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Effect of Wet-Mat Curing Time and Earlier Loading on Long-Term Durability of Bridge Decks: Executive Summary

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16. Abstract:
Researchers conducted an extensive literature search, survey of TxDOT districts, and survey of other state Departments of Transportation (DOTs) to determine the state of the art for bridge deck curing, early loading, early age behavior, and durability prediction models. Several concrete mixtures commonly used in regional districts throughout the state of Texas were tested. Each concrete mixture was tested under field conditions within its respective climatic region. Field testing and testing of field collected samples provided information on concrete strength, concrete maturity and permeability. Supplementary laboratory experiments were performed to determine permeability using the salt ponding method, and the rapid chloride penetration test, RCPT. Researchers used the laboratory tests to correlate results with field collected samples and concrete strengths. Both field and laboratory test data were compared with existing models for predicting concrete maturity for various mix designs and curing methods. Core samples from field sites were examined using petrographic techniques to determine air void contents, calcium hydroxide formation, aggregate/paste interface features, cracks, unhydrated cement grains and other petrographic features. Researchers related the variations of petrographic features with wet mat curing duration. Finally, researchers investigated the fracture properties of several medium-strength concrete mixes cured for various durations in order to characterize the extent of cracking that might allow the ingress of chlorides from de-icing salts to the reinforcing bars. The purpose of this report is to present an overview of the research project and a summary of significant findings from the research.

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by

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1. Introduction

Curing is the practice of maintaining a desirable state of moisture and temperature within a concrete for a period of time. The duration and effectiveness of a curing method affects the development of concrete properties including strength and durability. Insufficient moisture in concrete during its early age curing has been found to reduce compromise strength, produce cracks in the concrete and reduce long-term durability (Wojcik and Fitzjarrald 2001). For portland cements, typically the highest rate of heat generation occurs during the first 24 hours after initial contact between water and cement, and a large amount of heat generated from hydration evolves within the first three days (PCA, 1997). To prevent loss of mix water from evaporation due to the generation of heat of hydration and to provide sufficient moisture for cement hydration, concrete should be kept moist or saturated during this critical period.

There are primarily two approaches used to cure concrete; application of water to hydrating concrete (water curing) and sealing of concrete. Water curing supplies additional moisture to the hydrating concrete and prevents mix water evaporation. Sealed curing does not supply additional moisture but rather relies on the prevention of moisture loss.

1.1 Water Curing
Water curing can be performed by spraying or ponding water on the concrete surface or by placing moist coverings. However, spraying tends to consume large amounts of water, and is not economical when water supplies at the site are limited. If periodic spraying of water is performed, care must be taken not to allow the concrete to dry, otherwise crazing can occur (PCA 1998). Care must also be taken during the curing period to prevent erosion of freshly finished concrete.

Curing concrete by way of ponding requires maintaining a layer of water on the concrete surface. This is performed by surrounding the perimeter of the concrete with earth or sand dikes which can sustain a pond of water. Ponding is a good method to prevent moisture loss, provide sufficient moisture, and maintain a constant temperature during concrete hydration.

Moist coverings are another form of water curing and include cotton mats, burlap, and other moisture-retaining fabrics. These coverings should be: (1) applied on top of the concrete as soon as the concrete has hardened sufficiently, (2) saturated with water, and (3) kept continually moist for the duration of the curing period. Periodic supervision of moist coverings is necessary since coverings tend to dry out at a rate dependent on ambient conditions. Some state highway agencies have recently begun to adopt the practice of placing wet cotton mats immediately after the concrete is finished. This practice can be effective in preventing early-age moisture loss from concrete. However, excess moisture can alter the porosity of the top part of the concrete slab, and therefore its long-term impact on concrete durability is left to be seen.

1.2 Sealed Curing
Sealed curing can consist of plastic sheeting, waterproof paper or membrane-forming curing compound. Plastic sheeting or waterproof paper should be applied to the surface of the concrete as soon as possible. However, it cannot be placed too soon or marring of the surface will occur. Plastic sheeting traps evaporated moisture within the sheeting. The moisture condenses on the

sheeting and redistributes itself over the surface of the concrete. This condensed moisture helps continue the hydration process.

The use of curing compounds or membranes is another method of sealed curing. Curing compounds have become a very popular form of curing as they can be applied much sooner than sheets or mats. Although curing compounds have found wide acceptance, they provide the least amount of curing protection and they do not necessarily prevent evaporation of mix water. They are also extremely sensitive to the application process and if not applied correctly, they are useless. When sealed curing is done, mix water is the primary means for hydration, with possible help from moist curing if applied later. The use of curing compounds is best after there has been some initial time of moist curing (e.g., sprinkling water, ponding, or saturated covering).

1.3 Wet-Mat Curing in Texas
The Texas Department of Transportation (TxDOT) allows the use of "wet mats" to aid in the curing of concrete in the Standard Specification, Item 420 (TxDOT, 2004). Fresh concrete in bridge decks and other structural elements is kept continuously wet by maintaining wet cotton mats in direct contact with the fresh concrete for a specified curing period. The specification requirement for wet mat curing is 8 days for decks with Type I cement, 10 days for decks with Type II or I/II cement, and 10 days for decks with supplementary cementitious materials (TxDOT, 2004). The specification allows opening to traffic after design strength is achieved and concrete surface treatment has been applied. The concrete can thus be opened to all traffic after the specification requirement of 8 – 10 days wet mat curing plus a day for the surface to dry and a day to apply the concrete surface treatment, for a total of 10 – 12 days. The 1995 specification required a minimum of 14 days of wet-mat curing to allow construction vehicles not exceeding three-quarter tons and a minimum of 21 days of curing before opening to all traffic. The 1982 specification required 14 days before construction traffic was allowed and a minimum of 30 days before opening to all traffic. The longer times required by the earlier specifications were based upon concerns that younger concrete might have more microcracking due to applied loads.

1.4 Research Objectives
Although concrete mix designs have evolved towards achieving high early strengths, there is a paucity of quantitative field and laboratory data on the durability properties of early-loaded concrete. TxDOT and the general public would like to open newly-cast concrete bridge decks to full traffic as early as possible to relieve roadway congestion and to decrease project costs. The objective of this research program was to collect and analyze field and laboratory data leading to a better understanding of the relationships between concrete mix designs commonly used in concrete bridge decks across the State of Texas, curing practices, allowance of early loading, and long-term durability of the concrete bridge decks.

1.5 Research Approach
Researchers conducted an extensive literature search, survey of TxDOT districts, and survey of other state Departments of Transportation (DOTs) to determine the state-of-the-art for bridge deck curing, early loading, early age behavior, and durability prediction models (Phelan and Yasmin, February 2001). Several concrete mixtures commonly used in regional districts throughout the State of Texas were tested (Garcia-Monzon, 2006). Each concrete mixture was

tested under field conditions within its respective climatic region. Field testing and testing of field-collected samples provided information on concrete strength, concrete maturity and chloride permeability. Supplementary laboratory experiments were performed on field-cast concrete specimens to assess concrete durability using several parameters and metrics. Tests conducted on field specimens included resistance to chloride permeability using the salt ponding method, compressive strength, flexural strength, abrasion resistance, freeze-thaw resistance, surface scaling and fracture toughness. Researchers used the laboratory tests to correlate results with field-cast samples and concrete strengths. Both field and laboratory test data were compared with existing models for predicting concrete maturity for various mix designs and curing methods (Garcia-Monzon, 2006). Core samples from field sites were examined using petrographic techniques to determine air void contents, calcium hydroxide formation, aggregate/paste interface features, micro-crack formation, unhydrated cement grains and other petrographic features (Lee, 2000). Researchers related the variations of petrographic features with wet-mat curing duration. Finally, researchers investigated the fracture properties of several medium-strength concrete mixes cured for various durations in order to characterize the extent of cracking that might allow the ingress of chlorides from de-icing salts to the reinforcing bars (Amarasiri, 2003).

1.6 Purpose of This Report
The purpose of this report is to present an overview of the research project and a summary of significant findings from the research.

2. Research Method

2.1 Construction of Model Field Bridge Decks
Seven concrete mix designs widely used in different parts of the State of Texas were included in this study. These were selected based on regional climatic conditions and other local conditions including coarse aggregate type used in concrete and other mix constituent materials. Due to scheduling and other logistical constraints, the number of field sites was reduced to five. However, the two additional sites were still made a part of the research study by using their mix designs and local materials to conduct laboratory tests on specimens cast at Texas Tech University. The five field sites were located at TxDOT districts in Lubbock, El Paso, Fort Worth, San Antonio and Houston. At each site, a relatively small-scale, though full-size, bridge deck was constructed. Each model field deck was cast to accommodate six panels, with each one subjected to wet-mat curing durations of 0, 2, 4, 8, 10 and 14 days. A curing regimen similar to the standard TxDOT practice was adopted. Immediately after the slab was cast, membrane curing compound was sprayed on the concrete, and once the cement in the concrete reached final set, the wet cotton mats were placed. No cotton mat was placed on the 0-day wet mat cure panel but spraying membrane curing compound was used .

Cores were taken from each bridge deck panel to measure its compressive strength and chloride permeability (using the Rapid Chloride Permeability Test). In addition, concrete specimens were cast in the field alongside the model deck for additional testing in the laboratory. These tests included compressive strength of cast cylinders, flexural strength, freeze-thaw resistance, linear shrinkage, salt scaling resistance, abrasion resistance and fracture toughness. In addition, petrography analysis of concrete specimens cored from the deck slab was conducted. For the

two mix designs for which no test slabs were constructed, the chloride permeability test was conducted on lab cast 4-inch diameter cylinders.

The field test slab was designed and constructed to mimic standard TxDOT procedures as closely as possible. The slab was typically 12 feet wide and 32 feet long, and all five field slabs were built in a similar fashion with a few exceptions such as overall dimensions and the types of beams used. Precast beams were placed on two abutments. A double bay design (Figure 1) was used in Lubbock, El Paso and Fort Worth districts with three precast beams over a single span and precast panels on either side of the center beam. The 4.5 inches thick in situ slab was cast on the precast panels to give the deck a total thickness of 8.5 inches. The single bay bridge deck with two beams was used in the San Antonio and Houston Districts. Whenever possible, a contractor from the area was hired to complete the bridge deck to help simulate actual field conditions. The concrete was vibrated, floated, and finished using practices common to the local area. In general, bridge decks had broom and/or tine finishes. Type "T" 22 gauge copper-constantan shielded wire was used to monitor and record the temperature of concrete for 28 days. Each of the six sections was instrumented with six thermocouples placed at mid-depth of concrete slab, four at the corners of each bay and two in the middle.

Figure 1. Construction of a Two-Bay Model Bridge Deck Slab

After the bridge deck was poured, curing compound was sprayed on the surface of each section to prevent moisture loss. This process was usually done within the first half hour after the pour. Once the concrete achieved initial set, cotton mats were laid on the 2-, 4-, 8-, 10-, and 14-day cure sections of the concrete surface and wetted to provide the necessary moisture for hydration continuation. An automated system consisting of a water tank, a pump with a timer, and a series of soaker hoses was employed to maintain moisture in the cotton mats. Since periodic supervision was not possible at the field site, evaporation of moisture from the cotton mats was minimized by placing plastic sheeting on top of the cotton mats. Cotton mats and plastic

sheeting were removed from the corresponding slab panel at the end of each curing duration being evaluated; 0-, 2-, 4-, 8-, 10-, and 14-days wet-mat curing. Curing periods were based on actual calendar days. The 0-day cure section of the bridge deck did not receive any wet-mat curing, but curing compound was applied to its surface. Monitoring of ambient conditions and concrete temperatures continued for 28 days. The bridge deck was cored for compressive strength tests at 4, 7 10, 14 and 28 days after casting. Coring for rapid chloride permeability testing was done at 56 days. Three replicate cores were taken from each slab panel as needed for the evaluation of curing effectiveness.

2.2 Evaluation of Three Curing Methods

An eighth concrete mix, commonly used in the Amarillo district bridge decks, was used to comparatively evaluate the effectiveness of three curing regimens. The experiments were conducted in February 2004 in the structures laboratory at Texas Tech University. Although the placed concrete was shielded from environmental elements, (i.e., snow, wind, rain, and sunlight), the experiment was not in a totally controlled environment. Atmospheric ambient conditions coupled with existing work in the structures laboratory, (e.g. leaving overhead door open to move items in and out of the laboratory), caused internal laboratory temperature and relative humidity to fluctuate at times. As a result, the concrete was cured in a cold environment.

Three concrete slabs, similar to the field slabs cast for the concrete mix, albeit smaller, were cast in the laboratory. Each slab consisted of six panels, each corresponding to a particular curing duration similar to field test slabs. Each of the three slabs was subjected to a unique curing method. Each slab was 18-feet long, 4-feet wide and 4 ½-inches thick. The slabs were elevated approximately six inches from the laboratory floor to allow air circulation both above and below the slab.

Each slab was subjected to a different curing method; conventional, "throw-on," and "mist." The conventional moist cure treatment is the same as that currently used by TxDOT and was used for other field test slabs cast in this research. After placement, the concrete surface was finished to a broom texture. A membrane curing compound was applied to the concrete surface approximately 45 minutes to 1 hour after placement. Once final set of the concrete was achieved - approximately 3 hours after placement - saturated cotton mats were placed on the concrete surface and covered by polyethylene sheeting. Curing media was kept in place for durations of 2, 4, 8, 10, and 14 days. After a section of a slab received its wet-mat curing for the predetermined duration, curing media were removed and the concrete was exposed to laboratory conditions. The 0-day cure section of the conventional cure slab received a curing compound treatment but no additional moist curing.

For the "throw-on" curing method, immediately after the concrete was poured and a smooth finish was applied, saturated cotton mats were placed directly on the finished surface and covered with polyethylene sheeting. Curing compound was not applied to any panel of the "throw-on" slab including the 0-day cure panel. Curing media was in place for the durations of 2, 4, 8, 10, and 14 days on certain sections of the slab.

For the "mist" cure method, after placement of concrete, each panel was leveled, floated, and a broom finish was applied. None of the panels in the slab received a curing compound

application. Immediately after final finish of the surface, an elevated polyethylene sheeting canopy was set in place over individual sections. A hose and a number of water misters were secured to the interior of each canopy. Hoses from each of the canopies were connected to a water manifold. Water misters were turned on periodically within the first 24 hours when needed, based on a visual inspection. Misting canopies were removed from each panel other than the 0-day panel after 24 hours and saturated cotton mats covered by polyethylene sheets were placed over the curing concrete surfaces. This curing media was left in place for the remainder of the predetermined curing duration for each section. The 0-day section of the "mist" cure slab did not receive a curing compound application. The 0-day section of the "mist" slab received a broom finish as opposed to the smooth finish of the "throw-on" slab.

3. Significant Findings

3.1 Literature Review and Survey of DOTs
Based on the findings of the literature search, state DOT surveys and TxDOT district surveys, it appears TxDOT's effort to investigate the relationships between early loading and wet mat curing durations to bridge deck concrete durability is state-of-the-art research. No state agency was found to have performed similar research for bridge decks along with a significant field investigation component. Agencies indicated a certain desire to have bridges loaded earlier, but not to the extent that was originally expected. Follow-up calls were made to bridge and/or construction divisions of all 50 state DOTs. Correspondence resulting from these calls indicates that durability concerns prevent most agencies from allowing traffic on the bridge deck with a curing duration of less than 7 days. Of the 50 agencies contacted, 35 currently require 7 days or more of wet mat curing. In addition, at least three agencies currently requiring 3 – 4 curing days indicated that, as their new specifications are being prepared, they are in the process of beginning to require a 7-day minimum cure time. The current trend for many states is to require a minimum 14-day curing duration, mostly due to the increased use of slow-hydrating high-performance concrete.

3.2 Compressive Strength and Maturity
The objective of this portion of the research project was to compare the compressive strengths of in-situ 4-inch diameter cores to predicted strengths based on strength-maturity curves developed from field-cured maturity (FMAT) cylinders and lab-cured maturity (LMAT) cylinders. Also, comparisons were made between in-situ strength and the conventional (CONVT) cylinder strength method. These tasks were performed through field and lab testing.

Developed strength-maturity curves from FMAT cylinders usually predicted compressive strength values within 10% of the in-situ concrete strength for wet-mat cured concrete. Correlation between strength-maturity curves and in-situ concrete strength development is strong provided mix proportions are nearly identical. When comparing strength gain trends from developed strength-maturity relationships, whether from FMAT or LMAT cylinders, it is observed that beyond 4 days of moist curing did not provide significant strength gain. In-situ strength determination based on CONVT cylinder breaks was found to be less accurate than the maturity method in general. Also, CONVT cylinders typically yielded strengths anywhere from 24% higher to 25% lower than in-situ concrete strengths. Since there was a considerable

difference in strength determination between field and lab conditions, it would be of good use for these setups to be duplicated under strict quality control guidelines.

Also, climatic factors on the field site could considerably affect strength gain during and after the pour. Some of these factors include ambient temperature, wind velocity, humidity, and weather conditions (i.e., cloud cover, fog, direct sunlight, etc.). The development of a curing matrix in future research could help determine an appropriate wet-mat curing time. If all the variables are known (i.e., atmospheric conditions, concrete type, size of section, maturity, etc.) curing durations based on a curing matrix could be specified to ensure proper strength gain and help ensure durable concrete.

The findings from this research confirm what was previously known about the maturity method. It can be successfully implemented to determine in-situ strength of concrete provided strict quality control is in place. Although these results match better than might be expected, the prediction could be further improved if moisture levels were also considered. Conventional cylinders are satisfactory when assessing in-situ strength in this manner, but involve much guesswork to determine when desired strengths have been achieved in the field. The maturity equivalent age calculation can be misleading at times due to the lack of a moisture or humidity variable in the Arrhenius and Nurse-Saul functions.

3.3 Chloride Permeability

This section summarizes the influence of wet-mat curing duration and mix design parameters on chloride permeability of bridge deck concrete measured using the Rapid Chloride Permeability Test (RCPT AASHTO T277) and the Chloride Ponding Test (AASHTO T259). Permeability of concrete plays a major role in determining the service life of the bridge deck. For reinforced concrete bridge decks, a key form of deterioration is steel corrosion due to chloride ingress into concrete. This leads to subsequent deterioration in strength, serviceability, aesthetics, and overall durability of the bridge deck. Chloride ingress is primarily the result of de-icing chemicals used on bridge decks.

3.3.1 Chloride Ponding Test

From the ponding results of the mixtures it was observed that chloride permeability decreased with increased curing duration. This is attributed to the fact that curing improves the hydration process, resulting in dense pore structures that lead to a decrease in concrete permeability. Experimental results show that no significant benefit for resistance to chloride permeability was observed beyond two days of moist curing for the El Paso and San Antonio mixtures. Lubbock, Atlanta, and Houston mix results showed that resistance to chloride permeability improved up to four days of moist curing, beyond which no significant improvements were observed. Fort Worth and Pharr mixtures showed improvements up to eight days of moist curing.

Fort Worth and Lubbock sites, which contained 22% and 31% Class F fly ash respectively, displayed low to very low chloride permeability as shown by the total integral chloride content. This is likely due to the fact that they were ponded for only 90 days (as opposed to 180 days), and the top surfaces were not abraded. Furthermore, their samples were tested nearly two years after they were cast. The Pharr and Atlanta site mixes, which contained siliceous gravel as coarse aggregate, show the highest permeability among all the mixes tested. This could be attributed to

the more porous transition zones typically present between the siliceous gravel course aggregate and the cement paste. It was also found that permeability of concrete decreases as percentage of fly ash (either class F or class C) increases from around 20% to around 30%.

From the seven sites under study, it was shown that steel reinforcement can be put at a distance of 1.25" below the top surface because chloride concentration falls below the threshold chloride content at 1.25" for all of the samples at all of the sites. However, a higher cover thickness is recommended for bridge decks due to the likelihood of cracking related to plastic shrinkage, and in some cases, thermal cracking. Current TxDOT specifications recommend a 2-inch clear cover for most concretes except in areas where high amounts of deicing chemicals are used, in which case a 2.5-inch clear cover is specified.

3.3.2 Rapid Chloride Permeability Test (RCPT)
Previous research has shown that the Rapid Chloride Permeability Test (RCPT) can be an effective test to evaluate the chloride permeability of concrete. Results can be obtained within two days of sample extraction compared to the 90 days it takes to get results from the chloride ponding test. The RCPT results have shown to be sensitive to mix proportioning including the use of mineral admixtures. Mineral admixtures such as fly ash and ground granulated blastfurnace slag (ggbs) significantly improve the performance of concrete in the RCPT test. The El Paso mixture tested in this research had 50 percent portland cement replaced by ggbs. Currently the El Paso district recommends the use of 35 to 50 percent cement replacement with ggbs for the purpose of mitigating alkali-silica reactivity in concrete. In terms of resistance to chloride penetration indicated by RCPT, the El Paso mix with 50 percent ggbs was found to have better performance compared to mixes from San Antonio (with 21 percent Class C fly ash) and For Worth (with 23 percent Class F fly ash). San Antonio RCPT results showed lower permeability values than that for Fort Worth.

In addition to the mix design and material selection, duration of wet-mat curing is another important criterion that plays a major role in chloride permeability. For the mixtures tested, two to eight days of wet-mat curing provided effective reductions in chloride permeability. Two days of moist curing was also found to be satisfactory for slag concrete. Fly ash was observed to be more effective in reducing the permeability of concrete at higher curing durations.

3.3.3 Comparison of Ponding and RCPT Tests
A comparison was made between the ponding test (AASHTO T259) and the RCPT (AASHTO T277) based on the water soluble integral chloride content for all curing durations and on the percent weight of concrete. It can be concluded that there exists a reasonable correlation between AASHTO T259 and AASHTO T277. It is also shown that the correlation using the percent weight of concrete ($R_2 = 0.62$) is higher than the correlation using the water soluble integral chloride ($R_2 = 0.48$).

From the comparison of results of these two tests, it was found that the classification of El Paso, Lubbock, San Antonio, and Houston mixtures based on these two tests showed different trends, while similar trends were observed for Pharr, Atlanta, and Fort Worth mixes. This leads to the conclusion that RCPT may not represent the true long-term chloride penetration for all mixtures tested. Therefore, it may be appropriate to look for an alternative test method that can provide a

direct measurement of the chloride ion concentration rather than an indirect process where concrete conductivity is used. This is the main reason ponding is always recommended, although it has practical limitations such as length of test.

Data available from one district mix design (Amarillo) showed that 0-day cure sections had a "high" permeability for all three treatments applied. The most improvement in permeability resistance was within the conventionally cured sections. Allowing the cure duration of 4 and 14 days for this treatment resulted in concrete with a permeability bordering between "low" and "moderate." There was some improvement with an increase in cure duration for the "throw-on" treatment. Both the 4- and 10-day cure durations for this treatment produced a "moderate" permeability concrete. However, there was almost no improvement for the 4-day "mist" cured section. This section remained at a "high" classification for four days of curing. Permeability was reduced to "moderate" with 14 days of "mist" curing. These results imply that permeability can be reduced by utilizing a curing compound in conjunction with a period of moist-curing. Moist-curing with the absence of a curing compound will limit the improvement in resistance to permeability for this mixture. RCPT results for the 0-day field-cast deck slabs revealed higher electrical conductivity when compared to the 4- and 10-day sections. Cure durations of 4 and 10 days had similar permeability values. This implies little improvement in permeability resistance will be achieved between 4 and 10 days of curing. This is the same pattern noticed with compressive strength development.

3.4 Resistance to Freeze-Thaw Damage
In the United States, particularly in temperate regions, freeze-thaw cycles create a serious problem in the concrete structures. In sub-freezing temperature, de-icing chemicals are used on roads and bridges to remove the snow and ice. When deicing chemicals are used the following sequence of events occurs: the ice melts, concrete thaws, melt water is absorbed into concrete, salt becomes more concentrated in the surface concrete as melt water is diluted. In addition, residual moisture in pores freezes and expands, producing cracks. Subsequent freeze/thaw cycles result in the propagation of these cracks. Therefore, alternating freeze-thaw cycles has the potential to deteriorate concrete lacking in adequate freezing and thawing resistance.

The freeze-thaw resistance test (ASTM C666) was conducted on field prepared specimens. Generally, concrete is considered to have an adequate resistance to internal deterioration under repeated cycles of freezing and thawing when the durability factor obtained from the freeze-thaw resistance test after 300 cycles of freezing-thawing is 60% or greater. Data obtained from the ASTM C666 test was the primary means of comparing different concrete mixes to establish their relative performance under freeze-thaw cycling conditions. Relative dynamic modulus of elasticity (RDME) provides an indirect measure of the presence of pore spaces bigger than capillary pores.

Scaling of concrete surface causes weight loss in the concrete specimen. In actual concrete applications, concrete surface scales markedly when exposed to freeze-thaw cycling and to de-icing salt. The freeze-thaw resistance test ASTM C666 is considered to provide more severe testing conditions compared to normal field conditions. Therefore, scaling observed in the laboratory is likely to be more severe than under actual field conditions. In almost all field mixes tested, there was an initial gain in weight followed by weight loss due to scaling damage on the

specimen surface. All mixtures were found to be satisfactory when compared to the 60% damage ratio when measured using the RDME. As for the curing duration, all mixtures tested showed no significant additional benefit beyond 4 days of moist curing when the percent weight loss of specimens was used as the comparison parameter. There was no noticeable variation in the RDME value for its different curing durations.

3.5 Fracture Resistance

Results from fracture tests conducted in this research suggest that no significant improvement of fracture properties is attained beyond 4 days of curing. It is possible that curing durations beyond 4 days increase the stiffness of concrete and may adversely affect the creep properties of concrete that help in the control of crack propagation. The results would imply that bridge decks made from medium-strength concretes be cured for approximately 4 days, with the exception of those containing large amounts of slag. However, further testing on such concretes should be carried out to determine the variations of the other durability with duration of curing.

3.5.1 Field-Cast Notched Cylinders

From the data obtained by testing field-cast notched cylinders, it is apparent that the concrete gets more brittle with increased duration of curing, at least at the test age of 28 days. The gain in strength with increased curing is not significant beyond 4 days of curing for this size of specimen. Furthermore, it would be erroneous to conclude from the data obtained that concrete, in general, gets stronger in fracture strength with increased duration of curing, as tests on cylinders of larger diameter may have resulted in entirely different trends.

3.5.2 Size-Effect Tests at 16-Day Age and 7-Day Age

The size-effect test on concrete as proposed by Bazant was developed to provide a more accurate "material" property to represent concrete fracture toughness, which is independent of specimen size. Size-effect tests conducted at 16-day age and 7-day age shows that concretes with relatively large amounts of slag, or possibly fly ash, take a long duration to cure, and have smaller fracture strengths than other types of concretes. Concretes made from Type I cement that do not contain any fly ash are more brittle than concretes containing Type I/II cement and fly ash.

At 7 days of age, most concretes tested seemed to have gained fracture strength and increased in size of fracture process zone (an indicator of less brittleness) upon increased duration of curing. However, at 16 days of age, concretes that produce specimens with larger failure loads have started to become more brittle and lose fracture toughness when the duration of curing is increased. The clear exception to the above is the concrete with relatively high (50%) slag content, which is still gaining fracture toughness and becoming less brittle upon increased duration of curing. It is highly probable that for some concretes there is an optimal level of hydration beyond which the fracture toughness starts to drop.

3.5.3 Fatigue Fracture
It was found that there is a distinct upward trend in the number of cycles to failure of cylinders as duration of curing is increased for data generated at the testing age of 28 days. A less marked increase in the number of cycles to failure with increased duration of curing was observed at 10-day age. It should be pointed out that for many concretes, the notched cylinders tested under static loading at 7-day age showed decreased failure loads with increased duration of curing, while the trend was reversed at 16-day age. The test data generated at the age of 10 days reflect the static loads to failure of the cylinders at this age, because there is a strong correlation between static failure loads and fatigue strength.

3.5.4 Absorption-Desorption Tests
Concretes containing Type I cement with no fly ash show smaller increases in hydration levels from curing beyond 8 days, while concretes containing Type I/II cement and fly ash show small improvements in hydration levels from curing beyond 8 days. Testing on larger specimens delivered absorption-desorption data that was less sensitive to curing duration than data generated from smaller specimens, and it seems logical to conclude that bridge decks are less sensitive to curing durations as far as hydration levels are concerned, because of their relatively large size when compared to test specimens.

3.6 Shrinkage
It is important to understand when (i.e., at what age) concrete bridge decks can safely be opened to full traffic without compromising durability. Experiments were performed on various district mixes to help understand the effects of curing on different concrete properties. Under this phase of the study, free shrinkage strain, modulus of elasticity and split tensile strength tests were performed on selected mixes for different curing durations. The measured values for free shrinkage strain for each mix were used to calculate the tensile stress induced in concrete due to that shrinkage when the concrete is fully restrained. It was conservatively assumed that concrete begins to crack when the shrinkage tensile stresses at 100% restraint exceed the split tensile strength. The calculation of tensile stress was done for the conditions of both creep and no creep.

The results of free shrinkage tests performed on TxDOT bridge deck concrete mixes were used to understand the effects of curing duration on free shrinkage strains. Three concrete mixes (i.e. Pharr, Fort Worth and Lubbock) were used to study the relationship between loss of moisture and free shrinkage strain. Using measurements of specimen weight at different ages, concrete moisture content was calculated. Results from these tests indicated that a decrease in free shrinkage strain was observed with increasing curing duration. This trend was more profound in the El Paso mix with 50 percent cement replacement with ggbs, and could be attributed to the slow hydration of ggbs extending well beyond the curing durations considered in this study. Results from these tests also showed that ambient relative humidity had a greater effect on the free shrinkage strain than any material property.

Elastic modulus and split tensile strength tests were conducted to assist in the prediction of age of first shrinkage-induced crack to better understand the effects of curing duration on restrained shrinkage cracking. Modulus of elasticity results did not indicate a significant correlation with curing durations, and it was also observed that modulus of elasticity did not noticeably increase after the age of 4 days. The moduli values used to predict tensile stresses were obtained from

compression tests, and it was assumed that the modulus of elasticity of concrete is the same in both tension and compression. Split tensile strength results also did not show a significant increase with increasing curing duration. The split tensile strength results also indicated that there is no noticeable increase in the split tensile strength after an age of 4 days for any curing duration.

Prior research provides evidence that a delay in the age at first crack can result in decreased long-term crack widths. Therefore, an acceleration of the first shrinkage-induced crack can result in an increase in crack widths that can lead to faster bridge deck deterioration. From the prediction of the age of first shrinkage-induced crack with no creep, no noticeable delay in the age of first crack was observed from an increase in curing duration. When creep relaxation was considered a significant increase in the age of first shrinkage-induced crack was observed with an increase in curing duration from 4 days to 10 days. However, the difference between 4 day and 7 day curing was found to be insignificant. The effect of creep relaxation was considered by assuming an ultimate creep strain equal to the elastic strain as suggested in the literature.

Based on the above discussion it can be concluded that from a shrinkage perspective, a 4 day cure is sufficient for bridge decks with mixes using Types I or III cements without fly ash. However, conducting restrained tests would be beneficial as the change in curing duration can be implemented. It can also be concluded that from a shrinkage perspective, 4 day cure can also be used for bridge deck mixes with Types II or I/II cements or for bridge deck mixes with fly ash as cement type or fly ash content is not expected to have any significant effect on shrinkage of concrete. However, additional parametric study on cement types and fly ash contents from shrinkage perspective would be beneficial before the change in curing duration is implemented for these mixes.

3.7 Scaling and Abrasion

3.7.1 Scaling
Scaling is a common surface defect often associated with concrete materials exposed to weathering and deicing salts, typically characterized by peeling or flaking of the concrete surface. Scaling can result from several different factors including: a) low air-entrained concrete; b) deicing salts; c) improper finishing operations, particularly when bleed water remains on the surface; and d) improper curing. For highway bridge decks, this concrete surface deterioration can produce direct paths for water and/or salts to migrate and interact with embedded steel reinforcing bars, thus leading to corrosion. Premature and/or excessive finishing, along with an insufficient curing duration (of 8 to 14 days), typically increase the amount of surface scaling. A high water-cement ratio results if bleed water is worked back into the top of the concrete surface, generally causing a low strength in the upper surface layer and more permeable upper surface layer.

Experts have utilized various testing approaches to determine the potential for concrete to scale. In one approach, specimens are frozen with pure water on the surface. A salt solution is then applied immediately onto the ice before thawing. A second approach calls for an application of a salt solution on the concrete surface for both the frozen and thawed states. A third approach stipulates that the initial freeze of the specimens is without any liquid on the surface. A salt

solution is then poured onto the surface before thawing. Results of these three approaches have shown that the second procedure is superior to the first and also that almost no scaling occurs when the third procedure is used. It has also been noted that no scaling arises when the salt solution is missing or is replaced by pure water. Further, it has been observed that when the outer salt solution is accidentally missing - for example, due to leakage - scaling stops. Finally, it has been concluded that surface scaling almost never appears in the absence of an outer salt solution and without actual freezing temperatures.

Several standardized procedures have been developed to assess the deicer salt scaling resistance of concrete. ASTM C 672, also known as the "ponding" method, is the most widely used deicer test procedure and is now the basis of several national and international standards. Samples are usually subjected to a total of 50 freezing and thawing cycles. The freezing period typically lasts 16 to 18 hours at 0ºF (-18ºC), followed by a thawing period of 6 to 8 hours at 73ºF (23ºC). Evaluations are made at intermediate cycle numbers. The assessment of concrete performance relies only on the visual inspection of surface condition.

The scope of this investigation is to report on the relative performance of concrete test specimens subjected to continuous cycles of freezing and thawing, as described in ASTM C 672. The purpose of this test is to evaluate the mixture proportioning, surface treatment, curing, or other variables on resistance to scaling. The test has been performed for different TxDOT district mixtures: Fort Worth, San Antonio, Lubbock, Houston, Pharr, Atlanta, and El Paso, as shown in Figure 1. Table 1 shows the types of materials used for the different mixtures. As indicated in the table, the San Antonio, Pharr, Atlanta, and El Paso mixtures were all laboratory-cast specimens. The Fort Worth, Lubbock, and Houston mixtures were cast in the field. The water-cementitious materials (w/cm) ratio for the seven mixtures ranged from 0.41 to 0.46.

A number of these seven mixtures tested are rarely exposed to freezing temperatures in Texas. Thus, the resistance to scaling is not necessarily a primary concern. However, the Lubbock mixture in particular, is generally exposed to numerous freezing and thawing cycles each year. This particular mixture showed little resistance to scaling. Though the El Paso mixture also showed little resistance to scaling, it will rarely encounter freezing and thawing cycles. In addition, the El Paso mixture, which contained 50% slag as cement replacement, is no longer used by TxDOT as a bridge deck mix design and the maximum allowable slag percentage has since been reduced to 35%. It will be interesting to determine if similar scaling results occur with the new mixture containing 35% slag.

In general, it is commonly felt that when bleed water is not present on a concrete surface, its resistance to deterioration by scaling is increased as the number of curing days increases. Interestingly, the majority of the test sets performed did not follow this expected pattern. For three of the seven concrete mixtures tested, the extent of scaling deterioration increased directly with increased curing durations. Also, it appears that when the content of cementitious materials is limited to approximately 585 lbs per cubic yard, the mixture has superior scaling resistance. Two of the seven mixtures apparently had either excessively high water-cementitious (w/cm) ratio or finishing problems in the field as they experienced significant deterioration from even the 0-day curing duration.

With the variety of concrete mixtures and finishing techniques that were utilized with the mixtures tested, it is difficult to scientifically conclude a linkage between curing duration and scaling potential. As cementitious materials contents increase in HPC mixture designs and as "wet mat" curing durations become lengthier, sensitivity analyses of scaling resistance for particular HPC mixtures under a variety of controlled weather conditions, finishing procedures, and curing scenarios are warranted.

3.7.2 Abrasion

Abrasion tests were carried out according to ASTM (2003) standards on 5 in.-cube specimens to determine the effects of changes in duration of curing on resistance to abrasion of concrete mixes. Test data indicated there is no appreciable improvement in abrasion resistance of mixes tested beyond four days of moist curing. The only exception was the Amarillo mix which showed improvement until 8 days of curing.

The ASTM specifications for the abrasion test state that the abrading wheels should be mounted so that they can move independently. However, to the wheels must be tightened against each other somewhat to prevent them from deviating from the vertical plane. It was discovered while abrading the specimens that if the wheels are tightened too hard, they will not move independently, and will drag over the concrete surface, increasing abrasion. It was found to be very difficult to duplicate the same friction levels between the abrading wheels for all mixes. Thus, the differences between abrasion losses of mixes could have been affected by this caveat. A possible method of improving the reproducibility of the results could be to require that the abrading wheels be tightened against each other with a standard torque of a wrench.

The abrading wheels get progressively less sharp as a number of surfaces are abraded. 0, 2, 4, 8, and 14-day cure specimens were used in the abrasion test. It is "natural" to start abrading the 0-day cure specimens, then the 2-day cure specimens and so on. However, this procedure is flawed because a systematic error could be imposed on the data due to the wheels becoming progressively blunter. Therefore, it is better to test a 0-day cure specimen, a 2-day cure specimen, until the first 14-day cure specimen, then test the second 14-day cure specimen, the second 10-day cure specimen and so on until the second 0-day cure specimen is tested. This method will reduce the chances of the increasingly blunter wheels affecting trends found in the data. The latter scheme was used in abrading Amarillo specimens. It is not known in what order the specimens of other mixes were abraded.

3.8 Petrographic Investigations

The petrographic studies were conducted using an optical microscope for the cores collected from the test slabs from Lubbock, El Paso, Fort Worth, Houston and San Antonio sites. The study indicated that curing (hydration), mineral additives, aggregates and possibly environmental factors can contribute to the development of characteristic features of hardened cement pastes which have a great implication on the overall concrete strength and durability of a particular concrete.

The air void contents in the Lubbock and El Paso samples were strongly controlled by curing days. The 0- and 2-day curing samples from Lubbock site are distinct in the fact that they have unusually high total and irregular air voids. Some of them show characteristic features of a

bleeding channel which was rarely observed in samples with longer than 2-day curing. The total air void contents are sharply dropped up to 2 or 4 days of moist curing and remained relatively constant thereafter. The size distributions of circular air voids in the El Paso samples also show a clear correlation with curing. The air voids gradually shift toward smaller sizes as the curing duration is increased.

Samples with little or no curing (0- and 2-day curing) invariably have large air void contents (> 6%) and consequently have an increased potential for low strength. A large proportion of irregular air voids and bleeding channels observed in those samples can also reduce their resisting abilities for chemical attacks (e.g., sulfate attack, acidic waters) and accordingly can reduce durability of the concrete.

The petrographic examination confirms that the amount of unhydrated cement grains decreases as curing duration increases. However, quantitative determination of the residual cement grains needs to be followed to better understand the relationship between the degree of hydration and curing days.

The amount of void-infilling calcium hydroxide is higher in samples with shorter curing days in the cases of Lubbock and Fort Worth site samples. Some of the calcium hydroxide is likely to be of secondary origin due to subsequent moisture movement. This again suggests that an increased amount of void-infilling calcium hydroxide crystals in "insufficiently cured" samples probably reflect the higher permeability of those samples. The samples of 0-and 2-day curing from these sites have high void contents which are often characterized by large proportions of irregular voids. Consequently these samples are expected to have higher permeability and an increased potential for moisture movement. The increased permeability allows more water and chemical ions to get into the concrete and thus facilitates concrete deterioration, and consequently adversely affects the overall concrete durability.

Shorter curing day samples from Lubbock and Fort Worth sites (0- and 2-day curing samples) often have aggregates encrusted by a wide void-rich zone. This void-rich zone at the aggregate boundaries reduces bonding strength between the aggregate and cement paste and consequently causes poor mechanical performance.

Unhydrated cement grains in the El Paso site samples are far smaller in size and volumetric content than those of the other two sites. The concrete for the El Paso deck slab consists of 50% cement and 50% ground granulated blast furnace slag (*ggbs*), which is the reason for the noticeably reduced amount of the cement grains in the El Paso samples.

Calcium hydroxide in samples from the El Paso and Fort Worth sites are volumetrically far less than those in Lubbock site samples. Further, calcium hydroxides are unexpectedly rare in samples from the El Paso site. Major determining factors for the reduced calcium hydroxide crystallization in the El Paso and Fort Worth site samples are likely due to the effects from the mineral admixtures used in those sites. A high proportion of ground granulated blast furnace slag (*ggbs*) in the El Paso deck slab (50% of the binder in weight) reduces lime/silica ratio and consequently suppresses the formation of calcium hydroxide (St. John et al., 1998). Although no hydration products are produced when *ggbs* is exposed to water, *ggbs* can react with calcium

hydroxide which is formed during the hydration of Portland cement to form a cementitious material and thus reduce the amount of calcium hydroxide in hardened cement pastes (e.g., Lea, 1970; Hooton, 1987). The precise mechanisms by which fly ash participates in pozzolanic reactions are uncertain and the reactions are complex (e.g., Mehta, 1985; St. John el al., 1998). However, the possible pozzolanic reactions and decrease in lime/silica ratio due to fly ash in the concrete are likely responsible for the reduced calcium hydroxide formation in the Fort Worth site samples.

The petrographic observation indicates that cracks are developed in a greater degree in the samples from the El Paso site than those from the other two sites. Although a large proportion of the cracks are drying shrinkage cracks in the hardened cement paste, some of them are developed in the periphery of an aggregate and suggest that shrinking and/or absorptive aggregates may have played a role for the well-developed shrinkage cracks in the El Paso site.

The durability of a concrete bridge deck is strongly influenced by the presence of microcracks and the pore structure in hardened cement paste. The cracks interconnect flow paths and voids and consequently increase permeability of the concrete. The well-developed shrinkage cracks in the El Paso site samples therefore adversely affect the overall durability of the concrete.

Crushed limestone was used as coarse aggregate in the three test slab concretes for Lubbock, El Paso and Fort Worth, although minor amounts of crushed mafic volcanic rocks have also been used in the bridge deck concrete in the El Paso site. The crushed limestone aggregates in the Lubbock and Fort Worth site bridge deck concretes do not show any clear textural and mineralogical differences. However, those used in the El Paso site are frequently intruded by calcite veins and frequently contain internal fissures. Crushed limestone aggregates from this site often show clear textural variations from areas of coarse dolomitic crystals to those of fine micritic calcite crystals. These features observed in the aggregates from the El Paso site samples are obviously undesirable traits because they constitute textural flaws that may weaken the aggregates. Several siliceous coarse aggregates observed are likely from quartz veins intruding the limestone source rock and contain well-developed cracks which are often filled with dark gel-like materials possibly formed due to the alkali-aggregate reaction.

Most of the cracks developed in samples from the El Paso site are drying shrinkage cracks in the hardened cement paste, with the exception to those developed in the periphery of an aggregate. Drying shrinkage is mostly related to water loss from the concrete. Considering the lower water/cement ratio for the bridge deck concrete in El Paso compared to that in the Lubbock site, it is not likely that differences in water/cement ratio were responsible for the observed differences in crack development. A more likely explanation is that climatic factors such as temperature and relative humidity probably played a role in the observed differences in crack development. The cracks interconnect flow paths and voids and consequently increase permeability of the concrete, which can also reduce their ability to resist chemical attacks (e.g., sulfate attack, acidic waters) and accordingly reduce durability.

3.9 Summary of Findings and Conclusions

As explained in the previous sections of this chapter, a number of tests were conducted to evaluate the impact of concrete curing duration on both its strength and durability. Based on the results of this research, a Threshold Curing Duration (TCD) was identified for each property where possible, and is identified in the table on below.

Table 1. Threshold Curing Duration for Concrete Properties

Concrete Property	Threshold Curing Duration (TCD) in Days	General Conclusions
Compressive Strength	4	Curing period should be based on maturity (equivalent age) as opposed to calendar days
Flexural Strength	4	Test results show high variability which makes the identification of trends difficult.
Modulus of Elasticity	4-8	
Fracture Toughness	4	TCD was 14 days for the El Paso mix, which can be attributed to slow strength due to presence of 50% ggbs
Fatigue Fracture Resistance	4-8	TCD was 14 days for the El Paso mix, which can be attributed to slow strength due to presence of 50% ggbs
Chloride Permeability	2-4	• Results of the RCPT and salt ponding tests show reasonably good correlation for the mixes tested. • Supplementary cementitious material (SCM) significantly improved resistance to chloride permeability (20 to 30 percent for any fly ash type) • Concrete with siliceous river gravel coarse aggregate show higher chloride permeability
Freeze-thaw resistance	4	El Paso mix with 50% slag performed the worst of the 7 mixes tested
Abrasion Resistance	2-4	Pharr District mix with no SCM performed the worst
Scaling	Inconclusive	Higher finishing efforts and extended curing durations show higher susceptibility to scaling
Shrinkage	4-10	• The free shrinkage strain was measured at a concrete age of 28 days and therefore showed significant influence from curing duration • Long-term impact of curing duration on shrinkage strain was not investigated in this study.

4. Strength-Durability Index

Observations made from tests conducted on the Amarillo (AMA) mix design resulted in the development of a framework for a Strength-Durability Index (SDI). The objective was to improve on the concrete maturity concept to incorporate concrete moisture into the index, resulting in a more robust predictor of concrete strength as well as durability. The durability component for this framework is based on results from the Rapid Chloride Permeability (RCPT) test.

4.1 Influence of Cure Treatment and Duration on Concrete Moisture

Pore humidity for the AMA slabs was affected by both the cure treatment and duration. Of the three treatments, all cured durations of the conventional cure treatment appeared to provide more stable pore humidity throughout the concrete age when compared to the fluctuations observed from the other two treatments. At an age of 14 days, "throw-on" and "mist" treatments with 0 days of curing went from producing a concrete with lower pore humidity to higher pore humidity with 10 days of curing when compared to the conventional treatment. Among the three 0-day sections, the conventional section had a higher pore humidity profile. This, however, changed when the cure duration increased to 4 days. At this cure duration, all treatments had similar pore humidity profiles throughout the age of the concrete. With 10 days of curing, both the "throw-on" and "mist" treatments had higher pore humidity profiles when compared to the conventional section with this same cure duration.

4.2 Influence of Cure Treatment and Duration on Compressive Strength

Under the laboratory conditions for the AMA mixture, all sections with 0 days of curing had lower compressive strengths when compared to sections with 4 and 10 days of curing. Compressive strengths from the conventional, "throw-on" and "mist" treatments with no days of moist-curing were relatively close to each other except at a test age of 15 days. At this age, the 0-day conventional section produced lower strengths compared to the 0-day "throw-on" and "mist" treatment. This was not expected since the 0-day conventional section received a curing compound which helped maintain higher pore humidity throughout its age. The higher pore humidity in this case caused a negative effect on compressive strength results but does not mean it is a weaker concrete. The higher pore humidity for the 0-day conventional specimens suggests the possibility of a higher degree of hydration which could have led to a more brittle concrete.

This in turn may have caused more micro-cracking in the 0-day conventional specimens during coring. Additionally, these specimens were in a more moist state when observing the pore humidity prior to testing. This moisture condition may have also been a factor in lowering the compressive strength. At test age of 15 days, "throw-on" and "mist" treatments with cure durations of 4 and 10 days had higher compressive strengths when compared to the 4- and 10-day conventionally cured sections. Typically the 4- and 10-day sections for a given cure treatment yielded similar compressive strengths at 15 days. This was also evident of the 4- and 10- day cure sections of the field-cast deck slabs at test ages of 14 and 29 days. This suggests that a prolonged cure period beyond 4 days for a slab will not significantly increase compressive strength.

4.3 Influence of Cure Treatment and Duration on Concrete Permeability
From the limited AMA RCPT data available, results show that 0-day cure sections had a "high" permeability for all three treatments. The most improvement in permeability resistance was within the conventionally cured sections. Increasing the cure duration to 4 and 14 days for this treatment resulted in concrete with a permeability bordering between "low" and "moderate". There was some improvement with an increase in cure duration for the "throw-on" treatment. Both the 4- and 10-day cure durations for this treatment produced a "moderate" permeable concrete. However, there was hardly any improvement for the 4-day "mist" cured section. This section remained at a "high" classification for 4 days of curing. Permeability was reduced to "moderate" with 14 days of "mist" curing. These results imply that permeability can be reduced by utilizing a curing compound in conjunction with a period of moist-curing. Moist-curing with the absence of a curing compound will limit the improvement in resistance to permeability for this mixture. RCPT results for the 0-day field-cast deck slabs revealed higher electrical conductivity when compared to the 4- and 10-day sections. Cure durations of 4 and 10 days had similar permeability values. This implies little improvement in permeability resistance will be achieved between 4 and 10 days of curing. This is the same pattern noticed with compressive strength development. Ponding results from the ELP, FTW, SAT, and HOU concrete mixtures revealed that 0 days of curing produce the highest chloride concentrations when compared to counterpart specimens with some duration of cure. The 4-day cure for these mixtures generally identified the curing threshold for an improved resistance against chloride permeability. Curing past 4 days typically resulted in little to no improvement in permeability resistance. Similarly, the AMA mixture demonstrated an increasing resistance to chloride ion ingress with prolonged curing durations.

4.4 Arrhenius Equivalent Age, Equivalent Hydration Period and SDI
Results of the Arrhenius equivalent age – compressive strength relationship show a wide scatter from the best-fit Freiesleben Hansen (FH) strength gain curve. The reason for the wide scatter is that Arrhenius equivalent ages are computed using age and concrete temperature history. Although this method has been shown to work when adequate moisture is provided during curing, it is not certain that these conditions exist in the field. It was the intention of this study to subject concrete to a variety of curing conditions. Therefore to improve the determination of the equivalent ages, pore humidity was monitored throughout the age of the concrete. With a pore humidity profile for each cure treatment and duration, an equivalent hydration period was determined for each section. The equivalent hydration period was first suggested by Bažant and Najjar (1972) to determine water diffusion in concrete. Using their suggested relative hydration curve parameters, these equivalent hydration ages were plotted with their corresponding compressive strengths. The data points were slightly altered but still scattered from the best-fit FH strength gain curve. Therefore in finding ways to improve on the calculation of equivalent hydration period, the author was not restricted to the relative hydration rate proposed by Bažant and Najjar (1972). It is believed that each concrete mixture and cure treatment poses its own characteristics and thus will dictate the relative hydration rate. These revised hydration curves are referred to as relative hydration age factor curves to distinguish them.

The combination of the Arrhenius equivalent age function and the relative hydration age factor resulted in the strength durability index (SDI). With this improvement, SDI values were plotted with corresponding compressive strengths. The result was a better agreement between observed

data points and the predicted best-fit FH strength gain curve. This shows some evidence that Arrhenius equivalent ages can be adjusted to account for the moisture history of the concrete by incorporating a relative hydration age factor. The limited amount of RCPT data suggests that an increasing SDI will result in a lower permeable concrete. This however must be investigated further to determine its validity to many concrete mixtures. Intuitively, it is considered that each concrete mixture has a given SDI value it must reach for the mixture to attain adequate strength and permeability resistance. With the development of SDI-strength and SDI-permeability curves, an optimal SDI value can be determined and used as a guideline to terminate curing or load concrete pavement.

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