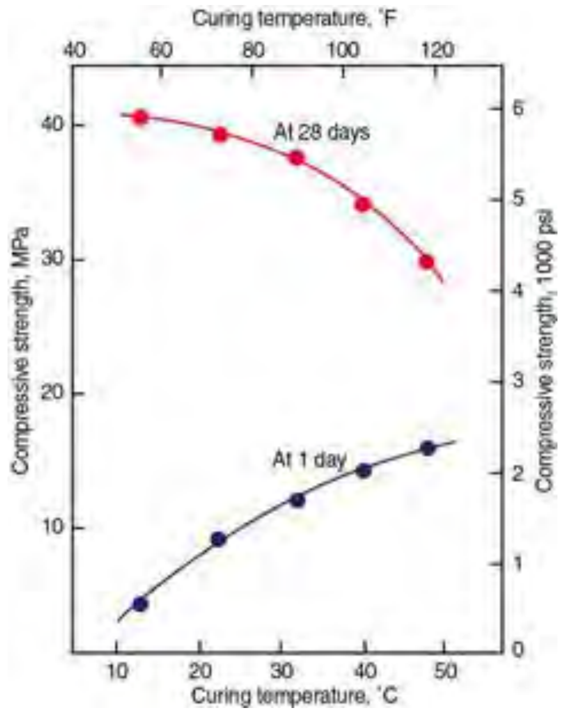


Figure 2.1.: Effect of Curing Temperature on Compressive Strength ***(Adopted from Design & Control of Concrete Mixtures)***

Evaporation from freshly placed concrete on site

The Figure below shows the effect of air temperature, humidity, concrete temperature, and wind velocity together on the rate of evaporation of water from freshly placed and unprotected concrete.

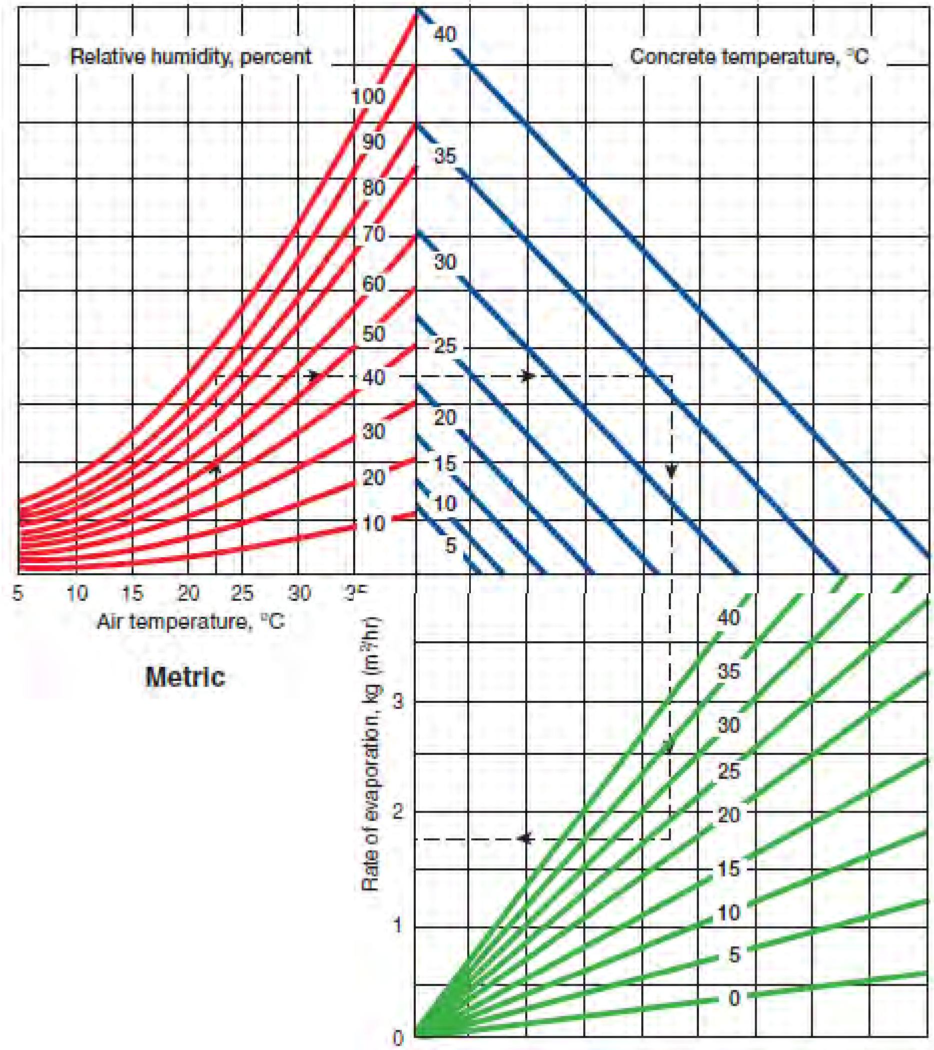


Figure 2.2.: Effect of concrete and air temperatures, relative humidity, and wind velocity on rate of evaporation of surface moisture from concrete. (Adopted from Design & Control of Concrete Mixtures)

The evaporated water should be replaced for further hydration of cement or in conditions like this in the site prevention mechanisms for evaporation should be applied. Otherwise the hydration process will cease.

A later provision of ACI Standard 308-81 that relates to bleeding and bleed water is the instruction about when to apply membrane-forming curing compound. It says: "For maximum beneficial effect, liquid membrane-forming compounds must be applied after finishing and as soon as the free water on the surface has disappeared and no water sheen is visible, but not so late that the liquid curing compound will be absorbed in to the concrete.

If the ambient evaporation rate exceeds 1.0 kg/m^2/hr the concrete may still be bleeding even though the surface water sheen has disappeared and steps must be taken to avoid excessive evaporation. The proper time to apply curing compound was approximately at the time of setting of the cement, which is, of course, the time when bleeding must cease. (Mather, B., 1987)

2.4. CURING REQUIREMENTS

The first time that an ACI committee issued a report dealing specifically with curing was in the late 1950s (ACI 612, 1958). This report contained five basic requirements for curing as summarized below. (Meeks, K. W., Carino, N. J., 1999)

(1) *Adequate water content:* Proper curing involves maintaining suitable moisture content in the paste. This can be accomplished using many different curing methods, or combinations of various methods. All these methods, however, involve two basic concepts. Either the surface of the concrete is kept moist by supplying an external supply of water (water curing), or the loss of moisture is controlled by the use of impervious coatings, membranes, coverings, or by the concrete formwork.

(2) *Maintain adequate temperature:* Ideally the concrete temperature should be maintained above freezing at a relatively constant value throughout the period of curing. The concrete must also be protected from high temperatures. As stated, high temperatures at early ages may impair the long-term properties. Controlling the temperature can be a difficult matter since there are three potential sources of heat, the surrounding environment, absorption of solar heat, and the heat generated from the hydration reactions.

(3) *Preservation of reasonably uniform temperature throughout the concrete body:* The committee recommended curing at a constant temperature a few degrees below the average temperature to which the concrete in the field would be exposed during its lifetime. They also recommend that any drop in temperature during the first 24 h after curing not exceed 16.7 C^o (30 F^o) for mass concrete or 27.8 C^o (50 F^o) for thin sections. This is to reduce the chance of cracking due to temperature gradients.

(4) *Adequate protection from damaging mechanical disturbances during the early period of Curing:* Any new concrete structure must be protected from heavy loads, large stresses, shock, and excessive vibration as the concrete gains strength during early curing. Concrete progresses to its hardened state as determined by the rate of hydration in the paste. This progress can be hampered if the concrete undergoes significant mechanical disturbances during the critical early-age period when the microstructure is beginning to develop. Damage at early age may prevent the concrete from attaining the desired strength and durability to perform satisfactorily.

(5) *Adequate time for sufficient hydration:* There must be enough time allowed for hydration to progress sufficiently to produce concrete having adequate properties for its intended use. The amount of time needed depends on a number of variables, curing temperature, type of cement, and moisture content of the paste.

These five requirements provide the foundation for acceptable curing practices. Among these, the requirement for protection against early-age mechanical disturbance is not completely understood. Some research has shown that a permanent loss in properties (specifically reinforcement bond strength) may occur (Altowaji, Darwin, and Donahey 1986). However, other studies have shown that there may not be permanent loss in properties due to excessive vibration during early ages. The latter conclusion is understandable because damage to the developing microstructure may be repaired (autogenous healing) by subsequent hydration. (Meeks, K. W., Carino, N. J., 1999)

2.5. HYDRATION OF CEMENT RELATED TO CURING REQUIREMENTS

Freshly mixed cement paste is considered to be in a plastic state and is comprised of a dispersion of cement grains surrounded by water. As hydration begins to occur, cement gel is one of the hydration products deposited in the water-filled space between cement grains. As hydration proceeds, two types of pores are formed: capillary pores and gel pores.

Hydration increases the amount of solid phase of the paste as water is consumed by chemical reactions. In addition, some of the water is absorbed onto the surfaces of the solids in the cement gel. If the supply of water is insufficient to keep these surfaces saturated, the relative humidity in the paste will decrease (self-desiccation). When the relative humidity drops below 80 %, the hydration rate slows down and it becomes negligible when the internal relative humidity drops to 30 %. Self-desiccation will not occur if the initial water-cement ratio of the paste is sufficiently high and the mix water is prevented from evaporating (sealed condition). (Meeks, K. W., Carino, N. J., 1999)

Different researches showed that a water-cementitious material ratio (w/cm) greater than 0.42 is theoretically needed to achieve complete cement hydration. (Siddique, S., et al., 2013)

A cement paste, mortar, or concrete cured in a sealed condition will self-desiccate, resulting in the creation of coarse capillary pores within the microstructure. For water-cement ratios (w/c) greater than approximately 0.42, there is sufficient water in the mixture. Hence, complete hydration of the cement can be achieved theoretically without supplying additional water to the cement paste. Even if complete hydration were achievable, however, the lack of additional curing water may still result in the creation of relatively large pores with in the final microstructure.

The addition of curing water would assure that all pores remain water-filled and eligible as locations for the precipitations and growth of hydration products during curing.

Spears (1983) indicated that proper curing maintains relative humidity above 80 percent and, thereby, advances hydration to the maximum attainable limit. Proper curing decreases concrete permeability, surface dusting, thermal-shock effects, scaling tendency and cracking. It increases strength development, abrasion resistance, durability, pozzolanic activity and weatherability.

The concurrent goals of hydration are to connect the original cement particles into a possible strong network and to disconnect the original water-filled capillary pore spaces as much as possible.

Understanding the influence of curing practices on this microstructure development is critical for developing rational curing practices.

There are different researches conducted to study the relationship between curing and hydration characteristics.

Bentz, D., Stutzman, P., 2006, conducted a research to compare hydration characteristics, and Microstructure of cement pastes with water-cement ratios (w/c) of 0.35 and 0.435, cured under saturated and sealed conditions. Cement pastes with initial w/c = 0.35 and 0.45 on a mass basis were mixed at 20 ^{o}C. Cast wafers (=5g) of the prepared pastes, approximately 32 mm in diameter and 2 to 5 mm in thickness, were placed in small capped plastic vials to be cured at 20 ^{o}C. After approximately four hours of curing, any accumulated bleed water was removed from the vials using a pipette, to assess the true effective w/c of the pastes. Pastes with w/c of 0.35 contained negligible bleed water, but for the w/c of 0.45 after removing the accumulated bleed water, a paste with an effective w/c of 0.435 remained.

During the research, three curing conditions were employed. In saturated curing, a small amount of distilled water was placed on top of the paste wafers after removing the bleed water. In sealed curing, the wafers were simply sealed in their plastic vials after removal of the bleed water. In sealed/saturated curing, the wafers were cured under sealed conditions for 7 days, then the plastic vials were opened and a small amount of distilled water was added on top of the wafers. All curing was conducted inside of a walk-in environmental chamber maintained at 20 ^{o}C. At various ages between 1 and 256 days, wafers were removed from their vials and crushed in to small pieces. Some of the small pieces were retained for Scanning Electron Microscopy (SEM) and Low Temperature Calorimetry (LTC) analysis. The remaining pieces were further crushed to a fine powder, flushed with methanol in a thistle tube under vacuum to stop their hydration, for determination of degree of hydration.

After the cured specimens were prepared for viewing at a magnification of 500xs in SEM, each image was then analyzed to estimate the area fraction of four components of the hydrated cement paste microstructure: capillary porosity, calcium hydroxide (CH), calcium silicate hydrate gel (C-S-H) along with hydration products, and unhydrated cement. And in LTC analysis, small pieces of the hydrated cement pastes were also used. For each LTC experiment, one small piece of the relevant cement paste was surface dried using an absorbent towel and placed in small open stainless steel pan. The pan with the sample, along with an empty reference pan of similar mass to the empty sample pan, was placed in the calorimeter cell. A freezing scan was conducted between 5 and -55 ^{o}C. The peaks observed in a plot of heat flow versus temperature correspond to water freezing in pores with various entryways (pore necks). The smaller the pore entryway, the more the freezing peak is depressed. Thus, the presence of, absence of, or change in peaks can be used to infer information concerning the characteristic sizes of percolated (connected) water-filled pores in the microstructure of the hydrating cement paste. The third method used was LOI for the determination of degree of hydration. In this method the non-evaporable water content of each crucible sample was determined as the mass loss between 105 and 100 ^{o}C divided by the mass of the ignited sample. Then the values of non-evaporable water content were converted to estimated degree of hydration based on the phase composition of the cement and published coefficients for the non-evaporable water contents of the various cement clinker phases. (Bentz, D. P., Stutzman, P., 2006)

Finally, Bentz D., Stutzman, P., came up with the following results from the three experimental programs.

In the degree of hydration measured using the LOI technique three major observations were taken:

1. A higher degree of hydration is ultimately achieved in the w/c = 0.435 pastes, due both to their higher water content and to the presence of more space available for the precipitation and growth of hydration products.
2. For both w/c values, sealed curing results in a lower degree of hydration at later ages. As would be expected, this decrease is more significant for the lower w/c cement pastes.
3. In terms of achieved degree of hydration, the sealed/saturated curing condition appears to provide equivalent performance to the saturated curing condition for the thin cement paste specimens employed in this study.

The results found from SEM method

Typical processed SEM micrographs for the w/c = 0.35 and 0.435, 92-days cement pastes are provided in Figures 2.3 and 2.4, in these figures, unhydrated cement particles are white, calcium hydroxide is light gray, C-S-H and other hydration products are dark gray, and capillary pores are black.

1. For hydration under sealed conditions, there exists a set of large (empty) capillary pores for both w/c systems. These pores are present due to the chemical shrinkage and self-desiccation occurring during hydration, as the largest pores is observed to be the first to empty during either internal or external drying at early ages.
2. For saturated and sealed/saturated curing, there are fewer of these large pores. For these saturated conditions, more and coarser pores are observed in the w/c = 0.435 system, due to the large initial spacing between cement particles.

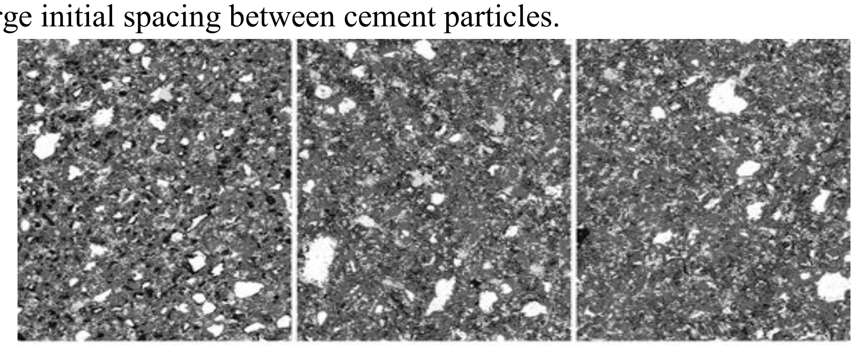


Figure 2.3: 92 day segmented SEM microstructures for w/c = 0.35 cement pastes (Bentz, D. P., Stutzman, P., 2006)

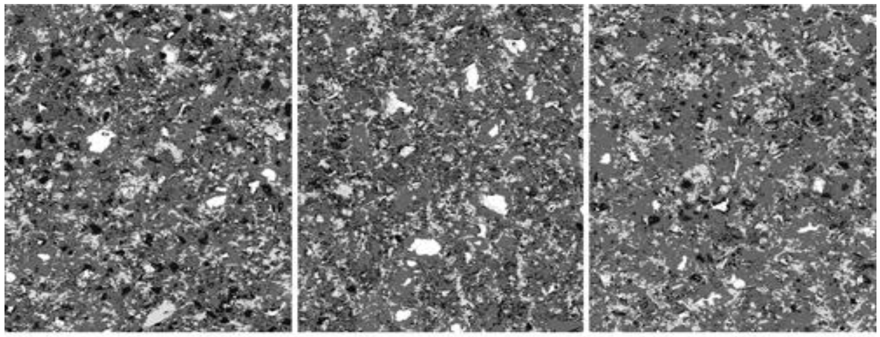


Figure 2.4: 92 day segmented SEM microstructures for w/c = 0.435 cement pastes (Bentz, D. P., Stutzman, P., 2006)

Based on the results of the three different experimental methods, which are SEM, LTC and LOI, Bentz, D., and Stutzman, P., came up with the following conclusions:

1. The connectivity of the pore structures is strongly influenced by the w/c, curing conditions, and the alkali content of the cement, and in turn will dramatically impact the permeability, resistance to freezing and thawing, and overall durability of the final concrete. Curing for strength and curing for durability may require different curing practices to promote development of the micro-structural features that are most beneficial in each case.
2. Very low w/c (<=0.35): internal curing may be needed when it is desirable to avoid self-desiccation, autogenous stress and strains, and their accompanying local damage to the hydrating cement paste microstructure.
3. Low w/c (0.35 to 0.45): internal or external curing may be a viable option, but saturation of the hydrating cement paste should be maintained as long as possible
4. Intermediate w/c (0.4 to 0.45): sealed/saturated curing may be a viable option when curing for durability; otherwise, eternal curing should be adequate, and
5. High w/c (>0.45): it will likely be very difficult to depercolate the pore structure regardless of the curing practice employed.

Siddique, S., et al., 2013, also conducted a research to examine the effect of curing water availability and composition on cement hydration.

In his study, Type I cement, silica fume, slag cement, a mid range water reducing admixture was used.

The w/cm of cement pastes was varied from 0.275 to 0.35 to study the interplay between curing method and w/cm. Mortar with w/cm of 0.45 were used to study the effects of fine light weight aggregate with internal porosity on hydration.

A water-based liquid curing compound was used in this study. Distilled water, saturated lime water, and cement pore water were used to investigate the effects of water curing and ionic concentration of curing water on hydration. Fresh cement pore water was collected by extracting water from cement paste made with the same cement used in this study and with w/cm of 1.5.

Both the cement paste and mortar were mixed at room temperature and placed in isothermal Calorimetry within 15 minutes from the addition of water to the cementitious materials. And the concrete was mixed according to ASTM C192/C192M (2007). Then the curing substances were applied to sample surface to avoid disturbance of curing liquid on the cement paste and its effect on the w/cm.

The concrete compressive strength was measured using a 100x200 mm cylinder following ASTM C39/C39M (2011).

An eight-channel isothermal calorimeter was used in this study to measure the heat evolution of the cementitious systems used. And the procedure is as follow:

1. The cement and mortar samples were mixed
2. The samples are then weighted
3. Then curing is added when needed
4. Within 15 minutes after beginning mixing, the samples are placed in the isothermal calorimeter
5. Finally, the degree of hydration was calculated from the cumulative heat of hydration using Eq. (2.1) to (2.3).

$$\alpha(t) = \frac{H\ (t)}{H_u} \qquad [Eq. 2.1]$$

Where: α(t): the degree of hydration at time t

H(t): the cumulative heat of hydration from time 0 to time t; and
H_u: the total heat available for reaction

$$H_u = H_{cem}.P_{cem} + 461.P_{slag} + 1800.P_{FA-CaO}.P_{FA} \qquad [Eq.\ 2.2]$$

Where: P_{slag}: the slag to total cementitious content mass ratio
P_{FA}: the fly ash to total cementitious content mass ratio
$P_{FA\text{-}CaO}$: fly ash Cao to total fly ash content mass ratio; and
H_{cem}: the available heat of hydration of the cement.

$$H_{cem} = 500.P_{C_3S} + 260.P_{C_2S} + 866.P_{C_3S} + 420.P_{C_4AF} + 624.P_{SO_3} + 1186.P_{Free\ Ca} + 850.P_{MgO} \qquad [Eq. 2.3]$$

Where: H_{cem}: the total heat of hydration of Portland cement at α=1.0

P_i: the ratio of mass of the i-th component of total cement mass.

From the experimental study, Siddique, S., et al, (2013) found the following results:

1. Water-cured cement paste samples showed a higher cumulative heat of hydration than sealed cement paste samples after 7 days.
2. The degree of hydration for the sealed samples increased almost linearly with the increase in w/cm. Water-cured samples, however, showed a nonlinear response.
3. Water-cured samples at a w/cm of 0.275 showed a lower increase in degree of hydration than the 0.3 w/cm sample at all sample thickness, possibly because of more limited space for hydrated products to grow.
4. The use of curing compounds in a sealed condition increased the hydration of cement paste
5. Water cured samples and the curing compound sample showed very similar increase in degree of hydration. The water based curing compound probably increased the amount of available water for hydration, which increased the cement hydration.
6. Very little difference was seen in the degree of hydration of mortar samples with internal curing, as would be expected at w/cm greater than 0.42.
7. Even at w/cm of 0.45, the use of FLAIR improved the degree of hydration of mortar than external water curing.
8. To understand the effect of curing timing on the strength development of concrete, concrete cylinders were cured using three different curing conditions. The concrete immersed in water immediately after finishing showed a significant increase in strength compared to sealed specimen and delayed wet curing. Wet curing immediately after finishing resulted in 27% higher 28-days cylinder strength than that of cylinders sealed for 24 hours followed by curing in a moist room.

To determine the significance of curing in the volumetric proportion of the paste let‟s see another research conducted by adopting (Fig. 2.5 and 2.6) different w/c ratio and two curing conditions (sealed and moist curing). The two figures below shows the volumetric condition for the two curing conditions.

Figure 2.5 below shows the predicted volumetric proportions for fully hydrated pastes of different water-cement ratios cured under sealed conditions. The curve with the solid circles represents the original volume of un-hydrated cement. The distance between the curve with the diamonds and the abscissa represents the volume of cement gel after hydration. For low water-cement ratios, the volume of cement gel is the distance to the curve with the open circles, which represents volume of un-hydrated cement remaining after all the water is consumed by hydration. In reality, hydration ceases when the relative vapor pressure (relative humidity) within the capillaries drops below a critical value. Hence the actual critical value of the water-cement ratio above which complete hydration can occur is greater than 0.42, and Neville suggests that a more realistic value of w/c is 0.50.

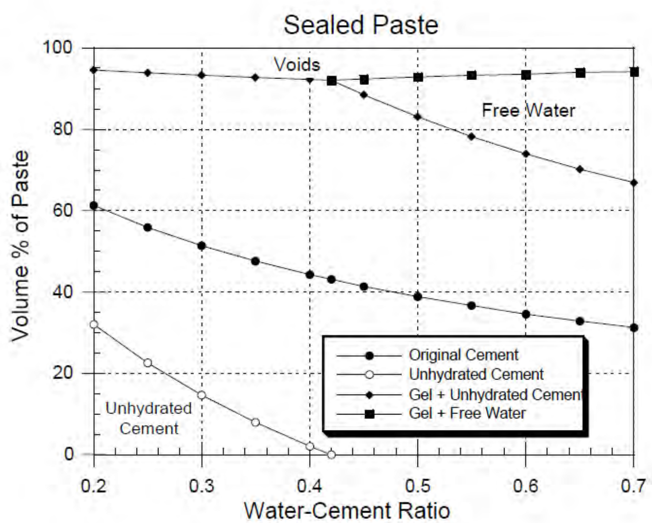


Figure 2.5: Theoretical volumetric composition of fully hydrated cement pastes cured under sealed conditions (Adopted from Curing of high performance concrete)

The other curing condition assumes that an external supply of water is available to maintain the capillary pores saturated as the cement hydrates. The additional water that enters the paste to maintain saturation can be used to hydrate additional cement until one of two conditions is attained: (1) all the cement has hydrated, or (2) all the available space is filled by cement gel. By using the condition that the volume of cement gel equals the original volume of cement plus water, it can be shown that the dividing line between these two conditions occurs at a water-cement ratio of about 0.36.

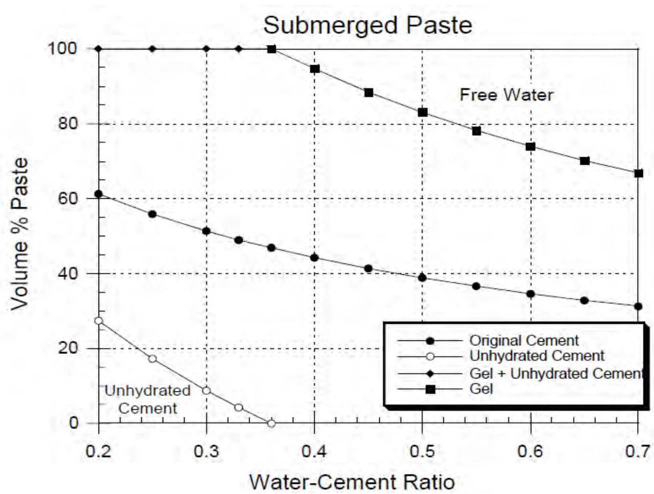


Figure 2.6: Theoretical volumetric composition of fully hardened cement paste cured under water provided capillaries are maintained saturated. (Adopted from Curing of high performance concrete)

Under submerged condition, it is theoretically possible to have a "fully" hydrated paste without capillary pores, while sealed conditions will result in capillary pores in all cases.

Generally concrete can be classified in to normal grade concrete and high strength concrete. In normal grade concrete the initial water-cement ratio used in the mix design is greater than the water required for "complete" hydration but in high strength concrete from the beginning the water in the concrete mix is less than that required for "complete" hydration of cement.

Due to a lack of quality control in the field, concretes and mortars often experience considerable drying before the cement paste matrix has undergone "complete" hydration. (Bentz, D. P., Stutzman, P., 2006)

In actual condition there are many factors that can affect the moisture in the concrete to drop below the required amount for “complete” hydration. One of those factors is environmental condition. Environmental condition means, temperature effect, relative humidity, wind speed, etc. In the previous sections it is discussed that as the internal relative humidity drops the hydration process will cease. And the one reason for the internal relative humidity to drop is due to evaporation of the moisture present in the concrete.

2.6. CURING AFFECTED ZONE

Concrete is most sensitive to moisture loss and therefore, most sensitive and responsive to curing at its surface, where it is in contact with dry, moving air or absorptive media such as a dry sub grade or porous formwork. (ACI 308R-01)

Curing affected zone is defined as the portion of the concrete most influenced by curing measures. This zone extends from the surface to a depth varying from approximately 5 to 20mm depending on the characteristics of the concrete mixture such as w/cm and permeability and the ambient conditions, (Spears, R. E., 1983)

Senbetta, E., & Scholer, C., F., (1984) in their study of a new approach for testing concrete curing efficiency concluded that, poor curing affects only the exposed surface for a depth of approximately 3 cm for the worst atmospheric and curing conditions encountered in their study.

Mather, B., (1987), also stated that, if the effect of curing influences the strength development only to a depth of 25 mm below the surface of the concrete.

Figure 2.7 below shows the variation of the internal relative humidity of concrete at different depths of the specimen. As we go down from the surface of concrete its relative humidity becomes relatively high.

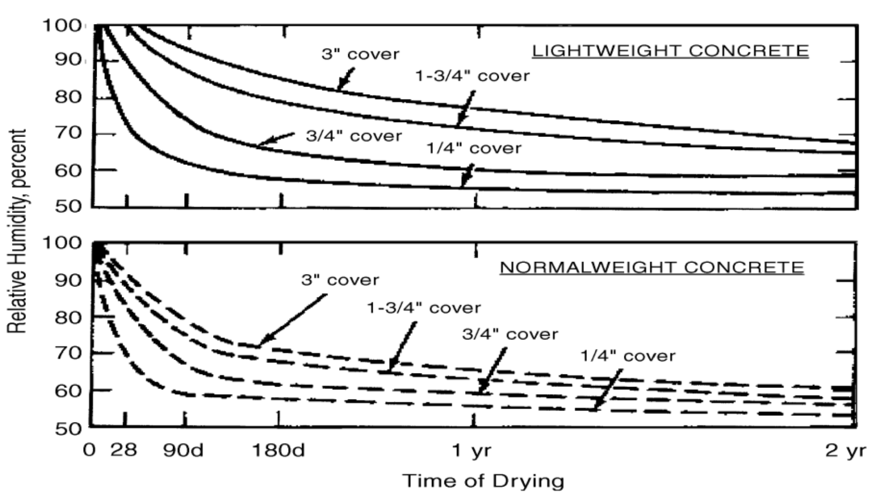


Fig 2.7: Example of variation of internal relative humidity with depth from surface of concrete cylinder (Hanson 1968), [1 in. = 25.4 mm]. (Adopted from ACI 308R-01)

2.7. METHODS OF CURING

There are different classifications on methods of curing. Let"s see classification of curing methods by Mindess and Kosmatka and his co- workers;

Mindess classification of curing methods:

> *"There are many methods and materials that can be used for moist curing of concrete. These can be divided in to two groups."* (Mindess, S. et al., 2003)

- Water curing: those that supply additional moisture as well as prevent moisture loss. This include: ponding, spraying, or sprinkling or by using saturated coverings
- Sealed curing: those that prevent loss of moisture only. Waterproof paper, plastic sheeting, and curing membranes are the most widely used materials for sealed curing.

Kosmatka and his co-workers classify curing methods in three general types with the idea of concrete can be kept moist (and in some cases at a favorable temperature) by three curing methods.

The first two methods by Kosmatka are the same as Mindess classification but they added the third type of curing method which is known as accelerated curing, which is termed as curing at elevated temperature as per Mindess classification. The importance of accelerated curing is to increase the rate of strength development of concrete.

Kosmatka, et al. (2003) classification of curing methods

- Methods that maintain the presence of mixing water in the concrete during the early hardening period. These include Ponding or immersion, spraying or fogging, and saturated wet coverings. These methods afford some cooling through evaporation, which is beneficial in hot weather.
- Methods that reduce the loss of mixing water from the surface of the concrete. This can be done by covering the concrete with impervious paper or plastic sheets, or by applying membrane-forming curing compounds.
- Methods that accelerate strength gain by supplying heat and additional moisture to the concrete. This is usually accomplished with live steam, heating coils, or electrically heated forms or pads.

Generally Methods of curing fall broadly into the following categories:

- Those that minimize moisture loss from the concrete, for example by covering it with a relatively impermeable membrane.
- Those that prevent moisture loss by continuously wetting the exposed surface of the concrete.
- Those that keep the surface moist and, at the same time, raise the temperature of the concrete, thereby increasing the rate of strength gain. This method is typically used for precast concrete products.

In selection of curing methods ACI 308R-01 stated that:

"While there are many methods for controlling the temperature and moisture content of freshly placed concrete, not all such methods are equal in price, appropriateness, or effectiveness. The means and methods to be used will depend on the demands of each set of circumstances. The economics of the particular method of curing selected should be evaluated for each job, because the availability of water or other curing materials, labor, control of runoff (if water is continuously applied), and subsequent construction, such as the application of floor coverings or other treatments, will influence price and feasibility."

2.7.1. Water Curing

This are curing method which prevent moisture loss by continuously wetting the exposed surface of the concrete

This is by far the best method of curing as it satisfies all the requirements of curing, namely, promotion of hydration, reduction of shrinkage and absorption of the heat of hydration. It is pointed out that even if the membrane method is adopted, it is desirable that a certain extent of water curing is done before the concrete is covered with membranes. Water curing can be done in the following ways:

2.7.1.1. Ponding or immersion

Though seldom used, the most thorough method of water curing consists of immersion of the finished concrete in water. (ACI 308R-01)

Application: Ponding is sometimes used for slabs, such as culvert floors or bridge decks, pavements, flat roofs, or wherever a pond of water can be created by a ridge, dike, or other dam at the edge of the slab. (ACI 308R-01)

Specifications: The curing water should not be more than about 11C^o cooler than the concrete to prevent thermal stresses that could result in cracking. (Kosmatka, S. et al., 2002)

The curing water should be free of aggressive impurities that would be capable of attacking or causing deterioration of the concrete.

Requirements on curing water are relatively simple. ASTM C 94 contains requirements on mixing and curing water. Major limits are on chlorides and sulfates. Where staining is a concern, there are often limits on iron. (U. S. Department of Transportation, 2005)

2.7.1.2. Fogging and Sprinkling

Fogging requires the use of an inexpensive but specially designed nozzle that atomizes the water into a fog-like mist. The fog spray should be directed above, not at, the concrete surface, as its primary purpose is to increase the humidity of the air and reduce the rate of evaporation. This effect lasts only as long as the mist is suspended in the air over the slab. This means frequent or continuous fogging is necessary, and the frequency of application should be increased as wind velocity increases over the concrete surface. (ACI 308R-01)

Application: Fogging and sprinkling with water are excellent methods of curing when the air temperature is well above freezing and the humidity is low.

Specifications: Water from fogging should not be worked into the surface in subsequent finishing operations.

Water from fogging should be removed or allowed to evaporate before finishing.

2.7.1.3. Wet coverings

Fabric coverings saturated with water, such as burlap, cotton mats, rugs, or other moisture-retaining fabrics, are commonly used for curing

Application: Wet coverings of earth, sand, or sawdust are effective for curing and are often useful on small jobs.

Wet hay or straw can be used to cure flat surfaces

Fabrics may be particularly useful on vertical surfaces since they help distribute water evenly over the surface and even where not in contact with it, will reduce the rate of surface evaporation.

Specifications: Burlap must be free of any substance that is harmful to concrete or causes discoloration. New burlap should be thoroughly rinsed in water to remove soluble substances and to make the burlap more absorbent.

The burlap shall be made of jute or kenaf at the option of the manufacturer. It shall have a plain weave and conform to the physical requirement given in tables.

Care should be taken however, that the surface of the concrete is not stained, perhaps by impurities in the water, or by the covering material.

If wet hay or straw are used, it should be placed in a layer at least 150 mm thick and held down with wire screen, burlap, or tarpaulins to prevent its being blown off by wind. (AASHTO M182-91 (2000))

Table 2.1.: Physical requirement of burlap

Class	Mass per linear meter	Yarns per Meter of Warp	Yarns per Meter of Filling	Mass per Square Meter*, g
1	233	315 to 433 inc.	315 to 433 inc.	229
2	248	354 to 472 inc.	354 to 433 inc.	244
3	310	433 to 512 inc.	394 to 472 inc.	305
4	372	433 to 512 inc.	433 to 512 inc.	366

*A plus or minus tolerances of 5 percent will be permitted

Unless otherwise specified the burlap shall have minimum width of 1016mm inclusive of selvage and shall be in one continuous piece of not less than 23m. (AASHTO M182-91 (2000))

Major features in water added curing

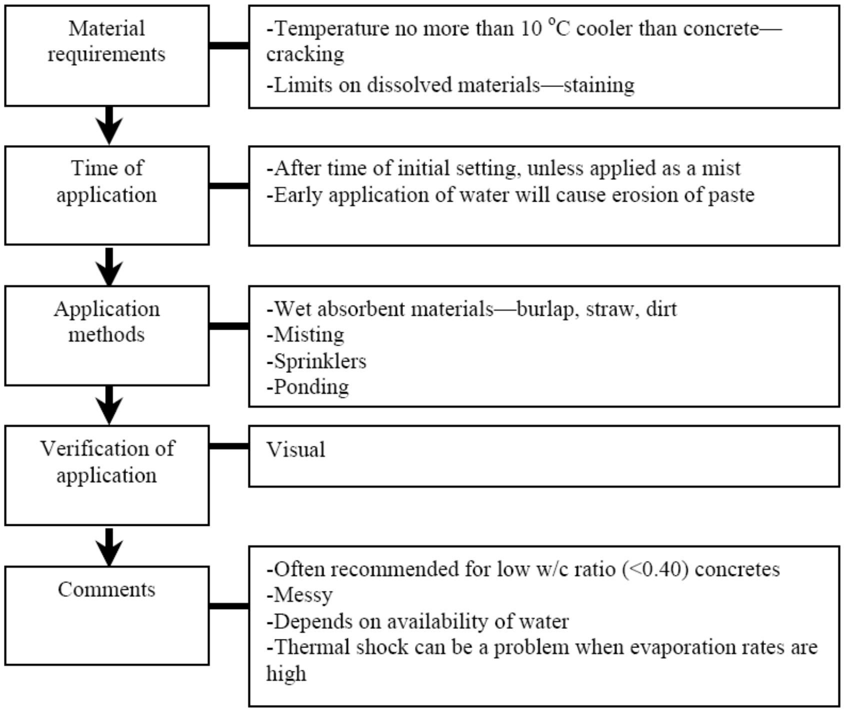


Figure 2.8: Chart. Major features of curing with added water ***(Source: Federal Highway Administration, http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/02099/chapt4.cfm)***

2.7.2. Curing by preventing excessive loss of moisture from the concrete

Sometimes, concrete works are carried out in places where there is acute shortage of water. The lavish application of water for water curing is not possible for reasons of economy. Curing does not mean only application of water; it means also creation of conditions for promotion of uninterrupted and progressive hydration. It is also pointed out that the quantity of water, normally mixed for making concrete is more than sufficient to hydrate the cement, provided this water is not allowed to go out from the body of concrete. For this reason, concrete could be covered with membrane which will effectively seal off the evaporation of water from concrete.

Large numbers of sealing compounds have been developed in recent years. The idea is to obtain a continuous seal over the concrete surface by means of a firm impervious film to prevent moisture in concrete from escaping by evaporation. Some of the materials, which can be used for this purpose, are:

- Waterproof paper, rubber compounds, etc.
- Bituminous compounds,

- Polyethylene or polyester film,
- Covering the concrete with an impermeable membrane after the formwork has been removed
- By the application of a suitable chemical curing agent (wax etc)
- Leaving formwork in place or
- By a combination of such methods

2.7.2.1. Impervious paper

It is a composite consisting of two layers of kraft paper bonded together with bituminous material and reinforced with fiber, used for covering the surface of fresh concrete to inhibit moisture loss during the curing period. (AASHTO M171-00)

An important advantage of this method is that periodic additions of water are not required. Curing with impervious paper enhances the hydration of cement by preventing loss of moisture from the concrete. In addition to curing, impervious paper provides some protection to the concrete against damage from subsequent construction activity as well as protection from the direct sun. It should be light in color and non-staining to the concrete. Paper with a white upper surface is preferable for curing exterior concrete during hot weather. (Kosmatka, S. et al., 2002)

Applications: It is an efficient means of curing horizontal surfaces and structural concrete of relatively simple shapes. (Kosmatka, S. et al., 2002)

Specifications: Curing paper shall consist of two sheets of kraft paper cemented together with bituminous material in which are embedded cords or strands of fiber running in both directions and not more than 32 mm apart. The paper shall be light in color, shall be free of visible defects, and shall have a white surface on at least one side. (AASHTO M171-00)

Other requirements of the impervious paper like tensile strength, is also specified under AASHTO M171.

2.7.2.2. Plastic Sheets

Plastic sheet materials, such as polyethylene film, can be used to cure concrete. Polyethylene film is a lightweight, effective moisture retarder.

Plastic film has a low mass per unit area and is available in clear, white, or black sheets.

Application: It can be easily applied to complex as well as simple shapes.

White film minimizes heat gain by absorption of solar radiation. Clear and black sheeting have advantages in cold weather by absorption of solar radiation but should be avoided during warm weather except for shaded areas. (ACI 308R-01)

On flat surfaces such as pavements, the film should extend beyond the edges of the slab at least twice the thickness of the slab. The film should be placed flat on the concrete surface, avoiding wrinkles, to minimize mottling.

Specifications: AASHTO M171 under standard specification for sheet materials for curing concrete specifies the requirement of plastic sheets as:

> *"Polyethylene Film shall consist of a single sheet manufactured from polyethylene resins. It shall be free of visible defects and shall have a uniform appearance. The clear type shall be essentially transparent. The opaque film shall contain white pigment."*

And about its dimension the same article specifies:

> *"The nominal thickness of polyethylene film shall be no less than 0.0040 in. (0.10 mm) when measured according to specification D 2103. Thickness at any point shall be no less than 0.0030 in. (0.075 mm)."*

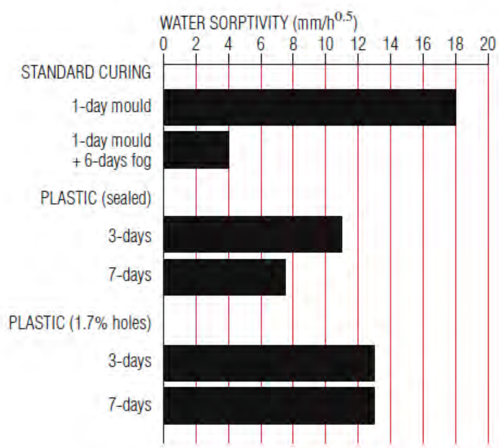


Figure 2.9: Effectiveness of plastic sheeting compared to standard curing.
(Source: http://www.concrete.net.au/publications/pdf/curing06.pdf

Major features of curing with water retention methods

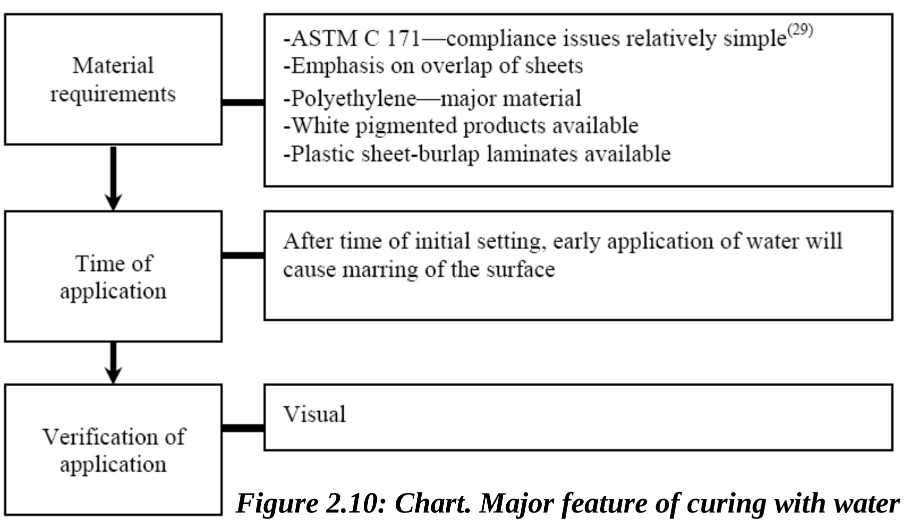


Figure 2.10: Chart. Major feature of curing with water retention method
(Source: Federal Highway Administration, http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/02099/chapt4.cfm)

2.7.2.3.Membrane – Forming Curing compounds

Liquid membrane-forming compounds consisting of waxes, resins, chlorinated rubber, and other materials can be used to retard or reduce evaporation of moisture from concrete. They can be used for curing not only freshly placed concrete but also for extending curing of concrete after removal of forms or after initial moist curing. The working mechanism of this type of curing method is by forming a film on the surface of the concrete to protect the loss of moisture from the top surface. Curing compounds are effective when there is initially sufficient amount of water in the concrete to complete the hydration process. Otherwise curing method that supply additional water are preferable.

Application: Liquid membrane-forming curing compounds should be applied with uniform and adequate coverage over the entire surface and edges for effective, extended curing of concrete.

Liquid membrane-forming compounds should be applied immediately after the disappearance of the surface water sheen following final finishing. Delayed application of these materials not only allows drying of the surface during the period of peak water loss, but also increases the likelihood that the liquid curing compound will be absorbed into the concrete and hence not form a membrane.

Specifications: Requirements of curing compounds are specified in AASHTO M148 under standard specification for Liquid Membrane – Forming Compounds for curing concrete. And it describes about their types, general requirements, different properties, applications, etc… some of these are:

Under water retention properties it says

> "Liquid membrane – forming compounds, when tested in accordance with 10.1, shall restrict the loss of water to not more than 0.55 kg/m^2 in 72 h."

Under reflectance properties

> "Type 2 liquid membrane – forming compounds, when tested in accordance with 10.2, shall exhibit a day light reflectance of not less than 60%."

Under drying time requirement

> *"Liquid membrane – forming compounds, when tested in accordance with 10.3, shall dry to touch in not more than 4 h."*

And many more requirements of curing compounds are specified in AASHTO M 148.

The effectiveness curing compounds varies quite widely, depending on the material and strength of the emulsion, as is illustrated in Figure 2.11 below

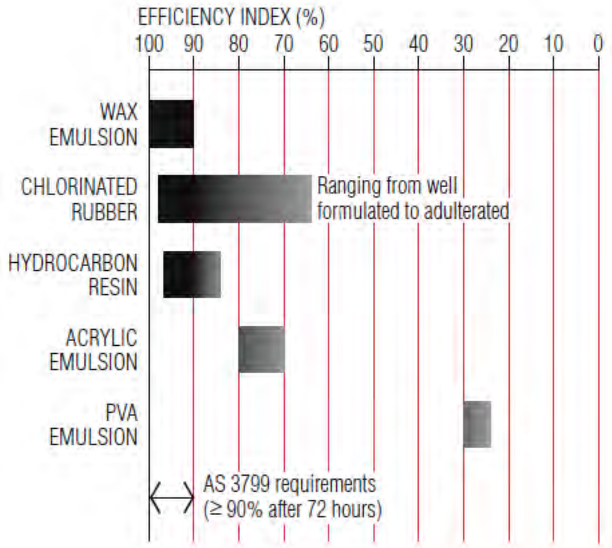


Figure 2.11: Comparative efficiency of curing compounds
(Source: http://www.concrete.net.au/publications/pdf/curing06.pdf

Major features in curing compound practice

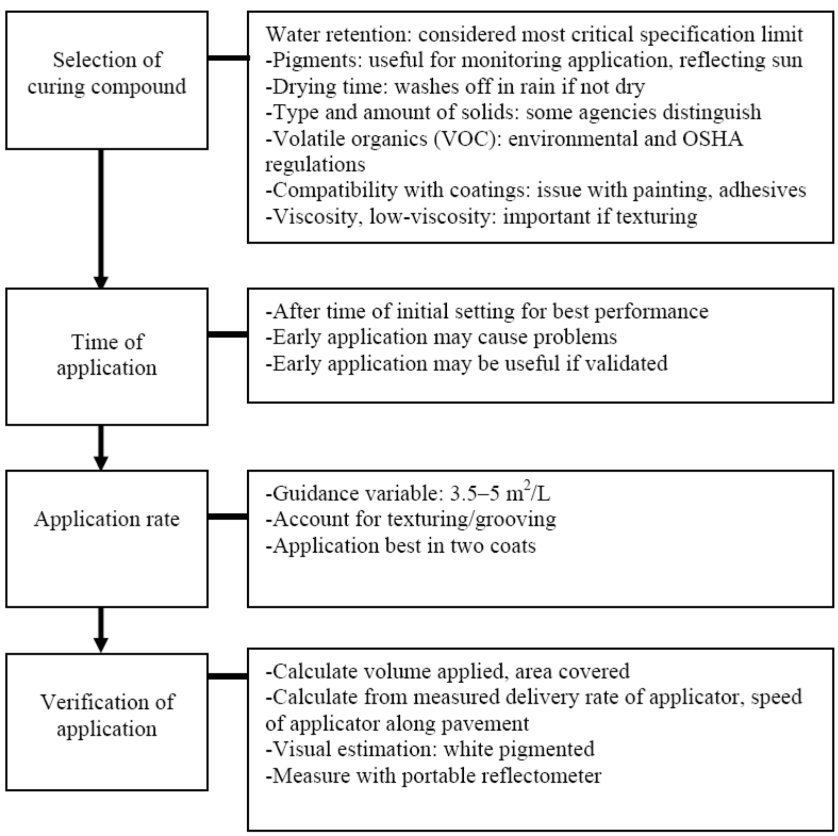


Figure 2.12: Chart. Major features in curing compound practice
(Source: Federal Highway Administration, http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/pccp/02099/chapt4.cfm)

2.7.3. Internal Moist Curing

Internal moist curing refers to methods of providing moisture from within the concrete as opposed to outside the concrete. This water should not affect the initial water to cement ratio of the fresh concrete. The two internal curing methods most often described in the literature are the use of pre-wetted lightweight (low- density) fine aggregate or super absorbent polymers (SAPs). Different researches showed that the use of pre-wetted light weight aggregate has the potential to decrease porosity. In addition to decreasing porosity, internal curing has also shown to decrease permeability. Another most important benefit from using internal curing, however, is the reduction of self-desiccation and the associated shrinkage. (Kosmatka S., et al., 2002; Lopez, M., et al., 2008; Maekawa, K., et al., 1999)

2.7.4. Forms left in place

Forms provide satisfactory protection against loss of moisture if the top exposed concrete surfaces are kept wet.

Leaving formwork in place is often an efficient and cost-effective method of curing concrete, particularly during its early stages. In very hot dry weather, it may be desirable to moisten timber formwork, to prevent it drying out during the curing period, thereby increasing the length of time for which it remains effective. It is desirable that any exposed surfaces of the concrete (e.g. the tops of beams) be covered with plastic sheeting or kept moist by other means. It should be noted that, when vertical formwork is eased from a surface (e.g. from a wall surface) its effectiveness as a curing system is significantly reduced. (U. S. Department of Transportation, 2005)

2.7.5. Curing through Application of heat

The development of strength of concrete is a function of not only time but also that of temperature. When concrete is subjected to higher temperature it accelerates the hydration process resulting in faster development of strength. Concrete cannot be subjected to dry heat to accelerate the hydration process as the presence of moisture is also an essential requisite. Therefore, subjecting the concrete to higher temperature and maintaining the required wetness can be achieved by subjecting the concrete to steam curing. A faster attainment of strength will contribute too many other advantages mentioned below. The exposure of concrete to higher temperature is done in the following manner:

- Steam curing at ordinary pressure
- Steam curing at high pressure
- Curing by Infra-red radiation
- Electrical curing.

SUMMARY Considerations for selecting a curing method

General	**Type of member**	→ Is the member vertical or horizontal? Some methods are affected or excluded by orientation, eg ponding. → Is the member thin or thick? Thick sections such as large columns or mass concrete are mostly 'self-curing' but require temperature gradient at outer layers to be limited. → Is the member insitu or precast? Precast members are suited to low-pressure steam curing while precast products may benefit from autoclaving.
	Environment	→ Does the location affect the availability or cost of some curing materials? eg water in an arid region. → Is the weather likely to be hot or cold? If the temperature is higher than 30°C or less than 10°C special precautions need to be taken. → Is the site exposed to winds? If so, special precautions may be required to prevent plastic shrinkage cracking; sprinkling methods may be affected; or extra care required when using plastic sheeting.
Impermeable membrane curing	**Retention of formwork**	→ What is the effect on site operations and construction cycle schedule? → Is there likely to be cold weather? This method allows easy addition of insulation. → Is uniform concrete colour specified? If so, a constant stripping time will need to be maintained to avoid hydration colour change.
	Plastic sheeting	→ What is the effect on access and site operations? → Is there a safety consideration? Plastic sheeting may be slippery, and is therefore a hazard in horizontal applications. → Is there likely to be hot or cold weather? Colour of sheeting should be selected to suit. → Is the situation such that the seal can be maintained with minimum risk of holing. → Is uniform concrete colour specified? If so, the sheeting must be kept clear of the surface to avoid hydration staining.
	Curing compounds	→ What are the manufacturer's recommendations? Both the rate of application and the timing are critical for effectiveness. Does the product comply with AS 3799. → What is the concrete surface texture? Coarse textures require higher application rates. → Can a uniform application be achieved in the particular situation? Two applications at right-angles help. Sites exposed to wind create problems. → Is there likely to be hot or cold weather? A suitably pigmented compound can help. → Are there to be applied finishes (render, tiles, etc)? Residue from compounds can affect the 'bond' of later applied finishes. → Is there a health consideration? Compounds may be toxic, and their use in enclosed situations may therefore be hazardous.
Water curing	**Ponding**	→ What is the effect on access and site operations? → Is suitable 'dam' material available? A clay soil is the most suitable. → Is there likely to be hot weather? Ponding is an efficient means of maintaining a uniform temperature on slabs. → Is concrete colour or appearance a consideration? 'Dam' materials, particularly clay, tend to stain.
	Sprinkling	→ What is the effect on site operations? → Is there an adequate water supply? → What is effect of run-off? Usually some form of drainage is required. → Will required volume/timing be such as not to damage the concrete surface? → Can application be maintained continuously? Intermittent wetting and drying can be deleterious. → Is site exposed to winds? This makes continuous application very difficult.
	Wet coverings	→ What is the effect on site operations? → Can they effectively cover all surfaces? → Is site exposed to wind? Wet coverings are easier to keep in place than plastic sheeting. → Is concrete colour or appearance a consideration? If so, sand should have low clay content; fabrics and water should contain no impurities. → In the case of sand, its supply or removal a problem? → Can coverings be kept continuously moist? Intermittent wetting and drying can be deleterious.

Figure 2.13: Summary considerations for curing concrete, (Source: http://www.concrete.net.au/publications/pdf/curing06.pdf

2.8. PROPERTIES OF CONCRETE INFLUENCED BY CURING

Because of curing directly affects the degree of hydration of cement curing has an impact on the development of all concrete properties.

Different researches are conducted to see how curing affects physical properties of concrete. Some of the physical properties which are affected by curing are:

- Water permeability
- Oxygen permeability
- Freezing and thawing durability
- Surface absorption
- Abrasion resistance
- Compressive strength

2.8.1. The effect of curing on water permeability of concrete

Water permeability is a durability requirement of concrete. Permeability refers to flow of a fluid through a material under the action of a pressure gradient. In hardened cement paste permeability is related to the connectivity of capillary pores. Powers and Brownyard (1947) noted that for a properly cured, low water-cement ratio paste the permeability can be expected to be as low as that of granite.

Regarding the effect of curing on improving water permeability, let us see figure 2.7 which is adopted from ACI 308 R. Two curing durations were applied to study the significance of curing on water permeability, which are one day curing followed by air dry for 90 days and moist curing for 7 days. This study was conducted for different w/c. Finally hydraulic permeability versus w/c ratio graph was drawn. Test results showed that there is an improvement on water permeability on the concrete which is moist cured for 7 days than the concrete which is cured for only one day and exposed in air for 90 days. This is illustrated in Figure 2.7 below. (ACI 308R-01)

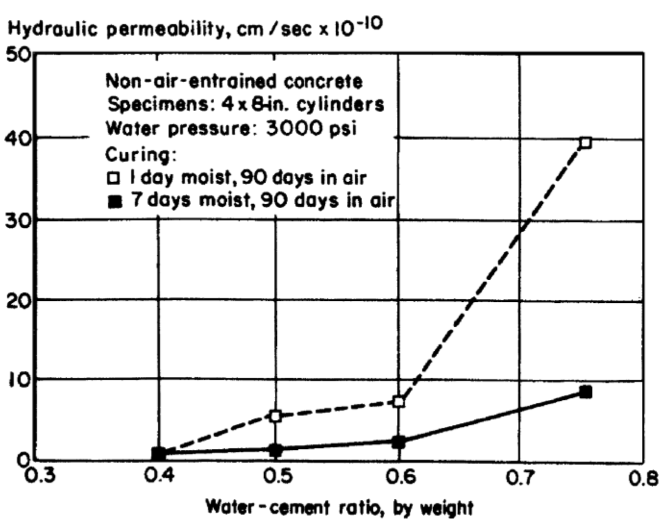


Fig 2.14: *Influence of curing on the water permeability of concrete (Kosmatka and Panarese 1988) (1 cm/s = 0.39 in./s). Adopted from ACI 308 R*

2.8.2. The effect of curing on oxygen permeability of concrete

Grube and Lawrence in 1984; Gowripalan et al. in 1990 conducted a research to determine the significance of curing on oxygen permeability of concrete. And the result showed that curing and elongated curing duration can significantly reduce the oxygen permeability.

The result of their research is then put figuratively in graphs for different w/c. For both w/c of 0.5 and 0.65 the data in the graphs shows curing is highly influential on the long- term property of concrete, which is oxygen permeability.

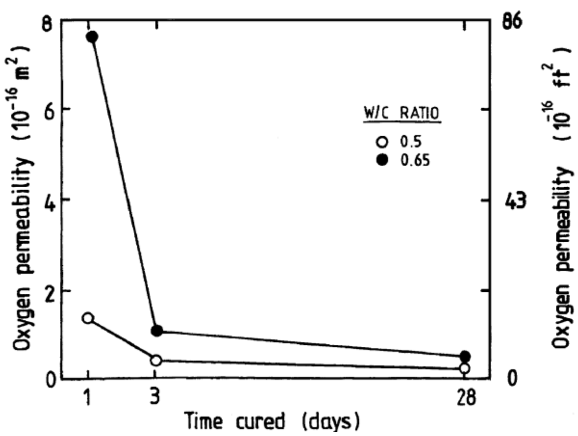


Fig. 2.15: *The effect of curing on reducing the oxygen permeability of a concrete surface (Grube and Lawrence 1984; Gowriplan et al. 1990), Adopted from ACI 308R*

As w/c increases the effect of curing in reducing oxygen permeability become higher. For example the graph shows as the curing duration changes from 1day to 3days, the concrete with w/c ratio of 0.5 has a difference of approximately $1.1*10^{-6}$ m^2 in water permeability, but for w/c ratio of 0.65 the difference in oxygen permeability turn out to be six times higher.

As a Summary the review by Gowripalan et al. (1990) provides the following important observations related to curing to ensure adequate durability:

- The initial curing period results in the most benefit.
- Low water-cement ratio concretes are less sensitive to initial curing.
- Concretes made with blended cements require longer durations of moist curing, but they will have improved durability-related properties compared with similar concretes made with Portland cement only.
- Water absorption tests are useful for assessing curing efficiency, but the problem of moisture conditioning has hampered their standardization.

2.8.3. The effect of curing on freezing and thawing durability

To see the effect of curing on freezing and thawing durability a research was conducted by Murdock, Brook, and Dewar in 1991. The research showed that curing is significant in improving the freezing and thawing durability of concrete.

The effect of curing on freezing and thawing durability is conducted by varying the duration of moist curing from 1day up to 28days and the result shows the significant increase in resistance of freezing and thawing.

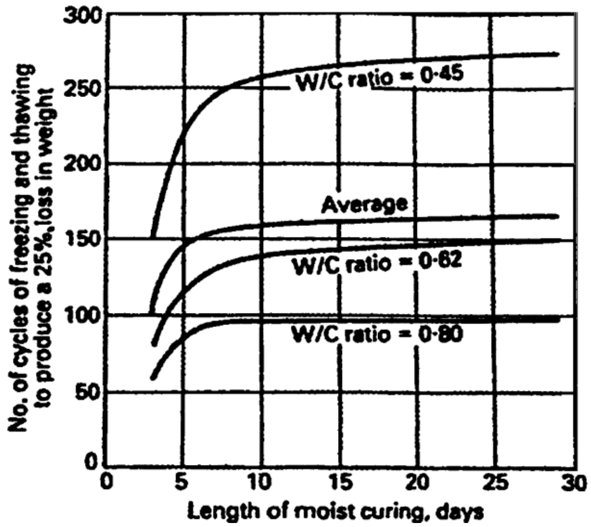


Fig. 2.16: Influence of duration of moist-curing time on freezing and thawing durability of concrete, also as a function of w/c *(Murdock, Brook, and Dewar 1991). Adopted from ACI 308 R*

2.8.4. The effect of curing on surface absorption

Senbetta and Scholar (1984) developed a new approach for measuring curing effectiveness. The research was conducted by studying the effect of curing on surface absorption. The test procedure involved using 89 mm thick mortar slabs subjected to various curing conditions. Type I Portland cement was used with two different types of sand, natural masonry sand and graded standard sand. An assessment was made of the difference in pore structure at various depths of the test slabs based on the absorptivity of the mortar. The general procedure and the results they found are as follows.

- Drill 25 mm (1 in) diameter cores through the mortar slabs after curing.
- Cut the cores into 10 mm (0.4 in) thick disks and dry them at room temperature under vacuum for 48 h. Measure the mass of the dried disks.
- Place the upper surface of the disks in contact with a free water surface for one minute.
- Measure the gain in mass of absorbed water. Convert the mass of absorbed water to volume of water. Calculate the "coefficient of absorptivity"

Senbetta and Scholer studied the performance of the above procedure for slabs exposed to five curing conditions as follows:

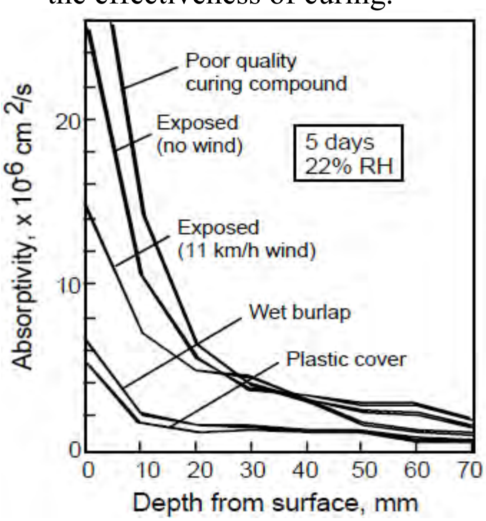
- Covered with wet burlap,
- Covered with plastic sheet,
- Coated with curing compound,
- Left exposed, and
- Left exposed in a windy environment.

The slabs were cured from 1 d to 5 d in a chamber maintained at a temperature of 27 °C (81 °F). Slabs were exposed to relative humidity of 22 %, 44 %, and 72 % during the curing periods. A fan created a windy environment in one part of the curing chamber.

Based on the statistical analysis of the data for the 5 day old samples, Senbetta and Scholer established a quantitative dividing line to distinguish between adequate and inadequate curing. The dividing line was based on the differences in absorptivity at depths of 10mm and 60mm.

Based on the results of this study, Senbetta and Scholer (1984) concluded that:

- Absorptivity can be used as a simple and accurate measure of cement hydration and pore structure development in cement paste.
- Poor curing practices may only affect the concrete surface to a depth of approximately 30 mm (1.2 in).
- The use of absorptivity differences between two depths, or zones, of a specimen to measure the effectiveness of curing may be applicable to any concrete mixture. This is because the quantity of interest is based on the difference between two zones of the same sample.
- More work is needed to confirm that the method can be used as a general method to confirm the effectiveness of curing.



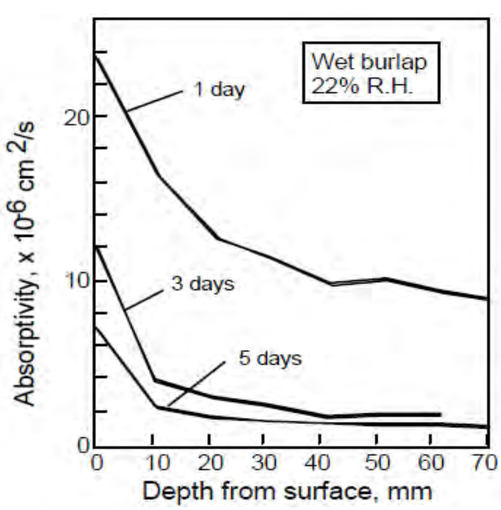


Figure 2.17: Effect of curing method and duration on surface absorptivity (Adopted from Senbetta and Scholar 1984)

2.8.5. The influence of curing on abrasion resistance of concrete

Curing has a significant influence in abrasion resistance of concrete. This can be supported by the research conducted by Dhir, Hewlett, and Chan in 1991.

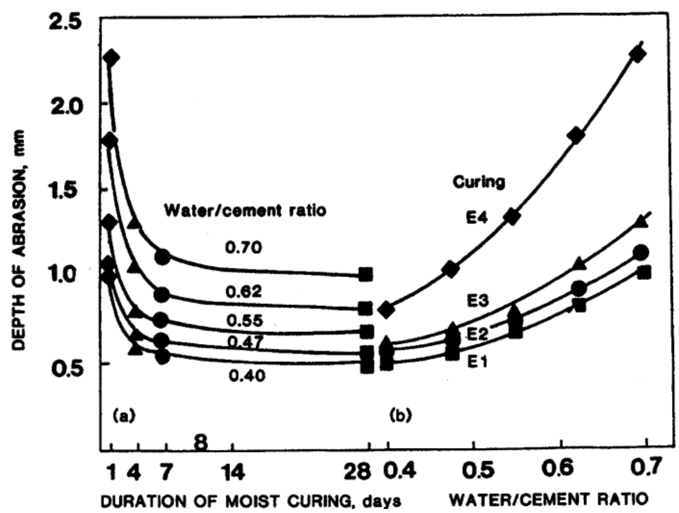


Fig. 2.18: Dhir, Hewlett, and Chan (1991) demonstrated the relationship between abrasion resistance and curing (1 mm = 0.04 in.). Note: E1= 24 h wet burlap followed by 27 days immersion curing in water at 20 C (68 F); E2= 24 h wet burlap followed by 6 days immersion curing in water at 20 C (68 F) and 21 days in air at 20 C (68 F) and 55% RH; E3= 24 h wet burlap followed by 3 days immersion curing in water at 20 C (68 F) and 24 days in air at 20 C (68 F) and 55% RH; and E4= 24 h wet burlap followed by 27 days in air at 20 C (68 F) and 55% RH. Adopted from ACI 308 R

2.8.6. The effect of curing on compressive strength of concrete

The research conducted by Gonnerman and Shuman in 1928 indicates that curing is a significant process in improving the strength of concrete. The research was done by applying moist curing with a curing duration of 3d, 7d, 28d and entire time. Some samples were also exposed to air entire time. Finally results showed that the moist cured samples had an improved strength compared with samples which were air dried entire time. In addition to this results also showed that extended curing duration has a significant effect on improving the compressive strength of concrete. The research by Gonnerman and Shuman is more illustrated on figure 2.19 below.

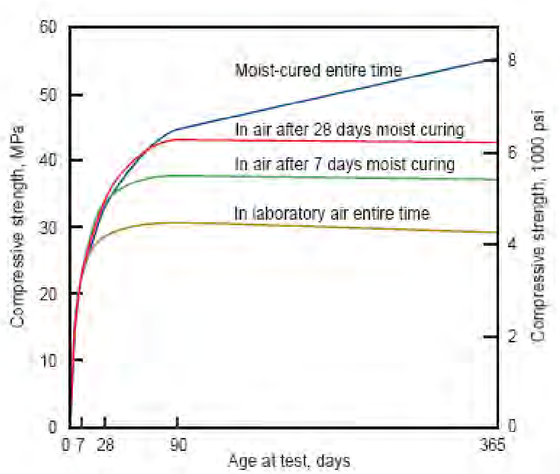


Fig. 2.19: Effect of moist curing time on strength gain of concrete (Gonnerman and Shuman 1928) Adopted from Design and control of concrete mixtures by (Kosmatka, et al., 2003)

2.8.7. The effect of curing on Durability of Concrete

Senbetta and Malchow (1987) studied the effects of different curing methods on durability of concrete. The curing duration for the various curing methods used in the research was 14 days. The test specimens were made with Type I Portland cement with no admixture. The water cement ratio was approximately 0.67.

Their conclusions were a good curing practice improves durability-related properties compared with air-dried samples. The best methods were sealing with wax, covering with plastic sheets, and storage in 100 % RH chamber. When we see the curing practice based on sealing the concrete, it was just as effective as moist curing. This can be due to the higher water cement ratio used in the study which ensured sufficient supply of water for “complete” hydration. We saw from figure 2.4 that the actual critical value of the water-cement ratio above which complete hydration can occur is greater than 0.42, and Neville suggests that a more realistic value of w/c is 0.50.

Other major conclusions from this research were:

- Good curing practices can improve the abrasion resistance by at least 50 % compared with air curing or poor curing methods.
- Proper curing methods can significantly reduce drying shrinkage and cracking.
- The capillary porosity of a concrete specimen can be reduced by as much as 80 % through good curing methods. This has positive effects on the properties of absorptivity, corrosion resistance, and scaling resistance.

2.9. DURATION/LENGTH OF CURING

Increasing the duration of moist curing improves the mechanical and durability properties of concrete. The challenge is to determine the minimum duration of curing that is necessary to achieve the required level of performance for the specific application, taking into account all pertinent parameters.

Parameters affecting curing duration: -Hilsdorf lists four parameters which must be considered when establishing minimum curing durations (Hilsdorf 1995):

- Curing sensitivity of the concrete as influenced by composition: - water-cement ratio and strength development properties of the cement are the most important factors affecting this parameter.
- Concrete temperature: - the rate of hydration (and, therefore, strength development and reduction in porosity) is affected greatly by this parameter.
- Ambient conditions during and after curing: - this parameter affects the severity of drying of the surface layer.
- Exposure conditions of the structure in service: - these affect the required “skin” properties for adequate service life.

The Portland Cement Association (PCA) also mentioned different factors that have to be considered in selecting the length of adequate curing. Some of these are:

- Type of cementitious materials used
- Mixture proportions
- Specified strength
- Size and shape of concrete member
- Ambient weather conditions
- Future exposure conditions (http://www.cement.org/tech/cct_curing.asp)

Specifications related to duration of curing

Curing should be continued until the required concrete properties have developed or until there is a reasonable assurance that the desired concrete properties will be achieved after the curing measures have been terminated and then exposed to the natural environment.

In determining the appropriate duration of curing, concrete properties which are desired in addition to compressive strength should be considered. For example:- if both high compressive strength and low permeability are required concrete performance characteristics then the curing needs to be long enough to develop both properties to the specified values. The appropriate duration of curing will depend on the property that is the slowest to develop. Other considerations in determining the specified duration of curing include the cost of applying and subsequently maintaining various curing measures, and the risk and costs associated with not achieving the necessary concrete properties if curing is insufficient. (ACI 308R-01)

Strength requirement

Curing should be continued until the required concrete properties have developed or until there is a reasonable assurance that the desired concrete properties will be achieved after the curing measures have been terminated and then exposed to the natural environment. (ACI 308R-01)

American Concrete Institute ACI 301 and ACI 308R-01 recommends a minimum curing period corresponding to concrete attaining 70% of the specified compressive strength. The often specified 7-days curing commonly correspond to approximately 70% of the specified compressive strengths. The 70% strength level can be reached sooner when concrete cures at higher temperatures or when certain cement/admixture combinations are used. Similarly, longer time may be needed for different material combinations and/or lower curing temperatures.

ACI Committee 308 recommends the following minimum curing periods

Concrete (other than high-early-strength) shall be maintained above 10 °C and in a moist condition for at least the first 7 days after placement, High-early-strength concrete shall be *maintained above 10 °C and in a moist condition for at least the first 3 days, except accelerated curing.* (ACI 318M-08)

ACI 308R-01 also recommends the following minimum curing durations for different types of cement based on ASTM C 150 classification.

- ASTM C 150 Type I cement 7 days
- ASTM C 150 Type II cement 10 days
- ASTM C 150 Type III cement 3 days
- ASTM C 150 Type IV or V cement 14 days
- ASTM C 595, C 845, C 1157 cements variable

ASTM Standard specification for the curing of Portland cement:

> "*The concrete shall be so cured that the compressive or flexural strengths of specimens of the concrete 28 days old, are not less than 90 % of the strengths of 28-days-old specimens of the same concrete cured in moist air at a constant temperature of 21 °C (70 °F).*" (ASTM Standards, 1945)

EBCS 2, 1995

> *"(1) In hot weather there is great need for continuous curing, preferably by water. The need is greatest during the first few hours, and throughout the first day after the concrete is placed."*

> *"(2) In hot weather, forms shall be covered and kept moist. The forms shall be loosened, as soon as this can be done without damage to concrete, and provisions made for the curing water to run down inside them. During form removal, care shall be taken to provide wet cover to newly exposed surfaces to avoid exposure to hot sun and wind. At the end of the prescribed curing period (10 days is recommended), the covering shall be left in place without wetting for at least four days, so that the concrete surface will dry slowly and be less subject to surface shrinkage cracking."*

When we see the above specification from EBCS in specifying the curing duration it only considers hot weather condition. But, as it was discussed earlier there are so many factors that can affect duration of curing (Referee Section 2.9).

Durability Requirement

Durability is related to other important properties of concrete besides strength such as, resistance to carbonation, porosity, permeability, and abrasion resistance. Studies to define curing requirements for required levels of durability must address the development of these durability-related properties.

2.10. MONITORING THE EFFECTIVENESS OF CURING

Curing efficiency is defined as, "*...the ability to keep the water in the concrete to guarantee high quantities of chemically bound water and thus to guarantee a high degree of hydration*." (Meeks, K. W., Carino, N. J., 1999)

According to American Concrete Institute report under ACI 308R_01, the following are some of the methods that can be used to assess or monitor the effectiveness of curing.

- By monitoring the environmental conditions in which the concrete is placed to evaluate the need for temperature and moisture control;
- By Verifying that the specified curing procedures have been used;
- By monitoring the quantitative changes in the immediate environment as a result of curing procedures;
- By monitoring the moisture content and temperature in the concrete; and
- By monitoring the physical properties of the concrete, as influenced by the application of curing procedures. Properties of the concrete near to the surface are the most sensitive to curing and are often the most useful or reliable indicators of curing effectiveness.

ACI 308-81 discusses evaluation of curing procedures primarily in terms of the development of strength. Since curing is intended to allow the development of hydration products and hydration products can be created in the originally water-filled space and strength is the direct measure of the degree to which the originally water-filled space becomes filled with hydration products; it is completely logical to measure the effectiveness of curing by measuring strength development. If the effect of the curing influences the strength development only to a depth of 25 mm below the surface of the concrete, one should perhaps use strength specimens having a maximum dimension of 50 mm. (Mather, B., 1987)

There are also different methods for assessing the effectiveness of curing which were developed by different researchers. For example, Senbetta and Scholar, 1984 developed a new approach for testing of concrete curing efficiency. The method they developed for assessing the adequacy of curing is absorptivity test, by using absorptivity differences between two different zones, such as the tops and bottoms of slabs. Other methods such as water sorptivity, rate of carbonation, water penetration test, mercury intrusion, and rapid chloride permeability test can also be used for assessing the effectiveness of curing. These tests can tell us the property of concrete or mortar near the surface (Meeks, K. W., Carino, N. J., 1999)

2.11. COMPARISON BETWEEN COMPRESSIVE STRENGTH OF MORTAR AND CONCRETE MIXTURES

Mahyuddin, R. and Eethar, T. D. did a research entitled "comparative study between flowable high strength mortar and flowing high strength concrete". In their study mortar and concrete mixtures with a w/c of 0.4 with and without silica fume were prepared. During the research a total of four mixes with a varying percentage replacement of silica fume were prepared. Fresh mortar mixtures were cast into 50 mm cube molds and 100 mm cube molds were used for concrete casting.

From the study they concluded that there is a clear relation between compressive strength and flexural strength for each of mortar and concrete mixes and it is observed that the compressive strength of concrete is higher than that of mortar and this is because of the mechanical interlocking of the coarse aggregate contributes to the strength of concrete in compression.

Table2.2: Concrete and Mortar mixes and Results for comparative study between mortar and concrete

Mix Designation	% Replacement of Silica fume	Water-binding material ratio	SP-Admixture [%]	7th day Compressive strength	28th day Compressive strength
Mortar Mixture					
M1	0	0.4	1.6	38.5	48.4
M2	6	0.4	1.8	41.3	52.6
M3	8	0.4	2.0	44	53.8
M4	10	0.4	2.2	45.1	55.6
Concrete Mixture					
C1	0	0.4	1.6	43.7	56.3
C2	6	0.4	1.8	47.2	60.1
C3	8	0.4	2.0	49.1	61.4
C4	10	0.4	2.2	49.8	63.6

M-Mortar Mixture, C-Concrete Mixture

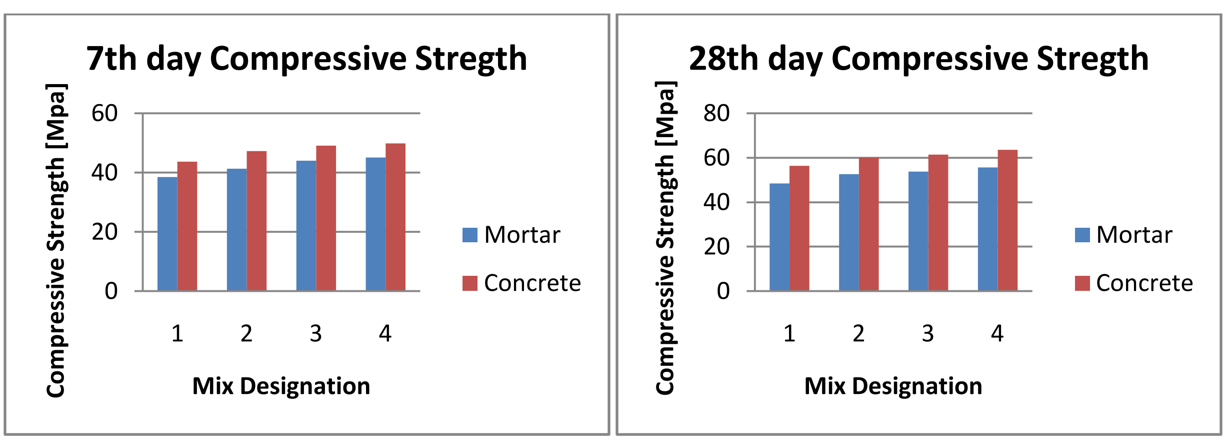


Figure 2.20: Comparison between compressive strength of mortar and concrete mixtures with w/c of 0.4

From the observed results, there is more or less a constant relationship between 28th day compressive strength of mortar and concrete mixes.

Table2.3: Difference in compressive strength between mortar and concrete mixtures

Mix Designation		Difference in Compressive Strength	
		7th day [MPa]	28th day [MPa]
C1	M1	5.2	7.9
C2	M2	5.9	7.5
C3	M3	5.1	7.6
C4	M4	4.7	8.0

For the above finding, the difference in compressive strength between mortar and concrete mixtures at 7th and 28th day is about 5.2MPa and 7.75MPa in average respectively.

As it was discussed earlier the molds used for preparing concrete specimens was 10cm cubes, but if we use 15cm cubes the difference in compressive strength between mortar and concrete mixtures will be less than the figures mentioned above. Because of the confinement effect during testing, concrete specimens with lesser depth will have greater compressive strength. If we take a conversion factor of 1.05, to convert compressive strength of 15cm cube specimens to 10cm cubes ($fcu,_{10}$ = 1.05x($fcu,_{15}$), the difference in compressive strength between mortar and concrete mixtures at 7th and 28th day will be approximately 3MPa and 5MPa respectively.

CHAPTER THREE -- REVIEW OF CURING PRACTICES IN ADDIS ABABA

The first objective of this research is assessing the current curing practice and the awareness about it in the construction industry in Addis Ababa. For fulfilling this objective a questionnaire was developed and distributed to be filled by the practitioners in the building construction industry at Addis Ababa. Their response is analyzed and presented as follows.

3.1. NUMBER OF QUESTIONNAIRE DISTRIBUTED AND THEIR RESPONSE RATE

Table 3.1: Questionnaire response rate

	Questionnaire Distributed	Collected Questionnaire	Response Rate
Number	230	106	46.1%
Level of Confidence:	90%	80%	
Margin of Error:	5.4%	6.2%	

The number of questionnaire distributed was determined using developed sampling excel (annex 7) based on the required level of confidence and margin of error needed to be achieved. The first piece of information we need to calculate the margin of error is to determine what level of confidence we desire. This number can be any percentage less than 100%. And after the questionnaire was collected with a response rate of 46.1% (see table 3.1) the level of confidence and margin of error is re-determined from the available number of collected samples which is 106. Because of the low response rate of the questionnaire distributed, the level of confidence is reduced from the original value which was 90%. The margin of error is also re-determined by using the achieved level of confidence. The finding found through questionnaire survey from the total 106 respondents has a level of confidence of 80% with 6.2% margin of error.

3.2. METHOD OF ANALYSIS

Mean Score (MS) value was calculated using the equation shown below.

$$MS = \sum \{(f * S) \dagger N\}. \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \{1\}$$

Where:

- f = frequency of responses to each rating S = Score given to each factor
- N = the total number of responses concerning the factor

Mean value tells us where the center of the data set is. Let us see one example to present it more clearly based on the response from the questionnaire distributed.

Example: Which grade of concrete is mostly produced in the construction industry in Addis Ababa. The table below shows the frequency or the number of times each grade of concrete is chosen by the respondents.

Table 3.2: Sample questionnaire response

	Frequency Table					
Grade of concrete	C20	C25	C30	C40	Other	Total
Number of Respondents	14	81	24	6	6	131

Then, let us give a code or a score for each grade of concrete; say 1 to 5 starting from C20 respectively. If we use the above formula we will get a mean of 2.31. This mean value indicates that the result is in between 2 and 3 towards a score value of 2 which is C25. Therefore, the conclusion is mostly produced grade of concrete is C25 as it is most frequently chosen by the respondents and then C30.

Table 3.3: Rating scale for Mean Score

Rating scale	Mean Score Scale
1	$0.00 \leq MS < 1.50$
2	$1.50 \leq MS < 2.50$
3	$2.50 \leq MS < 3.50$
4	$3.50 \leq MS < 4.50$
5	$4.50 \leq MS < 5.00$

3.3. RESULTS AND ANALYSIS FROM QUESTIONNAIRE SURVEY

Status of respondents:

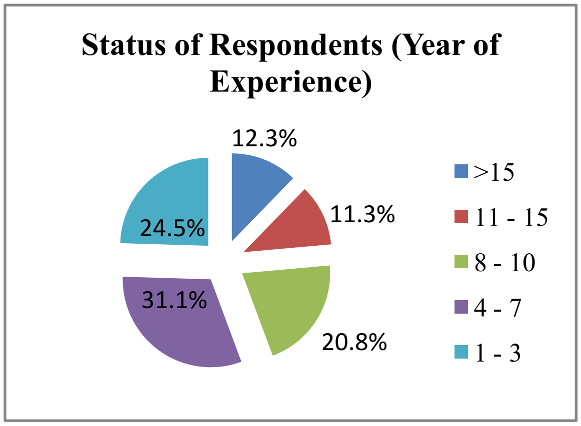


Figure 3.1: Status of Respondents (Year of Experience)

Grade of concrete mostly produced in Addis Ababa

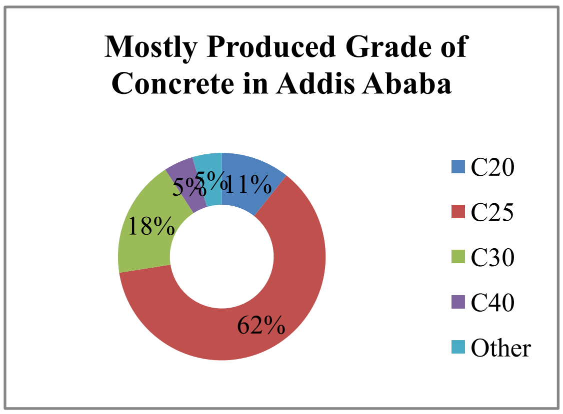


Figure 3.2: Mostly produce grade of concrete in Addis Ababa

Analysis: The majority of respondents agreed that mostly produced grade of concrete is C25

MS = 2.31, *(Score given: C20 = 1,* ***C= 25 = 2****, C30 = 3, C40 = 4, Other = 5)*

Type of cement mostly used to produce the specified type of concrete

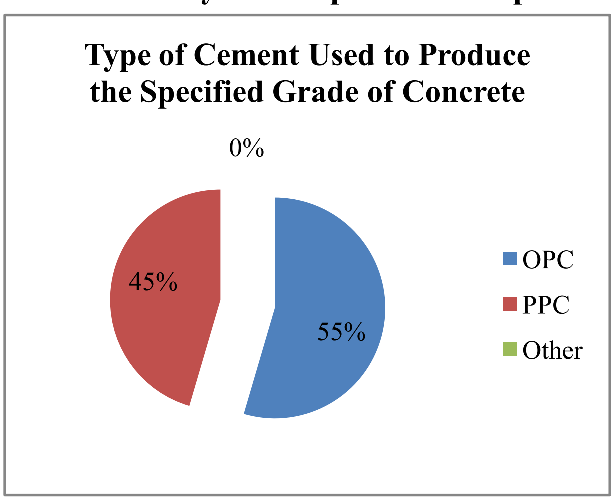


Figure 3.3: Type of cement used to produce the specified type of concrete

Analysis: The respondents agreed that OPC & PPC are mostly used types of cement approximately in equal proportion.

MS = 1.45, *(Score given: OPC= 1, PPC = 2, Other = 3)*

The effect of curing or the lack of it on the properties of concrete

Respondents mentioned the following as the effect of curing or the lack of it.

- Strength
- Durability
- Crack
- Hydration reaction
- Bond b/n concrete and reinforcement bar
- Color (the color of concrete can be changed from grey to white if there is deficiency)

Some of the respondents mentioned one of the above as the effect of curing and some of them mentioned two or more of the above effects. Mostly mentioned effects are strength &durability, Strength, Durability & Crack together

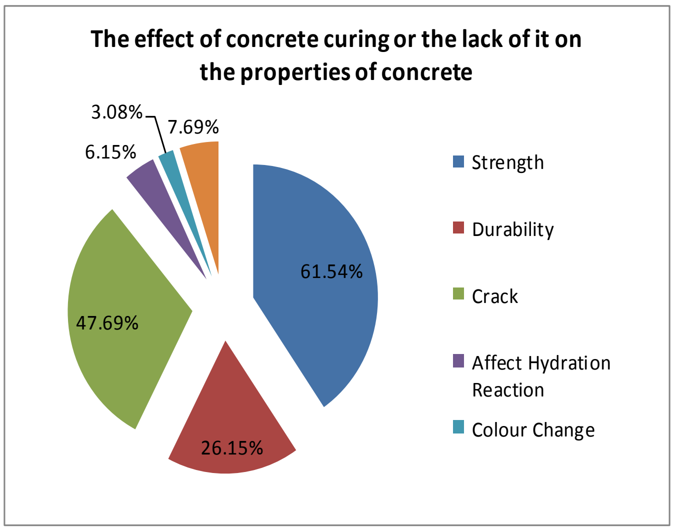


Figure 3.4: The effect of curing or the lack of it on the properties of concrete

Most of the respondents are aware of the effect of curing on strength and durability of concrete. They also said that the formation of crack on the surface of concrete can be due to lack of proper curing

The attention given to curing in the construction industry in Addis Ababa

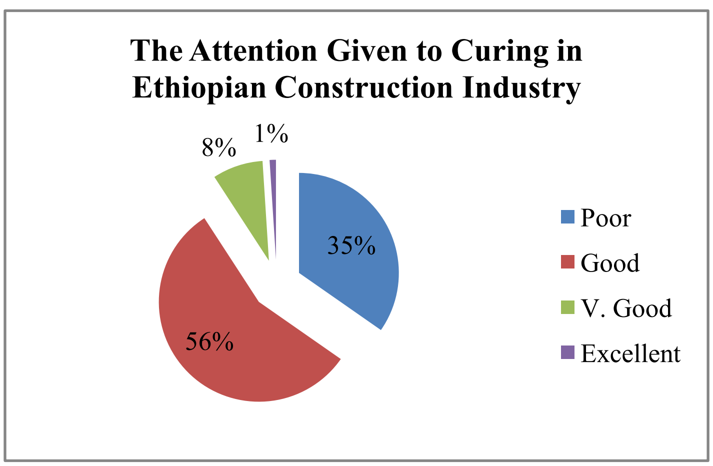


Figure 3.5: The attention given to curing in the construction industry in Addis Ababa

Analysis: The majority of respondents agreed that the attention given to curing in Addis Ababa is good.

MS = 1.76, *(Score given: Poor= 1,* ***Good = 2****, V. Good = 3, Excellent = 4).*

Mostly applied curing method for structural members in Addis Ababa

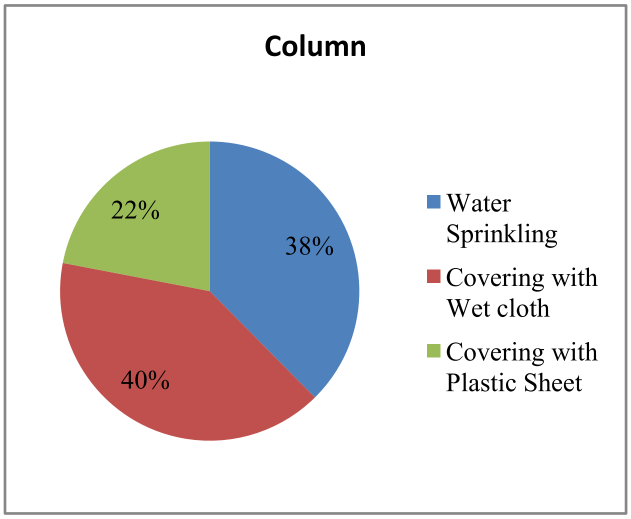


Figure 3.6.1: Mostly applied curing Method for structural members in Addis Ababa (Column)

Analysis: Covering with Wet Cloth is mostly practiced curing method for Column as it is agreed by the majority of respondents

MS = 1.84, *(Score given: Water Sprinkling = 1,* ***Covering with Wet Cloth = 2****, Covering with Plastic Sheet = 3)*

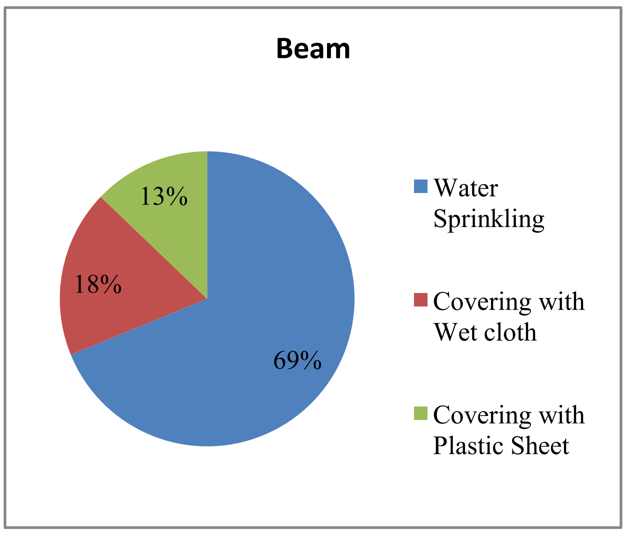


Figure 3.6.2: Mostly applied curing Method for structural members in Addis Ababa (Beam)

Analysis: Water Sprinkling is mostly practiced curing method for Beam as it is agreed by the majority of respondents

MS = 1.44, *(Score given:* ***Water Sprinkling = 1****, Covering with Wet Cloth = 2, Covering with Plastic Sheet = 3*

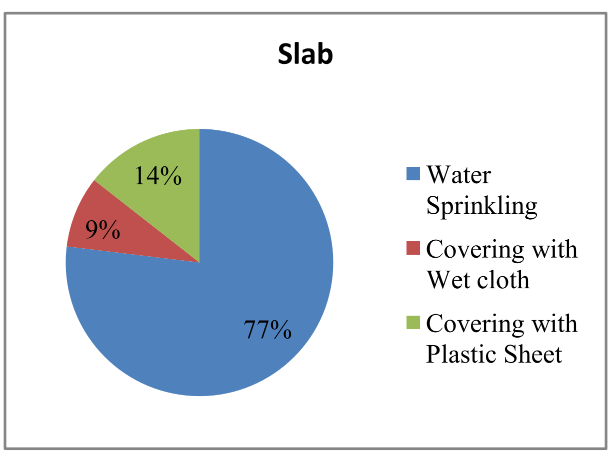


Figure 3.6.3: Mostly applied curing Method for structural members in Addis Ababa (Slab)

Analysis: The majority of respondents agreed that Water Sprinkling is mostly practiced curing method for Slab.

MS = 1.38, *(Score given:* ***Water Sprinkling = 1****, Covering with Wet Cloth = 2, Covering with Plastic Sheet = 3*

Most frequently practiced curing duration for each curing method

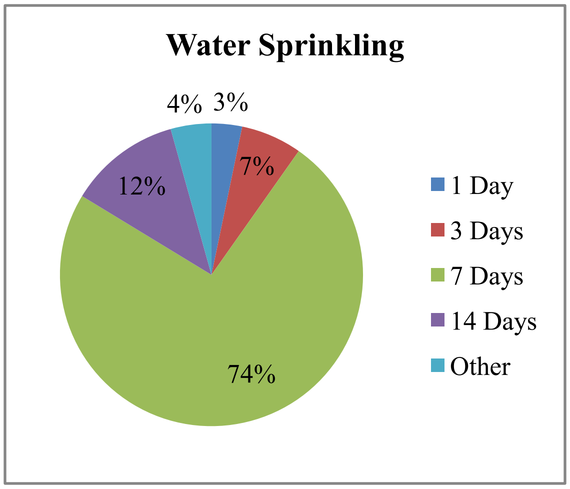


Figure 3.7.1: Most frequently practiced curing duration for each curing method (Water Sprinkling)

Analysis: Most frequently practiced curing duration for Water Sprinkling Method is 7 days as it is agreed by the majority of the respondents.

MS = 3.08, *(Score given: 1 Day = 1, 3 Days = 2,* ***7 Days = 3****, 14 days = 4, Other = 5)*

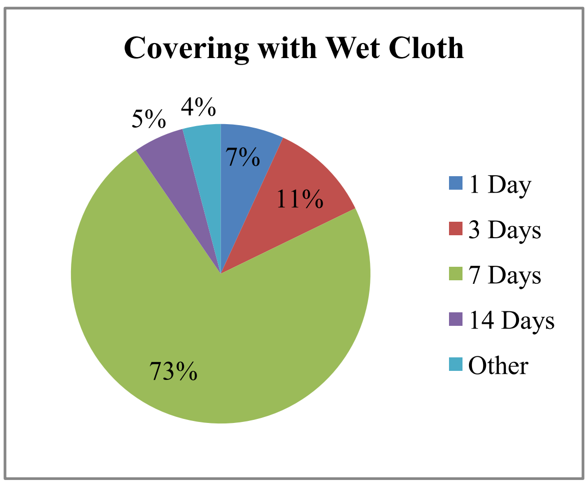


Figure 3.7.2: Most frequently practiced curing duration for each curing method (Covering with Wet Cloth)

Analysis: Majority of the Respondents agreed that 7 days is mostly practiced curing duration for covering with wet cloth method of curing.

MS = 2.89, (*Score given: 1 Day = 1, 3 Days = 2,* ***7 Days = 3****, 14 days = 4, Other = 5)*

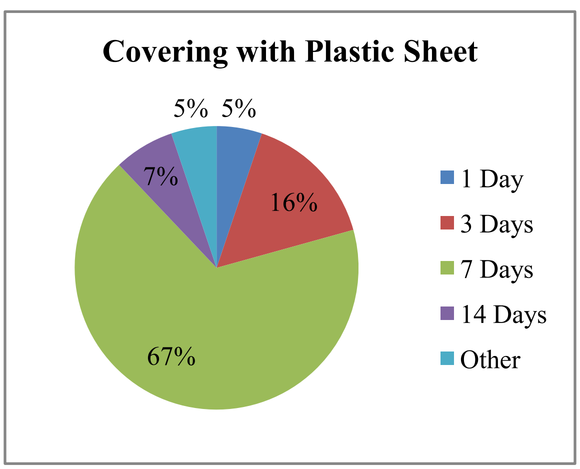


Figure 3.7.3: Most frequently practiced curing duration for each curing method (Covering with Plastic sheet)

Analysis: Seven days curing duration is most frequently practiced curing duration for curing method of covering with plastic sheet as it is agreed by majority of the respondents.

MS = 2.91, *(Score given: 1 Day = 1, 3 Days = 2,* ***7 Days = 3****, 14 days = 4, Other = 5)*

The frequency of watering period in water adding method of curing

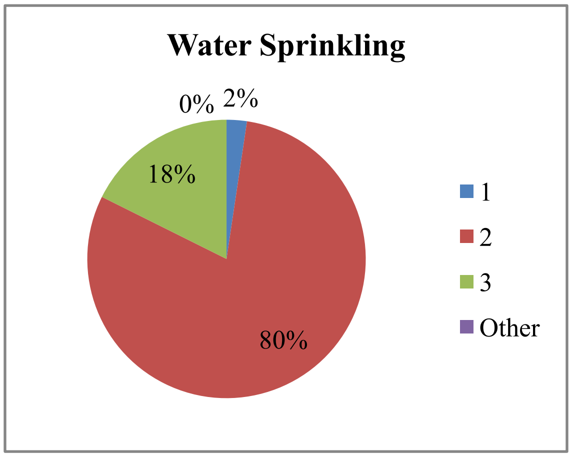


Figure 3.8.1: The frequency of watering per day in water adding method of curing (Water Sprinkling)

Analysis: The majority of respondents strongly agreed that 2 times a day is mostly practiced frequency of watering when the curing method is water sprinkling.

MS = 2.15, *(Score given: 1X = 1,* ***2X = 2****, 3X = 3, Other = 4)*

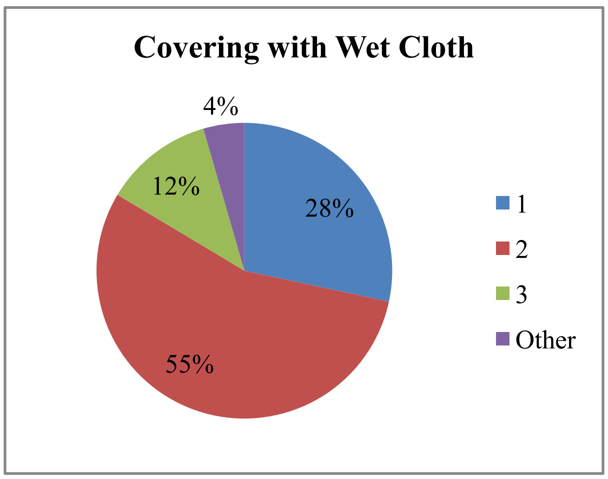


Figure 3.8.2: The frequency of watering per day in water adding method of curing (Covering with Wet cloth)

Analysis: The majority of the respondents agreed that 2 times a day is mostly practiced frequency of watering when covering with wet cloth is the method of curing.

MS = 1.93, *(Score given: 1X = 1,* ***2X = 2****, 3X = 3, Other = 4)*

Availability of criteria or requirement specified to select the curing method and curing duration for a specific project

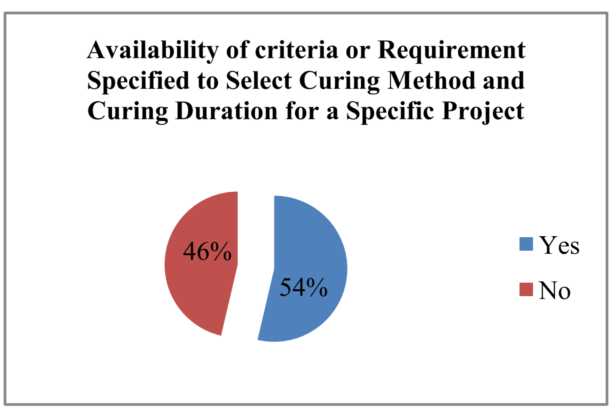


Figure 3.9: Availability of criteria or requirement specified to select curing method and duration for a specific project

Analysis: The majority of respondents agreed that there is a criterion to specify curing method for a specific project.

MS = 1.46, *(Score given: Yes = 1, No = 2)*

Majority of the respondents agreed on the availability of requirements for the selection of different curing methods for the specific project. But what they consider it as criteria is the one which is mentioned on EBCS regarding hot weather concreting, which recommends 10 days minimum curing duration in hot areas.

Variation in curing practice and duration related to weathering condition of the area

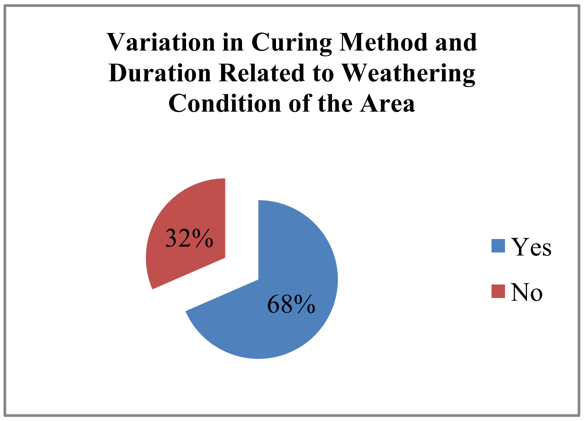


Figure 3.10: Variation in curing method and duration related to weathering condition of the area

Analysis: The majority of the respondents agreed that there is a variation in the curing method and duration related to weathering condition of the area.

MS = 1.32, *(Score given:* ***Yes = 1****, No = 2)*

Even if most of the professionals agreed on the variation in curing practice, but according to their comment this variation only considers climatic condition. This climatic condition is on Ethiopian summer (May – August). During this time they reduce the curing duration and the frequency of watering per day. In other case variation in curing method related to type of cement, grade of concrete and other climatic condition like, wind, relative humidity and temperature are not considered in specifying curing method and duration.

Starting day for application of curing

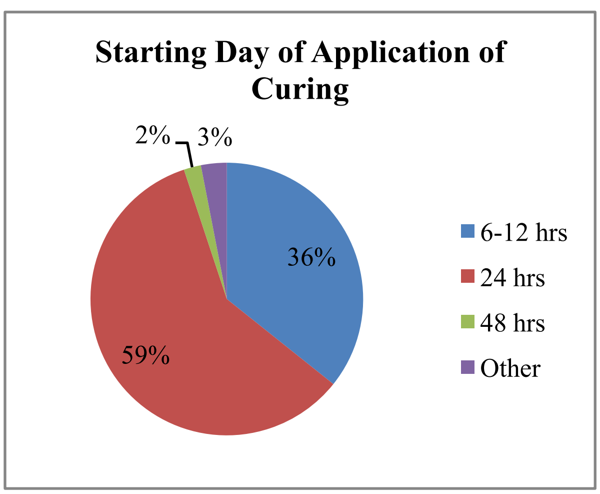


Figure 3.11: Starting day for application of curing

Analysis: Majority of the respondents said that most of the time the application of curing is started with in 24 hrs. Curing begins on the next day after casting of concrete.

MS = 1.72, *(Score given: 6-12hrs = 1,* ***24hrs = 2****, 48hrs = 3, Other = 4)*

Supervision during curing to check whether it is done properly or not

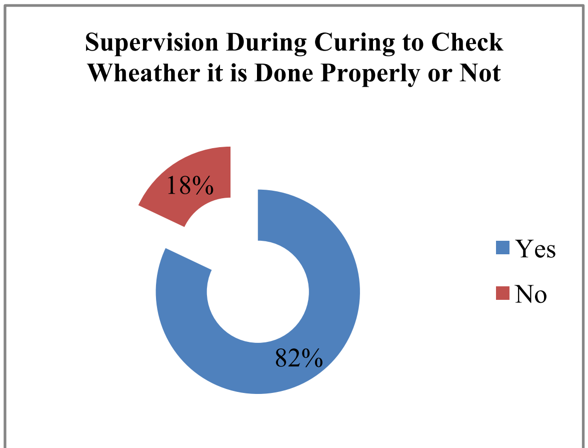


Figure 3.12: Supervision during curing to check whether it is done properly or not

Analysis: The majority of the respondents agreed that there is supervision during curing.

MS = 1.18, *(**Yes = 1**, No = 2)*

Here what they consider it as supervision is a supervision which is made by looking the surface of concrete, whether it is wet or not. But even if it is wet they didn"t check whether the curing is adequate or not.

The status of curing practice satisfying specification requirements for curing method

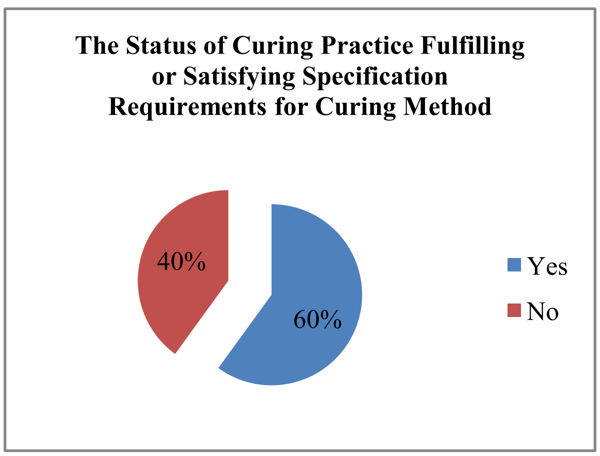


Figure 3.13: The status of curing practice fulfilling or satisfying specification requirements for curing method

Analysis: The majority of respondents believed as if the current curing practice satisfies curing requirements.

MS = 1.40, *(Score given: Yes = 1, No = 2)*

Most of the respondents said that our practice satisfies curing requirements and specifications, although their practice is water added curing with watering once a day for 7 days whether the cement used is OPC, PPC or any other type. This indicates that they are not familiar with different curing specifications. Based on their response most of them are familiar with EBCS, but as it was discussed earlier EBCS is not sufficient on curing specifications. It only specifies minimum curing duration for hot-weather concreting. There is no specification on the duration of curing related to different types of cement, ambient conditions, grade of concrete, etc.... But when we see ACI-308 it specifies minimum curing duration for different types of cement, specified strength, and ambient temperature condition.

Most of the practitioners are not familiar with curing specifications, like ACI 308,

Procedure followed to assure that concrete is cured sufficiently and effectiveness of curing practices in Addis Ababa regarding the capacity to attain the desired properties

It is surprising that there is no any procedure followed to assure concrete is cured sufficiently. The responsibility for curing the concrete is given to the daily laborer. The professional only checks whether the structure is cured or not by just looking the surface of the concrete. No one checks whether the curing is adequate or not. Most of the respondents agreed that they don"t believe and expect the current curing practice to be effective. They point out some of the reasons for the lack of effectiveness. These are negligence by the labors, scarcity of water, lack of supervision and even sometimes the curing part can be ignored if water is not available. They also said that most of the time the seasons helps. Relatively some of the seasons, June to September, are characterized by low temperature and high average relative humidity.

But when we see the climatic condition of Addis Ababa the average annual relative humidity is 60.7% and average monthly relative humidity ranges from 49 % in February to 82% in July (See the figure below, figure 3.14)

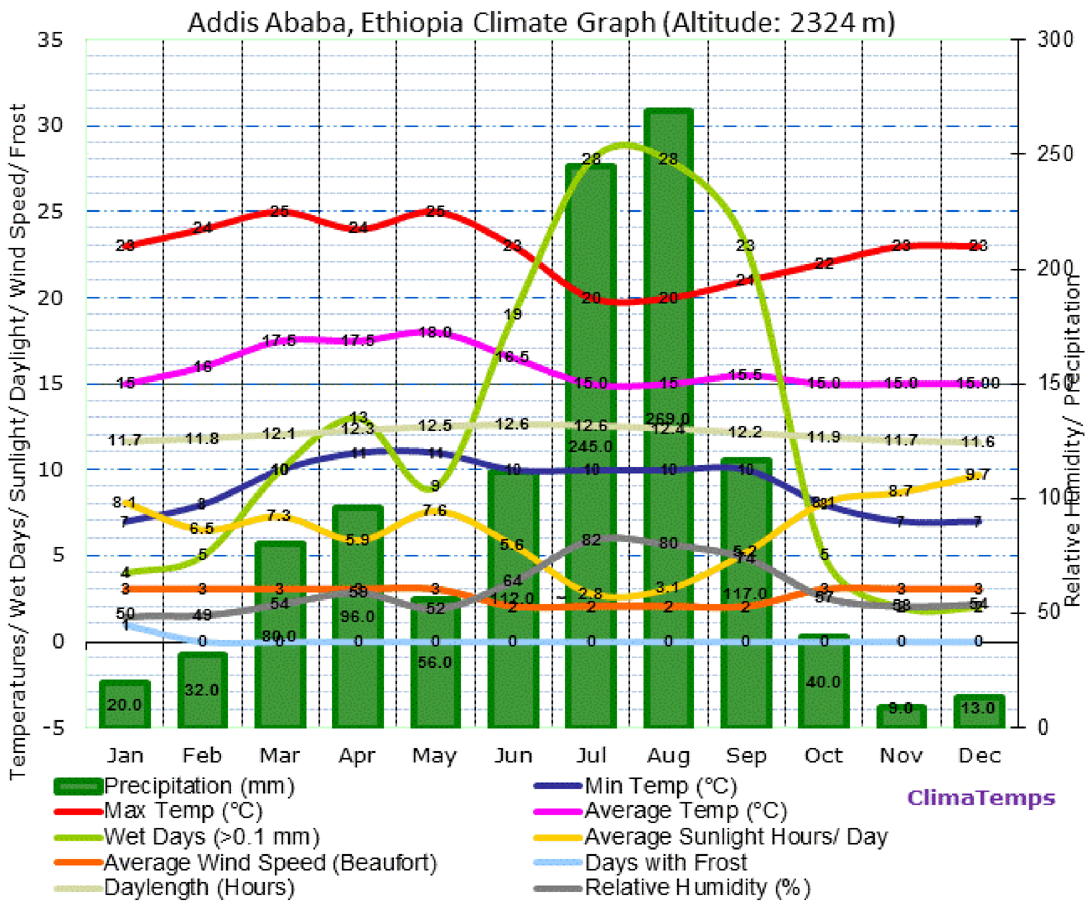


Figure 3.14: Addis Ababa climate graphs in metric unit ***(Source: http://www.addis-ababa.climatemps.com/graph.php)***

Representativeness of concrete samples sent to laboratory (for compressive strength test) and the concrete cured on the site from the point of view of method of curing?

From those who respond for this question, none of them agreed that the concrete samples sent to laboratory for compressive strength test are representative samples for the concrete in the site. Because those samples sent to laboratory for compressive strength test are cured under moist condition but the actual condition is different. The concrete on the site don't get sufficient amount of water. Sometimes the contractor ignores the curing part when there is scarcity of water on the site. They emphasized that once the concrete is casted no one gives attention whether the concrete is properly cured or not.

This part of the research had the objective of assessing the current curing practices and the awareness given to curing. To assess the status of our curing practice and the awareness given some questions were designed in the questionnaire. There are questions about the current curing practices, the respondents thinking about the attention given to curing and on the other hand they are also asked about the effect of curing on the properties of concrete. Most of them who said the attention given to curing is good on the other place responded that mostly practiced curing duration for water added curing is 7 days with once a day frequency of watering. And they also again responded on another question that the current curing practice they are using satisfies curing requirements, even if the starting time for application of curing measures is one day after the concrete is casted.

When we combine the overall responses of the questionnaire, there is awareness on the necessity of curing and the consequences of lack of it but there is a problem in the implementation.

CHAPTER FOUR -- ASSESSMENT OF THE EFFECTIVENESS OF DIFFERENT CURING PRACTICES IN ADDIS ABABA

4.1. EXPERIMENTAL PROGRAM

The experimental program was designed to evaluate the effectiveness of current curing practices and the influence of the prevalent curing practices on the compressive strength of mortar. The curing methods which were employed are described and designated as in Table 4.3. Mortar samples were prepared and cured in the actual environment during the winter time, which is December to February.

4.1.1. DEPENDENT AND INDEPENDENT VARIABLES

The first step done in the experimental study was identifying the control variables, variables which are unchanged throughout the experiment, dependent variables, independent variables and constants. For this research with the objective of assessing the effectiveness of curing, the following are considered as the independent variables, dependent variables and constants.

4.1.1.1. Independent variables: The presumed cause in an experimental study. All other variables that may impact the dependent variable are controlled. The values of the independent variable are under experimenter control.

The following are the independent variables:

1. Water cement ratio (w/c)
2. Method of curing
3. Curing duration

4.1.1.2. Dependent variables: The presumed effect in an experimental study. The values of the dependent variable depend upon another variable, the independent variable.

The variables mentioned below were the dependent variables

1. Cubic compressive strength
2. Water absorption

4.1.1.3. Constants: Those which are constant or unchanged throughout the research.

In the research the following were kept constant

1. Properties of constituent materials
2. Workability of mortar mix
3. Degree of compaction
4. Exposure condition

4.1.2. Materials

The following are the details for the materials used in this study.

Cement: Commercially available Portland Pozzolana Cement from Messebo was used.

Fine Aggregates: locally available natural sand was used in the overall study. The physical properties of the fine aggregates are given in Tables 4.1.

Table 4.1: Physical Properties of fine aggregate

Properties of Washed River Sand	
Absorption	5.3%
Moisture Content	2.2%
Specific Gravity	
Bulk Oven Dry	2.31
Bulk Saturated Surface Dry	2.44
Fineness Modulus	2.96

Admixture: Commercially available super-plasticizer

4.1.3. Mix Proportions

During the course of this study, three different mortar mixtures with a w/c of 0.3, 0.4, and 0.5 were prepared for compressive strength (cubic- strength) and absorption test. Details of the mix proportions for all the mixtures are tabulated in Tables 4.2. During mortar mixing the only variable was the w/c.

Table 4.2: Mix Proportion of Mortar

Mix No.	Water-Cement ratio	Cement/Fine Aggregate Ratio
1	0.3	1:2.5
2	0.4	1:2.5
3	0.5	1:2.5

4.1.4. Casting

All batches of mortar were cast inside the laboratory in a small capacity mixer. The mixing and casting is conformed to ASTM C192. Each batch was used to cast 66 standard size 50 mm cubes. The standard sized cubic specimens were cast in two layers with each layer vibrated on a vibrating table for 10 to 15 seconds. After the compaction operation, the top of the specimen was smooth finished by means of a trowel, and was then exposed to actual environmental condition except laboratory cured samples. The specimens were demolded after 24 hr, and then subjected to different curing condition. And from the total of 66 samples required per each mix only 33 samples were required for the test. Therefore, those with defect were rejected. But their rejection was after the test was conducted and their coefficient of variation is computed. Those samples which made the standard deviation bigger are taken out from the average.

4.1.5. Curing Methods

The following are the curing methods used in the experimental study.

Table 4.3.: Curing methods used and their designation

Designation	Curing method
WC3	Sprinkling twice a day without cover for 3 days
WC7	Sprinkling twice a day without cover for 7 days
WC14	Sprinkling twice a day without cover for 14 days
BC3	Sprinkling twice a day with burlap cloth cover for 3 days
BC7	Sprinkling twice a day with burlap cloth cover for 7 days
BC14	Sprinkling twice a day with burlap cloth cover for 14 days
SC3	Sealed Curing for 3 days
SC7	Sealed Curing for 7 days
SC14	Sealed Curing for 14 days
STD	Curing by Ponding in the lab. Which is considered standard curing

4.1.6. Type of test used for assessment of curing effectiveness

In this research compressive strength test on mortar cubes of size 50 mm were used to assess the effectiveness of curing. The suitability of the test method for assessing curing effectiveness is studied using theoretical justification and experimental study, which is by comparing results of compressive strength test and water absorption on same samples subjected to the same curing method.

4.1.6.1. Justification for the use of strength test on mortar cube samples

It is discussed that curing is the most significant process for the hydration of cement. The strength of concrete is highly dependent on the strength of the paste phase. And the paste develops its strength through hydration reaction.

Compressive strength is a bulk property, but curing affects the top 20-30mm depth from the surface of concrete which is curing affected zone (CAZ). The depth of standard concrete moulds is 100 or 150 mm (cubic) and 250 or 300 mm (cylindrical). Compared to the total depth of the mould the CAZ is small, so that the compressive strength of concrete may not be a good indicator for curing effectiveness. Although this is the case some researchers used compressive strength as one method of assessing curing effectiveness in arid areas. This is seen in the research done in Saudi Arabia. This paper presents the efficiency of two curing methods commonly employed in Riyadh as a case study for evaluation of curing efficiency under severe hot and dry weather conditions. The efficiency of curing methods was measured in terms of concrete compressive strength at 28 days. (Arafah, A. M., et al.)

Regarding the use of compressive strength for evaluating the effectiveness of curing, Mather B., (1987) stated that, "if the effect of curing influences the strength development only to a depth of 25 mm below the surface of the concrete, one should perhaps use strength specimens having a maximum dimension of 50mm." Mortar moulds have a depth of 50 mm which means related to CAZ about 50% and more of its depth is affected by curing. In addition to the depth of the specimen, the percentage composition of cement in mortar is greater than which is found in normal grade concrete and since curing affects hydration of cement one can observe the significance of curing in mortar specimen than that of concrete.

4.1.6.2. Experimental study

To assess the effectiveness of curing methods water absorption and compressive strength tests on mortar samples were used. The absorption test was used to assess the effect of curing on capillary porosity. Then compressive strength test was conducted on mortar samples. Finally, the results of water absorption and compressive strength test were compared to check whether the result tells us the same thing about the cuing method regarding its effectiveness.

4.1.7. Method of Analysis

The effect of the different curing methods is compared with that of standard laboratory curing, which is moist curing entire time. Here it is comparing the properties developed through different curing practices to that of standard laboratory cured samples.

ASTM Standards on Concrete Curing Methods, which was published on ACI journal in 1945 stated that "the concrete shall be cured that the compressive strength of the specimens of the concrete 28 days old, are not less than 90% of the strength of 28 days old specimen of the same concrete cured in moist air at a constant temperature of 21 C^0. ACI 318 under the commentary part also stated that for the field curing to be adequate, the compressive strength of cylindrical specimens of the concrete 28 days old should be at least 85% of the same concrete cured in moist condition entire time.

When we say effectiveness of cuing we are talking about the capacity of the curing method to create suitable condition, which is adequate moisture and favorable temperature, for hydration reaction. And when we say hydration reaction it is the chemical combination of cement and water. The physical and durability properties of concrete have a direct relationship with the complex internal micro-structural building blocks of concrete. We can get good quality concrete having the desired properties, if the cement has fully hydrated and developed its cohesive and adhesive property.

Previously it was discussed that curing affects the top 25 to 30 mm depth from the surface. If we use 150 mm concrete cube the curing only affects about 20% of the total depth; if we use 300 mm deep cylindrical sample the effect is within 8% of the total depth. Hence, compressive strength of concrete specimen with larger depth may not be a good indicator for evaluating adequacy of curing. But in case of mortar specimens the effect will increase up to 50% and more. Therefore, the effect of curing is more significant on mortar specimens having a depth of 50 mm than concrete samples. For this research, the 28 days compressive strength of mortar samples cured under different curing practices was used to evaluate the effectiveness of curing.

Therefore, the method of analysis used to assess the effectiveness of curing is by determining the ratio of compressive strength of mortar specimen cured under field condition to that of standard laboratory cured samples.

It is the researcher opinion that the two terms „adequacy‟ and „effectiveness‟ of curing has to be seen separately. Adequacy of curing is all about efficiency of curing for the development of the desired properties. Assessing the adequacy of curing for the development of the desired properties of concrete by conducting tests on mortar specimens may not be good enough unless there is a developed correlation between compressive strength and absorption capacity of mortar and concrete specimens. But researches should that there is a clear relationship between compressive strength of mortar and concrete (see section 2.11). Because the adequacy of curing is a function of exposure condition, mixture proportion and properties under question. A given curing method can be adequate for the desired compressive strength but it may not be adequate if durability is desired. But when we say curing effectiveness it is the ability of the curing method in creating suitable condition for the paste phase to have "complete‟ hydration so that the pore size and pore distribution will be minimum. In this research the compressive strength of standard laboratory cured samples are assumed to be the full potential of the mixture. Therefore, if the field curing doesn‟t allow the development of at least 70% compressive strength of the standard laboratory cured samples at time of termination or 85% at 28th day, the curing is considered to be ineffective. Effectiveness of curing is related with ability of curing to create suitable condition in order to have "complete" hydration of the paste phase.

About the criteria for evaluating the effectiveness of curing measures, ACI 308R-01 recommends a minimum curing duration by considering attainment of 70% of the specified compressive strength of concrete during termination of curing. Based on this value ACI recommends 7 day as minimum curing duration. But certain type of cement, chemical admixtures and high temperature can reduce the curing duration to be below 7 days. In case of cold temperature, other cement combination of materials such as pozzolanic materials or both can increase the curing duration.

For the test results found from experimental study standard deviation and coefficient of variation was calculated.

Formula used to determine standard deviation and coefficient of variation:

$$\sigma = \sqrt{\frac{\sum_1^n (X-\mu)^2}{n-1}} \quad \text{[Eq. 4.1]}$$

$$CV = \frac{\sigma}{\mu} \quad \text{[Eq. 4.2]}$$

Where: CV = Coefficient of Variance

σ =Standard deviation

μ = Mean (Average)
n= Total number of data

Coefficient of variation (CV) is the ratio of standard deviation and mean. The coefficient of variation (CV) measures the precision. The higher the precision (the lower the %), the higher the likelihood that there was no difference in the way each individual test was performed.

ASTM C 39 and C 670 have set an acceptable range of the coefficient of variation.

Table 4.4: Acceptable range of coefficient of variation (Source ASTM C39/39M)

	Coefficient of Variation (CV)	Acceptable range of	
		2 results	3 results
Single operator			
Laboratory conditions	2.37%	6.6%	7.8%
Field Conditions	2.87%	8.0%	9.5%

4.2. RESULTS, ANALYSIS AND DISCUSSION

4.2.1. Correlation between results of absorption test and compressive strength of mortar specimen

The first part of the experimental study was to study the effect of curing on absorption capacity and compressive strength of mortar specimens. Absorption test was used to evaluate the effectiveness of a curing method related to the effect of curing on capillary porosity of the test samples that affect absorption and to correlate with compressive strength test results.

The results and analysis of absorption and compressive strength tests are shown in Table 4.4 below.

For all curing methods and duration, w/c has a significant role on the development of the desired properties of concrete. In case of standard laboratory curing, the lower the water-cement ratio the lower water absorption was observed. Water absorption is an indicator of the extent and distribution of porosity. For those laboratory cured samples, mortar specimens having w/c of 0.3 has the lower water absorption capacity compared with specimens with w/c of 0.4 and 0.5. But when we see samples cured in the field, the ratio of water absorption of field cured samples to moist cured samples is higher for low w/c mixtures. This can be due to lack of adequate supply of water for the samples with low w/c. The initial water added during mixing may not be sufficient for "complete" hydration; researches also showed that theoretically w/c of 0.42 is needed for "complete" hydration (Siddique, S., et al., 2013). But when there is external supply of water for extended duration the water absorption shows a reduction for all w/c.

Concrete properties, physical and mechanical, are governed by growing micro scale pores, which are developed through hydration reaction. The hydration reaction is influenced by the available moisture inside the concrete. In general, for most of the concretes encountered in practice, it is the quality of the hardened cement-paste matrix that determines the permeability of the concrete.

The mortar samples which were subjected to water added curing showed an increase in compressive strength compared to air-dried samples.

The results showed that for w/c of 0.3 the ratio of absorption capacity of air dried mortar specimen to standard laboratory cured samples is significantly high. And this ratio becomes reduced as the water cement ratio is increased to 0.4 and 0.5. In case of compressive strength of mortar samples, as the water-cement ratio is increased the ratio of compressive strength of air dried samples to that of standard laboratory cured samples showed an increment. The results are as it would been expected. As the water cement ratio is low it affects the micro structure development of cement paste due to lack of adequate moisture. And the microstructure development affects the porosity and other physical properties of concrete or mortar.

As the w/c is low and insufficient for "complete" hydration, there will be empty pores which are not filled by hydration product these causes a reduction in compressive strength and an increase in water absorption capacity.

On other curing method which is sprinkling water for 3, 7 and 14 days, an increase in the compressive strength and a reduction in water absorption was observed when there is extended curing duration. But the variation in compressive strength as well as water absorption was not as such significant compared to air dried sample. The increase in curing duration from 3 days to 7 days and from 7 days to 14 days didn"t show a significant decrease in absorption as well as an increment in compressive strength. For example, in case of air-dried sample with w/c of 0.3 its compressive strength was 19.25MPa which is 54% of laboratory cured sample and its water absorption is 135% of laboratory cured sample. But in case of moist curing 26.71MPa (76%) (3days curing), 27.09MPa (77%) (7days curing) and 27.39MPa (77%) (14 days curing) was recorded. The water absorption of these mortar samples was 125% (3days), 123% (7days) and 121% (14days).

From the two test results of air-dried sample, which is the compressive strength and water absorption, we can observe that curing is the most significant process in concrete production. Additionally results also showed that the difference in absorption as well as compressive strength of mortar cubes is small as the curing duration increases from 3 to 7 and from 7 to 14 days. The reason for this case can be the time at which the samples were cured. The time was during Ethiopian summer, July and August (see the note below), which are characterized by high relative humidity and low temperature. Therefore, the significance of extended curing may not show significant difference in the property of concrete or mortar.

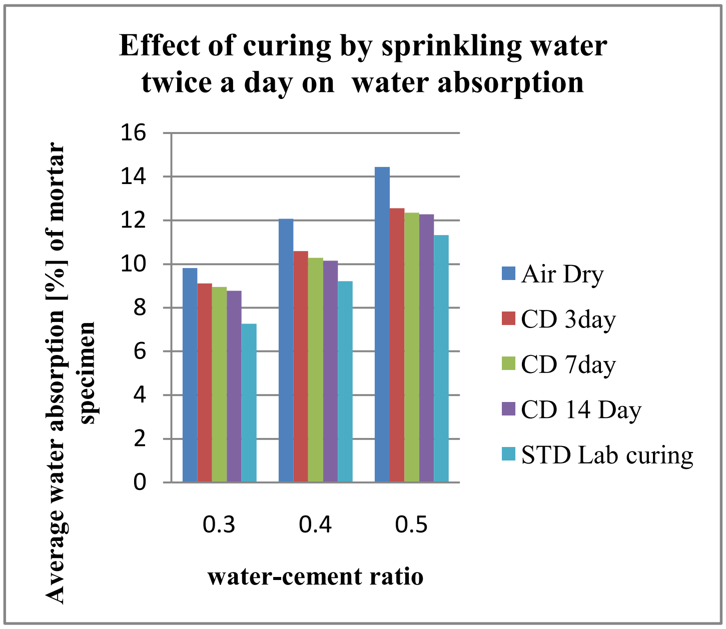
Note: The experimental study was conducted in two phases, first phase to correlate results of water absorption and compressive strength test results, which was done from July to August. And the second phase was to study the effectiveness of current curing practices using compressive strength test on mortar specimen, which was done from December to February.

Table 4.5: Results of Water Absorption & Compressive strength tests; to justify use of compressive strength of rich mortar as a measure of curing effectiveness

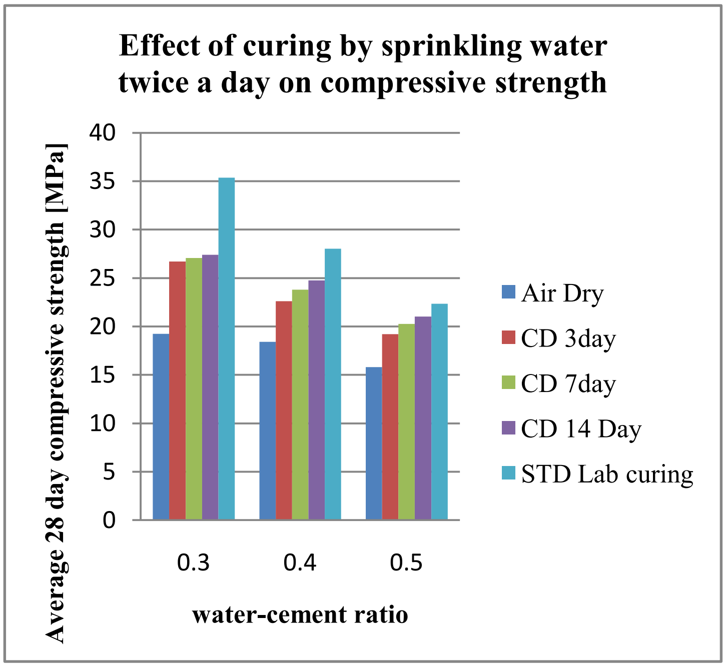
Curing Method	W/C	Curing Duration	Avg. % water absorption	Coefficient of Variation	Avg.*	Coefficient of Variation	Ratio of % Absorption [Col. 4] per moist cured samples	Ratio of 28th day Compressive Strength [Col.7/Strength of standard lab cured samples]
WC	0.3	3 days	9.11	1.40	26.71	2.90	1.25	0.76
		7 days	8.95	2.85	27.09	1.10	1.23	0.77
		14 days	8.78	1.08	27.39	2.12	1.21	0.77
	0.4	3 days	10.60	1.75	22.62	1.35	1.15	0.81
		7 days	10.28	2.34	23.81	3.62	1.12	0.85
		14 days	10.16	4.32	24.76	5.02	1.10	0.88
	0.5	3 days	12.55	3.31	19.20	2.92	1.11	0.86
		7 days	12.35	0.56	20.25	2.30	1.09	0.91
		14 days	12.28	3.08	21.04	5.35	1.09	0.94
Air Dry	0.3	28 days	9.81	6.76	19.25	6.24	1.35	0.54
	0.4	28 days	12.08	9.83	18.42	3.62	1.31	0.66
	0.5	28 days	14.45	1.10	15.80	2.86	1.28	0.71
Lab	0.3	28 days	7.27	4.10	35.37	1.34	1.00	1.00
	0.4	28 days	9.21	9.19	28.02	1.10	1.00	1.00
	0.5	28 days	11.32	3.14	22.35	1.56	1.00	1.00

*= Average 28 days compressive strength of mortar samples

Absorption Vs Compressive Strength



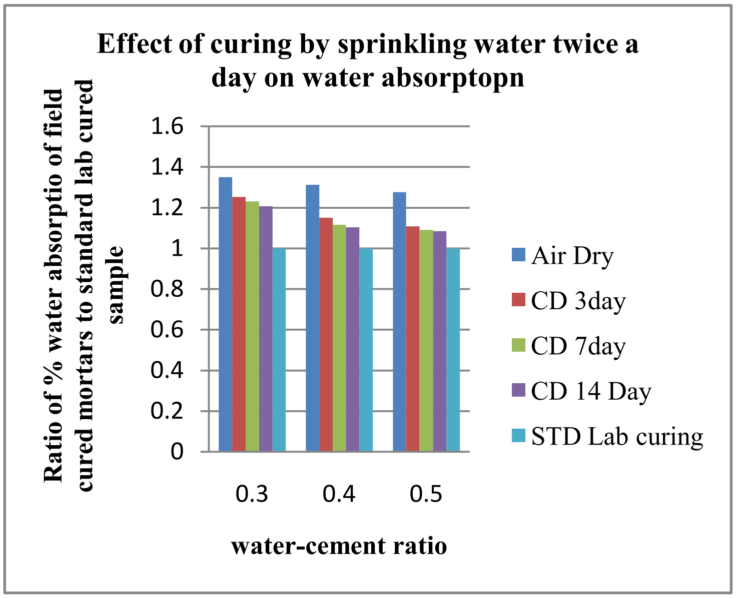
Sprinkling Water Curing Method , **Average % Absorption**, w/c = 0.3, 0.4 & 0.5					
Air Dry	CD 3days	CD 7days	CD 14 Days	STD Lab curing	W/C
9.81	9.11	8.95	8.78	7.27	0.3
12.08	10.6	10.28	10.16	9.21	0.4
14.45	12.55	12.35	12.28	11.32	0.5



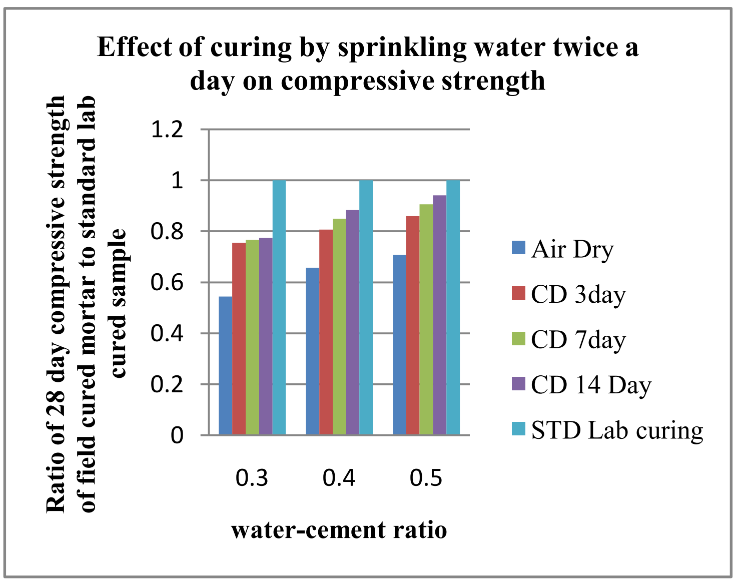
Sprinkling Water Curing Method, **Average 28th day Compressive Strength**, w/c = 0.3, 0.4 & 0.5					
Air Dry	CD 3days	CD 7days	CD 14 Days	STD Lab curing	W/C
19.25	26.71	27.09	27.39	35.37	0.3
18.42	22.62	23.81	24.76	28.02	0.4
15.8	19.2	20.25	21.04	22.35	0.5

Note: Standard Lab Curing and air-dry has a curing duration of 28 days

Figure 4.1: Average water absorption of mortar samples (TOP) and Average compressive strength (BOTTOM) for curing by sprinkling water twice a day with different curing duration



Sprinkling Water Curing Method, **Ratio of % Absorption**, w/c = 0.3, 0.4 & 0.5					
Air Dry	CD 3days	CD 7days	CD 14 Days	STD Lab curing	W/C
1.35	1.25	1.23	1.21	1.00	0.3
1.31	1.15	1.12	1.10	1.00	0.4
1.28	1.11	1.09	1.08	1.00	0.5



Sprinkling Water Curing, **Ratio of Average 28th day Compressive Strength**, w/c = 0.3, 0.4 & 0.5					
Air Dry	CD 3days	CD 7days	CD 14 Days	STD Lab curing	W/C
0.54	0.76	0.77	0.77	1.00	0.3
0.66	0.81	0.85	0.88	1.00	0.4
0.71	0.86	0.91	0.94	1.00	0.5

Figure 4.2: Ratios of water absorption of mortar samples (TOP) and Ratio of compressive strength (BOTTOM) for curing by sprinkling water twice a day with different curing duration

Therefore, from the observed results we can use compressive strength of mortar specimen as a measure of curing effectiveness. But further studies have to be made to compare with other standard methods for measuring curing effectiveness, like depth of carbonation, water absorption, permeability, abrasion resistance, etc…. In this research, rich mortar mixtures with 1to 2.5 ratio was used for assessing the effectiveness of curing.

Here let me repeat what was stated previously about justification on the use of compressive strength of mortar samples for assessing the effectiveness of curing.

Mather, B. (1987) said that, "if the effect of curing influences the strength development only to a depth of 25 mm below the surface of the concrete, one should perhaps use strength specimens having a maximum dimension of 50mm."

4.2.2. Mortar compressive strength test results

This experimental test was conducted to assess the effectiveness of curing by conducting compressive strength test on Portland cement mortar.

For this research three different field curing method in addition to standard laboratory curing and air-dry were used. The compressive strength at 28th day was conducted on mortar samples with w/c of 0.3, 0.4 and 0.5 and the ratio of field cured samples to standard laboratory cured samples were then determined.

During testing of mortar cubes, cement-powders were found from the broken mortar samples with w/c of 0.3 and 0.4 which were subjected to air-dry and sealed curing. This showed that the initial water added at the time of mixing was not adequate for "complete" hydration; therefore, additional supply of water is needed. This observation is also observed on samples with w/c of 0.3 and 0.4 and cured by sprinkling water for only 3 days.

From the experimental study, reduction in ratio of 28th day compressive strength of field cured to laboratory cured samples was observed as the water-cement ratio is reduced. Mortar samples having w/c of 0.3 shows the lowest ratio of compressive strength when compared to w/c of 0.4 and 0.5. As water-cement ratio increased from 0.3 to 0.4 and from 0.4 to 0.5 the ratio of compressive strength of mortar specimen subjected to field curing to standard laboratory cured specimens showed an improvement. As the w/c is reduced, the ratio of 28th day compressive strength of field cured to laboratory cured samples was found significantly reduced. For low w/c the curing methods used are not effective. But when w/c increases, the ratio of compressive strength of field cured to laboratory cured samples is relatively higher. Since the initial w/c is high, the mortar may not need as such high supply of water. The water added during mixing can be sufficient if it is protected from evaporation except the bleed water. This indicates that the necessity for curing has an inverse relation with water-cement ratio. The necessity for water added curing becomes reduced as the water-cement ratio is higher than required for complete hydration.

For all curing methods, as the curing duration is increased from 3 to 7 days and from 7 to 14 days there is an increase in the ratio of 28th day compressive strength of field cured to standard laboratory cured samples.

Samples cured for only 3 days have compressive strength closer to air-dried samples than standard laboratory cured samples. This is worse specially for sealed curing.

Water added curing by covering with wet cloth enhances the compressive strength of mortar specimens. The ratio of 28^{th} day compressive strength of mortar samples cured by covering with burlap to that of standard laboratory cured samples was found relatively higher, even very high as the curing duration is extended up to 14 days.

Compared to other curing methods sealed curing was found inadequate, which showed the lowest ratio of compressive strength next to air-dried samples. The inadequacy of sealed curing becomes even worse when the w/c is 0.3. The ratio of 28 day compressive strength of sealed samples to laboratory cured samples is low. As the water-cement ratio is increased this ratio showed an improvement, but it is still inadequate. The ratio of compressive strength of sealed samples to standard laboratory cured samples is very low as it can be seen from the results table shown below.

As we can see the results on table 4.6 to 4.8; the ratio of 28^{th} day compressive strength of mortar samples with w/c of 0.5 and subjected to WC curing method for 3, 7 and 14 days to that of continuously moist cured samples was 0.7, 0.77 and 0.85. In case of BC this ratios are 0.73, 0.83 and 0.93. About SC and air-dried samples they attained ratio of 0.56 (3 days), 0.67 (7days), 0.71 (14days) and 0.51 respectively. As we can see from the table below, except water added curing for 14 days the ratio is significantly low. In all cases covering with wet cloth achieved a higher ratio of compressive strength compared to other curing methods and sealed curing was the lowest. Even the compressive strength of samples sealed for 3 and 7 days is closer to air-dried samples.

Ratio of 28^{th} day compressive strength of field cured to laboratory cured samples is lower in case of w/c ratio of 0.4 than w/c ratio of 0.5. For WC method of curing (3, 7 and 14 days) ratios of compressive strength are 0.68, 0.75 and 0.79 respectively and similarly BC attained a ratio of 0.69, 0.74 and 0.8. In case of SC and AD method of curing the ratios of compressive strength to that of continuously moist cured sample is 0.54 (3days), 0.56 (7days), 0.57 (14days) and 0.47 respectively. As the water-cement ratio is increased the necessity of curing will become reduced.

Results showed that ratio of 28^{th} day compressive strength of field cured to standard laboratory cured samples was significantly low when the w/c is 0.3 and increases as the w/c increases to 0.4 and 0.5.

As the w/c ratio equals to 0.3, WC method of curing attained a ratio of 0.55 (3days curing), 0.60 (7days curing) and 0.64 (14 days curing). And that of BC attained ratio of 0.60, 0.63 and 0.66 with a curing duration of 3, 7 and 14 days respectively. In case of SC and AD the ratios significantly reduced to 0.48 (covered for 3days), 0.5 (7days), 0.52 (14 days) and 0.3 (air-dried) respectively.

As we can see from the results on table 4.7 and 4.8, the compressive strength of mortar specimen having w/c of 0.3 and moist cured (entire time) is less than a mortar with w/c of 0.4 which is not as expected. The reason for the reduction in compressive strength can be due to dosage of super-plasticizer used in order to have the same workability with a mortar mixture having w/c of 0.5. In case of mortar mixtures having w/c of 0.3 and mixed with admixture it took one additional day to demold the samples than mixtures with w/c of 0.4 and 0.5. This needs further study to assess the effect of dosage of admixture on the compressive strength of concrete.

- *>=45% Strength loss relative to standard laboratory cured samples*
- *30-45% Strength loss relative to standard laboratory cured samples*
- *15-30% Strength loss relative to standard laboratory cured samples*
- *<=15% Strength loss relative to standard laboratory cured samples*

Table 4.6: Results of compressive strength test of mortar specimen with W/C of 0.5

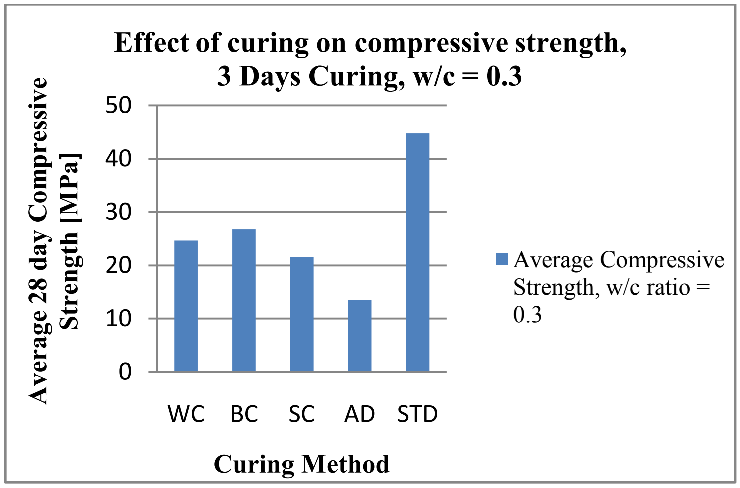
water-cement ratio = 0.5						
No.	Curing Practice	Curing Duration [Day]	Average 28th Compressive Strength [MPa]	Ratio of Comp. Strength of field cured mortars to Lab. Cured samples	Standard Deviation	Coefficient of Variation
1	Sprinkling Water Twice a Day	3	22.77	**0.70**	0.49	2.17
2		7	24.71	**0.77**	0.97	3.92
3		14	27.41	**0.85**	1.64	5.86
1	Covering with Burlap Cloth + Sprinkling Water Twice a Day	3	23.53	**0.73**	1.35	5.74
2		7	26.69	**0.83**	1.18	4.43
3		14	29.90	**0.93**	1.60	5.27
1	Covering with Plastic Sheet	3	18.10	**0.56**	0.53	2.91
2		7	21.58	**0.67**	0.39	1.81
3		14	22.82	**0.71**	0.99	4.32
1	Air Dry	28	16.34	**0.51**	0.99	6.03
1	Standard Laboratory Curing	28	32.30	**1.00**	1.62	5.03

Table 4.7: Results of compressive strength test of mortar specimen with W/C of 0.4

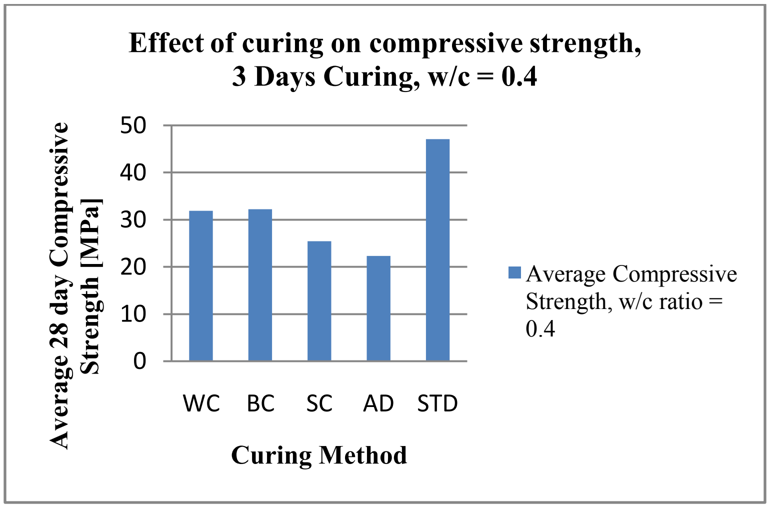
water-cement ratio = 0.4						
No.	Curing Practice	Curing Duration [Day]	Average 28th Compressive Strength [MPa]	Ratio of Comp. Strength of field cured mortars to Lab. Cured samples	Standard Deviation	Coefficient of Variation
1	Sprinkling Water Twice a Day	3	31.89	**0.68**	0.88	2.76
2		7	35.11	**0.75**	0.85	2.43
3		14	37.20	**0.79**	1.29	3.46
1	Covering with Burlap Cloth + Sprinkling Water Twice a Day	3	32.25	**0.69**	0.36	1.11
2		7	35.07	**0.74**	0.93	2.66
3		14	37.88	**0.80**	3.67	9.69
1	Covering with Plastic Sheet	3	25.43	**0.54**	1.85	7.28
2		7	26.55	**0.56**	1.59	5.91
3		14	26.88	**0.57**	0.22	0.83
1	Air Dry	28	22.34	**0.47**	0.37	1.64
1	Standard Laboratory Curing	28	47.08	1.00	0.35	0.74

Table 4.8: Results of compressive strength test of mortar specimen with W/C ratio of 0.3

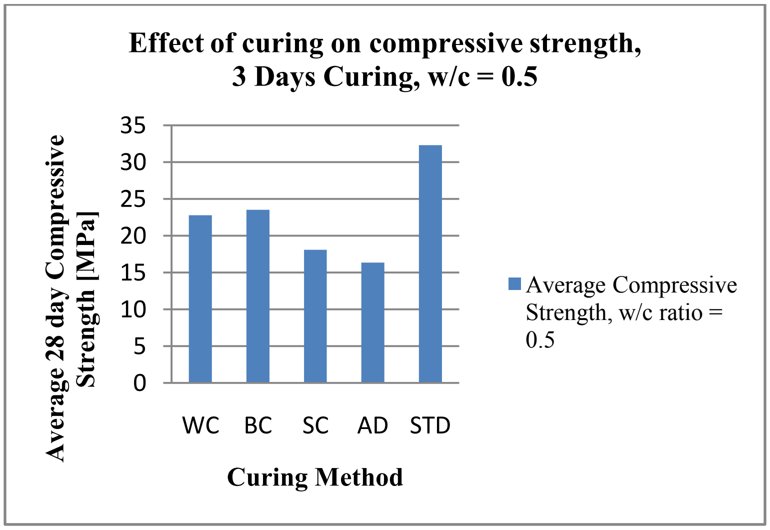
water-cement ratio = 0.3						
No.	Curing Practice	Curing Duration [Day]	Average 28th Compressive Strength [MPa]	Ratio of Comp. Strength of field cured mortars to Lab. Cured samples	Standard Deviation	Coefficient of Variation
1	Sprinkling Water Twice a Day	3	24.69	**0.55**	0.58	2.36
2		7	26.74	**0.60**	0.42	1.58
3		14	28.64	**0.64**	1.31	4.58
1	Covering with Burlap Cloth + Sprinkling Water Twice a Day	3	26.78	**0.60**	0.79	2.94
2		7	28.10	**0.63**	2.61	9.29
3		14	29.40	**0.66**	0.93	3.17
1	Covering with Plastic Sheet	3	21.57	**0.48**	0.74	3.42
2		7	22.31	**0.50**	0.59	2.64
3		14	23.35	**0.52**	0.90	3.85
1	Air Dry	28	13.52	**0.30**	0.87	6.46
1	Standard Laboratory Curing	28	44.76	1.00	0.43	0.97



Average Compressive Strength, w/c = 0.3	
Average Compressive Strength	Curing Method+3 days duration
24.69	WC
26.78	BC
21.57	SC
13.51	AD (28 days)
44.76	STD (28 days)

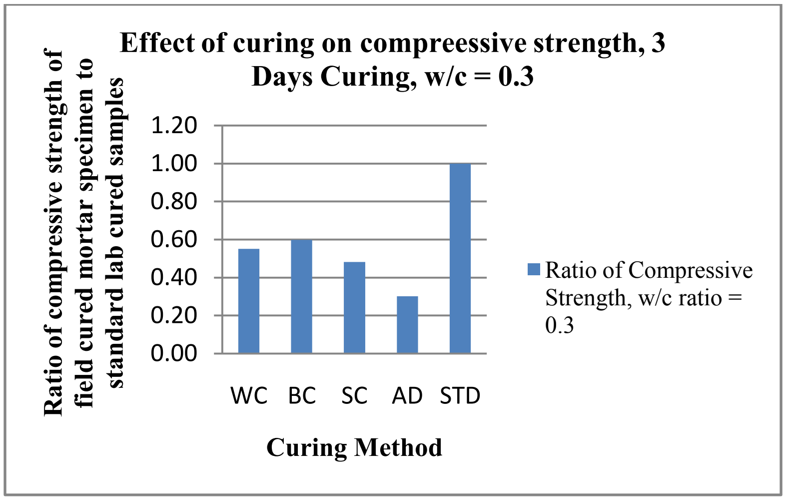


Average Compressive Strength, w/c = 0.4	
Average Compressive Strength	Curing Method+3 days duration
31.89	WC
32.25	BC
25.42	SC
22.34	AD (28 days)
47.08	STD (28 days)

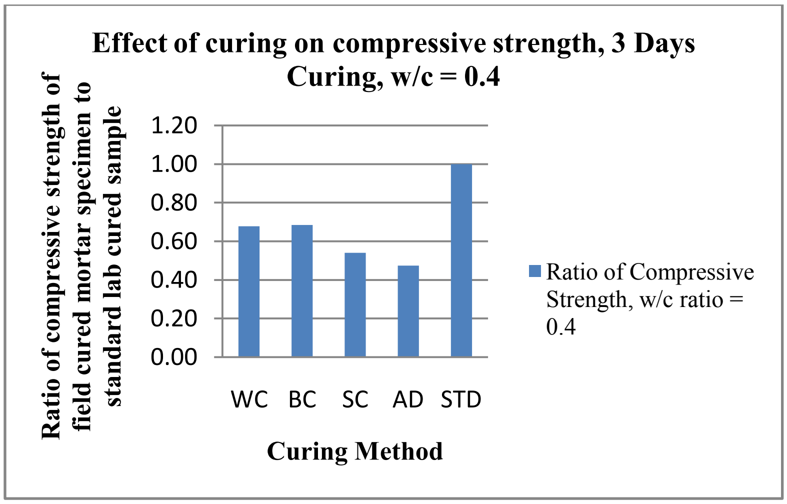


Average Compressive Strength, w/c = 0.5	
Average Compressive Strength	Curing Method+3 days duration
22.77	WC
23.53	BC
18.1	SC
16.34	AD (28 days)
32.3	STD (28 days)

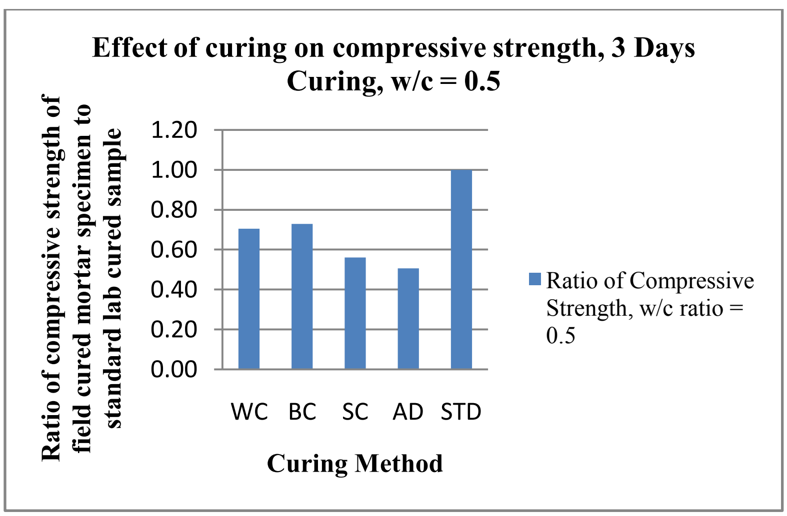
Figure 4.3: *Average 28th day compressive strength [MPa] of portland cement mortar, w/c of 0.3, 0.4 & 0.5 subjected to different curing methods with curing duration of 3 days*



Ratio of Compressive Strength, w/c = 0.3	
Ratio	Curing Method+3 days duration
0.55	WC
0.60	BC
0.48	SC
0.30	AD (28 days)
1.00	STD (28 days)

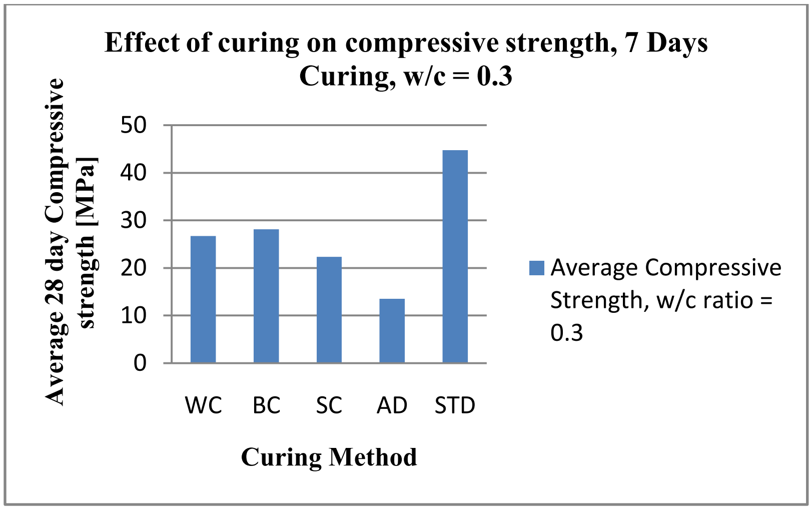


Ratio of Compressive Strength, w/c = 0.4	
Ratio	Curing Method+3 days duration
0.68	WC
0.69	BC
0.54	SC
0.47	AD (28 days)
1.00	STD (28 days)

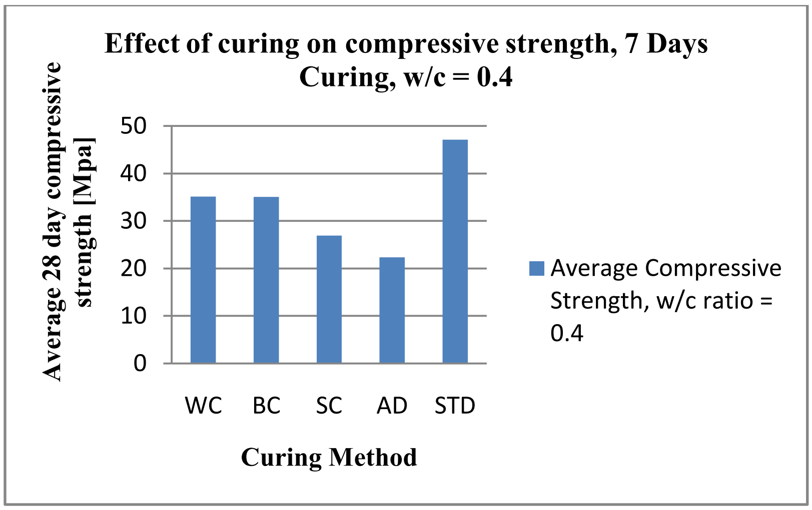


Ratio of Compressive Strength, w/c = 0.5	
Ratio	Curing Method+3 days duration
0.70	WC
0.73	BC
0.56	SC
0.51	AD (28 days)
1.00	STD (28 days)

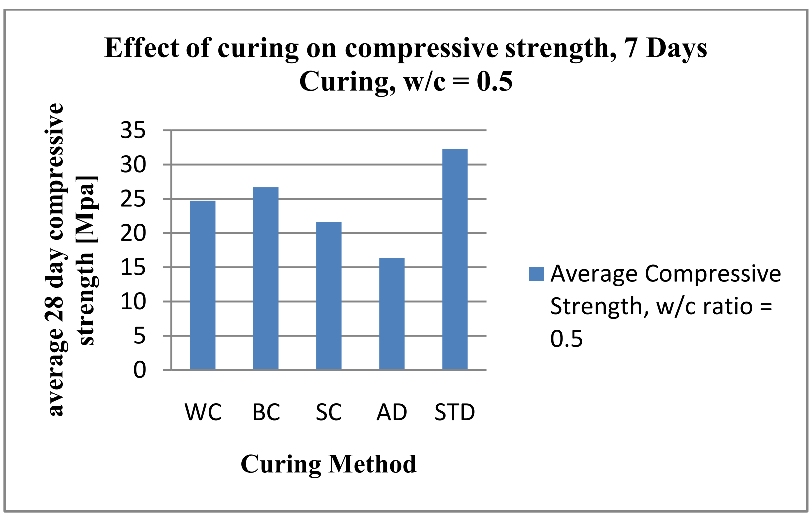
Figure 4.4: *Ratio of compressive strength [MPa] of field cured portland cement mortar samples to standard lab. cured samples, w/c of 0.3, 0.4 & 0.5 with a curing duration of 3 days*



Average Compressive Strength, w/c = 0.3	
Average Compressive Strength	Curing Method+7 days duration
26.74	WC
28.1	BC
22.31	SC
13.52	AD (28 days)
44.76	STD (28 days)

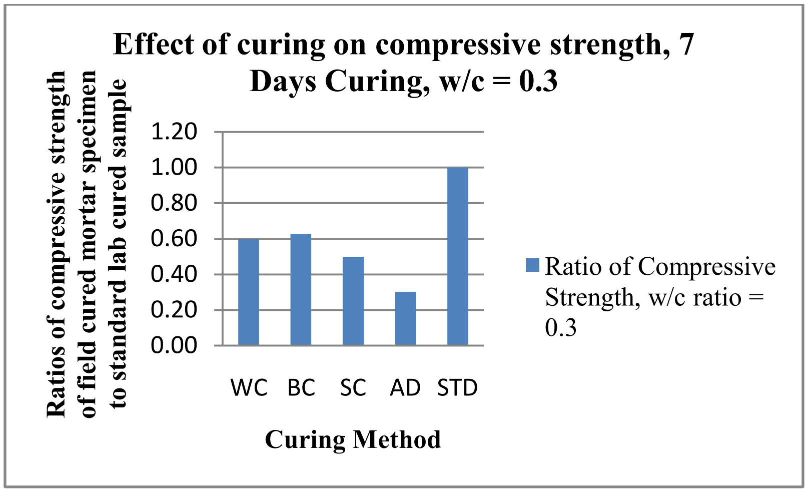


Average Compressive Strength, w/c = 0.4	
Average Compressive Strength	Curing Method+7 days duration
35.11	WC
35.07	BC
26.89	SC
22.34	AD (28 days)
47.08	STD (28 days)

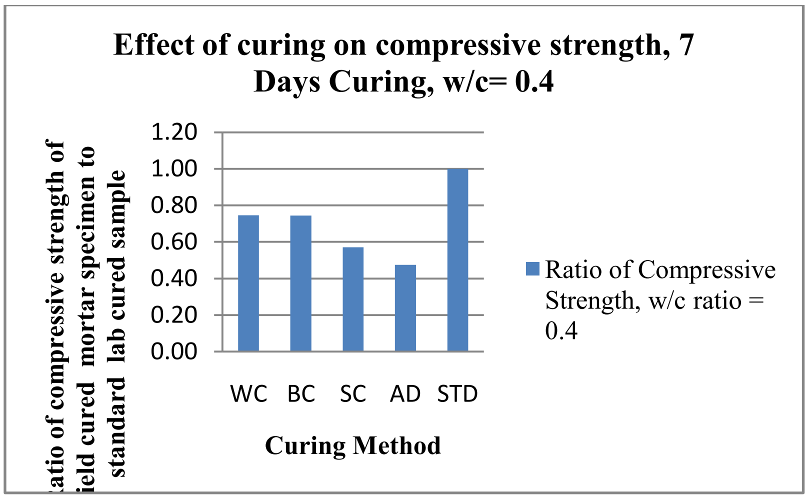


Average Compressive Strength, w/c = 0.5	
Average Compressive Strength	Curing Method+7 days duration
24.71	WC
26.69	BC
21.58	SC
16.34	AD (28 days)
32.3	STD (28 days)

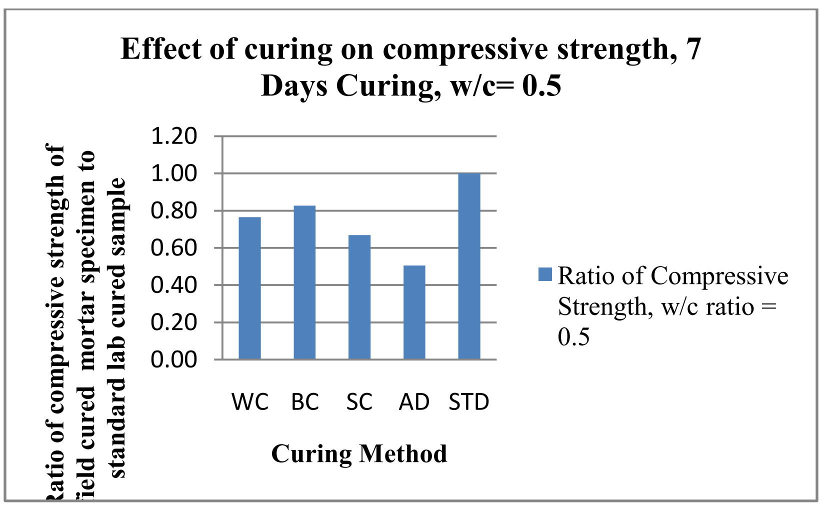
Figure 4.5: *Average 28th day compressive strength [MPa] of portland cement mortar, w/c of 0.3, 0.4 & 0.5 subjected to different curing methods with curing duration of 7 days*



Ratio of Compressive Strength, w/c = 0.3	
Ratio	Curing Method+7 days duration
0.60	WC
0.63	BC
0.50	SC
0.30	AD (28 days)
1.00	STD (28 days)

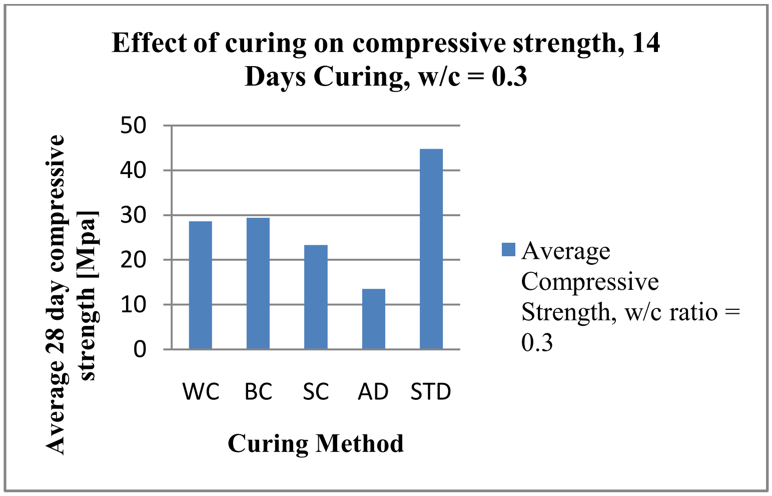


Ratio of Compressive Strength, w/c = 0.4	
Ratio	Curing Method+7 days duration
0.75	WC
0.74	BC
0.57	SC
0.47	AD (28 days)
1.00	STD (28 days)

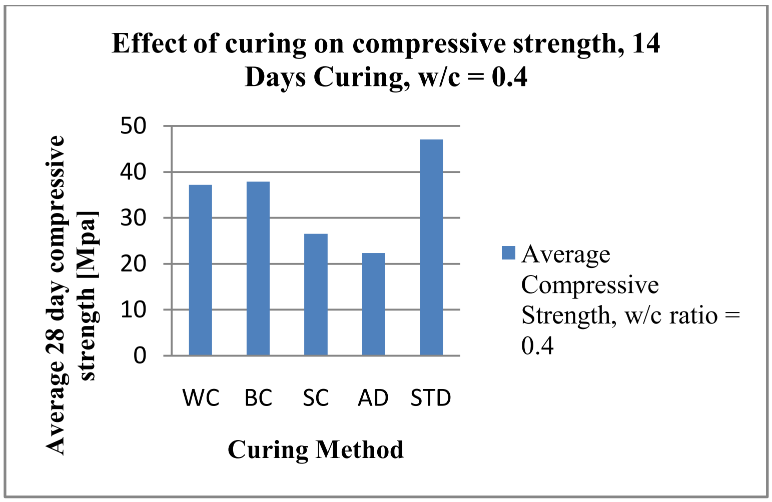


Ratio of Compressive Strength, w/c = 0.5	
Ratio	Curing Method+7 days duration
0.77	WC
0.83	BC
0.67	SC
0.51	AD (28 days)
1.00	STD (28 days)

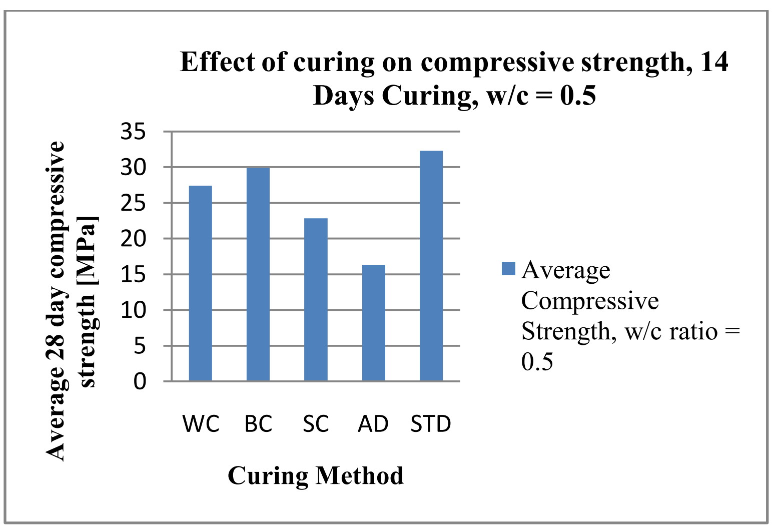
Figure 4.6: *Ratio of compressive strength [MPa] of field cured portland cement mortar samples to standard lab. cured samples, w/c of 0.3, 0.4 & 0.5 with a curing duration of 7 days*



Average Compressive Strength, w/c = 0.3	
Average Compressive Strength	Curing Method+14 days duration
28.64	WC
29.4	BC
23.35	SC
13.51	AD (28 days)
44.76	STD (28 days)

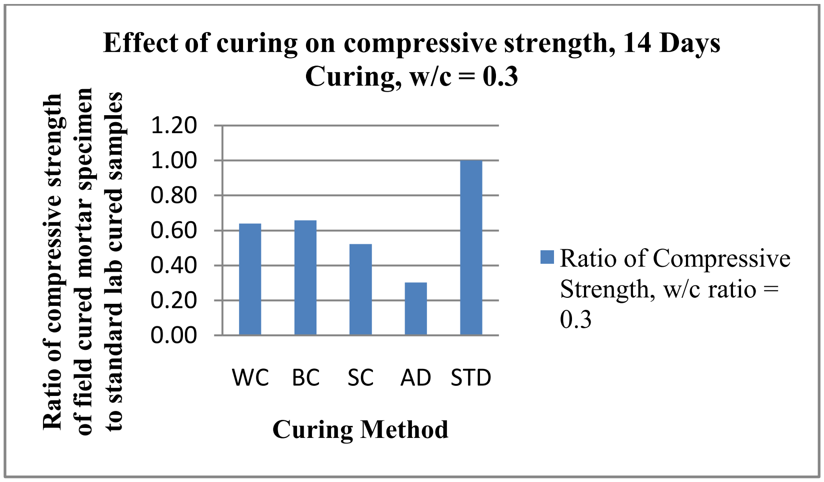


Average Compressive Strength, w/c = 0.4	
Average Compressive Strength	Curing Method+14 days duration
37.2	WC
37.88	BC
26.55	SC
22.34	AD (28 days)
47.08	STD (28 days)

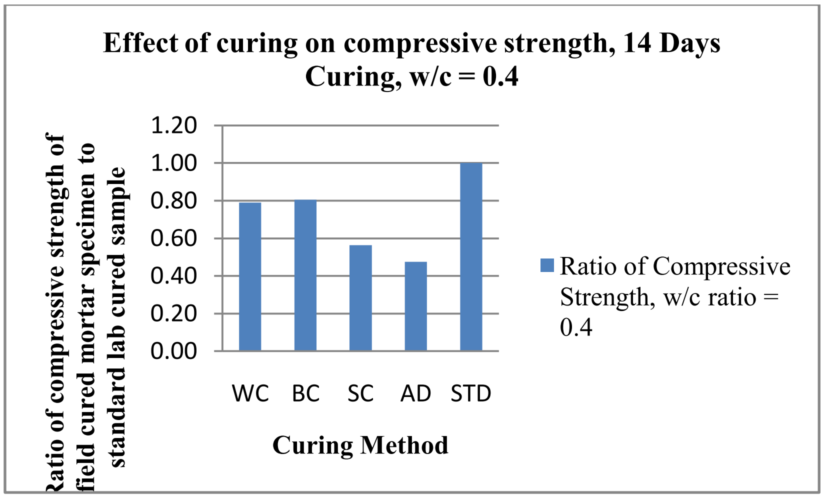


Average Compressive Strength, w/c = 0.5	
Average Compressive Strength	Curing Method+14 days duration
27.41	WC
29.9	BC
22.82	SC
16.34	AD (28 days)
32.3	STD (28 days)

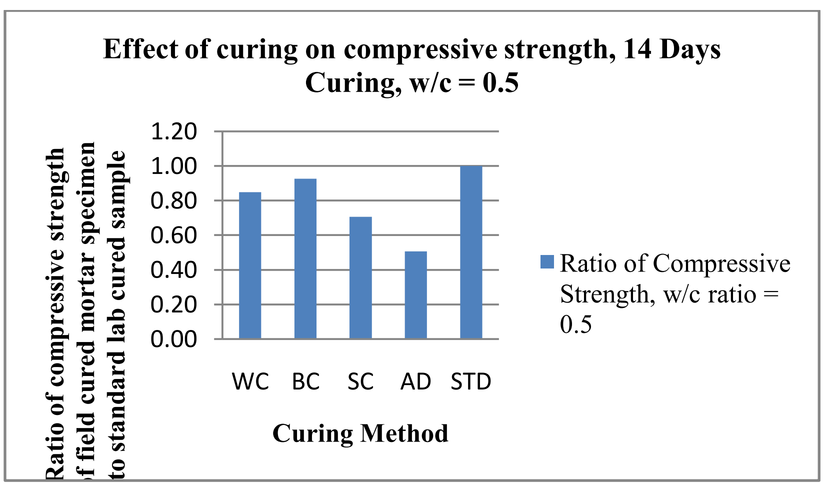
Figure 4.7: *Average 28th day compressive strength [MPa] of portland cement mortar, w/c of 0.3, 0.4 & 0.5 subjected to different curing methods with curing duration of 14 days*



Ratio of Compressive Strength, w/c = 0.3	
Ratio	Curing Method+14 days duration
0.64	WC
0.66	BC
0.52	SC
0.30	AD (28 days)
1.00	STD (28 days)



Ratio of Compressive Strength, w/c = 0.4	
Ratio	Curing Method+14 days duration
0.79	WC
0.80	BC
0.56	SC
0.47	AD (28 days)
1.00	STD (28 days)



Ratio of Compressive Strength, w/c = 0.5	
Ratio	Curing Method+14 days duration
0.85	WC
0.93	BC
0.71	SC
0.51	AD (28 days)
1.00	STD (28 days)

Figure 4. 8: *Ratio of compressive strength [MPa] of field cured portland cement mortar samples to standard lab. cured samples, w/c of 0.3, 0.4 & 0.5 with a curing duration of 14 days*

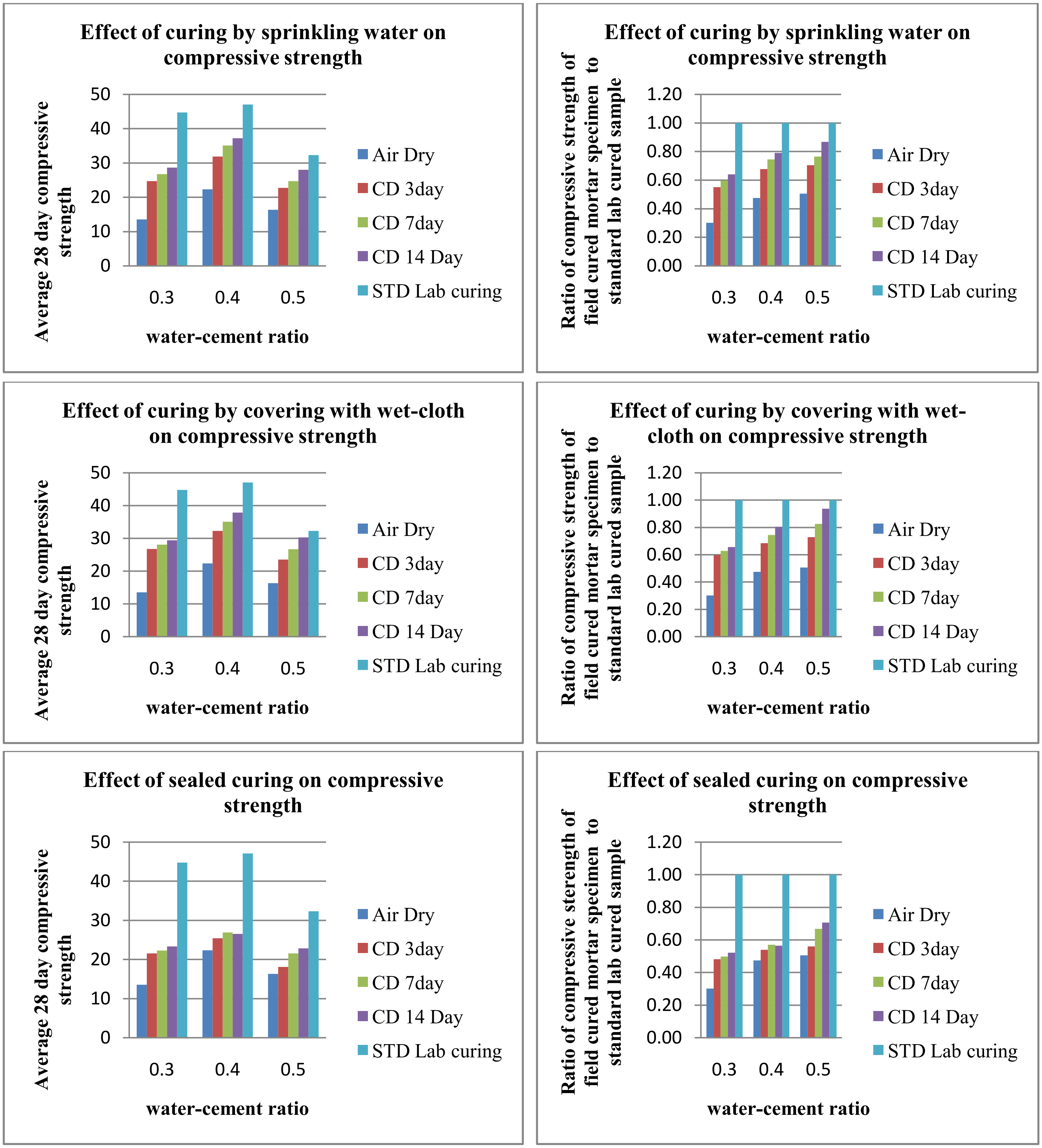


Figure 4.9: *Average 28th day compressive strength [in MPa]* ***(Left)*** *and ratio of compressive strength of field cured (d/t methods of curing) to standard lab. cured mortar samples* ***(Right)*** *with w/c of 0.3, 0.4 & 0.5,*

4.2.3. Discussion

ACI 308R-01 under "monitoring curing and curing effectiveness", one of the methods mentioned to monitor curing effectiveness is by checking the physical properties of concrete, whether the desired physical properties are developed or not.

Since one of the physical properties is compressive strength, in this research curing effectiveness is measured by evaluating the compressive strength of mortar cubes. Because of the shallowness of the curing affected zone measuring the compressive strength of concrete, property of concrete at depth, may not indicate curing effectiveness. But when we see the surface area to volume ratio of 50mm mortar cubes it is relatively larger. Mather, B., (1987), also stated that; "if the effect of curing influences the strength development only to a depth of 25 mm below the surface of the concrete." Since about half the depth of mortar cubes is highly affected by curing measures. Therefore, measuring the compressive strength of mortar cubes can be a good indicator of curing effectiveness.

For this research Portland Pozzolana Cement (PPC) was used to prepare 50mm mortar cubes to assess the effectiveness of different curing methods on w/c of 0.3, 0.4 and 0.5.

About the criteria for evaluating the effectiveness of curing measures, ACI 308R-01 recommends a minimum curing duration by considering attainment of 70% of the specified compressive strength of concrete at termination of curing. Based on this value ACI recommends 7 day as minimum curing duration. But certain type of cement, chemical admixtures and high temperature can reduce the curing duration to be below 7 days. In case of cold temperature, other cement combination of materials such as pozzolanic materials or both can increase the curing duration.

ACI 308R-01 stated that 70% of the specified strength shall be developed at termination of curing. It also emphasizes that during termination of curing we have to be sure that the remaining 30% will be developed after termination of curing. The minimum curing duration specified in ACI 308R-01 is conditional, it stated that curing has to be terminated, "…if the anticipated post curing conditions allow the concrete to continue to develop 100% of the specified strength".

For w/c of 0.5, based on the 70% criteria discussed above, water added curing with a frequency of two times a day for three and seven days were found ineffective. But when the curing is under burlap for 14 days it shows a significant improvement and it was found effective.

Except the 14 days water added curing on mortar specimen with w/c of 0.5, the strength developed at termination of curing was below 70% of the moist cured samples. But it is not only at termination of curing; post curing strength is not also fully developed. Therefore, based on the 70% criteria the curing methods used are not effective for w/c of 0.3 and 0.4. And when we see w/c of 0.5, except the 14 days water added curing all other curing practices was also found ineffective. Here ACI 308R-01 also stated that the curing duration can be more than 7 days for cement containing pozzolanic material. As it was stated earlier the cement used for this research was Portland Pozzolana Cement. And the other thing is the post curing condition; the average relative humidity was about 50% and

Temperature of about 25C^o. Because of these two reasons a curing duration of 3 and 7 days with a watering frequency two times a day was found ineffective.

In this research not only at the time of curing termination but at 28th day the strength developed, in most of the curing conditions, is almost less than 70% of the standard laboratory cured samples. Most of the curing measures didn"t facilitate the mortar specimens to develop 70% of the standard laboratory cured samples at termination of curing. Based on ACI 308R-01 the post curing conditions should allow the development of 100% of the specified strength but the actual strength developed was significantly low. In most of the cases the strength of field cured samples was below 70% and in some cases it is in between 70 to 85% of the standard laboratory cured samples which was expected to be 100% based on ACI 308R-01 requirement. This showed that the curing was inadequate. As stated by ACI 308R-01 we have to be aware of the post curing condition before we terminate curing measures.

For w/c of 0.3, 0.4 and 0.5 which was used in this research, sealed curing for 3, 7 and 14 days was also found ineffective. Even the 28th day compressive strength of mortar specimens sealed beyond 3 days doesn"t show a significant increment. Hence, use of plastic sheeting for more than three days has no significant effect on long term strength of low w/c mixtures.

Different researchers like Powers 1948; Mills 1966; Cather 1994; Meeks & Carino 1999; showed that low w/c mixtures sealed against water loss or water entry can dry themselves from the inside. This problem is most commonly associated with mixtures with a w/c around 0.4 or less and is responsible for an almost negligible long term strength gain in mainly low w/c mixtures. (ACI 308R-01)

Powers (1948) also demonstrated that concrete mixtures with a w/c less than approximately 0.5 and sealed against loss of moisture cannot develop their full potential hydration due to lack of water. Such mixtures would therefore benefit from externally applied curing water. He also stated that because the hydration can proceed only in saturated space, the total water requirement for cement hydration is "about 0.44g of water per gram of cement, plus the curing water that must be added to keep the (capillary pores of) the paste saturated. (ACI 308R-01)

Powers and Brownyard 1947, Powers 1948 stated that the key to development of both strength and durability in concrete, however, is not so much the degree to which the cement has hydrated but the degree to which the pores between the cement particles have been filled with hydration products. And the degree to which the pores are filled depends on the initial volume of the pores and the degree to which the cement is hydrated. (ACI 308R-01)

The current curing practices are found ineffective for low water-cement ratio mixtures, w/c of 0.3 and 0.4. Since the initial porosity in low w/c mixes is low there is a reduction in the required degree of hydration to fill the initial pore spaces, which has a significant effect on the physical properties of concrete (ACI 308R-01). From water absorption tests in this research, there is a reduction in water absorption, for those samples subjected to moist curing, as the w/c is reduced. This is because the initial porosity is very low in case of low w/c mixtures. However, the ratio of water absorption of field cured to moist cured samples is significantly high as the w/c decreases. This showed that the moisture available during field curing for filling the porosity through hydration reaction was not sufficient.

Neville 1996 also showed that continued hydration of the cement is possible "only when sufficient water is available both for the chemical reactions and for the filling of the gel pores being formed." A mass fraction of between 0.21 and 0.28 of chemically bound water is required to hydrate a unit mass of cement. An average value is approximately 0.25 (ACI 308R-01). The amount of gel water adsorbed on to expanding surface of the hydration products and in the gel pores is about equal to the amount that is (chemically) combined with the cement(ACI 308R-01). And it is about 0.2 of the mass fraction of the hydrated cement. This showed that about 0.45 g of water per gram of cement is required for complete hydration. Therefore, external supply of water is essential for concrete or mortar mixture with a w/c below 0.45. Other researchers like Siddique, S., et al., (2013) showed that this number is about 0.42 and researchers like Powers (1948) stated that it is about 0.44 (ACI 308R-01). Therefore, preventing the loss of moisture from mixtures having w/c of 0.5 and above can be sufficient for "complete" hydration and development of the desired properties, such as strength.

Since w/c of 0.5 is greater than required for complete hydration, preventing the loose of the initial water used during mixing is considered to be sufficient, but sealed curing was found ineffective. The samples were sealed after 24hrs since it was casted. Late application of curing is the major factor. This is not only for sealed curing but also for other curing methods. The one factor for the ineffectiveness of curing measures is delayed curing, because the loss of water at initial stage is significant.

Previous researches also demonstrated the effect of 24h delay in curing on the properties of concrete. Sawyer (1957) demonstrated the effect of delayed curing on abrasion resistance which shows a significant increment in depth of wear compared to a specimen subjected to immediate curing. A research by Sidiqque, M. S., et al. (2013) also showed that wet curing immediately after finishing resulted in 27% higher 28-day cylinder strength than that of cylinders sealed for 24 hours followed by curing in a moist room. The 27% reduction in compressive strength can also be higher if the specimen is left unsealed prior to moist curing. This shows the significance of early application of curing.

What does the test results from mortar samples tells us about concrete?

The main concern of curing is to create favorable condition for the hydration of cement grains. As it was discussed earlier on chapter two, the absence of curing affects the top 20-30mm depth from the surface. Curing is essential for the hydration reaction of cement and it is through hydration reaction that there will be a growth of cement matrix in the micro-structural development. Since curing affects the surface of concrete or mortar, its effects on the early age mechanical properties of concrete having larger depth may not be seen significantly because mechanical property is a bulk property but curing affects the top few millimeters of the samples. This doesn't mean curing doesn't have a significant effect on the mechanical properties of concrete.

Due to lack of curing, if there is no adequate moisture and favorable temperature, the micro-structural development will be limited on the surface of concrete. If the growth of cement matrix is limited it leads to development of open pores. It is often said that the total porosity and porosity distribution of the hardened cement matrix that influence the amount and rate of moisture transport in concrete respectively. Transport of liquids and gases takes place in the pores, micro-cracks and voids of the concrete, for example:

- Chloride ions mainly reach the reinforcing bars through water filled pores and/or cracks, gaps and joints. Since corrosion leads to the increase in the volume of steel, cracking and spalling of concrete may follow, thus further deteriorating of structures
- Sulphate attack also depends on sulphate ion transport through water filled pores
- The movement of water in the pore void structure determines freeze-thaw resistance of concrete.

These deterioration processes can be physical, chemical or mechanical and their effect is to weaken the integrity and tightness of the complex internal micro-structural building blocks of concrete. (Maekawa, K., et al., 1999)

Curing is essential for minimizing open porosity on the surface of concrete to produce safe and more durable concrete, so that the structure can last long.

Effectiveness of curing is all about the capacity of the curing to create suitable condition for hydration reaction, which is adequate moisture and favorable temperature, essential for the development of internal building blocks of concrete. The mechanical as well s durability properties of concrete are dependent on the growth of cement matrix. After the growth of cement matrix the cement paste can form a good bond with other constituent materials so that we can get concrete having the desired properties. If the curing is found ineffective to create favorable condition for the hydration reaction of cement grains, it will totally affect the properties of concrete. Development of cement matrix is dependent on hydration of cement. We can have “complete” hydration if there is adequate moisture. And through hydration reaction concrete can develop the desired mechanical and durability properties. If the curing fails to give suitable condition for hydration reaction it means the curing is not adequate for the development of the desired properties of concrete.

Durability is the length of time serviceability and safety of structures remains. (Maekawa, K., et al., 1999)

CHAPTER FIVE -- CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The current curing practices and the awareness about curing was studied using questionnaire survey. Moreover effectiveness of current curing practices in Addis Ababa was explored using experimental study on mortar cubes. From these studies, the following conclusions have been drawn:

- There is awareness about curing in the construction industry in Addis Ababa, but the problem is in the implementation. Most of the practitioners are aware of the consequence of lack of curing.
- Results of water absorption and compressive strength of the same mortar cubes of 50 mm dimension were found comparable about the effect of the curing measure. Hence, compressive strength test on mortar cubes can be used for checking the effectiveness of curing. But more work needs to be done to confirm this.
- The current curing practices are found ineffective for low water-cement ratio, w/c of 0.3 and 0.4.
- In case of w/c of 0.5, water added curing with a frequency of two times a day for three and seven days were also found ineffective. But based on the 70% criteria, when the curing is under burlap cloth for 14 days it shows a significant improvement and it was found effective.
- For all w/c used in this research, w/c of 0.3, 0.4 and 0.5, sealed curing was found ineffective. Use of plastic sheeting for more than three days has no significant effect for mixtures with low w/c. Those samples which were sealed beyond three days have almost the same 28th day strength with those sealed for only three days.
- For w/c of greater than 0.5 a curing duration of 14 days, for the current curing practices, is essential if the cement type is PPC. But for low w/c mixtures, there should be adequate supply of water at early age. Extended curing, which is beyond 3 days, has no as such significant effect on low w/c mixtures.
- Two major factors can be pointed out for ineffectiveness of current curing practices. The first one is inadequate supply of water. When we see the atmospheric condition in the dry seasons, the rate of evaporation is significantly high. And the second factor is late application of curing measures.

RECOMMENDATIONS

- There should be a clear test procedure to check the adequacy of curing on site.
- Increasing the frequency of watering per day in the dry seasons or early application of curing can be one option to increase the efficiency of the current curing practices. But more work has to be done to select the most effective watering frequency and starting time for application of curing.
- Further studies has to be done to select effective curing methods for concrete with low w/c and it is better to look for other curing methods like internal moist curing, water added curing incorporated with sealed curing for concrete with low w/c. Different researches showed that internal moist curing is helpful to minimize self desiccation, which is significant in low w/c mixtures. The current curing practices shouldn"t be applied without improvement for concrete with low w/c.
- Since this research is done in the specific season and area, further studies have to be done to assess the effectiveness of current curing practices with different exposure conditions and cement types.
- Curing effectiveness can be further studied using different tests like surface water absorption, permeability, and surface abrasion resistance, generally tests which can show the properties of concrete or mortar near the surface.
- Since the curing effectiveness is studied using mortar specimens, it is better to develop correlation between compressive strength of mortar and concrete specimens so that we can clearly understand the level of effectiveness of curing on the development of concrete properties.

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APPENDIX:

Annex 1: Questionnaire for Engineers

Addis Ababa University
Addis Ababa Institute of Technology
School of Civil& Environmental Engineering

Questionnaire for Engineers

Dear Sir/Madam

I, the researcher, am an academic staff of Addis Ababa Institute of technology, currently doing my M.Sc. in Civil Engineering under Construction Technology and Management at Addis Ababa Institute of technology. I am doing my M.Sc. research/thesis entitled: Assessment of the effectiveness of different curing practices in Addis Ababa with the aim of investigating the current practices of curing to assess their effectiveness.

Your genuine, honest and prompt response to the questionnaire will have contribution to the success of the research. Your response will be kept confidential, and anonymity will be maintained. Moreover, the information you provide will be used strictly for academic purpose and be reported in aggregate form.

Filling the questionnaire will not take more than 30 minutes. I thank you in advance for the time you devote, effort you make, and consideration you give in filling this questionnaire.

If you have any question concerning the items of the questionnaire, please call on mobile: 0912-04-54-71/0922-87-38-54, or e-mail walelignsamson@gmail.com

With Great Respect

Samson Walelign

Questionnaire

Title: Assessment of the effectiveness of different curing practices in Addis Ababa

Objective of the Research:

- Assessing the attention given to curing in the construction industry specifically in Addis Ababa in order to show the status of our practice.
- Assessing whether our current curing practices are effective or not, as a result the industry will know which practice to be used or to be improved.

Since this survey is required for academic research, your prompt response is highly appreciable.

1. Respondent's Name (Optional):
   ____
2. What is your category as per MoWUD of Ethiopia: (e.g. P.E.)______________
3. Your year of work experience in the building construction Industry: [1 - 3] [4-7] [8-10] [11-15] [>15] (Check the box)
4. Which grade(s) of concrete is (are) mostly produced/used in the construction industries, especially in Addis Ababa, for structural use? (Check the Box)
   [C20] [C25] [C30] [C40] [Other]
   If you check "Other", Specify ____________________
5. What type of cement is mostly used to produce the specified concrete grade?
   [PPC] [OPC] [Other]
   If you check "Other", what is the type of cement? ____________________
6. What do you think about the effect of curing or the lack of it on the properties of concrete?____
   ____
   ____
   ____
   ____
7. What do you think about the attention given to curing in Ethiopian construction industry?
   Poor [ ] Good [ ] V. Good [ ] Excellent [ ]
   ____
   ____
   ____
   ____________________________(Any further comments regarding the attention given)

8. Which curing method(s) are mostly applied in Addis Ababa for structural members (from your experience)? (Check the box)

	Column	**Beam**	**Slab**
Water Sprinkling method	☐	☐	☐
Covering with Wet cloth	☐	☐	☐
Covering with plastic sheet	☐	☐	☐
Other	☐	☐	☐

____ (If you check "Other" please specify)

9. Is there any variation in curing practice and duration based on weathering condition and types of cement? (For example: when the cement is PPC or OPC):

Yes ☐ No. ☐

If yes, please specify? ____

10. When does the application of curing will start after the concrete is put in place/molded?

6-12hr after	24hr after	48hr after	

11. Is there any supervision during curing of concrete to check whether it is done properly or not?
Yes ☐ No ☐

If yes, by whom? Skilled/Unskilled, ____

12. What is the most frequently practiced curing duration for each curing method?

	Curing Day(s)				Other_______
Water sprinkling method	1	3	7	14	
Covering with wet cloth	1	3	7	14	
Covering with plastic sheet	1	3	7	14	
____________________	1	3	7	14	

13. What is the frequency of watering per day in water curing method?

	Frequncy/day			_______ (if other)
Water Sprinkling method	1	2	3	
Covering with Wet cloth	1	2	3	
____________________	1	2	3	

14. Are there any criteria or requirement specified to select the curing method and curing duration for a specific project? (Any Standard or Code) Yes ☐ No ☐

If yes, please mention it.______________________________

15. Do you think that the curing practices for your projects satisfy specification requirements for curing methods (e.g. continuous supply of water in water adding method, minimum 14 day curing for PPC cement, etc…)? Yes ☐ No ☐

16. What do you do on your curing method or duration in case of scarcity of water or high cost of transportation?

____
____
____

17. What do you think about the **effectiveness** of our curing practices regarding the capacity to attain the desired properties of concrete?

A. On strength of concrete

____
____
____
____

B. On durability of concrete

____
____
____

18. How do you describe the representativeness of concrete samples taken for quality control (those samples sent to laboratory) and the actual condition of concrete in the site regarding the curing practice in the site and the curing applied on test samples?

____
____
____
____
____

19. What comment would you like to give about curing practice in Addis Ababa?

____
____
____
____

Time is the precious gift of mankind, and I would like to thank you for your kind gift!!

------------------------------ GOD BLESS ETHIOPIA ------------------------------

Annex 2: Exposure condition during experimental study

Day	Temperature [^{0}C]			Relative Humidity [%]			Wind Speed [KM/hr] (max. /avg.)		
	Morning	After noon	Night	Morning	After noon	Night	Morning	After noon	Night
1	13.4	25.6	18.2	67.6	32.5	58.2	11.3/4.5	18.2/10.3	7.6/3.1
2	11.5	26.3	19.1	65.4	41.3	47.3	9.3/2.9	12.5/5.1	8.9/4.6
3	12.7	24.9	15.9	59.6	44.5	61.5	7.3/3.5	9.6/4.7	8.7/5.3
4	15.2	27.1	18.5	64.5	36.8	50.9	14.2/8.4	14.0/5.5	6.3/2.0
5	15.5	25.8	17.3	68.1	41.8	67.1	10.5/3.7	11.8/7.8	6.7/2.2
6	15.9	27.1	16.9	63.1	46.5	64.6	7.8/2.7	11/3.5	6.5/3.3
7	12.9	24.1	19.2	67.4	44.1	55.3	6.3/2.1	16.1/10.9	18.7/12.1
8	15.8	25.5	20.5	62.8	37.5	43.5	8.2/2.5	17.5/6.7	5.4/2.2
9	13.5	28.6	19.2	65.2	28.3	47.2	12.9/5.5	15/11.1	5.5/2.2
10	14.5	26.0	17.5	65.5	27.2	49.2	13.2/6.5	17.7/8.8	10.2/8.6
11	12.8	25.8	18.2	63.1	31.3	51.2	9.9/3.9	11.4/8.6	4.8/3.1
12	13.1	25.4	17.6	59.7	29.5	48.3	12.3/4.2	10.8/3.5	7.8/6.3
13	11.8	27.1	15.3	58.5	23.2	49.2	7.6/2.8	17.1/8.0	5.6/2.8
14	14.3	25.1	14.9	61.5	27.4	58.3	15.3/5.6	9.5/2.4	9.4/4.5

Annex 3: Summary of results of water absorption versus compressive strength test of Portland cement mortar samples

Curing Method	W/C	Curing Duration	Weight of cube mortar mould		% Absorption 100*[SSD - OD]/OD	Avg.	Coefficient of Variation	Compressive Strength [MPa.]	Avg.	Coefficient of Variation	Ratio of % Absorption per Lab. Cured samples	Ratio of Compressive Strength per Lab. Cured samples
			Oven Dry [gm]	SSD [gm]								
WC	0.3	3 days	255	278	9.02	9.11	0.02	27.26	26.71	0.60	1.25	0.76
			250	273	9.20			26.16				
		7 days	251	273	8.76	8.95	0.06	27.30	27.09	0.09	1.23	0.77
			263	287	9.13			26.88				
		14 days	260	283	8.85	8.78	0.01	26.98	27.39	0.34	1.21	0.77
			264	287	8.71			27.80				
	0.4	3 days	258	285	10.47	10.60	0.03	22.40	22.62	0.09	1.15	0.81
			261	289	10.73			22.83				
		7 days	277	305	10.11	10.28	0.06	24.42	23.81	0.74	1.12	0.85
			268	296	10.45			23.20				
		14 days	264	290	9.85	10.16	0.19	25.64	24.76	1.54	1.10	0.88
			277	306	10.47			23.88				
	0.5	3 days	257	290	12.84	12.55	0.17	18.80	19.20	0.31	1.11	0.86
			253	284	12.25			19.59				
		7 days	250	281	12.40	12.35	0.00	20.58	20.25	0.22	1.09	0.91
			252	283	12.30			19.92				
		14 days	247	278	12.55	12.28	0.14	20.24	21.04	1.27	1.09	0.94
			258	289	12.02			21.84				
Air Dry	0.3	28 days	253	279	10.28	9.81	0.44	18.40	19.25	1.45	1.35	0.54
			257	281	9.34			20.10				
	0.4	28 days	271	306	12.92	12.08	1.41	17.95	18.42	0.45	1.31	0.66
			267	297	11.24			18.89				
	0.5	28 days	251	287	14.34	14.45	0.03	15.48	15.80	0.20	1.28	0.71
			254	291	14.57			16.12				
Lab	0.3	28 days	254	273	7.48	7.27	0.09	35.70	35.37	0.22	1.00	1.00
			255	273	7.06			35.03				
	0.4	28 days	265	291	9.81	9.21	0.72	27.80	28.02	0.10	1.00	1.00
			267	290	8.61			28.24				
	0.5	28 days	253	281	11.07	11.32	0.13	22.10	22.35	0.12	1.00	1.00
			242	270	11.57			22.59				

Annex 4: Summary of compressive strength test results of Portland cement mortar samples with w/c of 0.5

W/C Ratio = 0.5										
No.	Curing Practice	Curing Duration [Day]	Mould Size [mm]	Surface Area [mm^2]	Type of Test: Failure Load [KN]	Type of Test: Compressive Strength [MPa]	Average Comp. Strength [MPa]	Ratio of Comp. Strength to Lab. Cured samples	Standard Deviation	Coefficient of Variation
1	Sprinkling Water Twice a Day	3	49x49	2401	55.08	22.94				
2			49x48	2352	54.45	23.15	22.77	0.70	0.49	0.24
3			50x49	2450	54.41	22.21				
1		7	50x49	2450	61.01	24.90				
2			50x51	2550	60.33	23.66	24.71	0.77	0.97	0.94
3			50x50	2500	63.92	25.57				
1		14	51x51	2601	72.72	27.96				
2			51x50	2550	68.11	26.71	27.41	0.85	1.64	2.70
3			51x51	2601	71.66	27.55				
1	Covering with Burlap Cloth + Sprinkling Water Twice a Day	3	51x51	2601	57.8	22.22				
2			49x50	2450	61.06	24.92	23.53	0.73	1.35	1.83
3			50x51	2550	59.81	23.45				
1		7	51x52	2652	69.97	26.38				
2			51x51	2652	68.12	25.69	26.69	0.83	1.18	1.40
3			52x51	2652	74.23	27.99				
1		14	51x50	2550	81.59	32.00				
2			51x51	2601	75.06	28.86	29.90	0.93	1.60	2.55
3			50x51	2550	73.54	28.84				
1	Covering with Plastic Sheet	3	50x51	2550	46.33	18.17				
2			50x49	2450	45.56	18.60	18.10	0.56	0.53	0.28
3			50x50	2500	43.87	17.55				
1		7	50x49	2450	52.22	21.31				
2			49x50	2450	53.97	22.03	21.58	0.67	0.39	0.15
3			49x49	2401	51.38	21.40				
1		14	50x49	2450	53.99	22.04				
2			50x51	2550	61.02	23.93	22.82	0.71	0.99	0.97
3			50x50	2500	56.25	22.50				
1	Air Dry	28	49x50	2450	39.45	16.10				
2			49x49	2401	37.21	15.50	16.34	0.51	0.99	0.97
3			49x50	2450	42.69	17.42				
1	Laboratory Curing with Ponding	28	50x49	2450	83.66	34.15				
2			51x51	2601	80.95	31.12	32.30	1.00	1.62	2.64
3			50x51	2550	80.62	31.61				

Annex 5: Summary of compressive strength test results of Portland cement mortar samples with w/c of 0.4

W/C Ratio = 0.4										
No.	Curing Practice	Curing Duration [Day]	Mould Size [mm]	Surface Area [mm²]	Type of Test: Failure Load [KN]	Type of Test: Compressive Strength [MPa]	Average Comp. Strength [MPa]	Ratio of Comp. Strength to Lab. Cured samples	Standard Deviation	Coefficient of Variation
1	Sprinkling Water Twice a Day	3	51x51	2601	83.64	32.16				
2			50x50	2500	81.52	32.61	31.89	0.68	0.88	0.77
3			50x51	2550	78.82	30.91				
1		7	51x51	2601	91.42	35.15				
2			51x51	2601	89.04	34.23	35.11	0.75	0.85	0.73
3			50x50	2500	89.85	35.94				
1		14	50x51	2550	96.52	37.85				
2			50x50	2500	89.29	35.72	37.20	0.79	1.29	1.65
3			52x52	2704	102.8	38.03				
1	Covering with Burlap Cloth + Sprinkling Water Twice a Day	3	49x49	2401	78.37	32.64				
2			49x49	2401	76.69	31.94	32.25	0.69	0.36	0.13
3			50x50	2500	80.43	32.17				
1		7	49x49	2401	82.5	34.36				
2			49x49	2401	83.35	34.71	35.07	0.74	0.93	0.87
3			50x49	2450	88.51	36.13				
1		14	51x51	2601	109.2	41.98				
2			49x49	2401	83.79	34.90	37.88	0.80	3.67	13.47
3			50x49	2450	90.04	36.75				
1	Covering with Plastic Sheet	3	50x50	2500	64.42	25.77				
2			50x50	2500	58.57	23.43	25.43	0.54	1.85	3.43
3			51x50	2550	69.06	27.08				
1		7	49x48	2352	61.99	26.36				
2			49x49	2401	64.32	26.79	26.55	0.56	1.59	2.53
3			49x48	2352	62.32	26.50				
1		14	50x51	2550	69.91	27.42				
2			52x51	2652	74.59	28.13	26.88	0.57	0.22	0.05
3			50x50	2500	62.72	25.09				
1	Air Dry	28	50x50	2500	56.26	22.50				
2			50x49	2450	53.7	21.92	22.34	0.47	0.37	0.13
3			50x51	2550	57.61	22.59				
1	Laboratory Curing with Ponding	28	49x49	2401	112.7	46.94				
2			49x50	2450	114.7	46.82	47.08	1.00	0.35	0.12
3			52x52	2704	128.4	47.47				

Annex 6: Summary of compressive strength test results of Portland cement mortar samples with w/c of 0.3

W/C Ratio = 0.3										
No.	Curing Practice	Curing Duration [Day]	Mould Size [mm]	Surface Area [mm^2]	Type of Test: Failure Load [KN]	Type of Test: Compressive Strength [MPa]	Average Comp. Strength [MPa]	Ratio of Comp. Strength to Lab. Cured samples	Standard Deviation	Coefficient of Variation
1	Sprinkling Water Twice a Day	3	50x51	2550	63.28	24.82				
2			50x50	2500	60.13	24.05	24.69	0.55	0.58	0.34
3			50x51	2550	64.25	25.20				
1		7	50x49	2450	66.7	27.22				
2			50x51	2550	67.43	26.44	26.74	0.60	0.42	0.18
3			51x51	2601	69.06	26.55				
1		14	50x51	2550	73.27	28.73				
2			51x52	2652	79.29	29.90	28.64	0.64	1.31	1.72
3			50x50	2500	68.2	27.28				
1	Covering with Burlap Cloth + Sprinkling Water Twice a Day	3	50x50	2500	64.68	25.87				
2			50x51	2550	69.25	27.16	26.78	0.60	0.79	0.62
3			50x51	2550	69.63	27.31				
1		7	50x49	2450	71.35	29.12				
2			51x51	2601	78.16	30.05	28.10	0.63	2.61	6.82
3			50x49	2450	61.58	25.13				
1		14	50x50	2500	72.33	28.93				
2			49x50	2450	74.67	30.48	29.40	0.66	0.93	0.87
3			49x49	2401	69.15	28.80				
1	Covering with Plastic Sheet	3	50x49	2450	51.94	21.20				
2			50x51	2550	57.17	22.42	21.57	0.48	0.74	0.54
3			50x49	2450	51.68	21.09				
1		7	50x50	2500	55.07	22.03				
2			50x49	2450	53.68	21.91	22.31	0.50	0.59	0.35
3			50x51	2550	58.61	22.98				
1		14	50x49	2450	56.88	23.22				
2			49x49	2401	54.09	22.53	23.35	0.52	0.90	0.81
3			49x50	2450	59.56	24.31				
1	Air Dry	28	51x50	2550	37.03	14.52				
2			50x49	2450	32.11	13.11	13.52	0.30	0.87	0.76
3			49x49	2401	31.04	12.93				
1	Laboratory Curing with Ponding	28	48x49	2352	104.5	44.45				
2			49x49	2401	107	44.57	44.76	1.00	0.43	0.19
3			49x49	2401	108.7	45.25				