TIMELY AND UNIFORM APPLICATION OF CURING COMPOUND ON CONCRETE PAVEMENT

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ABSTRACT

Concrete curing is a critical stage during construction for volume stability, long-term strength development, and ultimate durability. Poor curing can lead to shrinkage, scaling, and other durability issues. Proper concrete curing maintains sufficient moisture in the concrete and allows continuous hydration. The high surface are-to-volume ratio of concrete pavement is making it difficult to maintain a uniform moisture content throughout the pavement, therefore curing concrete will provide a better environment for concrete to develop uniform and equal hardened properties. While a variety of curing techniques can be used, including wet curing, internal curing, and forced chemical curing, membrane-forming curing compounds (MFCCs) are often the easiest and most cost-effective technique to minimize evaporation for pavements and slabs placed on grade. The application of MFCC has been adopted by States Department of Transportation (DOT). However, achieving a quality curing has been challenging because of the limitations of techniques that can be implemented on field to evaluate the effectiveness of curing compound application on concrete pavement in real time. Some states DOTs rely on the use of the calibrated white paper sheet examination or the experience of the engineer for evaluation of the curing compound application effectiveness. Additionally, most of the evaluation tests are performed on hardened concrete and not applicable or difficult to assess for fresh concrete in the field.

This study has developed a test method embedded resistance that can measure curing effectiveness in real-time during the early age of concrete. The embedded resistance as a measure to assess drying behavior of fresh concrete to quantify the effectiveness of curing Embedded resistance is a technique that uses concrete moisture content to assess the effectiveness of curing compound effectiveness on concrete. Concrete goes through phase change from plastic phase to solid during the early age. This transition is mainly caused by the hydration reaction. During the early age of concrete cement reacts with water to produce hydration reaction products and the excess water evaporate due to drying, leading to concrete microstructure development. However, at early age the presence of moisture in concrete makes concrete less resistant to current flow, as the electrical current in concrete moves through the pore spaces. With time more pores spaces in concrete are filled up with hydration reaction products, subsequently concrete becomes more resistant to the current flow, as electrical conductivity ability of concrete depends on the conductivity of the fluids inside the interconnection of pores system, the degree of saturation of the concrete, and the permeability. Therefore, using the resistance technique to trace moisture content in concrete can be an important tool to assess curing compound application effectiveness on fresh concrete.

The study evaluated the effect of curing compound applications rates and application time using the embedded resistance technique. Furthermore, this study investigated the effects of curing compound application time on freshly placed concrete, the effect of curing conditions as well on the performance of concrete cured before and after the initial setting time, and lastly the effect of curing compound application rates and uniformity during the application. Tests were indexed against the standard moisture loss testing in addition to a newly developed real-time assessment of moisture loss and curing by embedded resistance. Ultimately with the goal of providing a correlated measure of moisture loss from field measurements. Lastly, surface profile degree of

hydration and the maturity curve were performed in this study to under the effect of curing compound application rates on degree of hydration and strength gain.

The findings from this study demonstrated that resistance is able to distinguish between samples with and without curing compound and significant differences in drying observed between the surface and relatively shallow depths. Additionally, the testing techniques were able to differentiate between the quality and rate of curing compound application and evaluate performance across a variety of environmental conditions. These findings indicate that a resistance-based approach could be a low-cost and non-destructive technique to evaluate the effectiveness of curing compound applications in real-time. Additionally, the study showed that a correlation can be found between moisture retention test, degree of hydration and the embedded resistance test. Based on the findings the embedded resistance test could be a suitable replacement for moisture loss test the test is much simpler and quicker test to be performed both in the lab and in the field.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of the School of Graduate Studies, have examined a dissertation titled "Timely and Uniform Application of Curing Compound on Concrete Pavement" presented by Etienne Beya Nkongolo, candidate for the Doctor of Philosophy degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1 INTRODUCTION

1.1. Statement of the research problem

Concrete pavement is designed to provide a long service life. However, the concrete curing regime affects the durability of concrete. Concrete is cured in order to maintain adequate moisture and temperature for a sufficient period to favor hydration reaction, which results in concrete strength gain and microstructure development. For large concrete structures or pavement exposed to different environmental conditions at early age, quality curing is required to obtain design strength and long service life. There are different methods of curing concrete, but most of states agencies have adopted the use of Membrane Forming Curing Compound (MFCC) due to less maintenance and low cost. However, there are no existing methods for quantifying or systematically evaluating the quality or effectiveness of curing in the field. Many specifications rely on the curing application rate which is the quantity of curing compound that can be applied on a specific surface area of concrete pavement, and for some other States Department of Transportations (DOT) the acceptance of the curing compound application is depending on the inspector's experience and quality standards such as uniform coverage and how curing compound appears mostly compared to white paper sheet. Therefore, this study is exploring ways to provide a methodology that can be used as quality control, capable of measuring or monitoring the effectiveness of a curing compound applications in the field.

1.2. Background

Concrete is the most crucial construction material in the world for the development of civil infrastructure (Taffese and Nigussie 2023). Nevertheless, its strength and durability are subject to various factors. Poor Curing of concrete can be one of the factors that can negatively impact the strength and durability of concrete. Concrete curing is the act of maintaining adequate moisture

and temperature in the concrete to maximize the hydration process for a defined period, so that concrete develops in such a way that the desired material properties are obtained (Vandenbossche 1999; ACI 2016). Curing is fundamental to concrete performance and durability. Concrete curing facilitate the cement hydration reaction to occur between water and cement, and the hydration reaction products are at the cause of concrete strength gain and low permeability as the occupy the pores spaces left by water in concrete and at the same time binding the aggregates together and creating a solid mass that reduces the porosity of the concrete and developing concrete physical and mechanical properties (Neville and Brooks 2010; Taffese and Nigussie 2023). Ensuring that the desired strength development and long-term durability of concrete are met, action should be taken when curing to prevent water evaporation from the concrete surface during the early age life of concrete (Pawar and Kate 2020). Concrete curing can be achieved through different methods such as ponding, fogging and the application of membrane forming curing compound (Taylor et al. 2019). The use of membrane forming curing compound is mostly adopted techniques for curing of concrete pavement.

MFFC forming curing compound is chosen for concrete pavement curing due to the ease of the application and to provide a uniform strength development of the pavement due to the large volume-to area ration of the concrete pavement. However specific quantification of curing effectiveness is difficult to find. Some states Department of Transportation (DOT) use the highly calibrated white paper examination, and some rely on the visual observation of the engineer. Additionally, some construction specifications such as Wisconsin Construction and Materials Manual, ASTM International among others do not provide proper configuration to qualify curing effectiveness characteristics in terms of the type of performance expected from a given environment. Curing effectiveness is attached to a list of specific concrete pavement distress types

such as plastic and drying shrinkage, cracking, scaling, joint spalling, and freeze-thaw deterioration. Plastic shrinkage occurs when the rate of water loss at the surface of concrete exceeds the rate of bleed water available (Vandenbossche 1999), with time shrinkages developed at the surface of concrete can create cracks, weakening the concrete surface leading to spalling and scaling thus allowing the penetration of harmful substances such as salt and other in concrete and affecting the durability and service life of concrete (Combrinck and Boshoff 2013), therefore MFCC is used to help prevent shrinkage cracking by reducing the rate of water evaporation from the concrete surface. For a MFCC provide a better performance in terms of moisture retention, curing compound needs to be applied properly in terms of right time of application, amount that should be applied and lastly uniformity during the application (Joshaghani and Zolinger 2017).

Most specifications for membrane-forming curing compound application require an application rate of 180-200 ft^2/gallon with little regard for field conditions or the potential for over or under-curing. Although, ASTM C309 curing compound selection criteria for concrete paving such as water retention, pigment types, drying time, type and amount of solids, VOC, and compatibility with coatings have been identified, researched, and found to have utility for product approval, none of these have been systematically related to pavement performance or even a performance-related parameter that is practical and measurable under field conditions. Furthermore, ASTM C156 standards test of water retention by concrete curing materials, is focused on water retention and requires a controlled environmental chamber that has a potential of evaporation from 0.65 to 1.1 kg/m^2/hr. (0.133 to 0.225 lb./ft^2 /hr.). The standard water loss limit according to ASTM C309 and American Association of State Highway and Transportation Officials (AASHTO) M148 is 0.55 kg/m^2 (0.113 lb./ft^2) for a duration of 72 hr. at 100°F at 200 ft^2/gallon. This standard water loss limit is based on the strength of stripped and coated cylinders

dating to the 1930s and 1940s with much coarser cements, little to no SCMs, poorly optimizes aggregate gradations, and much higher water-to-cementitious ratios. However, the ASTM C156 presents some limitations such as, test is conducted on mortar specimen which exhibit higher evaporation rate than concrete, poor reported precision between laboratories, cannot be considered for field application since testing is only conducted under fixed ambient conditions (temperature, relative humidity, and wind speed), and a determine application rate among others (Sun and Zolinger 2015). Quality concrete curing is achieved through uniform and proper application of curing compound (Helgeson 2014).

1.3. Purpose and goals

The study entails the qualification of curing compound application effectiveness relative to effects on long-term performance of concrete pavement. Curing quality combined with weather conditions at the time of construction are important factors in the performance and durability of concrete pavements. Adequately cured concrete has adequate moisture for continued hydration and development of strength, volume stability, resistance to freezing and thawing, and abrasion and scaling resistance.

The main objectives are:

- Determining the evaporation rates inside the environmental chambers for all the curing conditions for the laboratory work.
- Collecting data in accordance with the experimental design of the mix matrix. Including evaluation of baseline properties of every concrete batch produced, determining the compressive strength and surface resistivity of the mixture design.
- Investigating the effect of curing conditions, application rate, uniform application and lastly the application time of the membrane forming curing compound of fresh concrete produced

in the laboratory, by performing test such as Moisture retention (ASTM C156), surface profile degree of hydration and embedded resistance, and lastly identifying the correlation between these tests.

- Observing and recording when and how uniformly the curing materials are applied by assessing representative concrete pavement projects in Wisconsin,
- Documenting how curing compound application times and coverage relate the development of distress (such as: shrinkage, cracks, scaling, or delamination) on concrete pavement, and
- Developing a measurable methodology to establish optimal times and assess uniform application.
- Validating the use of embedded resistance measurement as new technique to assess curing effectiveness through field work investigations.
- Introducing Real-time curing, which is a concept that helps to connect laboratory determined properties, field measurement and long-term performance.

1.4. Research questions.

This study will provide answers to the following questions:

- How does the application rate affect concrete quality curing?
- How does the application time affect concrete quality curing?
- How does curing condition affect concrete quality curing?
- How to determine real-time concrete curing?

1.5. Dissertation organization

The remaining chapters of the dissertation will be set out as follows:

Chapter 2: This chapter provides a literature review on concrete curing process, starting by defining concrete, usages, concrete pavement construction stages, hydration reaction, different types of concrete curing, membrane forming curing compound application, and evaluation techniques, concrete hardened properties and lastly the use of resistivity in concrete.

Chapter 3: This chapter details how the sampling, mixing casting, curing and testing were performed to achieve the study's objectives.

Note: This study reported chapters 4 to 6 in the format of journal papers.

Chapter 4: Nkongolo, E.B., King, D., Taylor, P., and Kevern, J.T. Preliminary Investigation into Using Resistance Techniques to Assess Concrete Curing

Chapter 4 presents a study that proposes electrical resistance as a measure to assess drying behavior of fresh concrete to quantify the effectiveness of curing. The findings of this study demonstrate that resistance is able to distinguish between samples with and without curing compound and significant differences in drying observed between the surface and relatively shallow depths.

Chapter 5: Nkongolo, E.B. and Kevern, J.T. Embedded Resistance as a Technique to Monitor Concrete Curing

Chapter 5 provides a correlation between the embedded resistance technique and the concrete moisture retention test in a study that investigated the effects of curing compound application time on freshly placed concrete, the effect of curing conditions as well on the performance of concrete cured before and after the initial setting time, and lastly the effect of curing compound application rates and uniformity during the application. Tests were indexed against the standard moisture loss testing in addition to a newly developed real-time assessment of moisture loss and curing by embedded resistance. Ultimately with the goal of providing a correlated measure of moisture loss from field measurements.

Chapter 6: Nkongolo, E.B. and Kevern, J.T. Determination of Concrete Curing-affected Zone Using Embedded Resistance Technique.

Chapter 6 provides an understanding of determination of concrete curing-affected zone. The study used embedded resistance technique and the surface profile degree of hydration to investigate the depth of the CAZ from the surface of concrete. The findings from the study were able to determine the region where curing has an impact on concrete. Below the determined region regardless of the evaporative conditions or application rates, concrete behaves the same and developed identical hardened properties.

Chapter 7: Finally, summaries the general conclusions about the significant findings obtained from this study and recommendations for further research important to this study.

CHAPTER 2: LITERATURE REVIEW

2.1. Concrete

Concrete is a second most used material in the world after water because of the availability and the cost associated to the use (Naik 2020). Moreover, concrete is the composite material made from a mixture of water, cement, and aggregates that hardens over time to become a strong, solid substance (Makul 2021; Tunç 2018). Furthermore, concrete is strong, durable and the versatility of concrete allows it to be molded into almost any shape. The handling, placing, and curing conditions strongly influence the final product (ACPA 2010). Concrete is strong in compression and weak in tension (Yankelevsky 2024), due to its availability concrete is used in a variety of construction projects, such as houses, schools, hospitals, airport, bridges, sidewalks, highways and pavement among others. There are different types of concrete: reinforcement concrete, lightweight concrete, high strength concrete, high-performance concrete, and precast concrete.

2.2. Concrete pavement

2.2.1. Concrete pavement construction stages

Concrete pavement construction is a composite of so many stages starting from field investigation, base and subbase preparation, aggregates, cement and admixtures selection, batching, transportation, paving and opening to service (Taylor et al. 2019). All the stages need to be taken into consideration in order to construct a concrete pavement with a long service life. On site, concrete pavement construction starts by preparing a rigid pavement subgrade/base to provide uniform support between the concrete slab and the soil foundation. Field verification is an important stage of concrete pavement construction prior of concrete transportation process, as it ensures subbase is maintained in good condition and will not draw water from the hydrating cement paste. For the study focus will be on concrete pavement construction stages starting from batching, transportation, paving, surface finishing, curing and opening to service.

2.2.2. Concrete batching

Concrete batching is defined as the process of measuring and combining ingredients such as cementitious material, aggregates, water and admixtures to produce concrete in predetermined proportions (Kaza et al. 2020). This stage comes after the concrete mix design for a specific project has been developed and all the ingredients gathered in a location that prevent deterioration. Once the quantity of each ingredient is determined either by volume or weight, these ingredients are transplanted into the mix to create a consistent quality of concrete. During concrete production the mixing of cementitious materials should maintain the desired water-to-cementitious materials (w/cm) ratio. Quality assurance, suitable arrangement of materials and equipment, and correct weighing of the materials are the essential steps that must be completed before any mixing takes place. While proper mixture proportions and batching are fundamental to concrete durability, construction in the field is just as important for long-term performance and since it is influenced by many uncontrollable factors such as weather, proper site construction practices are important. Figure 2.1 represents a typical example of a concrete batch plant.

Figure 2.1 Concrete batching plant.

2.2.3. Transportation

Concrete transportation refers to the transfer of concrete from the batch/mixing plant to the construction site. During transportation the concrete mix should be covered, when needed, to avoid change of water content and temperature of the concrete prior to placement. While transporting concrete attention should be taken in order to avoid concrete segregation and decrease in workability before placement. Concrete should be carried from a mixing plant to a job site within 30 to 60 minutes for small jobs, one to two hours is an acceptable time for jobs requiring a truck mixer or agitator truck (Figure 2.2). Concrete transportation is also depending on the constituents of the mix, size and type of construction, the ambient conditions, the distance from the batch plant to the construction site and lastly the cost (Taylor et al. 2019). Delay in transporting concrete should be avoided to prevent honeycomb from forming.

Figure 2.2 Concrete transportation.

2.2.4. Placement

Quality control test such as air content, slump test and others are performed on fresh concrete to ensure consistency, and that concrete have met the designed properties. During construction of rigid pavement, concrete is placed using a slip form paver (which requires a low slump concrete) or a fixed form paver (which requires a more workable concrete) (Taylor et al. 2019). To provide high-quality concrete the paving operation requires that all equipment to be used must be suitable for the application, well maintained used by the specialized or trained personnel. Slip-form paving (Figure 2.3) is the most widely used paving method in modern concrete paving construction (Liu and Wang 2020). During concrete placement the slipform paving operates by extruding the concrete into the shape of the slab. The slip-form paver consolidates, screeds, and initially finishes the concrete in one continuous operation without the need of forms. Slip-form

paving is very efficient and can provide smooth concrete pavement. Because there are no forms, the plastic concrete must be able to hold the pavement edge.

Figure 2.3 Concrete placement using a slip-form paver.

2.2.5. Finishing

Concrete surface finishing occurs after the concrete has passed through the paver. The concrete surface is finished using a 10 to 20 ft hand-operated straightedge to close holes and create a tight surface (Figure 2.4). If the concrete is not workable, crews may overwork the surface and reduce air content or be tempted to add water to complete finishing. Both over finishing and adding water are not advised as they can lead to surface scaling caused by freeze-thaw and deicer damage. After finishing, two operations are used to create microtextured and macro-texture. Micro-texture

is created by dragging turf, burlap, or coarse carpet along the pavement surface. Finally, macrotexture is created with a tinning device or rake that makes transverse or longitudinal grooves in the wet pavement surface. The orientation, depth, and spacing of the grooves should be specified for each job (ACPA 2010). The texture, both micro and macro, influence the exposed surface area and curing compound application rate for complete coverage with rougher sections requiring a higher application rate.

Figure 2.4 Concrete pavement surface finishing using a burlap.

2.2.6. Curing

After concrete surface finishing, texturing, and tinning, concrete is cured to prevent moisture from evaporating (Taylor et al. 2019). The concrete curing stage is achieved in several ways including water spray or fog, wet burlap sheets, insulating blankets and liquid membrane forming curing compound depending on the project. The application of membrane forming curing

compound is the most common curing method for concrete pavements (Chyliński 2022). Curing compounds are applied and the significance of controlling moisture in concrete shortly after installation cannot be overstated. Concrete internal relative humidity is primarily regulated by proper curing with the zone nearest the surface (1/4 in.) directly affected. Curing compounds slow surface drying and maintain a relative humidity near the surface more like the remainder of the slab, lowering the risk of surface damage from differential shrinkage (Taylor et al. 2019). Figure 2.5 displays a curing cart busy applying curing compound on fresh concrete pavement.

Figure 2.5 Concrete pavement curing process using membrane forming curing compound.

2.2.7. Jointing and Sealing

It is generally known that concrete is strong in compression and weak in tensile. When tensile stresses in concrete overcome the tensile strength, this develops cracks in concrete (Taylor et al. 2019). Therefore, after concrete has developed sufficient strength shortly 6 to 24 hours after

curing, it can sustain the sawing operation as presented in Figure 2.6. The change in temperature and relative humidity between the surface and base cause a friction in concrete which result in concrete shrinkage. Therefore, to relieve the stress and prevent concrete from cracking randomly, concrete pavement is cut into small slabs using control joints to allow concrete to crack at predefined locations. Concrete as other materials expands and contracts due to the change in temperature and moisture content, and the contraction and expansion activity can cause premature concrete failure (Jędrzejewska, et al. 2020; Taylor et al. 2019). The transverse and longitudinal saw cut in concrete indicates a weak point where a crack should initiate and then propagate to the bottom of the slab. Therefore, it is important to consider all factors that can lead to a better joint cutting. However, while numerous additional variables specific to sawing exist such as timing, type of sawing equipment, and condition of sawing equipment, significant distresses related to moisture loss or curing compound damage during sawing have not been observed or able to be directly attributed (Crovetti and Kevern 2018).

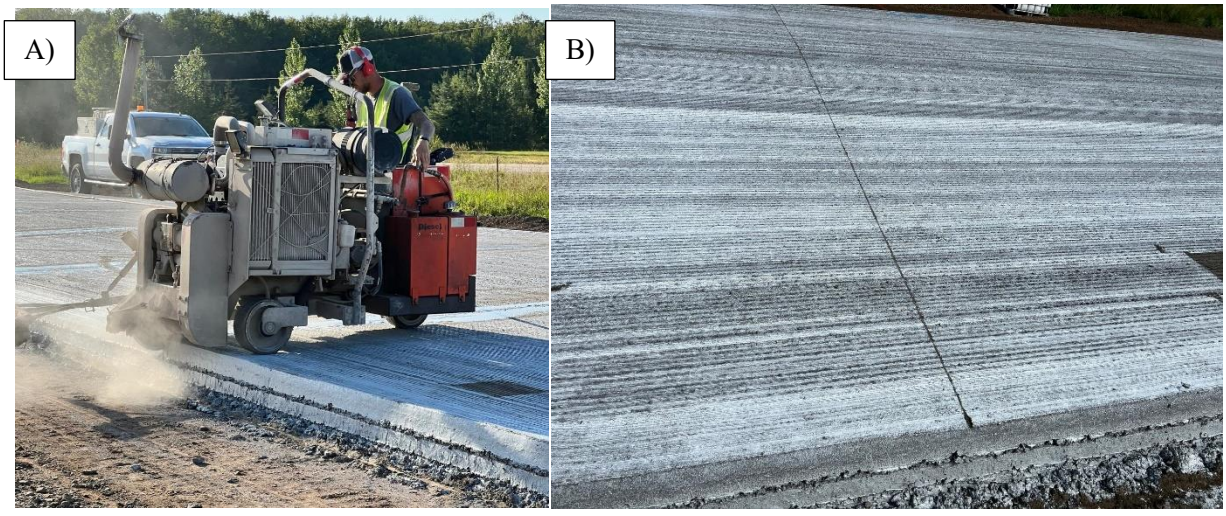

Figure 2.6 Concrete pavement saw cutting (a) Sawing machine (b) Vertical joint.

2.2.8. Opening to traffic

The last stage of concrete pavement construction is the opening to traffic. The opening to traffic takes place once the concrete has gained enough strength to prevent unwanted distresses before applying loads. Instead of using the strength of a cylinder or beam that cured and acquired strength under different conditions than the pavement, the strength utilized to calculate opening time should be the real strength of the concrete pavement. As a result, the maturity approach is recommended for determining in-place strength before traffic opening. (Taylor et al. 2007). Maturity is a function of time and temperature with curing and hydration a significant contributor to temperature and degree of hydration. However, concrete curing is fundamentally linked to traffic opening performance. The following section provides details on concrete pavement curing stage.

2.3. Concrete curing

Concrete curing is the act of maintaining adequate moisture and temperature in the concrete to promote and maximize hydration and pozzolanic reaction (ACI 2016). By controlling moisture loss from the surface of concrete, this will keep concrete nearly saturated and relative humidity above 80%. Concrete internal temperature and relative humidity influence both hardened properties and durability of concrete (Kosmatka et al. 2002; Taylor et al. 2019). Additionally, a relative humidity below 80 % will cause hydration reaction to cease thus leading concrete to stop strength gain (Joshaghani & Zollinger 2017), a better concrete curing practice should be able to prevent more moisture loss from fresh concrete and subsequently keeping more in concrete to enhance hydration reaction. Concrete pavement curing can be classified into two phases initial and final curing (Taylor et al. 2019). Initial curing is defined as the period from concrete placement through the completion of surface finishing. During initial curing concrete bleed water rises as solid materials settle and subsequently evaporates or is consumed in hydration of the surface

cementitious materials. Therefore, minimizing moisture loss during initial curing is necessary to reduce the loss of water and prevent plastic shrinkage from taking place (Rothstein 2017) Techniques to minimize moisture loss include fogging, wind shades, or application of surface moisture retardants. Final concrete curing includes the period after final surface finishing and is important to prevent continued moisture loss and incomplete hydration at the surface (Poole 2006). Final concrete curing is considered as concrete curing and can be accomplished through water addition methods (ponding and fogging) or water retention method (application of membrane forming curing compound).

2.3.1. Water addition concrete curing technique

Concrete curing can be achieved through ponding or spraying and fogging as means of water added techniques. Ponding method of curing concrete consist of immersing the entire surface of hardened concrete into water for the duration of curing period (Taylor et al. 2019). This technique consists of building a dike of earth or sand or wet gunny bags, hessian cloth and jute matting around the concrete and flood the surface with water. This curing technique satisfies all the curing requirements, namely, promotion of hydration reaction, elimination of shrinkage and lastly absorption of heat of hydration. However, this curing technique is mostly suitable for laboratory work or small jobs, because it is labor intense and requires permanent supervision (Pawar & Kat 2020) this required concrete surfaces to remain without being marred and water lost due to evaporation or leakage surfaces is replaced at a rate sufficiently to maintain the pond (ACI 308). Moreover, concrete surface should be always kept wet and do not allow alternate wetting and drying of the concrete surface. This method can help maintain a uniform stable temperature which is highly needed for efficient concrete curing. The ponding method of curing is mainly used on bridge decks and other reinforced structural elements many be produced with low w/cm and

susceptible to significant autogenous shrinkage. Bridge decks are commonly covered with wet burlap (Osei et al. 2019; Gowsika et al. 2017).

Fogging is performed by covering the entire surface area of the concrete to be cured. Water is applied to maintain the relative humidity above the slab at a level to prevent surface drying and the accumulation of standing water on the surface. Concrete surfaces should be kept continuously wet and avoid wetting and drying of concrete surfaces. However, this means of curing provides good results only when the environmental conditions are great, temperature above freezing point of water and has a low relative humidity. Soaker hoses are used for curing concrete, the burlap to be used for curing shouldn't contain any harmful to concrete or causing concrete color change (Srinath et al. 2021; Gowsika et al. 2017). During spraying and fogging curing methods, nozzles are used to create fog mist on the surface of concrete to raise air relative humidity (Taylor et al. 2019). Higher air relative humidity prevents evaporation from the surface of the concrete. Fogging is used as well to prevent surface cracking. During this curing process precautions should be taken to avoid concrete surface drying out, which can negatively affect hydration process. However, this curing method is not cost effective and has a higher water footprint than other curing methods and can only be used in the region where freezing conditions are not experienced. However, as concrete pavement construction has become faster and more widespread, the industry has progressed to the use of Membrane Forming Curing Compound (Taylor et al. 2019)

2.3.2. Membrane forming curing compound.

The application of membrane forming curing compound on fresh concrete has become a common method of curing concrete pavement due to the large surface area-to-volume ratio and the cost associated to the application (Vandelsbosh 2002). The high surface are-to-volume ratio making it difficult to maintain a uniform moisture content throughout the pavement, therefore

curing concrete will provide a better environment for concrete to develop uniform and equal hardened properties (Vandelsbosh 2002). Curing compounds are organic materials that form a protective layer over the surface of the fresh concrete and subsequently reduce the rate of moisture loss from concrete (Taylor et al. 2019). MFCC are organic materials used with water, alcohol, petroleum fractions, or a combination as a solvent and carrier for the membrane chemistry (Whiting and Synder 2003). Once applied the solution breaks and the carrier evaporates, leaving behind a low permeability membrane. Common MFCC chemistries consist of waxes, resins, chlorinated rubber, and acrylics. Evaporation retarding performance is directly related to the chemistry and solids content of the MFCC. MFCC are applied to the surface of fresh concrete immediately after the bleed water has evaporated or absorbed back in the concrete. The most common curing materials used for DOT concrete pavement construction include white-tinted wax or poly alpha-methyl styrene (PAMS). Wax curing compounds, while low-cost, can negatively influence the surface friction until it is effectively worn away. Hajlbabee et al. (2016) state that a solvent-based curing compound such as poly alpha-methyl styrene (PAMS) was more effective than two water-based curing compounds in providing water retention due to a better surface wetting that produces fewer imperfections. More than one coat may be necessary for a successful surface seal to prevent water from evaporating and DOT specifications such as employed by TXDOT require two coats (Choi and Won 2008).

MFCC are selected to be used on a specific project based on the properties such as water retention capability, reflectance, drying time following the ASTM C1315 and ASTM C309 (Vandelsbosh 2002). MFCC reflectance properties are described in ASTM C309 and ASTM C1315 is defined as the ability of curing compound to reflect radiant heat from the sun and helps in keeping temperature inside the concrete and control temperature for hydration and reduces early-

age concrete surface stress due to drying shrinkage (Sun 2013; Wange et al. 2002). Moreover, reflectance properties of curing compound reduce moisture evaporation rate sand decrease early age stresses. The recommended reflectance properties of curing compound are more than 60% according to ASTM C309 (Sun 2013; Vandelsbosh 2002). The water retention capacity of curing compound is defined as the ability of curing compound to hold moisture inside hydraulic cement specimen for a defined period, is one of the major properties to look at when selecting and evaluating performance of a curing compound for a specific job. This property is tested according to AASHTO T 155 or ASTM C156. These test methods provide a standard test method for estimating the water retention ability of curing compounds, and they are performed in environmental controlled curing condition. The standard water-retention limit from these tests is expected to be moisture loss of less than 0.55 kg/m^2 after 72 hours. For specimens applied with a curing compound at a fixed rate of application of curing. However, for hot weather curing ACI 305 R, requires a reduced water-retention limit of 0.39 kg/m^2 for concrete curing where then evaporation rate is above 0.50 kg/m2/hr. (Poole 2005; ACI 305R; ACI 308). Nevertheless, test results for moisture loss are not consistent from laboratory to laboratory depending on the operation methods and precision from oner user to another (Sun 2013; Poole 2005), variation in standard deviation single operator 0.123kg/m^2; and a multi-laboratory standard deviation of 0.30 kg/m^2, these standard deviation are extremely large, ASTM C309 requires a water retention for type 2 Class b curing compound of less than 0.55kg/m^2.

MFCC once applied on fresh concrete must dry and the drying time property is an important factor to look at when selecting curing compound. Drying time determination allows the contractor to proceed with joint sawing tasks on the surface of concrete, and also to prevent curing compound to be washed away by rainwater if it rains. According to AASHTO M148 and ASTM

C 150, curing compound is expected to dry not more than 4 hours after it has been applied (Poole 2005). This drying time is determined based on the laboratory condition with an evaporation rate of0.43 kg/m^2/hr., the test result is an approximate value and could be the cause of compliance dispute. Therefore, some States DOT's require a shorter drying time, there is an empirical equation that can be used to anticipate the amount of drying time needed under poor drying conditions, such as evaporation rates of less than 0.10 kg/m^2/hr. Volatile organic content (VOC). VOC is mostly listed on the product safety data sheet or can be determined using ASMT D1644. The allowable VOC content in curing compounds should be less than 350 g/L and less than 700 g/l for concrete curing/ sealing compounds of volatiles solvents according to National Volatile Organic Compound Emissions Standards for Architectural Coating (Vandelsbosh 2002). Materials with low VOC contain large amounts of water, thus leading to a long drying time under low evaporation rates (Poole 2005; Vandelsbosh 2002).

In addition to chemistry, color is an important factor controlling MFCC performance. While limiting evaporation is quite effective, bituminous compound absorbs heat because of the dark color and as a result, the temperature in the concrete body rises, which is undesirable. A limewash may be recommended to be applied to the black coating to reduce heat absorption. Because of the temperature considerations, many MFCC are white pigmented or contain a dye to help ensure uniform coverage. According to ASTM C 309-19 Standard Specifications for Liquid Membrane Forming Curing Compounds for curing concrete specifies the allowable evaporation rate, reflectivity, and basic carrier/solvent solution. Additionally, ASTM C309 classifies curing compounds into 3 types based on color and solid constituents and two classes based on the solid chemistry as shown in Table 2.1.

Table 2.1 ASTM C309 curing compound classification.

Color		Solid constituent	
Types	Description	Class	Description
1	Clear or Translucent w/out Dye	A	No Restriction
1-D	Clear or translucent w/Fugitive dye	B	Resin
2	White pigmented		

MFCC was created to develop an evaporative barrier sprayed quickly over large swaths of exposed surface, reducing labor and time required by other curing methods. MFCC are applied using a spraying machine or hand-held sprayer. Shobber (1974) conducted a study on the evaluation of curing continuously reinforced concrete pavement using white-pigmented liquid membrane and white translucent polyethylene paper film curing. For these two methods, tensile and compressive strength were similar. Both the MFCC and film curing produced acceptable crack-spacing distributions when climatological conditions were favorable, although neither produced acceptable crack-spacing distributions during hot weather paving conditions.

Cramer and Anderson (2012) performed a study investigating the performance and durability of various concretes with five different types of MFCC. The MFCC used included: white pigmented wax emulsion, white pigmented linseed oil emulsion, white pigmented PAMS, acrylic, and chloride rubber epoxy. Testing included chloride ion penetration, water evaporation, and resistance to carbonation. Final finishing and curing compound application occurred at two hours after casting. Results showed type of coarse aggregate (limestone or igneous gravel) had little or no effect while different performance was related to cementitious material combination. Scaling was much higher in the slag and fly ash combinations than the conventional Portland cement mix. MFCC moisture loss did not correlate with scaling. Overall, the best protection was offered by the

acrylic sealing compound. Therefore, effective concrete curing guidelines should consider the mix type and the state of the concrete surface at the time of MFCC application and not only rely on moisture loss. Table 2.2 presents a summary for the most common MFCC.

Table 2.2 Summary of Membrane Forming Curing Compounds

Types	**Advantages**	**Disadvantages**
Wax	Low VOCs No special handling Can be used as a debonding agent. Easily sprayed with most used spraying equipment Can be removed with hot water	Soft Loses efficiency with time. Hampers adhesion of paint Concern with surface friction
Resin	Dissipates Less prone to abrasion than wax Variable VOCs can be low. Can be removed with hot water	Comparatively short shelf life
Chlorinated rubber	High degree of moisture retention. Can act as a barrier against ion ingress. Forms a thick layer. Dissipates quickly. Long shelf life	Expensive Dissipates quickly. High VOCs are flammable and can be hazardous. Runoff can be harmful to the environment

Table 2.2 Summary of Membrane Forming Curing Compounds

Types	**Advantages**	**Disadvantages**
Acrylic	Environmentally friendly Increase surface hardness. Deeper penetration Film does not dissipate and can act as a sealer. Water or solvent carried.	Can peal from surface. Does not dissipate.

2.3.3. Concrete quality curing

After selecting the best curing compound for a specific project. Concrete quality curing is achieved by considering the other factors such as application time, application rate, uniformity in application and the ambient condition. Application time is one of the factors to take into account when using MFCC in order to achieve quality curing. Membrane forming curing compound provides their best working capacity if applied after initial set, final finishing and once the bleed water has evaporated from the surface of concrete (ACI 308). It is important to apply curing compounds at the right time, applying membrane forming curing compound before bleed water has evaporated lead membrane to underperform. MFCC should be applied once the free water disappears from the surface of concrete and there is not any water sheen visible. ACI 308 states that, MFCC should be protected from any damage during the curing period.

The application rate is another factor to consider in order to achieve quality curing. The quantity of curing compound applied and how it is applied should be controlled to achieve quality curing. The application is mostly determined based on the area, the volume and the density of the

materials to be used. Small quantity MFCC may not provide better coverage, thus leading to more moisture loss and does not favor hydration reaction. ASTM C156 requires an application rate of 180 Gal/ft^2. In most cases the application rates are displayed on the manufacturer safety data, but some DOTs may modify to their specifications. The amount of curing compound used should be enough to seal all exposed concrete surfaces. Curing compounds 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 application (Loeffler et al. 1987). Although every DOT considers the minimum application 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 rough surfaces.

Uniform applications of curing compound are a key to achieving quality curing. Membrane forming curing compound needs to be applied uniformly, which means all concrete surface area should receive equal amount of materials without marring concrete surface (Vandelsbosh 2002; Minnesota Transport Research Committee 1979). Uniform coverage of curing compound is usually controlled by the equipment used (curing machine), nozzle type, nozzle spacing and boom height, nozzle orientation, wind shield and curing machine speed are factors to look at to achieve uniform coverage. However, uniformity is mostly assessed through visual inspection, or some

States DOTs use the highly calibrated white paper sheet examination to determine uniform coverage of concrete surface, which does not provide the real covering information, and some rely on the application of a portable reflectometer (Choi and Won 2008), which used a photocell to measure intensity of light reflected from the concrete surface is measured and data are evaluated based on the whiteness of curing compound. Whereas whiteness is proportional to the amount of curing compound applied. However, these evaluation techniques are only effective for white-pigmented compound and not the non-pigmented curing compound. Proper ventilation should be provided during the application of MFCC. Lastly, the ambient conditions such as temperature, relative humidity, wind speed and evaporation rate at the time of application of curing compound need to be taken into consideration as well to achieve a quality curing. Wind speed affect uniform coverage of curing compound, strong wind speed will result in non-uniform coverage,

2.3.4. Hydration reaction

The main constituents of hydraulic cement such as Tricalcium silicate, dicalcium silicate, Tricalcium aluminates and Tetracalcium alumino silicate and gypsum react with water during an exothermic chemical reaction called hydration reaction and the products of this reaction are the cause of concrete strength gain (Wang & Park, 2017). During hydration reaction the cement paste set and hardens. Hydration reaction begins when Portland cement meets water for the first time, the cement particles partially dissolve, and the various dissolved components start to react at different rates to produce hydration products (Gartener et al. 2008). During hydration the chemical reactions occurring are generally more complex than simple conversions of anhydrous compounds into hydrates and are controlled by the exact mineral composition, combination, and reaction conditions creating a plethora of various potential hydration products at any given concrete age. The new hydration compounds produced cause the cement paste to harden, bond to the aggregate

in the concrete mixture, and become strong and dense (Artioli and Bullard 2013). Additionally, the hydration products will occupy some of the original space previously occupied by mixing and water that did not take place in hydration reactions will either remain in the concrete in the capillary pore system or evaporate out once the concrete dries which leads to change in volume of concrete (Taylor et al. 2019).

Cement hydration is an exothermic reaction consistent with a large thermodynamic driving force for dissolution. The heat generated during the reaction does not reach for a long time, thus indicating that the reaction can continue for years as long there is available water and unreacted cement, thus leading to concrete continuous strength gain, The hydration of cement paste is responsible for the development of concrete properties (Taylor et al. 2019). Therefore, controlling hydration process will result in concrete developing desirable properties. As available moisture and the hydration reaction are intrinsically linked, measurement of hydration using isothermal calorimetry is one technique suitable in the laboratory of assessing the degree of hydration. The hydration takes place in five stages of strength development as assessed by isothermal calorimetry. Stage 1 (mixing stage) is characterized by the rapid dissolution and reaction of aluminates and gypsum in the presence of water to create a gel-like substance that coats the cement compounds. A rapid initial large amount of heat is generated and dropped as gypsum controls the initial aluminate reactions. During this stage the tricalcium aluminate dissolves and reacts with water and calcium hydroxide to form calcium aluminate hydrates crystals (gel-like substances) as presented in Figure 2.6.

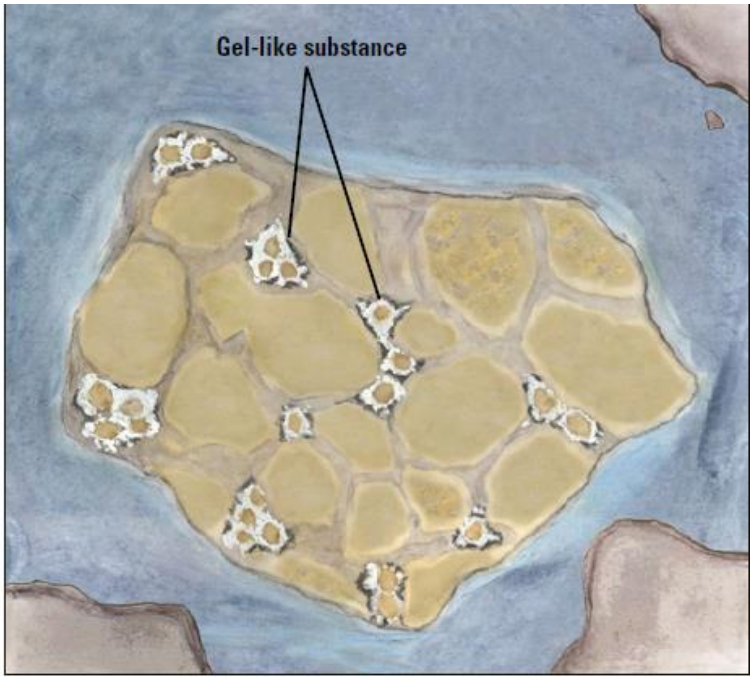

Figure 2.7 Formation of a gel-like substance during mixing stage of hydration.

In Stage 2 (Dormancy) is characterized by slow rate of reaction and small amount of heat generated. The second stage lasts for about two to four hours, during this stage concrete is still cool and in plastic stage which facilitates the transportation, placing and finishing. However, during dormant concrete pH value will keep on increasing as cement dissolves and the water become saturated with dissolved calcium and hydroxyl ions as shown in Figure 2.8 (Taylor et al. 2019).

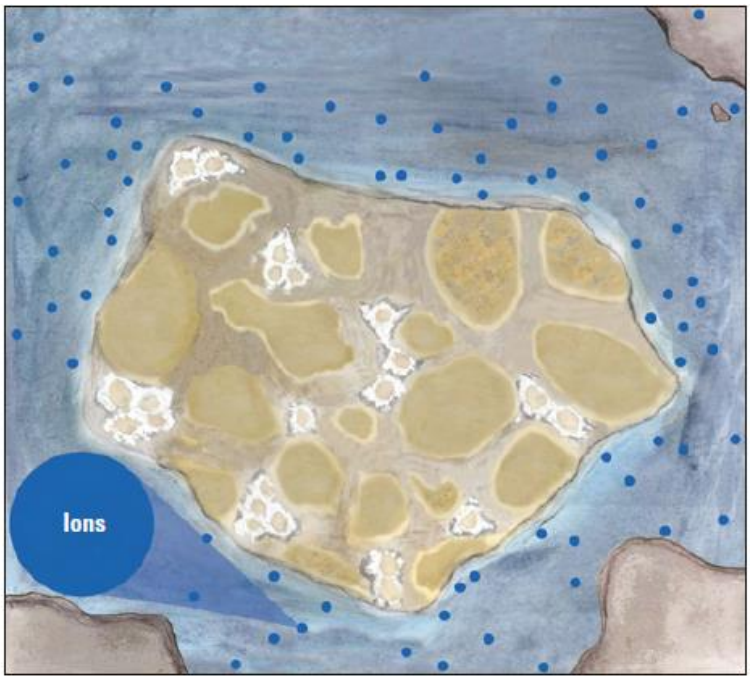

Figure 2.8 Concrete during dormancy stage.

During hydration reaction stage 3 (Hardening), concrete will start stiffening marking the initial set time, while other cement components such as tricalcium aluminate and sulfate continue to react thus forming ettringite which contributes to concrete early age strength development. One point to highlight is the tricalcium aluminate and sulfate reaction keeps on taking place until all the sulfates are consumed, and this can last up to 24 hours from the time of mixing. In stage 3 the pH exceeds 13, and hydration products are rapidly formed, and strength gain accelerates. Strength at the initial set is typically less than 250 psi. Between initial and final set, the concrete surface can be finished, and curing commences. Near the end of stage 3 the concrete will pass through final set, where concrete is sufficiently hard that all finishing activities cease display the growth of cement hydration reaction products during stage 3.

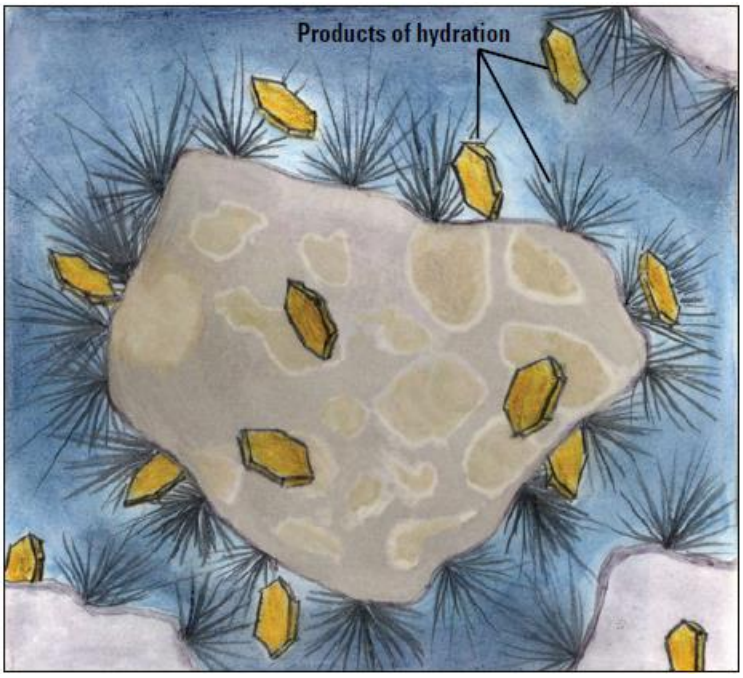

Figure 2.9 Concrete during hardening stage. Highlight Growth of hydration products (Taylor et al. 2019).

Stage 4 identified as cooling stage, represents continued hydration, strength gain, and maximum calorimetric heat generation. Concrete sawing activities occur late in stage 3 and throughout stage 4. During this stage the rate of alite reaction slows down due to the buildup of hydration products, which start to interfere with contact between the remaining cement and water in the concrete. Additionally, the amount of heat generated reaches the peak and starts dropping off. However, concrete is still more porous and can only tolerate light weight. Tensile stresses start building up faster than tensile strength and cause concrete to crack. The remaining tricalcium aluminate will react with ettringite and available water to form monosulfate generating a negligeable increase in heat, more hydration reaction products are formed and growing Figure 2.10. However, monosulfate does not contribute to concrete physical properties.

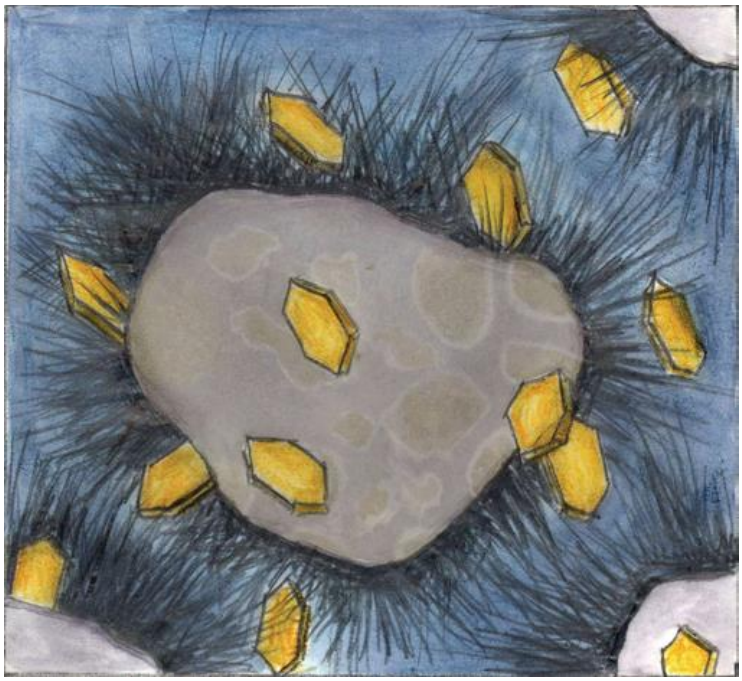

Figure 2.10 Concrete during cooling stage. Highlight more hydration reaction products growing (Taylor et al., 2019).

Stage 5 (Densification) of hydration reaction represents all densification and strength gain after about 24 hours where most of the pore refinement and permeability reduction occurs. Calorimetry is a useful tool for assessing activity timing for particular concrete mixtures and can help evaluate setting and sawing behavior under a range of anticipated construction temperatures. During this stage the rate of belite reaction begins to be noticeable as most of alite have reacted. Hydration products will continue to grow and mesh into a dense solid as presented in Figure 2.11, therefore it is important to keep moisture in concrete, as long as cement and water are still present, concrete slab will keep on gaining strength and reducing permeability. The rate of hydration reaction of concrete is affected by the composition of cement, cement fineness, mix proportions, temperature and admixture used in the concrete mix.

Figure 2.11 Meshing of hydration products during the densification of concrete (Taylor et al. 2019)

2.4. Concrete hardened properties

The curing of concrete strongly influences the properties of hardened concrete; this process develops the properties of hardened cement paste with sufficient water and heat over time (Taylor 2014). Concrete curing promotes hydration, prevents water loss in concrete, and keeps the material saturated or nearly saturated if possible or for sufficient time (Safar 2019). Among the properties of hardened concrete developed are strength, permeability, freeze-thaw, and volume change.

2.4.1. Strength

Concrete strength is a commonly measured property of concrete, mainly because strength is relatively easy to assess and provides a fair analog with other properties. The age at which a given strength is required varies depending on the need. Concrete is strong in compression but weak in tension; therefore, testing is usually a compression test on cylinders or cubes (Taylor 2014). The water to cement ratio is among the factors that affect the strength of concrete because

of the decrease in capillary porosity. This observation is valid for the entire range of curing conditions, ages, and types of cement available (ACPA 2010).

The cement composition and fineness influence the strength of concrete and, indirectly, the amount of cement used in the mixture. Finer cement tends to hydrate faster than coarser cement because it has a larger surface area and limited later strength development. In general, the early strengths of Class F fly ash and slag cement are typically lower than those of similar mixtures containing only Portland cement, but the ultimate strengths are often higher. Bouzoubaa (2004) states that silica and metakaolin found in fly ash increase the strengths at early and later ages. (Taylor 2014). Ternary mixtures developed to achieve a given 28-day strength will exhibit more significant strengths than plain mixtures at greater ages. The maximum strength is mostly obtained after 28 days of curing (Raheem et al. 2013; Slam & Slam 2013).

2.4.2. Permeability, porosity, and resistivity

Curing compound effectiveness is determined by the ease with which each fluid flows and moves through the concrete. Permeability, porosity, and resistivity test are among the tests used to evaluate the effectiveness (Li et al. 2021; Safiuddin et al. 2005). Permeability is defined as the ease with which fluids can penetrate concrete. Reducing the permeability properties of the concrete can slow or stop durability-related distresses. A contractor always desires concrete with lower permeability, and it can ensure long durability. There are no practical tests to assess the permeability of a given concrete directly, but one approach is to use an analog such as electrical conductivity. Because the ionic charge in fluids in the pore system is faster than in the solids of the hydrated cement paste, this makes sense (Tikalsky 2011).

The porosity, defined as the ratio of void volume to the total volume, plays a role in determining the strength of concrete. The decrease in capillary porosity increases the compressive

strength of the concrete. For the concrete to produce good strength, it should be well compacted to such an extent that voids are minimized. The ratio of mass difference divided by the concrete volume is considered porosity and is related to the water to cement ratio of concrete. The technics such as Mercury intrusion, helium intrusion, and calculations from measurements of weight loss or by the methods of vacuum water absorption are among technics used to determine porosity in concrete (Li et al. 2015)

The curing effectiveness test uses the amount of charge that passes through specimens to represent the permeability of specimens, the higher the charge, the higher the permeability. (Whiting and Snyder 2003). The permeability test is done to determine the relative permeability of the specimens; the idea of the test was to relate the permeability of concrete to the curing quality of curing compounds. It was considered that a better curing quality could lead to better hydration of concrete and lower porosity at the surface of concrete, thus would result in a lower permeability of concrete. This test is not precise. Therefore, ASTM reports that test results by a single operator on samples of the same size and from the same batch should not vary by more than 42%. Curing effectiveness is correlated to the permeability of the concrete (Zhutovsky and Kovler 2012)

2.4.3. Freeze-thaw.

Freeze-thaw is a problem faced by the concrete exposed to cold weather. Cold weather can cause damage to the concrete due to pressures exerted by water attracted to the freezing front and expanding as it freezes. While saturation may be limited to a short depth, cracking at the surface can open the system, allowing further damage to occur, making the freeze-thaw damage cyclic (Taylor 2014)

Once a salt solution penetrates the microstructure of concrete pavement. The water in the solution is removed either by freezing or by evaporation. Therefore, the remaining salts may

crystalize out and expand depending on the chemistry of the salt. Damage could also be caused by osmotic pressures created by salt concentration differences in the pore solution near and far from the freezing front. Differential movements in the surface ice and the concrete at the surface are also said to cause surface scaling and superficial cracking. The addition of fly ash to the concrete can reduce the severity of the surface scaling. There is a perception that increasing slag cement content in a mixture will reduce scaling resistance, particularly above 50 percent dosage (Tikalsky 2011).

2.4.4. Volume change

Change in concrete volume is caused by the changes in moisture and temperature and deflects in response to loading. Moreover, the concrete volume change is observed when the moisture from the initial mixing begins to evaporate. The volume change is observed through shrinkage, curling, and other properties of concrete that are not properly cured. Shrinkage describes as the decrease in either length or volume of a material resulting from changes in moisture content or chemical changes; this is mainly caused by the loss of moisture from drying concrete primarily due to evaporation.

Drying shrinkage occurs after the concrete has set and results in random cracking and plastic shrinkage, which occurs due to moisture loss before the concrete sets, resulting in plastic cracking at the surface. This property can be minimized by keeping water or paste in the concrete content as low as possible. Yang et al. (2017) states that increasing cement fineness tends to increase shrinkage.

Concrete curling is when the edges of concrete pavement or slab deflect compared to the middle. Curling is mainly caused by a difference in volume change between the slab's top and bottom. Mainly when the difference in temperature or moisture occurs. The pavement dries out

faster on the surface, causing the edges of the pavement to deflect upwards—the curl results in a loss of contact between the slab and subbase. Curling is most noticeable at the construction joints, but it can also occur at saw-cut joints or random cracks (Suprenant and Malisch 1999). The fundamental cause of curling is through-slab thickness differential strain occurring primarily due to humidity (Suprenant and Malisch 1999).

The primary factors controlling dimensional changes of concrete that lead to curling are drying shrinkage, construction practices, moist or wet subgrades, and day-night temperatures cycles. To avoid or prevent concrete curling, it is recommended to use the lowest practical water content in the concrete. Curing the concrete thoroughly, including joints and edges, if membrane-curing compounds are used, it is recommended to apply twice at the recommended rate, in two applications and at right angles to each other (Siddique et al. 2005).

2.5. Curing compound application effectiveness techniques

The effectiveness of a curing compound is tied up to the surface condition of the concrete. The concrete curing method effectiveness is determined on the type of material utilized, the construction process, and lastly the intended use of the hardened concrete (Atsbha and Zhutovsky. 2022). Moreover, the ambient condition such as wind velocity, relative humidity, atmospheric temperature, and water to cement ratio of the mix and types of cement used in the combination can affect the concrete pavement's curing quality. Several tests are conducted to assess the effectiveness of the curing process. Moisture retention, penetration resistance, reflectance, relative humidity, and dielectric constant among others that will be details below.

2.5.1. Visual evaluation

Visual inspection of concrete is one of the most useful non-destructive techniques and methods used to evaluate a concrete structure (ACI 2008). During this test, the inspection should

be conducted by someone who has a good understanding and knowledge of the concrete to document any observations related to environmental exposure, durability, and performance (ACI 2008). Visual inspection of curing compound application is essential as it can detect if the curing compound was uniformly applied if there is any deficit. Moreover, it can provide information that may lead to identifying the cause of observed distress. The effectiveness of the visual evaluation depends on the knowledge and experience of the investigator. The limitation faced when dealing with visual evaluation or inspection is that internal detects are not noticed. Moreover, no quantitative information about the properties of the concrete is obtained; therefore, associating the visual evaluation with other non-destructive techniques will be the best option to maximize all the information.

2.5.2. Image analysis

Camera-based image analysis is one non-destructive technology used to study micro-crack propagation in asphalt concrete and concrete subjected to compression (Choi and Shah 1997). The application of digital image correlation was performed on various materials such as metals, composites, Portland cement concrete, biomechanical materials, wood, and paper, among others, to determine material characterization, model verification, structural design, and quality control (Youngguk 2003)

DIC compares images of deformed specimens with that of an initial or undeformed specimen (Hansen et al. 2021). The equipment used for the digital image correlation test is a digital camera, a lighting system, a frame grabber, a PC, and software for pot analysis as presented in Figure 2.12. DIC analysis essentially involves measuring the grayscale level at each pixel location, thus creating a map within the area of interest (Choi and Shah 1997). Each spot on this map is compared with the initial, undeformed image, and the movement of each pixel in the horizontal

and vertical directions is determined, from which displacements and strains are calculated using advanced mathematical techniques (Choi and Shah 1997). Chen et al. (2011) used a novel combination of standard multi-light source photography and texture-based feature extraction in conjunction with neutral network analysis to identify and classify the extent of concrete cracks. The results of this study show that digital image processing and data-driven feature extraction methods can be used to distinguish between good quality and damaged concrete surfaces.

The advantages of using DIC techniques are it is non-destructive technology, a non-contact system, this technique can be used in a small space of time and does not require too much effort to complete. Moreover, DIC measures full-field displacements from the area of interest and measures large deformations without losing resolution. Surface deformation and strain can be calculated using DIC at any place visible to cameras. This method enables measurements to be taken on length scales without losing measurement quality for various physical scales (Roux 2006). A digital camera is used as a sensor that provides information (Seo 2003). DIC measurements are verified by comparing vertical displacements for a specimen's middle and bottom sections subjected to monotonic tension with conventional linear variable differential transformer measurements. The DIC images captured during the test visualize the evolution of the failure process zone at the crack tip. The figure below displays the setup of DIC measurement.

Figure 2.12 Camera set-up digital image correlation (Chen et al., 2012)

2.5.3. Rate and application time.

The application of the MFCC requires the use of equipment that can help the uniform application of the materials. Different equipment, such as a manhandled sprayer, a spraying pump, and a curing machine (Figure 2.13), apply the curing compound. All these equipment will be of no use if they don't ensure a uniform application that is key to the curing materials' performance. Membrane forming curing compounds should be applied homogeneously for better performance. Uniform applications provide a solid, white opaque coverage on all exposed concrete surfaces compared to a white sheet of typing paper. The uniformity of the curing compound is obtained when the equipment to be used for the specific work functions correctly. Nozzle, nozzle spacing, boom height, nozzle orientation, and spraying machine speed should be cleaned and fixed before the operation. Additionally, the curing cart speed can be adjusted or determined once a nozzle has been chosen, and the pump pressure is known following Equation 3 (Vandenbossche 1999).

Moreover, the manufacturers should provide the nozzle's flow rate at different pump pressure. Nozzle flow rate and equation 1 help in determining the curing cart speed.

$$\boldsymbol{v} = \frac{\boldsymbol{Coeff.*F}}{\boldsymbol{C*W}}$$ Equation 2-1

V = Cart speed, (Km/hr.), Coeff. = 6 when using SI unit (0.13636), F= Flow rate (litters per minutes per nozzle or gallons per minutes per nozzle), C= desired coverage, liters per square meter (gallons per square foot) and lastly W= Nozzle spacing, cm (inches).

Figure 2.13 Curing compound spraying machine after on fresh concrete after curing.

Curing compounds should be applied homogeneously to provide a uniform, solid, white opaque coverage (equal to a white sheet of typing paper) on all exposed concrete surfaces. Curing compound is not adequate for a specific job if not well applied. A better curing application is a

function of the application rates, curing time, and mode of application of the materials. There is a given range of curing compound application between 2.5 m^2/L and 5m^2/L (Senbetta 1988). Uniform application creates a continuous film with no gaps or pinholes for maximum moisture retention to ensure a better curing application. Each department of transportation has its curing application rate. Minnesota transportation department requires curing compounds to be applied at a rate of 1 gallon per 200 feet square (Vandenbossche 1999).

A study performed by (Helgeson, 2014) exanimated the effect of curing compound application time after concrete finishing. Different times 30 minutes, 2 hours, and 4 hours were considered, and repeatability was evaluated. According to the findings of this investigation, scaling resistance differed depending on the mix type and curing ingredient type. None of the curing chemicals had the same level of scaling resistance as wet room curing. The efficiency of most curing agents appears to depend on the concrete's surface condition. The presence of bleed water varied by mix type, and when bleed water was present, the curing agents' efficiency was usually reduced. While PAMS resin-based curing compounds appeared to be equally successful regardless of application duration, wax-based, linseed oil, and acrylic curing compounds did not. Depending on the cementitious additives, 2 to 4 hours was usually required for the optimum results.

2.5.4. Moisture retention

The moisture retention test is among the standard test described by ASTM 156 (ASTM 156 2005). Each specimen must be placed in a test chamber that keeps a specific temperature, relative humidity, and evaporation rate. The moisture retention test is done by measuring each specimen's mass loss. ASTM C156 requires that initial specimen masses be recorded after the edges of the specimens have been sealed with wax curing compound. As needed, the mass losses will be

determined after 72 hr., and additional mass-loss measurements will be recorded at least six times throughout the 28-day testing period.

The study conducted by Sun (2013) states that the moisture retention test is straightforward, but the precision is not reliable. A high level of variability of standard deviation between laboratories makes it difficult to confirm whether a curing compound has met the standard or not. Several factors, such as the precision of controlled temperatures, wind speed, time of application, and rate of application of curing compounds, contribute to the poor accuracy between laboratories. (Poole 2006). Moreover, moisture retention is limited to fixed ambient conditions and a single application rate or curing compounds under a laboratory environment, making it difficult to set standards for all field tests as the field environment is exposed to various conditions. Therefore, many states' departments of transportation modified the standard test requirement and made their standards (Sun 2013). Nevertheless, the inapplicability of the moisture retention test under a field environment prevents its direct application.

2.5.5. Relative humidity test

A relative humidity test is also used to determine the effectiveness of curing compounds. Proper concrete curing aims to maintain appropriate temperature levels and moisture content during the early age of concrete. To achieve this goal, surface evaporation of concrete which depends on air temperature, concrete temperature, air relative humidity, and wind velocity, should be controlled. Higher rates of evaporation indicate more significant moisture variations within the concrete immediately below the surface. So, applying curing materials on the fresh concrete pavement will decrease evaporation. Moreover, curing compound application will reduce with time the variation of relative humidity below the surface, therefore making internal relative humidity an important factor in indicating the quality of curing operation and curing effectiveness.

A relative humidity test can be used for laboratory or field evaluation of the curing effectiveness of the early age concrete using sensors that can provide accurate relative humidity data. Relative humidity correlates with curing effectiveness through the data given by the sensors; these sensors are placed at different depths inside the concrete and on the surface. Capacitive sensors measure changes in the capacitance of a thin hygroscopic polymer film as it absorbs moisture (Grasley et al. 2006). The readings are done at a specific time. RH values are estimated from the calibrated reference curve in a precision humidity chamber with a chilled mirror hygrometer. The technology on the internal RH of early age concrete is still in progress, with various humidity types.

2.5.6. Ground penetrating radar.

Ground-penetrating radar (GPR) is a geophysical imaging technique used for subsurface exploration and monitoring. GPR is widely used within the engineering, geological, mining and archeological field. GPR has been applied very effectively in bridge construction in several cases to locate tendon ducts and provides positive results (Funk et al. 1997; Maierhofer 2003). GPR has been recently used in the concrete field as a technique to evaluate concrete condition due to the higher resolution of any subsurface imaging, it is a not -invasive method and is a safer and non-destructive techniques (Gehrig et al. 2004). Additionally, GPR is used to identify the subsurface condition of the concrete, which is used to determine the moisture availability for potential concrete curing. GPR is a technology mainly used to evaluate the states of concrete and coating. GPR operates by pacing it above or dragged across the surface of the target area of assessment in a GPR device's operation as presented in Figure 2.14. Short pulses of electromagnetic energy are sent out to penetrate the material. As the pulses encounter an interface between two different

materials of different dielectric constants, a portion of the energy is reflected. The signal frequencies of GPR ranged from 400 MHz to 2 GHz for most applications.

Figure 2.14 GPR equipment to be used for dielectric constant reading.

GPR has been applied very effectively in bridge construction in several cases to locate tendon ducts and provides positive results (Maierhofer 2003). Additionally, GPR can be used across the depth of the tested structural profile. GPR is operated by transmitting electromagnetic pulses into a pavement structure. This method results in an accurate determination of the surface dielectric constant. The DC values depend on arrival time and amplitude. The reflected pulses, referred to as the radar waveform, display the DC and thicknesses of the layers within the pavement (Joshaghani and Zollinger 2021). The dielectric constant correlate with the moisture content contained in the concrete, the variation of the water content over time affects the DC readings. If the water evaporates from the concrete surface, this will cause the DC values to decrease accordingly. By assessing the relationship between DC and water content over time, one can

determine the evaporation rate under laboratory and field conditions (Joshaghani and Zollinger 2017; Joshaghani 2019). Therefore, DC measurements are an excellent way to determine the moisture retention capability of various curing methods.

A correlation was reported between the dielectric constant and the efficiency of a given curing compound with the moisture retention capability based on a laboratory study done by Zollinger and Sun (2013). Thus, the dielectric measurements showed the quality of curing compounds under different environmental conditions and different water-to-cementitious ratios (w/cm).

2.5.7. Capillary suction

The buildup of Capillary pressure in the pore system of the material due to the loss of water is the leading cause of the shrinkage of concrete in the plastic stage. Early age cracks caused by capillary shrinkage may have a negative impact on concrete pavement durability. It is recommended that the capillary pressure be measured in situ within the first hours after casting to avoid early age damage. Since the measured capillary pressure, it is possible to make decisions concerning the timing of concrete curing measures and to evaluate the effect of such measures (Slowik et al. 2014). The main objective of doing capillary pressures test is to keep the capillary pressure below the critical value to prevent shrinkage cracking in the plastic stage. The capillary pressure sensors can be used to determine the capillary pressure in the concrete. A manufacturer-calibrated pressure transducer is used, which measures the pressure difference between the fluid at the measurement port and the atmosphere. It has a stable casing to protect the electronic components. A cable provides the power supply and the connection to the data logger (Slowik et al. 2014).

2.5.8. Ultrasonic pulse velocity

UPV systems aim to locate and map voids, honeycomb, cracks, delamination, and other damage in concrete, wood, masonry, stone, ceramics, and metal materials. UPV tests are a nondestructive technique performed to predict the strength of early age concrete based on measuring the velocity of compression stress waves (Kewalramani and Gupta 2005). The UPV measurements are used in structural engineering to determine material properties, detect defects, and assess deterioration (ACI 2003)

A pair of transducers near the specimen via a coupling medium is used to accomplish UPV. The commonly used type of ultrasonic transducer is a piezoelectric transducer. The piezoelectric element in one transducer is excited by an electrical voltage signal in the shape of a spike, causing it to vibrate at its resonance frequency, resulting in ultrasonic waves. These vibrations excite the material with a wide range of ultrasonic frequencies through contact, generating stress waves communicated to the receiving transducer. Ultrasonic wave time to propagate to the receiving transducer is measured and defined as flight time. The UPV is computed from a distance between transducers and the measured flight time. The equipment used for ultrasonic pulse velocity measurement consists of three components: Transducers. (One generating transducer from which ultrasonic pulses are transmitted. A receiver transducer receives the pulses). A pulse-receiver. The data acquisition system indicates the travel time from the transmitter to the receiver.

Ultrasound pulse velocity can also be used in concrete to determine the compressive strength of concrete since UPV is dependent on the elastic modulus and the density (Kewalramani and Gupta 2005). The elastic modulus and the compressive strength of concrete increase with maturity. Thus, the pulse velocity may estimate the compressive strength of the tested concrete, even though as concrete matures, these two properties increase at different rates (ACI 2003). UPV

method can determine the time it takes an ultrasonic pulse to travel through the concrete. When the concrete quality is good in terms of density, a higher velocity is achieved., uniformity, and homogeneity—a procedure to determine the strength of hardened concrete by Ultrasonic Pulse Velocity. Concrete quality in terms of uniformity, the presence or absence of internal flaws, cracks, and segregation can be assessed using the outlined guidelines. The guideline has been developed for characterizing the quality of concrete in structures in terms of ultrasonic pulse velocity. (ACI 2003).

2.5.9. Automated techniques

The internet of things techniques is also one the upcoming tests used to evaluate curing compound application effectiveness. MFCC is applied on fresh concrete to prevent or slow the evaporation of moisture from the concrete surface to enhance hydration reaction. It is without doubt that moisture will evaporate from the concrete, so to determine the amount of moisture that evaporated from concrete surface in real time was still a problem. However, the Internet of things (IoT) techniques uses an optimal automatic water curing which continuously measure the actual amount of water evaporated from concrete in real time.

Based on the study performed by Taffese and Nigussie (2023), it was observed that IoT can be used as mean of evaluating concrete curing effectiveness and provide solution on real time. The IoT technique uses embedded sensors that measure the actual water loss and automatically water the surface of concrete. The system's architecture includes multiple wireless temperature and relative humidity sensors embedded in the concrete infrastructure, smart water valves, water pipes with sprinklers, and an IoT gateway. The temperature sensor determines the optimal timing for the watering cycle and monitors the concrete's strength development. On the other hand, the relative humidity sensor tracks the concrete moisture, enabling the measurement of water loss from the

concrete element (Taffese and Nigussie 2023). Furthermore, The IoT gateway collects real-time temperature and relative humidity data from the concrete infrastructure that requires watering, processing it near the source. This enables prompt responses and helps minimize data transmission costs. It sends information to the smart water valve based on sensor data analysis to spray water when the moisture content of the concrete falls below the set threshold and to stop spraying when the concrete is sufficiently hydrated. This process is repeated until the concrete reaches the desired strength level, which is estimated using internal concrete temperature data and the Maturity method. This method assumes that the compressive strength of the hardened concrete is proportional to its internal temperature–time history during the early stages of development.

CHAPTER 3: METHODOLOGY

3.1. Introduction

This section presented all the experimental and fieldwork performed in the study that led to the success of this project. The research work was divided into two phases: laboratory and field phases, each phase aimed at comprehending concrete performance exposed to different types of curing methods. The first phase of the work was completed in the laboratory at the University of Missouri Kansas City (UMKC) and the second phase was undertaken at different locations in the States of Wisconsin. The laboratory phase of this study started by developing a curing table following the curing conditions combinations to match the likely climate scenarios for paving in Wisconsin such as Early season, mid-season, and late season to comprehend the range of anticipated weather and curing performance.

After developing the curing table by identifying different evaporative rates inside the environmental chambers, a laboratory concrete mixture design was developed corresponding to Wisconsin DOT mixture design WisDOT "A" using PLC and limestone aggregate developed using the WisDOT DT2221 optimal mix spreadsheet. Additionally, a testing plan was developed which include determining concrete baseline properties such as air content, unit weight, slump test, setting time, compressive strength, surface resistivity and maturity meter. In addition to the baseline tests, surface profile degree of hydration, moisture loss test following the ASTM C156 standard, and embedded resistance were also included in the testing plan. For, the case of the lastly mentioned tests the effects of parameters such as curing compound application rates, application times, application quality and curing conditions were investigated. The effect of curing affected zone was also investigated in this study using the embedded resistance test that was developed to

assess the effectiveness of curing compound in real time and surface profile degree of hydration determined the hydration evolution between the cured affected zone and the interior of concrete.

3.2. Materials and chemicals

3.2.1. Sampling and storage

The materials used in this study are presented in the following Table 3.1. Cement, coarse and fine aggregates were from local sources. Same as for the admixtures and the curing compound.

Table 3.1 Materials and sources.

Materials	Source
Types IL cement	
Intermediate aggregates	
Coarse aggregates	
Fine aggregates	USA
High range water reducer	
Air entraining agent	
PAMS curing compound	

3.2.2. Cement

Types IL-12 cement was the only cementitious material used for all the laboratory concrete batches produced. Cement chemical and physical properties as provided from the mill report are listed in Table 3.2 Cement container was sealed to prevent any interaction with air and kept in a dry laboratory condition.

Table 3.2 Cement properties

Chemical Composition wt. %		
Silicon dioxide (Sio2)		19.2
Aluminum oxide (Al2O3		4.4
Ferric Oxide (Fe2O3)		2.8
Calcium Oxide (CaO)		62.7
Magnesium Oxide (MgO)		1
Sulfur Trioxide (SO3)		2.8
Loss on Ignition (LOI)		5.7
CaCO3 in Limestone		93
Total Alkali as Eq		0.54
Physical Tests		
Fineness Blaine (m2/kg)		414
Autoclave expansion (%)		0.03
compressive Strength (PSI) 7-day	7-day	4960
	28-day	6280
Setting time (ASTM C191), initial time (minute)		103

*Wt. % stands for percentage by weight of the compounds.

3.2.3. Aggregates properties

The aggregates used were coarse and intermediate crushed limestones from the Randolph quarry and the fine aggregate was from Missouri river sand. All the coarse and fine aggregates used in this study meet the ASTM C33 requirements. The properties of the aggregates used are presented in the Table 3.3 and Table 3.4 respectively.

Table 3.3 Coarse aggregates properties

Coarse Aggregate Type	Specific Gravity	Absorption	P200	Abrasion mass loss	Fineness modulus
57/67	2.77	0.8	0.2	24	6.66
3/4"	2.72	1	1.9	23	6.41

Table 3.4 Fine aggregate properties.

Fine aggregate types	Absorption (%)	P200 (%)	Specific gravity (%)	Fineness modulus
River sand	0.6	0.3	2.64	2.69

3.2.4. Chemical admixtures and curing compound.

The concrete mixture was dosed using a polycarboxylate High range water reducing admixture and Airalon 7000 Air entraining-agent containing a vinsol resin-based. Poly alpha methyl styrene curing compound meeting the ASTM C309 and classified as type 2, class A& B was used and applied using pump sprayer or a brush for other application rates. The PAMS curing compound used has the volatile organic content (VOC) content limits of 350g/liter and reflectivity greater than 60 percent, and specific gravity of 0.98.

3.3. Experimental procedures

The overall schematic representation of all the steps involved in achieving the goals of the project is presented in Figure 3.1. The work started by developing the mix design and gathering all the materials that were going to be used in the project. Once everything was set the mixing and testing stages began and all the details are described in the following sections.

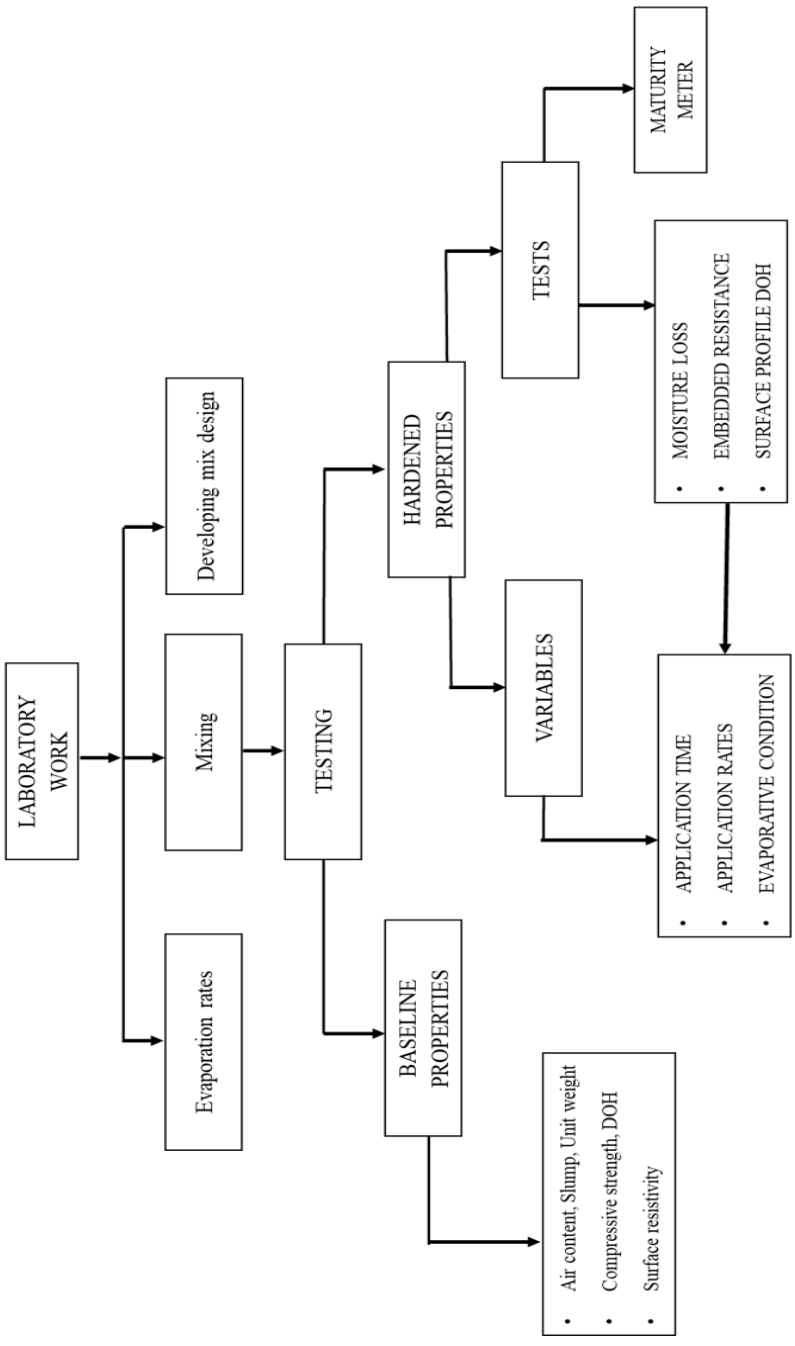

Figure 3.1 Experimental outline

3.4. Laboratory work

The research work started by developing the mixture design (Table 3.5) corresponding to Wisconsin DOT mixture design WisDOT "A" using PLC and limestone aggregate developed using the WisDOT DT2221 optimal mix spreadsheet. The second stage was determining the evaporation rate inside the environmental chambers used for curing concrete specimens by varying temperature and relative humidity, ten evaporative conditions were selected in this study representing different field curing conditions as presented in Table 3.6. Additionally, after concrete mixing and casting four variables were used to investigate the effect of each of them on concrete performance. The variables investigated in the laboratory phases were time of curing compound application, curing compound application rate and application quality, and lastly curing conditions (evaporative rates). For each of the evaporative conditions, four curing compound application rates were evaluated (uncured, non-uniform 180 ft^2/gal, uniform 180 ft^2/gal, uniform 400 ft^2/gal).

The application time was investigated by applying curing compound before and after initial set, while the curing condition was investigated by curing concrete specimens produced in different evaporative conditions. For every concrete batch produced the baseline properties (unit weight, air content, slump, setting time, compressive strength, and surface resistivity) were determined to ensure consistency between the batches. Surface profile degree of hydration determined the hydration evolution between the cured affected zone and the interior of concrete, concrete moisture retention capacity was determined for all the curing conditions, and lastly, a continuous resistance technique test was developed to assess the effectiveness of curing compound in real time.

Table 3.5 Concrete mix design

Materials	**Mix proportions, kg/cm^3**
Cement 1L	325
Fine Agg.	795
Intermediate aggregates.	695
Coarse aggregates.	385
Water	130
w/cm	0.42

Table 3.6 Evaporative conditions

Evaporate condition ID	**Unit, kg/m^2/hr.**
CC1	0.769
CC2	0.155
CC3	0.259
CC4	0.410
CC5	0.483
CC6	0.074
CC7	0.113
CC8	0.205
CC9	0.040
CC10	0.007

3.4.1. Evaporation rate determinations

The evaporation rate inside the curing chambers was determined by calculating the mass loss of water samples after 24 hours. Water samples in plastic containers were placed at different locations inside the curing chambers. The weight of the empty container and water were recorded before and after, same as the inside diameter of the container. The container filled with water was then stored in a curing chamber set in a controlled temperature and relative humidity. the evaporation rate was then calculated using the following equation 3-1:

$$\boldsymbol{ER} = \frac{\Delta \boldsymbol{mass}}{\frac{\boldsymbol{mean\ Area}}{\boldsymbol{time}}} \qquad \text{Equation 3.1}$$

3.4.2. Mixing and curing conditions

Concrete was produced using a rotating drum type mixer following ASTM C192. The mixture contained a vinsol resin-based air entraining admixture and polycarboxylate water reducer. The Aggregate quality control was maintained by washing coarse aggregate, oven drying both fine and coarse aggregate 24 hours prior to mixing and allowing to cool to room temperature while covered before mixing. Prior of mixing the concrete mixer was sprayed with water to avoid the mixing water to be sucked by the mixer and affecting the water to cementitious ratio. After casting, curing compound application, the specimens were stored in environmental chambers set at a specific temperature and relative humidity throughout the curing period. The four different application rates used in this study are presented in Figure 3.2.

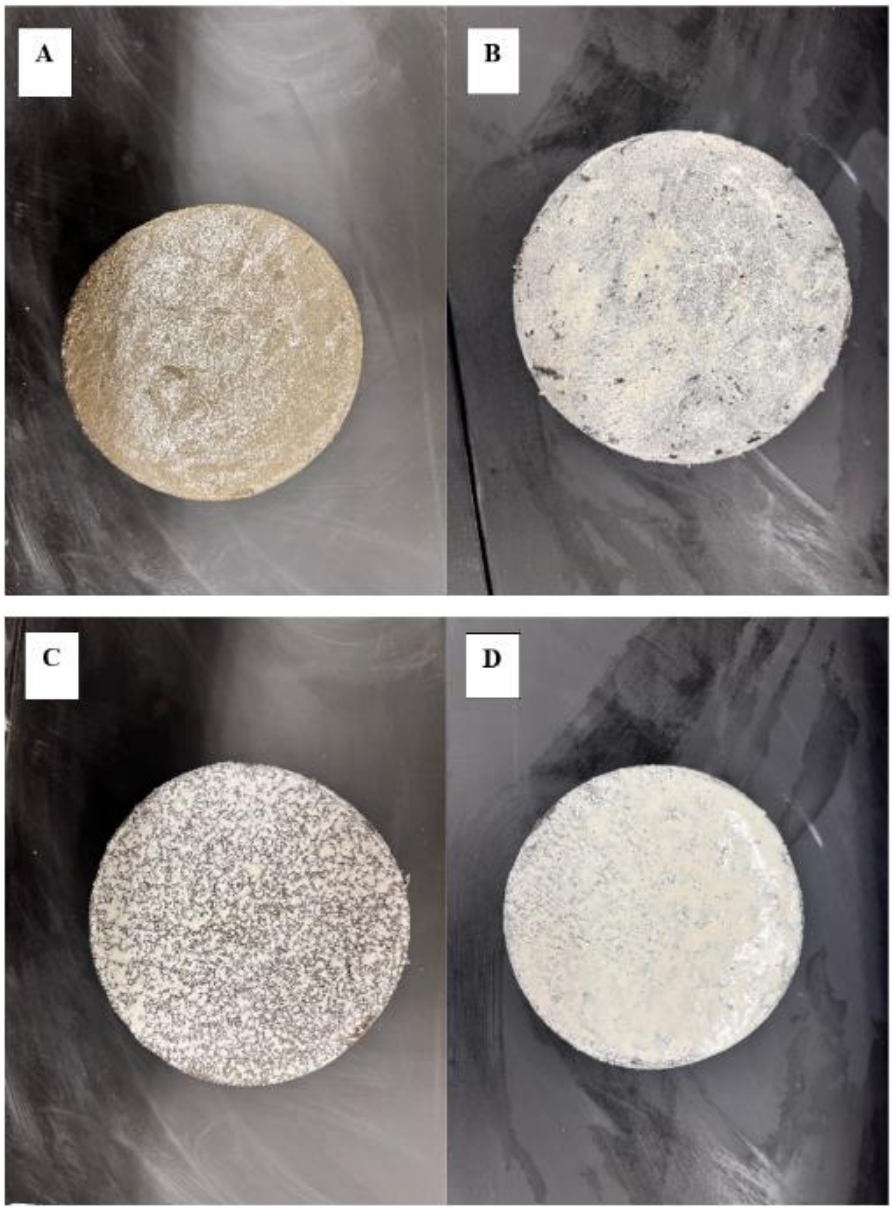

Figure 3.2 Different application rates used. A: Uncured, B: 9.8U, C: 4.4NU and D: 4.4U

3.4.3. Fresh concrete tests

For every concrete batch produced, pressure method air content was determined following the ASTM C231 standard, slump test following ASTM C143, and lastly concrete unit weight was determined as well following ASTM C138. Concrete fresh properties were determined to check

the concrete mixture consistency. Only concrete batches that had air content, slump value and unit weight values within the acceptable range were then used for casting and further testing.

3.4.4. Setting time

Concrete setting time was investigated using Vicat apparatus (ASTM C 403), and Ultrasonic pulse velocity for every batch produced as presented in Figure 3.3. Sample for Vicat apparatus were collected by extracting mortar using sieve number 4 (4.75 mm) from concrete batch produced, Vicat set up is presented in Figure 1a, and for UPV test was performed on concrete specimen cast in 4*8 in. cylinder mold. The cylinder mold was placed in a plastic frame Figure 1b, where two transducers were placed; one at the bottom in contact with the bottom part of the cylinder and one transducer placed at the top of the cylinder. To create a contact between the top transducer with the top surface of the concrete a plexiglass sheet at the size of the cylinder was used. To reduce the attenuation of the wave at the interface of the transducer with the mold or plexiglass sheet a commercial gel couplant was applied.

Figure 3.3 Setting time equipment used. A: Vicat apparatus set-up, B: UPV set-up.

3.4.5. Compressive strength test

Samples for compressive strength were cast and curried in accordance with ASTM C31. The compressive strength was determined after 1, 3, 7 and 28 days of curing. After mixing, specimens were cast in 4X8 in. cylinders mold and capped, left to cure in laboratory conditions for the first 24 hours, there after cylinders were demolded and placed in a humidity controlled wet room with 100% relative humidity throughout the curing period. For each curing time three cylinders were tested to failure for compressive strength following the ASTM C39 standard.

3.4.6. Surface resistivity test

The surface resistivity test was conducted following the AASTHO T358 procedure. The surface resistivity was determined after 1, 3, 7, and 28 days of curing. The samples were cast in

4X8 in. cylinder molds, after 24 hours of curing in the laboratory condition samples were demolded and stored in a 100% relative humidity curing room. To measure the resistivity, the cylinder was taken out of the curing room and dried at surface saturated dry condition during the specified testing time as presented in Figure 3.4.

Figure 3.4 Surface resistivity testing unit.

3.4.7. Moisture loss test

The moisture retention test was completed first on mortar following the ASTM C156 standard to verify the performance of the selected MFCC and later the same procedure was followed on concrete with the exception of varying curing compound application time, application rate, and the curing condition as shown in Table 3.7**.** The effect of application rates was investigated by applying MFCC at four different application rates 0 (uncured), 400 ft^2/gal (400 U) uniformly applied using a brush, 180 ft^2/gal non-uniformly (180 NU) applied using a pump sprayer

and l80 ft^2/gal (180 U) uniformly applied using a pump sprayer. The effect of application time was investigated by applying curing compound right after final surface finishing (approximately 30 minutes after mixing and 120 minutes before the initial set) and after the bleed water was no longer present (after the initial set). Lastly, the effect of curing condition was investigated by curing concrete specimens in a temperature and humidity-controlled environmental chamber set at 10 different combinations of evaporation rates. Concrete weight was recorded every 24 hours throughout the 72 hours of curing to determine moisture loss following ASTM C156.

Table 3.7 Moisture retention test factorial design

Application time and rates		Curing condition
Curing time (t)	Application rates (ft^2/Gal)	(kg/m^2/hr.)
Before Initial Set	0	0.7687
After Initial set	400	0.1550
	180 (NU)	0.2590
	180 (U)	0.4098
		0.4834
		0.0737
		0.1127
		0.2054
		0.0395
		0.0074

3.4.8. Surface profile degree of hydration

The degree of hydration (DoH) was performed using methods proposed by Fagerlund (2009). The DoH was determined from samples used to determine concrete strength at the ages of 1, 3, 7, and 28 days. The compressive strength samples were cured in lime water and represent the

best possible hydration as a control. Immediately after the compressive strength test, concrete samples were crushed. These samples were ground using a mortar and pestle to a uniform fine powder and sieved using sieve number 30. The second set DoH herein identified as surface profile degree of hydration was determined using concrete samples cast in 6x3 in. cylinder molds. The surface profile DoH was determined by measuring the DoH from the powder obtained from a depth of 1/16th in. and at 0.5 in from the surface (Figure 3.5). After casting, the specimens were left in the laboratory condition until the bleed water was gone and curing compound was applied at the four different application rates (Uncured, 400U, 180NU and 180U). Samples were then stored in a controlled temperature and relative humidity environmental chamber set at 10 different evaporation rates. DoH was then determined at the age 1, 3, and 7 days of curing. DoH was determined from the collected powder through ignition where, 5 g of the ground sample was placed in a ceramic crucible and in an oven at 105 °C for 2 hours to obtain the weight of the free evaporable water. Then, samples were placed in a furnace at 1000 °C for 1 hour to obtain the weight of the non-evaporable water. The non-evaporable water was taken as the mass loss between 105 °C and 1000 °C, the measurements were corrected to account for loss on ignition of the cement. The quotient w^0_n/c (which is the chemically bound water at complete hydration of cement quantity) of 0.25 was assumed in this study as shown in the following equation (Fagerlund 2009).

Figure 3.5 Surface profile degree of hydration sample.

$$\alpha = \frac{Wn}{\frac{C\,effective}{\frac{W_o^n}{C}}} \qquad \text{Equation 3.2}$$

Where: α = degree of hydration in percentage, W_n is the amount of chemically bound water determined. C effective is the mass of the cement after ignition, and lastly the ratio was assumed to be 0.25

3.4.9. Embedded resistance test

Embedded resistance was measured using a 2-pin array arrangement which contained a non-conductive plastic frame holding 4 stainless steel probes, 2 for each depth (surface and 0.5 inches) as shown in Figure 3.6. Two of the probes were just in contact with the surface of the concrete and the others were embedded 0.5 in (12.5 mm) into the concrete below the cure-affected depth. The sides of the probes were protected using nylon sleeves to ensure that data was collected

only from the concrete at the probe tip. The frame was set 1 in. above the surface to allow the free movement of air on the concrete surface. An arbitrary cutoff of 160 kΩ/cm was selected as the maximum resistance value for recording resistance based on the range of initially observed results and the precision drift of the equipment. Samples for embedded resistance testing were cast in 6x3 in. cylinder molds. Embedded resistance was measured on the same environmental conditions and application rates as shown previously.

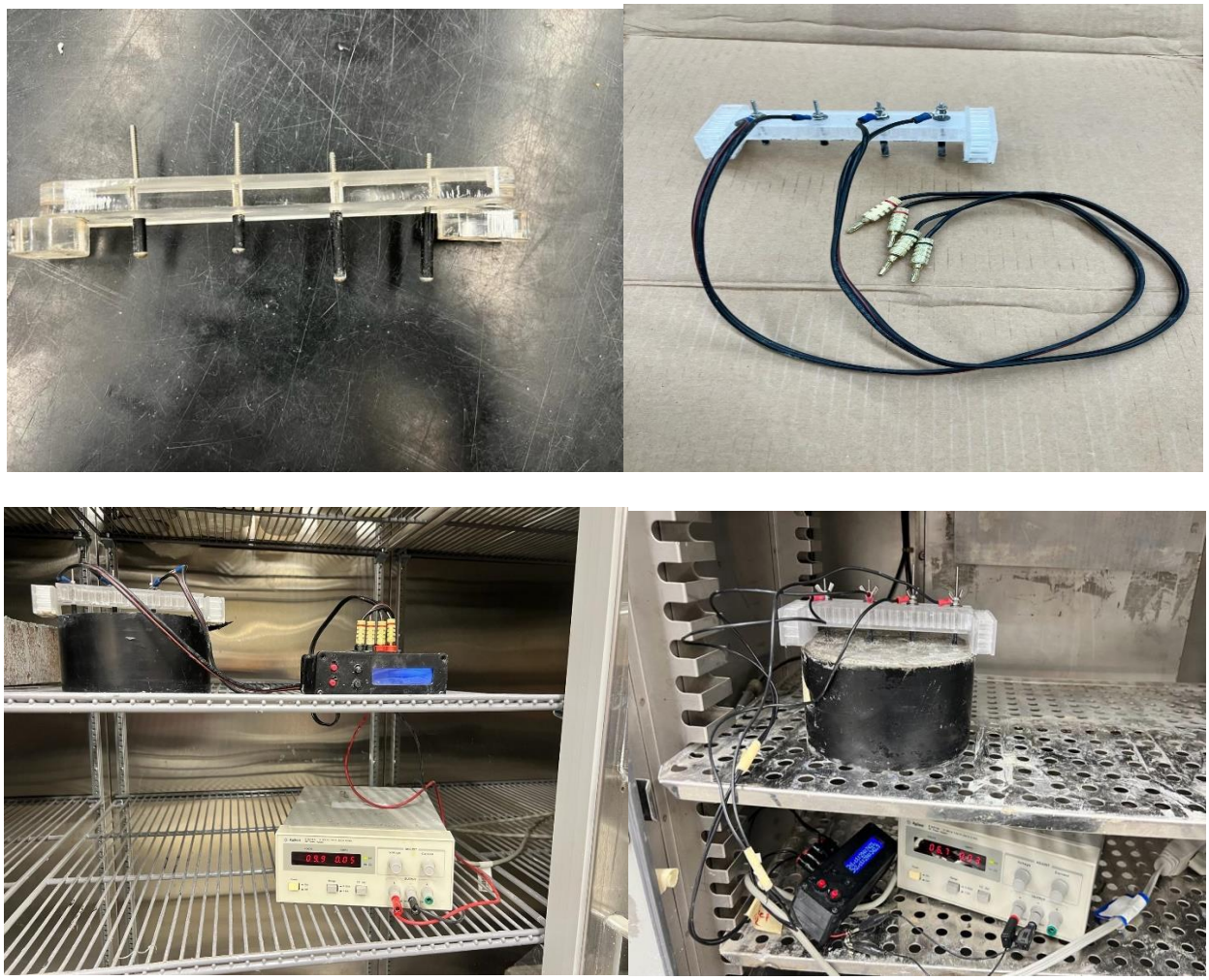

Figure 3.6 Embedded resistance test set-up.

3.4.10. Maturity test

Concrete maturity was developed following the ASTM C192 standard, 15 concrete cylinders were made from the same batch that was used to make samples for embedded resistance and degree of hydration. Specimens were cured in a water bath kept at 23C. at least two concrete cylinders were crushed to determine the compressive strength following ASTM C39 standard. Simultaneously, temperatures are recorded at each age in correspondence to the strength data to evaluate the maturity index according to Nurse-Saul equation (Eq.3.3). To determine the maturity curve average compressive strength data are plotted as a function of the average maturity index and determining the actual concrete strength using the maturity curve developed.

$$\boldsymbol{M(t) = \sum(T_a + T_0)\Delta t}$$ Equation 3.3

Where: M(t)= the temperature time factor at age t, T_a = average concrete temperature during time interval, T_o = datum temperature (Taken between 0 and -10^{0}C depending on the concrete mixture design), and Δt= time interval (days or hours). Figure 3.7 presents the cylinder prepared for the maturity test.

Figure 3.7 Maturity test samples.

CHAPTER 4: PRELIMINARY INVESTIGATION INTO USING RESISTANCE TECHNIQUES TO ASSESS CONCRETE CURING

4.1. Abstract

Concrete curing is a critical stage during construction for volume stability, long-term strength development, and ultimate durability. Poor curing can lead to shrinkage, scaling, and other durability issues. Proper concrete curing maintains sufficient moisture in the concrete and allows continuous hydration. Curing for concrete pavements often involves the application of a membrane-forming curing compound to help minimize moisture evaporation and promote desirable concrete property development. However, assessing the application rate of curing compounds and effectiveness on freshly paved concrete is difficult, as most evaluation methods are performed on hardened concrete and not applicable or difficult to assess for fresh concrete in the field. This study proposes electrical resistance as a measure to assess drying behavior of fresh concrete to quantify the effectiveness of curing. The findings of this study demonstrate that resistance is able to distinguish between samples with and without curing compound and significant differences in drying observed between the surface and relatively shallow depths. Additionally, the testing techniques were able to differentiate between the quality and rate of curing compound application and evaluate performance across a variety of environmental conditions. These findings indicate that a resistance-based approach could be a low-cost and non-destructive technique to evaluate the effectiveness of curing compound applications in real-time.

4.2. Introduction

Concrete curing is the act of maintaining adequate moisture and temperature in the concrete to maximize the hydration process (ACI 308 2016) and hydration ceases when the relative humidity falls below 80% (Joshaghani and Zollinger 2017). While a variety of curing techniques can be used, including wet curing, internal curing, and forced chemical curing, membrane-forming

curing compounds (MFCCs) are often the easiest and most cost-effective technique to minimize evaporation for pavements and slabs placed on grade. Concrete curing is crucial to reduce early-age cracking and for the development of desired hardened properties such as low permeability (Pawar and Kate 2020; Sldozian and Hamad 2019). Conversely, poor curing results in premature deterioration in the form of plastic and drying shrinkage cracking, scaling, joint spalling, and freeze-thaw deterioration (Sldozian and Hamad 2019; Wang et al. 2002).

According to American Concrete Institute (ACI) committee 308, concrete possesses a near-surface cure-affected zone which is strongly related to surface durability and differentiated from performance of the interior, bulk concrete. While the cure-affected zone does not have a specifically agreed-upon definition, the generally accepted depth is 0.25 to 0.75 in. (6-19mm) (Rothstein 2017). As concrete may result in numerous different shapes and volumes, the amount of exposed surface area is quite different between a pavement slab and a foundation. If curing is only a surface effect, it has a minimal impact on the strength of large elements and data showing loss of strength related to curing is based on small cylinders where the effect is sample size dependent. For slabs, the effect of curing is observed in the surface layer performance including abrasion resistance and permeability (Poole 2006).

Concrete curing can be classified into initial and final curing (ACI 308 2016). Initial curing is defined as the period from concrete placement through the completion of surface finishing. During initial curing, concrete bleed water rises as solid materials settle and subsequently evaporates or is consumed in hydration of the surface cementitious materials. Therefore, minimizing moisture loss during initial curing is necessary to reduce the loss of water and prevent plastic shrinkage from occurring (Taylor et al. 2004). Techniques to minimize moisture loss include fogging, wind shades, or application of surface moisture retardants. Final concrete curing includes

the period after final surface finishing has been completed and is important to prevent continued moisture loss and incomplete hydration at the surface (Poole 2006). Final concrete curing can be accomplished through the addition of external water through ponding, fogging, or water retention measures. Ponding is labor-intensive and often not cost-effective (Raza et al. 2020). Curing utilizing water-retention techniques includes plastic sheeting or wet burlap or application of membrane-forming curing compounds (MFCCs). While highly effective when installed correctly, plastic sheeting presents significant drawbacks, such as the inability to install over large areas, securing to minimize ballooning, and surface marking (Raza et al. 2020; Sun 2013). MFCCs is the cost-effective method for curing concrete on a large scale due to the ease of application, little supervision required after application, and the ability to sufficiently minimize moisture loss (Sun 2013; Senbetta 1988).

MFCCs are chemical solutions of a wax or resin dissolved in water or other chemical solvents. Once applied to a newly paved concrete pavement surface, the solution breaks and the water or solvent evaporates leaving behind the wax or resin to form a membrane over the surface of the pavement. The membrane seals to retain moisture in the concrete by lowering the evaporation rate and blocking the concrete pores (Pawar and Kate 2020). ASTM C309 (ASTM C309 2003) classifies curing compounds into 3 types based on color and solid constituents and two classes based on solid chemistry as shown in (Table 4.1).

Table 4.1 Curing compound classification (ASTM C309)

COLOR		**SOLID CONSTITUENT**	
Type	Description	Class	Description
1	Clear or Translucent w/out Dye	A	No Restriction
1-D	Clear or Translucent w/Fugitive Dye	B	Resin
2	White Pigmented		

MFCCs are easily applied using a hand-held sprayer or curing cart for large surface-areas and several factors are considered when applying and evaluating the effectiveness of MFCC, including ambient conditions, time of application after finishing, application rates, uniformity of application, type of curing compound, and surface texture of the concrete (Kropp et al. 2012; Ye et al. 2010; Jana 2007; Vandenbossche 1999). Measurement methods for MFCCs include visual inspection, penetration resistance (Joshaghani and Zollinger 2021), image analysis, dielectric constant (Choi et al. 2012), compressive strength (Wang et al. 2002), abrasion resistance testing (Sun 2013), rapid chloride permeability testing (Ye et al. 2010), moisture retention (Wang et al. 2002), reflectance (Choi et al. 2012), relative humidity testing (Ye et al. 2010), sorptivity (Wang et al. 2002), capillary pressure sensor development (Slowik et al. 2014; Jamali et al. 2022), and degree of hydration (Wang et al. 2002). These tests provide useful information related to concrete curing; however, most are only performed on hardened concrete, making them difficult to use in the field or as the basis for adjustments during the early age of concrete. Most methods have a small footprint and do not assess variability across a pavement. The objective of this research was to develop a test method to measure curing effectiveness in real-time during the early age of concrete.

Electrical resistivity has become a powerful and low-cost technique to assess the amount and connectivity of pores in the hydrated concrete structure and predict future durability. Resistance is a measure of how easily a current passes through a medium agnostic of geometry or distance whereas resistivity includes geometry and factors such as temperature. While related, resistance and resistivity are not directly comparable which is why the following experimentation is divided into two phases. The initial work utilized the standard Wenner 4-pin resistivity probe commonly used for concrete quality control, but with data collected from probes inserted into fresh

concrete. The follow-on work developed a test method utilizing electrical resistance as a measure or moisture loss in fresh concrete and quantify the effectiveness of curing, inspired from the Wenner electrical resistivity work. As concrete transitions from a plastic to a solid phase, free moisture in concrete decreases and resistance increases, as the liquid phase of concrete is a better electrical conductor than the solid phase (AASHTO T358 2018). As concrete transitions from plastic to solid, hydration products grow and interconnect increasing density, also increasing resistance (Wang et al. 2002). At early ages (<3 days) the influence of drying influence resistance much greater than the densification. Therefore, measuring the resistance at the surface and at a given depth inside of fresh concrete provides insight into how well the application of curing compound is retaining moisture within the near-surface area and/or whether a lack of curing leads to moisture loss.

4.3. Materials and methodology

The research program was divided into two parts. The first used uncoated nails as probes embedded into two different concrete mixtures (WP-0.40 and WP-0.43) at two depths 0.50 in. and 0.25 in. (2.5 mm and 6.25 mm) with uncured and MFCC-treated samples subjected to a single environmental condition. Data was collected through a standard 4-pin Wenner Probe resistivity array with a correction factor applied for a flat surface geometry. The Wenner approach was developed for single points in contact with a concrete surface. The device was used for an initial assessment to test the possibility of the approach. After potentially actionable data was collected an updated device was created. The second portion used a single mixture (ER-0.42) and a custom-built 2-pin array to evaluate resistance at the surface and embedded depth of 0.5 in. (12.5mm) through probes shielded using nylon sleeves to isolate the point of measurement to the cure-affected zone. The probe distance for the 2-pin array matched the 1.5 in. (37.5 mm) spacing of the

more common Wenner array. Using this arrangement, a voltage was applied through the embedded pins, current measured, and resistance determined using Ohm's law. The second portion evaluated concrete cured at two environmental conditions (high and low). High evaporative condition 100°F (38°C) and 32% relative humidity and lower evaporative condition 73°F (23°C) and 50% relative humidity. Testing included four curing applications none 0 ft^2/gal (0 m^2/l), 180 ft^2/gal (4.5m^2/l) (uniformly and non-uniformly applied), and 400 ft^2/gal(10m^2/l) uniformly applied.

4.3.1. Materials, Mixing, and Curing

Mixtures were selected to represent common paving mixtures with slump less than 2 inches and air content between 5 and 6% (Table 4.2). Mixtures WP-0.40 and WP-0.43 used ASTM C150 (ASTM C150 2007) cement meeting both Type I and Type II requirements and ASTM C618 Class F Fly Ash (ASTM C618 2019). Mixture ER-0.42 used Type 1L cement (ASTM C595) containing 12% limestone. All mixtures used ASTM C33 (ASTM C33 2016) river sand and limestone intermediate and coarse aggregate. Admixtures included a polycarboxylate water reducing admixture and olefin-based air-entraining admixture. The curing compound used for the Wenner tests (WP-0.40 and WP-0.43 mixtures) was a white-pigmented wax meeting ASTM C309 (ASTM C309 203), classified as Type 2, class A. The compound used for the embedded tests (ER-0.42 mixture) was a poly alpha methyl styrene (PAMS) based product meeting ASTM C309 Type 2B (ASTM C309 203).

After mixing, casting and surface finishing, the specimens were left in a laboratory condition until bleed water evaporated before application of MFCC. For the Wenner Probe portion of the testing, curing compound was applied at 200 ft^2/gal (5 m^2/l) using a brush. For the embedded resistance portion, specimens were cured using a pump sprayer or brush Figure 1(A) with four different application rates:

- An uncured reference Figure 4.1(A)
- 180 ft^2/gal (4.5m^2/l) (Uniform) applied using a pump-sprayer Figure 4.1(D)
- 400 ft^2/gal (10 m^2/l) (Uniform) applied using a brush Figure 4.1(B).
- 180 ft^2/gal (4.5m^2/l) (non-uniform) applied using a pump-sprayer Figure 4.1(C).

Table 4.2 Mix proportions.

	Mixtures, lbs./yd^3 (kg/m^3)		
Materials	**WP-0.40**	**WP-0.43**	**ER-0.42**
Cement 1L	NA	N/A	545 (325)
Cement (I/II)	450 (267)	500 (297)	N/A
Class F Fly Ash	110 (65)	125 (74)	N/A
Fine Agg.	1405 (834)	1485 (881)	1340 (795)
Intermediate Agg.	315 (187)	N/A	1170 (695)
Coarse Agg.	1420 (843)	1500 (890)	650 (385)
Water	225 (133)	270 (160)	220 (130)
w/cm	0.40	0.43	0.42

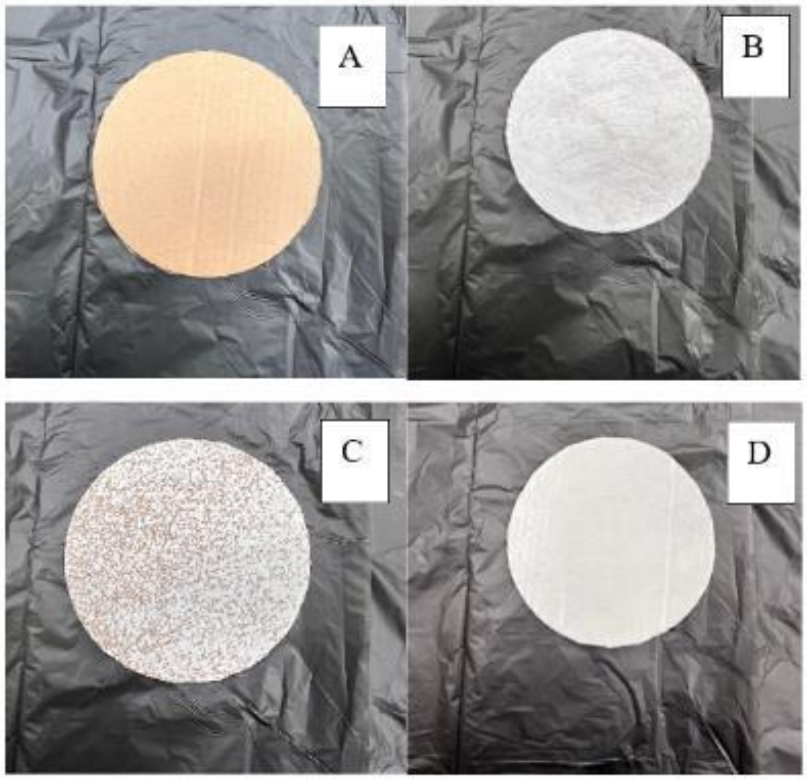

Figure 4.1 Cardboard with no curing compound, (B) Cardboard with 400 ft^2/gal curing compound applied using a brush (400U), (C) Cardboard with non-uniformly applied curing compound at 180 ft^2/gal (180NU), and (D) Cardboard with uniformly applied curing compound at 180 ft^2/gal (180U).

4.3.2. Concrete testing

- Wenner Probe Approach

For the first part of this study, 4 in. x 4 in. x 14 in. (100mm x 100mm x 350mm) samples were prepared following the WP- 0.40 and WP-0.43 mixture designs shown in Figure 4.2. Curing compound was applied at a single rate of 200 ft^2/gal (5 m^2/l) over the cured samples and a box fan was used to blow air over both the cured and uncured samples at a lab temperature of 73°F (23°C) and 50% relative humidity. Using the ACI 308 nomograph, the evaporation rate was estimated at 0.11 lb./ft^2/hr. (0.54 kg/m^2/hr.). The effect of w/cm was evaluated by comparing unshielded probes inserted to 0.5 in. (12.5mm) between WP-0.40 and WP-0.43 and the effect of probe depth was

compared for mixture WP-0.43 using probes inserted and concrete consolidated after probes insertion at either at 0.5 in. (12.5mm) or 0.25 in. (6.25mm). Probes were held in place using non-conductive wood Figure 4.2(A). The test setup showing cured and uncured samples is shown in Figure 4.2(B) with the fan blowing lengthwise. An air gap was included between the concrete and supporting frame to allow air movement and not prevent drying of the surface. Resistivity was measured manually by connecting the electrodes on the Wenner probe Figure 2(C) to the tops of the nails on the test frame. Resistivity measurements were taken up to 12 hours when the researcher went home. By the next morning measurement values exceeded the range of the Wenner probe.

Figure 4.2 (A) Test set up, (B) pair of samples with and without curing compound, and (C) commercial Wenner Probe device.

- Embedded Resistance Approach

The embedded resistance probe used a 2-pin arrangement in a non-conductive plastic frame to hold four stainless steel probes, two for each depth (Figure 4.3). Two of the probes were just in contact with the surface of the concrete and the others were embedded 0.5 in (12.5 mm) into the concrete. The sides of the probes were protected using nylon sleeves to ensure that data was collected only from the concrete at the probe tip location. Similar to the previous arrangement, the frame was set 1 in. (25 mm) above the surface to allow the free movement of air at the concrete surface Figure 4. 3(A). A data logger was used to record resistance development with time at 5-

minute intervals. The complete set-up is shown in Figure 4. 3(B). An arbitrary cutoff of 160 kΩ/cm was selected as the maximum value for recording resistance based on the range of initial observed results and precision drift of the equipment. Samples for embedded resistance testing were 12 in. x 12 in. x 4 in. (300mm x 300mm x 100mm) with the plastic cutoff cylinder shown in Figure 4. 3(B) only used here to show the bridge height.

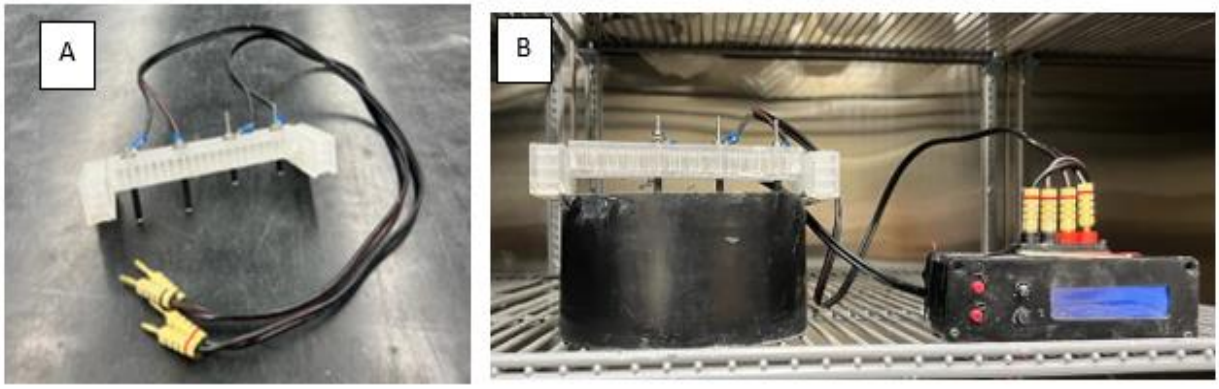

Figure 4.3 Embedded surface resistance device.

4.4. Results and Discussion

4.4.1. Wenner Probe Approach

Results for resistivity measured using the 4-pin Wenner probe as measured on top of embedded nails are shown in Figure 4.4. Resistivity increased with time for all samples, indicating moisture loss in the near-surface region. In all cases, irrespective of depth, samples with curing compound (Cured) had lower rates of resistivity increase than the corresponding uncured (Uncured) samples. For the uncured samples, the rate of resistivity gain increased rapidly starting at 2 hours after mixing. For the cured samples, resistivity only began to increase at 4 hours after mixing.

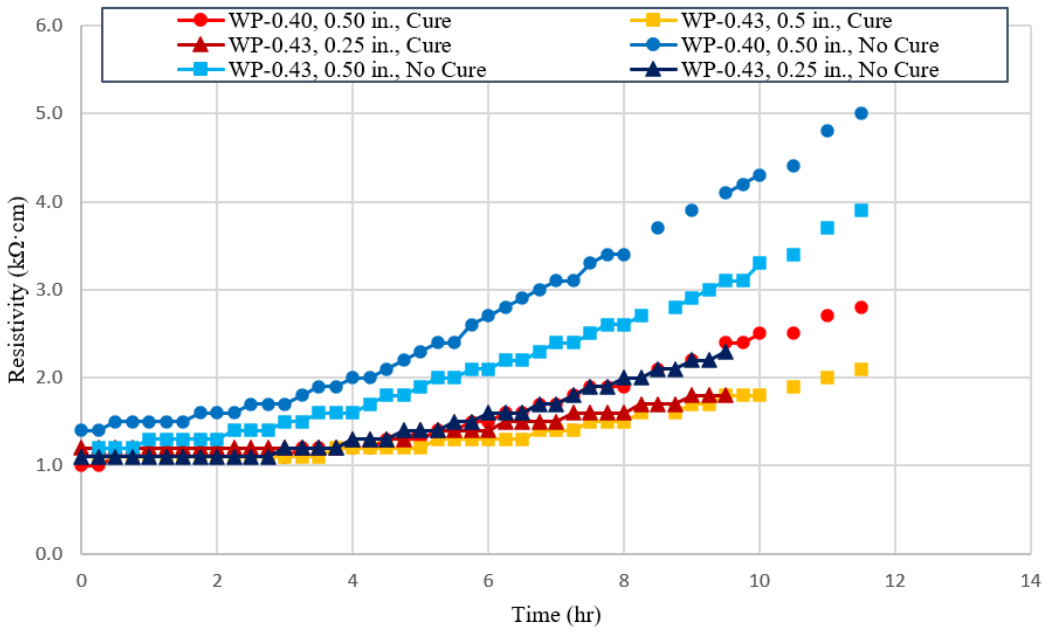

Figure 4.4 Wenner Probe Results

Resistivity increased to a greater magnitude for the WP-0.40 Cured and Uncured samples compared to the corresponding WP-0.43 Cured and Uncured samples, likely due to the lower w/cm and faster pore emptying. A greater fraction of the available moisture may have been lost to hydration and evaporation in the samples with the lower w/cm. Resistivity increased less for the WP-0.43, 0.25 in. (6.25 mm) probe depth samples compared to the corresponding WP-0.40 and other WP-0.43 samples that were tested at the 0.5 in. (12.5 mm) probe depth. The finding of a smaller increase in resistivity at the shallower probe depth was surprising, as it might have been expected that more moisture loss would occur closer to the surface, especially if evaporation plays a role in the increase in resistivity. One possible explanation for this finding is that inserting the nails to a shallower depth did not disturb the fresh concrete surface as much as inserting them to a greater depth, leading to less moisture loss from the area around the nails.

4.4.2. Embedded Resistance Approach

Resistance data for the 2-pin embedded resistance array is shown in Figure 4.5 for the low evaporative conditions 0.032 Ib/ft^2/hr. (0.156 kg/m^2/hr.) and Figure 4.6 for the high evaporative conditions 0.158 Ib/ft^2/hr. (0.769 kg/m^2/hr.). Consistent with the previous Wenner Probe results, resistance increased with time, rapidly increasing after initial set. Resistance at the 0.5 in. (12.5mm) level was similar across all conditions, indicating a sufficient depth to differentiate between the cure-affected zone and the interior of the concrete. Time to the 160 kΩ/cm test maximum was reached in about half the time in the hot and dry conditions compared to the lower evaporative rate conditions, indicating good agreement between the anticipated impact on surface drying.

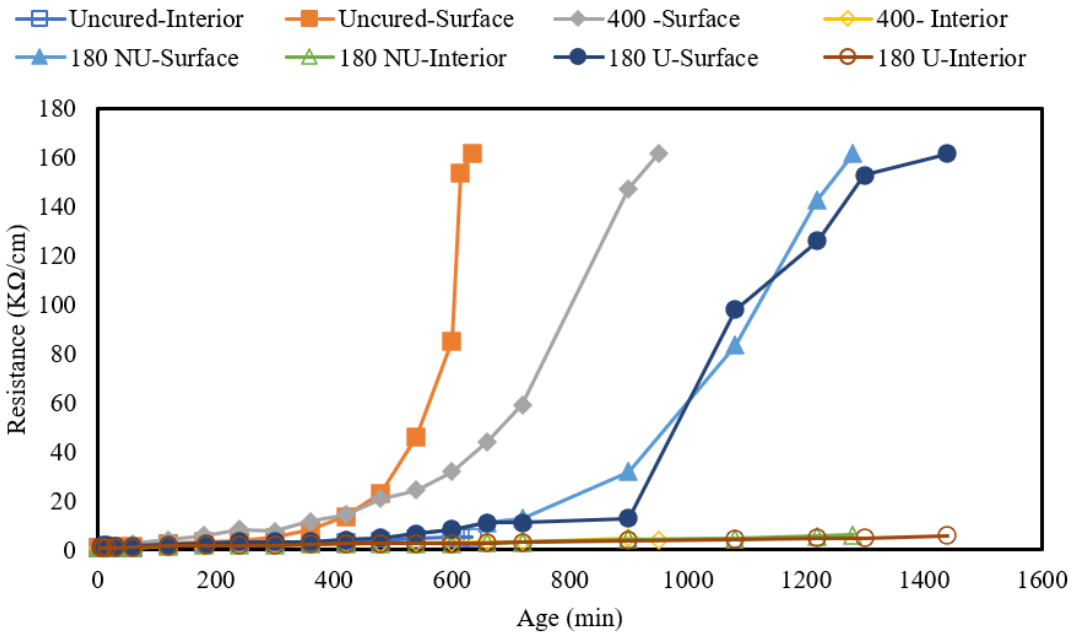

Figure 4.5 Resistance for low evaporative condition (23C,50% RH) with Interior = 0.5 in. (12.5 mm) probe depth.

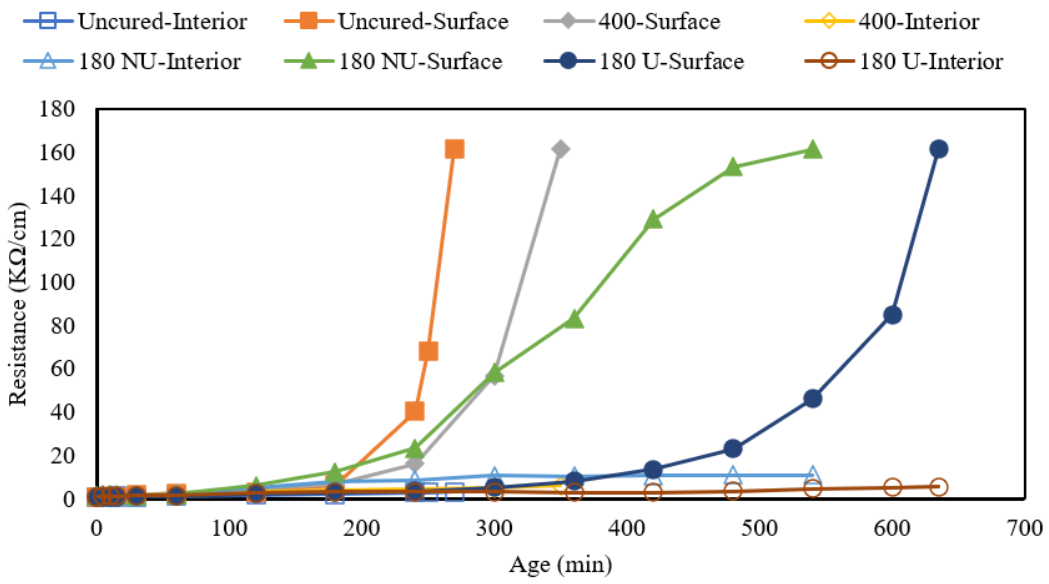

Figure 4.6 Resistance for high evaporative condition (38C,32% RH) with Interior = 0.5 in. (12.5 mm) probe depth.

Considering the low evaporation rate results presented in Figure 4.5, a substantial difference in resistance was observed between the cured and uncured specimens. While visually the specimens with uniformly applied curing compound at either uniformly at the recommendation rate 180 ft^2/gal (4.5m^2/l) (180U) or uniformly at half the recommended rate 400 ft^2/gal (10m^2/l) (400U) appeared similar, resistance rose much faster for the 400U samples. For the lower evaporation rate condition, there was no difference in resistance response between the uniformly (180U) applied non-uniformly applied (180NU) samples at the 180 ft^2/gal (4.5m^2/l) rate. For the higher evaporative conditions shown in Figure 4.6**,** surface resistance increased much more rapidly for all curing conditions. Like the lower evaporative conditions, samples with half the recommended curing compound (400U) had a much faster rise in resistance than the appropriately cured specimens (180U). The importance of uniformly applying curing compound was more

significant for the higher evaporation rate tests, with the non-uniform specimens (180NU) rising much more quickly than the same rate uniformly applied (180U).

A comparison between the surface resistance value uncured and properly cured specimens at both environmental conditions is shown in Figure 4.7. Uncured samples at the low evaporative conditions had similar performance to samples cured uniformly at 180 ft^2/gal (4.5m^2/l) (180U) under the high evaporative conditions.

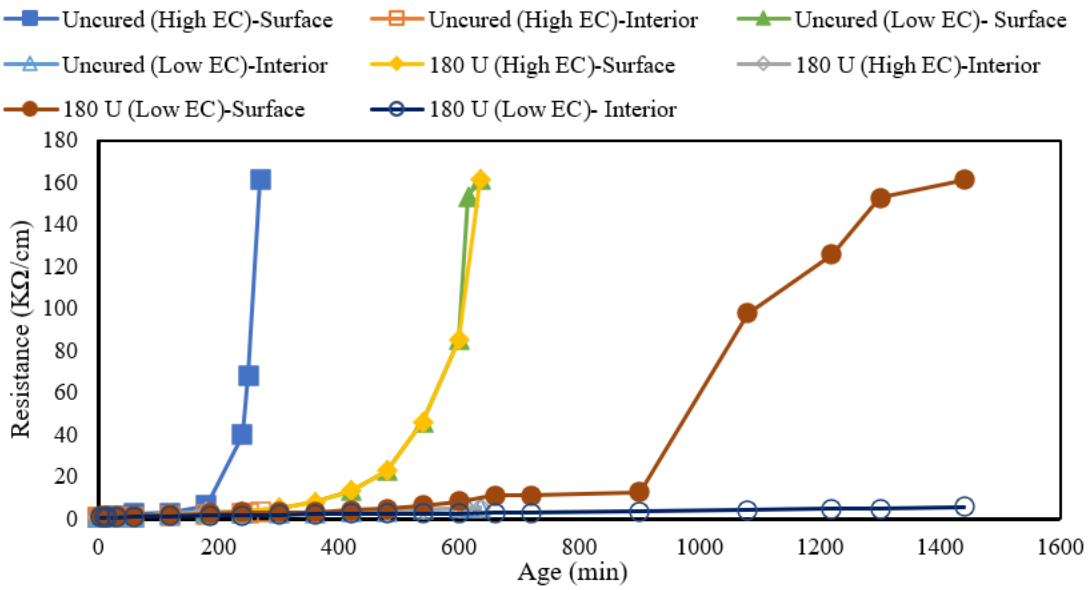

Figure 4.7 Resistance data comparison between the uncured and properly cured specimens from both low and hot evaporative conditions (High EC refers to high evaporative condition (38C32%), and Low EC refers to low evaporative condition 23C50%)

4.5. Conclusion and recommendation

This paper presented an initial investigation into using resistance to assess the quality of curing compound application on fresh concrete. Two techniques were used, an average measurement through an unshielded probe using a Wenner probe and a comparison of resistance values between a surface and shielded embedded probe. Both techniques were able to distinguish

between cured and uncured specimens. Moreover, the embedded resistance probe technique was able to distinguish between the quality and rate of curing compound application, even when specimens were visually indistinguishable. Uniformity of curing compound application was not significant for the lower evaporative conditions but quite significant for the higher evaporation rate.

These findings suggest that resistance can be a tool for real-time assessment of concrete curing. As resistivity is linked to a variety of other long-term properties, future research may provide additional links to the appropriate timing of curing compound application, sawing timing, and hardened durability properties.

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CHAPTER 5: : EMBEDDED RESISTANCE AS A TECHNIQUE TO MONITOR CONCRETE CURING

5.1. Abstract

The use of membrane-forming curing compounds on fresh concrete has been widely adopted by many States' Departments of Transportation as it is feasible where there is a deficiency of water, on sloping surfaces where curing with water is challenging, and in cases where large areas like pavement have to be cured. However, the evaluation of the curing compound application effectiveness is difficult because most of the evaluation test methods are not performed during the early age of the concrete. Moreover, the ASTM C156 standards test of water retention for the qualification of curing compounds has met criticism as the moisture retention is performed only on the mortar specimens, with a fixed application rate and curing condition. Therefore, in this study, the embedded resistance technique was used as a test replacement for the moisture retention test to assess concrete curing. The findings from this study showed that a correlation can be found between the moisture retention test and the embedded resistance test. Based on the findings, the embedded resistance test could be a suitable replacement for the moisture loss test, because the test is much simpler and quicker to be performed both in the lab and in the field.

5.2. Introduction

The curing of concrete and especially concrete pavement has significant effects on the long-term performance and durability due to the high amount of exposed surface which is also the functional surface. The application of a membrane forming curing compound (MFCC) is a relatively low-cost technique to reduce moisture loss from the concrete pavement and ultimately improving the quality of concrete pavement surface (Vandenbossche 1999). Especially for large installations where wet curing or covering with plastic is im-practical and expensive, MFCC is the only viable option (Hajibabaee et al. 2018). MFCCs are solutions of wax or resin in water or other

chemical solvents. When applied to the surface of fresh concrete, the solution breaks down and the water or solvent evaporates leaving behind the wax or resin to form a membrane which minimizes evaporation and supports continued hydration (Pawar and Kate 2020; Nkongolo et al. 2024). According to ASTM C309, MFCCs are classified into types based on color, solid constituents, and solids chemistry (ASTM C309 2003). Moreover, MFCCs are also tested for compliance with moisture retention, coverage, drying time, flash point, and reflectance (Vandenbossche 1999). ASTM C309 (ASTM C309 2003) specifies a maximum moisture loss limit of 0.55 kg/m^2 as tested according to ASTM C156, while ASTM C1315 (ASTM C1315 2019) restricts the maximum moisture loss to no more than 0.4 kg/m^2 within 72 hours (ASTM C156 2005). In the United States (U.S.), there is not a single specification for MFCC with many including 24 hours moisture loss requirements, limiting the time of application, or requiring multiple applications. No technique currently exists to assess the application rate in the field with the visual comparison to a sheet of printer paper common, but not quantifiable or enforceable. The large surface area-to-volume ratio of concrete pavement is a challenge for maintaining uniformity across the pavement (Taylor et al. 2019; Taffese and Nigussie 2023).

Most specifications for MFCC application require an application rate of 3.7–5 m^2/L with little regard for field conditions or the potential for over- or under-curing (ASTM C156 2005). Other than ASTM C309 and the previously mentioned adjustments to moisture loss, no current specifications provide guidance on how to qualify curing effectiveness in terms of the type of performance expected for given environmental conditions. Unfortunately, curing effectiveness is not a singular value such as strength and is attached to a variety of concrete performance indicators, including drying shrinkage, cracking, scaling, joint spalling, curling and warping, and freeze–thaw deterioration, amongst many others. For instance, concrete plastic shrinkage occurs when the rate

of water loss from the surface exceeds the rate at which bleed water is available and is directly linked to curing effectiveness (Taylor et al. 2019). The evaporation rate is a function of concrete temperature, air temperature, wind speed, relative humidity, color of the fresh concrete, and solar gain (Sun 2013). However, ASTM C156 (ASTM C156 2005) has met criticism as the moisture retention is per-formed only on the mortar specimens with a fixed application rate and curing condition and has low precision with a single-operator standard deviation of 0.13 kg/m^2 and a multi-laboratory deviation of 0.30 kg/m^2 (Sun 2013; Cather 1992; Helgeson 2014). While the usefulness of a laboratory-based quality control test is arguable, moisture loss using any actual adapted measure is not possible in the field.

Besides bulk moisture loss, the effectiveness of a curing compound is also governed by the integrity of the membrane formed. Factors that impact the integrity of the membrane include the effectiveness of the curing compound material (Choi et al. 2012; Kropp et al. 2012), the amount applied, the application timing, the surface texture (Vandenbossche 1999), concrete bleeding (Jana 2007), application uniformity, and environmental conditions (Ye et al. 2010). The American Concrete Institute (ACI) recommends the optimal time to apply is after the final surface finishing, when the bleed water has evaporated from the concrete surface (ACI 308R 2016). However, this guidance is complicated by evaporative conditions that, when too high, can prematurely signal the end of bleeding or, when too low, extend the period that water ap-pears on the surface. The former condition has been particularly troublesome, as multiple studies have noted that pinholes and cracks can form in the membrane as bleed water can segregate the freshly placed curing compound (Vandenbossche 1999; Helgeson 2014); meanwhile, the latter can create plastic shrinkage cracking.

Concrete goes through a phase change from a plastic phase to a solid at an early age. This transition is mainly caused by the hydration reaction (ASTM C192 2020). During the early age of concrete, cement reacts with water to produce hydration reaction products, and the excess water evaporates due to drying, leading to concrete microstructure development. However, at an early age, the presence of moisture in concrete makes concrete less resistant to current flow, as the electrical current in concrete moves through the pore spaces. With time, more pore spaces in concrete are filled up with hydration reaction products. Subsequently, concrete becomes more resistant to the current flow, as the electrical conductivity ability of concrete depends on the conductivity of the fluids inside the interconnection of the pore system, the degree of saturation of the concrete, and the permeability. Therefore, using the resistance technique to trace moisture content in concrete can be an important tool to assess curing compound application effectiveness on fresh concrete.

In this study, we investigated the effects of curing compound application time on freshly placed concrete, the effect of curing conditions as well on the performance of concrete cured before and after the initial setting time, and lastly the effect of curing compound application rates and uniformity during the application. Tests were indexed against the standard moisture loss testing in addition to a newly developed real-time assessment of moisture loss and curing by embedded resistance. Moisture is critical for developing desirable concrete properties but not easily measured in practice and especially at early ages. This study is significant because embedded resistance can provide a correlated measure of moisture loss from field measurements.

5.3. Materials and methodology

In this study, a conventional highway paving mixture was used, as shown in Table 5.1, which contains Type IL cement (Central Plains, Kansas City, MO, USA), river sand (Holliday

Sand, Kansas City, MO, USA), and optimized gradation of limestone (Martin Marietta, Kansas City, MO, USA) with a 25 mm nominal maximum aggregate size. The MFCC was a poly alpha methyl styrene (PAMS) (2200 White, WR Meadows, Hampshire, IL, USA) meeting ASTM C309 (ASTM C309 2003) Type 2B requirements.

Table 5.1 Lab testing mixing design.

Materials	**Mix Proportions, kg/m^3**
Cement 1 L (12%)	325
Fine aggregates.	795
Intermediate aggregates.	695
Coarse aggregates.	385
Water	130
w/cm	0.42

5.3.1. Mixing and Testing

Concrete was produced using a rotating drum-type mixer following ASTM C192 (ASTM C192 2020). The mixture contained a vinsol resin-based air-entraining admixture (AirAvalon, GCP Applied Technologies, Alpharetta, Georgia, USA) and polycarboxylate water reducer (ADVA190, GCP Applied Technologies, Alpharetta, Georgia, USA). Aggregate quality control was maintained by washing coarse aggregate, oven drying both fine and coarse aggregate 24 Hours prior to mixing and allowing it to cool before mixing. Baseline characterization testing included air content test following ASTM C231 (ASTM C231 2008), slump ASTM C143 (ASTM C143 2004), unit weight ASTM C138 (ASTM C138 2001), compressive strength ASTM C39 (ASTM C39 2018, AASHTO T358 2018) surface resistivity AASHTO T358 (AASHTO T277 2018) and setting time using Vicat apparatus (ASTM C-191) (ASTM C191 2021) and ultrasonic pulse velocity (UPV) (Taylor and Wang 2015).

For the moisture retention and embedded resistance tests, the investigation was performed using four evaporation rates and four application rates as shown in Table 5.2. For the remainder of the article, the evaporative rates are identified as low (10 °C, 75% RH), medium (23 °C, 50% RH), moderate (32 °C, 50% RH), and high (38 °C, 32% RH). The effect of uniformity was determined using four application rates: uncured (0 m^2/L), 9.8 m^2/L uniform (9.8 U), 4.4 m^2/L non-uniform (4.4 NU), and 4.4 m^2/L uniform (4.4 U). Figure 5.1 shows an example of each. Specimens were cured using a pump sprayer; for the 9.8 U samples, a brush was used.

Table 5.2 Testing curing conditions.

Curing Conditions				
Temperature (°C)	**Relative Humidity. (%)**	**Evaporation Rates ($kg/m^2/h$)**	**Term**	**Application Rates (m^2/L)**
38	32	0.76	Low	0 (Uncured)
32	50	0.41	Medium	9.8 U
23	50	0.15	Moderate	4.4 NU
10	75	0.01	High	4.4 U

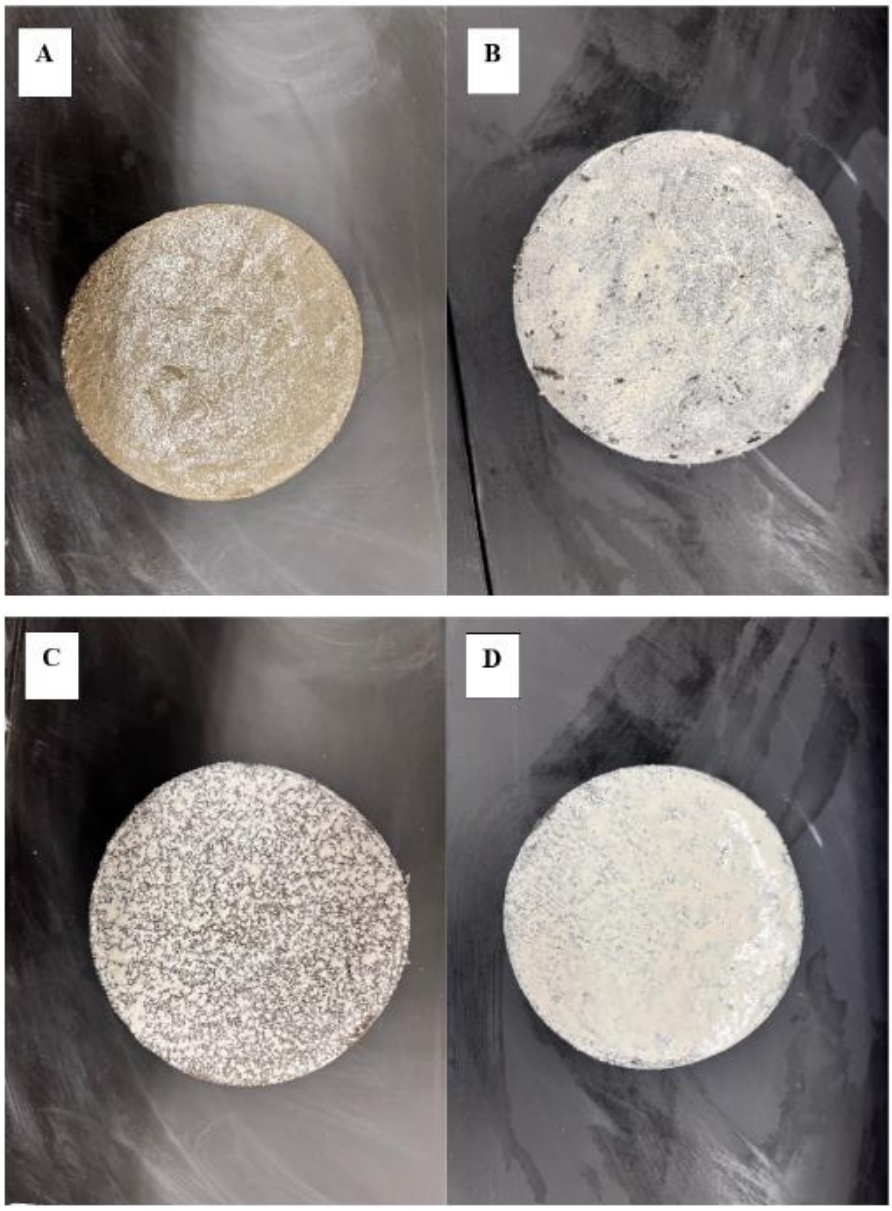
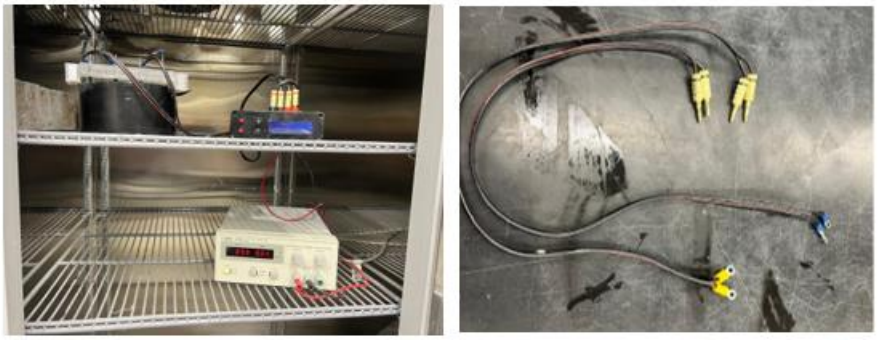


Figure 5.1 Concrete application rates: (A) uncured; (B) 9.8 U; (C) 4.4 NU; (D) 4.4 U.

A moisture loss test was performed on both the specified mortar and the actual concrete to assess anticipated differences in the field according to the ASTM C156 (ASTM C156 2005) process. The concrete mass was recorded at the ages of 0,24, 48, and 72 h, and the mass loss was determined following the equation provided by the ASTM C156. Additionally, for the concrete

moisture retention test, the following three additional variables were used: application time, application rate, and evaporative rate. The effect of application time was investigated by applying MFCC immediately after the final surface finishing (approximately 30 min after mixing and 120 min before the initial set) and after the bleed water was no longer present (after the initial set).

The embedded resistance test was performed on concrete cast in 150 mm × 75 mm cylinder molds. The variables investigated were only application rates, evaporative rates (as presented in Table 5.2), and the probe depths. After applying the curing compound, the resistance probes were embedded to record the resistance at the surface of the concrete just below the curing compound layer and at 12.5 mm into the concrete, below the cure-affected depth. The embedded resistance probe used a two-pin arrangement in a non-conductive plastic frame to hold four stainless steel probes, two for each depth. The sides of the probes were protected using nylon sleeves to ensure that data were collected only from the concrete at the probe tip location. The frame was set 25 mm above the surface to allow the free movement of air at the concrete surface A data logger was used to record resistance development with time at 5 min intervals. The complete set-up is shown in Figure 5.2. Resistance was recorded at 5 min increments until the maximum cutoff value of 160 kΩ/cm was reached.



(A) (B)

Figure 5.2 Embedded resistance set-up. (A) Data logger resistance probes connected to concrete. (B) Resistance probe.

5.4. Results and Discussion

5.4.1. Concrete Baseline Properties

The baseline concrete properties are shown in Table 5.3. All results are acceptable and expected for paving concrete suitable for application in freeze–thaw climates. The average 28-day compressive strength was 41 MPa after lime water curing. Surface resistivity was 15 kΩ-cm, classified as moderate chloride ion permeability by AASHTO T277 or ASTM C1202 (AASHTO T277 2018, ASTM C1202 2022).

Table 5.3 Baseline properties results.

Slump (mm)	Unit Weight(kg/m$^{3)}$	Air Content (%)	Initial Set (min)	Final Set (min)
37.5	2403	5.2	155	240

5.4.2. Moisture Retention Test

Figure 5.3 shows the comparison of moisture loss performed on the standard reference mortar and on the paving, concrete cured following the ASTM C156 standard. As expected, both specimens experienced moisture loss throughout the curing period, with the most moisture loss observed during the first 24 h. After 72 h. of curing, the mortar specimens had less moisture loss compared to concrete. The high moisture loss observed in concrete could be due to the presence of coarse aggregates that cause more bleed water during the early time stages of concrete.

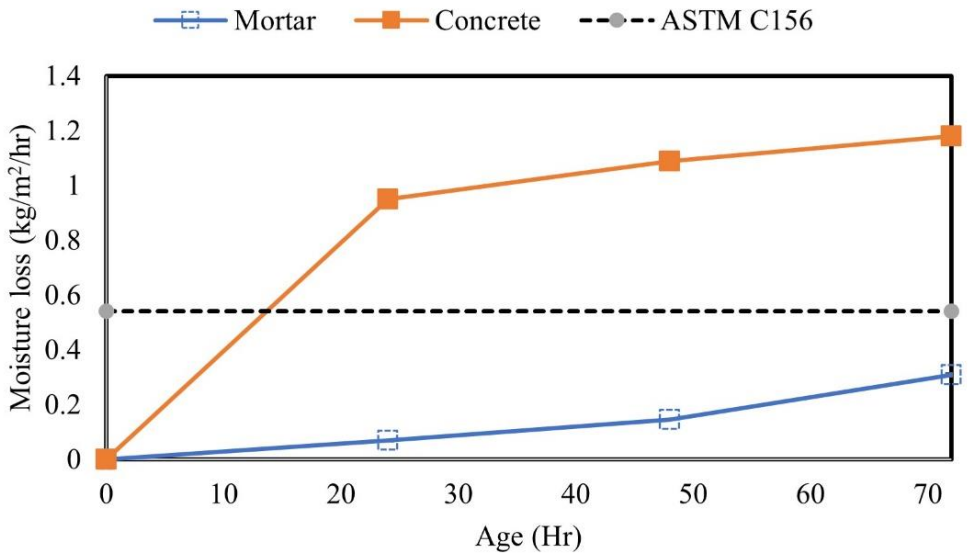


Figure 5.3 Comparison between ASTM C156 and concrete specimens cured at 4.4 m^2/L in 38C32%.

Figure 5.4 presents the comparison of moisture loss results performed on concrete only while varying the application rates and curing conditions. The four application rates were 0 m^2/L, 9.8 m^2/L applied using a brush, 4.4 m^2/L non-uniform applied using a pump sprayer, and lastly, 4.4 m^2/L uniformly applied using a pump sprayer; the four evaporative conditions were identified as low, medium, moderate, and high. The low evaporative condition (A) was performed at 10 °C

and 75% RH with an estimated evaporation rate of 0.00732 kg/m^2/h. The medium evaporative condition (B) was performed at 23 °C and 50% RH with an evaporation rate of 0.1515 kg/m^2/h. The moderate evaporative condition (C) was performed at 32 °C and 50% RH with an evaporation rate of 0.4098 kg/m^2/h. The high evaporative condition (D) was performed at 38 °C and 32% RH with an evaporation rate of 0.7585 kg/m^2/h. The data presented are average values from triplicate testing. As expected, the moisture loss from the samples increased with higher evaporative conditions with the uncured samples having the greatest moisture loss. The effect of application rate and quality became more noticeable with the increased evaporation rate. At the lowest two evaporation rates, the uniformity and rate were not significant factors. At the highest two evaporation rates, the uniformity was less important than the application rate.

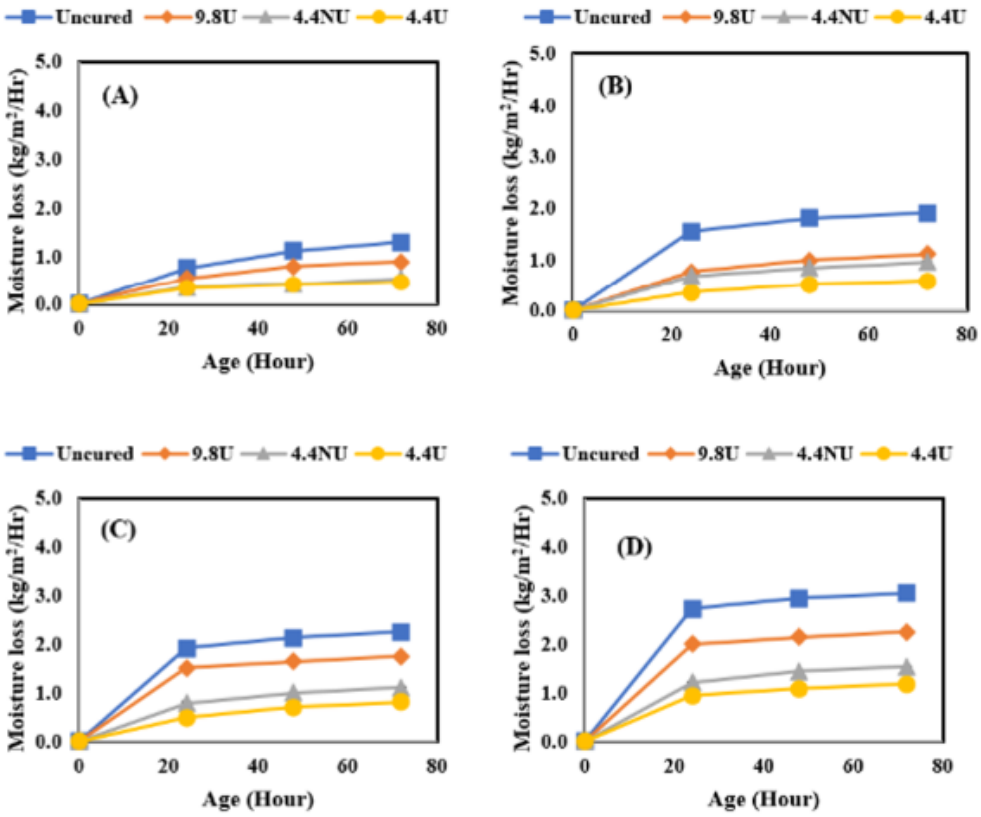


Figure 5.4 The effect of evaporative conditions on moisture loss. (A) Low; (B) medium; (C) moderate; (D) high evaporative conditions.

In this study, the effect of curing compound application time was further investigated by comparing the moisture loss behavior of concrete when MFCC was applied directly after final surface finishing (120 min before the initial set) or after the initial set (210–240 min from the time when cement met water). It should be noted that the evaporative conditions of the laboratory are quite low resulting in a much longer time for bleed water to evaporate than would be experienced in field conditions. The comparison was performed by comparing moisture loss after 72 hours of curing for all four application rates identified as uncured, 9.8U, 4.4NU, and 4.4U and four curing conditions. Figure 5.5 shows the results for the lowest, Figure 5.6 for the medium, Figure 5.7 for

the moderate, and Figure 5.8 for the highest evaporative conditions. In all cases, the samples where MFCC was applied while bleed water was present had the greatest moisture loss. While some of the difference can be attributed to evaporation during the 120 min between the before and after conditions, the additional moisture loss is more than can be attributed to evaporation alone. It has been well described that in all but the harshest conditions, most of the bleed water is reabsorbed as pores empty during hydration (Henkensiefken et al. 2009). Applying the MFCC to wet concrete likely dilutes the chemicals and creates a more permeable final film. Whatever the mechanism, it is important to ensure that the MFCC is applied after bleed water is no longer present. While the timing is important, the slow loss of bleed water corresponds to low evaporative conditions which are much less sensitive to curing effects and likely not of high importance.

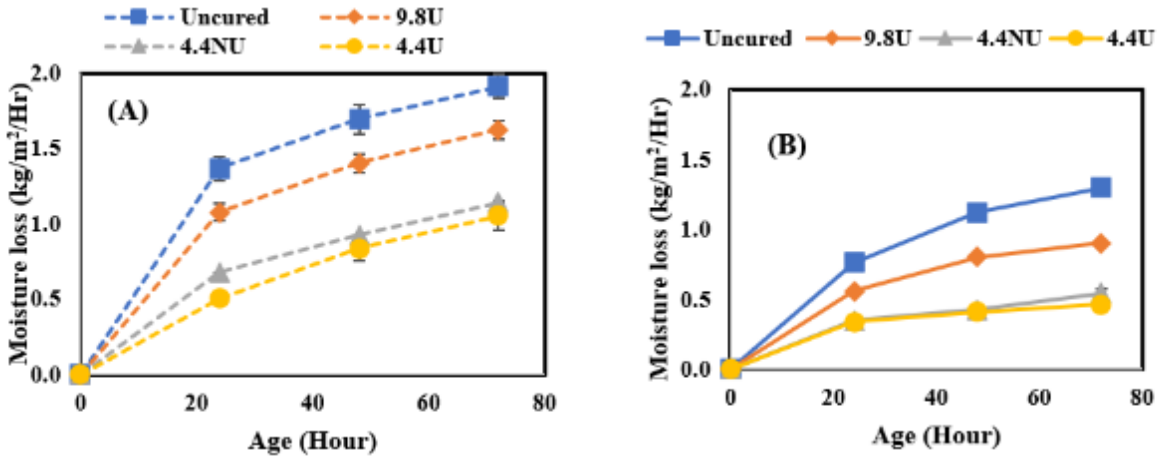


Figure 5.5 Low evaporative condition moisture loss results. (A) Before set results; (B) after set results.

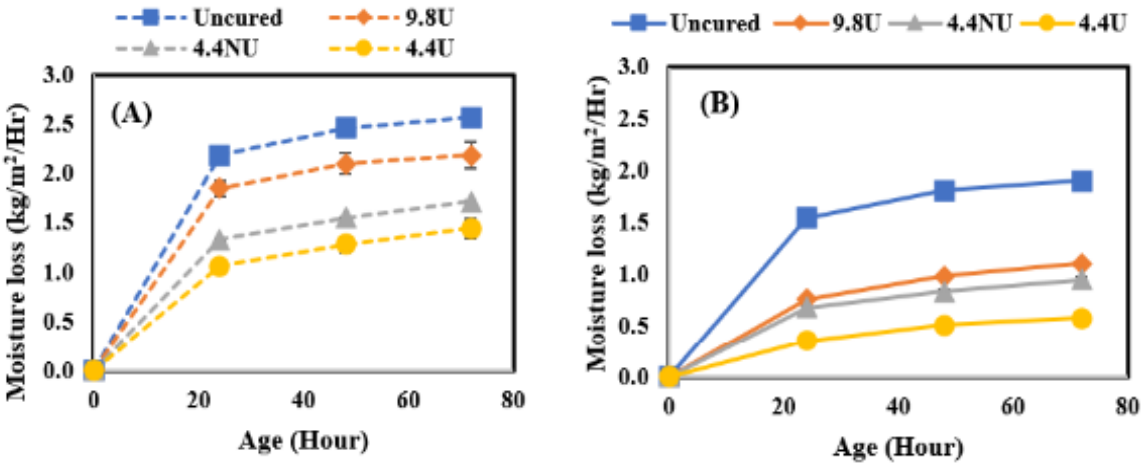


Figure 5.6 Medium evaporative condition moisture loss results. (A) Before set results; (B) after set results.

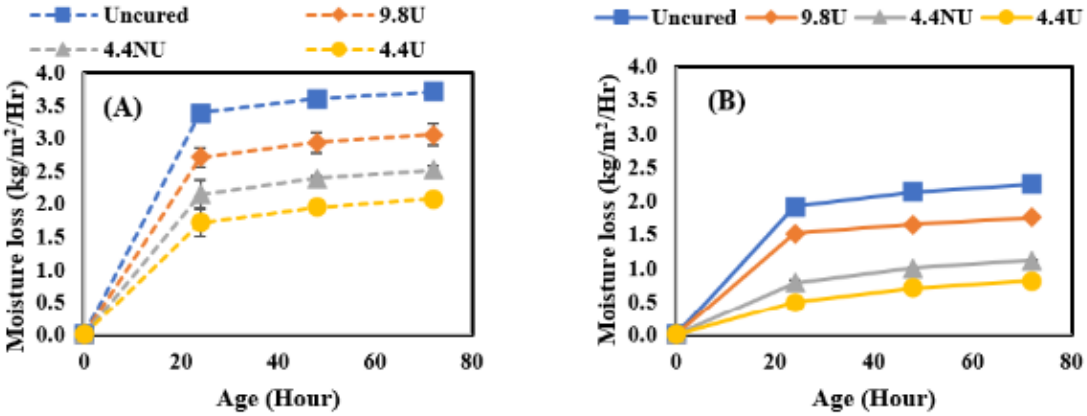


Figure 5.7 Moderate evaporative condition moisture loss results. (A) Before set results; (B) after set results.

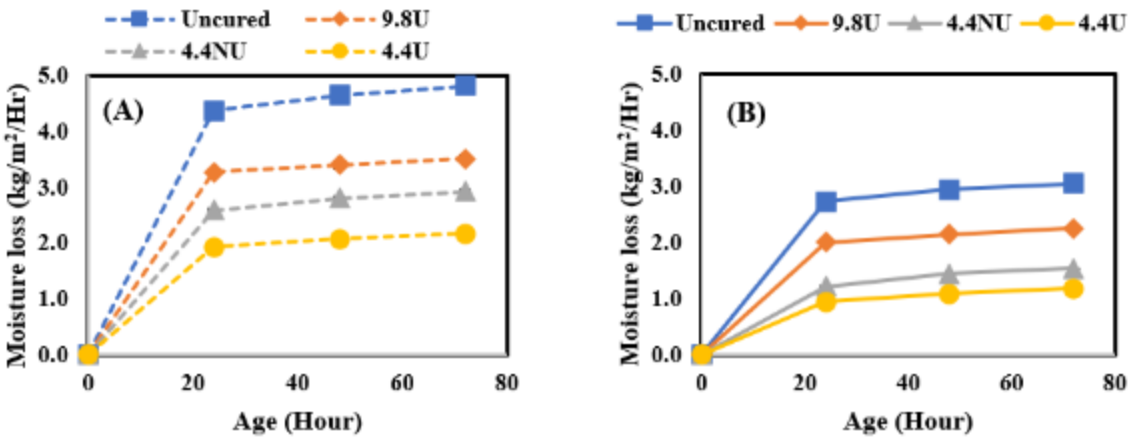


Figure 5.8 High evaporative condition moisture loss results. (A) Before set results; (B) after set results.

Additionally, statical t-tests were performed between the application rates for both sets of curing application times and curing conditions. The t-test demonstrated the difference between the application rates at a 95 percent confidence level. The major highlight was that there was no significant difference between 4.4NU and 4.4U for the sample cured at lower evaporative conditions and the finding simply means that at lower evaporative conditions, the application quality is not important. The best option is to apply the correct amount of MFCC on the concrete without overly focusing on uniformity. Additionally, the effect of the application time was significant, with the initial set of specimens presenting high moisture loss even though a curing compound was applied to prevent moisture from evaporating. This indicates that curing concrete too soon does not benefit the performance of concrete in terms of moisture retention capacity; therefore, the concrete curing time is an important factor to consider in order to produce good concrete.

5.4.3. Embedded Resistance Data

The embedded resistance results for moderate evaporative condition (32C50%RH) for all the application rates, uncured, 9.8U, 4.4NU, and 4.4U, are shown in Figure 5.9. The surface resistance data increased with time at different rates depending on the application rates and application quality. During the early age life of concrete, concrete transitions from the plastic phase to the solid phase. The uncured specimens were first to reach the maximum cutoff point of 160 kΩ/cm, followed by 9.8U and 4.4NU, and lastly, the 4.4U was the last to reach the maximum resistance. Additionally, the resistance values at the 12.5 mm depth were similar for all the application rates, demonstrating that 12.5 mm is below the cure-affected zone.

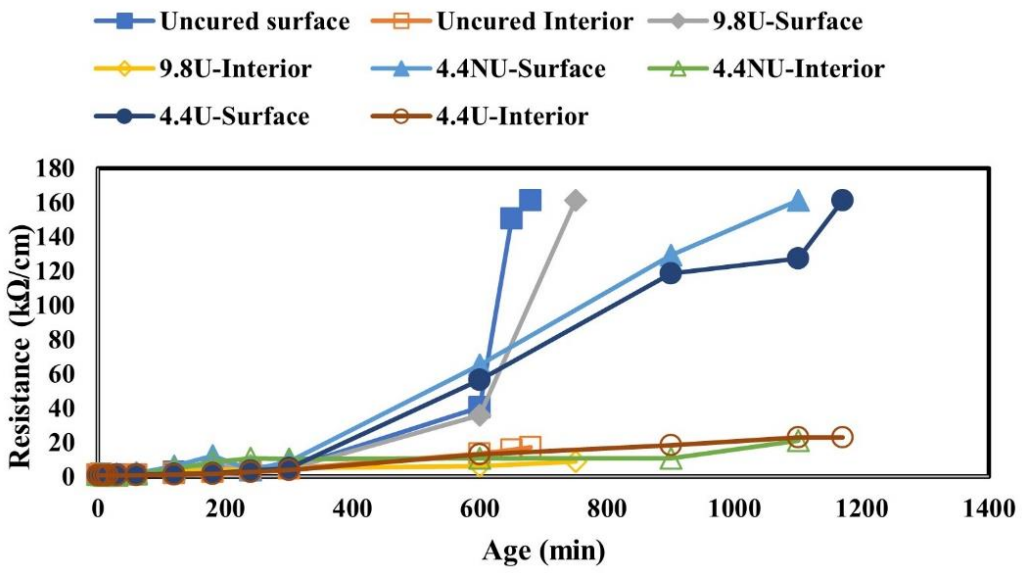


Figure 5.9 Concrete drying behavior investigated using resistance techniques.

The concrete surface is cured to prevent or slow moisture from evaporating. Concrete during plastic states/phase is less resistant to current flow due to the presence of moisture or fluid in the pore's spaces. However, with time, the moisture/water in the concrete is used up through a hydration reaction, and some evaporate due to the drying caused by the ambient conditions, thus

causing the concrete to become more resistant to current flow. A curing compound is applied to slow moisture loss and favor hydration. The effect of the application rates was investigated by comparing time to maximum resistance for all the evaporation rates used. The results revealed that the uncured specimens were faster to reach the maximum resistance, followed by 9.8U, 4.4NU, and lastly, 4.4U, and thus indicating the effect of application rates on the moisture retention behavior of concrete.

The effect of the evaporative conditions was investigated by curing concrete in four evaporation rates named low (0.00732 kg/m^2/h), medium (0.1515 kg/m^2/h), moderate (0.4098 kg/m^2/h), and high (0.7585 kg/m^2/h). For each evaporation rate, concrete specimens were cured using the four application rates of uncured, 9.8U, 4.4NU, and 4.4U. Presented in Figure 5.10 is the surface resistance time to maximum resistance for each application rate plotted against the evaporation rate.

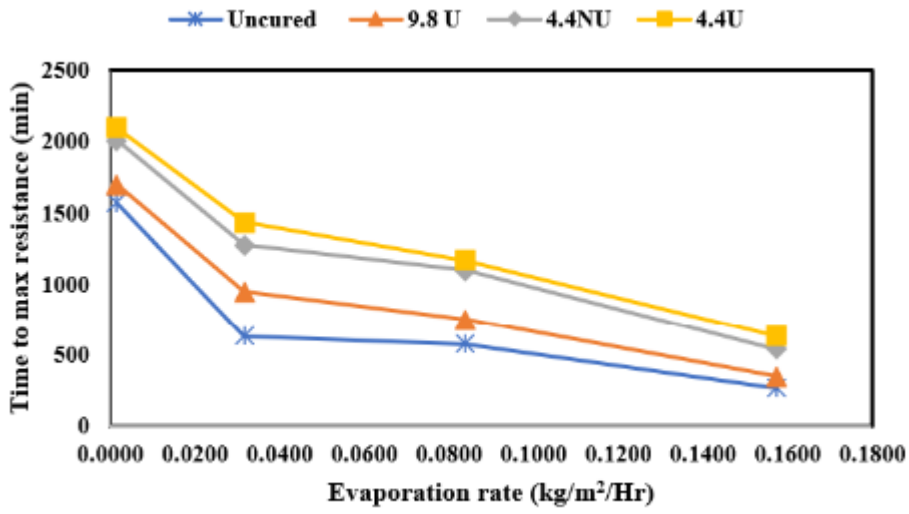


Figure 5.10 Time to maximum surface resistance for all the application rates and evaporation rates used in this study.

The results revealed that time to maximum surface resistance depended on the application rate and curing conditions. Resistance increases in all the cases (all the application rates and curing conditions) due to the concrete drying process and hydration reaction. However, the rates of resistance increase depended on the curing conditions (application and evaporative rates). Specimens cured at higher evaporative rates presented a faster resistance increase than the rest of the conditions, and the low evaporative rates specimens presented a slower resistance increase. Based on the findings from this study, it can be said that the resistance increase is inversely proportional to the evaporative rates. Increasing the evaporative condition decreases the time to the maximum resistance cut point, and the observation was the same for all of the curing conditions.

5.4.4. Correlation between Moisture Loss and Embedded Resistance Data

The relationship between the moisture loss and embedded resistance was developed by plotting the surface resistance time to the maximum resistance value against moisture loss after 72 h of curing. The results presented in Figure 5.11 are for all four application rates (uncured, 9.8U, 4.4NU, and 4.4U) and the four evaporative conditions mainly low (0.00732 $kg/m^2/h$), medium (0.1515 $kg/m^2/h$), moderate (0.4098 $kg/m^2/h$), and high (0.7585 $kg/m^2/h$). The embedded resistance test is inversely proportional to the moisture loss. The results demonstrated that specimens with higher moisture loss have a shorter time to the maximum resistance value. In all cases, regardless of the evaporative conditions, uncured specimens had a higher moisture loss than the other specimens and at the same time presented a faster surface resistance, followed by 9.8U and 4.4NU, lastly, the 4.4U specimens had a low moisture loss in all the evaporative conditions. This trend was consistent with the embedded resistance results where the 4.4U specimens had the longest time to the maximum resistance values.

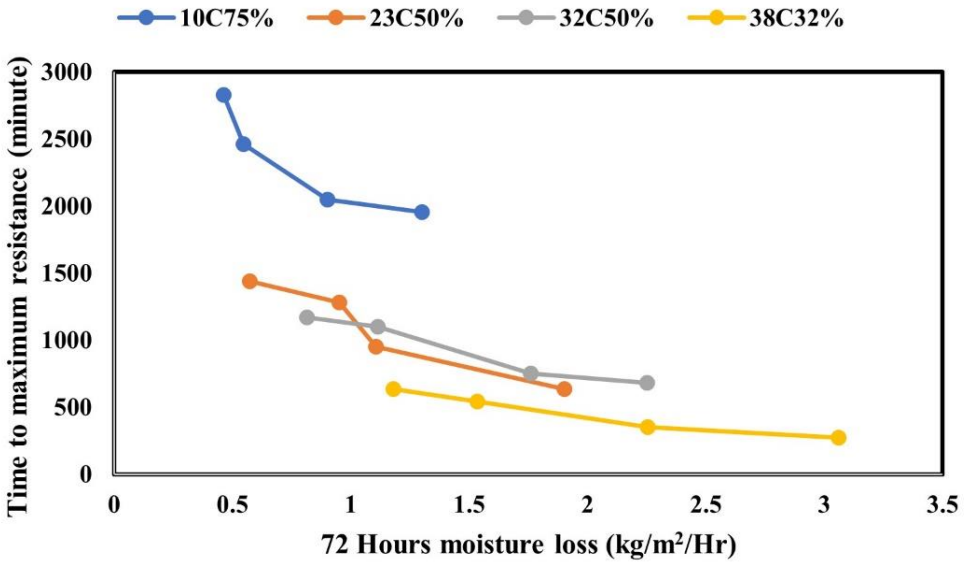


Figure 5.11 Time to maximum surface resistance for all the application rates and evaporation rates used in this study.

5.5. Conclusion and recommendation

The research presented in this paper investigated the effect or impact of the membrane-forming curing compound on concrete pavement by varying time to curing, application rates, and evaporative conditions. The findings from this study demonstrated the following:

1. Curing concrete early while bleed water is still available affects the MFCC performance and causes more moisture loss.
2. Concrete should be cured at all costs, as in all cases, uncured specimens have a higher moisture loss than the cured specimens, regardless of the application rates.
3. Additionally, at lower evaporative conditions, curing compound application quality does not really affect concrete performance; the effect of curing quality is more significant at higher evaporative conditions than at lower evaporative conditions.

4. The effect of the application rates and evaporative conditions was also proven to be significant while using the embedded resistance test.

Furthermore, a correlation between the moisture loss test and embedded resistance test was developed, demonstrating that embedded resistance can be used to assess concrete moisture loss both in the laboratory and in the field because the test is a much simpler and quicker test to perform and could be a suitable replacement for moisture loss test. Future research should include indexing the resistance and moisture loss to properties of concern such as the degree of hydration and microstructural porosity.

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CHAPTER 6: DETERMINATION OF CONCRETE CURING-AFFECTED ZONE USING EMBEDDED RESISTANCE TECHNIQUE

6.1. Abstract

The large surface-area-to-volume ratio of concrete pavements increases moisture loss through evaporation during placement and hydration. To minimize moisture loss in early aged concrete, curing compounds are often used in slab construction. Concrete pavement is cured to enable uniform hardened properties development across the concrete slab. Properties of hardened concrete depend on many factors including the cement degree of hydration. Quality curing enables hydration reaction to take place for an extended period and allow the formation of a well-developed microstructure and subsequently affecting the mechanical and durability characteristics of concrete. Curing has an active influence up to a certain depth known as Curing Affected Zone (CAZ) from the surface of concrete, and its properties depend on the extent of hydration. The moisture content in CAZ governs the characteristics of its microstructure. However, there has never been a clear assessment of CAZ depth. Therefore, this study used the embedded resistance technique and the surface profile degree of hydration to investigate the depth of the CAZ from the surface of concrete. The findings from the study were able to determine the region where curing has an impact on concrete. Below the determined region regardless of the evaporative conditions or application rates, concrete behaves the same and developed identical hardened properties.

6.2. Introduction

Concrete is the second most used materials in the world after water (Aleem and Arumairaj 2012; Meyer 2002), due to the availability of the material and the versality property of concrete. Concrete is strong in compression and weak in tension, therefore, to achieve Concrete designed or hardened properties there are so many factors to look at including curing process (Gokulanathan et al. 2021; Idowu and Black 2018). Concrete curing process affects the strength development by

controlling the moisture loss and subsequently favoring the hydration reaction (Taylor et al. 2019; Idowu and Black 2018). The hydration reaction is an exothermic chemical reaction that occurs when cement encounters water for the first time (He et al. 2023; Al-Jabari. 2022). When Portland cement meets water the cement particles partially dissolve, and the various dissolved components start to react at different rates to produce hydration products (Gartener et al. 2008). During hydration, the chemical reactions occurring are generally more complex than simple conversions of anhydrous compounds into hydrates and are controlled by the exact mineral composition, combination, and reaction conditions creating a various potential hydration product at any given concrete age. The new hydration compounds produced causes the cement paste to harden, bond to the aggregate in the concrete mixture, and become strong and dense (Artioli and Bullard 2013). Additionally, the hydration products will occupy some of the original space previously occupied by voids, and water that did not take place in hydration reactions will either remain in the concrete in the capillary pore system or evaporate out once the concrete dries which leads to change in volume of concrete (Taylor and Voigt 2007). The hydration of cement paste is responsible for the development of concrete properties. Therefore, controlling hydration and providing a longer hydration process will result in concrete developing desirable properties. The hydration reaction in concrete ceases once the relative humidity inside concrete drops to below 80 percent (Zeyad et al. 2022; Jin et al. 2022). A proper concrete curing maintains a temperature and relative humidity in concrete in a range that favors the hydration reaction, concrete microstructure development and reducing the porosity and lowering the permeability as well. If concrete is not well cured, particularly at the early age, it will not achieve the designed properties and subsequently the durability will be affected due to a lower degree of hydration (Liu et al. 2021; Wang and Lee 2012). Curing of concrete define as an act of enhancing the hydration reaction by controlling the moisture

loss at the surface of concrete (Nkongolo et al. 2024). Concrete pavement curing can be classified into two phases initial and final curing (Taylor et al. 2019). Initial curing is defined as the period from concrete placement through the completion of surface finishing. During initial curing concrete bleed water rises as solid materials settle and subsequently evaporates or is consumed in hydration of the surface cementitious materials (Bustillo Revuelta, M. and Bustillo Revuelta 2021; Taylor et al. 2019). Therefore, minimizing moisture loss during initial curing is necessary to reduce the loss of water and prevent plastic shrinkage from taking place (Rothstein 2017) Techniques to minimize moisture loss include fogging, wind shades, or application of surface moisture retardants. Final concrete curing on the other hand includes the period after final surface finishing and is important to prevent continued moisture loss and incomplete hydration at the surface (Poole 2006). Final concrete curing is considered as the actual concrete curing and can be accomplished through water addition methods (ponding and fogging) or water retention method (plastic sheeting or application of membrane forming curing compound).

The application of membrane forming curing compound on fresh concrete has become a common method of curing concrete pavement due to the large surface area-to-volume ratio and the cost associated to the application (Vandenbossche 1999). The high surface are-to-volume ratio making it difficult to maintain a uniform moisture content throughout the pavement, therefore curing concrete will provide a better environment for concrete to develop uniform and equal hardened properties (Vandenbossche 1999). Curing compound are organic materials that form a protective layer over the surface of the fresh concrete and subsequently reducing the rate of moisture loss from the concrete (Taylor et al. 2019). MFCC used with water, alcohol, petroleum fractions, or a combination as a solvent and carrier for the membrane chemistry (Whiting and Synder 2003). Once applied the solution breaks and the carrier evaporates, leaving behind a low

permeability membrane. Common MFCC chemistries consist of waxes, resins, chlorinated rubber, and acrylics. Evaporation retarding performance is directly related to the chemistry and solids content of the MFCC. MFCC are applied to the surface of fresh concrete immediately after the bleed water has evaporated or absorbed back in the concrete. The most common curing materials used for Department of Transportation (DOT) concrete pavement construction include white-tinted wax or poly alpha-methyl styrene (PAMS). Wax curing compounds, while low-cost, can negatively influence the surface friction until effectively worn away. Hajlbabee et al. (2018) state that a solvent-based curing compound such as poly alpha-methyl styrene (PAMS) was more effective than two water-based curing compounds in providing water retention due to a better surface wetting that produces fewer imperfections. More than one coat may be necessary for a successful surface seal to prevent water from evaporating and DOT specifications such as employed by Texas Department of Transportation (TXDOT) require two coats (Choi & Won 2008). MFCCs are easily applied using a hand-held sprayer or curing cart for large surface-areas and several factors are considered when applying and evaluating the effectiveness of MFCC, including ambient conditions, time of application after finishing, application rates, uniformity of application, type of curing compound, and surface texture of the concrete (Kropp et al. 2012; Jana 2007; Joshaghani and Zollinger 2021). The effectiveness of MFCC application can be evaluated using visual inspection, penetration resistance (Joshaghani and Zollinger 2021), image analysis, dielectric constant (choi et al. 2012), compressive strength (Wank et al. 2002), abrasion resistance testing (Sun 2013), rapid chloride permeability testing (Ye et al. 2010), moisture retention (wank et al. 2002), reflectance (Choi and Won 2008), relative humidity testing (Grasley et al. 2006), sorptivity (Wank et al. 2002), capillary pressure sensor development (Slowik et al.,2014; Jamali et al., 2022), degree of hydration (Wank et al., 2006), embedded resistance techniques (Nkongolo et al., 2024).

The property of concrete to go from plastic to solid states during early age life, can facilitate the use of electrical resistivity to assess the amount and connectivity of pores in the hydrated concrete structures. In concrete electrical current flows through the pore solution, during the plastic phase the electrical resistance is low due to the presence of high volume of moisture and increases with time. However, concrete is cured to maintain sufficient moisture for an elapse of time. Therefore, using resistance technique to assess curing compound application effectiveness in real time can be a good tool to be used in both laboratory and field. This study aimed to evaluate the effect of curing compound application rates and curing conditions on concrete performance using the surface profile degree of hydration test and the embedded resistance. Additionally, the study investigated the depth of curing affected zone by running a surface profile degree of hydration test. Furthermore, the maturity curve was developed to correlate concrete degree of hydration with concrete strength gain over time.

6.3. Materials and methodology

Materials used for mixing were Types IL cement with 12 percent limestone content meeting the ASTM C150, fine aggregates from Mo River Sand, two types of coarse aggregates 3/4 in. and intermediate 1/2 in. crushed limestone coarse aggregate meeting the ASTM C33. Two chemicals' admixtures polycarboxylate High range water reducing admixture and Airalon 7000 Air entraining-agent containing a vinsol resin-based were used as well. The curing compound used was Poly alpha methyl styrene (PAMS) based curing compound meeting ASTM C309 and classified as class Type 2B.

Mix design used was selected to represent common highway paving mixtures with slump less than 2 inches and air content between 5 and 6% (Table 6.1). Concrete was produced using a rotating drum type mixer following ASTM C192. The Aggregate quality control was maintained

by washing coarse aggregate, and oven drying both fine and coarse aggregate 24 hours prior to mixing and allowing them to cool to room temperature while covered before mixing. To evaluate the curing compound effectiveness on concrete using surface profile degree of hydration and embedded resistance, three application rates 0 (uncured), 9.8 ft^2/gal (9.8 U) uniformly applied using a brush and 4.4 ft^2/gal (4.4 U) uniformly applied using a pump sprayer were used to investigate the effect of application rates on concrete. Furthermore, the effect of curing condition was investigated as well in this study by curing concrete specimens in different controlled evaporation rate environmental chambers.

Table 6.1 Concrete mixture proportions

Materials	**Mix Proportions, kg/m^3**
Cement IL (12%)	325
Fine aggregates.	795
Intermediate aggregates.	695
Coarse aggregates.	385
Water	130
w/cm	0.42
HRWR (oz)	1.25
AEA (oz)	0.75
Strength after 28 days (psi)	6000

6.3.1. Embedded continuous resistance.

Embedded resistance was measured using a 2-pin array arrangement which contained a non-conductive plastic frame holding 4 stainless steel probes, 2 for each depth (surface and 0.5 inches). Two of the probes were just in contact with the surface of the concrete and the others were embedded 0.5 in (12.5 mm) into the concrete below the cure-affected depth. The sides of the probes were protected using nylon sleeves to ensure that data was collected only from the concrete at the

probe tip. The frame was set 1 in. above the surface to allow the free movement of air on the concrete surface. An arbitrary cutoff of 160 kΩ was selected as the maximum resistance value for recording resistance based on the range of initially observed results and the precision drift of the equipment. Samples for embedded resistance testing were cast in 6 in. x 3 in. cylinder molds with the plastic cutoff cylinder shown in (Figure 6.1) only used here to show the bridge height. The effect of application rates and curing conditions were investigated as presented in the factorial design (Table 6.2).

Table 6.2 Factorial design for Embedded resistance test

Application rates	**Evaporative conditions (EC)**	
Application rates (m^2/liter)	EC ID	($kg/m^2/hr.$)
0	CC1	0.7687
9.8 (U)	CC2	0.1550
4.4 (U)	CC3	0.2590
	CC4	0.4098
	CC5	0.4834
	CC6	0.0737
	CC7	0.1127
	CC8	0.2054
	CC9	0.0395
	CC10	0.0074

Figure 6.1 Embedded resistance samples set-up.

6.3.2. Surface profile and cylinder Degree of Hydration

In this paper the concrete surface profile degree of hydration is referred to the DOH estimated from two different location or depth in concrete (the surface and 0.5 in. depth) and was estimated using the equation of non-evaporable water by loss on ignition (LOI) proposed by Fagerlund, (2009). At the end of each curing age, concrete powder was collected from the surface and at 0.5 in. depth using a mechanical grinder as presented in Figure 6.2. Concrete powder collected were dried in an oven at 105° C until constant mass to remove all evaporable water, then heated in an electric furnace set at a temperature of 1000° C for 3 hours. The non-evaporable water was taken as the mass loss between 105° C and 1000° C, corrected for the LOI of the dry cement powder. The degree of hydration (α) was then calculated as the ratio of the non-evaporable water

content per gram cement to the amount at complete hydration, which is assumed to be equal to 0.23g H_2O/g cement in this study. Additionally, to evaluate the effect of curing compound application rates and curing conditions on concrete using the degree of hydration, four application rates 0 (uncured), 400 ft^2/gal (4.4 U), 4.4 ft^2/gal non-uniformly (4.4 NU) and 4.4 ft^2/gal (4.4 U) uniformly applied and cured in four different curing conditions as presented in Table 6.3. The DOH samples were cast in 3x6 in. cylinder molds. After casting, the specimens were left in the laboratory condition until bleed water was gone and curing compound was applied. Samples were then stored in a controlled temperature and relative humidity environmental chamber set at 4 different evaporation rates. DoH was then determined at the age 1, 3, and 7 days of curing.

Table 6.3 Surface profile Degree of Hydration factorial design

Application rates (ft^2/Gal)	Evaporative condition (EC)	
	EC ID	Evaporation rates(kg/m^2/hr.)
0	CC1	0.7687
400 (U)	CC2	0.1550
180 (U)	CC4	0.4098
	CC7	0.0074

Figure 6.2 Surface profile DoH set-up.

$$\alpha = \frac{W_n}{\frac{C_{effective}}{\frac{w_o^n}{c}}} \qquad \text{Equation 6.1}$$

Where: α = degree of hydration in percentage, Wn is the amount of chemically bound water determined. C.effective, Wo/c is the quotient.

6.4. Results and Discussion

6.4.1. Surface profile Degree of Hydration

The estimated surface profile degree of hydration of all the specimens application's rates and curing conditions are presented in Figure 6.3 the sample collected from the surface of concrete, just below the layer formed by curing compound, and in Table 6.4 the DOH results of sample collected at 0.5 in. depth. The sample was collected in triplicate and presented in Table 6.4 is the average value of all the recorded DOH. As expected, irrespective of the depth the degree of hydration was relatively proportional to the time of curing in all cases, increasing with curing age. However, the rate of increase was depending on the application rate, with uncured sample

presented a low DOH than the cured specimens. The more increase in DOH was observed during the first 24 hours of curing.

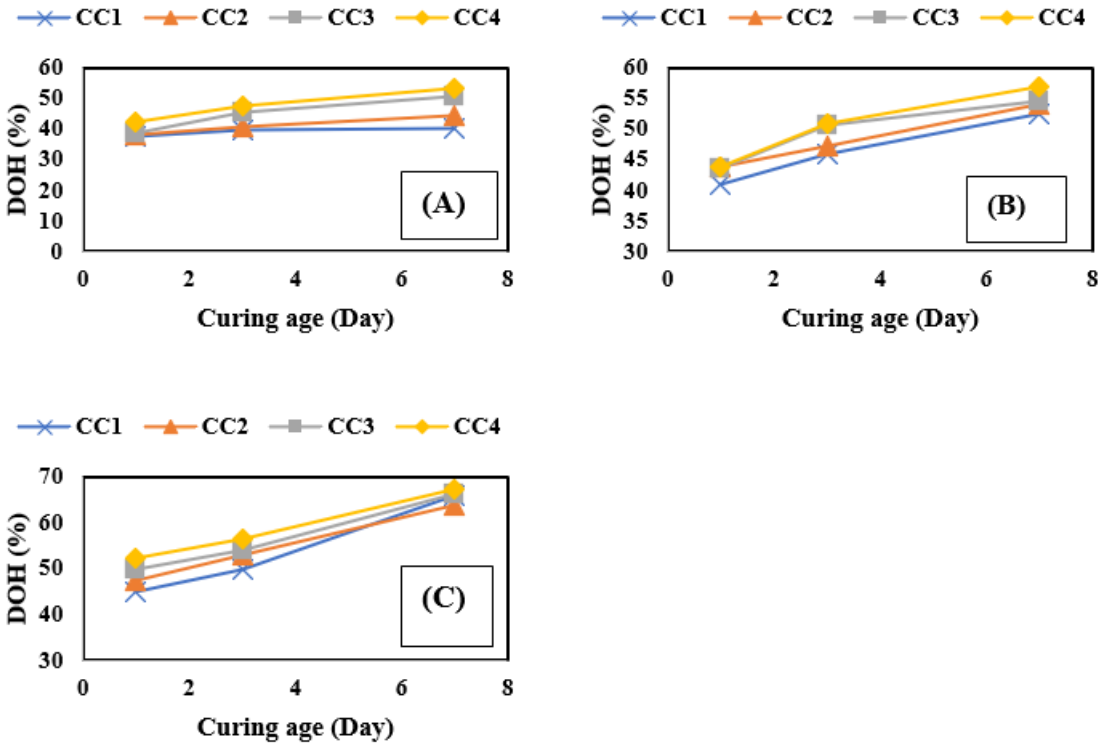

Figure 6.3 DoH of uncured specimens for all curing conditions. A: Uncured samples, B: 9.8U and C: 4.4U

It was observed that, the application rates and curing conditions affect the DOH at the surface of concrete. Uncured samples presented a low DOH in all cases, however compared the uncured specimens DOH in all the curing conditions Figure 6.3 (a). Specimens cured in high evaporative condition have the lowest DOH followed by the moderate, medium and low EC. This demonstrates the effect of curing condition on concrete performance. The low surface DOH of concrete presented by uncured samples could be explained by moisture evaporation or drying effect at the surface of concrete mainly caused by temperature and relative humidity. The effect of

application rates was further investigated by comparing DOH of specimens cured at 9.8 U Figure 6.3(b) and 4.4 U Figure 6.3(c), the 4.4 U specimens performed better in terms of keeping moisture and allowing more hydration reactions to take place compared to 4.4 U. Thus, demonstrating the effect of curing compound application rates on concrete DOH. Additionally, for uncured specimens cured in medium, moderate, and high EC; difference in DOH was more remarkable after 7 days of curing. Concrete specimens cured at 9.8U application rate, difference in DOH was significant between specimens cured in High and Low EC throughout the curing age. Lastly, for samples cured using 4.4U application rate, the difference in DOH was significant between the low and high EC samples; during the first 24 hours of curing, however after 7 days of curing the change was not significant. The difference in DOH was not significant between the specimens cured in medium and moderate evaporative condition and moderate and high evaporative condition specimens. Presented in Table 6.4 is the DOH data for samples collected at 0.5 in depth from all the curing conditions and application rates. The finding was DoH at the 0.5 in. depth was statistically similar for all treatments, environmental conditions, and ages suggesting that the cure-affected zone does not extend to 0.5 inches.

Table 6.4 Interior or 0.5 in. depth DOH for all curing conditions

0.5 in. depth DOH (%)				
Age (day)	**CC1**	**CC2**	**CC3**	**CC4**
1	55.57	55.57	55.57	53.53
3	56.36	56.04	55.89	56.57
7	68.2	67.75	67.89	68.39

6.4.2. Embedded resistance technique.

The embedded resistance results for the specimens cured in CC5 evaporative condition (21C50%RH) for all the application rates: Uncured, 9.8U, and 4.4U are shown in Figure 6.4. The effectiveness of curing compound of concrete was evaluated by looking at the time it will take the surface resistance of each specimen to reach the maximum value of 160kΩ. The resistance value was increasing with time in all cases; However, the uncured samples were first to reach the maximum followed by 9.8U and 4.4U was the last to reach the maximum value to demonstrate the impact of curing on concrete. However, the resistance values at the 0.5 in. depth were the same for all the application rates used. Highlighting that this depth is outside the curing-affected zone.

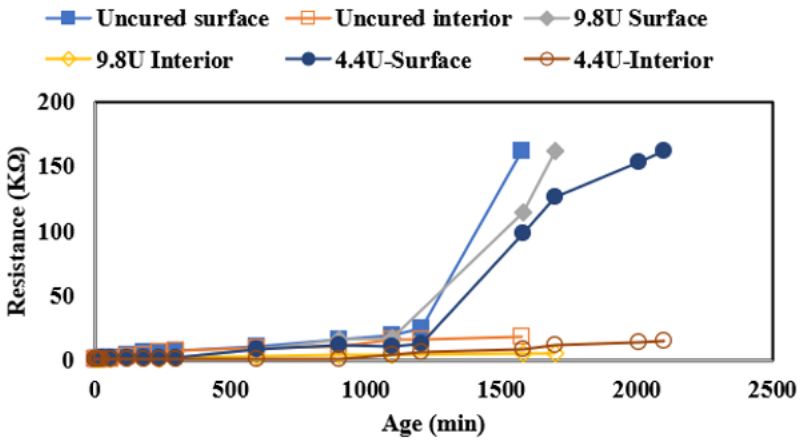

Figure 6.4 Embedded resistance results.

The application rate plays a vital role during concrete curing. In order to maintain more moisture in concrete during early life, enough curing compound needs to be applied all over the exposed area. Comparing the 9.8U specimens to 4.4U specimens, visually they look the same providing the same coverage, However, in terms of performance the 4.4U performed better than the 9.8U, keeping moisture in concrete for an extended period than the 9.8U counterparts.

Presented in Table 6.5 is the threshold value or the acceptable time that may take a specific concrete to reach the maximum resistance under different evaporative condition and application rates.

Table 6.5 Threshold value for acceptance of any application rates

Curing condition	**Threshold time (min)**		
ID	**Uncured**	**9.8 U**	**4.4 U**
CC1	270	350	620
CC2	615	950	1400
CC3	1100	1200	1400
CC4	650	750	1100
CC5	450	600	950
CC6	1400	1500	2600
CC7	1200	1400	1900
CC8	900	1000	1700
CC9	1500	1700	2000
CC10	1900	2000	2800

The data presented herein are based on the laboratory work performed. Based on the results presented above, it was observed that besides the application rates, the evaporative conditions affect as well concrete performance in terms of moisture retention. The low evaporative conditions provided a longer time to maximum resistance, this trend was consistent for all the application rates. The time to maximum resistance was decreasing with an increase in evaporative condition. Thus, demonstrating the effect of drying on concrete.

6.5. Conclusion and recommendation

The research paper investigated effect of membrane forming curing compound application rates and curing condition on concrete in terms of strength gain and microstructure formation. The research investigated further the range of concrete curing affected zone. The findings from the study demonstrated that the application rates and curing conditions only affect the concrete layer within the curing affected zone. Below the CAZ concrete is not sensitive to the curing regime. Furthermore, the evaporative rate and application rates plays a vital role in terms of microstructure development for the CAZ. The threshold time to maximum resistance increase helps to assess the effectiveness of curing compound application rates at different evaporative conditions. Further, study should be performed on the field running the same test in order to develop a relationship between laboratory and field conditions.

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CHAPTER 7: CONCLUSION

7.1. Research summary.

The study aimed to develop a methodology that can be used as a mean to quantify concrete curing effectiveness during the early life of concrete to enhance the concrete curing stage and subsequently favoring the hydration reaction and the durability, volume stability, resistance to freezing and thawing, and abrasion and scaling resistance.

The following findings were discovered by achieving the aim of the study:

Both techniques were able to distinguish between cured and uncured specimens. Moreover, the embedded resistance probe technique was able to distinguish between the quality and rate of curing compound application, even when specimens were visually indistinguishable. Uniformity of curing compound application was not significant for the lower evaporative conditions but quite significant for the higher evaporation rate.

These findings suggest that resistance can be a tool for real-time assessment of concrete curing. As resistivity is linked to a variety of other long-term properties, future research may provide additional links to the appropriate timing of curing compound application, sawing timing, and hardened durability properties.

curing concrete early while bleed water is still available affects the MFCC performance and causes more moisture loss.

Concrete should be cured at all costs, as in all cases, uncured specimens have higher moisture loss than the cured specimens, regardless of the application rates.

Additionally, at lower evaporative conditions, curing compound application quality does not really affect concrete performance; the effect of curing quality is more significant at higher evaporative conditions than at lower evaporative conditions.

The effect of the application rates and evaporative conditions was also proven to be significant while using the embedded resistance test.

Furthermore, a correlation between the moisture loss test and embedded resistance test was developed, demonstrating that embedded resistance can be used to assess concrete moisture loss both in the laboratory and in the field because the test is much simpler and quicker test to perform and could be a suitable replacement for moisture loss test.

- Taking into account the amount of bleed water evaporated between completion of initial finishing and present at the ideal time to apply MFCC (after bleed water was no longer present), moisture loss was higher when MFCC was applied while bleed water was present.
- Moisture loss, degree of hydration, and embedded resistance all correlated with higher moisture loss, lower DoH, and increased resistance with increased evaporation rates.
- When comparing application quality, it was more important to have enough MFCC over less, uniformly applied as demonstrated by the superior performance of the 180NU compared to 400U samples.
- Results at the interior location of 0.5 in. were insensitive to MFCC application quality or environmental condition supporting that location as a good baseline outside of the cure-affected zone.
- Embedded resistance testing was supported by both moisture loss and DoH. Embedded resistance is a much simpler and quicker test to perform and could be a suitable surrogate for both.

The abovementioned findings were achieved by answering the following questions:

- How does the application rate affect concrete quality curing?

The application rate is an important to control during concrete curing, it can affect concrete quality curing in away like. If concrete is not cured it will be exposed to the ambient condition without any protection, and moisture will evaporate from concrete surface and causing concrete to dry out fast. Thus, leading to drying shrinkage and cracking and concrete not developing uniform hardened properties. Hardening concrete in the early age will not have sufficient tensile strength to resist tensile stresses caused by volumetric contraction at its surface due to evaporation. The Additionally, from this study it was observed that application rates affect curing quality in a way that an adequate amount of curing compound should be applied in order to have a quality curing. Some curing coverages may look similar by visual inspection however, still producing different performance.

- How does the application time affect concrete quality curing?

The effect of application time was investigated by comparing the moisture loss behavior of concrete when MFCC was applied directly after final surface finishing (120 minutes before the initial set) or at the initial set (210-240 minutes from the time when cement met water). It should be noted that the evaporative conditions of the laboratory are quite low resulting in a much longer time for bleed water to evaporate. The comparison was performed by comparing moisture loss after 72 hours of curing for all the four application rates identified as Uncured, 400 U, 180 NU and 180 U and all the curing conditions. In all cases the samples where MFCC was applied while bleed water was present had the greatest moisture loss. While some of the difference can be attributed to evaporation during the 120 minutes between the before and after condition, the additional moisture loss is more evaporation. It has been well-described that in all but the harshest conditions, most of the bleed water is reabsorbed as pores empty during hydration. Applying the MFCC to wet

concrete likely dilutes the chemicals and creates a more permeable final film. Whatever the mechanism, it is important to ensure MFCC is applied after bleed water is no longer present.

- How does curing condition affect concrete quality curing?

The evaporative rate controls the drying effect of concrete. Specimens cured in low evaporative conditions retains more moisture than specimens cured in high evaporative conditions. this was demonstrated in this study using different test moisture retention, surface profile degree of hydration and embedded resistance.

Additionally, at lower evaporative conditions, curing compound application quality does not really affect concrete performance; the effect of curing quality is more significant at higher evaporative conditions than at lower evaporative conditions. Furthermore, it was observed that at lower evaporation rates the

7.2. Overall achievement and impact of the states of practices

The embedded resistance technique developed in the study contributed to the improvement of quality curing during concrete pavement construction. by using this technique, the effectiveness of curing compound application assessment can be performed during the early age life of concrete by providing data in real-time without compromising concrete hardened properties development. The significance of the study could be summed up as following:

- The embedded resistance technique uses low-cost equipment, small in size that can be used in the laboratory or in the field.
- The technique is a non-destructive technique that only uses sensors that can be embedded at any depth in concrete.

- The effectiveness of concrete curing compound application was evaluated by looking at a time where the resistance value of a specimens could reach the maximum cut-off point which was set following the equipment capacity.
- The results of the embedded resistance could be correlated with other existing test used to evaluate the effectiveness of curing compound application.

7.3. The novelty of the study

The novelty of the study is listed below:

- Developed a new technique of evaluating curing compound.
- Correlating the new techniques with the already existing assessment techniques
- Discovering that in low evaporating conditions what matters is the application rates rather than the uniformity.
- Determining the curing affected zone.
- Time to curing is an important factor during curing.

7.4. Discussion of the potential further research

Based on the observations made throughout the process of achieving the aim and objectives of this study, several recommendations can be made that would necessitate further investigation to improve the findings of the present study. Thus, the suggestions made for future studies are listed below:

- The investigation of the pores size of cementitious materials with non-destructive methods.
- As resistivity is linked to a variety of other long-term properties, future research may provide additional links to the appropriate timing of curing compound application, sawing timing, and hardened durability properties.

- Future research should include indexing resistance and moisture loss, degree of hydration to properties of concern such as microstructural porosity.

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VITA

Etienne Beya Nkongolo is an emerging engineer with extensive experience in Chemical and Civil Engineering. He obtained the bachelor's and master's degrees in chemical engineering from Cape Peninsula University of Technology. Dr. Nkongolo's master's degree research focused on the passive treatment of acid mine drainage using coal fly ash. Additionally, he also worked at the Environmental Nano Science Group in Cape Town, South Africa as a research assistant. Afterward, Dr. Nkongolo moved to the United States in 2021 to start the IPh.D. program in Engineering and Geosciences disciplines at the University of Missouri Kansas-City. His PhD research focused on evaluation of curing compounds application effectiveness on concrete pavement using a resistance technique. The success of this research project led to the publication of 3 peer-reviewed articles. His newly developed technique of assessing concrete curing effectiveness was used during paving season in Wisconsin State and provided insightful result, ultimately improved concrete curing process. Additionally, Dr. Nkongolo has acquired experience in concrete mix design development, concrete pavement design, concrete pavement distresses development assessment and mitigation. Dr. Nkongolo is ready to bring his knowledge and skill set to positively impact the world of concrete pavement