Investigation into Improved Pavement Curing Materials and Techniques: Part I (Phases I and II)

Iowa DOT Project TR-451
CTRE Project 00-77

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EXECUTIVE SUMMARY

Concrete curing is closely related to cement hydration, microstructure development, and concrete performance. Application of a liquid membrane-forming curing compound is among the most widely used curing methods for concrete pavements and bridge decks. Curing compounds are economical, easy to apply, and maintenance free. However, limited research has been done to investigate the effectiveness of different curing compounds and their application technologies. No reliable standard testing method is available to evaluate the effectiveness of curing, especially of the field concrete curing.

The present research investigates the effects of curing compound materials and application technologies on concrete properties, especially on the properties of surface concrete. This report presents a literature review of curing technology, with an emphasis on curing compounds, and the experimental results from the first part of this research—lab investigation. In the lab investigation, three curing compounds were selected and applied to mortar specimens at three different times after casting. Two application methods, single- and double-layer applications, were employed. Moisture content, conductivity, sorptivity, and degree of hydration were measured at different depths of the specimens. Flexural and compressive strength of the specimens were also tested. Statistical analysis was conducted to examine the relationships between these material properties.

The research results indicate that application of a curing compound significantly increased moisture content and degree of cement hydration and reduced sorptivity of the near-surface-area concrete. For given concrete materials and mix proportions, optimal application time of curing compounds depended primarily upon the weather condition. If a sufficient amount of a high-efficiency-index curing compound was uniformly applied, no double-layer application was necessary. Among all test methods applied, the sorptivity test is the most sensitive one to provide good indication for the subtle changes in microstructure of the near-surface-area concrete caused by different curing materials and application methods. Sorptivity measurement has a close relation with moisture content and degree of hydration. The research results have established a baseline for and provided insight into the further development of testing procedures for evaluation of curing compounds in field. Recommendations are provided for further field study.

1. INTRODUCTION

1.1. Research Background

To “cure” concrete is to provide concrete with adequate *moisture* and *temperature* to foster cement hydration for a sufficient period of *time*. Proper curing of concrete is crucial to obtain design strength and maximum durability, especially for concrete exposed to extreme environmental conditions at an early age.

Research has shown that a high curing temperature (up to 212°F or 100°C) generally accelerates cement hydration and concrete strength gain at early age. Curing temperatures below 50°F (10°C) are not desirable for early age strength development. When the curing temperature is below 14°F (-10°C), the cement hydration process may cease (American Concrete Institute [ACI] Committee 308, 2000). As a result, concrete needs to be kept in formwork for a longer time when cast in a cold weather condition. Cement hydration is an exothermic reaction, which generates a certain amount of heat. If the heat of hydration is kept in the concrete, it will benefit the cement hydration and concrete strength development. As a result, insulation and sealing materials are commonly used for concrete curing.

The relative humidity (RH) in concrete also significantly influences the rate of cement hydration. Normally, the moisture in the freshly placed concrete is in excess of that required for complete cement hydration. If this moisture can be kept within the concrete, it will promote cement hydration. However, if the moisture evaporates and the relative humidity of the concrete falls below 80%, cement hydration may cease (Mindess and Young, 1981). The degree of saturation of a hydrating concrete governs the pore structure, permeability, diffusivity, and absorption characteristics of the hardened concrete.

Loss of moisture also causes concrete to shrink. If a concrete element shrinks freely and uniformly, no shrinkage crack will develop. However, if the surface concrete shrinks much more than the interior concrete, tensile stresses will develop, and this may cause surface cracking. If cracking occurs before the concrete has gained sufficient strength, it is called premature cracking. Proper curing practices can either provide or retain sufficient moisture in the concrete, thus reducing or preventing premature shrinkage cracking.

Curing time is another key for proper cement hydration and concrete strength development. Good curing practices (proper temperature and high humidity) activate cement hydration, thus shortening the curing time required for the concrete to reach its designed strength. Poor and/or insufficient curing may result in premature deterioration in the form of plastic and drying shrinkage cracking, scaling, and joint spalling.

1.2. Problem Statement

Random cracking in concrete pavements has been reported during the first few days after construction. The problem is directly related to concrete curing. Concrete curing practice employs burlap or insulating blankets and sprayed liquid membrane-forming curing compounds on pavements to reduce moisture and heat loss during the early age of cement hydration (within seven days). Burlap or insulating blankets are considered ideal for retaining heat and moisture, but their application is labor intensive and time consuming, and their insulation effectiveness is often affected by the wind. In contrast, liquid membrane-forming curing compounds could provide a similar insulation and be applied much more easily. Control of heat and moisture loss by application of a curing compound, especially in hot or cold weather conditions, has aided contractors in enhancing concrete quality, permitting early open of pavements to traffic and extending the available construction season.

Concrete practice has indicated that the performances of curing compounds are closely related to the characteristics of the curing materials, application methods (single- or double-layer spray), and application time. However, little research has been reported on the effectiveness of curing compounds and application technologies. There are no reliable testing methods available to evaluate the effectiveness of curing. Presently, white-pigmented curing compounds are commonly used in Iowa, while poly-alpha methylstyrene and other curing products are common in many other states. Research is needed to explore alternative curing compounds and optimal application techniques for Iowa concrete pavements. This project is the direct result of work identified by the Construction Quality Initiative (CQI) group from the Iowa Department of Transportation (Iowa DOT) and construction industry.

1.3. Project Objectives

The objectives of this research are twofold:

1. To identify and evaluate alternative curing materials and techniques that meet the goals of the Iowa DOT to improve moisture retention in newly placed concrete pavements.
2. To develop a suitable evaluation method for measuring the effectiveness of the compounds on the pavement at construction.

1.4. Scope of the Research

This research focuses on evaluating curing compound materials, application technologies, and their effects on concrete properties, especially on the surface concrete properties. The project contains two parts: lab investigation (Part 1) and field application (Part 2).

This report presents a literature review of curing technology, with an emphasis on curing compounds, and the experimental results from Part 1 of the curing project—lab investigation. In the experimental work, three curing compounds were selected and applied to concrete (mortars and pastes) at three different times after casting. Two application methods, single- and double-layer applications, were employed. Moisture content, conductivity, sorptivity, and degree of hydration were measured at different depths of the specimens. Flexural and compressive strength of the specimens were also tested. Statistical analysis was conducted to examine the relationships among these material properties. In addition to evaluating the effectiveness of curing compounds and application techniques, the current research results also provide insight into the development of test methods for characterization of the surface concrete properties.

2. LITERATURE REVIEW

According to ACI Committee 308, commonly used concrete curing methods can be divided into two categories: (1) the “water-adding” technique, which provides concrete with water or moisture continuously or frequently through water ponding, fogging, sprinkling, steaming, or covering with saturated material; and (2) the “water-retaining” technique, which prevents excessive temperature and water loss from the concrete by means of sealing materials, such as plastic sheets, or by application of membrane-forming curing compounds to the freshly placed concrete. Through the years, concrete curing practice has changed; in many cases it has shifted from “water-adding” to “water-retaining” (Gowripalan et al., 1990).

Among “water-adding” techniques, ponding or immersion is considered as the most effective method for facilitating cement hydration, but it is seldom used because of the labor, time, and cost as well as the feasibility to build a water pond on some concrete structures. Fog spray or sprinkling is a relative inexpensive and effective curing method. However, it can be used only when adequate water is available and ambient temperature is well above freezing. Materials that hold sufficient moisture, such as burlap, cotton mats, rugs, curing, sand and sawdust, and straw or hay, are also frequently used to cover the surface of concrete pavements. The moisture held in these materials can be released slowly for concrete curing. (Burlap holds moisture effectively, and therefore it is widely used.) However, when these materials dry out, periodic moistening is required. Covering pavement surfaces with these materials requires considerable labor and time.

Among “water-retaining” techniques, sealing materials such as plastic film and reinforced papers are often used to cover concrete surfaces for early age curing. These techniques are not only labor and time consuming, but their applications are also limited by the wind. Liquid membrane-forming curing compounds are the most widely used materials in the United States for curing of concrete pavements and bridge decks. Curing compounds are economical, easy to apply, and maintenance free (Senbetta, 1988).

Based on the Florida standard for radon-resistant new commercial building construction, “Curing compound is a liquid that can be applied as a coating to the surface of newly placed concrete to retard the loss of water, or in the case of pigmented compounds, also to reflect heat so as to provide an opportunity for the concrete to develop its properties in a favorable temperature and moisture environment” (Murley, 1996). The remainder of this chapter discusses the results of a literature survey on liquid membrane-forming curing compounds.

2.1. Types of Liquid Membrane-Forming Curing Compounds

Typical curing compounds consist of wax or resin, which is emulsified in water or dissolved in a solvent (Vandenbossche, 1999). After applied to the surface, the water or solvent evaporates and then the wax or resin forms a membrane on the surface. This membrane helps retain moisture in the concrete. Concrete cured with curing compounds is kept partially saturated near the surface during the curing period. The depth of the moisture zone is dependent on the moisture-retaining characteristics of the membrane employed.

Based on their chemical composition and manufacturing process, curing compounds can be divided into the following categories (QCL Group, 1999): (1) wax emulsion, (2) acrylic emulsions, (3) chlorinated rubber-based compounds, (4) hydrocarbon resins, and (5) polyvinyl acetate (PVA)–based compounds.

2.1.1. Wax Emulsion

These curing compounds consist of emulsions of wax in water or dissolved in a suitable solvent. This method of curing compares well with others, but it affects the bond of surface treatments (topping and vinyl) to the concrete surface.

2.1.2. Acrylic Emulsions

These materials offer relatively good curing, and they also tend to permit a better bond for subsequent treatments than other compounds.

2.1.3. Chlorinated Rubber-based Compounds

These are either synthetic or natural rubber polymers, dissolved in a suitable solvent. They have high curing effectiveness, but care should be taken in their use as the solvents are toxic and flammable.

2.1.4. Hydrocarbon Resins

The majority of these curing compounds are of natural or synthetic resins dissolved in a solvent. After an application, the solvent in the curing compound will evaporate, and a membrane will form on the surface of the concrete, which provides the concrete with excellent curing. However, under extreme weather conditions this membrane becomes brittle and breaks down under the action of sunlight and weathering, thus reducing its effectiveness.

2.1.5. PVA-based Compounds

Tests on PVA-based curing compounds generally show that they are of limited effectiveness in preventing moisture loss from the concrete. Their capabilities are influenced by their solids content, which varies markedly between manufacturers.

By contrast, ASTM classifies liquid membrane-forming curing compounds by the color of the compound and the solid constituent present for forming the membrane. ASTM 309 includes the following classifications:

- Type 1—clear
- Type 1-D—clear or translucent with fugitive dye
- Type 2—white pigmented
- Class A—no restrictions
- Class B—resin-based compositions

2.2. Requirements for Liquid Membrane-Forming Curing Compounds

As mentioned previously, the purpose of curing compounds is to retain moisture and temperature in concrete for cement hydration. As a result, the ability of water retention and heat reflectance of a curing compound must be specified for a quality curing.

2.2.1. Water Retention

Water or moisture retaining ability is the ability of a material to prevent the loss of moisture from a hydraulic cement mortar.

Together with ASTM C309, “Standard Specification for Liquid Membrane-Forming Compounds for Curing Concrete,” ASTM C156, “Test Method for Water Retention by Concrete Curing Materials,” provides a standard test method for estimating the water retention ability of curing compounds. The water retaining value, determined by this method, is used to assess the suitability for contributing to an appropriate curing environment for concrete. But the test results obtained may be highly variable as indicated by the precision statement. The single-operator standard deviation is 0.13 kg/m^2 (0.03 lbs/ft^2), and multi-laboratory standard deviation is 0.30 kg/m^2 (0.06 lbs/ft^2) (Vandenbossche, 1999). These standard deviations are extremely high compared with the required value of less than 0.55 g/m^2 (0.03 lbs/ft^2) in 72 hours for Type 2 Class B curing compounds.

Table 2.1 shows test results from the Minnesota Department of Transportation (Mn/DOT) (from Vandenbossche, 1999). As shown in the table, the standard deviations of the tests are very large, which indicates that “the lack of precision of ASTM C156 is so severe that it can be difficult to conclude whether a given compound has passed or failed the test” (Senbetta, 1988). Mn/DOT tested 141 samples from three different companies and suggested that reducing the maximum allowable evaporation loss would help prevent the use of the marginal curing compound.

Table 2.1. Water Loss and Variation of Curing Compound

Products	**Average Water Loss (kg/m^2)**	**Sample Standard Deviation (kg/m^2)**	**Number of Samples**
W.R. Meadows 1250-White	0.20	0.08	40
W.R. Meadows 2230-White	0.24	0.17	10
Vexcon Enviocure 100-White	0.49	0.28	12

Many factors affect the laboratory test results. These factors include the precision of the control of the temperature, humidity and air circulation in the curing cabinet, preparation and sealing of the mortar specimens, the age and the surface condition of the mortar specimen when the curing product is applied, and the uniformity and quantity of the curing membrane (ASTM C309). Some of these factors are not well considered in ASTM C156.

Because the ASTM C156 method is not reliable, some state departments of transportation (DOTs) try to modify the test and have their own specifications. These changes include changing the specimen size and shape; changing the method of calculating the test results; specifying test results at 24 hours and 72 hours; using heat lamps and wind to simulate sunny and windy conditions; using different temperature, relative humidity, and wind conditions in the cabinet; and using different mortar mixtures (Senbetta, 1988).

The Iowa DOT uses the efficiency index and moisture loss to evaluate a curing compound material (Iowa 901-D). The Iowa DOT specifies the efficiency index of a curing material shall not be less than 95.0%, except that the material shows moisture loss of less than 1.0% of the quantity of water remaining in the test specimen at the time the curing material is applied (Iowa DOT, 1997). Mn/DOT decreases the allowable water loss of 0.15 kg/m^2 (0.03 lbs/ft^2) in 24 hours and 0.40 kg/m^2 (0.08 lbs/ft^2) in 72 hours. The California Department of Transportation requires the curing compound resin to consist of 100% poly-alpha-methylrene. This type of curing compound has good water retention properties.

2.2.2. Reflectance Properties

Type 2 liquid membrane-forming curing compounds include a white pigment, which helps to reflect radiant heat from the sun and results in less of an increase in temperature within the concrete throughout the curing period than do other curing methods. The reflectance of curing compounds also reduces the rate of evaporation and decreases early age stresses. ASTM C309 states that reflectance shall not be less than 60%.

2.2.3. Other General Requirements

According to ASTM C309, there are other requirements curing compounds should meet. The drying time should not be more than four hours; the volatile portion of liquid membrane-forming compounds should be neither toxic, nor have flash points less than 50ºF (10ºC); liquid membrane-forming compounds should not react deleteriously with concrete and its components; compounds should be of a consistency that they can be readily applied by spraying to a uniform coating at a material temperature above 40ºF (4ºC).

ASTM C309 also states, "Permanent colors other than white, or other special attributes are beyond the scope of this specification and are subject to negotiation between the purchase and the supplier." Some curing compounds need to meet special requirements, such as alkali resistance, adhesion-promoting qualities, and resistance to degradation by ultraviolet (UV) light, in addition to their moisture-retention capability as measured by ASTM C156.

2.3. Typical Properties of Curing Compounds

Although all used curing compounds are required to meet ASTM standards, each curing compound has its own characteristics, which make it different from other compounds. Table 2.2 shows typical properties of selected curing compounds. Because of the difference in properties of the curing compounds, curing compounds should be applied under the instruction of the manufacturers.

Table 2.2. Typical Properties of Curing Compounds

Name	ASTM Specification	Moisture Retention		Reflectance (%)	Flash Point (^{0}F)	VOC Content (g/L)	Coverage Rate (ft^2/gal)	Color
		(%)	(g/cm^2)					
Sealtight 1600-White	Type 2 Class A	89.0*	—	53*	212	350	200	White
Sealtight 2250-White	Type 2 Class B	—	0.03	70	135	292	200	White
Sealtight 1645-White	Type 2 Class A	95.9*	—	67*	N/A	350	200	White
Atlas Tech-1315	Type 1 Class A & B	—	0.28	N/A	N/A	300	300	Clear

* These values are obtained from Iowa DOT tests. The numbers in the moisture retention column are efficiency index, which is used at the Iowa DOT to represent the moisture retention. Other values in the moisture retention column are moisture loss after 72 hours.

2.4. Application Technologies of Liquid Membrane-Forming Curing Compounds

Once a curing compound is selected, application technology is a key for the quality of the curing. There are a number of unsuccessful applications of curing compounds, many of which result from improper application time, insufficient amount, and/or nonuniform coverage of curing compounds (Mather, 1990).

2.4.1. Time of Application

For maximum beneficial effect, liquid membrane-forming compounds must be applied to concrete as soon as final finishing operations are complete and after surface water sheen has disappeared and no water sheen is visible, but not so late that the curing compounds will be absorbed into concrete.

If the concrete has not ceased to bleed, it is too soon to apply the curing compound no matter how dry the surface has become as a result of the evaporation rate exceeding the bleeding rate. When the evaporation rate exceeds that of the bleeding, the surface appears dry even though bleeding is still occurring. If the curing compounds are applied at this time, two undesirable conditions may occur: (1) evaporation is effectively stopped but bleeding is continuing, which will cause one layer bleeding water under the concrete surface (this condition promotes scaling); (2) evaporation is temporarily stopped but bleeding water may still continue, which causes map cracking of the membrane film with reduction in water retention capability. For this second situation, reapplication of curing compounds is required (ACI Committee 308, 2000; Transportation Research Committee, 1979).

If a curing compound is applied to a concrete surface that has dried, the curing compound will be absorbed and will not form a membrane. The curing compound–saturated dry surface layer of concrete will cease to gain strength, and it will disintegrate under traffic and severe weathering.

2.4.2. Amount of Application

The amount of curing compound used should be enough to seal all exposed concrete surfaces. Curing compound shall not be permitted to enter joints, nor shall it be allowed on surfaces to be subsequently joined with other concrete surfaces. An additional coat of compound shall be applied to surfaces showing discontinuity of coverage. Areas covered with curing compound and damaged by construction operations within the seven-day curing period shall be re-sprayed as specified. Areas subjected to heavy rainfall shall also be recoated.

A more direct approach to increasing the effectiveness of the curing compound membrane is to increase its thickness by increasing the rate of spraying (Loeffler et al., 1987). Therefore, the most common method for ensuring proper curing concrete is to control the spraying speed. The typically used spray rate ranges between 2.5 and 5.0 m^2/L (102 and 204 ft^2/gal). However, many state DOTs have their own specification for the minimum spraying speed. Table 2.3 shows spraying speeds of two DOTs as compared to the typical. Although every DOT considers the minimum spray rate, only several DOTs consider the surface texture of concrete when specifying spray rate. Different textures require different curing compounds to achieve the same curing results. Smooth surfaces require less curing compound than do rough surfaces.

Table 2.3. Spraying Rate for Liquid Membrane-Forming Curing Compounds

	Typical	Iowa DOT	Mn/DOT
Spraying rate (m^2/L)	2.5–5.0	3.3	4.0

2.4.3. Uniformity of Application

In addition to correct spray rate, the continuity is also very important. The spray operation should be performed using approved equipment to form a continuous and uniform water-impermeable film without marring the surface (Transportation Research Committee, 1979). For Type 1-D white-pigmented curing compounds, if the pigments are dispersed uniformly in the curing compound, it is possible to detect the nonuniform application by careful visual inspection. For clear or translucent compounds without dye, the ability to visually inspect uniformity is less certain. Therefore, clear or translucent compounds must be inspected for uniformity shortly after application. Mn/DOT indicates that five factors affect the ability to obtain a uniform coverage: nozzle type, nozzle spacing and boom height, nozzle orientation, cart speed, and wind shield.

2.5. Summary of the Literature Survey

Curing is important for concrete to achieve desirable strength and durability. The purpose of curing is to facilitate cement hydration by providing or retaining adequate moisture and temperature in concrete for sufficient time. Among many curing materials and methods, applications of liquid membrane-forming curing compounds are the most widely used for curing pavements, bridge decks, and other concrete structures because they are economical, easy to apply, and maintenance free.

Various types of curing compounds exist in the market; however, no reliable method is available to evaluate the effectiveness of the curing compounds. Current ASTM standards do not take into consideration key variables such as extreme temperature, wind velocity, and radiation from the sun. The test method for water retention has a high standard variation. Many DOTs have modified the ASTM methods and have developed their own specifications. However, unsuccessful applications of curing compounds are often reported, and they are frequently related to improper application time, insufficient amount of spray, and nonuniform coverage of exposed concrete surface.

As curing compounds are increasingly used, it is important to modify current standards or to develop new parameters that can characterize curing compounds effectively. To ensure a quality application of a curing compound, spraying methods and technology—such as application time, amount, number of layers, and spraying equipment—need to be studied. Since curing compounds keep the near-surface-area concrete partially saturated during the curing period, it is significant to study the effects of different curing compounds and application technologies on pore structure, permeability, and absorption characteristics of the near-surface-area concrete.

3. EXPERIMENTAL WORK

In order to evaluate curing materials, application methods, and test methods for curing effectiveness, three curing compounds were selected and applied to concrete (mortars and pastes) at three different times after casting. Two application methods, single- and double-layer applications, were employed. Moisture content, conductivity, sorptivity, and degree of hydration were measured at different depths of specimens. Flexural and compressive strengths of some of the specimens were also tested. The results are compared with those from the specimens without application of curing compounds.

3.1. Curing Materials

The curing compounds used in this project are 1645-White, 1600-White, and 2255-White. Compound 1645-White is a water-based curing compound currently used by the Iowa DOT. Its water retention efficiency index is 95.9% and cost is $2/gallon. Compound 1600-White is also a water-based curing compound that meets ASTM specification but not the Iowa specification. Its efficiency index is 89.0% and cost is a half of that of 1645-White. Compound 2255-White is a resin-based curing compound currently used by Mn/DOT. Its efficiency index is 98.1% and cost is as three times as that of 1645-White. Typical properties of the three curing compounds are given in Table 3.1.

Table 3.1. Typical Properties of Selected Curing Compounds

Name	ASTM Specification	Efficiency Index (%)	Solids Content (%)	Approximate Cost ($/gal)
1645-White	Type 2 Class A	95.9	29.2	2
1600-White	Type 2 Class A	89.0	17.1	1
2255-White	Type 2 Class B	98.1	43.5	6.5

3.2. Curing Methods

3.2.1. Reference 1: Air Curing

Reference 1 simulates the worst curing condition in a mild weather condition. The samples without any curing compound were cured in a room until testing. The room temperature was approximately 76.5^{o}F and the relative humidity was 38%.

3.2.2. Reference 2: Wet Curing

Reference 2 simulates the best wet-curing condition in a mild weather condition. The samples without any curing compound were covered with burlap and cured in a fog room until testing. The temperature in the fog room was approximately 73^{o}F and the relative humidity was higher than 95%.

3.2.3. Reference 3: Oven Curing

The samples without any curing compound were cured in an oven until testing. The oven was turned on at 7:00 AM and turned off at 7:00 PM. The relative humidity in the oven was about 35%. The typical oven temperature is shown in the Figure 3.1.

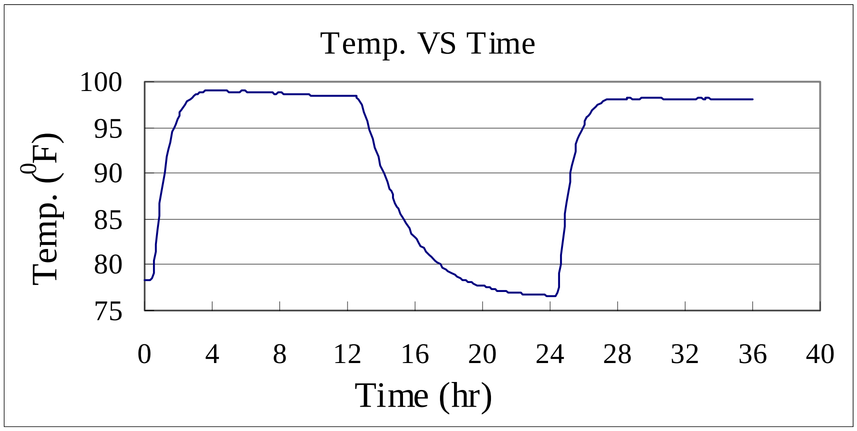


Figure 3.1. Typical Oven Temperature

3.2.4. Case 1: Air Curing + Single-Layer Curing Compound

In this case, a selected curing compound was sprayed on specimens at 0.25, 0.5, and 1.0 hours after casting. The specimens were cured in the air (with a temperature of 76.5°F and a relative humidity of 38%) before and after application of curing compound until testing.

3.2.5. Case 2: Oven Curing + Single-Layer Curing Compound

In this case, a selected curing compound was sprayed on specimens at 0.25, 0.5, and 1.0 hours after casting. The specimens were cured in the oven (see Figure 3.1 for the oven temperature; relative humidity of 35%) before and after application of curing compound until testing.

3.2.6. Case 3: Oven Curing + Double-Layer Curing Compound

In this case, two layers of a curing compound were applied onto the surface of the specimens. The first layer was sprayed at 0.25, 0.5, and 1.0 hours after casting. The second layer of the same curing compound was spayed 5 minutes after the first application of the curing compound. Samples were cured in the oven (same temperature and relative humidity as in Case 2) before and after application of curing compound until testing.

3.3. Specimens

3.3.1. Paste Specimens

Small cement paste slabs were prepared with a dimension of 10 inches by 5 inches by 4 inches. Holcim Type I cement was used. In order to apply a water-based curing compound onto the slabs at a very short time after casting, a dry mixture was required. As a result, a water-to-cement ratio (w/c) of 0.28 was selected for all paste specimens. Three 2-inch cores were taken from the paste slabs for degree of cement hydration tests.

3.3.2. Mortar Specimens

Two types of mortar samples were cast: one was a 2-inch by 2-inch by 4-inch prism, and the other was a 10-inch by 5-inch by 4-inch slab. The prism specimens were used for moisture content and sorptivity tests. In order to measure moisture content and sorptivity of a specimen at different depths, the specimen needed to be broken into three pieces: top, middle, and bottom. In order to prevent moisture loss from cutting of the specimens, two notches were designed to divide the specimens into three equal pieces.

The slabs were used for temperature monitoring, conductivity tests, and compression tests, in which 2-inch by 4-inch cylinders were cored from the slabs. Holcim Type I cement and Hallett Sand (fineness modulus of 2.94) were used. The sand to cement ratio was 2.75, and the w/c was 0.42 for all the mortar specimens.

3.3.3. Concrete

Concrete beams, with a dimension of 4 inches by 4 inches by 18 inches were prepared for flexural strength tests. The concrete mix proportions are shown in Table 3.2. The concrete beams were cured in the oven for 1 day, de-molded at the second day, and then cured in the fog room for other 6 days before flexural tests.

Table 3.2. Concrete Mix Proportions

	Source	**Weight (lb/ft^3)**
Coarse aggregate	Ft. Dodge	80
Fine aggregate	Cordova	63
Cement	Holcim I/II	29
Air entraining agent	Daravair 1400	6.0 ml
Water	Tap water	14

3.4. Compound Spray

Curing compounds were sprayed on specimens according to Iowa DOT test method No. 901-D (May 2000). After well shaking and mixing, the tested curing compound was put into a paint sprayer as shown in Figure 3.2. The sprayer was attached to a compressed air supply that adjusts pressure. The curing compound was then uniformly sprayed on the surface of the specimen until the prescribed rate had been applied. The amount of the curing compound in the sprayer was recorded before the spray, and the compound was sprayed until the remaining curing and sprayer weighed the same as the calculated weight (to the nearest 0.1 g).

Figure 3.2. Paint Sprayer with Compressed Air Supply

3.5. Test Methods

Eight different tests were conducted: (1) moisture content, (2) sorptivity, (3) degree of hydration, (4) compressive strength, (5) conductivity, (6) temperature, (7) flexural strength, and (8) thermogravimetric analysis (TGA).

3.5.1. Moisture Content

Moisture content was measured from a set of three mortar prisms at age 1 and 3 days. In the tests, a 2-inch by 2-inch by 4-inch mortar prism was fractured along the designed notches into three pieces: top, middle, and bottom. Each piece was weighed to the nearest 0.01 of a gram (W_i) and then put in an oven at a constant temperature of 105°C to remove free water. After heating for 48 hours, the pieces of samples were weighed again (W). The moisture content (MC) is given by

$$MC = [(W_i - W) / W] * 100\% \quad (3.1)$$

Figure 3.3 illustrates the test procedures for moisture content measurements.

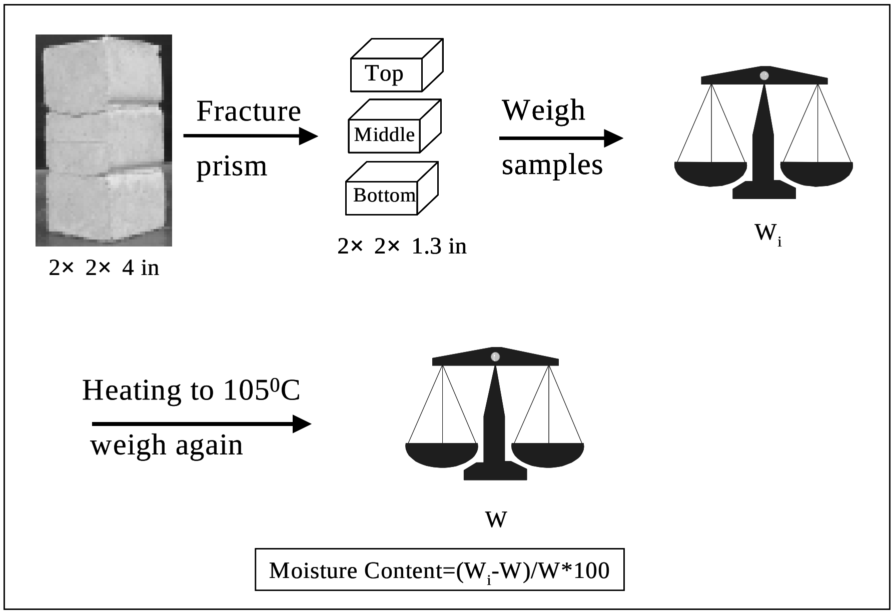


Figure 3.3. Test Procedures for Moisture Content Measurement

3.5.2. Sorptivity

Sorptivity was also measured from mortar prisms at age 3 days. In this test, a 2-inch by 2-inch by 4-inch mortar prism was evenly cut into three pieces with slow sawing. The bottom surface of the bottom piece was cleaned or smoothened using a sand paper. For each piece, the dimensions of the bottom cross sections were measured, the lateral surfaces were sealed with five-minute epoxy, and the top surface was covered with plastic. After the samples were weighed to the nearest 0.01 of a gram, the bottom surface was immersed into tap water to a maximum depth of 3 mm. The water level was kept constant. The samples were then weighed at time intervals of 1 minute, 5 minutes, 10 minutes, 20 minutes, 30 minutes, 1 hour, 6 hours, and even longer if necessary. Before each weighing, the surfaces, which were in contact with water, were pressed against a paper towel to remove any excess water. The test was finished when the slope of mass gain per unit area versus square root time was constant. This constant slope is the sorptivity coefficient. Figure 3.4 illustrates the test procedures for sorptivity measurements.

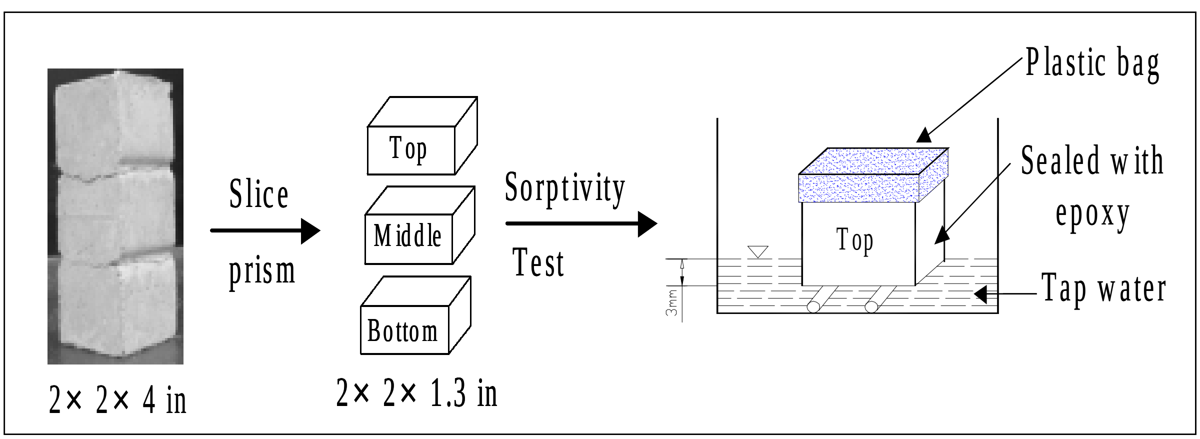


Figure 3.4. Test Procedures for Sorptivity Measurements

3.5.3. Degree of Hydration

A 2-inch core was drilled from the paste sample. Three 0.5-inch thick pieces were cut from the top, middle, and bottom of the core. Each piece was crushed, sieved with a number 16 sieve, weighed and filled into a crucible (the crucible was weighed before putting the sample in). The crucibles were put in an oven at a constant temperature of 105°C and weighed again after 18 hours to obtain the amount of evaporable water (W_{105}). For achieving the weight of hydrated water, or non-evaporable water, the crucibles were put back in the furnace, heated to 1000°C, and after kept at this temperature for one hour, put in the desiccators. After having reached the room temperature, they were weighed again (W_{1000}). The amount of non-evaporable water can be calculated from the difference between the two weights at 105°C and 1000°C. The degree of cement hydration (α) is proportional to the non-evaporable water, and it can be expressed as the following (Mindess and Young, 1981):

$$\alpha = [(W_{105} - W_{1000}) / (0.24 * W_{1000})] * 100\% \quad (3.2)$$

Figure 3.5 illustrates the test procedures for degree of cement hydration.

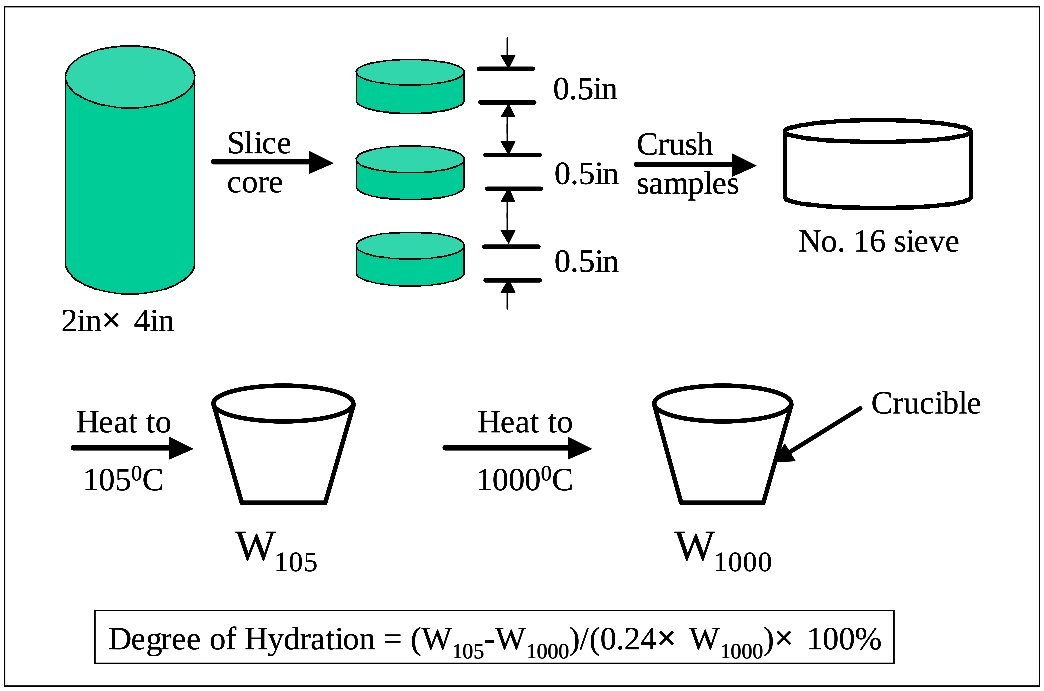


Figure 3.5. Test Procedures for Degree of Cement Hydration

Note that TGA also provides information on amount of non-evaporable water in specimens. Comparison of the degrees of cement hydration calculated from the two tests will be presented later.

3.5.4. Compressive Strength

The compression tests were performed for 2-inch by 4-inch mortar cylinders, according to ASTM C39, “Test Method for Compressive Strength of Cylindrical Concrete Specimens,” at age 3 and 7 days. Three 2-inch cylinders were drilled from the mortar slab. The surfaces of each cylinder were capped using the gypsum. The cylinders were loaded at a constant rate, 20–50 psi/minute, after the gypsum had dried.

3.5.5. Conductivity

After a mortar slab was cast, two copper plates (2 inches wide by 0.75 inches deep by 0.125 inches thick) were inserted into the sample; they divided the sample equally in length. The Solomat MPM 2000 conductivity meter was used to measure the resistivity between the two copper plates. The measurements were taken every hour for a total of 24 hours at relatively low alternate current (A.C.) frequency (1000 Hz). This A.C. technique avoids errors due to polarization of the electrodes. Figure 3.6 illustrates the sample and device used for conductivity measurements.

Figure 3.6. Sample and Device Used for Conductivity Measurements

3.5.6. Temperature

The 21X data logger was used to measure the temperature inside the mortar. The measure point was about 1 inch from the side and 2 inches from the surface. The temperature was continuously recorded for one week.

3.5.7. Flexural Strength

The flexural test was conducted on 7-day concrete beams based on ASTM C78, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)." The distance between two loading points was 4 inches, and 12 inches between two supporting points.

3.5.8. Thermogravimetric Analysis

The Hi-Resolution TGA 2950 Themogravimetric Analyzer from TA Instruments was used in the TGA test. The 50-mg paste powder was heated in the N_2 to 1000°C at a constant heating rate of 10 degrees/minute. Figure 3.7 illustrates the equipment used for the TGA tests.

Figure 3.7. Equipment Used for TGA Tests

4. TEST RESULTS AND DISCUSSION

4.1. Moisture Content

As mentioned previously, concrete mixes usually contain an amount of water in excess of that required for complete hydration to obtain a desired workability. As cement hydrates, some of the water will be chemically or physically bound; the other unbound or free water has the potential to evaporate. Also, at the very beginning of cement hydration, some solid particles in the concrete tend to settle due to their gravity, and the solid settlement facilitates free water to rise to the concrete surface. Thus, fresh concrete loses surface moisture as soon as it is exposed to drying.

The amount of moisture loss in concrete varies with the type of cement, water content, placement temperature, curing materials, and curing time. Figure 4.1 presents a typical variation of moisture content along the depth of a specimen. Generally, the top part of a specimen (with or without application of curing compound) has the lowest and the middle part has the highest moisture content, and the bottom has slightly lower moisture content than the middle part of the concrete.

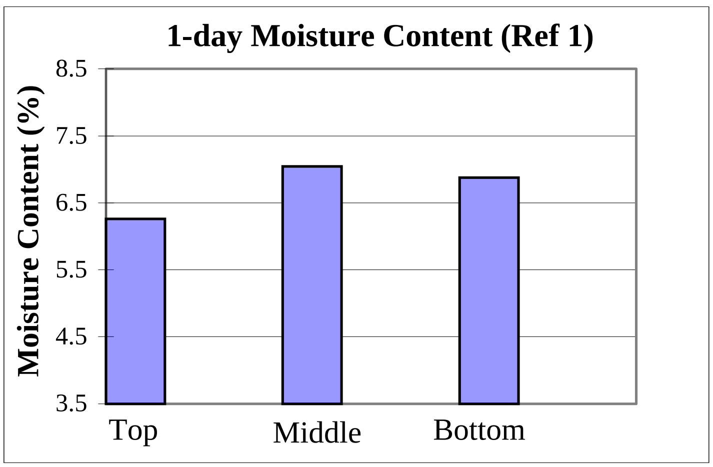


Figure 4.1. Typical Moisture Content Distribution with Depth

The low moisture content in the top part of the concrete is clearly due to moisture loss from the surface. The slightly low moisture content in the bottom part of the concrete might be due to settling and bleeding. In this research, properties of the top part of the concrete are of special interest and are discussed in detail.

4.1.1. Effect of Type of Curing Compound

Figure 4.2 displays the one-day moisture content of mortar specimens made with different curing materials and applied at different times. The specimens with curing compounds were stored in room air curing conditions before and after the compound spray. Their results were compared with the two reference specimens (without curing compound), one of which was cured in the same room in the air (Ref. 1) and the other of which was cured in a standard fog room (Ref. 2).

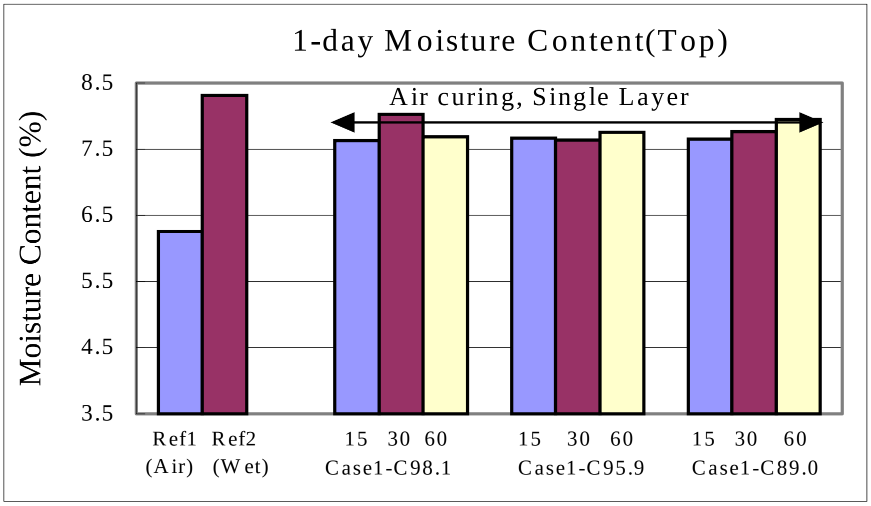


Figure 4.2. Moisture Content of Air Cured Specimens at One Day

As shown in the figure, the moisture content of the Ref. 1 specimen is the lowest (6.3%) of all specimens; that of the Ref. 2 specimen is the highest (8.3%). All specimens applied with curing compounds had moisture content of 7.5%–8.0%. This indicates that the application of curing compounds does prevent moisture loss efficiently. However, there is little difference in one-day moisture content between different curing compounds, possibly due to the limited amount of moisture lost in that short time period.

Figure 4.3 demonstrates the three-day moisture content of the same mortar specimens as presented in Figure 4.2. Figure 4.3 shows that the moisture content of the Ref. 1 specimen decreased from 6.3% at one day to 5.4% at three days; the Ref. 2 specimen had little change in its moisture content over this time period. Although higher than that in the Ref. 1 specimen, the moisture content of the specimen spayed with curing compound 1600 (C89.0) was much lower those in specimens sprayed with curing compounds 1645 (C95.9) and 2255 (C98.1). This indicates that curing compound 1600 (C89.0) has the lowest moisture retention ability of the three curing compounds used, which is consistent with its low efficiency index.

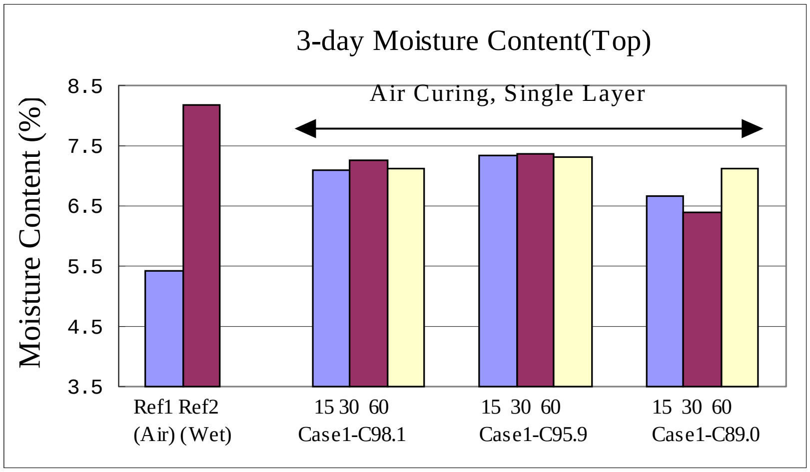


Figure 4.3. Moisture Content of Air Cured Specimens at Three Days

Under severe exposure conditions, such as a hot weather condition, the effects of curing compound application on moisture retention become much clearer. As shown in Figures 4.4 and 4.5, in oven curing conditions, the Ref. 1 specimen, without curing compound, had a moisture content of 4.7% at one day and 3.6% at three days; the specimens with curing compounds had a moisture content of 6.7%–7.4% at one day and 6.5%–7.0% at three days.

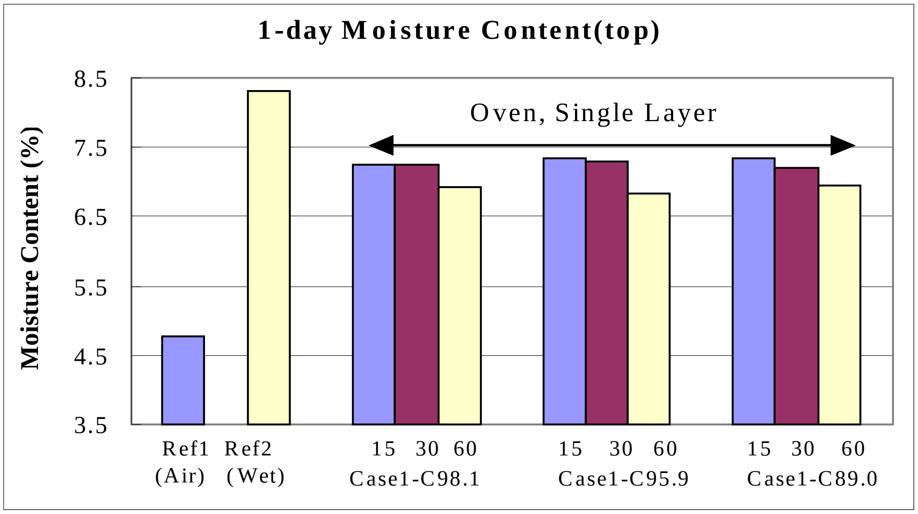


Figure 4.4. Moisture Content of Oven Cured Specimens at One Day

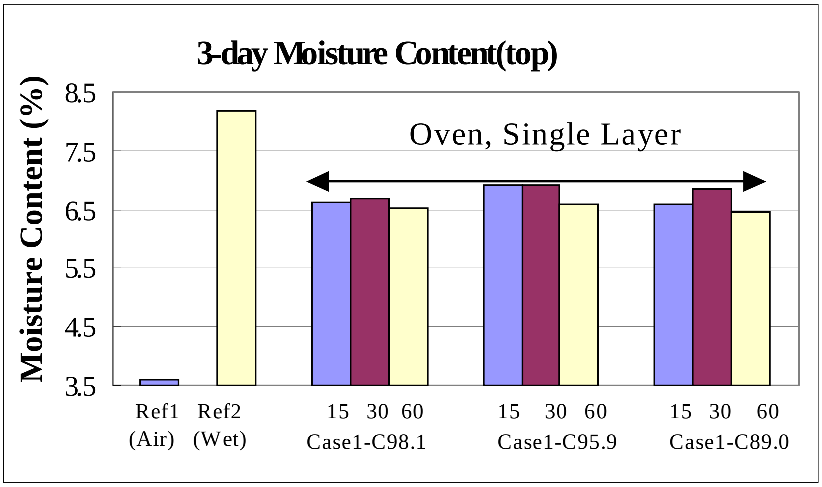


Figure 4.5. Moisture Content of Oven Cured Specimens at Three Days

Compared with air curing, the one-day moisture content of oven cured specimens, on average, increased 1.5%. But the moisture content of samples covered with curing compound improved by 2.4%, compared with samples without curing. This may be caused by the high evaporation rate at high temperatures. Therefore, it is more effective to apply curing compounds in hot weather conditions than in mild weather conditions with respect to moisture content.

4.1.2. Effect of Application Layers and Time

Figures 4.6 and 4.7 exhibit the one- and three-day moisture content of specimens with double layers of curing materials. The tests were performed only on curing compound 1645 (C95.9) and 1600 (C89.0) since curing compound 2245 (C98.1) is expensive and its double-layer application would increase cost significantly.

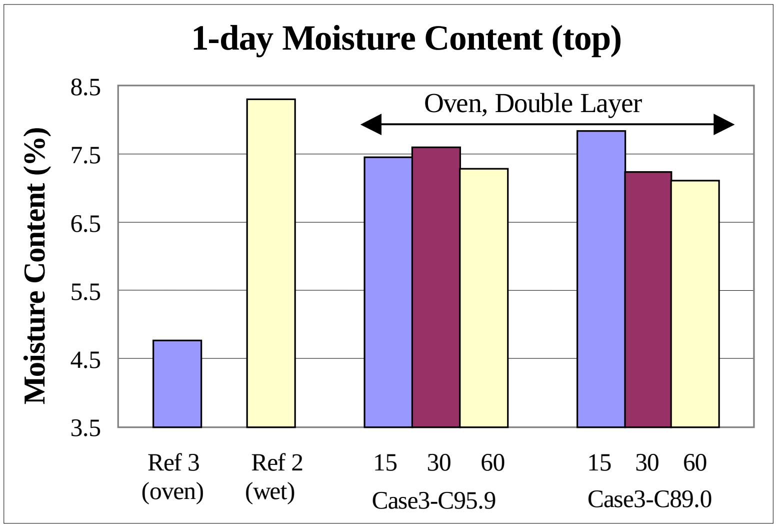


Figure 4.6. Moisture Content of Oven Cured Specimens at One Day—Double Layer

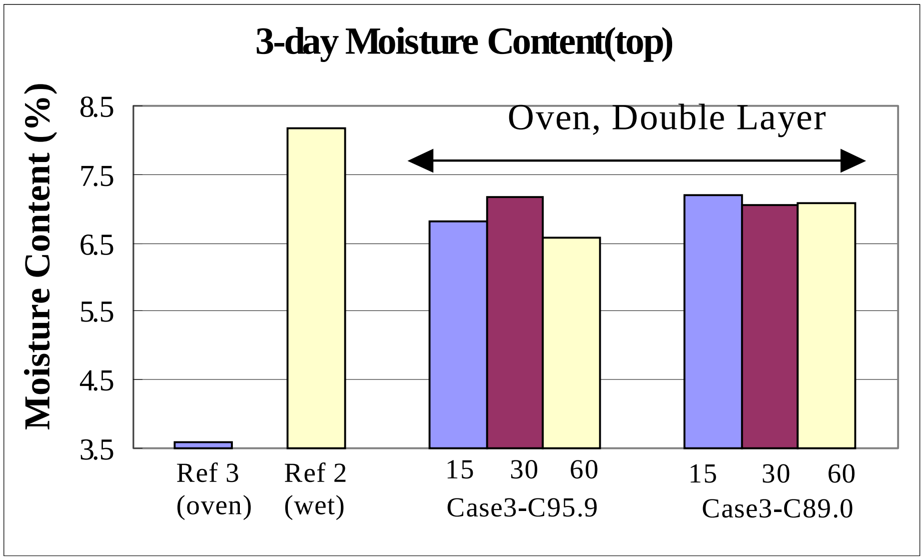


Figure 4.7. Moisture Content of Oven Cured Specimens at Three Days—Double Layer

Compared with single-layer application, as shown in Figures 4.4 and 4.5, double-layer application of curing compounds 1645 (C95.9) and 1600 (C89.0) had little improvement in moisture retention. This may indicate that the moisture content measurement is not sensitive enough to evaluate the differences between double- and single-layer application if curing compound is applied uniformly. (Note that in the present lab experiment all curing compounds were uniformly applied.)

Figures 4.4–4.7 also show that the time of curing compound application appeared to have little effect on moisture content at room temperature. However, in a hot weather condition (oven curing), the moisture content slightly decreased as the spray time increased, except for the sample sprayed with compound 1645 (C95.9) at 30 minutes. This indicates that the application time should be different in different field conditions. In hot weather conditions, curing compounds should be applied earlier than in mild weather conditions.

4.2. Electrical Conductivity

As cement hydration progresses and free water is lost, the numbers and/or mobility of ions in the concrete pore solution are changed. This in turn causes a change in the electrical conductivity of the concrete.

A typical result from an electrical conductivity measurement is shown in Figure 4.8. The electrical conductivity of the mortar specimen increases at the initial stage of cement hydration, reaching a peak at 1–3 hours, and then gradually decreases with time.

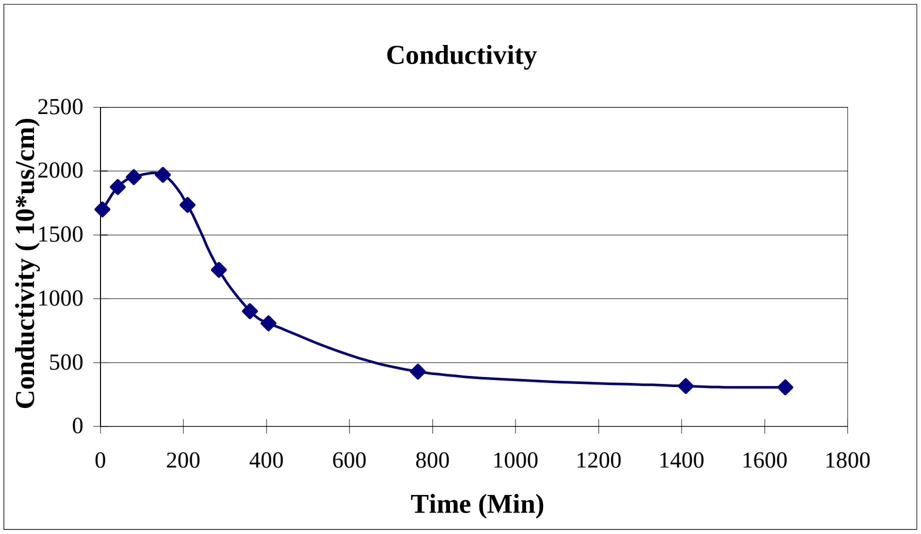


Figure 4.8. Typical Conductivity Curve

(Compound 1600, sprayed at 15 minutes, oven condition.)

For given materials and mix design, the conductivity of concrete depends primarily on the cement hydration process and moisture content in the concrete. At the initial stage of cement hydration, the spaces between cement particles are generally filled with mixing water. The electrical conductivity of the specimen increases with time because of a rapid ion dissolution and high mobility of the ions in the concrete pore system.

As hydration progresses, the amount of water in the mortar pores reduces and the water becomes saturated with Ca^{2+}, Na^{+}, K^{+}, OH^{-}, and other ions. These ions are, however, readily absorbed by the formation of a thin layer of hydration products, which form an envelope around the unhydrated cement grains. This envelope consists of electrical double layers of adsorbed calcium ions and counter-ions that lead to a decrease of both the number and mobility of ions. Consequently, the electrical conductivity of the specimen starts to decrease after reaching the maximum (Ragai and Salem, 2001).

In addition to the cement hydration process, the moisture content of a specimen has significant influence on its conductivity value. Since specimen Ref. 3 (oven cured without curing compound) had the lowest moisture content and specimen Ref. 2 (fog room cured without curing compound) had the highest moisture content among the specimens tested, their conductivity curves formed the lower and upper boundaries, respectively, for all other conductivity curves. That is, the conductivity of all other specimens fell within the boundaries (see Figure 4.9). The electrical conductivity of samples sprayed with curing compounds with high efficiency indices is close to the upper boundary (Ref. 2), and vice versa.

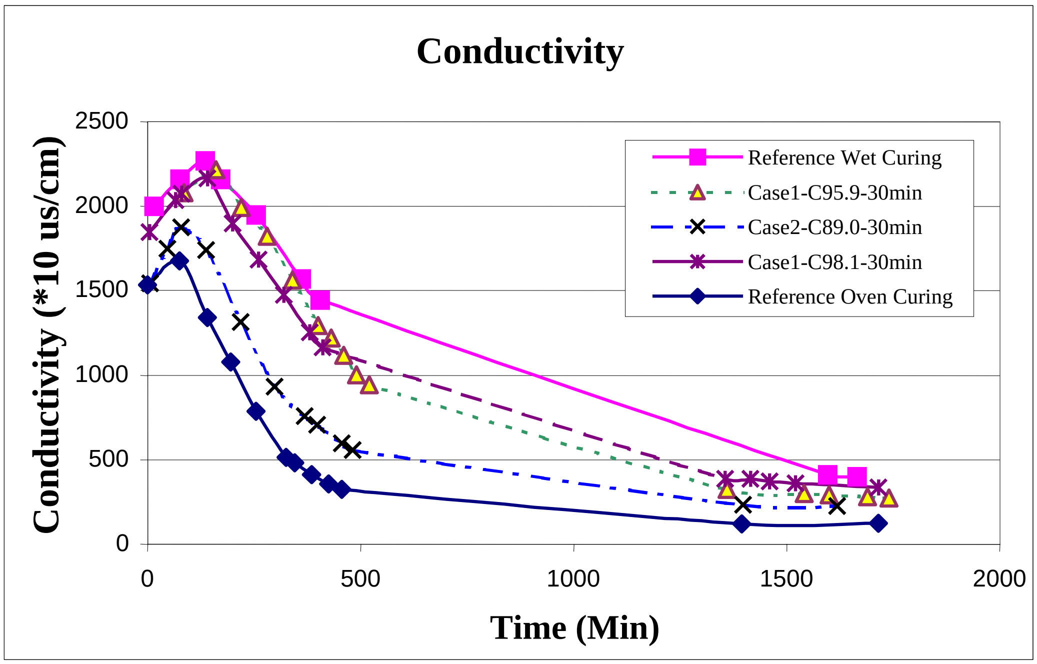


Figure 4.9. Conductivity Curves and Boundaries

4.3. Relationship Between Electrical Conductivity and Moisture Content

The statistical analysis software JMP was used for data analysis. The JMP output shows that conductivity measurements decrease with decreases in moisture content. The estimated relationship is shown in equation 4.1 and Figure 4.10.

$$\text{conductivity} = 1 / [A - B \log(MC)] \quad (4.1)$$

where A and B are constants, and MC is the moisture content of the specimen tested. Based on the present test data, A and B are 18.65 and 7.68, respectively. According to this relationship, the electrical conductivity measurement can be used to estimate the moisture content in the field. Note that the change of w/c ratio, material properties, and other factors will also affect the electrical conductivity. Therefore, the parameters A and B in the equation may change under different conditions.

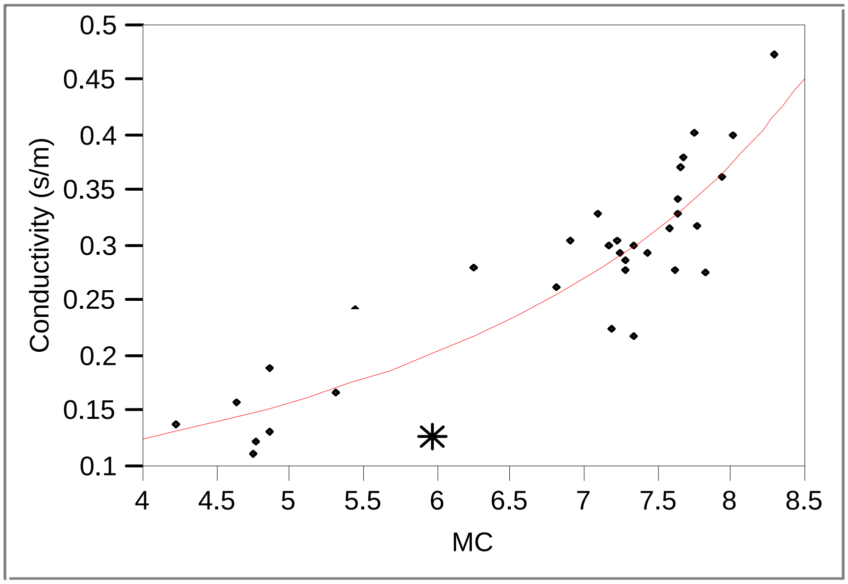


Figure 4.10. Relationship Between Conductivity and Moisture Content

4.4. Sorptivity

Exposed to a surface of free water, concretes and mortars absorb the water at a constant rate, which is defined as *sorptivity*. Sorptivity is closely related to the pore structure characteristics of the concrete or mortar. It is believed that water absorption is the most reliable test method to assess the effects of curing (Bentz et al., 1999). Poor curing will cause very high sorptivity. The effect of curing is more pronounced within about 30 mm (1.2 inches) from the surface. This region loses moisture to the atmosphere (Gowripalan et al., 1990). In this project, 1.3-inch-thick specimens were used.

4.4.1. Effect of Depth

The typical sorptivity test results from the top, middle, and bottom parts of a specimen are presented in Figure 4.11. As shown in the figure, the rate of water absorbed by the tested specimen is nonlinear at the beginning of the test, and then becomes linear with testing time. The slope of the absorbed water-time ($\sqrt{t}$) curve is the sorptivity value of the specimen. Due to temperature and moisture loss, the microstructure of the near-surface-area concrete often does not develop as well as that of the internal concrete. Therefore, the sorptivity of the near-surface-area concrete is generally higher than that of the internal concrete. The internal concrete (middle and bottom parts of the specimens) generally has higher moisture content and curing temperature, which facilitates cement hydration. Therefore, the microstructure in the internal concrete is better than that in the top part, thus resulting in low sorptivity.

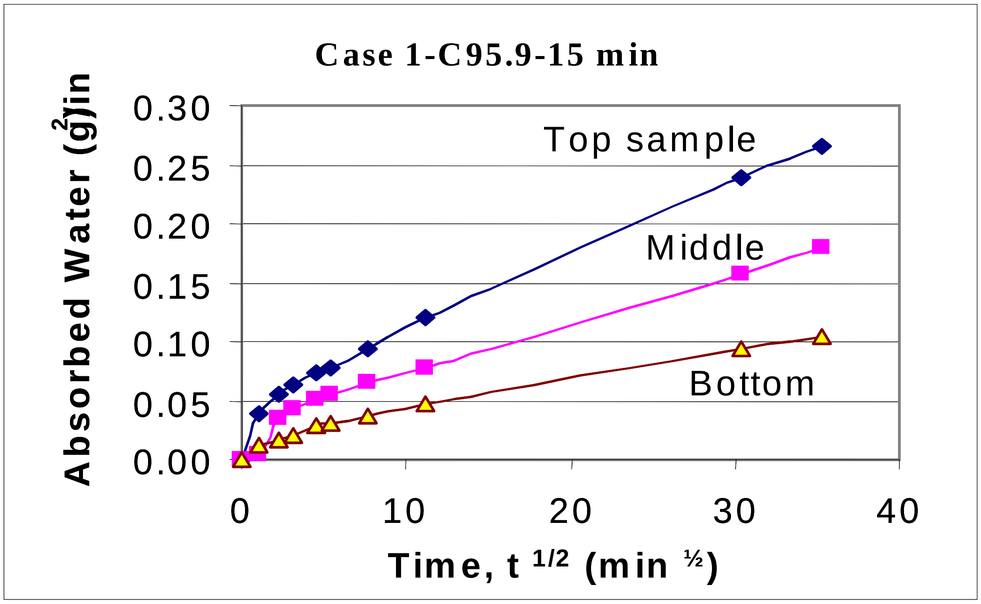


Figure 4.11. Typical Sorptivity Test Results

(Samples, compound 1645 sprayed at 15 minutes, were cured at room temperature for three days.)

4.4.2. Effect of Curing Compounds and Conditions

Figure 4.12 shows the effect of curing condition on sorptivity. It is observed from the figure that regardless of type of curing compound applied, specimens with double-layer application of curing compound and cured in the oven all had the lowest sorptivity, compared specimens with single-layer application of curing compound. Although moisture content measurements did not show clear benefits of double-layer application on curing effectiveness, the sorptivity measurements here clearly demonstrate that double-layer application of curing compound improves the microstructure, especially the pore structure, of the concrete.

Figure 4.13 shows the effect of type of curing compound on mortar sorptivity. It can be observed that regardless of application technique and exposure condition, the specimens with curing compound 2255 (C98.1) had the *lowest* sorptivity; specimens with curing compound 1600 (C89.0) had the *highest* sorptivity; and the specimens with curing compound 1645 (C95.9) had mediate sorptivity. This trend is consistent with the trend from the Iowa effectiveness index tests.

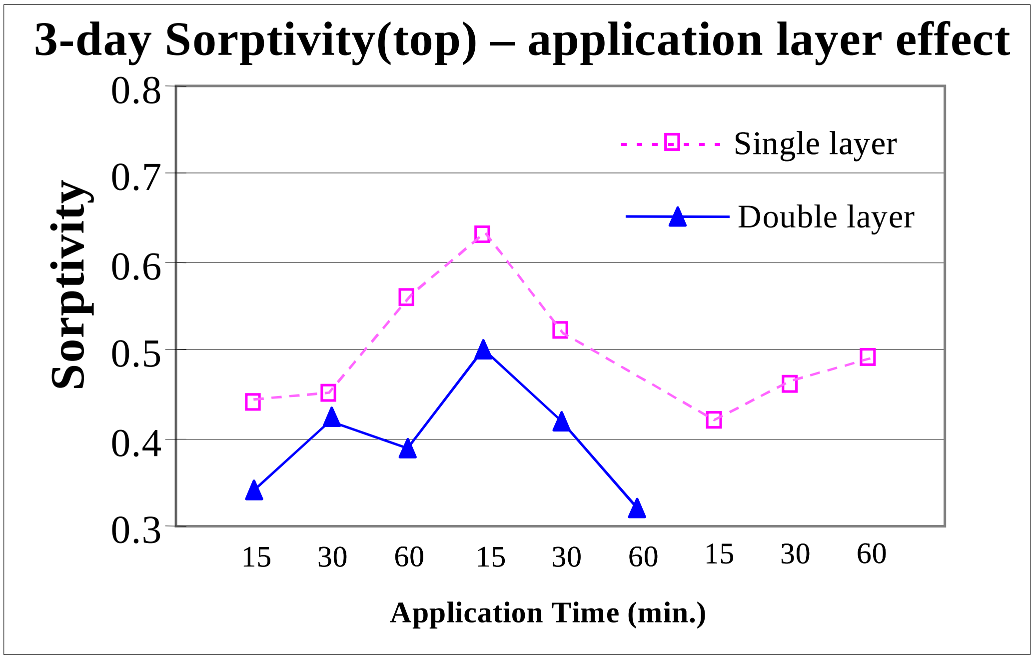


Figure 4.12. Effect of Curing Compound Application and Curing Condition on Sorptivity

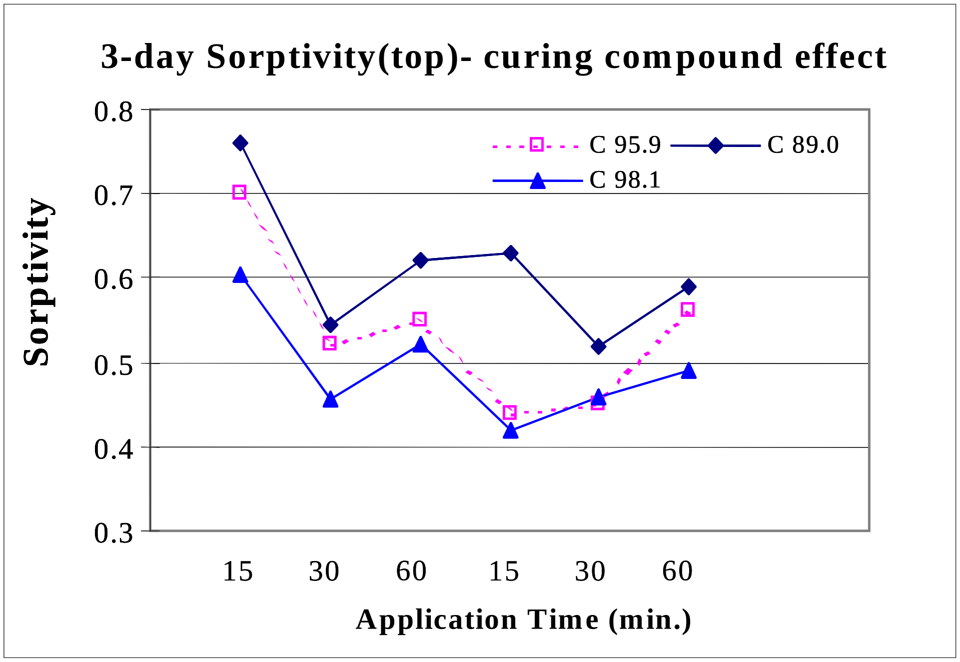


Figure 4.13. Effect of Type of Curing Compound on Sorptivity

4.4.3. Effect of Application Time

Figures 4.14 and 4.15 show the effect of the application time under different curing conditions. For air curing (Figure 4.14), the samples sprayed at 15 minutes had the highest sorptivity and those sprayed at 30 minutes had the lowest sorptivity. It is possible that at 15 minutes after casting, the mortar specimens had not ceased to bleed; that is too soon to apply the curing compound. The bleed water was seen on the specimen surface, which sometimes caused the curing materials to float on the surface of the specimens, resulting in nonuniform coating. At 60 minutes after casting, the mortar specimen surface might start to dry; some curing materials might be absorbed onto the mortar surface, thus preventing formation of an effective membrane and increasing the mortar sorptivity.

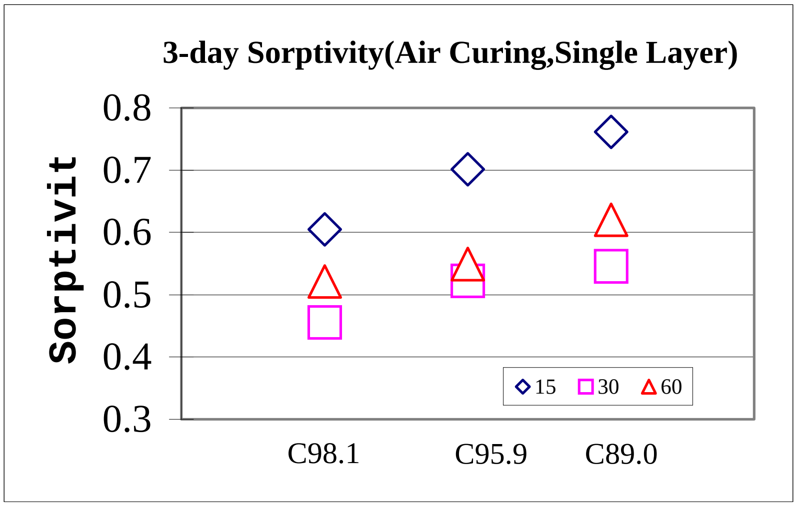


Figure 4.14. Effect of Application Time on Sorptivity—Air Curing, Single Layer

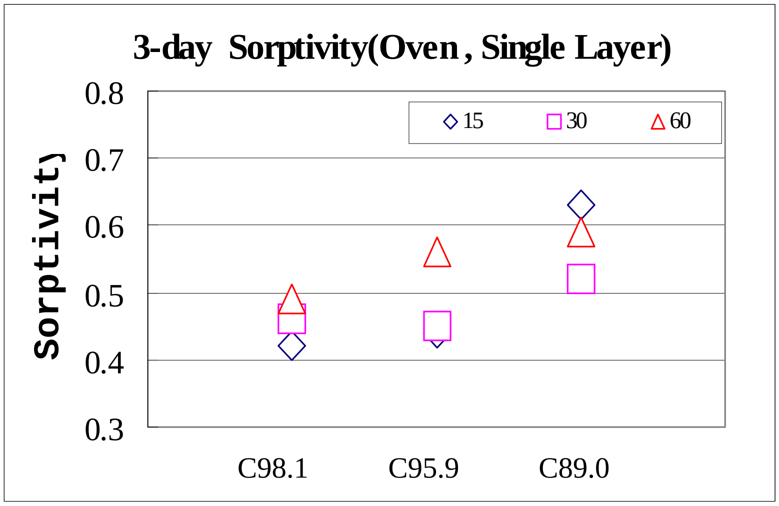


Figure 4.15. Effect of Application Time on Sorptivity—Oven Curing, Single Layer

However, the trend for oven curing (Figure 4.15) is different from that for the air curing. For oven curing, the sorptivity increases as the spray time increases, except for the sample with compound 1600 (C89.0) sprayed at 15 minutes. This result confirms that in hot weather conditions, early application of curing compounds is necessary for quality of curing.

4.5. Degree of Hydration

Two types of methods, furnace method and TGA method, were used to determine the degree of hydration. The furnace method is a very simple and cheap method. The TGA method is easier to control the test environment, quicker, and more expensive. The test data from these two methods were discussed, and the relationship between the two methods was studied.

4.5.1. Furnace Method

Figure 4.16 demonstrates the variation of degree of cement hydration with depth. Generally, the top part of a slab specimen (with or without application of curing compound) has the lowest and the middle part has the highest degree of hydration, and the bottom part has slightly lower degree of hydration than the middle part of the concrete. This trend is consistent with the trend of moisture content. The middle part of a tested specimen usually has high moisture content and high temperature; therefore, it has a high degree of hydration. The top and bottom parts of a tested specimen have low moisture content and possible heat loss; therefore, they display low degree of hydration values.

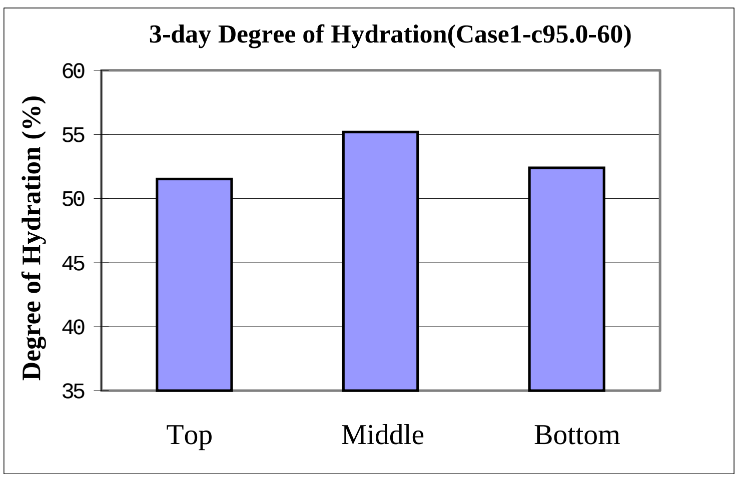


Figure 4.16. Typical Result of Degree of Cement Hydration along Specimen Depth

The degrees of hydration in the near-surface-area concrete specimens are shown in Figures 4.17 and 4.18. It is seen from the figures that the application of curing compound significantly improves the degree of hydration under both mild and hot weather conditions.

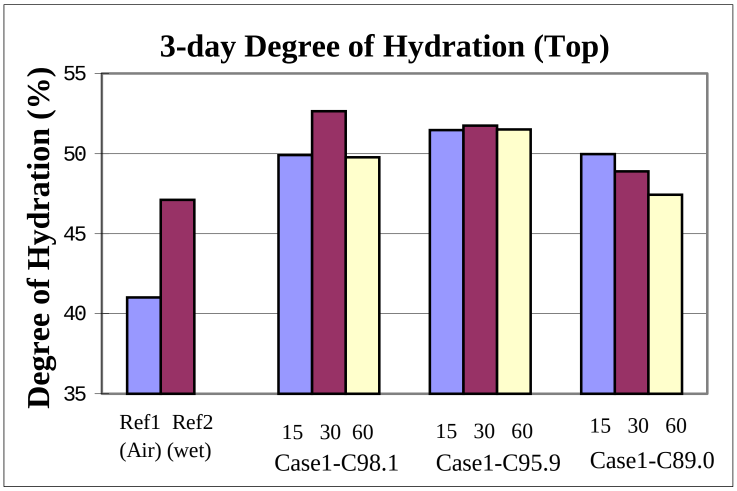


Figure 4.17. Effect of Curing Compound on Degree of Hydration—Air Curing

Under room temperature air curing or mild weather conditions (Figure 4.17), all specimens with single-layer application of curing compound (Case 1) had a degree of cement hydration over 47.5%; the reference specimen cured in the same curing condition without curing compound (Ref. 1) had a degree of cement hydration of 41.5%; the reference specimen cured in a fog room (Ref. 2) without curing compound had a degree of cement hydration of approximately 47.5%.

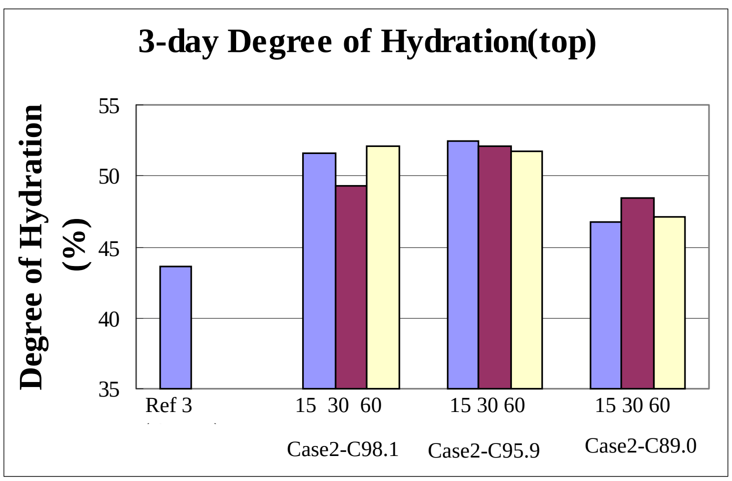


Figure 4.18. Effect of Curing Compound on Degree of Hydration—Oven Curing

Under oven curing or hot weather conditions (Figure 4.18), the specimens with single-layer application of curing compound (Case 2) had a degree of cement hydration of 47.0%–52.5%; the corresponding specimen without curing compound (Ref. 3) had a degree of cement hydration of approximately 43.5%. Compared with mild weather curing conditions (Case 1), hot weather curing conditions (Case 2) appear to activate cement hydration of all specimens. However, the differences in degree of cement hydration between the specimens with and without curing compounds were reduced under hot weather curing conditions, probably due to the more significant loss of moisture.

Figures 4.17 and 4.18 demonstrate that the type of curing compound also affects the degree of cement hydration. No matter whether under room or oven conditions, the specimens with curing compound 1600 (C89.0), on average, had the lowest degree of hydration. This is more pronounced when the specimens were cured in the oven. The specimens applied with curing compounds 1645 (C98.1) and 2255 (C95.9) had compatible degrees of cement hydration.

Figure 4.19 reveals the effect of application layers on cement hydration under hot weather conditions. It is observed that when a high-efficiency-index curing compound 1645 (C95.9) was used, the double-layer application had little improvement on cement hydration. This indicates that when uniformly applied, one layer of a high-efficiency-index curing compound is good enough for proper cement hydration, and no double-layer application of the curing compound is necessary. However, when a low-efficiency-index curing compound 1600 (C89.0) is used, a double-layer application of the curing compound clearly increases the degree of cement hydration. In this case, the second layer helps prevent the loss of moisture and heat, which in turn improve cement hydration.

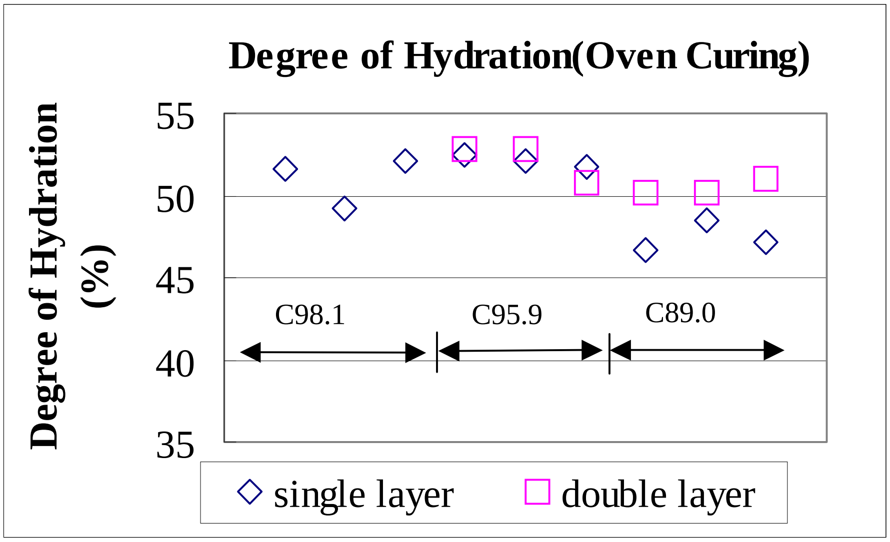


Figure 4.19. Effect of Application Layers on Degree of Hydration

4.5.2. Results from TGA Method

During the TGA test, the sample was heated at a constant rate, 10 degrees/minute, in a nitrogen atmosphere. The weight was automatically and continuously recorded. A typical test result is shown in Figure 4.20. There is a continuous and rapid loss of water below 145°C. In this region, the capillary water, most of the absorbed water, and some of the water of crystallization of calcium aluminate hydrates and ettringite, are lost (Taylor, 1964). The weight loss before 145°C is considered to be from the evaporable water in the paste. The loss of weight is continued at a slow rate after 145°C until almost 400°C. The abrupt change of the slope is due to the decomposition of the crystalline $Ca(OH)_2$. The two floating segments (145°C–400°C and 500°C–1000°C) of the TGA-based line in the figure indicate decomposition of C-S-H gel in the paste. The weight loss after 145°C is considered to be from the loss of evaporable water, which is related to the degree of cement hydration.

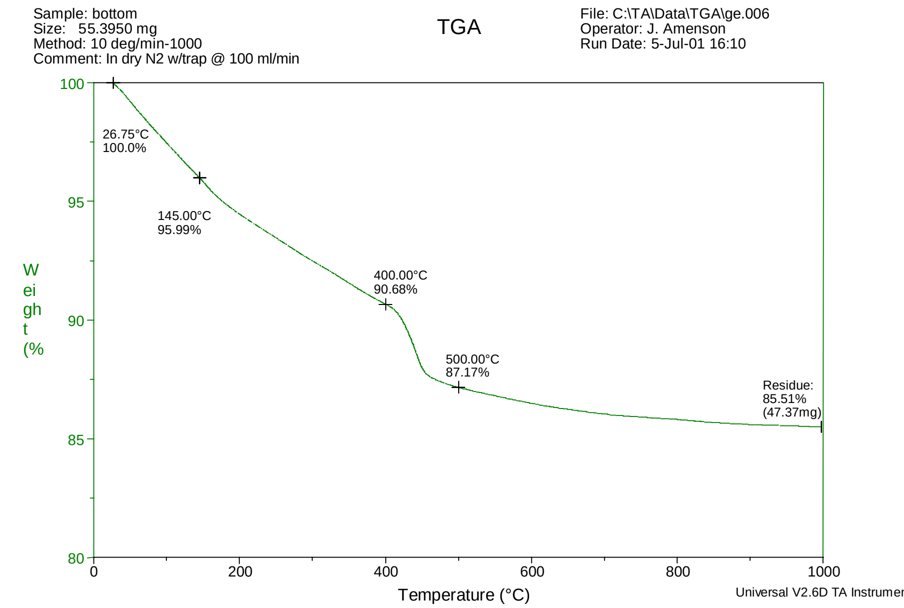


Figure 4.20. Typical Result from TGA Test

4.5.3. Comparison Between Furnace and TGA Tests

The degree of hydration results from furnace and TGA tests are compared in Figure 4.21. The furnace test results had slightly higher values than, but the same trend as, the TGA results. Generally, a TGA test requires expensive equipment, which is not always available in many concrete laboratories; and operation of the TGA test requires special training and experience, whereas the furnace test method for measuring degree of cement hydration is relatively simple and inexpensive, which gives it great potential to be widely used.

A statistical analysis was applied to find the relationship between the results from furnace and TGA tests (presented in Figure 4.22). The figure shows a strong linear relationship between the results from the two test methods ($R^2 = 0.90$). The small difference between these two methods could be partially caused by the control of locations selected from a TGA curve for determination of the evaporable water in cement paste.

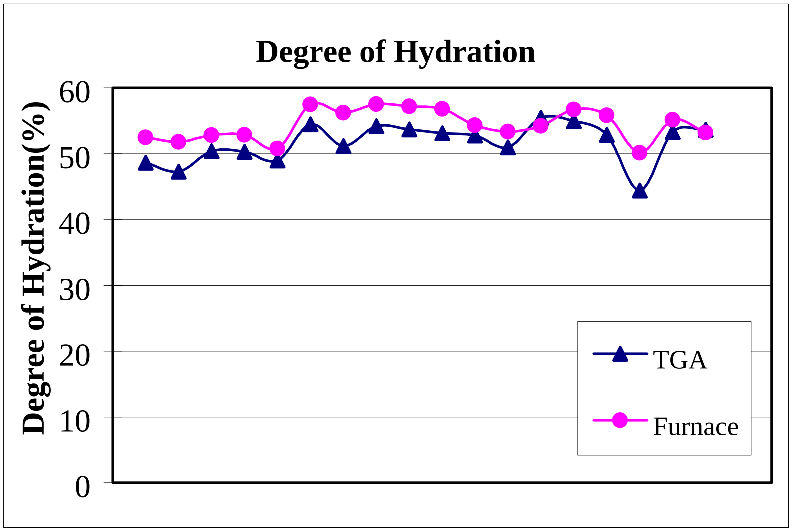


Figure 4.21. Comparison of Results from Furnace and TGA Tests

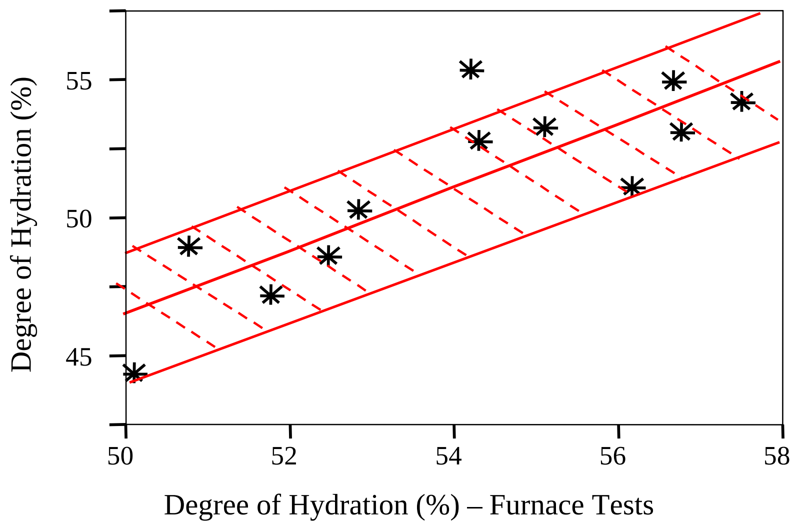


Figure 4.22. Relationship Between Results from Furnace and TGA Tests

4.6. Relationship of Sorptivity with Moisture Content and Degree of Hydration

Sorptivity is closely related to the pore structure characteristics and moisture condition of a tested material. During the cement hydration process, the pore spaces in the concrete are gradually filled with hydration products. The degree to which the pores are filled depends primarily on (1) the initial volume of pores in the cement paste, or the w/c of the paste, and (2) the degree to which the cement has hydrated, or degree of hydration (ACI Committee 308, 2000). In this project, a constant w/c ratio was used for mortar specimens, and another for paste specimens. As a result, the pore characteristics of the specimens were mainly controlled by the degree of cement hydration. For the specimens made with the same materials and mix proportion, their degree of hydration is predominantly governed by curing condition at a given age. Thus, a sorptivity value of a tested specimen may well reflect the curing effectiveness of the specimen.

In this project, the samples used for sorptivity tests were not dried. Therefore, the moisture content in the specimens also affected the sorptivity values. A statistical analysis was conducted to find whether there was any relationship between sorptivity, degree of hydration, and moisture content; the results are shown in Tables 4.1 and 4.2 and Figure 4.23.

Table 4.1. Summary of Fit

	Value
R^2	0.794495
R^2 adj.	0.765137
Root mean square error	0.244729
Mean of response	0.6848
Observations (or sum wgts)	25

Table 4.2. Parameter Estimates

Term	**Estimate Coefficient**	***t* -Ratio**	**Probability > |*t*|**
Intercept	29.111407	3.82	0.0010
MC	-3.556219	-3.20	0.0043
Hydration	-0.534835	-3.38	0.0028
MC * hydration	0.0663069	2.90	0.0086

In the statistical analysis, a linear relation of sorptivity with degree of hydration and moisture was assumed. A scatter plot matrix, Figure 4.23, is used to check the linear assumption. The figure is a plot of residue, which is the difference between the measured sorptivity value and the predicted value, versus each variable. Because these points are scattered in this figure, the linear model is shown to be right. No high-order items are needed in the equation. Otherwise, there would be a clear pattern. For example, if the sorptivity is also related to MC^2, the residual versus MC is conic.

The relation of sorptivity with moisture content and degree of cement hydration can be expressed by

$$\text{sorptivity} = 29.11 - 3.56(MC) - 0.53\alpha + 0.07(MC) * \alpha \quad (4.2)$$

where MC is moisture content and α is degree of hydration.

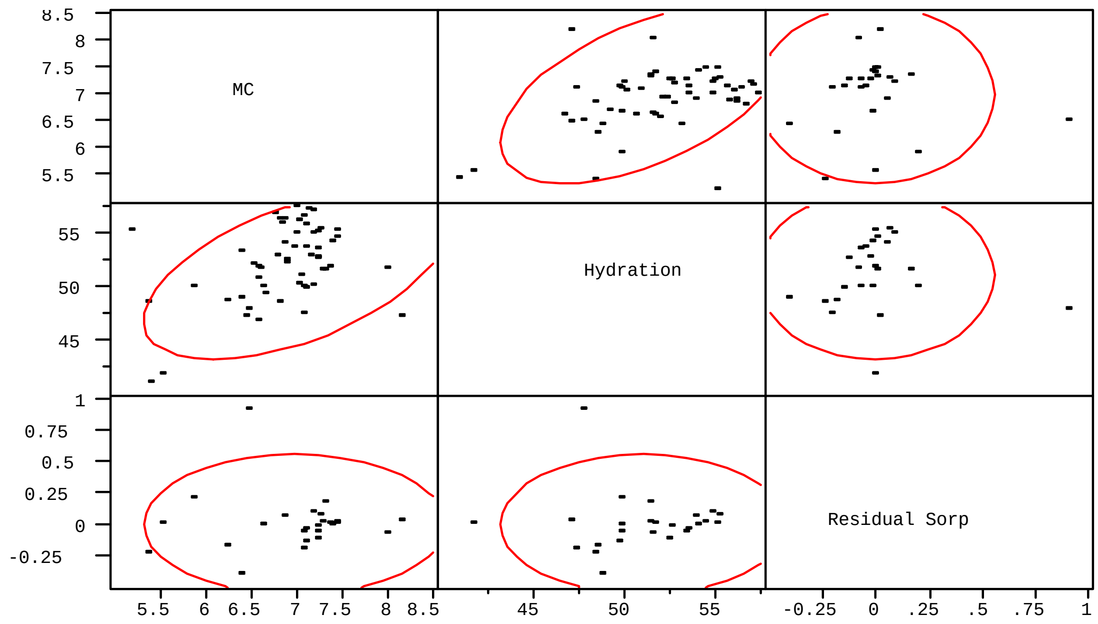


Figure 4.23. Scatter Plot Matrix of Test Data

Table 4.1 shows how strong the linear relation is in equation 4.2. R^2 is called the square of the sample correlation coefficient. $R^2 = 1$ indicates a perfect straight-line relationship; $R^2 = 0$ indicates the absence of any linear relationship. In equation 4.2, $R^2 = 0.79$, or $|R| = 0.89$. Generally, $|R| \geq 0.85$ indicates a strong linear relationship.

The coefficients of parameters in the equation meet "*t*-distribution". The importance of the parameters can be verified by the probability (*p*) of their coefficients. The *t*-ratio in Table 4.2, called the test statistic, is used to calculate the probability. The last column of Table 4.2 displays that probability ($>|t|$) is much less than 0.05, which implies that those parameters are important in the equation.

Note that the equation 4.2 resulted from given mortar materials and mix proportions. If different materials and mix proportions are used, the coefficients in the equation may change.

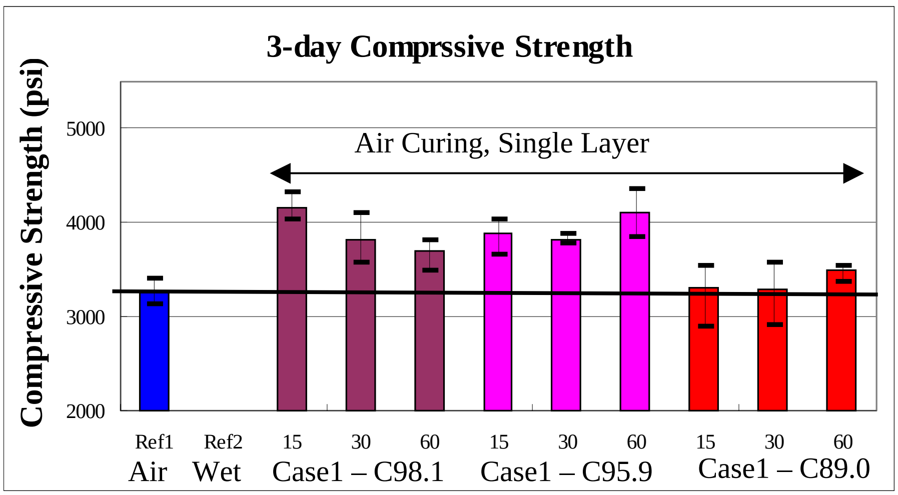
4.7. Compressive Strength

Compressive strength is often used as an indicator of curing effectiveness (Meeks and Carino, 1999). In the present research, three-day and seven-day compressive strength tests were conducted with 2-inch by 4-inch cylinder specimens cored from mortar slabs. The effects of curing on compressive strength are shown in Figures 4.24 and 4.25.

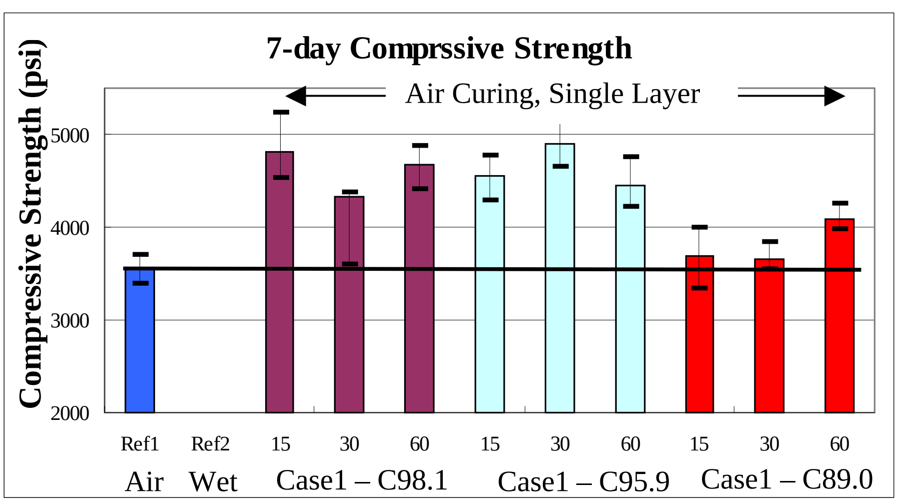
As observed in Figure 4.24, under room temperature air curing conditions, the specimens without curing compound had compressive strengths of approximately 330 psi at three days and 360 psi at seven days. Specimens applied with curing compound 2250 (C98.1) had compressive strengths of 370–420 psi at three days and 430–480 psi at seven days. Specimens applied with curing compound 1645 (C95.9) had compressive strengths comparable to those of the specimens made with curing compound 2250 (C98.1). Specimens applied with curing compound 1600 (C89.0) had similar compressive strength to the specimens without curing compound. It is possible that this curing compound kept only a certain amount of moisture that only affects the properties of the near-surface-area concrete, rather than bulk concrete. On the other hand, a high-efficiency-index curing compound might keep more moisture in the concrete and affect the properties of the concrete farther from the surface, thus improving compressive strength of the specimens.

At high temperatures, the effects of curing compounds are different. Moisture loss becomes critical to strength development. As a result, all three curing compounds improved mortar compressive strength. High-efficiency-index curing compounds, such as 2250 (C98.1) and 1645 (C95.9), appear to be more effective in strength improvement than low-efficiency-index curing compounds, such as 1600 (C89.0). Double-layer application did not significantly influence the compressive strength of the specimens.

Both Figures 4.24 and 4.25 indicate that there is no clear effect of application time of curing compounds on compressive strength. This may be explained by noting that the strength values reflect the bulk material property and the test method is not sensitive enough to reflect a property change in the near surface area (ACI Committee 308, 2000).

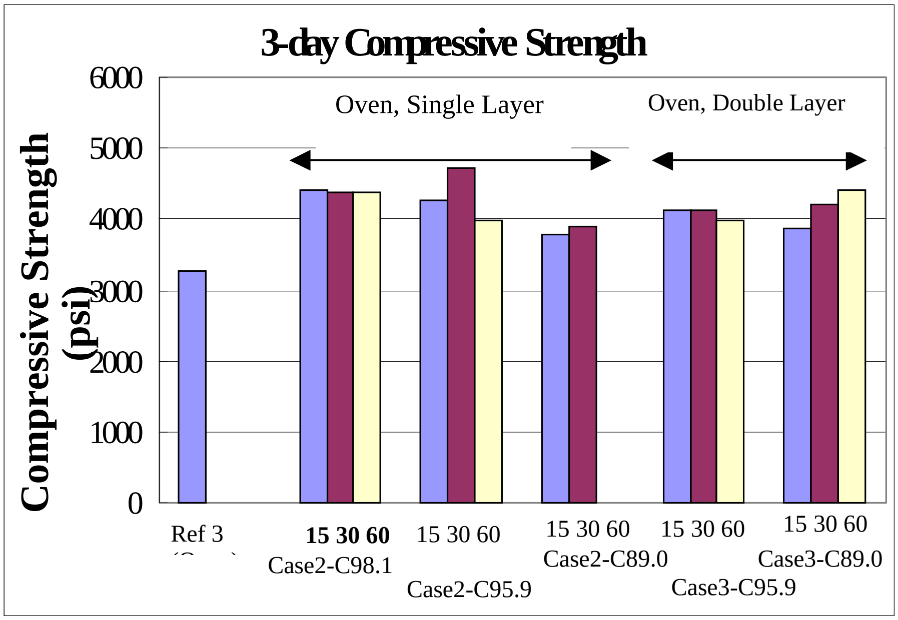


(a)

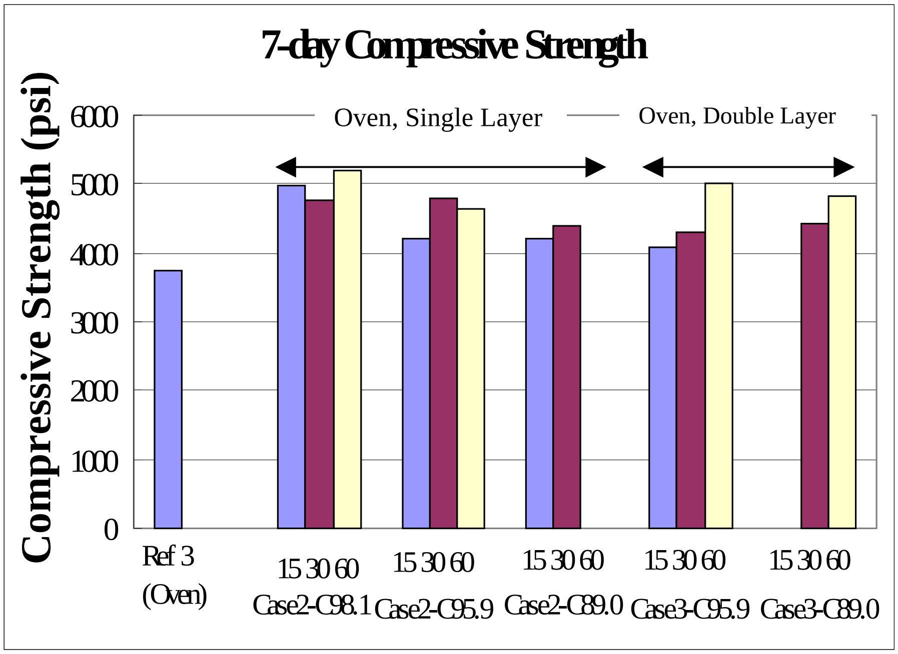


(b)

Figure 4.24. Effects of Curing Compounds on Compressive Strength—Air Curing



(a)



(b)

Figure 4.25. Effects of Curing Compounds on Compressive Strength—Oven Curing

4.8. Temperature and Maturity

When cement is mixed with water, the hydration process occurs. Cement hydration is an exothermal reaction, which generates heat. Since degree of cement hydration depends on both time and temperature, the strength of concrete in the field is often evaluated by a concept of maturity. Maturity is expressed as a function of the concrete temperature and time of curing (ACI Committee 308, 2000):

$$M(t) = \Sigma (T_a - T_o)\Delta t \tag{4.3}$$

where $M(t)$ = maturity (degree - hours), T_a = average concrete temperature during interval (°F), T_o = datum temperature (14°F), and Δt = time interval (hours).

In this project, the temperatures of the mortar slabs were measured, and the maturity was calculated according to Equation 4.3. Figure 4.26 illustrates the differences in maturity values between specimens with and without curing compounds under different exposure conditions. The figure also shows that under the same exposure condition, the specimens applied with different types of curing compounds or with the same compound but applied at a different time after casting displayed little differences in their maturity values. This implies that maturity methods may be not suitable for evaluating the effectiveness of curing compounds.

4.9. Flexural Test

Third-point bending tests were performed on four sets of concrete beams (4 inches by 4 inches by 18 inches) with or without a layer of curing compound. The curing compounds 2255 (C98.1), 1645 (C95.9), and 1600 (C89.0) were applied at 15 minutes after casting. The beams were cured in an oven (100°F) for one day, then de-molded and cured in a fog room (at 73°F and relative humidity greater than or equal to 95%) for another six days before testing. During flexural tests, loads were applied on the sides of the beams, rather than on the top surface where the curing compound was applied. The test results are presented in Figure 4.27. The figure illustrates that there is no significant difference in flexural strength between the specimens with or without curing compound, except that specimens applied with curing compound 1645 (C95.9) had slightly higher flexural strength.

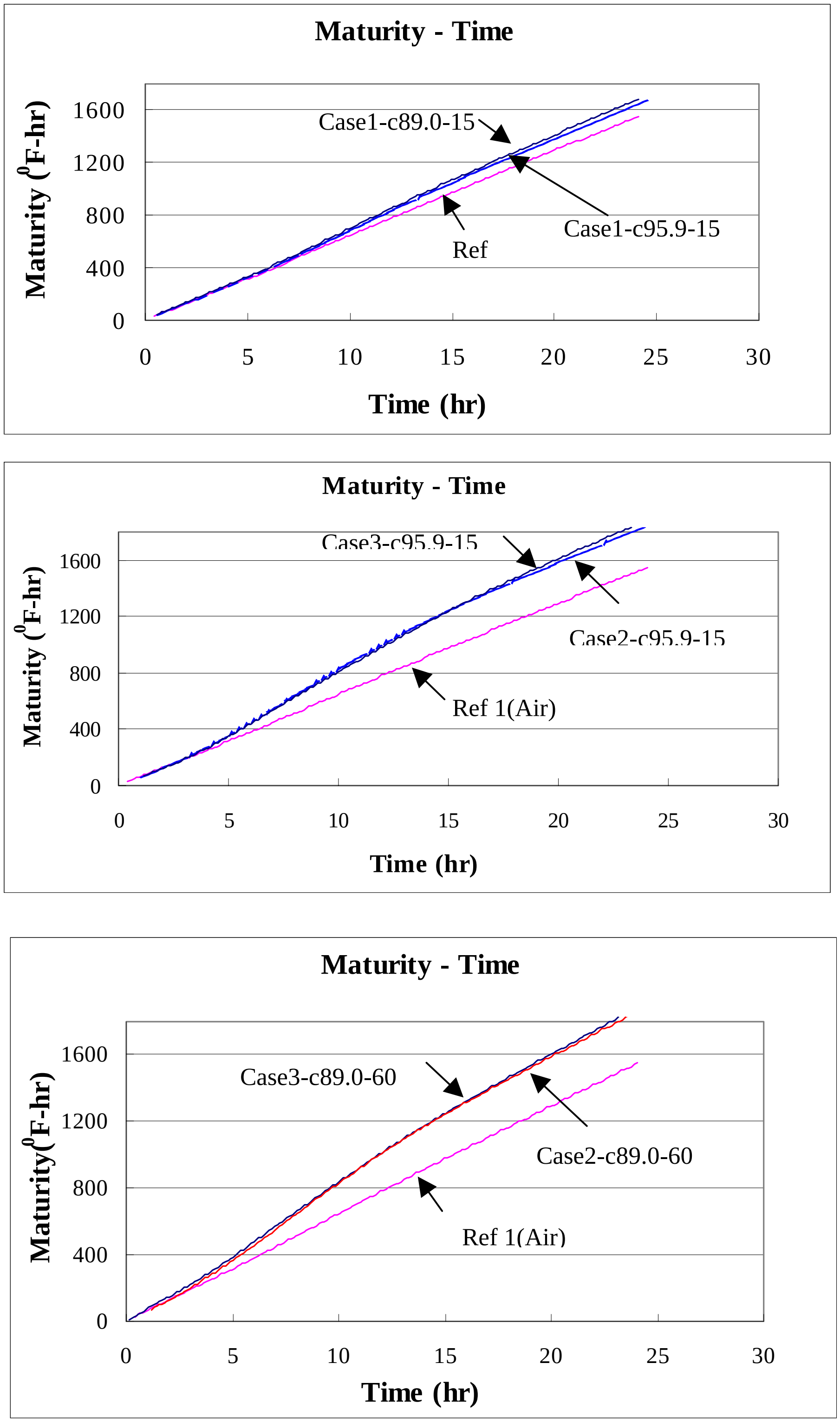


Figure 4.26. Results from Maturity Tests

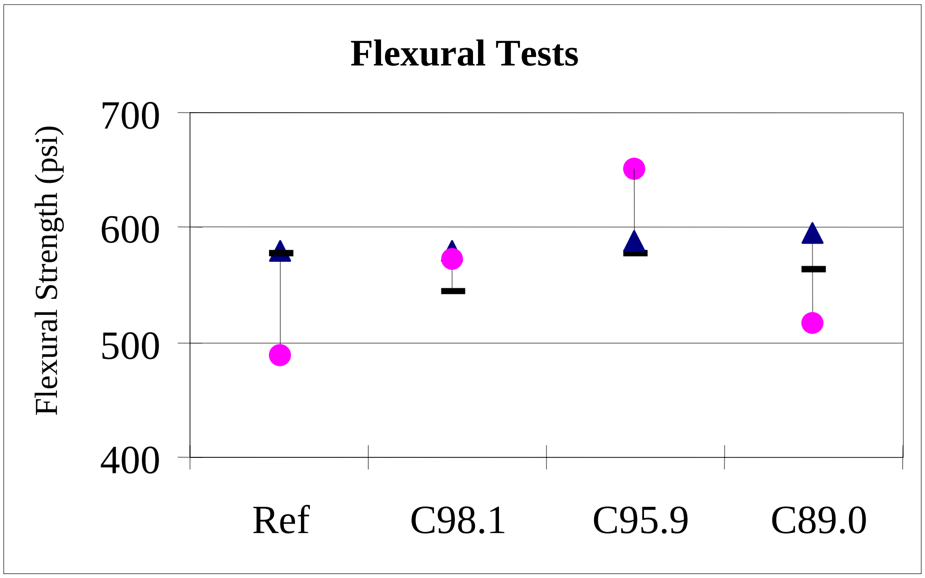


Figure 4.27. Flexural Strength under Different Curing Conditions

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Project Summary

Curing is important for concrete to achieve desirable strength and durability. The purpose of curing is to facilitate cement hydration by providing or retaining adequate moisture and temperature in the concrete for a sufficient time period. Among many curing materials and methods, application of a liquid membrane-forming curing compound is the most widely used for concrete pavements and bridge decks. Curing compounds are economical, easy to apply, and maintenance free. Concrete practice has indicated that the performances of curing compounds are closely related to the characteristics of the curing materials and application methods. Curing especially influences properties of the near-surface-area concrete, which is often the first defense line for concrete deterioration. However, limited research has been done investigating the effectiveness of different curing compounds and their application technology. Presently, there are no reliable standard testing methods available to evaluate the effectiveness of curing.

This research project investigates the effects of curing compound materials and application technology on concrete properties, especially on surface concrete properties. This report presents a literature review of curing technologies, with an emphasis on curing compounds, and the experimental results from Part 1 of this curing project—lab investigation. In the lab work, three curing compounds were selected and applied to concrete (mortars and pastes) at three different times after casting. Two application methods, single- and double-layer applications, were employed. Moisture content, conductivity, sorptivity, and degree of hydration were measured at different depths of the specimens. Flexural strength and compressive strength of the specimens were also tested. Statistical analysis was conducted to examine the relationships between these material properties. The major findings from the lab study are presented as below.

5.2. Major Research Findings

The following observations were made from the lab investigation:

1. Regardless whether or not a curing compound was applied, the properties of the near-surface-area concrete, such as degree of hydration and sorptivity, differed from those of internal concrete.

2. Application of a curing compound significantly increased moisture content and degree of cement hydration and reduced sorptivity of the near-surface-area concrete.

3. Specimens applied with a high-efficiency-index curing compound generally had lower sorptivity, higher conductivity, higher degree of hydration, and higher compressive strength values than specimens applied with a low -efficiency-index curing compound. The effects of type of curing compound on the properties of the near-surface-area concrete appeared to be more significant in hot weather conditions.

4. In mild weather conditions (room temperature air curing), specimens with curing compounds applied at 30 minutes after casting showed better properties (low sorptivity) than those with compounds applied at 15 or 60 minutes, probably due to the effect of bleeding water. However, in hot weather conditions (oven curing), early spray provided the concrete with high moisture content and low sorptivity. These results indicate that in concrete practice,

application time of a curing compound should be adjusted based on the concrete bleeding behavior and the environmental condition.

5. A double-layer application of a high-efficiency-index curing compound, such as 1645 (C95.9) and 2255 (C98.1), did not significantly improve the concrete's properties when compared with the corresponding single-layer application. However, a double-layer application of a low-efficiency-index curing compound, such as 1600 (C89.0), clearly improved the concrete's properties when compared with the corresponding single-layer application. The results indicate that if a high-efficiency-index curing compound is uniformly applied with a sufficient amount, no double-layer application is necessary; while a poor curing material and/or non-uniform application are employed, a double-layer application will improve concrete properties.

6. The effects of type of curing compound on properties of the near-surface-area concrete were demonstrated by the results from sorptivity, degree of hydration, and compressive strength tests but not from moisture content measurements.

7. Although conventional compressive and flexural strength tests are commonly performed for lab and field specimens and their results are often used as an quality index of concrete, our research indicates that these tests do not provide good indication for the subtle changes in the near-surface-area concrete. Therefore, the tests are not appropriate for evaluation of curing effectiveness.

8. Maturity tests demonstrated that specimens with curing compound had a slightly higher maturity value than those without curing compound. However, the test method used is not sensitive enough to show the effects of different types of curing compounds and different application times.

9. The degree of cement hydration measured from the furnace method demonstrated a similar trend, with slightly higher values, to that from TGA test.

10. Of all the test methods applied, the sorptivity test is the most sensitive one to provide a good indication for the subtle changes in microstructure of the near-surface-area concrete caused by different curing materials and application procedures.

11. Conductivity measurements of the near-surface-area concrete showed a close relation with moisture content of the concrete. The relationship can be expressed as follows:

$$\text{conductivity} = 1 / [A - B \log(MC)]$$

    where A and B are constants, related to concrete materials and mix proportion. Using this relationship, the water retention ability of a curing compound can be estimated by monitoring the conductivity of the surface concrete in the field.

12. Sorptivity measurements of the near-surface-area concrete demonstrated a close relationship with moisture content and degree of hydration (α). The relationship can be expressed as follows:

$$\text{sorptivity} = 29.11 - 3.56(MC) - 0.53\alpha + 0.07(MC) * \alpha$$

5.3. Recommendations

Note that a key aspect of the work is the lab procedure for testing curing compounds versus the field application of the curing compounds. In the lab, specimens have no texture and curing compounds evenly fill the pinholes in the specimens before testing. The specimens have near 100% efficiency of compound coverage in the lab spraying; this is certainly less than 100% in the field. The Part 1 research results have established a baseline for and provided insight into the further development of testing procedures for evaluation of curing compounds in the field. More research is needed in the Part 2 field study.

Based on the research results from the Part 1 (Phases I and II) study, the following suggestions are proposed to be considered in the Part 2 study (Phases III and IV) of the research project:

1. The Part 1 study has shown that curing compounds 2255-White and 1645-White showed comparable performance, and single-layer application of curing compound 1600-White showed a lower level of performance when compared with compounds 2255 and 1645. All the three curing compounds are suggested to be studied in the field again due to the consideration of the differences between field and lab conditions. The results from the curing compound applications will be compared with the wet curing technique, or wet burlap application.

2. The optimal application time for curing compounds is primarily dependent upon the moisture condition of the concrete surface, which is significantly influenced by the weather condition and bleeding characteristics of the concrete. Considering the effects of the wind and the radiant heat from the sun in hot weather on field concrete, early spray (such as 3, 5, or 8 minutes after paving) should be studied.

3. The results from lab tests have indicated that if a sufficient amount of a high-efficiency-index curing compound is uniformly applied, no double-layer application is necessary. Note that the lab specimens and the lab applications are in “near perfect” conditions for the application of curing compounds. In the field without perfect application and ideal environmental conditions, the effect of a double application may be more evident than in the lab. Therefore, it is suggested to verify performance of the concrete applied with a double-layer of curing compounds 1645 and 1600 in the Part 2 study.

4. Since double-layer application may not be necessary when a high-quality curing compound is well sprayed, it will be significant to investigate the effect of application rate, or amount of curing compound applied as a single layer, on curing effectiveness.

5. The Part 1 study has demonstrated that conductivity measurements have a close relationship with moisture content of concrete. The nondestructive conductivity test used in the Part 1 study can provide a quick and effective method to evaluate multiple locations in the Part 2 field research. It will also provide a valuable comparison of laboratory readings to field readings for the each curing compound and uniformity of compound application. We strongly recommend adopting this test method in the Part 2 field research.

6. Since conductivity is also influenced by concrete chemistry and temperature, the coefficient in the conductivity-moisture equation described in this report may change with different concrete materials, mix proportions, and weather conditions in a job site. To solve this problem, we suggest estimating water retention ability of curing compound based on the difference in conductivity between the near-surface concrete and interior concrete. (That is,

water retention ability (%) = $|\sigma_{surface} - \sigma_{interior}| / \sigma_{interior} * 100\%$, where σ is conductivity of concrete.) A device will be designed to measure the conductivity profile along the depth of the concrete pavement.

7. An alternate test method, such as moisture sensor, is also suggested to double-check the moisture content in the concrete pavement.

8. The Part 1 study results indicate that of all the test methods applied, the sorptivity test is the most sensitive one to provide a good indication for the subtle changes in microstructure of the near-surface-area concrete caused by different curing materials and application procedures. Therefore, we suggest testing sorptivity of selected field samples to evaluate the field curing effectiveness.

9. Although results from the Part 1 study indicate that the maturity test is not sensitive enough to show the effects of different types of curing compounds and different application times, the tests *did* demonstrate the difference between specimens with and without curing compound. The test should also be conducted in the Part 2 study to provide information on bulk concrete pavement strength development.

10. Properties of the near-surface-area concrete have more significant influences on concrete durability than on concrete strength. To further study the effects of curing compounds on properties of the near-surface-area concrete, permeability and splitting/tensile strength tests may be conducted for the surface concrete in the Part 2 study.

Table 5.1 summarizes the recommendations for the Part 2 field study.

Table 5.1. Summary of the Recommendations

	Recommendations			
	Compound	**Application Rate**	**Application Layer**	**Application Time**
Curing materials and application procedures (for hot weather)	Wet curing	—	—	—
	2255-White	Low and normal	Single	≤5 minutes
	1645-White	Low, normal, and high	Single and double	≤5 minutes (first) +2 minutes (second)
	1600-White	Low, normal, and high	Single and double	≤5 minutes (first) +2 minutes (second)
Field tests	Visual inspection			
	Conductivity			
	Moisture sensor			
	Maturity			
Field sample tests (optional for selected samples)	Sorptivity			
	Splitting/tensile strength			
	Rapid chloride permeability			

The detailed work program for the Part 2 field study will be provided in a separated document.

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