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Project Summary Report 0-4098-S
Project 0-4098: Use of Innovative Materials to Control Restrained Shrinkage Cracking in Concrete Bridge Decks
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October 2003

PROJECT SUMMARY REPORT

# Use of Innovative Materials to Control Restrained Shrinkage Cracking in Concrete Bridge Decks: A Summary

## Introduction

With the release of American Society of Civil Engineer's (ASCE) 2003 Progress Report, an update to the 2001 Report Card for America's Infrastructure in which the country's infrastructure received a grade of D+, it is obvious that the United States faces a growing epidemic of deteriorating infrastructure, and the problem is not getting any better. One of the weakest links in America's deteriorating infrastructure chain is its bridges, due mostly to the fact that bridges often traverse otherwise impassable routes and are, therefore, critical to the efficient flow of traffic and commerce. In fact, as of 2000, 27.5% of the nation's bridges (162,000) were structurally deficient or functionally obsolete (asce.org, 2003). Furthermore, according to a survey conducted in 1996 from respondents in several state departments of transportation, more than 100,000 bridge decks in the United States have suffered from early-age transverse cracking, a crack pattern that typically indicates the presence of drying shrinkage (Krauss and Rogalla, 1996). In fact, this project surveyed several transportation districts within Texas and determined that restrained shrinkage cracking was a concern. Additionally, two bridge decks in the Houston area suffering from cracking were surveyed as part of the project. Site visits were made and the bridge decks were determined to be suffering from drying shrinkage cracking.

The presence of early-age transverse cracking in concrete bridge decks is often what leads to the eventual structural deficiency of bridges in the long run because these cracks permit the ingress of harmful substances into concrete bridge decks. With the presence of cracks in concrete bridge decks, water, sulfates, chlorides, and other potentially corrosive agents are able to permeate to the interior of the bridge deck. These agents cause further deterioration in the form of even larger cracks, spalling, potholes, and eventually a loss of cross section of the bridge deck or reinforcing steel, which ultimately leads to an unsafe bridge. The repair of concrete bridge decks is often difficult and expensive because alternate routes are sometimes difficult or impossible to come by. It is thus better to prevent deterioration from starting in the first place; therefore, concrete must not be allowed to crack, especially at an early age.

## What We Did...

Since the economics of an efficient bridge structure require a high degree of restraint in the bridge decks, the most feasible way to prevent early-age transverse cracking is to approach the problem from the materials side. This means that the properties of concrete must be manipulated either through mixture proportion optimization (e.g. extensible concrete) or through the use of innovative materials (fibers, shrinkage-reducing admixture, etc.), which can be added to a concrete mixture to impart specific attributes, such as crack resistance. Understanding how effective these materials-based options are at mitigating drying shrinkage cracking forms the basis of the project.

An in-depth state-of-the-art literature review was performed by Michael Brown and Greg Sellers and is available in CTR report 4098-1 "Restrained Shrinkage Cracking of Concrete Bridge Decks: State-of-the-Art Review." It is recommended that the reader refer to this literature review to ensure a thorough understanding of the mechanisms of creep and shrinkage and the role they play in cracking of concrete. Enough information is presented here to ensure a basic understanding of the mechanisms involved in drying shrinkage cracking.

Thus, before attempting to modify the material properties of concrete, it is necessary to understand the basics of restrained shrinkage. Restrained shrinkage cracking occurs when concrete is prevented from making volumetric changes by a source of restraint, either internal or external. The sources of external restraint include friction between concrete and the superstructure as well as from shear studs needed to ensure composite action. Sources of internal restraint include reinforcing bars imbedded in the deck and aggregate within the concrete. In general, volumetric changes in concrete can result from creep, shrinkage of the concrete, or thermal loads. This project focuses on the volumetric changes imparted to the concrete by drying shrinkage and the role of creep in the mitigation of cracking; it does not address volumetric changes due to thermal loads.

The primary cause of both creep and drying shrinkage is the loss of adsorbed water, though the causes of the water loss for creep and drying shrinkage are radically different. For drying shrinkage, the driving force behind the water loss is the relative humidity, and for creep it is applied, sustained stress. Restrained shrinkage induces tensile stresses in concrete, while creep causes the concrete to flow in very small amounts and can serve to relax shrinkage stresses. Figure 1 illustrates the interplay between concrete tensile strength, tensile stress (from shrinkage), creep, and stress relaxation.

Certain properties of concrete will enhance its resistance to restrained

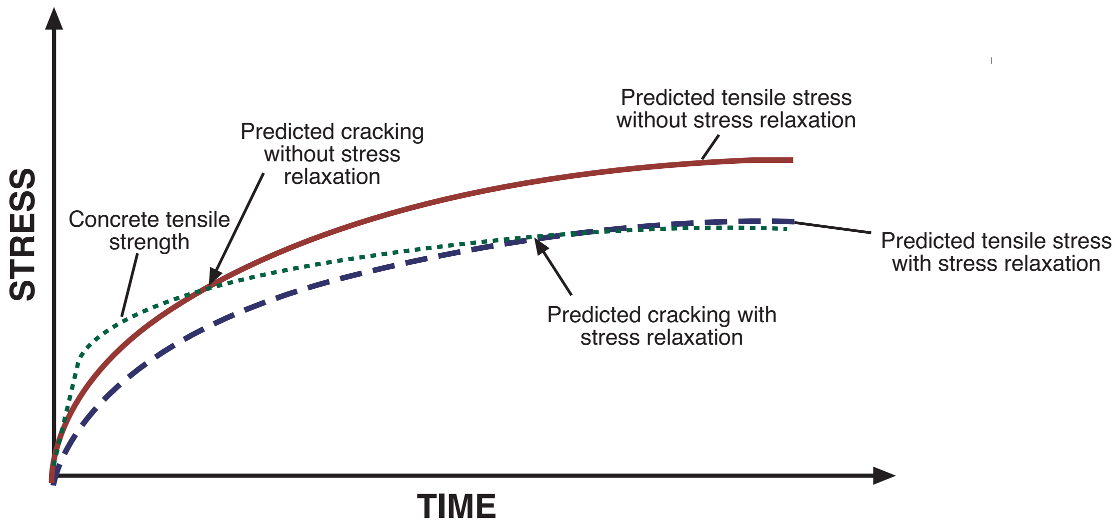


*Figure 1 - Time Dependence of Restrained Shrinkage on Creep (after Mehta and Monteiro 1993)*

shrinkage cracking. These properties will lower the probability that a mixture will crack due to drying shrinkage, but will not eliminate cracking caused by poor curing or construction techniques. Some of the most influential properties for mitigating restrained drying shrinkage cracking include:

- Low elastic modulus
- Low heat of hydration
- Low strength (low cement content)
- High creep
- High tensile strength and strain capacity

Whether these properties are obtained through the use of innovative materials such as shrinkage-reducing admixture (SRA), synthetic fibers, or shrinkage-compensating concrete, or through extensible concrete (High Volume Fly Ash), a mixture that makes use of these properties will help it resist restrained shrinkage cracking.

## What We Found...

### Laboratory Test Methods

Eight of the most promising candidate mixtures were selected from the literature review for further evaluation using various laboratory test methods. These laboratory methods, also derived from the literature review, are used to evaluate these innovative material-based mixtures to determine various properties related to shrinkage cracking.

The laboratory tests were divided up into two categories, fresh properties and hardened properties. Fresh property tests include AASHTO T 119 (Slump of Concrete), AASHTO T 152 (Air Content), ASTM C 138 (Unit Weight, Yield and Air Content), and ASTM C 1064 (Temperature of Fresh Concrete).

The hardened properties included AASHTO T 22 (Compressive Strength of Concrete), AASHTO T 198 (Splitting Tensile Strength of Concrete), ASTM C 469 (Modulus of Elasticity of Concrete), ASTM C 512 (Creep of Concrete in Compression), AASHTO T 160 (Drying Shrinkage of Concrete (Free Shrinkage)), AASHTO PP34-99 (Restrained Shrinkage Cracking of Concrete (Ring Method)), ASTM C 878 (Restrained Expansion of Shrinkage-Compensating Concrete), and AASHTO T 277 (Rapid Chloride Permeability).

Each of the eight mixtures derived from the literature review process was evaluated using these laboratory tests to determine the shrinkage cracking properties of the concrete. The results of these laboratory tests, presented in the comprehensive version of this report, enabled the researchers to select the most promising mixtures for further investigation in the form of large-scale bridge deck (LSBD) testing frames. The most promising mixtures were those mixtures that exhibited a relatively low free-shrinkage strain, high creep, a relatively low modulus of elasticity, and little or no restrained shrinkage cracking during the ring method test. A control mixture (TxDOT class S) and an HPC (High Performance Concrete) mixture were also included in the LSBD (even though they did not perform as well as the other innovative material-based mixtures) in order to permit comparison between the different portions of the project, especially between the laboratory testing and the LSBD testing.

### Large-Scale Bridge Decks

The LSBDs served as a more realistic test setup for determining the propensity for drying shrinkage cracking because of the nature of the test setup. The LSBD were designed to look and behave similarly to a real bridge deck, even though the span was only 20 feet and the width 10 feet. Typical reinforcement detailing, except for the lack of a top mat of shrinkage and thermal reinforcement, and precast concrete panels as stay-in-place formwork were utilized to ensure a close semblance with a typical concrete bridge deck.

The LSBD testing was divided into two phases. Phase I was the first phase and served as an opportunity to verify performance and behavioral expectations. Phase I consisted of two mixtures, an HPC and a mixture with a shrinkage reducing admixture (SRA). These two mixtures were selected so that a difference in the cracking behavior could be observed. In other words, it was expected and verified at the conclusion of the Phase I testing that the HPC mixture would crack due to its high cement content, while the SRA mixture would not, due to its reduction in free shrinkage. Concurrent with the pouring of the LSBD, several lab specimens from the Phase I mixtures were made. The laboratory specimens were evaluated using identical fresh and hardened laboratory tests explained earlier. Thus, the shrinkage properties from the laboratory tests of the Phase I specimens can be compared to the earlier laboratory tests on different mixtures and verified. Furthermore, the results of the laboratory tests on the Phase I specimens can also be correlated with the cracking behavior of the LSBD.

Phase I also served as a test of the LSBD itself. Based on the behavior of the two Phase I mixtures (HPC and SRA), it was determined that more end restraint was needed along with fewer shear studs in the middle region. Both these changes were incorporated into the Phase II LSBD to enhance the crack width so that it is easier to observe cracking in future LSBDs.

Once the ability to discern shrinkage cracking for the two mixtures was verified and improvements for crack width enhancement made, Phase II was initiated. Figure 2 shows the details of the LSBD set-up used in Phase II. This schematic illustrates two of the major changes made to the Phase I LSBD design, namely the removal of shear studs in the middle of the slabs and an increase in the amount of steel in the end regions. Phase II consisted of six more bridge decks, including a control, HPC, HVFA, SRA, fibers, and a shrinkage-compensating admixture. Laboratory specimens were again made to verify agreement between earlier laboratory testing and the current mixtures. The control and HPC LSBDs exhibited transverse drying shrinkage cracking at the middle of the bridge deck, as expected. The remaining mixtures (HVFA, SRA, fibers, and SCC) did not crack and therefore behaved successfully since they were able to adequately resist drying shrinkage cracking.

## The Researchers Recommend…

Due to the durability issues associated with early-age shrinkage cracking, it became necessary to investigate various solutions. The purpose of this project was to evaluate the use of various innovative materials in order to decrease the probability of new concrete bridge decks exhibiting early-age restrained drying shrinkage. A state-of-the-art literature review and a statewide cracking survey were performed in order to understand the current state of the art of concrete bridge deck cracking and what potential solutions, in terms of innovative materials used in concrete, exist for minimizing restrained drying shrinkage cracking. Also, from this literature review came several laboratory-based testing methods which are able to evaluate the drying shrinkage behavior of different mixtures. From the laboratory evaluation of various mixtures, eight mixtures were chosen to investigate further in a more realistic test setup in the form of large-scale bridge decks. The most promising mixtures, based on the results from the laboratory program and the LSBD, will be used in a full-scale, multi-span bridge deck implementation study.

Several observations were made during the course of the project which help in the formulation of recommendations to assess and minimize a mixture's propensity for restrained shrinkage cracking.

In the laboratory environment, free shrinkage of concrete (AASHTO T 160), restrained shrinkage (AASHTO PP34-99), and early-age strength properties, specifically compression (AASHTO T 22), tension (AASHTO T 198), and modulus of elasticity (ASTM C 469) testing, are highly recommended for determining the propensity for drying shrinkage cracking of concrete. An individual test by itself will not provide sufficient information as to whether a certain concrete mixture will have a high or low propensity for drying shrinkage cracking. However, the combination of results from all of these laboratory tests will enable one to determine the relative susceptibility to drying shrinkage cracking. An ideal drying shrinkage resistant mixture is one in which no restrained rings crack, there is a relatively low free shrinkage strain, and there exist extensible concrete strength properties such as a low initial modulus of elasticity value combined with low initial tensile and compressive strengths. Specific limits, such as how much free shrinkage is permissible or the highest modulus value possible, are difficult to prescribe due to the complexity of their interaction. Instead, the decision should be based on the overall outcome of the recommended tests.

Several candidate concrete mixtures, including those containing SRA, fibers, CSA, or HVFA, were found to be effective in reducing long-term shrinkage cracking. No mixture from these four mixtures is an obvious first choice for mitigating restrained drying shrinkage cracking since an in-depth look at the other variables, such as cost, handling and use issues, or the availability of materials, was not performed.

The next logical step after the large-scale bridge decks is to perform an implementation study in which each innovative material mixture is placed in a separate span of a multi-span bridge deck. An ideal candidate for a bridge deck would consist of a multi-span bridge deck that can be instrumented and monitored for the long-term. This would allow each of the innovative materials to be utilized and analyzed in a realistic environment. Thus, it is highly recommended that an implementation study be undertaken in which a multi-span concrete bridge deck is constructed using all eight laboratory mixtures in order to evaluate their resistance to drying shrinkage cracking under actual conditions.

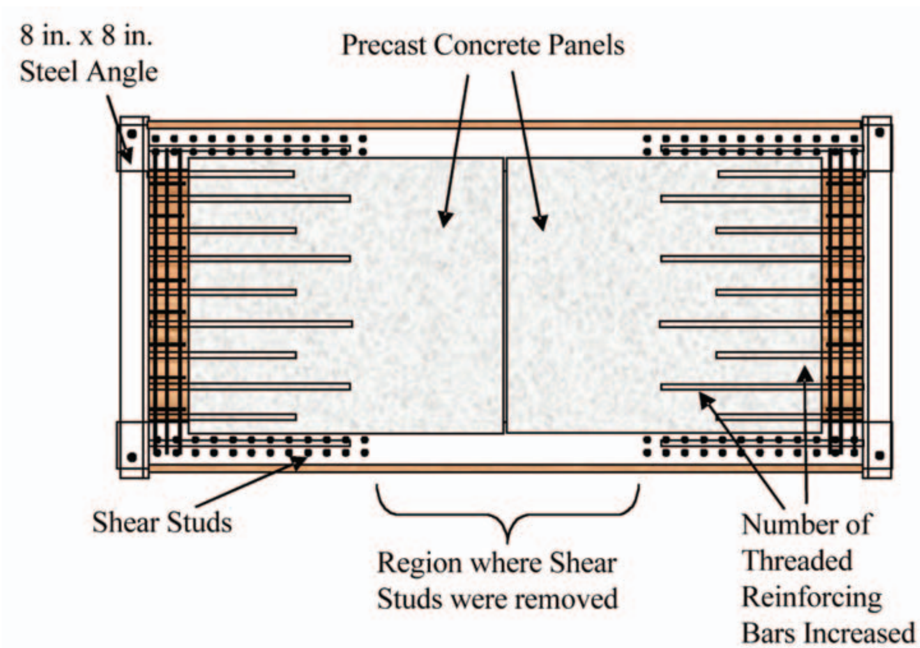


*Figure 2: Top view of Phase II LSBD before cast-in-place concrete (shows formwork)*

## For More Details...

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The research is documented in the following reports:

4098-1 *Restrained Shrinkage Cracking of Concrete Bridge Decks: State of the Art Review* June 2001
4098-4 *Use of Innovative Materials to Control Restrained Shrinkage Cracking in Concrete Bridge Decks* October 2003

To obtain copies of a report: CTR Library, Center for Transportation Research,
(512) 232-3138, email: ctrlib@uts.cc.utexas.edu

## TxDOT Implementation Status
## July 2004

Results from this investigation show there is no single laboratory test which can predict the propensity of a given concrete mix design for shrinkage cracking. Rather, the results from a battery of standard tests (free shrinkage, restrained shrinkage, compressive strength, tensile strength, and modulus of elasticity) must be evaluated to establish the relative shrinkage potential. The researchers have recommended follow-up work to evaluate various mixes in actual in-service bridge decks. This recommendation is being considered by TxDOT.

For more information, contact Tom Yarbrough, P.E., RTI Research Engineer, at (512) 465-7403 or email tyarbro@dot.state.tx.us.

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