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16. Abstract:

This report summarizes initial survey results of a long-term study on the effects of wet mat curing time and earlier loading on the long-term durability of concrete bridge decks. Surveys were sent to all 50 state departments of transportation (DOTs), with an 80% return rate, and to all 25 Texas Department of Transportation (TxDOT) districts, with a 100% return rate. The surveys reveal the the current state of practice across the United States with regard to: concrete mix design, curing methods and duration, and construction and full traffic vehicle loading times. In addition to survey results and follow-up phone calls to particular DOTs and TxDOT districts, a literature search on concrete durability issues is performed. Based on information obtained, multiple sites across the state of Texas have been suggested for field testing of concrete bridge deck durability. The suggested sites allow various representative bridge deck concrete mix designs to be tested in several different climatic regions across the state.

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EFFECTS OF WET MAT CURING AND EARLIER LOADING ON LONG-TERM DURABILITY OF BRIDGE DECKS: SURVEY RESULTS

Report 2116-1

by

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Project Number 0-2116

"Effects of Wet Mat Curing and Earlier Loading on Long-Term Durability of Bridge Decks"

Research Sponsor:

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Not intended for construction, bidding, or permit purposes. Engineer in charge of this research is Randal Scott Phelan, Ph.D., P.E., Texas Professional Engineer #86568.

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EXECUTIVE SUMMARY

Results of Tasks 1 and 2 of TxDOT Research Project 0-2116 entitled "Effects of Wet Mat Curing Time and Earlier Loading on Long-Term Durability of Bridge Decks" are presented in this interim report. Detailed discussions of these two tasks and their corresponding major work items are included in report sections to follow. This executive summary provides a brief overview of the research results to date.

Task 1 Overview

For Task 1, it was originally planned to a) conduct an extensive literature search, b) mail "wet mat curing" surveys to all 50 state DOTs and other international agencies, c) telephone interview U.S. bridge designers and contractors, d) analyze results and e) issue an interim report to TxDOT. All major items listed were completed—with two exceptions: 1) no surveys were sent to international transportation agencies and 2) contractors were not contacted. Contractors were not telephoned as it quickly became evident from talks with designers that bridge deck loading times are generally set by the state DOTs. Any variations likely would be discovered through contact with the DOT offices. In a similar manner, it became clear that follow-up calls to state agency offices were a more justified use of time than the original plan to pursue international transportation agency responses. Thus, a concentrated effort was made to increase the survey response rate from the 50 DOTs to determine the current state of practice in the U.S. The approach is considered successful in that a survey response rate of 80% was obtained.

The literature search focused on concrete a) bridge deck curing, b) early loading, c) early age behavior, d) maturity method and e) durability prediction models. Surveys were sent to 50 state transportation agencies (DOTs). The literature search is explained in more detail in Chapter 2.

The responses to DOT survey sections most closely related to this study are included in Chapter 3 of this report. These three sections are: a) agency bridge program, b) construction: curing and c) construction: loading. A sample of the transportation agency survey is included in Appendix A.

Task 2 Overview

Major anticipated work items under Task 2 were the mailing and the analysis of surveys sent to all 25 TxDOT districts. The surveys allowed determination of the approximate number of deck mix designs in use. Initially, it was felt that follow-up surveys would be mailed and an interactive Internet site would be developed. Time constraints led to a focus on follow-up phone calls in lieu of a second survey mailing. The survey response rate was an unexpectedly high 100%. Therefore, it was decided to abandon the interactive Internet web site effort and instead to simply post a downloadable copy of the survey file. A sample of the survey is included in Appendix B of this report. Essentially all survey sections, as well as concrete mix designs obtained from each of the 25 districts, are discussed in Chapter 4 of this report.

Overview of Findings

No state DOT was found to routinely load traffic at "early" concrete ages (e.g. < 7 days).[1] It was determined that most agencies are hesitant to go below what is considered a "conservative" loading age because of long-term concrete durability concerns. Nevertheless, several DOTs indicated that there continues to be a push for earlier loading times by contractors and users. Given this scenario, it appears logical, that the push for ever-decreasing times before allowing full traffic loads will continue. Based on these findings, the proposed research is viewed as timely and needed. Continuation of the current research project as planned is recommended.

[1] Upon conclusion of this research project, "early" loading will refer to a loading condition applied to a particular concrete mix prior to its "critical loading age". Because these "critical loading ages" will be determined over the course of this research project, they are not available now. As many responses from the surveys and phone calls indicate a minimum 7-day cure time, "early loading" currently is defined as "a loading of full legal traffic loads prior to 7 calendar days from the pour".

1 INTRODUCTION AND BACKGROUND

The effect of varying the amount of wet mat curing time and earlier loading on the long-term durability of concrete bridge decks is the focus of this research project. Research tasks include a) casting and monitoring of test deck slabs distributed across the state, b) laboratory testing and c) dynamic testing of test bridge deck slabs. At the conclusion of this five-year study, research findings will be used to update or confirm current TxDOT wet mat curing and time-to-loading requirements in appropriate TxDOT specifications. This interim report presents results from a) a background literature search, b) a nationwide state DOT transportation agency survey and c) a statewide TxDOT district survey on mix design.

In Texas, the requirement for wet mat curing is 8 days for decks with Type I or III cement and 10 days for decks with Type II or I/II cement or with fly ash. The most recent (9/98) Special Provision to Item 420, "Concrete Structures," allows traffic loading after design strength is achieved and concrete surface treatment has been applied—which can be in as few as 10 days. The 1993 specification requires 14 days before construction traffic and 21 days before full traffic is allowed (420.3(5)). The 1982 specification required 30 days before full traffic was allowed. This new provision represents a substantial reduction in required curing days from the 1993 and 1982 specifications. Both earlier specifications allowed 680-kg (¾-ton) construction traffic after 14 days. It is the intent of this 5-year study to determine a) the appropriate wet mat curing time for a minimum of seven TxDOT bridge deck concrete mix designs that will provide sufficient long-term durability and b) a method to follow to determine the appropriate curing times for other and/or future concrete mix designs.

2 LITERATURE REVIEW

2.1 Bridge Deck Curing

Quality mix design, structural design and placement procedures are important factors in achieving high quality concrete. In addition, proper curing of the placed concrete to ensure continued hydration is critical to achieving high-quality, durable concrete. Hydration is the chemical hardening process between portland cement and water and is the process during which concrete strength is developed. The most significant hardening and strength development, or curing, of concrete continues over a period of months. Though at a greatly reduced rate, this curing process continues over a period of years—and can continue somewhat indefinitely. Hydration generates significant amounts of heat during the first few curing days as a result of the chemical reactions that occur between the cement and water. Curing compounds and wet mat materials allow concrete to hold in more of the heat generated during hydration, lessens the temperature differential in a deck section, and thus shortens the time necessary to reach a design strength and desired durability. The curing material can be removed once design strength and durability requirements are achieved. Typically in bridge construction, wet mat curing is the preferred method of choice in that the material is a) fairly easy to place, b) not significantly affected by winds, c) fairly maintenance-free and d) durable—so its cost can be spread out on a number of projects. Concrete strength is developed at a high rate with minimal loss in ultimate strength when it remains between 130°F and 165°F during curing (Waddell, 93).

Temperatures located near the center and near the surface of a section usually differ. Care must be taken to ensure that the temperature reached throughout the cross section of the concrete pour remains relatively equal and that adequate water (or water vapor) is available for the hydration process to continue. When the surface of a section has no insulating material, heat generated by the hydration process freely transmits through the concrete to the environment. Low ambient moisture levels and high wind speeds exacerbate this process. Therefore, the temperature near the surface of a section typically is less than the temperature near the center—thus, a temperature differential. When the temperature differential between two locations in a concrete section becomes too great, cracking occurs. The exact temperature differential that causes cracking varies and is dependant on both the concrete mix and the size and shape of the section. In addition to lessening the temperature differential in the deck section, application of a wet mat curing material helps ensure adequate moisture levels are present in the concrete to allow continued hydration. To achieve desired concrete durability, the wet mat curing material should: 1) be applied as soon as possible after concrete set, 2) be continuously wet to ensure complete concrete hydration and 3) remain in place until the concrete has reached sufficient maturity for loads to be applied.

Whenever practical, it is desirable to pour in the early morning hours at ambient, or normal, mix temperature. If the concrete temperature becomes too high, mixing water may evaporate and a workable concrete mix can be difficult to achieve. When the concrete temperature falls too low, mixing water can freeze, then expand and cause fractures. To compensate for adverse weather conditions and to control the rate of hydration and concrete setting time, it is possible—though expensive—to either heat or cool the concrete before it is poured. The most common and usually least expensive method to improve curing conditions for the concrete involves installing some type of curing compound or wet mat material to the top of the bridge deck surface during the initial concrete hydration process. The use of the wetted burlap or cotton mats and/or polyethylene sheets is common throughout most of the U.S. Wet cotton mats are typically used in Texas (TxDOT, 93). When the air humidity level is low or when windspeed is high, foggers generally are employed to provide moisture needed for hydration to continue and therefore to help achieve a quality, durable finished concrete bridge deck.

Typically, the longer a bridge deck continues in a favorable curing condition, the more durable the finished product. There is a strong desire for all concerned parties (e.g. owners, users, contractors, etc.) to produce the most durable bridge deck possible. However, as is discussed in the subsection to follow, there are sometimes equally strong conflicting desires by some concerned parties (e.g. typically users and contractors) to allow "early"[1] traffic loads on the bridge deck. Traffic loads can occur either i) during construction or ii) after the bridge is opened to full legal loads. These traffic loads can include foot traffic, light vehicles, and even heavy permit loads. For each allowable loading condition, there should exist a certain concrete age, or maturity value, at which time the concrete will experience no long-term deteriorating effects

[1] As stated in the Executive Summary, upon conclusion of this research project, "early" loading will refer to a loading condition applied to a particular concrete mix prior to its "critical loading age". Because these "critical loading ages" will be determined over the course of this research project, they are not available now. As many responses from the surveys and phone calls indicate a minimum 7-day cure time, "early loading" currently is defined as "a loading of full legal traffic loads prior to 7 calendar days from the pour".

under repeated load cycles. To date, this concrete age has not been defined in general and can be considered a theoretical value.

During the course of this research project, we seek to define these "critical loading ages" for given concrete mix designs and loading conditions. Among other variables, the critical loading age can vary due to the: 1) given concrete mix design and mix constituents, 2) associated curing situation, and 3) particular loading scenario. As discussed previously, any load placed prior to the time required for the concrete to reach its particular critical loading age is considered "early". In general, early traffic loads lead to less durable bridge decks—due to: a) the initial load being applied to a lower strength concrete and b) premature elimination of available hydration moisture due to the presence of traffic.

2.2 Early Loading of Concrete

Typically in bridge design, "service" loads refer to initially opening to construction traffic and later to full traffic loads. The earlier a substantial load is applied to concrete, the increased likelihood there is for micro-cracking to occur as both compressive and tensile strengths are smaller (and therefore the capacity to resist the load is less). A great deal of micro-cracking will usually occur at the aggregate-cement paste interface, which accounts for one-third to one-half of the total volume of hardened cement paste (Neville, 1996). Therefore, this interface zone is expected to significantly contribute to the concrete permeability (Young, 1988).

As discussed previously, current TxDOT wet mat curing is:

Case A) 8 days minimum for bridge decks with Type I or III cement or

Case B) 10 days for bridge decks with Type II or I/II cement or fly ash [TxDOT 98].

Due to the September 1998 Special Provision to Item 420, "Concrete Structures," full traffic is now allowed after design strength is reached and surface treatment is applied. Allowing 2 days for surface treatment now allows full vehicle traffic for above Cases A and B to be 10 and 12 days respectively. This new provision represents a substantial reduction in required curing days from the 1982 and 1993 specifications.

Based on survey results discussed in more detail in Chapter 3 of this report, many state DOTs are interested (in general) in allowing earlier traffic loading times on bridge decks. Durability concerns however, primarily prevent most from allowing full traffic prior to at least a

7-day wet mat cure period. One exception is in Minnesota, where the approach is to ensure a minimum of 4 ½ days of curing under "ideal" conditions. Typical conditions in Minnesota, however, frequently require at least 7 days of curing. Other state practices are summarized in Table 3.4.

It is important to note that though the completed TxDOT "Transportation Agency" survey responses correctly repeated official state practices as described above (e.g. a minimum of 10 days before loading), some TxDOT projects have been allowed an exception to this requirement. Two exceptions are Projects S1 and S2 of the North Central Freeway in Dallas (US75), where at times only 4 days of wet mat curing were required (Hunt, 99). As is discussed in Section 2.4 of this report, this US 75 project is an exception in that the concrete maturity method was used and stringent concrete mix quality control measures were employed.

The 2000 AASHTO LRFD Bridge Construction Specifications requires a minimum 7-day wet cure for concrete mixes without pozzolans. For mixes having 10% or greater pozzolans, AASHTO specifies 10 days of curing for deck slabs. AASHTO allows light, i.e. 450 kg (1000 lbs) to 1800 kg (4000 lbs), vehicles and/or equipment to be on the deck after 24 hours from pour, provided there is no interference with the curing system and the deck surface is not damaged from the load (AASHTO, 00). AASHTO does not allow full traffic until 14 calendar days and f'_{c28}. The Australian Bridge Code specifically mandates a 7-day wet mat cure before bridge deck loading (Austroads, 92).

2.3 Early Age Behavior of Concrete

Early-age concrete behavior is very important to determine the implications of "early" loading of the bridge deck. The current practice for loading of the bridge deck appears to be based on the attainment of the required strength (typically compressive strength and/or flexural strength). The TxDOT Dallas District has used the concrete maturity method on several construction projects. The rate of strength development of concrete depends on a number of factors including cement type, water-cement ratio, curing method and curing temperature. Cement type and water-cement ratio are easily controlled by the mix design. Relative humidity near the concrete material is controllable. However, this is often left to the contractor. Unless close supervision is maintained, the required wet mat may dry prematurely—a condition that can adversely affect both durability and strength gain of the concrete. Outdoor concrete may continue to gain strength due to relative humidity in the environment and due to rainfall. Studies have shown that the 28-day strength for concrete moist-cured for 7 days and 28 days did not differ significantly (Price, 51). However, the longer the concrete was subjected to moist-curing, the more strength it gained even after 28 days. The question can be raised if the compressive and flexural strengths of the concrete really provide sufficient information to predict the long-term durability of reinforced concrete structures.

A seemingly intuitive "conclusion" is that increased curing times result in increased overall concrete quality. Though this conclusion is correct in general, it may not necessarily be true for all concrete durability parameters important to design. For example, studies conducted by Fu and Chang (1998) revealed that bond strength actually decreased when the curing period was increased from 7 to 28 days. This fact brings up an issue that is still not very well understood. Concrete, which is a particulate composite, contains a large number of microcracks even when it is not loaded. These microcracks occur at the interfaces between concrete-rebar, aggregate-cement paste and cement paste-mineral admixture. In addition, there are flaws formed by air voids in the system. Glucklich (1968) suggested the mere presence of micro-cracks does not reflect the strength (or lack thereof) for a particular concrete. He also indicated that as deformations increase in the presence of pre-existing cracks, the strength does decrease, but not to the extent that might be anticipated due to the possible gradual stabilization of cracks with the application of further loading. Studies conducted by Senadheera and Zollinger (1996) showed that even though concretes containing siliceous gravel and limestone coarse aggregates had comparable compressive and fracture toughness values, the performance of these concretes with regard to spalling in pavements was significantly different. These results highlight the need to test concrete subjected to different curing conditions for compressive and flexural strengths as well as repeated load fracture tests. These specimens can then be subjected to petrographic analysis to evaluate the crack propagation patterns.

The early-age properties of concrete also are influenced by creep and shrinkage characteristics. Flexural strength and modulus of rupture of concrete specimens with no shrinkage cracks were found to be higher than those with dry shrinkage cracks for certain specimen size and drying conditions (Planas and Elices, 1992). Creep effects depend on the stress ratio (applied stress to concrete strength ratio). Therefore, time-dependent behavior is considered an essential design factor for the safety and serviceability of civil engineering structures.

2.4 Maturity Method

Concrete age generally is assumed to be the number of calendar days from the pour date, irrespective of temperature fluctuations and/or curing methods used. Also, the compressive strength of the site pour generally is assumed to equal f'_c determined in cylinder compression tests. These two general methods (i.e. calendar days for "age" and cylinder tests for f'_c) are not fully accurate in all situations due to size effects and ambient air temperature fluctuations.

Another method to determine concrete strength is to measure the extent of hydration, or maturity, of both concrete test cylinders and the deck slab and compare these maturity records to a standard "heat signature" for the particular mix of concrete (Phelan, 89). Once a desired maturity value is reached on site, cylinders are tested to confirm predictions (SHRP, 93). The maturity method allows for better prediction of concrete strength development and, therefore, requires fewer test cylinders to be cast on site. However, accurately predicting concrete strength based on this method requires more sophisticated field equipment and a higher concrete batch plant quality control than typically is expected on a project. As discussed in Chapter 3 of this report, no state department of transportation currently utilizes the maturity method on a regular basis. However, based on satisfactory results from two, 2-mile segments on the Dallas North Central Expressway Construction Project, US 75, TxDOT is now finalizing procedures to allow for the maturity method to become a standard method of strength determination (Hunt and Mihm, 99).

The maturity method helps to eliminate many of the uncertainties involved with the standard concrete age and strength test methods discussed previously. By continually monitoring the hydration process, the true concrete age can be known with greater accuracy, and an improved method for predicting concrete strength development is possible. In addition, it is possible that future material selection and detailed task planning activities can be better optimized when concrete strength development predictions are based on a concrete mix "heat signature" curve (Phelan, 90).

2.4.1 Background

The maturity method is based on the assumption that samples of a given concrete mixture attain equal strengths if they attain equal maturity values (ASTM C 1074). A maturity model based on the chemical reactions that take place in the concrete during strength and maturity development along with the resulting amount of heat transferred is generated to correlate strength development to heat evolution and curing age of the concrete mix. The importance of the maturity method is not so much to reduce the number of cylinders required on a jobsite, but rather to reduce the amount of guesswork and lag times involved when estimating and monitoring concrete strength development.

Proper implementation of the maturity method requires that a strength-maturity relationship of a concrete mix be performed in a testing laboratory. During testing, a temperature history of the concrete is recorded while various strength tests are made. In accordance with ASTM specifications, these compressive strength tests are performed on three test specimens each at ages one, three, seven, fourteen, twenty-one and twenty-eight days from pour.

In addition to cylinders used for compression testing, at least two cylinders are prepared with embedded temperature sensors connected to maturity instruments or to temperature-recording devices such as data-loggers. At each age being tested, the average maturity value is recorded along with its corresponding compressive strength. Once the initial temperature as a function of time "fingerprint" of the mix has been recorded, it is used as a basis for estimating strength under a variety of conditions.

When using the maturity method to accurately estimate the in-place strength of poured concrete, temperature sensors must be placed in the section. It is preferable to place the sensors in positions that are the most critical or least favorable for strength development. The value of the minimum strength developed throughout a section is normally desired.

The maturity method allows the contractor to know "up-to-the-minute" measurements of the strength and maturity of the concrete poured in a nondestructive testing environment. Though cylinders, in general, will ultimately be tested against the design strength before a given strength can be safely assumed, the contractor is able to know more precisely when a certain strength has been achieved. This knowledge leads to less guesswork, and allows one to be better able to monitor variations of strength development due to unexpected weather changes and mix properties.

2.4.2 Drawbacks

The maturity method does have at least two drawbacks: 1) it does not specifically consider the ultimate strength of the concrete and 2) it requires a maturity-strength test for each particular concrete mix design. For example, consider when too much water is used in a concrete mix. It is possible for the early-age concrete temperatures to indicate that a certain early maturity value has been achieved. However, the temperature values, and associated maturity value calculations, would not indicate if a 28-day strength fails to be met (Holland, 87). Thus, 28-day concrete compressive cylinder tests typically are required to supplement the method. Also, though the maturity-strength test must be performed only once for each concrete mix, even minor adjustments to a particular mix can constitute a new mix that must be accompanied by a new maturity-strength relationship test to properly implement the method.

2.4.3 Benefits

The benefits of using maturity method are becoming better known as contractors have begun to experience real cost savings due to earlier traffic opening times, etc. The method is an excellent indicator of true cast in place concrete strength development (Kehl, 99) and can therefore play an important quality-control role as reduced wet-mat curing times are used. Nevertheless, owners such as TxDOT must balance 1) the initial construction efficiency possible with reduced wet mat curing times and concrete maturity monitoring with 2) potentially reduced long-term durability associated with early traffic loadings.

2.4.4 Maturity Scientific Models

There are two methods of maturity computations in use. The first method utilizes the Nurse-Saul "temperature-time factor" (TTF) maturity index developed in the early 1950s as shown in the following equation:

$$M = \sum_{0}^{t} (T - T_0)\Delta t$$

where:

$M =$ maturity index, degree Celsius-hours (or degree Celsius-days)

$T =$ average concrete temperature, degree Celsius, during the time interval Δt

$T_0 =$ datum temperature (usually taken to be) 10° C

$\Delta t =$ time interval

Because the Nurse-Saul function assumes concrete strength gain rate vs. temperature to be linear, it is not always accurate when curing temperatures vary substantially (Carino, 97). Beginning in 1977, researchers from Denmark, primarily Freieslenben Hansen, began to describe the effect of temperature on the rate of a chemical reaction as a function based on the Arrhenius equation (Hansen, 77). This second, more scientifically correct method, calculates an equivalent age of concrete to measure maturity and is recommended over the Nurse-Saul for most applications (SHRP, 93). The equivalent age at the reference temperature, typically 20°C, is the following equation:

$$t_e = \sum_{0}^{t} e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \Delta t$$

where:

$t_e =$ the equivalent age at the reference temperature

$E =$ apparent activation energy, J/mol

$R =$ universal gas constant, 8.314 J/mol-K

$T =$ average absolute temperature of the concrete during interval Δt, degrees Kelvin

$T_r =$ absolute reference temperature, degrees Kelvin

Though the above equation is more complicated for hand calculations, it presents no difficulty for modern computer-based applications.

2.4.5 Research Project Survey Results

Based on results of returned transportation agency surveys[2], it initially appeared that the maturity method was perhaps in general use in as many as five states. California, Iowa, Minnesota, New Mexico, and Texas indicated the method was utilized by their agencies.

[2] See Chapter 3.

Follow-up phone calls, however, revealed that practical use of the maturity method on bridge decks is not a regular occurrence.

Both the California and Minnesota Departments of Transportation implicitly use the "maturity" concept to ensure a minimum required concrete age. California requires a compressive concrete strength of 18 MPa (2600 psi) and a ten-day "age" before forms can be removed. Similarly, Minnesota has developed a table of required curing times based on the average concrete surface temperature for the previous 24 hours. Under the most ideal possible concrete temperature histories, concrete placed in Minnesota must be cured a minimum of 4 ½ days. However, these ideal conditions are rarely met and a 7-day minimum cure time is more realistic. Interestingly, if the "maturity" table is followed in Minnesota, compressive strength concrete cylinder tests are not required (MinnDOT, 99).

In California, full traffic is allowed when either f'_c = 23 MPa (3335 psi) or 28 calendar days from the pour have passed. Thus, California also has a provision where concrete compressive strength cylinders are not required in that should a contractor choose to wait 28 days prior to traffic loading, he/she is not required to break cylinders (Caltrans, 99). Though California and Minnesota employ the maturity concept in certain aspects of their specifications, currently neither of these two approaches can be considered to qualify with the previously stated description of proper application of the maturity method.[3]

Other states also are open to utilizing the maturity method, though implementation has not yet occurred. For example, New Mexico indicates that its specifications allow for the use of the maturity method, but currently it is not being performed (NMDOT, 99). Also, though Iowa restricts the use of the maturity method from concrete bridge decks, they have had favorable results using the method on concrete pavements (Iowa, 98).

2.4.6 Maturity Use in Texas

In Texas, as discussed previously, the maturity method is becoming more accepted due in large part to the successful implementation of projects S1 and S2 of the North Central Expressway in Dallas (US 75). The US 75 project was estimated to have user delays of $200,000 per day. The S2 project was completed ten months ahead of schedule. Much of the time savings can be attributed to reduced required wet mat curing times—in some cases as low

[3] See Subsection 2.4.1.

as 4 days. Such a reduction in wet mat cure times were possible because of the use of the maturity method and strict control on source materials used for the concrete mix throughout the project. Similarly, the S1 project was opened equally early in January 2000. This was also ten months earlier than originally planned. Again, use of the maturity method had a significant positive impact on the completion time (Hunt, 99).

2.4.7 Research Project Maturity Approach

It is the intent of this research project to utilize both the Nurse-Saul and the Arrhenius-based approaches for determining the concrete maturity. "Quadrel" by Digital Site Systems, Inc. of Pittsburgh, PA is a hardware/software equipment package that employs an Arrhenius-based equation to estimate maturity (Digital Site, 99). Quadrel uses methods based on the work of Freieslenben Hansen of Denmark to develop heat signature curves, maturity functions, and to simulate concrete strength development.

TxDOT currently collects and analyzes maturity data based on the Nurse-Saul method. It has been estimated that when ambient air temperatures range from 23°C (73°F) and 34°C (93°F), the Nurse-Saul index varies only 10% from the more accurate, but possibly less-conservative, Arrhenius-based functions (Kehl, 99). It is felt by the researchers of this project that the improved accuracy offered by the Arrhenius-based Quadrel system is required to effectively determine the "critical loading age" for each particular concrete mix being investigated. Thus, as described above, we will employ both maturity methods on each test site.

2.5 Concrete Durability

Concrete durability problems are often classified under chemical and physical phenomena. Leaching and efflorescence in cement paste, sulfate attack, alkali-aggregate reaction and rebar corrosion are classified under chemical phenomena. Physical phenomena include freezing and thawing damage, wear and abrasion, and damage due to temperature variation in concrete (Mindess and Young, 1981).

Curing of portland cement concrete can have a lasting effect on its hydration, strength development and durability. Much of the available literature treats concrete strength and durability separately, often arguing that the strength is the indicator of whether concrete is able to withstand the loads that are being imposed on it and durability is the resistance of the concrete to gradual deterioration. Neville (1996) defined a "durable" concrete as one that is able to withstand the processes of deterioration to which it is likely to be exposed. Mindess and Young (1981) indicated that a major difficulty in studying durability is predicting concrete behavior several decades into the future on the basis of short-term tests. Such short-term tests include the compressive and flexural strength tests typically done at 28-days of age. Therefore, a concrete material specialist really should try to predict the performance of concrete by taking into consideration the possible concrete deterioration mechanisms and the effects such deterioration may have on the expected concrete performance. Often, in the design of portland cement concrete structures, minimally acceptable concrete design stresses are compared to stresses caused by service loads (or, more practically, service loads are compared against concrete design capacity). However, structures such as bridges and pavements are subjected to stresses from repetitive loads that may cause stress levels in concrete that are smaller than the acceptable concrete design stress (or capacity), and failure of these structures are often caused by accumulated fatigue damage. Therefore, in studying bridge deck durability with reference to curing period and age at loading, the following questions need to be answered.

1. Effect of curing method and duration on concrete deterioration
2. Effect of curing method and duration on strength development and damage resistance of concrete
3. Effect of curing duration and mix design on bond strength of reinforced concrete
4. Effect of "early" loading on the fatigue life of a concrete bridge deck
5. Effect of concrete mix design characteristics on the rates of concrete deterioration and fatigue damage

Peterman et al. (1999) conducted a durability assessment of concrete bridges for Indiana DOT with full-span precast form panels and reported that long-term composite behavior of such bridges is enhanced by the application of a raked finish to the top surface of panels. This study was initiated based on the work done by Florida DOT with the same construction technique. They also found that epoxy-coated rebar did not perform well because corrosion of epoxy-coated rebar began a few weeks after chloride permeated to the depth of the steel. The use of low permeable concrete with adequate concrete cover was emphasized. However, they cautioned about the increase of cover because cracks will tend to be wider in negative moment regions and the corrosion of steel initiates at these locations. This study also showed the vulnerability of the current continuity correction for positive moment to excessive corrosion at interior support locations.

The single parameter that is considered to have the largest influence on concrete durability is the water-cement ratio. This ratio is the variable that singularly influences the pore permeability of concrete and is often the cause of much of the concrete deterioration that takes place. Concrete durability largely depends on the ease with which fluids can enter into, and move through, the concrete. Such movement may be in the form of actual flow, diffusion or sorption. It has been reported in the literature that the pore sizes that are relevant to permeability have diameters of at least 120 to 160 nm, and they have to be continuous. Larbi (1993) found that despite the higher porosity of the aggregate-cement paste interfacial zone in concrete, concrete permeability is controlled by the bulk cement paste, which is the only continuous phase in concrete. However, Roy et al. (1992) reported that the relationship between permeability and the hydrated cement pore structure is at best qualitative. What is important, however, is to increase the gel-space ratio in the hardened cement paste indicating a dense end-product with less porosity. Curing and temperature have a significant influence on the development of high gel-space ratios. Powers (1947) reported that hydration of cement is greatly reduced when relative humidity within the capillary pores drops below 80 percent. The effect of curing is significant mostly to the outer membrane of a concrete structure where plastic shrinkage, increased permeability and reduced abrasion resistance may result. The gel-space ratio has been shown to drop in instances when the relative humidity in concrete is low and/or when the concrete temperature is higher. Higher early concrete temperatures usually result in high early strengths, but at the expense of larger pore sizes and lower ultimate strengths.

Fu and Chang (1998) studied the effect of curing age on the bond between concrete and steel rebar. They found that bond strength decreased when the curing period was increased from 7 to 28 days. This finding is very useful for this research project, in that it aims at investigating the influence of curing period on concrete durability.

Durability Implications in the Use of Fly Ash, Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume

These materials are often finer than portland cement, and, therefore, it is believed that they improve particle packing resulting in reduced permeability (Glasser, 1992). However, even with this reduced permeability, both fly ash and GGBS increase the rate of carbonation of concrete actually making it a candidate for more corrosion. This increase in carbonation is supposed to further increase when portland blast furnace cement is used. Glasser also noted that silica fume concrete increases the resistance to chloride penetration when silica fume is used in excess of 10 percent. The influence of a blend of fly ash and silica fume in concrete is not well understood at this point. Class F fly ash appears to increase the sulfate resistance. However, there appears to be no conclusive evidence that Class C fly ash does the same.

Tests on mortar conducted by Bakker (1985) have shown that water permeability of mortar containing GGBS is reduced by a factor of 100. Such beneficial effects come from the denser microstructure of hydrated cement paste. Due to its low content of calcium chloride in concrete, the resistance to sulfate attack is also improved when GGBS is used.

3 NATIONAL TRANSPORTATION AGENCY SURVEY

A nationwide survey was performed to document the current state of bridge deck construction practice in the United States. This survey was conducted between July and August 1999. A preliminary questionnaire was developed and sent to TxDOT officials for correction and approval. After incorporation of recommendations, a final questionnaire was prepared. Transportation officials in all 50 state departments of transportation (DOTs) with expertise in bridge deck construction were contacted and sent questionnaires. A copy of this questionnaire is included in Appendix A. After responses to the questionnaires were received and analyzed, further information on several points of interest was collected by telephone calls.

Of the 50 state DOTs contacted, 40 responded to the questionnaire in time for this report. Most respondents included sections from their state specifications that were relevant to the construction of bridge decks. The three survey sections specifically relevant to this interim report have been selected for discussion. These three sections are: a) agency bridge program, b) construction: curing, and c) construction: loading. Findings are summarized in tabular form for each section.

3.1 Agency Bridge Program

Of the 40 states that responded, Texas has the highest number of bridges under its jurisdiction with 48,540. In addition to Texas, state agencies in California, Georgia, North Carolina, Ohio, Oklahoma, Pennsylvania, Tennessee and Virginia each have responsibility for more than 10,000 bridges. Survey results indicate most states have the majority of their bridge decks constructed with concrete. The amount of concrete slab and girder bridges is summarized in Table 3.1. Precast deck panels are utilized significantly in only a few states. Thirteen of the forty states reporting do not allow the use of precast panels.[4] A number of other states allow the use of panels, though implementation has been minimal.

Tennessee, Texas, and Missouri utilize precast deck panels in 50%, 85%, and 90% respectively, of their new concrete bridge decks. Remaining states utilize precast deck panels on

[4] It is important to note that the terms "panels" and "planks" are not used consistently between all states. For example, most states refer to a "panel" as a thin (i.e. 3-4" thick) plate element onto which a 4" to 4/12" cast in place topping pour is applied. The term "plank" typically is used to refer to a thicker (7" to 10") element that either has no topping or a thin (i.e. 2") nonstructural topping applied. Illinois, as one example, actually uses the term "plank" for the thinner section and "panel" for the thicker section.

Table 3.1 Agency Bridge Program, page 1 of 2 (Section 1.0 of Transportation Agency Survey)

No	State	Total Bridges in Agency	Bridges with Concrete Bridge Decks (CBD)	Concrete Slab & Girder Bridges	% CBD with Pre-cast Deck Panels	Avg. Panel Thickness (in)	Expected Life of Deck (yrs)	Avg. Deck Thickness (in.)	% Epoxy Coated Rebar in Bridge Deck
1	Alabama	5530	3590	2120	1	3.5	50	6.5	0
2	Alaska	960	580	---	6	7	25	9	100
3	Arizona [A]								
4	Arkansas	6960	4520	2030	0	N/A	20-25	8.0	10
5	California	12130	12110	---	0	N/A	20	7.5	1
6	Colorado	3690	2560	1230	1	3.5	25-35	8.0	18
7	Connecticut	5000	3750	3750	0	N/A	40-50	8	100
8	Delaware	1300	450	320	1	---	40	8	100
9	Florida	6240	4990	3390	0	---	50-100	8.0	0
10	Georgia	14500	14360	11480	3	3.5	50	7.5	1
11	Hawaii [A]								
12	Idaho	1730	---	---	0	N/A	30	8.0	100
13	Illinois	8090	6550	2750	1	3.0-3.5	50	7.5	100
14	Indiana	5600	5600	2520	1	3.0	30	8.0	100
15	Iowa	4000	4000	2400	1	3.0	30-50	7.5-8.0	100
16	Kansas	5170	5020	2000	5	3.0	25	8.5	100
17	Kentucky	8500	8330	7910	2	3.5	50	8.0	100
18	Louisiana	7900	4000	2000	30	9.0	50	10.0	0
19	Maine	3550	1780	460	5	4.0	40-60	8.0	5
20	Maryland	2470	1930	1690	0	N/A	40	9.0	100
21	Massachusetts	4990	3600	120	9	2.0	25-30	8.0	100
22	Michigan	4300	4200	3900	0	N/A	50	9.0	100
23	Minnesota	2960	2760	2480	1	5.0-9.0	35-40	9.5	100
24	Mississippi	5330	5060	3800	0	N/A	30-50	7.5	0
25	Missouri	6970	6920	4840	(new decks) 90	3.0	(after rehab) 75	8.5	100
26	Montana	2500	1750	1400	0	N/A	40-50	8.0	100
27	Nebraska	2470	2470	990	0	N/A	30	7.5	100
28	Nevada [A]								
29	New Hamp. [A]								
30	New Jersey	2350	2110	1860	0	N/A	25	8.0	(wood forms) 50 (other)100

Table 3.1 Agency Bridge Program, page 2 of 2 (Section 1.0 of Transportation Agency Survey)

No	State	Total Bridges in Agency	Bridges with Concrete Bridge Decks (CBD)	Concrete Slab & Girder Bridges	% CBD with Pre-cast Deck Panels	Avg. Panel Thickness (in)	Expected Life of Deck (yrs)	Avg. Deck Thickness (in.)	% Epoxy Coated Rebar in Bridge Deck
31	New Mexico	3650	3280	160	1	4.0	50	7.5-8.0	100
32	New York	7790	6470	4340	0.2	3.5	25-30	9.5	50
33	North Carolina	13280	8040	800	1	3.5	40	8.0	50
34	North Dakota	1500	1500	1380	0	N/A	30	8.0	7
35	Ohio	14940	11090	3230	0	N/A	50	Varies	100
36	Oklahoma	22870	11420	7660	1	4.0	50	8.0	100
37	Oregon [A]								
38	Pennsylvania	24840	12940	5260	0.01	8	50	8	21.8
39	Rhode Island	900	720	540	1	4.0	35-40	7.5	100
40	South Carolina	8210	7060	2050	1	3.5	30-75	7.0-8.0	1
41	South Dakota [A]								
42	Tennessee	19410	17760	5470	(new decks) 50	3.5	35	8.25	100
43	Texas	48540	38830	11650	(new decks) 85	4.0	75	8.0	35
44	Utah [A]								
45	Vermont [A]								
46	Virginia	18000	8500	7650	0	N/A	40	8.0	100
47	Washington	2990	2780	2560	1	unknown	40	7.5	50
48	W. Virginia [A]								
49	Wisconsin	4800	3300	2277	(experimental) 0.1	3.5-4.0	50-60	8.0-8.5	100
50	Wyoming [A]								

[A] *did not return survey*

less than 10% of new concrete bridge decks—with several not using panels at all. The average thickness of precast deck panels generally ranges from 75 to 100 mm (3 to 4 in). At least two states reported the use of 230-mm (9-in) planks. In particular, Louisiana uses planks 30% of the time.

Expected bridge deck design life ranges from 20 to 100 years, with 30 to 50 years being typical. Average deck thickness ranges from 165 to 255 mm (6.5 to 10.0 in), though 85% of the responses indicate a range from 190 to 215 mm (7.5 to 8.5 in). A 200-mm (8.0-in) deck slab thickness currently is the most common.

The use of epoxy-coated rebar varies widely among states, with most states using it for 100% of the deck mat rebar. However, a significant number of other states utilize this material only sparingly—and some not at all.

3.2 Curing

Concerning the use of curing compounds, Table 3.2 shows that some states use interim curing compounds while others do not. Normally, a curing compound is applied as soon as possible after the deck is poured. It usually is sprayed on immediately after the concrete finishing is completed. Typically, an immediate curing compound application will result in a reduction of shrinkage cracks. This immediate curing compound application is represented in the table as "as soon as possible," or "ASAP."

All states use some type of curing blanket. The time required to apply a curing blanket is summarized in the table. Generally, this time is as short as possible from pour, and typically does not exceed 24 hours. The most common material for a curing blanket in the U.S. is burlap (or sometimes burlene). Texas and several other southern and western states use cotton mats. Though answers varied considerably as to whether a curing blanket should be initially wet and/or continually wetted, all were in agreement that the concrete deck should be kept wet continually throughout the curing period. In general, state agencies report that they check for concrete wetness every 24 hours, with a number of agencies claiming they check every 6 hrs.

Most agencies reported they have no specific curing modifications for changes in either relative humidity or wind speed conditions, other than to refer to a nomograph and/or consult with the local field inspection engineer for any suggested alterations. In contrast, a number of the

Table 3.2 Construction: Curing, page 1 of 3 (Section 2.4 of Transportation Agency Survey)

No	State	Curing Compound		Curing Blanket					Minimum Required Wet Mat Cure Time
		Used as?	When applied?	When applied?	Material	Initially Wet?	Continually Wetted?	Checked for Wetness?	
1	Alabama	Interim	ASAP	ASAP, ≤ 24 hrs	Polyethylene film	Yes	No	every 24 hrs	7 days [A]
2	Alaska	No	N/A	½ hrs	Burlap	Yes	Yes	Every 12 hrs	7 days
3	Arizona								7 days [B]
4	Arkansas	Interim	ASAP	ASAP	Burlene	No	No	every 12 hrs	7 days
5	California	Interim	ASAP	4 hrs	Cotton, Rugs & Membranes	No	No	every 6 hrs	7 days [A]
6	Colorado	Interim	1/2 hr	ASAP	Burlap or Cotton	Yes	No	every 24 hrs	5 days [A]
7	Connecticut	No	N/A	ASAP	Cotton	Yes	Yes	Not specified	until f'c [A]
8	Delaware	Interim	ASAP	ASAP	Cotton, Burlap	Yes	Yes	Every 24 hrs	7 days [A]
9	Florida	Final	ASAP	ASAP	Burlap	No	Yes	every 6 hrs	7 days [A]
10	Georgia	No	N/A	Varies	White Copolymer	Yes	Yes	every 12 hrs	5 days
11	Hawaii								7 days [B]
12	Idaho	Interim	≤ 1 hr	≤ 4 hrs	Burlap	Yes	Varies	every 24 hrs	3 days (going to 7 days) [A]
13	Illinois	Interim	Varies	Varies	Burlap	No	No	> 24 hrs	7 days
14	Indiana	No	N/A	1 hr	Burlap	No	Yes	every 6 hrs	3 days (going to 7 days) [A]
15	Iowa	Interim	ASAP	ASAP	Burlap	Yes	Yes	every 6 hrs	4 days (going to 7 days) [A]
16	Kansas	Interim	ASAP	ASAP	Burlap	Yes	Varies	every 6 hrs	7 days
17	Kentucky	Interim	1hr	1 hr	Cotton, Burlap	Yes	Varies	every 24 hrs	7 days [A]
18	Louisiana	Interim	ASAP	ASAP	Burlene	No	No	every 12 hrs	5 days
19	Maine	No	N/A	ASAP	Burlap	Yes	Yes	every 24 hrs	10 days, or whenever cylinder cured with deck is > 0.8 f'c [A]
20	Maryland	No	N/A	1 hr	Burlap	Yes	Yes	Never	7 days [A]
21	Massachusetts	Interim	1 hr	1 hr	Burlap	Yes	Yes	every 24 hrs	5 days [A]
22	Michigan	Interim	ASAP	ASAP	Burlap	Yes	Yes	every 6 hrs	7 days

Table 3.2 Construction: Curing, page 2 of 3 (Section 2.4 of Transportation Agency Survey)

No	State	Curing Compound		Curing Blanket					Minimum Required Wet Mat Cure Time
		Used as?	When applied?	When applied?	Material	Initially Wet?	Continually Wetted?	Checked for Wetness?	
23	Minnesota	Interim	ASAP	24 hrs	Burlap, Burlene	Yes	No	every 24 hrs	4 days allowed, but 7 days typical due to weather
24	Mississippi	Final	ASAP	After initial set	Burlap	Yes	Yes	Every 6 hrs	7 days [A]
25	Missouri	No	N/A	ASAP	Burlap	Yes	Yes	Never	6 days
26	Montana	Interim	ASAP	After initial set	Burlap	Yes	Yes	Never	7 days [A]
27	Nebraska	Interim	---	---	Burlap	Yes	Yes	---	3 days [A]
28	Nevada								7 days [B]
29	New Hamp.								7 days [B]
30	New Jersey	Interim	1hr	ASAP	Burlap	Yes	Yes	every 6 hrs	7 days
31	New Mexico	Interim	1 hr	3-5 hrs	Cotton, Burlap	Yes	No	every 24 hrs	7 days [A]
32	New York	No	N/A	ASAP	Burlap	Yes	Yes	(At least) every 24 hrs	14 days [A]
33	North Carolina	No	N/A	1hr	Burlap	Yes	Yes	every 24 hrs	7 days
34	North Dakota	No	N/A	ASAP	Burlap	Not always	Yes	every 6 hrs	7 days
35	Ohio	Interim	ASAP	1 hr	Burlap	Yes	Yes	Never	7 days
36	Oklahoma	Interim	ASAP	After initial set	Cotton and burlap	Yes	No	Varies	10 days if 10% fly ash, 7 days otherwise
37	Oregon								7 days [B]
38	Pennsylvania	Interim	ASAP	1-3 hrs	Burlap	Yes	Yes	Every 12 hrs	7 days (rare exception is 3 days for an approved high early strength mix)
39	Rhode Island	No	N/A	ASAP	Burlap, Burlene	Yes	Yes	every 6 hrs	5 days [A]
40	South Carolina	Sometimes; Interim	ASAP	ASAP	Cotton, Burlap	Yes	No	every 24 hrs	7 days [A]
41	South Dakota								7 days [B]
42	Tennessee	Interim	1/2 hr	1 hr (ASAP)	Cotton, Burlap	Yes	Yes	every 24 hrs	5 days

Table 3.2 Construction: Curing, page 3 of 3 (Section 2.4 of Transportation Agency Survey)

No	State	Curing Compound		Curing Blanket					Minimum Required Wet Mat Cure Time
		Used as?	When applied?	When applied?	Material	Initially Wet?	Continually Wetted?	Checked for Wetness?	
43	Texas	Interim	ASAP	ASAP	Cotton	No	No	every 24 hrs	8-10 days (possible exception to 4 days if maturity method and approved material source restrictions are in place)
44	Utah								7 days [B]
45	Vermont								10 days [B]
46	Virginia	Interim	ASAP	ASAP	Poly sheeting	---	---	every 6 hrs	7 days
47	Washington	No	N/A	ASAP	Burlap	Yes	Yes	every 24 hrs	14 days
48	W. Virginia								7 days [B]
49	Wisconsin	No	N/A	1-4 hrs	Burlap	Yes	Yes	Every 24 hrs	7 days
50	Wyoming								7 days [B]

[A] *information was obtained from a phone call to the agency*
[B] *did not return survey, information was obtained from a phone call to the agency*

agencies reported they do have specific curing rules based on deck and/or ambient temperature fluctuations. Most agencies were concerned with preventing the deck from freezing for a period of days (e.g. 6 days from pour) through the use of curing/insulation materials and/or applied heat.

The minimum required duration of wet mat curing was determined using 1) completed survey forms, 2) reference to specific state specifications and 3) follow-up phone calls to all 50 state agencies. This data is included in Tables 3.2 and 3.3. Minimum wet mat curing times are summarized in Table 3.3 for the 50 state agencies. For agencies reporting multiple minimum times, the minimum is shown in Table 3.3. The table indicates 35 agencies currently require 7 days or more of wet mat curing time. In addition, 3 agencies, Idaho, Indiana and Iowa, indicated they will soon change their current 3 or 4 day requirement to 7 days. The rationale for the expected move to an increased number of required curing days for these three agencies is: a) concern over excessive shrinkage cracks currently found on their bridge decks, and b) an expected increased use of high early strength cement, with its associated expected need for longer curing times to ensure long-term durability.

Table 3.3 Agency Bridge Program: Minimum Required Wet Mat Cure Days Summary

Number of Agencies	**Minimum Required Wet Mat Cure Days**
1	Until f'c
4	3
3	4
6	5
1	6
31	7
2	10
2	14

Note: Information shown in this table is taken from the far right column of Table 3.2

Based on this data from each of the 50 States, TxDOT's 8- to 10-day wet mat cure requirement appears to be slightly conservative. However, it is interesting to note that though the Pennsylvania and Iowa Departments of Transportation allow a minimum 3- and 4-day wet mat cure respectively, they also require a 14-calendar-day and 28-day concrete age respectively before opening the bridge to full traffic.[5] Results of this research project should provide a better

[5] Refer to Tables 3.2 and 3.4

indication of the appropriateness of the required 8-10 days of wet mat curing time and additional 2-day wait prior to full traffic bridge deck loading for Texas.

3.3 Loading

In general, traffic loads are allowed based on concrete age and /or concrete compressive strength. Bridge deck loading information collected from the survey and from follow-up phone calls is summarized in Table 3.4. Approximately half of the state agencies that responded to the survey do not have a specific regulation for "limited" construction traffic, instead these agencies allow only "full" construction traffic. Other agencies allow light vehicles, construction equipment, foot traffic, etc. as limited construction traffic. In general, light vehicles are allowed after a 7- or 14-day wet cure—with some states requiring 21 days—and/or $0.7 f'_{c28}$ to $1.0 f'_{c28}$. More than half of the state agencies indicate they require a 28 day concrete cylinder strength, f'_{c28}, prior to allowing full construction traffic.

Follow-up calls were made to all 50 state agencies to determine the minimum allowable time (and/or other restrictions) required before the bridge deck can be opened to full legal traffic loads. The information is reflected in the "Full Regular Traffic" column of Table 3.4. As shown in the table, the requirements vary significantly between states. Most require a number of calendar days (typically 14 or 28 days) along with either a percentage of the design concrete compressive strength (typically f_c = 3200 psi) or a minimum required flexural beam concrete strength (typically f_t = 550 psi). Many agencies do not have a set number of required days and instead rely solely on the design compressive strength of the concrete. Others allow a set number of calendar days to pass (typically 28 days) and do not necessarily require the 28-day compressive strength to be checked.

Early loading is viewed as "critical" or "very important" by fourteen states and another eleven states said it was "somewhat important." California expressed a desire to be able to open bridges to full traffic in 1 day for deck replacement projects. Only 25% of the state agencies believe early loading significantly affects the strength and/or durability of the bridge deck concrete.

Table 3.4 Construction: Loading, page 1 of 4 (Section 3.0 of Transportation Agency Survey)

No.	State	Limited Construction Traffic		Full Construction Traffic		Full Regular Traffic	Early Loading Important?	Early Loading Affects Durability?
		Age	Vehicle Size/Type	Age	Vehicle Size/Type			
1	Alabama	10-day wet mat + 10-days & f'_c = 4000 psi	All	10-day wet mat + 10-days & f'_c = 4000 psi	All	10-day wet mat + 10-days & f'_c = 4000 psi	Somewhat Important	N/A
2	Alaska	7-day wet cure + 3200 psi	All (no limit)	7-day wet cure + 3200 psi	All	7-day wet cure + 3200 psi	Very Important	N/A
3	Arizona					f'_c [B]		
4	Arkansas	7-day wet cure + f'_c = 4000 psi	All	7-day wet cure + f'_c = 4000 psi	All	7-day wet cure + f'_c = 4000 psi	Not Important	N/A
5	California	2465 psi (17MPa)	≤ 4000 lbs	3335 psi (23MPa) or 28 days	All	3335 psi (23MPa) or 28 days	Very Important	N/A
6	Colorado	21 days or f'_{c28}	All	21 days or f'_{c28}(=4500 psi)	All	21 days or f'_{c28}(=4500 psi)	Somewhat Important	N/A
7	Connecticut	28 days	All	28 days	All	28 days + f'_{c28}	Somewhat Important	Yes
8	Delaware	4500 psi or 14 days	None	4500 psi	All	4500 psi	Somewhat Important	Undecided
9	Florida	Varies	Light vehicles	14 days or longer	All	14 days or longer + f'_{c28}	Don't Know	---
10	Georgia	3 days + 1500 psi 10 days + f'_{c28}	Buggies Storage	14 days + 3000 psi	Axle loads specified	14 days + f'_{c28} (3500 psi)	Not Important	N/A
11	Hawaii					28 days [B]		
12	Idaho	7 days wet cure + Approx 3500 psi	Light vehicles	7 days wet cure + f'_{c28}(4000 psi)	All	f'_c = 4000 psi [A]	Very Important	Yes
13	Illinois	7 day wet cure + f_t = 650 psi	All	7 day wet cure + f_t = 650 psi	All	14d & either f_t = 650 psi or f'_c = 4000 psi [A]	Somewhat Important	
14	Indiana	f_t = 550 psi	Light vehicles	After final cure	All	f_t = 550 psi (flex. beams) [A]	Somewhat Important	N/A
15	Iowa	4-day wet cure + (14-day age or f'_{c28})	Light vehicles	4-day wet cure + 28 day age	All	f_t = 550 psi (flex. beams) [A]	Critical	Yes
16	Kansas	3 days	Finishing equipment	7-day wet cure + 14-day age	All	14 days [A]	Very Important	Yes

Table 3.4 Construction: Loading, page 2 of 4 (Section 3.0 of Transportation Agency Survey)

No.	State	Limited Construction Traffic		Full Construction Traffic		Full Regular Traffic	Early Loading Important?	Early Loading Affects Durability?
		Age	Vehicle Size/Type	Age	Vehicle Size/Type			
17	Kentucky	Varies – based on cylinder strength	All	22 days or f'_{c28}	All	22 days or f'_{c28}	(most) Very Important (some projects) Critical	No
18	Louisiana	5-day wet cure + (Age 14 days or f_c =3200 psi)	All	5-day wet cure + (Age 14 days or f_c=3200 psi)	All	14 days or f_c = 3200 psi [A]	Somewhat Important	Yes
19	Maine	Typically 14 days with 7-day wet cure (cure may stop @ 80% design strength)	Light vehicles	Minimum 14 days	All, generally	Design Strength (f'_c = 4350 psi) + 4 days after curing is completed. [A]	Somewhat Important	Yes
20	Maryland	f_c = 3000 psi	Materials only	f'_{c28} = 4500 psi	All	f'_{c28} = 4500 psi	Very Important	N/A
21	Massachusetts	0.75 f'_{c28} + Typically 10 days old with 5-day wet cure (2-day wet cure & 5 days old for early strength concrete)	Slow speed light traffic	f'_{c28} = 4500 psi	All	22 days and f'_{c28} = 4500 psi [A]	Very Important	Yes
22	Michigan	7-day wet cure + 0.6f'_{c28}	Light vehicles	7-day wet cure + 14-days old + f'_{c28}(=6000 psi)	Mixers, slipform machines etc.	7-day wet cure + 14-days old + f'_{c28} (= 6000 psi)	Very Important	N/A
23	Minnesota	0.65 f'_{c28}	Light vehicles	7 days + f'_{c28}(=4300 psi)	All	14 days + f'_{c28} (may differ in winter) [A]	Somewhat Important	N/A
24	Mississippi	N/A	N/A	7 days & 4000 psi	All	21 days & 4000 psi	Very Important	No
25	Missouri	5-day wet cure + extra day of mats + f_c = 3200 psi	All	5-day wet cure + extra day of mats + f_c = 3200 psi	All	5-day wet cure + extra day of mats + f_c = 3200 psi	Not Important	Yes
26	Montana	14-day wet cure + 0.9 f'_{c28}	All	21 days old	All	21 days old + f'_{c28} (= 4500 psi)	Not Important	N/A
27	Nebraska	5 days + 0.8 f'_{c28}(=4000 to 8000 psi)	All	5 days + 0.8 f'_{c28}(=4000 to 8000 psi)	All	7-day wet cure + f'_{c28} (usually over 14 days)	Not Important	Undecided
28	Nevada	14 days + f'_{c28}	All	14 days + f'_{c28}	All	14 days + f'_{c28} [A]		
29	New Hamp.					28 days + f'_{c28} [B]		

Table 3.4 Construction: Loading, page 3 of 4 (Section 3.0 of Transportation Agency Survey)

No.	State	Limited Construction Traffic		Full Construction Traffic		Full Regular Traffic	Early Loading Important?	Early Loading Affects Durability?
		Age	Vehicle Size/Type	Age	Vehicle Size/Type			
30	New Jersey	7-day wet cure + 14 days old + f'_{c28} (4000 psi)	All	7-day wet cure + 14 days old + f'_{c28} (4000 psi)	All	7-day wet cure + 14 days old + f'_{c28} (4000 psi)	Very Important	Yes
31	New Mexico	7 days	All	7 days	All	Cylinder break at 28 days $\geq f'_{c28}$ [A]	Somewhat Important	No
32	New York	14 day cure + 7 days or f_c =3000 psi	<10 tons; <3 tons per axle	14 day cure + 14 days or f_c =3000 psi	All	14 day cure + i) 14 days or ii) f_c =3000 psi [A]		
33	North Carolina	14 days + f'_{c28} (4500 psi)	All	14 days + f'_{c28} (4500 psi)	All	14 days + f'_{c28} (4500 psi)	Don't know	N/A
34	North Dakota	7-day wet cure + 0.7 f'_{c28} (f'_c = 4700 psi)	All, generally	7-day wet cure + 0.7 f'_{c28} (f'_c = 4700 psi)	Case-by-case basis	7-day wet cure + f'_{c28} (= 4700 psi)	Somewhat Important	N/A
35	Ohio	7-day wet cure + membrane curing applied & dried + 7-day f_r = 650 psi (otherwise, 14 days); 30 days for winter concrete	All	7-day wet cure + membrane curing applied & dried + 7-day f_r = 650 psi (otherwise, 14 days); 30 days for winter concrete	All	7-day wet cure + membrane curing applied & dried + 7-day f_t = 650 psi (otherwise, 14 days); 30 days for winter concrete	Not Important	N/A
36	Oklahoma	1 day or f_c = 2500 psi	4000 lb vehicles	14 days + f'_{c28}	Rubber tire vehicles less than design load	14 days or f'_{c28} [A]	Somewhat Important	Yes
37	Oregon					14 days + f'_{c28} [B]		
38	Pennsylvania	1 day 5 days	Conveyers Motorized buggies	14 days + f_c= 4200 psi	Heavy Const. Traffic	14 days + f'_c (=4500 psi)	Don't Know	No
39	Rhode Island	21 days	Light Vehicles	28 days	All	28 days + f'_c (=5000 psi)	Very Important	No
40	South Carolina	1 day	Foot traffic	f'_c (=4000 psi)	All	f'_c (=4000 psi) + 14 days [A]	Very Important	N/A
41	S. Dakota					f'_{c28} [B]		

Table 3.4 Construction: Loading, page 4 of 4 (Section 3.0 of Transportation Agency Survey)

No.	State	Limited Construction Traffic		Full Construction Traffic		Full Regular Traffic	Early Loading Important?	Early Loading Affects Durability?
		Age	Vehicle Size/Type	Age	Vehicle Size/Type			
42	Tennessee	5-day wet cure + 7 days old + f_c=3000 psi	All	5-day wet cure + 17 days old + f_c = 3000 psi	All	5-day wet cure + 17 days old + f_c = 3000 psi	Very Important	Undecided
43	Texas	14 days	Light vehicles (1500 lbs)	21 days	All	21 days is typical (Wet mat cure time + 2 days is now allowed when requested)	Somewhat Important	Undecided
44	Utah					7 days + f'_{c28} [B]		
45	Vermont	10-day wet cure + f'_c; 0.85 f'_c for storage		10-day wet cure + f'_c		28 days + 0.85f'_{c28} [A]		
46	Virginia	f'_{c28}	All	f'_{c28}	All	28 days + f'_{c28} [A]	Very Important	Undecided
47	Washington	f'_c and 10 days old		14-day wet cure + f'_c (=4000 psi)		14-day wet cure + f'_c (=4000 psi)		
48	W. Virginia					f'_{c28} = 4000 psi [B]		
49	Wisconsin	21-days or f_c(=3500 psi)	Light Vehicles	28-days or f_c(=3500 psi)	All	28-days or f_c(=3500 psi)		
50	Wyoming	5-day wet cure + 0.8 f'_c	<6000 lbs	5-day wet cure + f'_c	> 6000 lbs	10 days + f'_{c28} [A]		

[A] *information was obtained from a phone call to the agency*
[B] *did not return survey, information was obtained from a phone call to the agency*

"All" = Legal loads
f_c = Compressive stress of concrete
f'_{c28} = Compressive strength of concrete
f_t = Flexural strength of concrete
f_r = Modulus of rupture of concrete

4 TxDOT DISTRICT SURVEY

The TxDOT district survey was undertaken to answer a number of questions including the mix design, construction and loading practices of all TxDOT districts and to assess each district's thinking on early loading of concrete bridge decks constructed using precast concrete panels and a cast-in-place (CIP) concrete slab. The survey was conducted in two phases. First, all districts were sent a detailed questionnaire that covered the following aspects of the district bridge construction program.

1. Details of the district bridge program using precast panels and CIP slabs
2. Construction practices including mix design, specifications for weather conditions, concrete placement and curing
3. Loading of completed bridge deck
4. Quality control of CIP deck concrete

Next, all district laboratory supervisors were requested to submit some of the most commonly used Class "S" concrete mix designs that were used for bridge deck concrete during the past year or so. The research team has received mix design and survey data from all 25 districts. A copy of the construction practices survey mailed to districts is given in Appendix B. Results from the mix design survey are presented in Table C-1 and those from the construction practices survey are presented in Tables C-2 to C-5. Some of the important findings from the TxDOT district survey are summarized in Table 4.1. This data is used to facilitate the selection of the seven test project locations where test slabs are to be constructed. The following were a few notable exceptions in the responses from districts.

1. Lubbock District does not allow use of precast panels in concrete bridge construction.[6]
2. Amarillo District uses a high performance concrete (HPC) mix in bridge decks.[7]
3. Dallas District has used the maturity method on several projects.
4. El Paso District has a bridge deck concrete mix with 50% GGBF slag as cement replacement.
5. Atlanta, Austin, and Dallas Districts use significant quantities (10-20%) of Type IP cement in bridge deck concrete.

[6] After a follow-up call to the Lubbock TxDOT office, it was determined that precast panels are not necessarily "disallowed" in Lubbock, they simply are not the "preferred" alternative.
[7] Though other TxDOT districts are known to utilize HPC (e.g. Lubbock, El Paso) in bridge decks, only the Amarillo district indicated this in the returned surveys.

Table 4.1. Summary of Important Data from TxDOT District Survey.

Local Region	District	National Climatic Region	Number of Mix Designs	Coarse Aggregate Type(s)	Cement Type(s)	Expected Service Life (yrs)
1*	Houston	I	7	SRG, CLS	I + Ty C	50
	Beaumont	I	3	CLS	I + Ty F II	50
	Yoakum	I, IV	2	SRG, CLS	I + Ty F/C I/II	50
2*	Corpus	IV	2	SRG	I/II + Ty F	50
	Pharr	IV	5	SRG	I + Ty C	50
	Laredo	IV	2	SRG	I II + Ty F/C	20, Unknown
3*	San Antonio	IV, V	14	CLS	I + Ty F/C I/II + Ty F/C	30
	Austin	V	3	SRG, CLS	I + Ty F/C I/II + Ty F/C	50+
4*	San Angelo	V, IV	3	SRG	II + Ty C I/II	30+,50
	Abilene	V	2	SRG	II	50
	Odessa	V	2			
	El Paso	V, IV	1	CLS	I/II + GGBS	30+
5*	Lubbock	V	2	CLS	II	30
	Amarillo	V	2	SRG	II + Ty C	50
	Childress	V	1	CLS, SRG	II + Ty C	30
6*	Brownwood	V	6	CLS	I/II + Ty F/C	40, ?
	Fort Worth	V, II	3	CLS	I/II	50
	Wichita Falls	V, II	1	CLS	II + Ty C	50
7	Dallas	II	4	CLS	I/II II + Ty C	50+
	Paris	II	3			
	Tyler	II	2	CLS	I II	30+
8*	Atlanta	II	5	SRG	I + Ty C II	50
	Lufkin	II	1			
9	Bryan	II	1	SRG, CLS	I + Ty C	50+
	Waco	V, II	1	SRG	I + Ty F	50

* - Recommended as possible location of test slab construction.

An important element in the selection of test slab locations is the climatic region. Lister (1972) presented a model where the United States was divided into six climatic regions as shown in Figure 4.1, which were based on the factors itemized in Table 4.2. These climatic regions were later adopted by AASHTO in their pavement design practices (AASHTO, 1993). Four of these six climatic regions (regions I, II, IV and V) are present within the state of Texas. A schematic showing these four climatic regions along with approximate TxDOT district boundaries, is shown in Figure 4.2.

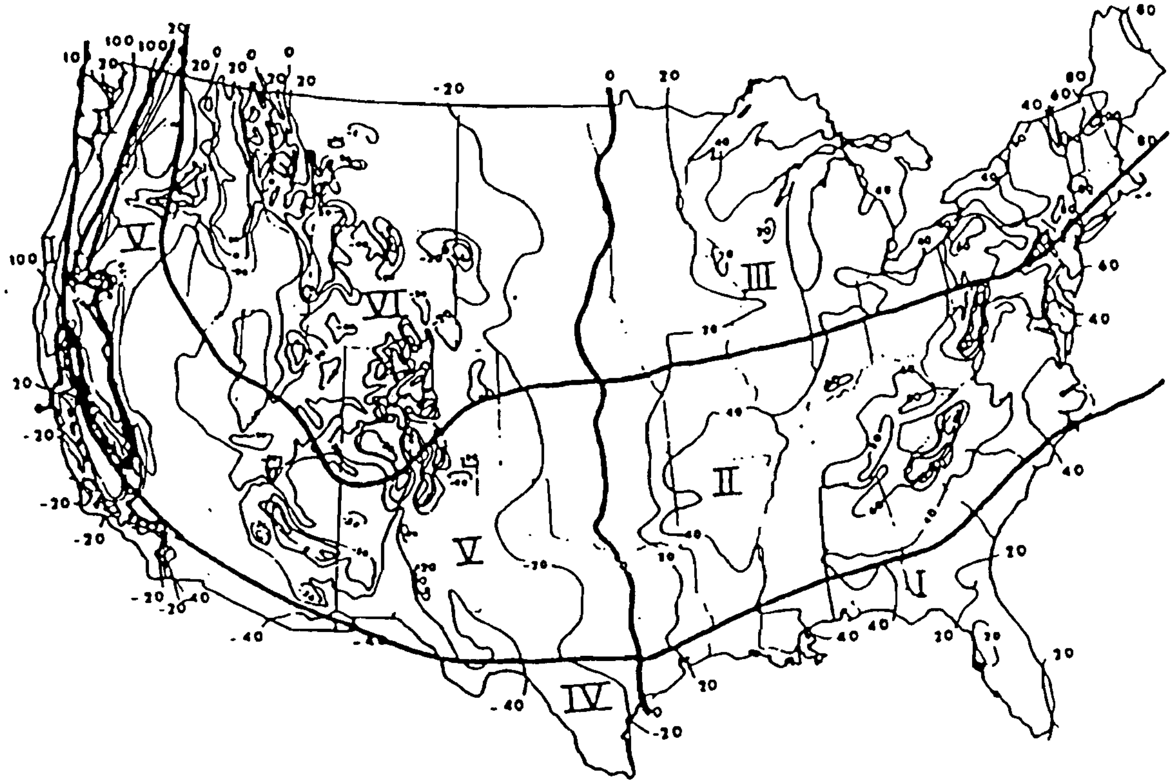

Figure 4.1. The Six Climatic Regions in the United States (Lister, 1972).

Table 4.2. Classification of the Six Climatic Regions in the United States (Lister, 1972).

Region	Climatic Characteristics
I	Wet, no freeze
II	Wet, freeze-thaw cycling
III	Wet, hard-freeze, spring thaw
IV	Dry, no freeze
V	Dry, freeze-thaw cycling
VI	Dry, hard-freeze, spring thaw

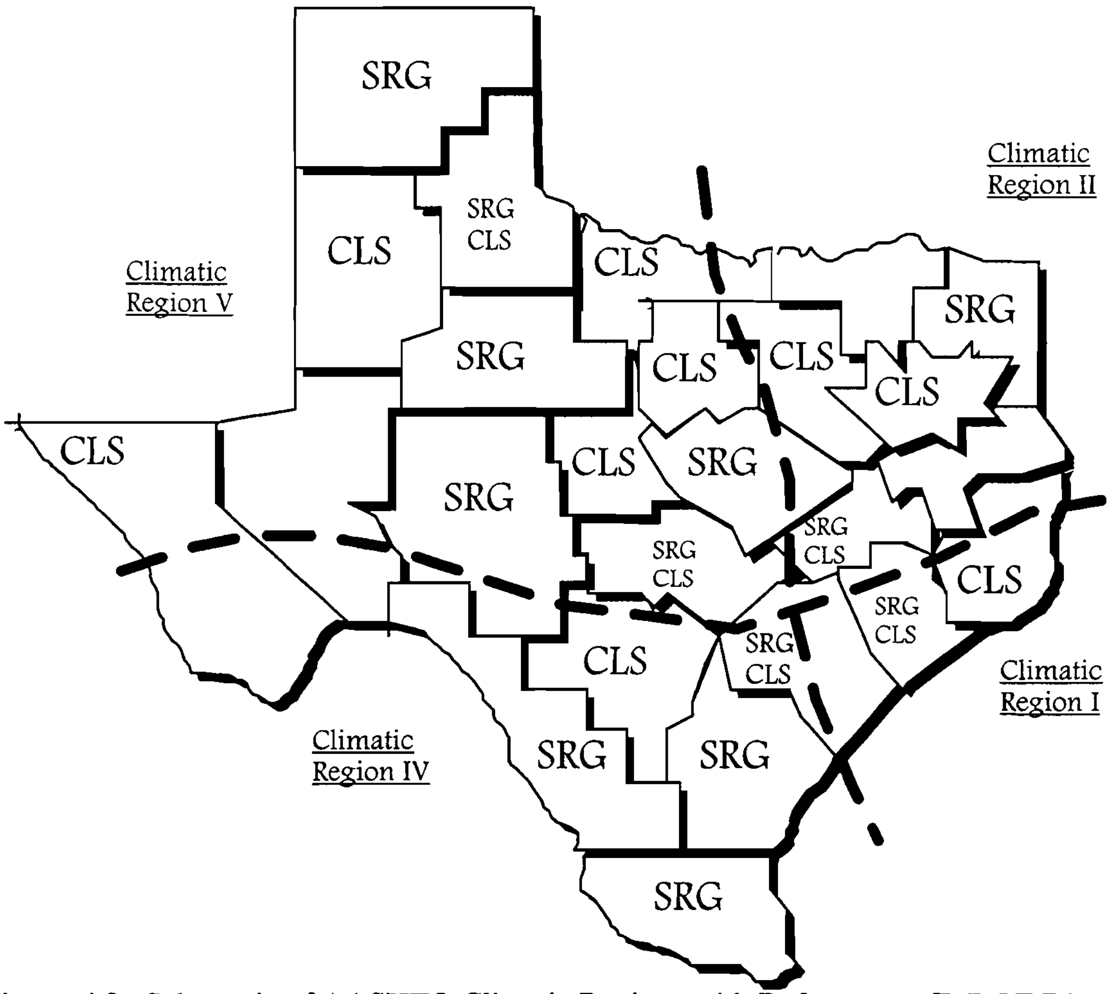

Figure 4.2. Schematic of AASHTO Climatic Regions with Reference to TxDOT Districts (CLS-Crushed Limestone; SRG- Siliceous River Gravel as Coarse Aggregate).

Based on Lister's climatic region classification, coarse aggregate types, cement types and the mineral admixture types used in TxDOT districts, the research team recommends the seven local regions 1, 2, 3, 4, 5, 6, and 8 as shown in Table 4.1 to locate the seven test slab projects as outlined in the research project statement.

Tables 4.3 and 4.4 outline the age of concrete when districts allow limited construction traffic and full traffic, respectively, on the completed bridge deck, and the data shows some variation in the district practices. Most districts allow limited construction traffic, which is typically a ¾-ton pickup, after 14 days and full traffic after 21 days. However, a few districts practice earlier loading times (10-12 days for Dallas), while others have more conservative loading times (21-28 days for Abilene).

Table 4.3. Age in Days when Limited Construction Traffic is Allowed on Bridge Deck.

Age (days)	Number of Districts	Remarks
10	2	Dallas, Waco
14	18	San Angelo has one area office that allows any type of traffic only after 28 days.
21	1	Abilene
Data unavailable	4	Childress, Lufkin, Odessa, Paris

Table 4.4. Age in Days when Full Traffic is Allowed on Bridge Deck.

Age (days)	Number of Districts	Remarks
12	1	Dallas
14	1	Waco
21	14	Atlanta has one area office that allows full loading after 28 days.
28	5	Brownwood has one area office that allows full loading after 21 days.
Data unavailable	4	Childress, Lufkin, Odessa, Paris

Table 4.5 shows a summary of responses to the survey question "*How important is early loading of bridge deck for traffic in your district?*" Several districts responded with multiple values of early opening importance—depending on the particular project. Table 4.5 reflects the highest importance level submitted by each district. The Dallas District raised the issue that it is a poor choice of words to use "early" to describe the age at loading since loading has to be based on meeting the requisite design criteria. Data from Table 4.5 shows that 20 of the 22 Districts that responded to the survey question consider that it is at least "Somewhat Important" for them to load their bridge decks "earlier" than it is prescribed in current standard specifications.

Based on factors including the climatic region, predominant coarse aggregate type, cement type and the mineral admixture, the districts listed in Table 4.6 are identified to locate the test slabs. These locations and the mix design parameters were selected based on current district practices in such a way that some limited statistical correlations could be gleaned from the data collected. These statistical correlations would include the effect of coarse aggregate type, cement type and pozzolan type. The corresponding district(s) to be used for statistical comparison are also listed in Table 4.6.

Table 4.5. The Importance of Early Loading of Bridge Deck for Traffic in TxDOT Districts.

Response	Number of Districts
Not important	2
Somewhat important	13
Very Important	3
Critical	4
No data available	3

Table 4.6. Recommended TxDOT District Test Slab Locations.

District	Climatic Region	Coarse Aggregate Type	Cement Type	Pozzolan Type	Statistical Comparison District(s)
Houston	I	CLS	I	Fly Ash Class C	Austin, Atlanta
Laredo	IV	SRG	II	Fly Ash Class C	Atlanta
San Antonio	IV/V	CLS	I	Fly Ash Class F	Houston
El Paso	V	CLS	I/II	GGBS	Fort Worth
Lubbock	V	CLS	II		Fort Worth
Fort Worth	V/II	CLS	I/II		El Paso, Lubbock
Atlanta	II	SRG	I	Fly Ash Class C	Houston, Laredo

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the findings of the literature search, state DOT surveys and TxDOT district surveys, it appears TxDOT's effort at quantifying early loading and decreased wet mat curing times to bridge deck durability is clearly state-of-the-art research. No state agency was found to have performed similar research along with corresponding field applications for bridge decks. Agencies indicated a certain desire to have bridges loaded earlier—though 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 prior to a 7-day wet cure. 35 out of 50 agencies 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.[8]

As indicated in Table 4.1, Local Regions 1, 2, 3, 4, 5, 6, and 8 have been selected for potential test sites based on climatic regions and local conditions (e.g., aggregate types and mix design variables) as discussed in Chapter 4. Based on the initial groupings, seven test site locations have been selected for upcoming field site pours. The seven include the following districts: 1) Houston, 2) Laredo, 3) San Antonio, 4) El Paso, 5) Lubbock, 6) Fort Worth and 7) Atlanta. Selection of these sites is summarized in Table 4.6 and discussed in Chapter 4.

In summary, the proposed research is viewed as timely and needed. Upon conclusion of this multi-year research project, the research team expects to be able to provide TxDOT with quantifiable and meaningful durability data based on a) time of loading, b) extent of curing and c) mix design and practices. Therefore, our recommendation is continuation of the current research project as planned.

[8] Idaho, Indiana and Iowa

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APPENDIX A

Transportation Agency Survey on Bridge Deck Construction Practices

Conducted by: Texas Tech University
Research Project: Effects of Wet Mat Curing Time and Earlier Loading on Long-Term Durability of Bridge Decks
TxDOT Program Coordinator: Ron Koester, P.E., Waco District
TxDOT Project Director: Kevin Pruski, P.E., CST/C
Project Advisors: Randy Cox, P.E., CST/C
J.M. Hunt, P.E, Dallas District
Don Harley, P.E (FHWA)
Mary Lou Ralls, P.E., CST/R

Your Agency: ____________________

Survey Date: ____________________

Your Personnel Responsible for Providing Data To This Survey (please list up to 3):

1. Name: ____________ address: ____________
   Div/Dept.: ____________ email: ____________
   Position: ____________ phone: ____________
   Sections of Survey Completed____________ fax: ____________

2. Name: ____________ address: ____________
   Div/Dept.: ____________ email: ____________
   Position: ____________ phone: ____________
   Sections of Survey Completed____________ fax: ____________

3. Name: ____________ address: ____________
   Div/Dept.: ____________ email: ____________
   Position: ____________ phone: ____________
   Sections of Survey Completed________ fax: ____________

Please provide us with a copy of your latest plan notes (general notes and provisions) applicable to the construction of bridge decks.

Contact Information: Dr. R. Scott Phelan, P.E.
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Department of Civil Engineering
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10^{th} St. & Akron
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806/742-3523 (tel); 806/742-3488 (fax)
email: scott.phelan@coe.ttu.edu

Section 1: <u>Agency Bridge Program</u>

Section 2: <u>Construction</u>

2.1 Weather Conditions

2.2 Mix Design of Bridge Deck Concrete

2.3 Concrete Placement

2.4 Curing

Section 3: <u>Loading</u>

Section 4: <u>Testing</u>

Section 1: <u>Agency Bridge Program</u>

1.1 What is the total number of bridges currently being serviced by your state or agency?

____

1.2 Of the total in (1.1) above, what is the total number or percentage of concrete bridge decks?

____

1.3 Of the bridges with concrete decks, what percentage is concrete slab and girder bridges? _______%

1.4 Do you allow the use of precast panels? Yes / No If so, what is the percent total of concrete bridge decks that used precast deck panels? __________________________%

1.5 Expected length of useful service of bridge decks? ______________________________

1.6 What is the average thickness of bridge decks? ______________________________________

1.7 What is the average thickness of precast deck panels? _________________________________

1.8 What % of steel rebar used in your bridge decks is epoxy coated? _________________________%

Section 2: Construction

2.1 Weather Conditions

2.1.1 What is the typical bridge deck construction season in your state or agency's jurisdiction?

From ____________ To _______________

2.1.2 For each of the following ambient weather parameters, please list the range of allowable values during your concrete bridge deck construction season.

Parameter	Allowable Range
Relative Humidity	_______________
	_______________
	_______________
Temperature	_______________
	_______________
	_______________
Temperature Differential	_______________
(in 24 hours)	_______________
	_______________
Wind Speed	_______________
	_______________
	_______________

2.2 Mix Design of Bridge Deck Concrete

2.2.1 What coarse aggregate types do you typically use in bridge decks in your state or agency (examples: gravel, limestone, etc.)? ____________________

2.2.2 Have you restricted the use of any aggregate types in bridge deck construction? (Y/N) ________
If yes, what are they? ____________________

2.2.3 What coarse aggregate gradations do you use in bridge decks in your state or agency? ____________

2.2.4 What fine aggregate gradations do you use in bridge decks in your state or agency? ____________

2.2.5 What types of Portland cement do you use in concrete bridge decks?

Type	% Use in Agency	Location Used (CIP Deck or Precast Panel)
________	________	________
________	________	________
________	________	________
________	________	________

2.2.6 What types of pozzolanic materials do you use in your state or agency and in what quantities?

Pozzolan Type	Quantity (% of total cement)	Location Used
Class F Fly Ash	________	________
Class C Fly Ash	________	________
Silica Fume	________	________
Granulated Blast Furnace (GGBF) Slag	________	________
Other (Specify)________	________	________

2.2.7 Do you use blended hydraulic cements such as Types IP and IS in your bridge decks? (Y/N) ________
If yes, please identify the types and corresponding approximate percentages. ____________________
____

2.2.8 What brand names and dosages of the following admixtures do you use in bridge decks?

	Admixture Brand #1		Admixture Brand #2		Admixture Brand #3	
	Description	Dosage	Description	Dosage	Description	Dosage
Accelerating Admixtures						
Retarding Admixtures						
Water Reducing Admixtures (WRA)						
High Range WRA (Superplasticizer)						
Air Entraining Agents						
Corrosion Inhibiting Admixtures						
Other (Specify)						

2.2.9 Do you use fibers to enhance the performance of your bridge deck concrete? (Y/N) ________
If yes, indicate the type and quantity used.

Type and Description of Fiber	Quantity
________________________	__________
________________________	__________

2.2.10 How does your state or agency verify the quality of your concrete? Please check all that apply.

Test	Design Value
28-day compressive strength	__________
7-day compressive strength for job control	__________
7-day flexural strength	__________
Maturity method	__________
Other (specify) ______________	__________

2.2.11 Please provide the following information on your most commonly used bridge deck concrete mix design. *(A copy of this standard mix design data/work sheet sent to us would be greatly appreciated.)*

Mix design	Parameter	**Standard Bridge Deck Mix**
Cost	Cost of Concrete	
Constituents Materials	w/c ratio	________________
	slump	________________
	cement content	________________
	cement type	________________
	course aggregate type/types	________________
	% coarse aggregate	________________%
	max. coarse aggregate size	________________
	% fine aggregate range	________________%
Strength	7 day fc	________________
	28 day f'c	________________
	maturity method	________________
Mineral admixture	% fly ash	________________%
	% silica fume	________________%
	% slag	________________%
	% GGBF slag	________________%
Chemical admixture	% air entertainment	________________
	% superplasticizer	________________
	% accelerator	________________
	% retarder	________________
	% water reducer	________________
	% corrosion inhibitor	________________
Usage	% use of mix design	________________%
	where typically used (CIP, panels, etc.)	

2.3 Concrete Placement:

2.3.1 Surface Preparation: For each of the following items, please check the one answer that best describes the activity as performed in the last 12 months.

	Always Thoroughly	Most of the Time Thoroughly	Most of the Time Substantially	Sometimes Substantially	Not Usually Substantially
Bridge Deck Cover Checked Uniformly Along Bridge Span					
Bridge Deck Surface Wetted Immediately Prior to Deck Pour					
Concrete Specifically and Thoroughly Vibrated in a Systematic Manner					
Concrete Specifically and Thoroughly Vibrated Under Deck Panel Overhang (if Precast Deck Panels Are Used)					

2.3.2 Is it allowed to withhold water at time of batching and then add water at job site? Yes/No

If so, how much? ______________________________

2.3.3 How do you typically place your concrete on the bridge decks? Please check all that apply. (Please provide as much information as possible on these methods.)

Method	% usage	Remarks
Drop Bucket	______	______________________
Pumping	______	______________________
Conveyer	______	______________________
Other (specify)	______	______________________

2.3.4 Type of screed

(a) Longitudinal %______________________
(Screed rails are perpendicular to c.l. bridge traffic direction)

(b) Transverse %______________________
(Screed rails are parallel to c.l. bridge traffic direction)

2.3.5 Do you have any special requirements for rate of concrete placement (e.g. ft/hour for a given deck width)?

Yes / No If yes, please describe: ______________________

____

2.4 Curing

	Circle One	How Long After Pour (hrs)	% of Total Concrete Deck Area Applied
2.4.1 Is curing compound applied?	Yes / No	______hrs	______%
2.4.2 If yes, is it an **interim compound?**	Yes / No	or **final compound?**	Yes / No
2.4.3 Is curing blanket applied?	Yes / No	______hrs	______%

2.4.4 If 2.4.3 is "Yes," please answer 2.4.4a-2.4.4d, otherwise, go to 2.4.5.

2.4.4a. Typically, what material type is used for your wet mat/blanket?

☐ Cotton ☐ Burlap ☐ Other (please specify): ________________

2.4.4b. Is curing mat/blanket initially wet when applied? Yes / No (circle one)

2.4.4c. Is water applied continuously to curing mat/blanket? Yes / No (circle one)

2.4.4d. In general, after initial installation how often is curing mat/blanket checked for dryness?

☐ never ☐ every 6 hrs ☐ every 12 hrs ☐ every 24 hrs ☐ > 24 hrs

2.4.5 Do you use the ambient relative humidity to alter your curing practices? Yes / No

If Yes, please describe your approach. ____

____

2.4.6 Do you use the ambient temperature or the daily temperature differential to alter your curing practices? Yes / No

If Yes, please describe your approach. ____

____

2.4.7 Do you use the wind speed to alter your curing practices? Yes / No

If Yes, please describe your approach. ____

____

Section 3: Loading

3.1 At what age of deck concrete do you allow limited construction traffic? ______________

3.2 What type of limited construction traffic is allowed? ______________

____

3.3 At what age of deck concrete would you allow full construction traffic? ______________

3.4 What type of full construction traffic is allowed? ______________

____

3.5 How important is early loading of bridge deck for traffic in your state or agency?

_____Not Important _____Somewhat important _____Very Important _____Critical _____Don't Know

3.6 If you checked either "Very Important" or "Critical" to the previous question, at what age would you like to open the bridge deck for traffic?

	Vehicle Size/Type	Age of Concrete
Limited Construction Traffic	______________	______________
Full Construction Traffic	______________	______________
Full Traffic	______________	______________

3.7 If you have had to open the bridge to full traffic early on a routine basis, do you feel this has affected the strength of and/or durability of the bridge deck concrete? (circle one)

Yes No Undecided Not Applicable

Comments:

____

____

____

3.8 If … a) your state or agency uses several "standard" mix designs and

b) the bridge deck opening varies with the mix design and the curing method, then please complete the following Table to provide a Mix Design-Curing-Loading matrix.

Mix Design-Curing-Loading Matrix

Curing Method	Material Used (Please List)	Mix Design ID	Time of Curing Application After Pour (hrs)	Duration of Curing (days)	Age when Construction Traffic is Allowed (days)	Age when Full Traffic is Allowed (days)
Curing Compound		Standard Mix:				
		Alternate Mix:				
		Alternate Mix:				
Curing Blanket		Standard Mix:				
		Alternate Mix:				
		Alternate Mix:				
Other *(Please Specify)*		Standard Mix:				
		Alternate Mix:				
		Alternate Mix:				

Section 4: Testing

4.1 Please provide information on all methods used by your Agency (including strength tests) to determine the suitability of your concrete mixes for application loads on the bridge deck? (These may include methods such as concrete maturity tests.) Please send a copy of the specifications.

Method	Specification Requirement
1. ____________________	____________________________
	____________________________
	____________________________
2. ____________________	____________________________
	____________________________
	____________________________
3. ____________________	____________________________
	____________________________
	____________________________
4. ____________________	____________________________
	____________________________
	____________________________

Please return the completed form in the enclosed envelope

Thank you for your time and kind assistance

APPENDIX B

TxDOT District Survey on Bridge Deck Construction Practices

Conducted by: Texas Tech University
Research Project: Effects of Wet Mat Curing Time and Earlier Loading on Long-Term Durability of Bridge Decks
TxDOT Program Coordinator: Ron Koester, P.E., Waco District
TxDOT Project Director: Kevin Pruski, P.E., CST/C
Project Advisors: Randy Cox, P.E., CST/C
J.M. Hunt, P.E, Dallas District
Don Harley, P.E (FHWA)
Mary Lou Ralls, P.E., CST/R

Your District: ______________________

Survey Date: ______________________

Your District Personnel Responsible for Providing Data To This Survey (please list up to 3):

1. Name: ______________ address: ______________
   Div/Dept.: ______________ email: ______________
   Position: ______________ phone: ______________
   Sections of Survey Completed__________ fax: ______________
2. Name: ______________ address: ______________
   Div/Dept.: ______________ email: ______________
   Position: ______________ phone: ______________
   Sections of Survey Completed__________ fax: ______________
3. Name: ______________ address: ______________
   Div/Dept.: ______________ email: ______________
   Position: ______________ phone: ______________
   Sections of Survey Completed________ fax: ______________

Please provide us with a copy of your latest plan notes (general notes and provisions) applicable to the construction of bridge decks.

Contact Information: Dr. R. Scott Phelan, P.E.
Texas Tech University
Department of Civil Engineering
M/S Box 41023
10th St. & Akron
Lubbock, Texas 79409-1023
806/742-3523 (tel); 806/742-3488 (fax)
email: scott.phelan@coe.ttu.edu

Section 1: District Bridge Program

Section 2: Construction

2.1 Weather Conditions

2.2 Mix Design of Bridge Deck Concrete

2.3 Concrete Placement

2.4 Curing

Section 3: Loading

Section 4: Testing

Section 1: District Bridge Program

1.1 Do you allow the use of precast panels? Yes / No If so, what is the percent total of concrete bridge decks that used precast deck panels? _______________________________%

1.2 Expected length of useful service of bridge decks? ___________________________________

1.3 What % of steel rebar used in your bridge decks is epoxy coated? ____________________________%

Section 2: Construction

2.1 Weather Conditions

2.1.1 What is the typical bridge deck construction season in your District?

From ____________ To _______________

2.1.2 For each of the following ambient weather parameters, please list the range of allowable values during your concrete bridge deck construction season.

Parameter	Allowable Range
Relative Humidity	______________________________
	______________________________
	______________________________
Temperature	______________________________
	______________________________
	______________________________
Temperature Differential	______________________________
(in 24 hours)	______________________________
	______________________________
Wind Speed	______________________________
	______________________________
	______________________________

2.2 Mix Design of Bridge Deck Concrete

2.2.1 What coarse aggregate types do you typically use in bridge decks in your district (examples: gravel, limestone, etc.)? ______________________

2.2.2 Have you restricted the use of any aggregate types in bridge deck construction? (Y/N) ________
If yes, what are they? ______________________

2.2.3 What coarse aggregate gradations do you use in bridge decks in your district? ____________

2.2.4 What fine aggregate gradations do you use in bridge decks in your district? ____________

2.2.5 What types of Portland cement do you use in concrete bridge decks?

Type	% Use in District	Location Used (CIP Deck or Precast Panel)
________	________	________
________	________	________
________	________	________
________	________	________

2.2.6 What types of pozzolanic materials do you use in your district and in what quantities?

Pozzolan Type	Quantity (% of total cement)	Location Used
Class F Fly Ash	________	________
Class C Fly Ash	________	________
Granulated Blast Furnace (GGBF) Slag	________	________
Other (Specify)________	________	________

2.2.7 Do you use blended hydraulic cements such as Types IP and IS in your bridge decks? (Y/N) ________
If yes, please identify the types and corresponding approximate percentages. ____________
____

2.2.8 What brand names and dosages of the following admixtures do you use in bridge decks?

	Admixture Brand #1		Admixture Brand #2		Admixture Brand #3	
	Description	Dosage	Description	Dosage	Description	Dosage
Accelerating Admixtures						
Retarding Admixtures						
Water Reducing Admixtures (WRA)						
High Range WRA (Superplasticizer)						
Air Entraining Agents						
Corrosion Inhibiting Admixtures						
Other (Specify)						

2.2.9 Do you use fibers to enhance the performance of your bridge deck concrete? (Y/N) __________

If yes, indicate the type and quantity used.

Type and Description of Fiber	Quantity
______________________	__________
______________________	__________

2.2.10 How does your district verify the quality of your concrete? Please check all that apply.

Test	Design Value
28-day compressive strength	__________
7-day compressive strength for job control	__________
7-day flexural strength	__________
Maturity method	__________
Other (specify) ________________	__________

2.3 Concrete Placement:

2.3.1 Surface Preparation: For each of the following items, please check the one answer that best describes the activity as performed in the last 12 months.

	Always Thoroughly	Most of the Time Thoroughly	Most of the Time Substantially	Sometimes Substantially	Not Usually Substantially
Bridge Deck Cover Checked Uniformly Along Bridge Span					
Bridge Deck Surface Wetted Immediately Prior to Deck Pour					
Concrete Specifically and Thoroughly Vibrated in a Systematic Manner					
Concrete Specifically and Thoroughly Vibrated Under Deck Panel Overhang (if Precast Deck Panels Are Used)					

2.3.2 Is it allowed to withhold water at time of batching and then add water at job site? Yes/No

If so, how much? ______________________________

2.3.3 How do you typically place your concrete on the bridge decks? Please check all that apply. (Please provide as much information as possible on these methods.)

Method	% usage	Remarks
Drop Bucket	_______	______________________
Pumping	_______	______________________
Conveyer	_______	______________________
Other (specify) ______________	_______	______________________

2.3.4 Type of screed (a) Longitudinal %______________________
(Screed rails are perpendicular to c.l. bridge traffic direction)

(b) Transverse %______________________
(Screed rails are parallel to c.l. bridge traffic direction)

2.3.5 Do you have any special requirements for rate of concrete placement (e.g. ft/hour for a given deck width)?

Yes / No If yes, please describe: ______________________________

____

2.4 Curing

	Circle One	How Long After Pour (hrs)	% of Total Concrete Deck Area Applied
2.4.1 Is curing compound applied?	Yes / No	______hrs	______%
2.4.2 Is curing blanket applied?	Yes / No	______hrs	______%

2.4.3 **If 2.4.2 is "Yes," please answer 2.4.3a-2.4.3d, otherwise, go to 2.4.4.**

2.4.3a. Typically, what material type is used for your wet mat/blanket?

☐ Cotton ☐ Burlap ☐ Other (please specify): ________________

2.4.3b. Is curing mat/blanket initially wet when applied? Yes / No (circle one)

2.4.3c. Is water applied continuously to curing mat/blanket? Yes / No (circle one)

2.4.3d. In general, after initial installation how often is curing mat/blanket checked for dryness?

☐ never ☐ every 6 hrs ☐ every 12 hrs ☐ every 24 hrs ☐ > 24 hrs

2.4.4 Do you use the ambient relative humidity to alter your curing practices? Yes / No

If Yes, please describe your approach. ________________________________

____

2.4.5 Do you use the ambient temperature or the daily temperature differential to alter your curing practices?

Yes / No If Yes, please describe your approach. ________________________________

____

2.4.6 Do you use the wind speed to alter your curing practices? Yes / No

If Yes, please describe your approach. ________________________________

____

Section 3: Loading

3.1 At what age of deck concrete do you allow limited construction traffic? ____________

3.2 What type of limited construction traffic is allowed? ____________

3.3 At what age of deck concrete would you allow full construction traffic? ____________

3.4 What type of full construction traffic is allowed? ____________

3.5 How important is early loading of bridge deck for traffic in your district?

_____ Not Important _____Somewhat important _____Very Important _____Critical _____Don't Know

3.6 If you checked either "Very Important" or "Critical" to the previous question, at what age would you like to open the bridge deck for traffic?

	Vehicle Size/Type	Age of Concrete
Limited Construction Traffic	____________	____________
Full Construction Traffic	____________	____________
Full Traffic	____________	____________

3.7 If you have had to open the bridge to full traffic early on a routine basis, do you feel this has affected the strength of and/or durability of the bridge deck concrete? (circle one)

Yes No Undecided Not Applicable

Comments:

3.8 If … a) your district uses several "standard" mix designs and

b) the bridge deck opening varies with the mix design and the curing method, then

please complete the following Table to provide a Mix Design-Curing-Loading matrix.

Mix Design-Curing-Loading Matrix

Curing Method	Material Used (Please List)	Mix Design ID	Time of Curing Application After Pour (hrs)	Duration of Curing (days)	Age when Construction Traffic is Allowed (days)	Age when Full Traffic is Allowed (days)
Curing Compound		Standard Mix:				
		Alternate Mix:				
		Alternate Mix:				
Curing Blanket		Standard Mix:				
		Alternate Mix:				
		Alternate Mix:				
Other *(Please Specify)*		Standard Mix:				
		Alternate Mix:				
		Alternate Mix:				

Section 4: Testing

4.1 Please provide information on all methods used by your district (including strength tests) to determine the suitability of your concrete mixes for application loads on the bridge deck? (These may include methods such as concrete maturity tests.) Please send a copy of the specifications.

Method	Specification Requirement
1. ____________________	______________________________
	______________________________
	______________________________
2. ____________________	______________________________
	______________________________
	______________________________
3. ____________________	______________________________
	______________________________
	______________________________
4. ____________________	______________________________
	______________________________
	______________________________

Please return the completed form in the enclosed envelope

Thank you for your time and kind assistance

APPENDIX C

Table C-1 TxDOT District Bridge Deck Mix Designs

District	Cement Type	CF	CAF	WCR	AF	Pozzolan Use Type	Pozzolan Use Percent	Aggregate Grade	Admixtures
Abilene	II	6.5	0.76	5.0	0.8?				
	II	6.5	0.76	5.0	0.8?				
Amarillo	II	6.5	0.73	4.5	6			4	WRA,AEA
	II (HPC)	7.8	0.71	3.8	6	C	16.7	3	WRA,AEA
Atlanta	Sunbelt(Balcones)_I/II	6.5	0.72	4.8	6	F	25		WRA,AEA
	Holnam(Ada,OK)	6.5	0.68	4.5	5				
	Ash Grove_I				6	C	25		WRA,AEA
	Sunbelt(Balcones)_I/II	6.5	0.70	5.0	6	C	25		WRA,AEA,ACC
	Sunbelt(Balcones)_I/II	6.5	0.70	5.0	6	F	25		WRA,AEA
Austin	TXI_I/II	6.5	0.73	4.7	6	C	30	4	AEA,RET
	Sunbelt_I/II	6.5	0.73	4.6	6	C	28	4	AEA,RET
	TXI_I/II	6.5	0.73	4.7	6	F	28	4	AEA,RET
Beaumont	River Cement_I/II	6.5	0.78	4.0	5	F	20		AEA,RET
	TXI_I/II	6.5	0.70	4.5	5	C	20	5	
	Sunbelt_I/II	6.5	0.75	4.6	5	F	20	4	AEA,WRA
Brownwood	Sunbelt_I/II	6.5	0.72	4.6	6	F	25	3	AEA,WRA/RET
	North Texas_I/II	6.5	0.76	4.5	6			3	AEA,RET
	Sunbelt_I	6.5	0.67	4.5	6	F	20	4	AEA,RET
	Sunbelt_I	6.5	0.68	4.8	5	F	20	4	AEA,RET
	Alamo_I	6.5	0.72	4.5	6	F	20	3	AEA,WRA,RET
	Alamo_I	6.5	0.72	4.7	6			3	AEA,WRA
Bryan	I	6.5	0.68	4.5	6	F	25	4	AEA,WRA
Childress	II	6.5	0.72	4.8	6				
Corpus		6.5	0.69	4.6	6			3	AEA,WRA,RET
	Alamo_I	6.5	0.75	4.5	5				AEA,RET
Dallas	Sunbelt-Balcones_I/II	6.5	0.70	4.6	6	C	35	4	AEA,RET
	Sunbelt-Balcones_I/II	6.5	0.70	4.6	6	C	35	4	AEA,RET
	Sunbelt_I/II	6	0.71	4.5	6	F	20	4	AEA,RET
	Sunbelt_I/II	6	0.71	4.5	6	F	20	4	AEA,RET
El Paso	I/II	6.5	0.65	4.8	6	GGBF	50	5	AEA
Fort Worth	TXI_I/II	6.5	0.71	4.7	6			4	
	North Texas_I/II	6.5	0.68	4.5	6	C	20	4	
	North Texas 308_I/II	6.5	0.72	4.7	4				
Houston	Capitol_I	6.5	0.75	4.1	5			2	AEA,RET
	Sunbelt_I/II	6.5	0.73	4.6	5	C	30		AEA,
	Alamo_I	6.5	0.71	4.1	6	C	33		AEA,RET
	Sunbelt_I/II	6.5	0.70	4.5	6			3	AEA,RET
	Sunbelt_I/II	6.5	0.70	4.5	6			2	AEA,RET
	N.Texas (Midl.)_I/II	6.5	0.70	4.5	5	C	30	2	AEA,RET
	Sunbelt_I/II	6.5	0.66	4.4	5	C	35	2	AEA,RET
Laredo	Capitol_I	6.5	0.70	5.0	5	C	20	3	AEA,WRA,RET
		6.5	0.71	4.5	5	C	15		
Lubbock	_I/II	6.5	0.74	4.8	5				AEA,RET
	_I/II	6.25	0.74	5.0	5				AEA,RET
Lufkin	TX Lehigh, Sunbelt_I	6.5	0.75	5.0	6			3	AEA
Odessa	Lonestar_I/II	6.5	0.72	4.8	6				AEA,WRA/RET
	Lonestar_I/II	6.5	0.72	4.8	6	F	15		AEA,WRA/RET
Paris	TXI,Midlothian_I/II	6.5	0.76	4.6	6			4	AEA,WRA
	Ash Grove_I	6	0.62	4.8	6	C	20	4	AEA,RET
		6.5	0.80	4.4	6			4	AEA
	Ash Grove_I	6.5	0.62	4.3	6	C	25	4	AEA,RET
Pharr	Texas Lehigh	6.5	0.70	4.7	6	C	25	4	AEA,RET
	Texas Lehigh	6.5	0.70	4.7	6	C	25		AEA,RET
	Capitol_I	6.5	0.74	4.5	6	C	20	4	AEA,RET
	Capitol_II	7.25	0.73	4.4	6			4	AEA,RET
	Capitol_II	7.1	0.74	4.5	6			4	AEA,RET

APPENDIX C

Table C-1 TxDOT District Bridge Deck Mix Designs

District	Cement Type	CF	CAF	WCR	AF	Pozzolan Use		Aggregate Grade	Admixtures
						Type	Percent		
San Angelo		6.5	0.75	5.0	6				
		6.5	0.68	4.8	6				
		6.5	0.68	4.8	6	?	30		
San Antonio	Texas Lehigh	6	0.75	5.0	6	C	25	3	AEA,RET
	Sunbelt_I	6.5	0.69	4.6	6	C	25	3	AEA,RET
	TXI_I	6.5	0.76	5.0	6	C	25	3	AEA,RET
	TXI_I	6.5	0.72	5.0	6	C	25	3	AEA,RET
	TXI_I	6	0.72	5.0	6	C	20	3	AEA,RET
	TXI_I/II	6.5	0.71	4.8?	6	C	20	3	AEA,RET
	Sunbelt_I/II	6.5	0.73	5.0	6	C	25	3	AEA,RET
	Alamo_I	6.5	0.71	5.0	6	C	30	3	AEA,RET
	Capitol_I	6.5	0.70	5.0	6	C	30	4	AEA,RET
	Capitol_I	6.5	0.70	5.0	6	C	25	4	AEA,RET
	Alamo_I	7	0.70	4.7	6	C	20	3	AEA,WRA
	Alamo_I	6.5	0.74	5.0	6	C	20	3	AEA,WRA
	Alamo_I	6.5	0.70	5.0	6	C	20	3	AEA,WRA
	Capitol_I	6.5	0.69	5.0	6	C	25	4	AEA,RET
Tyler	LaFarge(Balcones)_I	6.5	0.72	5.0	4	F	25		AEA,RET
	LaFarge(Balcones)_I	6.5	0.69	4.0	6	F	20		AEA,RET
Waco	Capitol_I	6.5	0.74	4.6	5			4	AEA,WRA
Wichita Falls	II	6.5	0.72	5.0	6				
Yoakum	Alamo_I	6.5	0.72	4.8	5			2	
		6.5	0.72	4.8	6	F	25	4	

Table C-2 TxDOT District Survey: General Bridge Construction Information

District	% Bridges w/Panels	Expected Service Life (yrs)	Ambient Weather Conditions @ Placing				Placement	Withhold Water & Add Later?
			Relative Humidity	Temperature	Temperature Differential	Wind Speed		
Abilene	50	50		Avoid Low Temparatures	Avoid High Diff. during 10-d curing		Bucket-90% Pump-50%	Yes
Amarillo	70	50			If cold front possible in 4-days, wait		Bucket-50% Pump-50%	Yes
Atlanta	15	50		>35°F-Rising			Bucket-90% Pump-10%	10 gals
Austin	75	50+					Bucket-30% Pump-70%	Within slump & w-c req.
Beaumont	45	50		>35°F-Rising 50°F for 72h 40°F-next 72h			Bucket-40% Pump-60%	Max. 24 gal
Brownwood	20	40		>35°F-Rising 50°F for 72h		<30mph	Bucket-90% Pump-10%	10 gal/CY
	5	?		32-100°F Ambient 50-85°F Concrete			Bucket-80% Pump-5% Tr.shoot-15%	Approx. 10%
Bryan	90	50+		>35°F-Rising			Bucket-50% Pump-50%	Upto 10 gal
Childress	50	30		>35°F-Rising >85°F with RET(?)			Bucket-80% Pump-20%	5-10 gals
Corpus	60	50		50-85°F for placed concrete			Bucket-10% Pump-90%	10 gals
Dallas	85	50+		50-85°F for placed concrete			Bucket-20% Pump-75% Conveyor-5%	As required
El Paso	100(new)	30+		50-85°F for placed concrete		<40mph	Pump-98%	15-20 gal
Fort Worth	50	50		35-100°F ambient if concrete delivered between 50-85°F			Bucket-20% Pump-80%	As required upto w-c ratio & within slump
Houston	75	50		>35°F-Rising 50-85°F Placed Concrete	24-hr forecast >32°F		Bucket-30% Pump-70%	Yes, no specific limit
Laredo	50	Unknown	>25% Approx.	40-95°F	30°F	<15 mph	Bucket-98%	Yes, upto w-c ratio
	100	20	45-55%	<85°F			Bucket-10% Pump-90%	Yes, upto w-c ratio and within slump
Lubbock	Not allowed	30		>35°F	Under adverse conditions, other alternatives sought. (I.e. night concreting)		Bucket-70% Pump-30%	Plant inspector discretion
Lufkin	90	30					Bucket-80% Pump-20%	5-10%
Odessa	100	40-50		50-85°F, Summer-Night Concreting		<20mph	Bucket-40% Pump-60%	Yes - Varies
Paris	100	50		>35°F			Bucket-50% Pump-50%	10% max
Pharr	90	50		>50°F			Bucket-50% Pump-50%	Yes, 5-15 gal
San Angelo	100	30+					Bucket-50% Pump-50%	Yes, within slump, w-c limits
	100	50		>50°F for 72h >40°F for another 72 hrs		10 mph average	Bucket-20% Pump-80%	20 gals
	1	50	0-40%(?)	40-110°F	Max 60°F	<30 mph	Bucket-75% Chute-25%	40 gals (Depends) on Temp., Ice addition

Table C-2 TxDOT District Survey: General Bridge Construction Information

District	% Bridges w/Panels	Expected Service Life (yrs)	Ambient Weather Conditions @ Placing				Placement	Withhold Water & Add Later?
			Relative Humidity	Temperature	Temperature Differential	Wind Speed		
San Antonio	90+	30					Bucket-30% Pump-70%	2-3 gal/CY
Tyler	65	30+		45-90°F			Bucket-80% Pump-20%	Yes, 30 gal or less
Waco	98	50	>70%	>35°F & rising <100°F		<20 mph	Bucket-40% Pump-60%	10%
Wichita Falls	95	50		>35°F & rising			Bucket-75% Pump-25%	Not to exceed w-c ratio
Yoakum	90	50	Not Raining	>35°F & rising			Bucket-30% Pump-70%	10-15 gal/CY

Table C-3 TxDOT District Survey: Mix Design Information

District	Coarse Aggregate		Portland	Flyash Use in Mix		GGBF	IP or IS	Admixtures	Fibers
	Type	Grade	Cement Type(s)	Type F	Type C		Cement Used?	Used	
Abilene	SRG	2,3	II					RET,WRA	
Amarillo	SRG	3	II		<30%			RET,WRA HRWR,AEA CIA	
Atlanta	SRG	4	I II		20%		IP-10%	RET,WRA,AEA	
		3	I		20%				
Austin	SRG CLS	3,4	I-50% I/II-50%	25%	30%		12%	RET,WRA HRWR,AEA	
Beaumont	CLS-95% SRG-5%	2,3	I II	25%				RET,WRA HRWR,AEA	
Brownwood	CLS	3	I/II	25%				WRA,AEA	
	CLS	3	I/II	Limited	Limited			RET,AEA	
	SRG	Varies							
Bryan	SRG,CLS	3,4	I		20%			RET,WRA,AEA	
Childress	CLS,SRG	4	II		20-35%			RET,WRA,AEA	Fiberglass 50lbs/8yd3
Corpus	SRG	Varies	I/II	20%				RET,WRA,AEA	
Dallas	CLS	3,4	II-10% I/II-90%	20%			IP-20%	ACC,RET,WRA HRWR,AEA	
El Paso	CLS	3,4,5	I/II			33-50% (Most mixes)		RET,AEA	
Fort Worth	CLS	2,3,4,5	I/II					WRA,AEA	
Houston	SRG CLS	2,3,4	I-99% II-1%		20-30%			RET,WRA, HRWR,AEA	
Laredo	SRG(Cr) CLS	3	I		<20% in substructure			Yes	
	SRG (no CLS)		II	20-35%	20-35%			Yes	
Lubbock	CLS	2,3	II					RET,WRA,AEA	Polyprop. fiber used in 1 project
Lufkin	CLS	3	I						
Odessa	SRG	2,3	I/II	15%				WRA,AEA	
Paris	SRG,CLS	4	I/II,II		10-15%			RET,WRA,AEA	
Pharr	SRG	4	I-Deck III-Panels		25-30%			RET,AEA	
San Angelo	SRG(Cr)				None			RET,AEA	
	SRG	3	II		30%			RET,HRWR AEA	
	SRG	3	I/II						
San Antonio	CLS	3,4	I-50% I/II-50%	20-25%	20-25%			ACC,RET,AEA	
Tyler	CLS	4,5	I II					WRA,AEA	
Waco	SRG	3,4	I	20-25%				RET,WRA,AEA	
Wichita Falls	CLS	4	II	Yes				RET,WRA,AEA	
Yoakum	SRG CLS	2,3	I I/II	25%	25%				

Table C-4 TxDOT District Survey: Curing and Quality Control Information

District	Quality Control Parameter	Quality Control Value	Curing Compound Applied?	Curing Blanket Applied?	Wet Blanket Material	Alter Curing for Relative Humidity?	Alter Curing for Temperature	Alter Curing for Wind Speed
Abilene	7-d Flex	3930kPa 3620kPa	Before losing moisture	Shortly After Initial Set	Cotton Winter-with Plastic		Per Spec	Use More Water
Amarillo	28-d CS 7-d CS:JC	28MPa	0.5 hrs	2 hrs	Cotton			
Atlanta	28-d CS 7-d CS:JC	4000 psi >4000psi* (pred)	2 hrs	3-4 hrs	Cotton Covered with Poly			
	7-d Flex	570 psi	1-2 hrs (after tining)	Used dry as insulation for polyeth.		High RH delays tining/compound application	Maintain concrete above 40°F Heat if needed	
Austin	28-d CS 7-d Flex	4000 psi 570 psi	1-2 hrs	Concrete Set	Cotton		For fogging & spray curing	
Beaumont	28-d CS(5%) 7-d Flex(95%)	4000 psi 570 psi	1 hr	6-7 hrs	Cotton	No	No	No
Brownwood	28-d CS 7-d Flex	4000 psi 570 psi		1-2 hrs	Cotton	No	No	Add water as needed
	28-d CS 7-d Flex		1 hr	4+ hrs (When you can walk)	Cotton	No	No	No
	28-d CS 7-d Flex	If 7-d Flex fails	When no free moisture	When dry enough not to damage	Cotton	No	No	No
Bryan	28-d CS 7-d Flex		1-2 hrs	3 hrs	Cotton	No	Not needed in South Texas	No
Childress	28-d CS 7-d CS:JC	4000 psi 525 psi	0.5-1 hr	8-9 hrs	Cotton	No	No	No
Corpus	28-d CS 7-d Flex 4-d form removal	4000 psi 570 psi 425 psi	1 hr	5 hrs	Cotton	No	Contractor must keep concrete bet 50-85°F	Mats wetted more often
Dallas	28-d CS 7-d Flex Maturity	525psi(II)	After tining	Initial Set	Cotton	Fogging before compound/wet mat often	If <40° within 72h, use poly sheets under mat	Fogging, more frequent wetting
El Paso	7-d CS:JC 7-d Flex		.5 hrs	1-2 hrs	Cotton	No	No	No
Fort Worth	28-d CS 7-d CS:JC 7-d Flex	4000 psi 70% of CS 525 psi	<1 hr	1-3 hrs	Cotton Burlap	C-1 Chart	C-1 Chart	C-1 Chart
Houston	28-d CS 7-d CS:JC 7-d Flex	4000 psi 70% of CS 570 psi(3-pt)	1 hr	4-8 hrs	Cotton	No	Yes, at <40°F insulating dry mats+poly or heat	No specs, but closely monitored
Laredo	28-d CS* 7-d Flex	4000 psi 570 psi	Varies with weather	Varies with weather	Cotton (with poly over mat)	No		No specs, but closely monitored
	7-d Flex*	570 psi	1 hr	2 hrs	Cotton	No	No	No
Lubbock	28-d CS* 7-d Flex *-when flex fails	4000 psi 525 psi	After bleed water evaporated	strong enough to walk on	Cotton (over plastic sheet)	No	No	No
Lufkin	28-d CS 7-d Flex	As per specs	ASAP					
Odessa	28-d CS 7-d Flex		ASAP	Final set	Cotton (+ Plastic)	Fog at low RH		
Paris	28-d CS 7-d Flex	4000 psi 525 psi	ASAP	1-5 hrs.	Cotton(+plastic when <40°F)			
Pharr	28-d CS 7-d Flex	4000 psi 570 psi	0.5-1 hr	Apprx. 3 hrs	Cotton	No	No	No
San Angelo	28-d CS 7-d Flex	28 Mpa 3620 kPa	1 hr	3 hrs	Cotton	No Usually not a factor	No	No
	28-d CS 7-d CS:JC 7-d Flex		0.5-1.5 hrs	1.5-4 hrs	Cotton + plastic over cotton mat	No	>40°F:Poly/Mat <40°F:Mat/Poly	Spray compound earlier
	7-d Flex		1 hr	1 hr Depends on set time	Cotton	No	Poly used	Checked more often
San Antonio	7-d Flex	570(Ty I) 525(Ty I/II)	After broom/tine	After initial set	Cotton	Low RH-Fogging before compound	Poly sheet and incr. Curing time in cold weather	Low RH-Fogging before compound
Tyler	7-d Flex 4-d Flex	570(Ty I) 525(Ty I/II) form removal	3 hrs	6-8 hrs	Cotton	No	No	Yes - Fogging etc.

Table C-4 TxDOT District Survey: Curing and Quality Control Information

District	Quality Control Parameter	Quality Control Value	Curing Compound Applied?	Curing Blanket Applied?	Wet Blanket Material	Alter Curing for Relative Humidity?	Alter Curing for Temperature	Alter Curing for Wind Speed
Waco	7-d Flex		2 hrs	5-6 hrs	Cotton	No	No	Check mats twice daily
Wichita Falls	28-d CS 7-d CS:JC 7-d Flex	4000 psi 70-80% 28-d 570/525 psi	When no free moisture	1-2 hrs	Cotton	No	High Temp-frequent checking & wetting	High wind-frequent checking & wetting
Yoakum	7-d Flex	570 psi	~3 hrs No free moist	~5 hrs Foot traffic possible	Cotton	No	If cold, trap hydration heat	More fogging with increased speed

Table C-5 TxDOT District Survey: Curing and Loading Information

District	Age @ Limited Construction Traffic (days)	Age @ Full Traffic (days)	Early Loading Important?	Early Loading OK?	Time @ Curing Compound	Curing Duration
Abilene	21	28	Very Important	Yes	6 hrs	7 days
Amarillo	14	28	Not Important	NA	0.5 hrs	7 days
Atlanta	14	21	Not Important	NA		
	14	30	Somewhat			
Austin	14	21	Very Important	Yes	2 hrs	8 days
Beaumont	14	21	Not Important	Undecided		
Brownwood	14	28	Somewhat			
	14	28	Somewhat	NA		
	14	21	Not Important			
Bryan	14	21	Critical	NA		
Childress			Somewhat			
Corpus	14	21	Somewhat	No		
Dallas	10	12	Critical	Yes	Compound:2-3h Mat:4-5 h	10 days
El Paso	14	21	Not Impt to Critical: Project Dependent	Undecided		
Fort Worth	14	21	Somewhat	NA		
Houston	14	21	Critical	No	1 hr	8-d:Ty I 10-d: Ty II or Flyash
Laredo	As per spec	As per spec	Very Important	NA		
	7-28 days	28 days	Somewhat	No		
Lubbock	14	21	Somewhat	NA	1 hr	10 days
Lufkin	14	21				
Odessa	14	21	Not Important	NA		
Paris	14	21-28	Somewhat to Very Important			
Pharr	14	21	Somewhat	NA		
San Angelo	14	21	Somewhat	No		
	14	21 28 for full traffic	NA		0.5-1 hr	10 days
	28	28	NA			
San Antonio	14	21	Somewhat	Undecided		
Tyler	14	21	Somewhat			
Waco	10	14	Somewhat	Yes		
Wichita Falls	14	21	Somewhat	NA		
Yoakum	14	21	Somewhat	NA		

APPENDIX D

Selected TxDOT Standard Specifications Applicable to Concrete Bridge Decks

ITEM 420 CONCRETE STRUCTURES

420.11 Placing Concrete-General

... If conditions of wind, humidity, and temperature are such that concrete cannot be placed without cracking, concrete placement shall be done in the early morning or at night....

... Where work has been started and changes in weather conditions require protective measures, the contractor shall furnish adequate shelter to protect the concrete against damage from rainfall, or from freezing temperatures as outlined in Article 420.12....

420.11(1) Placing Temperature. The temperature of all concrete at the time of placement shall be not less than 50°F. The temperature of cast-in-place concrete in bridge slabs and top slabs of direct traffic structures shall not exceed 85°F when placed.

420.11(6) Slabs. ...Carting or wheeling concrete batches over completed slabs will not be permitted until the slabs have aged at least 4 full curing days. For the remainder of the curing period, timber planking will be required for carting of concrete....

420.12 Placing Concrete in Cold Weather. ....Concrete may be placed only when the atmospheric temperature is greater than 35°F. Concrete shall not be placed in contact with any material coated with frost or having a temperature less than 32°F...

(a) The temperature of all unformed surfaces of bridge decks and top slabs of direct traffic culverts shall be maintained at 50°F or above for a period of 72 hours from the time of placement and above 40°F for an additional 72 hours.

420.13. Placing Concrete in Hot Weather. Unless otherwise directed by the Engineer, when the temperature of the air is above 85°F, an approved retarding agent will be required in all concrete used in superstructures and top slabs of direct traffic culverts.

420.15. Placing Concrete in Superstructure. .... Unless otherwise shown on the plans, for transverse screeding, the minimum rate of concrete placement shall be 30 linear feet of bridge deck per hour.....

420.20. Curing Concrete. ...All concrete shall be cured for a period of four (4) curing days except as noted herein.

Table 2. Exceptions to 4-Day Curing

Description	**Type of Cement**	**Required Curing Days**
Upper surface of bridge slabs...	I or III	8
	II or I/II	10
	All types with fly ash	10

...When the air temperature is expected to drop below 40°F, the concrete shall be covered with polyethylene sheeting, burlap polyethylene blankets, mats or other acceptable materials to provide the protection...

A curing day is defined as a calendar day when the temperature, taken in the shade away from artificial heat, is above 50°F for at least 19 hours, or on colder days if satisfactory provisions are made to maintain the temperature of all surfaces of the concrete above 40°F for the entire 24 hours. The required curing period shall begin when all concrete therein has attained its initial set....

(a) Wet Mat Curing

....Wet mat curing will be required for Part A in Table 3 when the anticipated ambient temperature is expected to remain above 40°F for the first 72 hours of the curing period.

Polyethylene sheeting, burlap-polyethylene blankets, laminated mats or insulating curing mats placed in direct contact with the slab will be required when the air temperature is expected to drop below 40°F during the first 72 hours of the curing period. These curing materials shall be weighted down with dry mats to maintain direct contact with the concrete and to provide insulation against cold weather.....

Table 3. Curing Requirements

STRUCTURE UNIT DESCRIPTION	REQUIRED		PERMITTED	
	Water for Complete Curing	Membrane for Interim Curing	Water for Complete Curing	Membrane for Complete Curing
A. Upper surfaces of Bridge Roadway, Median and Sidewalk slabs, Top Slabs of Direct Traffic Culverts	X	X (Resin Base)		

.... Membrane curing shall not be applied to dry surfaces, but shall be applied just after free moisture has disappeared...

ITEM 421. PORTLAND CEMENT CONCRETE

421.2(1) Cement. ..Unless otherwise shown on the plans or in the specifications, the cement shall be either Type I, IP, II or III Portland cement except as follows:

a. Type III cement shall not be used when the anticipated air temperature for the succeeding 12 hours will exceed 60°F.

b. ...All cement used in a monolithic placement shall be of the same type.

Type I/II cement may be considered as either Type I or Type II cement except as otherwise noted.

Type IP cement may be used in lieu of Type I or Type II cement except when otherwise required by the plans or specifications. When Type IP cement is used, additional fly ash will not be permitted.

Table 4. Slump Requirements

Concrete Designation	Desired Slump (Inches)	Maximum Slump (Inches)
A. Structural Concrete (3) Slabs, Concrete Overlay...	3	4

421.9. Quality of Concrete. ....The cement content, maximum allowable water/cement ratio, the desired and maximum slump, the proper amount of entrained air and the strength requirement for all classes of concrete shall conform to the requirements of this specifications....

Table 5. Classes Of Concrete

Class of Concrete	Cement per CY Min (sacks)	Min. Comp. Sgth (f'c) 28 day psi	Min. Flex. Sgth. 7 day psi	Max. Water Cement Ratio Gal/sk	Coarse Aggr. Grade No.	General Usage (information only)
S	6.5	4000	570 525(c)	5.0	2-3-4-5	Bridge slab;....

(c) When Type II or Type I/II cement is used.