NDOT Research Report

Report No. 530-14-803

Phase I: Minimization of Cracking in New Concrete Bridge Decks

May 2016

Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

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Cracking of newly constructed high-performance concrete (HPC) bridges is a problem recognized nationwide and the Nevada Department of Transportation has been plagued with this distress in their HPC concrete bridge decks. This research effort is a strategic attempt to reduce or eliminate random cracking that is caused by restrained shrinkage in new concrete bridge decks constructed in Nevada. The overall objective will be achieved through a three phase research program of which the results of Phase I are being reported in this document. Phase I research findings provide a synthesis of state, regional, and national practices and knowledge on factors contributing to HPC bridge deck cracking. With respect to materials and mixture proportioning, the overwhelming conclusion is that the shrinkage of the concrete mixture, especially at early-ages, must be reduced and the concrete's resistance to cracking must be Improved. A rigorous, Phase II laboratory experiment was designed and is presented herein. This Phase II laboratory experiment focuses on local materials and will assess the properties of concrete mixtures that are related to early-age drying shrinkage restraint cracking. Ultimately, these research findings could be used to revise standard specifications and special provisions for Nevada DOT bridge decks and eventually reduce the overall incidence of restraint cracking due to concrete drying shrinkage.</td></tr>
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FINAL REPORT

Phase I: Minimization of Cracking in New Concrete Bridge Decks

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Carson City, NV

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May 2016

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ABSTRACT

Cracking of newly constructed high-performance concrete (HPC) bridges is a problem recognized nationwide and the Nevada Department of Transportation has been plagued with this distress in their HPC concrete bridge decks. This research effort is a strategic attempt to reduce or eliminate random cracking that is caused by restrained shrinkage in new concrete bridge decks constructed in Nevada. The overall objective will be achieved through a three phase research program of which the results of Phase I are being reported in this document. Phase I research findings provide a synthesis of state, regional, and national practices and knowledge on factors contributing to HPC bridge deck cracking. With respect to materials and mixture proportioning, the overwhelming conclusion is that the shrinkage of the concrete mixture, especially at early-ages, must be reduced and the concrete's resistance to cracking must be Improved. A rigorous, Phase II laboratory experiment was designed and is presented herein. This Phase II laboratory experiment focuses on local materials and will assess the properties of concrete mixtures that are related to early-age drying shrinkage restraint cracking. Ultimately, these research findings could be used to revise standard specifications and special provisions for Nevada DOT bridge decks and eventually reduce the overall incidence of restraint cracking due to concrete drying shrinkage.

EXECUTIVE SUMMARY

Summary of Research Need

There is broad recognition that early-age cracking of HPC bridge decks continues to be a problem nationwide. The cracking is largely attributed to restraint, as many HPC mixtures suffer high drying shrinkage and poor resistance to cracking. To address this, there has been a movement toward adoption of concrete mixtures possessing adequate strength and reduced permeability, but are also less prone to shrinkage and cracking. Since adopting the use of HPC, the Nevada Department of Transportation (NDOT) has noted that random cracking continues to plague some newly constructed concrete bridge decks. These cracks require individual crack sealing and in cases of extreme cracking, treatment with polyester overlays, to seal the deck at great expense. National research efforts and findings provide valuable insights into the cause of cracking and potential solutions, but fall short of directly addressing NDOT's needs as they do not reflect Nevada's unique climatic conditions (most notably the low relative humidity), material sources, industry practices, and state of concrete technology.

The overall objective of mitigating early-age bridge deck cracking in Nevada will be achieved through a three phase research program; the results of the first phase, Phase I, being reported in this document. Phase I includes a synthesis of state, regional, and national knowledge and practice on factors contributing to early-age HPC bridge deck cracking, assessment of recently constructed bridges in Northern Nevada, interviews with local concrete technologists, and a Phase II research plan for conducting the next phase of the research program. Given the Phase I results, presented herein, NDOT has a better understanding of the issues causing cracking of HPC bridge decks and a Phase II laboratory research plan for the collection of test data and development of test methods for a Nevada solution.

Literature Review Findings

Early-age restraint cracking of concrete bridge decks is a widely reported problem, not only in Nevada and other states with similar arid climates, but throughout the United States. The cause of the problem can largely be separated into three general categories: 1) material and mixture design, 2) construction practices and ambient conditions, and 3) structural design factors. This study is focused on the first two categories and does not consider the third category.

With respect to materials and mixture design, the overwhelming conclusion is that the shrinkage of the concrete mixture, especially at early-ages, must be reduced while the concrete's resistance to cracking must be increased. Multiple strategies are available to reduce shrinkage, including reducing the volume of cementitious paste (accomplished by increasing the volume of aggregate through optimized aggregate grading), using prewetted lightweight aggregates (PLWA) to provide internal curing, and the use of shrinkage reducing admixtures (SRAs).

The current Nevada specifications have evolved over the last 15 years and are a step in the right direction, but are lacking in provisions that actually assess the characteristics of the concrete mixtures most closely linked to shrinkage and cracking tendency. The next step to improve current practice will be to execute a rigorous, well-designed laboratory experiment using local materials that assesses the properties of concrete mixtures that are related to early-age restraint cracking.

Field Evaluation of Existing Bridges

Seven bridges under NDOT jurisdiction were evaluated on the US 395/I-580 corridor in the greater Carson City, Nevada area. In addition to these NDOT bridge decks, three other recently constructed local bridge decks were visited in the Reno-Sparks area. The visual inspection results were evaluated in combination with mixture design records and construction history to develop a profile of each bridge in an attempt to identify key factors contributing to the observed performance.

Multiple factors contribute to concrete bridge deck cracking. Concrete mixture constituents and proportions impact the drying shrinkage potential of the concrete, which in turn induces stress due to restraint that may result in cracking. Unfortunately, the data available on the bridge decks evaluated is insufficient to draw any definitive conclusions regarding the relationship between mixture constituents and the occurrence of bridge deck cracking in recently constructed bridge decks in Northern Nevada. All of the decks observed are suffering some degree of cracking, with the exception of the recently cast deck on the Virginia Street Bridge in Reno. Cracking may develop in time, but it appears initially that the SRA resulted in a deck that is relatively crack free just after construction. This is an important observation given the fact that visible cracking on other bridge decks was reported during removal of the curing blankets.

Interview Summary

Experienced concrete technologists at two concrete materials laboratories located in the Reno area and two NDOT resident engineers (RE’s) were interviewed separately to ascertain their observations regarding bridge deck cracking in Northern Nevada. The interviews provided insights into the perception of those dealing locally with concrete bridge decks regarding causation of cracking and potential areas for improvement. The following summarizes major points made in these interviews:

- Bridge deck cracking continues to be a problem throughout Northern Nevada.
- Changes to curing practices have had little effect on the occurrence of the cracking, which appears very early on, even during the wet curing period.
- The major cause of cracking was attributed to poor stockpile management, particularly as reflected in non-uniformity in the moisture conditioning of the aggregates.

- Other aggregate issues were also cited, including poor aggregate-paste bond strength with aggregate dirtiness.

Phase II Laboratory Experimental Plan

Based on the results of the literature review, visual assessments of several recently constructed bridge decks, and interviews with individuals experienced in local bridge deck construction, a Phase II laboratory study has been developed to investigate material factors contributing to bridge deck cracking. In total, the Phase II laboratory evaluation will consist of the following five tasks:

- Task II-1: Selection of materials for use in the study.
- Task II-2: Testing of initial mixtures.
- Task II-3: Detailed testing of revised mixtures.
- Task II-4: Development of Phase III Research Plan.
- Task II-5: Phase II Report and approval of Phase III Research Plan

The Phase II laboratory plan will focus exclusively on mix design variables, such as aggregate type and gradation, rather than external construction variables such as curing and finishing practices. Many variables are considered for inclusion in the laboratory plan including investigating aggregates, cement, and supplemental cementitious materials specific to, and specified in, Nevada as well as using mixture design parameters common on Nevada DOT projects.

Following the identification of important variables, testing will be conducted to assess the primary factors under investigation, including shrinkage and strength, as well as other factors identified in previous projects as outlined in the literature review. The testing will identify the positive contribution of tactics engaged to reduce shrinkage as well as possible negative side to ensure that the concrete mixtures ultimately developed provide a broad-range of desirable attributes.

The proposed experimental approach consists of a partial factorial experimental design. If a full factorial design was carried out, it would include 1024 mixtures. This level of testing is not feasible within the time and resources available, nor is it necessary. Instead, an approach is suggested where 20 initial mixtures are made and subjected to limited testing and, based on the results of this testing, six revised mixtures will be selected for more detailed testing to complete the Phase II experimental plan.

It is hoped through the Phase II experimental plan proposed herein, relationships will be established between the simpler tests and more advanced tests that can be used for specification development in Phase III of this broader research study. Ultimately, these results could be used to revise standard specifications and special provisions for Nevada DOT bridge decks and eventually reduce the overall incidence of shrinkage cracking.

CHAPTER 1: RESEARCH APPROACH

1.1 Project Background

There is broad recognition that cracking of newly constructed high-performance concrete (HPC) bridge decks is a problem nationwide. The cracking is largely attributed to restraint, as many HPC mixtures suffer high drying shrinkage and poor resistance to cracking. To address this, there has been a movement toward adoption of concrete mixtures possessing adequate strength and reduced permeability, but are also less prone to shrinkage-induced cracking. With the use of HPC, Nevada Department of Transportation (NDOT) has noted that random cracking continues to plague some newly constructed concrete bridge decks. HPC is often characterized by relatively high cementitious contents (> 650 lbs/yd^3), one or more supplementary cementitious materials (SCMs), and water-to-cementitious ratios (*w/cm)* less than 0.40. The objective of the mixture proportions is to create high-strength, low-permeability concrete that will resist the ingress of chloride ions, thus delaying the onset of corrosion in the embedded steel.

Unfortunately, such concrete mixtures are often susceptible to early-age restraint cracking as they typically have high drying shrinkage potential and poor resistance to cracking. The problem is compounded as such mixtures also typically develop a dense, relatively impermeable microstructure soon after initial set, and thus even the use of wet curing can be ineffective in preventing shrinkage from occurring at an early age. The result is that new decks constructed with relatively impermeable concrete are compromised with multiple cracks that can provide a ready pathway for chloride ion ingress. These cracks require expensive and unsightly crack sealing, which is of unproven long-term effectiveness, or if the cracking is extreme, a polyester concrete overlay is placed over the entire deck at great expense.

A number of States have attempted to mitigate this type of cracking through implementation of lower strength, lower shrinkage concrete mixtures. Specific strategies to minimize shrinkage include reducing the cementitious content of the mixtures, using a moderate *w/cm* in the range of 0.40 to 0.45, and elimination of the use of ultra-fine supplementary cementitious materials (SCMs) such as silica fume. In some cases, less conventional means are being tried including prewetted lightweight aggregate (PLWA) for internal curing, shrinkage-reducing admixtures (SRAs), and even expansive cements. This national research is of value in understanding the problem, but falls short of directly addressing NDOT's needs as it does not reflect Nevada's distinctly different climatic conditions (most notably the low relative humidity), material sources, industry practice, and state of concrete technology.

1.2 Research Objective

This research is needed to reduce or eliminate random cracking in new concrete bridge decks constructed for NDOT. Recent experience has demonstrated that although improvements have been made over the last decade, bridge deck cracking remains a problem for NDOT, especially in the northern part of the state, because of Nevada's unique materials and climatic conditions. Considerable information exists to provide the basis for a solution, but only through a phased, rigorous research effort can the problem be solved. The overall objective will be achieved through a three phase research program of which the results of Phase I are being reported in this document. Phase I included a synthesis of state, regional, and national knowledge on factors contributing to HPC bridge deck cracking and developed a research plan for conducting the next phase of the research program. As a result of Phase I, NDOT has a better understanding of the issues causing cracking of HPC bridge decks and a research plan for conducting the next phase of the research including collection of test data and development of methods for a Nevada solution.

1.3 Research Methodology

The research methodology used in Phase I is summarized below.

<u>Task I-1: State-of-the-Practice Synthesis</u>

Task I-1 was conducted in the following three subtasks, conducted concurrently:

> Task I-1a – conducted a review of current NDOT specifications, special provisions, and practices including a full review of recently constructed concrete bridge deck projects. Specific information regarding HPC mixture proportions and construction practices were be reviewed and published information on bridge performance was gathered.
>
> Task I-1b – synthesized detailed information on regional practices with regards to the use of HPC for bridge decks. Specific information was reviewed from Arizona, California, Colorado, Idaho, New Mexico, Oregon, and Utah. The focus of this review was on hot, arid regions as this is more typical of conditions prevalent in Nevada.
>
> Task I-1c – reviewed national literature regarding HPC bridge deck cracking.

The execution of Task 1-1 resulted in a comprehensive synthesis of NDOT, regional, and national information regarding current practice and factors contributing to good performance of HPC bridge decks as presented in Chapter 2 of this report.

<u>Task I-2: Visual Assessment and Interviews</u>

Task I-2 involved visual assessment of a number of recently constructed bridge decks and interviews with select individuals representing industry and NDOT involved in the construction of HPC bridge decks. The visual assessment of the bridge decks revealed the type of cracking that was occurring and documented that it continues to be a problem even as NDOT specification had evolved over more than a decade. The results of the visual assessments are presented in Chapter 3 of this report. The interviews were conducted with commercial laboratory personnel who have a history of working on concrete bridge deck mixtures and select NDOT resident engineers with decades of field experience working on bridge decks. The purpose of the interviews was to garner firsthand knowledge that is not available in published sources from those that routinely work with HPC bridge decks in Northern Nevada. The results of these interviews are summarized in Chapter 4 of this report.

Task I-3: Development of Draft Phase II Research Plan

Task I-3 applied the findings of Tasks I-1 and drafted a Phase II Research Plan. Phase II is to be a laboratory study used to identify strategies and test methods suitable for implementation in Nevada to address materials components contributing to restrained shrinkage cracking of concrete bridge decks. It is envisioned that Phase II will have an18 month duration. The variables to be tested, test methods to be employed, and the testing matrix is described in Chapter 5 of this report.

Task I-4: Phase I Report and Phase II Research Plan

The last task in Phase I was Task I-4, which focused on the preparation of this Phase I Report. It includes the synthesis of information collected in Task I-1, the survey results collected in Task I-2, and the revised Phase II Research Plan based on NDOT's comments received in Task I-3.

CHAPTER 2: LITERATURE REVIEW

2.1 Recent NDOT Practice

2.1.1 NDOT's Bridge Deck Specification Circa 2001

In NDOT's *Standard Specifications for Road and Bridge Construction – 2001*, concrete used for bridge deck construction fell under Modified EA (also called Class EA – Modified), the properties of which are listed in Section 501, Table 1. The general characteristics of this concrete include cement contents between 611 and 752 lbs/yd^3, No. 57 stone for the coarse aggregate, and a maximum water-to-cementitious ratio (*w/cm*) of 0.44. In Subsection 501.02.03, it is stated that pozzolan conforming to Subsection 702.03.05 may be used to replace up to 17 percent, by mass, of the portland cement at a rate of 1.2 pounds of pozzolan for each pound of portland cement.

Subsection 501.03.09(c) discusses curing of concrete including concrete bridge decks, requiring that they be treated with a bridge deck curing compound conforming to Subsection 702.03.04. This subsection specifies an ASTM C309, Type 2, Class B white pigmented curing compound which shall be poly-alpha-methylstyrene (PAM). The curing compound is to be applied to the top surface of concrete bridge decks following the surface finishing operation and immediately after the moisture sheen begins to disappear from the surface, but before any drying shrinkage or craze cracks begin to appear. It is also specified that any damaged portions of the curing film must be repaired immediately with additional compound before the expiration of 7 days.

Subsection 646.04.06 in NDOT's *Standard Specifications for Road and Bridge Construction – 2001* addresses crack sealing of bridge decks. It is stated that the rate of application of a high-molecular weight methacrylate resin shall be approximately 0.09 gal/yd^2, and that the bridge deck surface is flooded with the resin allowing penetration into the concrete and filling of all cracks. This provision in the specification is a ready acknowledgement that concrete decks of this era were known to suffer cracking issues.

At around the time the NDOT's *Standard Specifications for Road and Bridge Construction – 2001* was being developed, a report on high performance concrete (HPC) was developed for NDOT by the University of Nevada-Reno (Wills and Sanders 2000). The objective of the study was to develop concrete performance specifications for Nevada, with a focus on bridge deck concrete in Northern Nevada. The study reviewed HPC requirements from FHWA as well as a number of States, and built a test program around noted parameters using local Northern Nevada materials. The materials investigated included two different portland cement sources, two Class F fly ashes at four replacement levels (0, 15, 20, and 25 percent by mass of total cementitious materials), one fine aggregate source, and three coarse aggregate sources. The maximum *w/cm* was set to 0.40 and the cementitious materials content to 700 lbs/yd^3.

In addition to standard strength testing on hardened concrete, the study examined shrinkage (using ASTM C157), permeability (using ASTM C1202), scaling resistance (ASTM C672), stiffness (ASTM C469), and alkali-silica reactivity (ASTM C1260 which is the same as AASHTO T 303).

The results of this study (Wills and Sanders 2000) varied. It is noted that although strength could often be obtained, permeability and shrinkage results were often poorer than desired. Further, most of the local sources of normal-weight aggregate were potentially alkali-silica reactive. It was concluded that the use of an effective pozzolan (such as a Class F fly ash) should be considered in Nevada's HPC mixtures as a way to both reduce permeability and increase resistance to alkali-silica reactivity (ASR). The report also recommended the adoption of a concrete mixture rating system, cited concerns regarding the high level of drying shrinkage measured in the mixtures tested, and stated that methods should be implemented to mitigate ASR.

2.1.2 NDOT's Bridge Deck Special Provisions 2001 to 2013

In recent years, *Special Provisions* have been used by NDOT in an attempt to address the limitations of the NDOT *Standard Specifications for Road and Bridge Construction – 2001* with regards to concrete bridge deck cracking, and potentially to implement some of the findings presented in the report by Wills and Sanders (2000). *Special Provisions* are issued on a project by project basis, and can be reviewed by downloading them from the NDOT's contracts website (NDOT 2016). Two recent *Special Provisions* were reviewed from the following contracts:

- Contract No. 3515 – US 395 from milepost 0.50 to 1.61 in Carson City.
- Contract No. 3530 – I-15 from milepost 29.55 to 31.36 in Clark County.

In the *Special Provisions* for the projects cited above, the properties of the Class EA – Modified concrete were changed from those present in the *Standard Specification for Road and Bridge Construction – 2001*. The new properties, listed in Section 501, Table 1, include a slight reduction in total cementitious content, allowing as little as 564 lbs/yd^3 at the low end of the range down from 611 lbs/yd^3, a reduced maximum *w/cm* of 0.40 down from 0.44, and the use of a three aggregates system consisting of a blend of two coarse aggregates and fine aggregate that considers the grading, workability factor, and coarseness factor, as outlined in ACI 302. The slight reduction in cementitious content and reduced *w/cm* would be expected to result in a reduction in drying shrinkage, assisted by the improved aggregate packing from the blending of the three aggregates (two coarse and one fine).

There are some other notable changes in the *Special Provisions* including the increased use of supplementary cementitious materials (SCMs), allowing the use of not only Class F fly ash, but also slag cement (minimum of 35 percent) and/or silica fume (3 percent to 7 percent). The *Special Provisions* require the use of Type II or Type V cement with a minimum of 20 percent pozzolan by mass in all concrete or alternatively a Type IP cement may be substituted. Class F fly ash may be used in conjunction with slag cement at a rate of 15 percent by mass of the total cementitious material. The maximum total SCM addition shall be 50 percent by mass of the total cementitious material. If silica fume is used, a trial slab must be constructed at least 30 days before construction is to be initiated to demonstrate the efficacy of the materials and construction methodology.

Another notable change in the *Special Provisions* was the addition of ASTM C469 elastic modulus testing and ASTM C1202 rapid chloride penetration testing to assess concrete mixtures. The two *Special Provisions* required a maximum ASTM C1202 test result of 2000 coulombs at 56 days for concrete used on bridge decks. This is not an exceptionally high number by National standards but is recognition that permeability is important.

Section 501.03.09 on curing was also modified in the *Special Provisions*, with the addition of the new Subsection 501.03.09(f) Bridge Deck Curing, which describes a bridge deck curing system employing pre-soaked burlap sheeting, soaker hoses, and polyethylene sheeting. Wet curing is to be initiated within 30 minutes of placement for a duration of ten days (or as specified) with 24 hour monitoring of its effectiveness. After completion of the wet curing period, the deck is to be sealed with a PAM curing compound.

Under the *Special Provisions*, cracks that occur in the bridge deck are to be repaired by epoxy injection from below, as specified, or by placing a multilayer polymer concrete overlay according to Section 496 of the *Standard Specifications*. For crack repair by epoxy injection, a two-component solventless, low viscosity, liquid adhesive epoxy specifically formulated for injection into cracks must be used. Epoxy shall conform to AASHTO M235 Type IV, Grade 1, 2, or 3, Class A, B, or C.

Overall, indications are that the use of NDOT's *Special Provisions* resulted in improved performance of their bridge decks. In NDOT's recent response to a survey conducted for NCHRP Synthesis 441 (Russell, 2013), it was stated that the improvement in deck performance is attributable to adoption of aggregate optimization (3-bins) and wet curing (10 day wet cure) practices. Yet the same survey recognizes that issues remain with regards to bridge deck cracking. The use of shrinkage reducing admixtures (SRAs) on concrete decks placed on steel girders was found not to be successful in reducing cracking, nor were evaporative retarders or curing compounds in any application.

Test methods used for acceptance of bridge deck concrete were cited as follows (Russell 2013):

- ASTM C1202, Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration.
- AASHTO T 303, Accelerated Detection of Potentially Deleterious Expansion of Mortar Bars Due to Alkali-Silica Reaction.
- ASTM C 469, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression.

The NDOT respondent to the NCHRP 441 survey also cited the use of California test methods for concrete creep (when required) and shrinkage, but no details were given on what CTM Test Number these would be. It is noted that creep was not cited in either of the *Special Provisions* reviewed above, and shrinkage testing (in accordance with ASTM C157) was only cited for use with Class S and SA concrete having over 752 lbs/yd^3 of cementitious materials.

Although the NDOT respondent to the NCHRP 441 survey indicated that improved concrete bridge deck performance has been realized through implementation of the changes contained in the *Special Provisions*, it is clear from Item #6 of the Agenda of the June 2, 2014 meeting of the *NDOT Board of Directors – Construction Working Group* that cracking of HPC bridge decks continues to be a problem (NDOT 2014A). As a result, it has been observed that there is an increase in the use of proprietary polymer concrete overlays in a number of recent bridge deck projects.

2.1.3 NDOT's Bridge Deck Specifications 2014

In 2014, NDOT revised their specifications, *Standard Specifications for Road and Bridge Design – 2014* (NDOT 2014B), incorporating many of the changes present in the *Special Provisions* for the concrete bridge deck mixture design and construction requirements to mitigate the development of bridge deck cracking. Among the primary changes, the Type EA concrete mixture design requirements were revised to be largely consistent with the recent *Special Provisions*. These are specified in Section 501, Table 1 of the *Standard Specifications for Road and Bridge Design – 2014* and in a *Special Provision Pull Sheet* that accompanies these specifications.

Table 2-1 compares the requirements specified in the new Table 1 to the old Table 1 in the *Standard Specifications for Road and Bridge Design – 2001*, it is observed that the minimum cement content has decreased from 611 lbs/yd^3 to 564 lbs/yd^3, the maximum allowable *w/cm* has dropped from 0.44 to 0.40, and the required amount of pozzolan has changed from a minimum of 17 percent to a minimum of 20 percent replacement, by mass of cement. Consistent with the *Special Provisions*, the new specifications require the use of a three aggregate blend (two coarse aggregates and one fine aggregate), setting specific requirements on the combined gradation. Also included is rapid chloride penetration testing (ASTM C1202), with a maximum allowable limit of 2000 Coulombs at 56 days.

With respect to construction practices, the *Standard Specifications for Road and Bridge Design – 2014* Subsection 702.03.04 requires 10 days of wet curing using a soaker hose, burlap and polyethylene sheeting. Following the wet curing period, a PAM-based curing compound liquid membrane forming curing compound is required.

Table 2-1. Concrete Properties for Class E and EA Modified, comparing NDOT's *Standard Specifications for Road and Bridge Design* from 2001 to 2014.

Concrete Property	**Year**	
	2001	**2014**
Cement Content	611 to 752 lbs/yd^3	564 to 752 lbs/yd^3
Grading Limits of Combined Aggregates	No. 57	¾ inch
Maximum *w/cm*	0.44	0.40
Slump Range	1 to 2.5 inches	½ to 4 inches
Entrained Air Range	5 to 7	4 to 7 (EA only)
Rapid Chloride Permeability	NA	2000 Coulombs @ 56 days

In addition, in the *Special Provision Pull Sheet* that accompanied the *Standard Specifications for Road and Bridge Design – 2014*, it is noted that if silica fume is used in the concrete, a trial slab must be conducted at least 30 days prior to placement of the deck to demonstrate construction proficiency and work cannot commence on actual placement until the Engineer is satisfied.

2.2 REGIONAL PRACTICES REGARDING CONCRETE FOR BRIDGE DECKS

To provide a basis for further improvement in mitigating bridge deck cracking in Nevada, regional practices were investigated for states with similar hot, arid climates. State practices investigated include those in use by Arizona, California, Colorado, Idaho, New Mexico, Oregon, and Utah as they have climates sufficiently close to that of Nevada. This review of regional practices includes current practices outlined in standard specifications as well as the results of DOT sponsored research projects.

2.3 Arizona Department of Transportation (ADOT)

In ADOT's *Bridge Design Guidelines* (2015), *Section 9: Decks and Deck Systems* discusses general design criteria including the need for a minimum 28-day concrete compressive strength of 4,500 psi, but nothing regarding concrete properties required to minimize cracking.

Section 1006 of the Arizona DOT *Standard Specifications for Road and Bridge Construction 2008* covers portland cement concrete, but no specific mixture design or proportioning is required for bridge decks. For Class S or E concrete (used for bridge structures), the required cementitious content lies between 520 and 752 lbs/yd^3 and the maximum *w/cm* is 0.55. Provisions are provided for up to 25 percent replacement of portland cement with fly ash or natural pozzolans, or up to 10 percent with silica fume. Additional SCMs can be added (not as a cement replacement) to address alkali-silica reactivity (ASR) and/or sulfate attack, with approval.

Section 1006-6.01(E) of the Arizona DOT *Standard Specifications for Road and Bridge Construction 2008* requires that bridge decks be cured by the liquid membrane forming curing compound method and the water curing method. The curing compound must be placed at a rate of one gallon per 100 square feet immediately following finishing operations and water curing is to be applied within 4 hours of deck construction.

No Arizona DOT research reports were found that specifically addressed concrete bridge deck cracking.

2.4 California Department of Transportation (Caltrans)

2.4.1 Caltrans Standard Specifications (2015)

The Caltrans *Standard Specifications* (2015) Section 51-1.02B – *Concrete,* sets the total cementitious content to be between 675 and 800 lbs/yd^3 for bridge deck slabs, with a minimum compressive strength of 3,600 psi at 28 days. Curing practices are provided under Section 51-1.03H – *Curing Concrete Structures,* which state that the top surface of the bridge deck must be cured using both the curing compound method and the water method. Maximum water content is set in Section 90-1.02G(6) – *Quantity of Water and Penetration or Slump* which states that the quantity of free water must not exceed 310 lbs/yd^3 of concrete plus 20 pounds for each required 100 pounds of cementitious materials in excess of 550 lbs/yd^3. Practically, this is a maximum *w/cm* of 0.45 to 0.50 for the range of cementitious materials specified for bridge decks. Yet it is generally known that Caltrans routinely used *w/cm* considerably lower than these allowable maximums.

Section 90 – *Concrete*, provides some additional guidance regarding bridge deck concrete. Section 90-1.02A – *General* provides shrinkage limitations for bridge deck concrete of 0.045 percent at 28 days drying when tested in accordance with AASHTO T 160, which is an unrestrained drying shrinkage test.

Section 51-1.01D(3)(b)(iv) – *Crack Intensity* provides a cracking criteria by which a new deck is judged. If any 500 ft^2 portion of the new deck has more than 50 feet of cracking having a width at any point in excess of 0.02 inch, the deck must be treated with methacrylate resin.

2.4.2 Caltrans Studies

Caltrans conducted an investigation into early-age cracking of concrete bridge decks. The study included an extensive literature review of Caltrans practice, practices used by other states, field investigations, and laboratory and modeling components to investigate the causes of cracking and identify potential solutions (Araiza et al. 2011).

Phase I: Minimization of Cracking in New Concrete Bridge

The field investigations included instrumenting two concrete box girder bridges constructed in California and monitoring the development of bridge deck cracking. The concrete mix designs for the two bridges varied by cementitious material content, coarse aggregate content, design compressive strength, and elastic modulus. During construction, both bridges were cured with an initial coat of liquid membrane forming curing compound followed by a wet cure with curing blankets. However, the time frame of these events varied between the bridges. Based on field observations, results from the experimental testing, numerical modeling, and the literature review, recommendations were made to minimize bridge deck cracking. Their primary recommendations include (Araiza et al. 2011):

- Eliminate the minimum cementitious content requirement to allow leaner mixes, while specifying a maximum cementitious content of 600 lbs/yd^3 and a maximum paste content of 27 percent by volume.
- Address plastic shrinkage cracking through the use of evaporation retarders and water fogging until wet curing media is installed, applying wet curing media as soon as practical (10 to 20 minutes after finishing), pre-moisten forms and reinforcing, and avoiding batching dry aggregates. It was felt that some of these items were already in the specifications and that Caltrans needs better enforcement in some cases.
- Consider initiating a study to evaluate whether rewetting the deck after 7 and 14 days of drying (after the initial wet curing) will recover some of the drying shrinkage and relax some of the irreversible drying shrinkage strain. Also, the optimum time to apply and remove insulation blankets should be investigated to minimize deck stresses and cracking.
- Specify immediate misting and wet curing (cotton mats or pre-wetted burlap) of finished concrete and prohibit the immediate use of membrane curing compound. Wet cure deck concrete for 14 days and afterwards apply two perpendicular coats of white pigmented membrane forming curing compound after wet curing is complete.
- Specify a minimum compressive strength for deck concrete of 3,600 psi (25 MPa) at 56 days, unless otherwise required and consider specifying a maximum compressive strength of 4,500 psi (31 MPa) at 7 or 14 days.
- Do not allow silica fume in deck concrete. Increase the wet curing period for concrete containing fly ash to a minimum of 21 days, when able. Allow ultra-fine fly ash, raw or calcined natural pozzolans, metakaolin, or slag cement in deck concrete only after testing for unrestrained shrinkage and cracking tendency is performed.
- Specify air entrainment of 6.0 to 8.0 percent for all bridge deck concrete regardless of exposure conditions.
- Limit plastic concrete temperature to no greater than 75 °F (24 °C) at the time of placement.

In addition to the primary recommendations listed above, this study provided the following secondary recommendations that are thought to be beneficial but less effective or important than the primary recommendations (Araiza et al. 2011):

- Specify the largest maximum aggregate size practicable, and in all cases use at least a 1 inch maximum aggregate size (No.57) gradation. Require that the Contractor provide results of an aggregate gradation optimization technique such as the modified coarseness factor chart (Shilstone), percent retained plot, the modified 0.45 Power chart or preferably the Kansas University software program *KU Mix* to optimize aggregate gradations. Paste content and shrinkage data should accompany this submittal.
- Require the Contractor to demonstrate that they can pump (if proposed), place, and cure the proposed mix adequately in a trial slab placement without cracking.
- Consider performing research on the use of PLWA to promote internal curing and reduce cracking risk.
- Lower the maximum free shrinkage limit for deck concrete to 0.040 percent at 28 days.
- Evaluate the use and cost effectiveness of shrinkage reducing admixtures (SRA) in deck concrete for priority projects, requiring increased quality control of air-void system properties on these projects. Consider a study to evaluate the effectiveness of SRA's in reducing deck cracking in several demonstration projects as well as the effectiveness of surface-applied SRA's.
- Shrinkage should be measured at the maximum admixture dosages that may be used with the actual admixtures to be used. Substitutions should not be allowed without shrinkage test data demonstrating no increase in free shrinkage.
- Specify and maintain the in-place concrete *w/cm* between 0.43 and 0.45.
- Do not allow concrete accelerators to be used in deck concrete. Test concrete retarders to ensure that they do not increase heat of hydration. Use immediate fogging and continuous moist curing if retarders are used.
- Consider requiring chemical admixture suppliers to submit independent test data for free shrinkage and modify approved admixture list as appropriate.
- Limit concrete to a maximum penetration of 2 inches (51 mm) and maximum slump of 4 inches (102 mm), except when mid- or high-range water reducers are used then specify a maximum penetration of 2 1/2 inches (64 mm).
- Provide adequate consolidation to the fresh concrete using thorough internal vibration and use the minimum diameter and amount of transverse reinforcement necessary to minimize settlement cracking.
- Continue to use current cement practices (ASTM C150 Type II or Type V and ASTM C595 blended cement, alkalinity limited to 0.60 percent). Do not allow substitutions of high-early strength (ASTM C150 Type III) cements or cements with greater than 0.60 percent alkalinity. If choices in cement are available, use cement with a tricalcium silicate content less than 45 percent and coarsely ground (less than 320 m^2/kg).

- Whenever possible and especially during hot weather, require deck placement to occur in late afternoon and evening, after 3 p.m.
- Hold pre- and post- pour meetings with the Contractor to discuss prevention of deck cracking and to obtain feedback. Include having the Contractor submit a cracking mitigation and curing plan and make the Contractor responsible for quality control of plastic concrete and perform quality assurance (QA) split sampling to avoid slowing concrete placement. Post-construction meetings should be held to gather and document opinions the bridge deck placement.
- Consider requiring deck mixes to be tested for restrained cracking tendency (ASTM C1581) in addition to free shrinkage (ASTM C157). Develop a database of the cracking tendency of the various mixtures.
- Prefer simply-supported bridges over continuous-span bridges. When continuous span bridges are designed, consider the negative moments caused in the girders above the supports and provide additional reinforcement to strengthen the section and control cracking. Use the minimum diameter and minimum amount of transverse reinforcement. Provide more closely spaced longitudinal reinforcement where applicable.

In an article published in Concrete International (Magenti et al. 2013), three Caltrans bridge engineers discuss the success they have experienced in using SRA's to cost effectively reduce concrete drying shrinkage below 0.030 percent in 28-day and effectively minimize cracking in new bridge decks. It was also suggested that the use of synthetic macrofibers might be effective in controlling cracking that does occur. This approach eliminates the need for expensive crack treatments, extending the life of bridge decks.

2.5 Colorado Department of Transportation (CDOT)

2.5.1 CDOT's Standard Specifications for Road and Bridge Construction – 2011

Section 600 of CDOT's *Standard Specifications for Road and Bridge Construction – 2011* outlines requirements for two concrete mixtures used for concrete bridge decks that will not receive a waterproofing membrane: Type H concrete and Type HT concrete (used only for the surface layer of the bridge decks). These two concrete mixtures must conform to the properties listed in Table 601-1 in the specification which specifies a minimum field compressive strength of 4,500 psi at 56 days, a cementitious materials content range between 580 and 640 lbs/yd^3, a range in total air content between 5 and 8 percent, and *a w/cm* between 0.38 and 0.42.

Class H concrete requires that an approved water-reducing admixture be used. Further, it requires that the mixture contains a minimum of 55 percent AASHTO M43 No. 67 coarse aggregate by weight of total aggregate, 450 to 500 lbs/yd^3 hydraulic cement, 90 to 125 lbs/yd^3 fly ash and 20 to 30 lbs/yd^3 silica fume. The required maximum permeability of this mix as measured by the rapid chloride penetration test (ASTM C1202) is 2000 coulombs at 56 days and no cracks should be exhibited before 15 days in the cracking tendency test (AASHTO T 334).

Class HT concrete has the same requirements as Class H concrete except it is required that a minimum of 50 percent AASHTO M 43 No. 7 or No. 8 coarse aggregate by weight of total aggregate should be used in lieu of the No. 67 coarse aggregate specified for Class H concrete.

Section 601.15 requires that a pre-placement conference be held prior to initial placement of the deck attended by representatives of the ready-mix producer and Contractor. Section 601.15(11)(b) requires that the Contractor construct a test slab at least seven days in advance of at least 4 yd^3 to verify the mix design, demonstrate the ability to perform placement, finishing, and curing operations, and to check quality control.

Section 601.15(11)(c) specifies that Class H and Class HT concrete shall be placed only when the concrete mix temperature is between 50 °F and 80 °F, and should not be placed when the air temperature exceeds 80 °F or the wind velocity exceeds 10 mph as determined by an on-site digital thermometer and anemometer, with the Engineer able to provide an exception if the data demonstrates that the evaporation rate is less than 0.20 $lbs/ft^2/hr$ based on figure 2.1.5 in ACI 305.

The curing of concrete bridge decks must conform to the specifications outlined in Section 601.16, which states a minimum curing period of 168 hours. From May 1 until September 30, the curing regime requires an initial application of a white-pigmented membrane-forming curing compound, followed by the water cure method. Decks placed between November 1 and March 31 must be cured using a white pigmented liquid membrane-forming curing compound, followed by a curing blanket method in lieu of the water cure method. Decks constructed in April or October can be cured in accordance with either method. Additional requirements are also made regarding the use of fogging.

2.5.2 CDOT Studies

The Colorado DOT published a report detailing the development of an optimized mix design to reduce bridge deck cracking (Xi and Xie 2001). Experimental mix designs were compared through laboratory testing with the independent variables being *w/cm* and cementitious materials content (both cement and fly ash were varied in quantity and type). Compressive strength, rapid chloride penetration (ASTM C1202), cracking tendency (at the time AASHTO PP34-98 but currently AASHTO T 334) and unrestrained drying shrinkage (ASTM C157) were tested for all mixes. Phase I of testing determined the mix designs with the lowest permeability by varying cement content, *w/cm*, and fly ash replacement percentage. The cement contents evaluated ranged from 450 to 515 lbs/yd^3, the fly ash replacement level varied between 20 and 25 percent, and the *w/cm* varied between 0.37 and 0.45. The *w/cm* was found to be proportional to the chloride penetration measured at 28 days.

The lower chloride penetration mixes were then tested in Phase II, with the examination of additional independent variables including aggregate gradation, fly ash type, and curing time. It was found that Class F fly ash both decreased the chloride penetration and increased cracking resistance to a greater degree than the addition of Class C fly ash. Additionally, chloride penetration was found to decrease with increasing coarse aggregate content and therefore both a larger maximum aggregate size and higher aggregate content were recommended for mix design. Finally, a wet curing time of less than 12 days was recommended, as curing times longer than 12 days were found to increase cracking during testing. Several of these testing findings were then incorporated into the state specification discussed previously.

2.6 Idaho Department of Transportation (IDOT)

2.6.1 Idaho DOT Standard Specifications of Highway Construction – 2012

Section 502, *Concrete*, of the Idaho DOT *Standard Specifications of Highway Construction – 2012*, addresses structural concrete. Concrete decks are made with Class 40AF or above where the numeric term (40 in this case) designates the 28 day compressive strength, the "A" means that the air content will be 6.5 ± 1.5 percent, and the "F" means that Class F fly ash will be used. In addition, Table 502.01.1 of the specification sets limits on minimum cement content that ranges from 560 to 660 lbs/yd^3 depending on the concrete Class, and sets a maximum *w/cm* of 0.44.

For construction requirements, Table 502.03-5 of the specifications states that formwork for bridge decks should remain in place a minimum of 10 days. Further, Section 502.03F specifies that bridge deck concrete should not be placed when the evaporation rate exceeds 0.15 lbs/ft^2/hour. A surface crack intensity assessment is conducted after curing, with the requirement that cracks must be filled with a methacrylate penetrating sealer if there are more than 50 feet of cracks having a width exceeding 1/8 inch in any location within a 60 yd^2 portion of the deck.

Curing of bridge decks is covered under Section 502.3J, which requires that the concrete surface be kept completely and continuously moist until a curing method is applied. Table 502.03-7 of the specification summarizes the curing methods applicable to bridge decks including a combination of Method A (water cure) or Method B (System 2 membrane-forming curing compound). Method A requires a single application of a membrane-forming curing compound (at 1 gal/150 ft^2) immediately after surface finishing and water curing is initiated once the concrete has set up sufficiently that it will not be damaged, but not later than four hours following the application of the curing compound. The wet cure will be maintained for at least 10 days. System 2 membrane-forming curing compound requires the use of an ASTM M 148, Type 2, Class B, white-pigmented curing compound.

2.6.2 Idaho Research Studies

The Idaho DOT participated in a research project during the construction of a bridge on US 95 over the Palouse River (Schmeckpeper and Lecoultre 2008). The bridge was heavily instrumented to monitor the progression of bridge deck cracking to better understand the phenomena. It was concluded that the shrinkage and the resultant cracking that occurred within 13 days of the deck placement occurred as a result of rapid cooling.

A major factor identified was the exceptionally high heat of hydration generated due to the high cement content of the concrete mixture. Additional transverse cracking, especially in the closure section of the bridge, occurred due to the continuous restraint provided at each edge of the pour which was placed against hardened concrete. From the results of the research, several recommendations to current practice were proposed including:

- Reduce the total cementitious content to 560 lbs/yd^3, 20 percent of which would be fly ash (context from report is a Class F fly ash) and use an air content greater than 6 percent.
- Set design compressive strength target of 1,200 psi over strength requirement at 28 days, allow 56 days to reach design strength, and limit the maximum compressive strength at 90 days.
- In terms of structural recommendations, vertical alignment of top and bottom should be staggered, and the skew limit should be less than 30°. These adjustments should help to minimize the additional stresses caused by excessive restraint.
- A minimum 7-day water method for curing.

2.7 New Mexico Department of Transportation (NMDOT)

The New Mexico DOT *Standard Specifications for Highway and Bridge Construction – 2014* specify class HPD concrete for bridge deck applications. This concrete is specified to have a minimum compressive strength of 4,000 psi at 28 days and a slump between 4.5 to 5.5 inches as shown in Table 509.2.8.1:1 of the specification. The aggregate gradation of HPD concrete mixtures must follow the Combined Gradation procedure as outlined in Section 509.2.8.3.1, which includes the calculation of a workability factor and coarseness factor in order to calculate the maximum aggregate size, and then the use of the 0.45 power chart to produce a target aggregate gradation. The minimum pozzolan content required is 20 percent by weight of cement. Additionally, a maximum drying shrinkage value of 0.05 percent is specified at 56 days of testing in accordance with ASTM C157. During construction, concrete must be placed in accordance with Section 512.3.7, such that bridge deck sections are generally less than 12 feet in any direction. Bridge decks must be cured in accordance with Section 511.3.10 as stipulated in Table 511.3.10:1 of the specification using a combination of liquid membrane forming curing compound, applied immediately after construction, followed by 7-days of water cure with saturated burlap and plastic sheeting.

2.8 Oregon Department of Transportation (ODOT)

2.8.1 Oregon DOT Standard Specifications for Construction - 2015

The Oregon DOT *Standard Specifications for Construction - 2015* specify several types of concrete in Table 02001-1 that are suitable for concrete deck applications including HPC. The specific concrete used for decks is identified on the plans, but will have required compressive strengths in excess of 4,000 psi and maximum *w/cm* of 0.40, unless the deck is to be constructed without entrained air. The maximum concrete temperature at time of placement for bridge decks is 80 °F.

One interesting concrete mixture component required in Section 02001.31(e) for all concrete bridge decks is the use of a superset extender to extend the initial set time by 90 minutes. Further, the nominal maximum aggregate size is ¾ inch or larger for bridge decks.

If a HPC deck is specified, it includes cementitious material with 66 percent portland cement, 30 percent Class F fly ash, and 4 percent silica fume. Cementitious materials with modifiers are proportioned in accordance with Section 02001.31(c) such that results from chloride penetration testing (AASHTO T 277), are less than 1,000 coulombs at 90 days. Allowable modifiers are described in Section 02001.31(c) and include between 12 to 18 percent fly ash, between 20 to 35 percent slag cement, and between 3 to 5 silica fume. Additional testing requirements for HPC mixtures are given in Section 02001.34 and include drying shrinkage testing (ASTM C157) although no acceptability limits are given for drying shrinkage.

Requirements for concrete bridge deck curing are given in Section 00540.51(b) and include the use of wind breaks for wind conditions that could increase the evaporation rate beyond 0.10 $lbs/ft^2/hr$ or when the evaporation rate exceeds the bleed rate as observed in the surface sheen during placement and finishing and the use of high pressure washers fitted with fog nozzles to maintain a high humidity above the concrete surface during deck placement. The concrete deck must be wet cured with either wet burlap or polypropylene fabric curing blankets covered with a polyethylene film for 14 days. Strict control on ambient temperatures during and following construction also exist.

Section 00540.54 describes the crack inspection and deck sealing process. All cracks must be sealed prior to opening to traffic.

Oregon DOT supported a study to investigate the effects of internal curing on bridge deck cracking (Ideker et al 2013). The testing concluded that PLWA reduced free shrinkage, especially when enhanced by including shrinkage reducing admixture (SRA) in the mixture design. However, of the single methods investigated, the use of an SRA alone was by far the most effective method for both reducing restrained shrinkage and increasing the time to cracking in the restrained shrinkage test. The most effective replacement amount for the pre-wetted FLWA was found to be 25 percent replacement, which decreased observed cracking. The final recommendations provided to the Oregon DOT including using both SRA and PLWA and externally wet curing all decks for at least 3 days.

A second research study investigated the potential for synthetic fibers to reduce cracking risk in HPC (Ideker and Banuelos 2014). Lab testing included strength (ASTM C39), free shrinkage testing (ASTM C157), restrained shrinkage testing (ASTM C1581), freeze/thaw testing (ASTM C672), and rapid chloride penetration testing (ASTM C1202). It was found that the inclusion of fibers reduced the free shrinkage and increased the time to cracking while also reducing crack widths. However, reducing the cement content lowered strength but did not reduce the free shrinkage. Additionally, they concluded that the use of limestone coarse aggregate reduced the risk of drying shrinkage and cracking likely due to the aggregate angularity.

2.9 Utah Department of Transportation (UDOT)

2.9.1 Utah DOT Standard Specifications – 2012

The Utah DOT *Standard Specifications – 2012* provide the requirements for portland cement concrete mixtures in Section 03055. Concrete class and mix design requirements are given in Subsection 2.1.A, Table 2. The requirements for concrete used for bridge decks (Class AA (EA)) has four mixes that vary by maximum aggregate size, which impacts the required minimum cementitious materials content and required total air content. The largest coarse aggregate size is 2 inches, which has a minimum cementitious materials content of 564 lbs/yd^3 and an air content range of 4.0 to 7.0 percent. The smallest coarse aggregate size is ¾ inch which requires a minimum cementitious materials content of 611 lbs/yd^3 and a range in air content of 5.0 to 7.5 percent. In all cases, the maximum allowable *w/cm* is 0.44, the maximum slump is 3.5 inches, and the minimum 28-day compressive strength is 4,000 psi, corresponding to a mix design 28-day compressive strength of 5,200 psi.

Section 03310, *Structural Concrete*, requires that high early strength Class AA(AE) concrete must also have a maximum drying shrinkage of 0.04 percent at 28 days in accordance with AASHTO T 160, although this is not specific to bridge decks.

Curing practices are outlined in Section 03390, Subsection 3.2, which specifies that for bridge decks, a membrane-forming curing compound must be applied at the manufacturer's recommended rate within 20 minutes after tining or finishing operations are complete while the concrete is still plastic. This is followed by the application of cotton or burlap mats which are kept continually damp for 14 days after placement.

2.9.2 UDOT Research Studies

The Utah DOT conducted a study of bridge deck cracking during the reconstruction of 71 concrete bridges on I-15 (Linford and Reaveley 2004). The reconstruction of these bridges were used as an opportunity to study factors (primarily structural) contributing to bridge deck cracking, and included the following variables:

- The inclusion of silica fume
- The use of precast concrete deck panels
- The spacing of steel girders with transverse post-tensioning
- The use of deep, long span spliced post-tensioned concrete girders.

Observations made during and following construction resulted in the following conclusions:

- Deck cracking was heavily influenced by the volume of concrete used in a single placement. Placements with extremely large widths or lengths accentuated the cracking tendency.
- All new bridges on I-15 showed full depth cracking attributed to the large volumes of deck concrete placed in a constrained environment. The report suggested that concrete placement should be done with consideration to moments caused by constraint and better placement strategies could result in lower stresses. For example, non-uniform placement of shear connectors and segmental placement of bridge deck concrete would be beneficial.
- Finally, the study concluded that while precast concrete decks also contained full depth cracking, all cracks occurred in predefined locations established during precasting. This was the primary benefit of using precast concrete decks.

2.10 Washington Department of Transportation (WSDOT)

The Washington State Department of Transportation (WSDOT) *Standards for Construction* recently underwent revisions in 2014. Many changes pertained to improving the performance and longevity of concrete bridge decks.

The changes implemented to the bridge deck specifications fell within three categories: Section 6-02.3(2)A- *Contractor Mix Design*, 6-02.3(10)D- *Concrete Placement, Finishing, and Texturing* (for bridge decks)) and 6-02.3(11)- *Curing Concrete*. Section 6-02.3(2)A was modified to remove the minimum cementitious content requirement, thus allowing for lower cementitious contents than before. Further, a requirement for minimum fly ash content was also eliminated. The maximum aggregate size was increased to 1-1/2 inch from 1 inch. The following testing requirements were also added:

- Freeze-thaw durability (AASHTO T 161) – 90 percent minimum durability factor after 300 cycles.
- Chloride penetration (AASHTO T 277) – less than 2000 coulombs at 56 days.
- Shrinkage (AASHTO T 160) – less than 0.032 percent at 28 days.
- Scaling (ASTM C672) – visual rating less than 2 after 50 cycles.
- Modulus of elasticity (ASTM C469) – Measured and submitted.
- Density (ASTM C138) – Measured and submitted.

Changes made to, 6-02.3(10)D- *Concrete Placement, Finishing, and Texturing* (for bridge decks) and 6-02.3(11)- *Curing Concrete* focused on initiating wet curing as soon as possible. In both the revised and updated specifications, the bridge decks are wet cured for 14 days with soaker hoses and presoaked burlap. However, the previous specification required texturing before the application of a curing compound and finishing with the addition of the presoaked burlap. In the revised specification, the bridge deck is textured after it has cured and hardened using a diamond-bladed saw rather than a tining rake dragged across the fresh concrete surface. The use of membrane-forming curing compound is prohibited. Instead fogging is applied immediately after placement prior to application of the wet curing.

Finally, the allowable temperature for bridge deck placement has been changed from a maximum placement temperature of 90°F to 75°F. The goal of this change was to reduce the peak temperature experienced by the slab which was found to create less restraint.

2.10.1 Washington DOT Research Studies

The impetus for Washington DOT adopting performance-related bridge deck specification was a research study conducted by Qiao, McLean, and Zhuang (2010). This study was specifically designed to mitigate early-age shrinkage cracking that was observed in many concrete bridge decks in Washington State which had resulted in decreased performance as it increased the effects of freeze-thaw damage, spalling, and corrosion of steel reinforcement. Shrinkage was identified as the major cause of this cracking, and experimental evaluation of multiple mixture designs concluded the following:

- The use of SRAs significantly reduced the free and restrained shrinkage.
- The partial replacement of portland cement with fly ash decreased concrete strength and increased cracking tendency.
- Paste volume plays an important role in the development of free shrinkage, and concrete mixtures with reduced paste volume have fewer tendencies for shrinkage cracking.
- Cracking tendency is related to both the tensile strength and free shrinkage of the concrete and concrete with acceptable strength and low shrinkage characteristics is expected to have relatively good cracking resistance.
- High-range water-reducing admixtures (HRWRAs) are effective at reducing water demand.
- The desired air content becomes more difficult to achieve in mixtures containing multiple chemical admixtures.
- Aggregates contribute broadly to the concrete properties, including shrinkage characteristics and cracking tendency.

Based on the experimental results, the following recommendations were made (Qiao, McLean, and Zhuang (2010) :

- The use of an SRA is recommended to mitigate early-age shrinkage cracking in concrete bridge decks
- The addition of fly ash is not recommended due to the potential effect of lowering early-age strength gain (note that ASR was not considered in this study).
- Reducing paste volume in concrete mixtures is recommended to increase the cracking resistance
- The largest practical size coarse aggregates should be used in construction.

- Trial batches are essential when several cementitious materials and chemical admixtures are used in the same concrete mix.

Based on the results of this study, the revised specifications were implemented in 2014. A follow up study was instituted to evaluate the performance of bridge decks constructed using the revised specification, comparing these decks to those constructed under the previous specification (Ferluga and Glassford 2015). A total of 28 bridge decks were inspected and evaluated; 15 of which were constructed with the performance-based specification and 13 constructed with the traditional prescriptive specification. These inspections revealed significantly less cracking of lower severity in the bridge decks constructed using the performance-based specification, strongly indicating that the changes in mixture design, placement, and curing practices outlined in the revised specifications were effective. Further, a review of construction cost found no indication that the cost of construction increased with the implementation of the performance-based specification. The general conclusion of this study is that bridge decks constructed under the new performance-based specification have much less early-age cracking than those constructed under WSDOT's traditional specification at no additional cost.

2.11 Summary of State Practices

The findings from the literature review of state agency specifications are summarized in Table 2-2 below for concrete mix design requirement and

Table 2-3 for testing requirements.

Table 2-2. Concrete bridge deck mixture design requirements by state.

State	**Maximum *w/cm***	**Cement Content (lbs/yd^3)**	**Aggregate Gradation**	**Shrinkage Testing (AASHTO T 160)**	**Chloride Permeability (ASTM C1202)**	**SCM Replacement**	**28-day Strength (psi)**
NV	0.40	564 to 752	Maximum ¾ inch		2,000 Coulombs @ 56 days		
AZ	0.55	520 to 752				25% fly ash or 10% silica fume	4,500
CA	0.45 to 0.50	675 to 800		0.045% at 28 days			3,600
CO	0.38 to 0.42	580 to 640	No. 7 or No. 8		2,000 Coulombs @ 56 days	90 to 125 lbs/yd^3 fly ash and 20 to 30 lbs/yd^3 silica fume	4,500 (56 days)
ID	0.44	560 to 660					
NM			0.45 power chart	0.05% at 56 days		20% pozzolan by weight	4,000
OR	0.40		Maximum ¾ inch		1,000 Coulombs @ 90 days	30% class F fly ash, 4% silica fume	4,000

UT	0.44	Minimum 564	¾ inch to 2 inch	0.04% at 28 days			4,000
WA			Maximum 1 inch		2,000 Coulombs @ 56 days		

Table 2-3. Concrete bridge deck construction requirements by state.

State	Water Cure	Curing Compound	Placement Temperature	Crack Width Testing
NV	10 days	PAM after wet curing	-	-
AZ	Within 4 hours of construction	1 gallon/100 ft^2	80 °F	-
CA	-	-	-	Treat cracks with methacrylate resin if there is more than 50 feet of cracking greater than 0.02 inch within a 500 ft^2 portion of the deck.
CO	5 to7 day after application of curing compound	1 gallon/100 ft^2	80 °F	
ID	Within 4 hours of construction and for 10 days	1 gal/150 ft^2	-	Cracks must be filled with sealer if more than 50 ft of cracking exceeding 1/8 inch within a 60 yd^2 portion of the deck.
NM	7 day after application of curing compound	Immediately after construction	-	-
OR	14 days	-	80 °F	-
UT	14 days	Within 20 minutes of tining	-	-
WA	14 days	Forbidden	75 °F	-

2.12 Review of Select National Literature Regarding HPC Bridge Deck Cracking

Cracking of newly constructed HPC bridges is not just a problem in the arid Southwest but is a pervasive problem nationwide. The cracking is largely attributed to concrete volume change and restraint, as many high-strength, low permeability bridge deck mixtures suffer high drying shrinkage and poor resistance to cracking. Further, the relatively high cement contents of these bridge deck mixtures not only contributes to drying shrinkage but can also result in high heat of hydration, generating high early-age thermal stress. To address this, there has been a movement toward the adoption of concrete mixtures possessing adequate strength and permeability, but are also less prone to shrinkage and thermally induced cracking. The key to successful implementation of this strategy is to not focus on concrete strength, permeability, shrinkage, and heat of hydration as separate issues, but instead consider the whole system together.

In the last decade, a number of studies have been conducted to more thoroughly identify the cause of the cracking and develop strategies to address it through changes in concrete mixture design and construction practices, including the use of some alternative cementitious systems.

Hadidi and Saadeghvaziri (2005) conducted an extensive literature review focused on transverse bridge deck cracking, reviewing the results of surveys, experimental work, and analytical studies that considered the effect of various factors on the development of early-age cracking. It was concluded that the causes of transverse concrete bridge deck cracking can be separated into three general categories: 1) material and mixture design, 2) construction practices and ambient conditions, and 3) structural design factors. The literature review stated that the first two items have been studied extensively over the past several decades, suggesting the importance of considering drying shrinkage in the concrete mixture design process.

Bentz et al. (2012) studied early-age bridge deck cracking in two Nevada bridges (Echo Wash and Valley of Fire bridges) and one in Wyoming (Snake River Bridge). The two Nevada bridges were constructed in 2009 and both exhibited considerable transverse cracking. In the investigation, materials similar to those used in the construction of the bridges were obtained and mortars prepared and evaluated for chemical shrinkage, autogenous shrinkage, and drying shrinkage. Cores were also obtained and analyzed to assess air contents, paste and aggregate volume fractions, and the overall nature of the concrete microstructure. In both cases, concrete batching data suggested that the concrete mixtures had been batched at a *w/cm* considerably lower than what was present in the approved concrete mixture proportions, reducing the *w/cm* from the as-submitted in design of 0.40 to a *w/cm* calculated from the batch tickets of 0.31 or 0.32 (Note: it is unclear how aggregate moisture was accounted for, if at all). Analysis of the concrete microstructure in extracted cores did not find the *w/cm* to be low, although there were signs of retempering and inhomogeneity suggesting water was added and the concrete re-mixed by the truck. The cracking of the Nevada bridge decks occurred following a dry period where average daily ambient relative humidity fell below 30 percent, greatly increasing the drying stresses and likely providing a final contribution to the observed cracking. Various materials-related factors were investigated as potential causes of the cracking including low *w/cm* and paste inhomogeneity, yet a singular definitive cause could not be found. Two strategies that were suggested to reduce the likelihood of cracking in future bridge decks were the use of a shrinkage-reducing admixtures (SRAs) and internal curing using PLWA.

NCHRP Synthesis 441 (Russell 2013) summarizes current HPC specifications and practices for bridges. The synthesis states that concrete bridge deck specifications have traditionally been prescriptive in nature, and although there has been some movement towards adoption of performance-related specifications, they largely remain prescriptive, with performance specifications appearing in Special Provisions for individual projects. Further, although improvements have been made, cracking remains a major concern for concrete bridge decks. The focus remains on reducing drying shrinkage through a combination of mixture design factors (e.g. avoiding high compressive strength mixtures, lowering the amount of total cementitious materials, reducing the amount of water added) and construction factors (e.g. application of wet curing, applying curing compound after wet curing), yet no single factor was identified to enhance concrete bridge deck performance.

Russell (2013) surveyed 31 state agencies about their procedures for both design and construction of concrete bridge decks, asking whether states had implemented their own strategies for minimizing deck cracking. The most commonly cited method of preventing bridge deck cracking was immediate wet curing, most typically lasting 7 days. Other cited strategies for mitigating bridge deck cracking included:

- Allowing only Type A or Type A/F admixtures to be used.
- Requiring at least 20 percent pozzolan replacement for cementitious material by mass.
- Requiring at least 55 percent coarse aggregate as a percentage of total aggregate.
- Specifying a minimum *w/cm*.
- Slump adjustments made only with admixtures.
- Requiring an on-site weather station to ensure ambient temperatures and climatic conditions are within specification range during casting.
- Requiring night time concrete placement.
- Utilizing internal curing (pre-wetted aggregates).
- Using polypropylene fibers.
- Limiting hand finishing.

Of the surveyed agencies, five stated that they conducted tests on hardened concrete in order to check the end product including permeability, surface resistivity, and chloride penetration resistance.

At the individual State level, a number have recently modified their bridge deck specifications in an attempt to address early-age cracking. In seminal work on this topic, Yuan (2011) documents the work conducted by the research team lead by David Darwin at the University of Kansas in developing a bridge deck concrete specification for the Kansas DOT having a low cracking tendency. Referred to as low-cracking, high-performance concrete (LC-HPC), this fundamental consideration expressed in this work is that not only is free drying shrinkage (e.g. ASTM C157) important, but restrained shrinkage (measured in the restrained shrinkage ring test described in ASTM C1581) should also be assessed. Further, an emphasis on strength alone often leads to increased cracking tendency. Various test methods were introduced as a way to create concrete bridge deck mixtures that are less prone to cracking.

Michigan DOT for has adopted Special Provision 12SP-604B-04 (2014) for their high-performance bridge deck concrete (Grade DM). It requires a minimum 28-day compressive strength of 4,500 psi, a total cementitious materials content between 517 to 658 lbs/yd^3, a maximum *w/cm* of 0.45, and an air content between 5.5 and 8.0 percent. Further, the use of an optimized aggregate gradation is often required. The Special Provision also calls for the use of 25 to 40 percent replacement of portland cement with slag cement and/or fly ash.

Chaunsali et al. (2013) describes the results of a recent effort in Illinois to mitigate cracking of concrete bridge decks while increasing durability. They considered the use of SRAs to reduce early-age cracking due to restrained drying shrinkage. Other experimental factors that were considered to influence the concrete's drying shrinkage were *w/cm*, aggregate stiffness, and the use of fly ash or silica fume. The effectiveness of SRA was assessed using the restrained cracking tendency test (ASTM C1581) which clearly showed a delay in time to cracking resulting from the addition of an SRA. In this study, the increase in SRA dosage reduced the drying shrinkage, but also resulted in a reduction of compressive strength.

Patnaik and Baah (2015) conducted a project for the Ohio Department of Transportation to investigate the effect of the inclusion of fibers on cracking as well as investigating the field behavior of continuous span structural (CSS) slab bridges. The bridge survey revealed extensive non-shrinkage cracking with cracks up to ten times the allowable maximum crack widths specified in ACI 224R-01 for bridge decks exposed to deicing chemicals. This indicated the rebar alone was insufficient to achieve the maximum crack limit requirement despite meeting all design requirements outlined in the specifications. Therefore, fibers were investigated as a supplementary material to help reduce this excessive cracking. Laboratory testing revealed that the addition of two types of fibers: polypropylene and basalt, significantly reduced crack widths and successfully redistributed the stresses. The specimens tested had smaller crack widths, higher cracking loads, higher ultimate failure loads, and large maximum mid-span deflections than the specimens without fibers.

D'Ambrosia, Slater, and Van Dam (2013) conducted a project for the Illinois State Toll Highway Authority to develop a performance-based specification to minimize the occurrence of cracking of concrete bridge decks. The approach taken was to holistically consider multiple concrete properties using performance testing, both during the mixture design process and during actual field construction. Multiple mitigation strategies were considered, with the focus not being on method but performance. Five mix designs were selected for detailed laboratory investigation including the standard Illinois bridge deck concrete mix as a control, three mixtures utilizing a single different cracking mitigation technique, and a final concrete mix design that incorporated all three crack mitigation techniques. The three selected cracking mitigation strategies were optimizing aggregate grading with reduced cementitious content, an SRA, and using prewetted FLWA. Laboratory testing compared the fresh properties (slump, air content, set time) and hardened properties (compressive strength, elastic modulus, rapid chloride penetrability, restrained cracking tendency, freeze-thaw durability, and drying shrinkage) of the five mixtures.

The laboratory testing revealed that the IDOT standard bridge IDOT concrete mix design had the least desirable hardened properties of all the mixtures tested with regards to cracking tendency and chloride penetrability (D'Ambrosia, Slater, and Van Dam 2013). The mixture made with SRA had the best shrinkage characteristics, but the compressive strength was the lowest, although still considerably higher than the specified 4,500 psi. The other mixtures all had improved behavior with respect to cracking tendency (based on ASTM C1581) over the IDOT standard bridge deck concrete mixture. Result from the unrestrained shrinkage test (ASTM C157) did not adequately rank the performance of these mixtures with regards to restrained cracking tendency demonstrating a limitation in this type of testing. Field testing of these mix designs corroborated these results. A *Special Provision* was written based on this work effective in October 2012 and since then dozens of bridge decks have been constructed with great success.

The Indiana Department of Transportation (INDOT) has investigated the use of PLWA to reduce early-age shrinkage cracking in high-performance concrete bridge decks (Di Bella et al. 2012.). By replacing a portion of the fine aggregate with an equal volume of the PLWA, a source of internal water becomes available as the concrete hydrates, reducing cracking tendency. Two bridge decks were constructed near Bloomington, IN, one with plain concrete and the other with a concrete made with PLWA. An experimental program was instituted that included the use of the dual restraining ring test (Schlitter et al., 2010) to assess the cracking tendencies of the two concrete. The dual ring test is similar to the standard restrained shrinkage ring test (ASTM C1581), but with benefits including restraining expansion that typically occurs in the standard restrained shrinkage ring test that is not typical of field conditions and the dual ring test can be an "active" test as the temperature can be varied to induce stress. In the work presented on the two bridge decks, the internally cured concrete showed superior shrinkage performance including reduced stress due to restrained shrinkage. Further, a visual inspection carried out one year after construction found that the bridge deck constructed with internal curing was free of cracking whereas two long cracks were present in the plain concrete bridge deck (Di Bella et al. 2012).

Another approach to addressing early-age bridge deck cracking due to restrained shrinkage is avoid the problem by using expansive cements. Chaunsali et al. (2013) describes the results of a recent effort in Illinois to mitigate cracking of concrete bridge decks, focusing on the use of expansive cements (Type K and Type G). Restrained expansion testing conducted in accordance with ASTM C878 demonstrated that concrete made with expansive cements, which counteract drying shrinkage through initial expansion, had minimal shrinkage at the end of 100 days. Specifically, they found that Type K and Type G cements could compensate for drying shrinkage at a 15 percent replacement level for Type K and a 6 percent addition of Type G cement based on shrinkage testing. Class F fly ash increased the expansion of Type K cement but silica fume decreased this expansion. Mock ups of full scale bridge decks were used in an attempt to determine the effectiveness of expansive cements under field conditions.

The Ohio Turnpike Commission began testing expansive ASTM C845 Type K cement in bridge decks as early as 1968 (Gruner and Plain 1993). In 1984, 50 bridges were replaced and of the three that were found without bridge deck cracking, one was the single bridge made with Type K cement. Further analysis of these 50 bridges identified three primary causes of bridge deck cracking: high cement content, low large aggregate content, and poor curing practices. The suggestion was made to incorporate more Type K cement into concrete bridge decks and more than 300 bridge decks were placed between 1985 and 1990 with Type K cement. As of 1993, no cracking was observed. A critical element in this success is that the use of Type K cement requires fogging during placement, timely placement (due to the increased slump loss as a function of time), and can be placed only when temperatures are below 80 °F (Gruner and Plain 1993).

The Michigan Department of Transportation conducted research on several methods of improving the lifespan of concrete bridge decks including the use of expansive Type K cement and comparing shallow versus deep concrete deck overlays (Staton 2000). Six bridge decks previously constructed with Type K cement were surveyed and found to be in good condition excepting transverse cracking near the beam-abutment interface which was attributed to the stress concentration created at that location. Ultimately, Type K cement was recommended only in the presence of internal reinforcing bars because cracking was found to be equivalent, if not worse, if Type K cement was used without internal reinforcement.

The Oklahoma Department of Transportation (OKDOT) commissioned a study to evaluate the use of optimized graded concrete to improve the workability of concrete that is to be pumped, such as is done commonly for bridge decks (Cook et al. 2015). Considerable laboratory work was done to support this effort, using a concrete pump in the laboratory to investigate flowability characteristics of various concrete mixtures. It was determined that if the aggregate is properly graded, a pumpable concrete mixture can be created for bridge applications having a total cementitious materials content of 564 lbs and a minimum slump of 4 inches. This study provided a proposed special provision for consideration by OKDOT, in which a modified “tarantula” curve (shown in figure 1) provides the recommend grading limits.

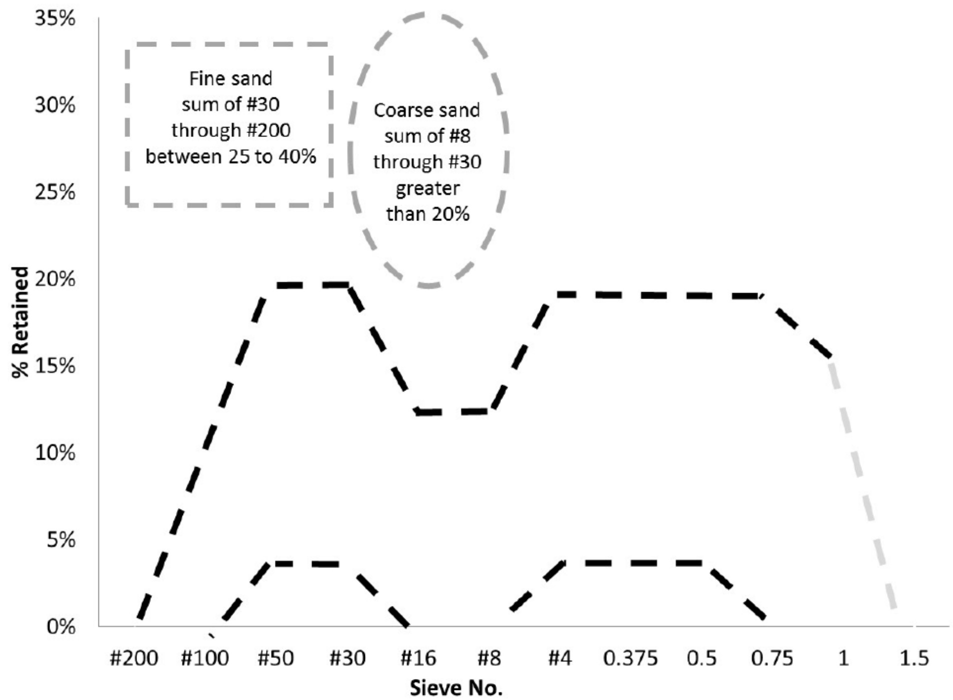


Figure 2-1. Recommended grading limits for bridge deck concrete that is pumped (Cook et al. 2015).

2.13 Summary

Early-age cracking of concrete bridge decks is a widely reported problem, not only in Nevada and other states with similar arid climates, but throughout the U.S. The cause of problem can largely be separated into three general categories: 1) material and mixture design, 2) construction practices and ambient conditions, and 3) structural design factors. This study is focused on the first two categories.

With respect to materials and mixture design, the overwhelming conclusion is that the shrinkage of the concrete mixture, especially at early-ages, must be reduced and its resistance to cracking must be increased. Multiple strategies to reduce shrinkage are available, including reducing the volume of cement paste (accomplished by increasing the volume of aggregate through optimized aggregate grading), using PLWA to provide a source of water for internal curing, and the use of SRAs (often found to be very effective although resulting in a decrease in compressive strength). Improved construction practices focus on close monitoring of ambient conditions (temperature and humidity) to reduce thermal stress and avoid highly evaporative conditions and the application of early wet curing that is maintained for a minimum of 7 days.

The current Nevada specifications are a step in the right direction, but there are no provisions that actually assess the characteristics of the concrete mixtures most closely linked to cracking tendency. A next step to improve current practice will be to execute a rigorous, well-designed laboratory experiment using local materials that assesses the properties of concrete mixtures that are related to early-age restraint cracking. This experiment is described in Chapter 5 of this report.

CHAPTER 3: FIELD EVALUATION OF EXISTING BRIDGES

To evaluate the performance of bridge decks constructed using recent and current NDOT specifications, seven bridges under NDOT jurisdiction on the US 395/I-580 corridor were visited in the greater Carson City, Nevada area. The visual inspection results were combined with mixture design records and construction history to develop a profile of each bridge in an attempt to link the mixture designs with observed performance. The seven bridges selected, including the location, mix design, contract number, and year constructed are summarized in Table 3-1. A map of the greater Carson City, Nevada area showing the location of the seven bridges is provided in Figure 3-1.

Table 3-1. Information for seven NDOT bridges investigated.

Bridge	Deck Mix Design	NDOT Contract	Location	Year Built
H-2298	586	2995	Northgate Lane	2001
I-2296			College Parkway	2001
H-2297			Emerson Drive	2001
I-2293	2897	3154	US-50/US-395 Interchange	2006
H-2288	7373HPC	3327	Fairview Avenue	2008
H-2287	1636 HPC	3400	Koontz Avenue	2010
H-2285	67MLF5T75	3516	Snyder Avenue	2014

3.1 NDOT BRIDGE PROJECTS

3.1.1 *Bridge H-2298: Northgate Lane, Bridge I-2296: College Parkway, and Bridge H-2297: Emerson Drive*

Three Nevada bridges bid in the same contract were constructed in accordance to the same special provisions and same mix design. NDOT Bridge H-2298 was placed in June 2001, Bridge I-2296 was placed in July 2001, and Bridge H-2297 was placed in September 2001. All three bridges are located on US-395/I-580 in Carson City, NV. Bridge H-2298 spans Northgate Lane, Bridge I-2296 spans College Parkway, and Bridge H-2297 spans Emerson Drive. These bridges carry relatively heavy traffic and the locations are given in Figure 3-1.

All three bridges were constructed under Contract 2995 using Mix Design 586. The bridge deck concrete was specified under Special Provisions as an EA Modified concrete. The aggregate blend combined one coarse aggregate and one fine aggregate, the gradations of which are given in Table 3-2.

Figure 3-1. Location of seven bridges investigated for bridge deck cracking (Google Maps).

Table 3-2. Aggregate gradation and properties for mix design 586.

Sieve Size	Coarse Aggregate	Fine Aggregate	Combined Aggregate
1.5"	100	100	100
1"	100	100	100
¾"	97	100	98
½"	53	100	75
3/8"	33	100	64
No. 4	3	98	47
No. 8	2	77	37
No. 16	0	56	26
No. 30	0	38	18
No. 50	0	20	9
No. 100	0	8	4
No. 200	0.7	2.1	1
SSD	2.23	2.59	-
Absorption	6.3%	3.1%	-
% of Total Aggregate	53.8	46.2	100

The sources and volume of each component in the standard mix design are given in Table 3-3. Admixtures used include a water-reducer and an air-entrainer, the dosages for each provided in Table 3-3. Additional concrete properties are provided in Table 3-4, including the water/cementitious materials ratio (*w/cm*), the slump, and the ASR expansion test results (based ASTM C1567). Additionally laboratory testing included compressive strength (ASTM C39). The results from this testing are given in Table 3-5.

Table 3-3. Concrete mix design properties for mix 586.

Component	Source and Type	Admixture Dosage (per/100 lbs cementitious)	SSD Weight/yd^3	Volume ft^3/yd^3
Coarse Aggregate, No. 57	All-Lite Pit	-	1400	10.061
Fine Aggregate	Bing Dayton Pit	-	1164	7.204
Cement	Calaveras Type I-II LA	-	564	2.869
Fly Ash	Class F, Bridger, WY	-	141	0.962
Water	-	-	265	4.247
Entrained Air	-	-	-	1.620
Water- Reducer	300 N	4.0 oz.	-	-
Air-Entrainer	AE-90	1.1 oz.	-	-

Table 3-4. Additional concrete properties for mix 586.

Additional Concrete Properties	
w/cm	0.38
Slump, in	2.5
ASR Expansion	0.05%
Air Content	6.0%
Paste Volume	30.0%

Table 3-5. Laboratory tested properties for mix 586.

Average Compressive Strengths	
Time	psi
3 day	3765
7 day	4900
14 day	5395
28 day	6255

The compressive strength far exceeded the 5,000 psi specified at 28 days in the Special Provisions. The cementitious materials content totaled 704 lbs/yd^3. The *w/cm* and slump fell within acceptable ranges specified in the Special Provisions. Further, the calculated paste volume of 30 percent is in excess of the 28 percent maximum paste volume recommended by Weiss (2015).

Figure 3-2 is a photo of the Bridge H-2298 bridge deck taken in June 2015 (14 years after construction). The bridge deck is exhibiting high density random cracking that is readily visible and is characteristic of restrained shrinkage. Similar cracking is observed in the Bridge I-2296 bridge deck, shown in Figure 3-3. The cracking in the center of the photo appears more severe and oriented over a skewed pier, but overall the density and randomness of cracking throughout the deck is again indicative of restrained shrinkage. A photo (Figure 3-4) of the last bridge deck constructed during this construction season, on Bridge H-2297, shows the same type of high density random cracking indicative of restrained shrinkage. This observations of these three decks, constructed using the same mixture design at different times during a single construction season, implies that the concrete mixture (mix design 586) was especially prone to restrained shrinkage cracking.

3.1.2 *Bridge I-2293: US-50*

Nevada DOT Bridge I-2293 is located on US-50, spanning US-395 in Carson City, NV, as shown in Figure 3-1. This bridge receives moderate traffic. The bridge was placed in March 2006 under contract 3154 using NDOT mix design 2897, specified under Special Provisions and designated as an NDOT E-modified concrete. Consistent with the Special Provision, the aggregate blend for this mix was combined from three different aggregate gradings (two coarse and one fine) as given in Table 3-6.

Figure 3-2. Bridge H-2298 bridge deck. Note high density random cracking throughout.

Figure 3-3. Bridge I-2296 bridge deck. Note the high density random cracking throughout, with some cracking oriented above underlying skewed pier.

Figure 3-4. Bridge H-2297 bridge deck. Note high density random cracking throughout.

Table 3-6. Aggregate gradation for mix design 2897.

Sieve Size	**Coarse Aggregate**		**Fine Aggregate**	**Combined Aggregate**
	No. 57	**No. 7 Stone**		
1.5”	100			
1”	100			100
¾”	85	100		94
½”	46	97		79
3/8”	29	55	100	64
No. 4	6	4	100	46
No. 8	1	2	85	37
No. 16	-	-	70	30
No. 30	-	-	51	22
No. 50	-	-	21	10
No. 100	-	-	6	3
No. 200	0.6	0.7	1.6	1.2
SSD	2.56	2.55	2.61	-
Absorption	5.9%	5.9%	2.7%	-
% of Total Aggregate	37.4	20.0	42.6	100

The sources and ratio of each component in the standard mix design are given in Table 3-7. Three admixtures were used in this mix design, including a water-reducer, an air-entrainer, and a hydration stabilizer, the dosages for each also given in Table 3-7. Additional relevant mixture properties are given in Table 3-8 including the *w/cm*, the slump, and the ASR expansion. Additionally, laboratory testing was completed for specific properties of the concrete over time, including elastic modulus (ASTM C469), the rapid chloride penetration test (ASTM C1202), compressive strength (ASTM C39), and unrestrained drying shrinkage (ASTM C157). The results from this testing are provided in Table 3-9. As can be seen, the total cementitious content totaled 685 lb/yd^3, the *w/cm* was 0.37, the slump was 6 inches, and ASR expansion was 0.06 percent; all values falling within acceptable ranges based on the project specifications

Table 3-7. Concrete mix design properties for mix design 2897.

Component	**Source and Type**	**Admixture (oz/100 lbs cementitious)**	**SSD Weight (lbs/yd^3)**	**Volume (ft^3/yd^3)**
Coarse Aggregate, No. 57	Canyon Creek Construction Moundhouse Pit	-	1047	6.554
Coarse Aggregate, No. 7		-	558	3.507
Fine Aggregate	Paiute Pit Deposit	-	1217	7.436
Cement	Nevada Type II	-	514	2.615
Fly Ash	ISG Class F from Bridger, WY	-	171	1.166
Water	-	-	250	4.006
Entrained Air	-	-	-	1.623
Water-Reducer	Grace Adva 170	8.00	-	0.093
Air-Entrainer	Grace Darex II	0.19	-	0.00
Hydration Stabilizer	Grace Recover	2.00	-	0.00

Table 3-8. Additional concrete properties for mix 2897.

Additional Concrete Properties	
w/cm	0.37
Slump, in	6
ASR Expansion	0.06%
Air Content	6.0%
Paste Volume	29.2%

Table 3-9. Laboratory determined hardened concrete properties for mix 2897.

Elastic Modulus		**RCP**		**Compressive Strengths**		**Shrinkage**	
Age	ksi	Age	coulombs	Age	psi	Age	%
28 day	4130	28 day	2900	3 day	2960	4 day	0.017
56 day	4460	56 day	1950	7 day	4280	7 day	0.025
-	-	84 day	1600	14 day	5170	14 day	0.036
-	-	-	-	28 day	6430	21 day	0.044
-	-	-	-	56 day	7665	28 day	0.053

From Table 3-9 it can be seen that the compressive strength far exceeded the 5,500 psi specified at 28 days and the rapid chloride penetration results at 56 days were very close to the 2000 Coulomb maximum specified in the NDOT special provisions. Although a shrinkage limit was not specified, the value of 0.044 percent at 21 days of drying exceeds the limit specified by the Illinois Tollway of 0.03 percent at 21 days drying. Further the calculated paste volume of 29.2 percent is in excess of the 28 percent maximum paste volume recommended by Weiss (2015).

Figure 3-5 is a photo of the bridge deck taken in June 2015 (after 9 years in service). Considerable random cracking is evident, likely due to restraint of shrinkage. This deck has subsequently been treated with a multi-lift overlay to effectively seal the cracks.

Figure 3-5. Bridge I-2293 bridge deck with visible cracking throughout.

3.1.3 *Bridge I-2288: Fairview*

Nevada DOT Bridge I-2288 is located at the interchange between US-395 and US-50 (Fairview Avenue) as shown in Figure 3-1. The bridge was placed in September 2008 under contract 3327 using NDOT mix design 7373HPC. This bridge deck was specified under Special Provisions as an EA modified concrete and a high performance concrete mix (HPC). The aggregate blend for this mix was combined from three different aggregates (two coarse and one fine) and the gradations are given in Table 3-10.

The sources and ratio of each component in the standard mix design are given in Table 3-11. Four admixtures were used in this mix design, including a water-reducer, an air-entrainer, a viscosity modifier, and a hydration stabilizer: the dosages for each are also given in Table 3-11. Additional properties are given in Table 3-12 including the *w/cm* and the slump. Additionally, laboratory testing was completed for elastic modulus (ASTM C649), rapid chloride penetration (ASTM C1202), and compressive strength (ASTM C39) over time. The results from this testing are given in Table 3-13.

Table 3-10. Aggregate gradation for mix design 7373HPC.

Sieve Size	**Coarse Aggregate**		**Fine Aggregate**	**Combined Aggregate**
	No. 67	**No. 8 Stone**		
1.5”	100			100
1”	100			100
¾”	100			100
½”	58	100		80
3/8”	30	100	100	66
No. 4	1	29	100	44
No. 8	1	4	94	39
No. 16	-	1	67	28
No. 30	-	1	40	17
No. 50	-	-	11	5
No. 100	-	-	3	2
No. 200	0.3	0.7	1.7	0.9
% of Total Aggregate	37.7	20.4	41.9	100

Table 3-11. Concrete mix design properties for mix 7373HPC.

Component	**Source and Type**	**Admixture (oz/100 lbs cementitious)**	**SSD Weight lbs/yd^3**	**Volume (ft^3)/yd^3**
Coarse Aggregate, No. 67	Moundhouse Pit	-	1030	6.550
Coarse Aggregate, No. 8		-	556	3.536
Fine Aggregate	Dayton Pit	-	1179	7.266
Cement	Nevada Type II	-	491	2.498
Fly Ash	Headwaters Class F, Bridger WY	-	136	0.928
Ultra Fine Fly Ash	Boral	-	57	0.361
Water	-	-	260	4.167
Entrained Air	-	-	-	1.620
Water-Reducer	BASF Poly 997	8.0	-	0.058
Air-Entrainer	BASF Micro Air	0.5	-	0.004
Hydration Stabilizer	BASF Delvo	2.0	-	0.015

Table 3-12. Additional concrete properties for mix 7373HPC.

Additional Concrete Properties	
w/cm	0.38
Slump, in	4
ASR Expansion	0.02%
Air Content	6.0%
Paste Volume	29.5%

Table 3-13. Laboratory tested properties for mix 7373HPC.

Elastic Modulus		**RCP**		**Compressive Strengths**	
Time	ksi	Time	Coulombs	Time	psi
28 day	3800	28 days	2270	3 day	2990
-	-	56 days	1840	7 day	4420
-	-	-	-	14 day	5090
-	-	-	-	28 day	6090

From Table 3-13, it can be seen that the 7-day compressive strength is close to the specified 4,500 psi @ 28 days design strength of the mix. The rapid chloride penetrability results were below the 2000 Coulomb maximum specified by the NDOT construction specifications at 56 days. The cementitious materials content totaled 684 lb/yd^3. The *w/cm* ratio, slump, and ASR expansion fell within acceptable ranges based on the Special Provisions. Further, the calculated paste volume of 29.5 percent is in excess of the 28 percent maximum paste volume recommended by Weiss (2015).

A photo of the bridge deck of the Bridge H-2288 bridge deck taken in April 2015 (7 years following construction) is shown in Figure 3-6. Moderate cracking is visible, some in a pattern of unknown origin, although restraint is a likely contributor.

Figure 3-6. Bridge H-2288 bridge deck with readily visible cracking throughout.

3.1.4 *Bridge H-2287: Koontz Avenue*

Nevada DOT Bridge H-2287 is on Koontz Avenue, spanning the future alignment of US-395 as seen in Figure 3-1. The traffic on this bridge is relatively light. It was placed in October 2010 under contract 3400 using NDOT mix design 1636 HPC under Special Provisions as an EA modified concrete and was a high performance concrete mix (HPC). The aggregate blend for this mix was combined from three different aggregates (two coarse and one fine), the gradations of which are given in Table 3-14.

Table 3-14. Aggregate gradation for mix design 1636 HPC.

Sieve Size	Coarse Aggregate		Fine Aggregate	Combined Aggregate
	No. 67	No. 8 stone		
1.5”	100			100
1”	100			100
¾”	91			96
½”	55	100		78
3/8”	34	100	100	68
No. 4	4	24	100	47
No. 8	1	2	86	37
No. 16	-	1	71	31
No. 30	-	-	52	23
No. 50	-	-	21	10
No. 100	-	-	6	3
No. 200	0.7	0.9	2.5	1.5
SSD	-	-	-	-
Absorption	-	-	-	-
% of Total Aggregate	48.6	8.6	42.8	100

The sources and ratio of each component in the standard mix design are given in Table 3-15. Four admixtures were used in this mix design, including a water-reducer, an air-entrainer, a viscosity modifier, and a hydration stabilizer. The dosages for each of these admixtures are also given in Table 3-15. Additional properties are given in Table 3-16 including the *w/cm* and the slump. Additionally, laboratory testing was completed for elastic modulus (ASTM C649), rapid chloride penetration (ASTM C1202), and compressive strength (ASTM C39). The results from this testing are given in

Table 3-17.

It can be seen that the 28-day compressive strength is close to the specified 5,000 psi 28 day design strength of the mix. The permeability was below the 2000 Coulomb maximum specified by the NDOT construction specifications. The cementitious materials content totaled 752 lb/yd^3. The *w/cm* ratio fell within acceptable ranges based on the Special Provisions. However, the slump was higher than the recommended maximum. Further, the calculated paste volume of 30.2 percent is in excess of the 28 percent maximum paste volume recommended by Weiss (2015). A photo of the bridge deck of bridge H-2287 taken in June 2015 (5 years following construction) is given in Figure 3-7. It can be seen that cracking is visible, although it is faint making the extent difficult to assess.

Table 3-15. Concrete mix design properties for mix 1636 HPC.

Component	**Source and Type**	**Admixture (oz/100 lbs cementitious)**	**SSD Weight lbs/yd^3**	**Volume (ft^3)/yd^3**
Coarse Aggregate, No. 67	Martin Marietta Spanish Springs pit	-	1410	8.400
Coarse Aggregate, No. 8		-	250	1.489
Fine Aggregate	Paiute pit	-	1201	7.374
Cement	Nevada Type II	-	602	3.063
Fly Ash	Nevada Type N	-	150	1.002
Water	-	-	255	4.087
Entrained Air	-	-	-	1.485
Water-Reducer	Grace Adva 190	8	-	0.063
Air-Entrainer	Grace Darex II	0.4	-	0.003
Viscosity Modifier	Grace VMAR 3	2.0	-	0.016
Hydration Stabilizer	Grace Recover	2.0	-	0.016

Table 3-16. Additional concrete properties for mix 1636 HPC.

Additional Concrete Properties	
w/cm	0.34
Slump, in	9
Air Content	5.5%

Paste Volume	30.2%

Table 3-17. Laboratory tested properties for mix 1636 HPC.

Elastic Modulus		RCP		Compressive Strengths	
Time	ksi	Time	Coulombs	Time	psi
28 days	3960	28 days	3150	3 days	2795
56 days	4345	56 days	1670	7 days	3760
-	-	-	-	14 days	4320
-	-	-	-	28 days	5200
-	-	-	-	56 days	6180

Figure 3-7. Bridge H-2287 bridge deck with faint cracking visible.

3.1.5 *Bridge H-2285: Snyder Avenue*

Nevada DOT Bridge H-2285 was placed in March 2014 on Snyder Avenue spanning the new alignment for US-395 as shown in Figure 3-1. It was constructed under contract 3516 using NDOT mix design 67MLF5T75 under Special Provisions as an EA modified concrete. The traffic on this bridge is relatively light. The aggregate blend for this mix was combined from three different aggregates (two coarse and one fine), the gradations of which are given in Table 3-18.

Table 3-18. Aggregate gradation for mix design 67MLF5T75.

Sieve Size	**Coarse Aggregate**		**Fine Aggregate**	**Combined Aggregate**
	No. 67	**No. 8 stone**		
1.5”	100	100	100	100
1”	100	100	100	100
¾”	100	92	100	96
½”	100	46	100	74
3/8”	99	28	100	65
No. 4	28	5	100	48
No. 8	2	2	88	39
No. 16	1	1	58	26
No. 30	1	1	34	15
No. 50	1	1	15	7
No. 100	1	1	5	3
No. 200	0.9	0.7	2.9	1.7
% of Total Aggregate	48.2	8.6	43.2	100

The sources and ratio of each component in the standard mix design are given in Table 3-19. Four admixtures were used in this mix design, including a water-reducer, an air-entrainer, a viscosity modifier, and a hydration stabilizer. The dosages for each of these admixtures are also given in Table 3-19. Additional properties are given in Table 3-20 including the *w/cm* and the slump. Additionally, laboratory testing was completed for elastic modulus (ASTM C649), rapid chloride penetration (ASTM C1202), and compressive strength (ASTM C39) over time. The results from this testing are given in Table 3-21.

It can be seen that the compressive strength at 14 days well exceeded the 5,000 psi 28 day design strength of the mix. The total cementitious content totaled 705 lb/yd^3. The *w/cm* and slump fell within acceptable ranges based on the Special Provisions.

Figure 3-8 is a photo of the Bridge H-2285 bridge deck taken in June 2015 (1 year after construction). It can be seen that despite just being constructed one year ago, cracking is readily visible on the surface, likely due to restraint.

Table 3-19. Concrete mix design properties for mix 67MLF5T75.

Component	Source and Type	Admixture (oz/100 lbs cementitious)	SSD Weight lbs/yd^3	Volume (ft^3)/yd^3
Coarse Aggregate, No. 67	Martin Marietta Spanish Springs pit	-	1400	8.340
Coarse Aggregate, No. 8		-	250	1.495
Fine Aggregate	Western Nevada Materials Concrete Sand	-	1204	7.467
Cement	Lehigh Type I/II	-	529	2.691
Fly Ash	Headwaters Class F fly ash	-	176	1.237
Water	-	-	261	4.183
Entrained Air	-	-	-	1.491
Water-Reducer	BASF Glenium 7500	8.0	-	0.056
Air-Entrainer	BASF Micro-Air	0.5	-	-
Viscosity Modifier	BASF VMA 362	3.0	-	0.021
Hydration Stabilizer	BASF Delvo	3.0	-	0.021

Table 3-20. Additional concrete properties for mix 67MLF5T75.

Additional Concrete Properties	
w/cm	0.37
Slump, in	6
Air Content	5.5%
Paste Volume	30.0%

Table 3-21. Laboratory tested properties for mix 67MLF5T75.

Elastic Modulus		**RCP**		**Compressive Strengths**	
Time	**ksi**	**Time**	**Coulombs**	**Time**	**psi**
28 day	4200	28 days	2283	3 day	3705
-	-	-	-	7 day	4840
-	-	-	-	14 day	5945
-	-	--	-	28 day	6550

Figure 3-8. Bridge deck of bridge H-2285 with some visible cracking.

3.2 Other Bridge Decks

In addition to the NDOT bridge decks, three other recently constructed local bridge decks were visited in the Reno-Sparks area. Two of the decks are part of the recently constructed SE Connector, extending Sparks Boulevard south of Greg Street in Sparks (see Figure 3-9). These are not yet opened to the public, but the eastern most bridge is open to construction traffic. The third bridge that was visited is the new Virginia Street bridge over the Truckee River in downtown Reno.

Figure 3-9. Location of new SE Connector bridges over the Truckee River in Sparks.

3.2.1 SE Connector Bridges

A visual assessment was conducted on the two bridges crossing the Truckee River as part of the SE Connector, extending Sparks Avenue to the south of Greg Street. The two bridges are side by side, but separate. The bridge lying to the east is currently carrying construction traffic whereas the one to the west has been un-trafficked since construction, nearly two years ago. Visual inspection of the two SE Connector bridges reveals very similar conditions. Fine random cracking is readily visible on both decks. Figure 3-10 shows a view looking down the deck where the cracks are barely visible, but the close up in Figure 3-11 clearly reveals the presence of cracking. At times the cracking appears to be oriented with what is likely transverse steel, but at other times it is random in nature. Similar cracking is visible on the western deck, as seen in the close up in Figure 3-12.

Although these are not NDOT bridge decks, they were constructed under the NDOT Special Provisions. No mixture design or testing data is available at this time.

Figure 3-10. View looking south on eastern deck of SE Connector with visible cracking that is difficult to see.

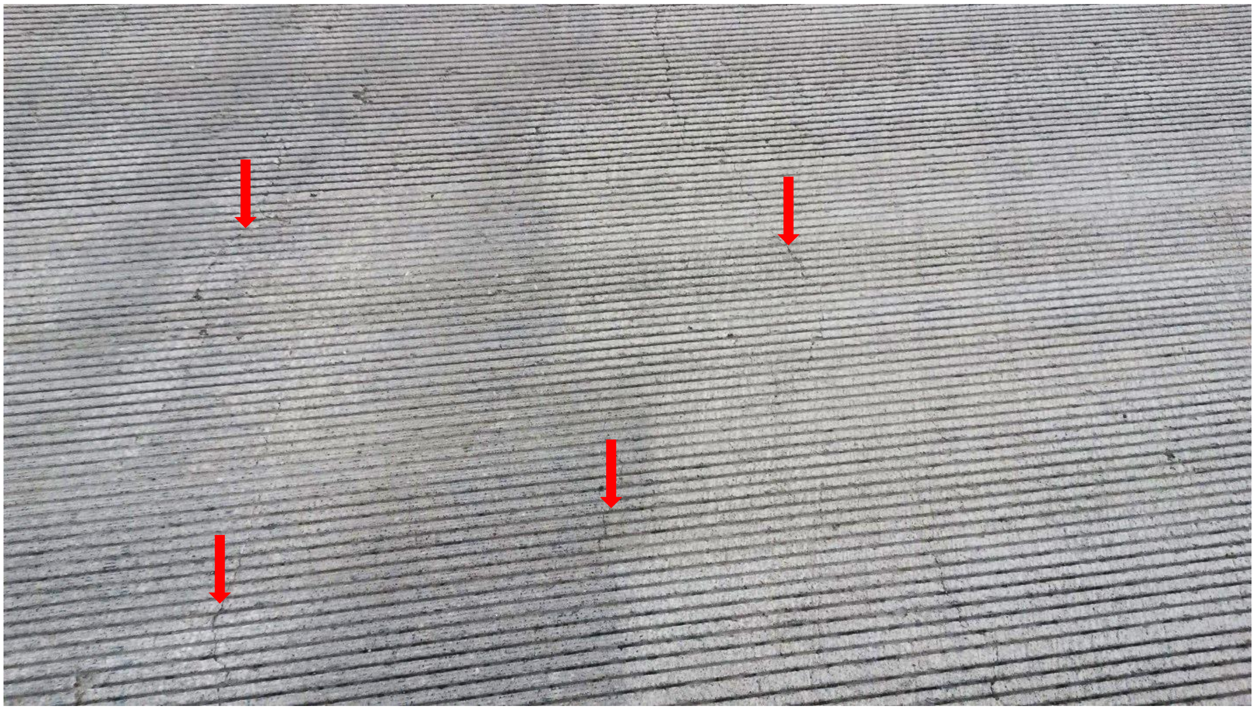


Figure 3-11. Close up of eastern deck of SE Connector with visible cracking.

Figure 3-12. Close-up of cracking on eastern deck showing fine cracks.

3.2.2 Virginia Street Bridge

The new Virginia Street Bridge deck was placed in January 2016. The deck is approximately 166 feet long by 90 feet wide, and includes two traffic lanes and sidewalks on each side. The bridge deck concrete is listed as a 4500 psi, 0.40 *w/cm*, air-entrained with fly ash, and a shrinkage reducing admixture (Mix Design No. 1428SRA). The aggregate blend for this mix was combined from four different aggregates (two coarse and two fine), the gradations of which are given in

Table 3-22. The sources and ratio of each component in the standard mix design are given in Table 3-23. Four admixtures were used in this mix design, including a mid-range water-reducer, an air-entrainer, a high-range water-reducer, and a shrinkage reducing admixture. The dosages for each of these admixtures are also given in Table 3-23. Additional properties are given in Table 3-24 including the *w/cm* and the slump.

Figure 3-13 and Figure 3-14 provide images of the Virginia Street Bridge taken in February 2016 (approximately 2 weeks after construction). It can be seen in Figure 3-13 that no cracks are visible on the main deck. Figure 3-14 shows two cracks that appear on the eastern sidewalk. These cracks seem to be associated with the layout of the sidewalk at this location. Although this deck is very young, most have reported cracking on other decks being visible as the curing blankets were being removed. If this deck remains relatively crack free, it speaks well of the efficacy of a shrinkage reducing admixture to mitigate bridge deck cracking.

Table 3-22. Aggregate gradation for mix design 1428SRA.

Sieve Size	Coarse Aggregate		Fine Aggregate #1	Fine Aggregate #2	Combined Aggregate
	No. 67	No. 7 Stone			
1.5”	100	100	100	100	100
1”	100	100	100	100	100
¾”	93	100	100	100	96
½”	56	93	100	100	77
3/8”	22	63	100	100	57
No. 4	4	8	100	100	43
No. 8	2	3	80	83	35
No. 16	2	2	48	57	24
No. 30	1	2	27	34	14
No. 50	1	1	14	15	7
No. 100	1	1	6	6	3
No. 200	0.8	1.0	2.0	3.0	1.7
% of Total Aggregate	51.5	8.2	4.0	36.3	100

Table 3-23. Concrete mix design properties for mix 1428SRA.

Component	Source and Type	Admixture (oz/100 lbs cementitious)	SSD Weight lbs/yd^3	Volume (ft^3)/yd^3
Coarse Aggregate, No. 67	Dayton Stone	-	1434	8.907
Coarse Aggregate, No. 7		-	230	1.418
Fine Aggregate #1	Dayton Manufactured Concrete Sand	-	113	0.694
Fine Aggregate #2	Dayton Concrete Sand	-	1009	6.270
Cement	Nevada Type II	-	512	2.605
Fly Ash	Bridger Class F	-	171	1.137
Water	-	-	267	4.279
Entrained Air	-	-	-	1.485
Water-Reducer	Eucon X15	8.0	-	0.057
Air-Entrainer	Eucon AEA 92	0.4	-	0.003
HRWRA	Eucon 37	5.0	-	0.036
Shrinkage Reducing Admixture	Eucon SRA-XT	15.3	-	0.109

Table 3-24. Additional concrete properties for mix 1428SRA.

Additional Concrete Properties	
w/cm	0.40
Slump, in	6
Air Content	5.5%
Paste Volume	29.7%

Figure 3-13. Overview of main deck of Virginia Street Bridge with no observed cracking.

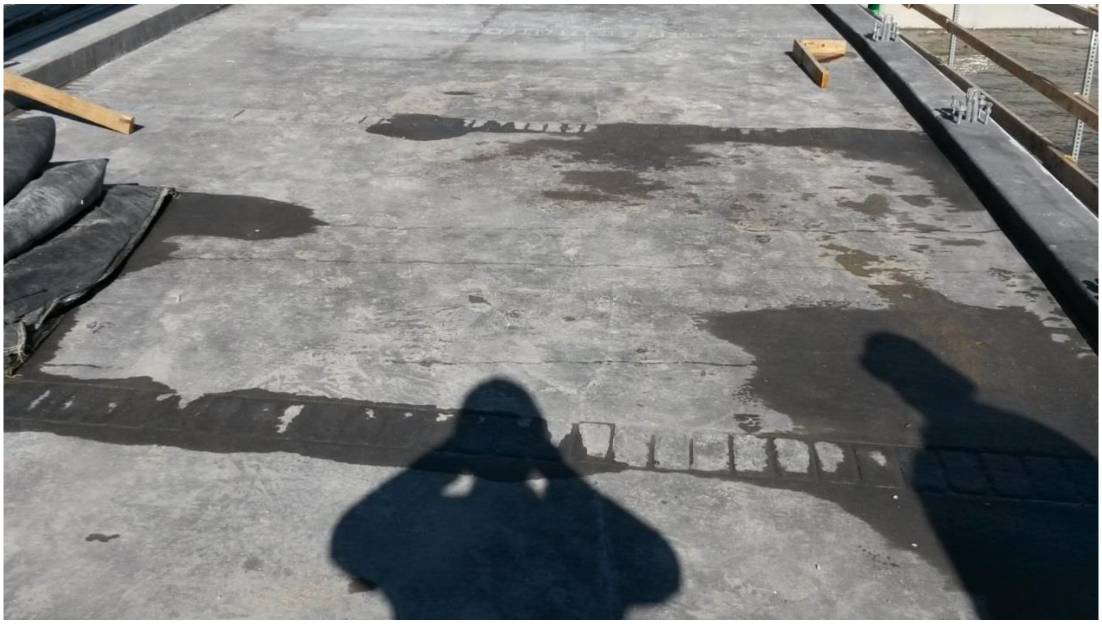


Figure 3-14. Two cracks observed on the eastern sidewalk of the Virginia Street Bridge.

3.3 Summary

Multiple factors can contribute to concrete bridge deck cracking. Concrete mixture constituents and proportions impact the drying shrinkage potential of the concrete, which in turn induces stress due to restraint that may result in cracking. Unfortunately, the data available is insufficient to draw any definitive conclusions regarding the relationship between mixture constituents and the occurrence of bridge deck cracking in recently constructed bridge decks in Northern Nevada.

There seems to be considerably more cracking on older decks, but by definition these decks are older and it is impossible to determine if the less severe cracking observed in newer decks will become worse in time. And for the most part, the older decks are more heavily trafficked as well. Of course an exception is the two decks observed that are part of the SE Connector. Although these were constructed within the last two years and have seen little to no traffic, the cracking observed is fairly extensive. The NDOT decks with the least amount of cracking were made with the Martin Marietta Spanish Springs aggregate, but again these were some of the newest, least trafficked decks. All of the decks observed are suffering some degree of cracking, with the exception of the recently cast deck on the Virginia Street Bridge. Cracking may develop in time, but this deck constructed with concrete containing a shrinkage reducing admixture is relatively crack free just after construction. This is an important observation given the fact that visible cracking on other bridge decks was reported during removal of the curing blankets.

CHAPTER 4: INTERVIEWS

In addition to discussing bridge deck cracking with the NDOT project team members, concrete experts at two concrete materials laboratories located in the Reno, Nevada area and two NDOT resident engineers (RE's) were interviewed separately to ascertain their observations regarding bridge deck cracking in Northern Nevada.

4.1 Concrete Materials Laboratory #1

The discussion initiated by reviewing the evolution of NDOT bridge deck specifications. It was stated that a lot of the pre-2000 bridge deck cracking issues could be attributed to the use of gap-graded aggregate which resulted in high water demand. The movement to the use of a combined aggregate grading consisting of three aggregate sizes has the potential for success, but it was admitted that a number of problems remained.

When asked whether early-age setting was an issue, it was felt it was not. With regards to plastic shrinkage cracking, the high rate of evaporation prevalent in Northern Nevada with high temperatures, low humidity, and high winds is clearly an issue that needs to be addressed. It was mentioned that the use of a fogging bridge can help prevent plastic shrinkage cracking and the use of a Kestrel Meter (http://kestrelmeters.com/products/kestrel-4300-construction-weather-tracker) was encouraged to measure evaporation rate.

It was felt that the biggest issue plaguing NDOT bridge decks in Northern Nevada seemed to be drying shrinkage cracking. Problems contributing to drying shrinkage cracking were grouped into the following five categories:

1. Moisture control/stockpile management. It was felt that the methods used at many concrete plants to keep aggregates uniformly wet were inadequate, thus there was a lot of non-uniformity regarding moisture content. This results in dry mixes that are water-starved, which in turn results in high levels of shrinkage, as well as other problems, as mix water is absorbed into the aggregates.
2. Many local aggregates lack the quality needed to make quality concrete either due to their high level of porosity (high absorption), poor strength, or general dirtiness. This has a big impact on the moisture control/stockpile management discussed previously. There is a lot of push back from the local materials suppliers/contractors to efforts to increase the aggregate quality requirements.
3. There is little control on the use polycarboxylate superplasticizer. Many producers/contractors are dealing with the moisture control/nonuniformity issue by overdosing with superplasicizers. This has all kinds of negative impacts on entrained air and shrinkage. This needs to be controlled much more than is currently done.
4. Quality varies widely with contractors and RE's which in turn leads to variable performance. Better training of RE's can assist in reducing this variability.

5. At the end of 10 days, the wet curing is rapidly removed and this may be shocking the system due to the immediate imposition of thermal and moisture gradients. Need to consider a more gradual reduction in curing.

When asked about local cement and pozzolans, it was felt that the properties of the cement/pozzolan are improving. High cement demand is primarily due to the poor aggregate stockpile management and poor quality aggregates as discussed above. Furthermore, contractors want to make sure they achieve strength as that is the material property that is most closely linked to them getting paid, and thus they over cement the mixtures to ensure adequate strength.

It was felt that education could play a very strong role in improving performance. In particular, educating NDOT RE's was viewed as being critical component in improving the quality of concrete bridge decks. Further, partnering was discussed as being helpful, in which the DOT, industry, and suppliers would get together to discuss the issues and develop solutions. It was mentioned that at one time there was a *High-Performance Concrete Task Force* and it was felt that this should be brought back.

In discussing current test methods, it was felt that the new specifications have moved in the right direction, having cleaned up some of the older test methods that were no longer useful. It was mentioned that recently shrinkage tubes have been acquired to evaluate autogeneous shrinkage in cement paste and mortar systems (ASTM C1698) and that this may prove useful. Recently the laboratory has been measuring resistivity (AASHTO T 358) using the Venner probe and has found it to have better repeatability than the rapid chloride penetration test (ASTM C1202). When asked about the use of shrinkage rings (ASTM C1581), they were viewed favorably but that the cost is prohibitive without there being a requirement.

4.2 Concrete Materials Laboratory #2

The conversation started with a general comment that "bridge deck cracking is normal." Seems like it is present on all projects to some degree and is quite severe on some. Even newer projects, like the SE Connector have some cracking, although they are not thought to be "extensive."

Some of this cracking is thought to be related to design, in which long expanses of deck are placed without joints and all tied together including the presence of integral abutments. Aside from cracking that is obviously linked to some type of structural restraint, map cracking is the predominant type of cracking. It is very prevalent and curing is not helping. Have tried multiple strategies and does not seem to make a difference.

The general consensus was that NDOT really likes polymer overlays, even prefers them, and thus most contractors have given up on preventing the cracking and simply include the construction of the polymer overlay into the bid.

The main cause of the cracking is thought to be related to the highly absorptive aggregates that dominate the local market. These aggregates will continue to soak up water for many hours even if submerged. Stockpile management is such that even though sprinklers may be running, the wetting is non-uniform and therefore when the aggregates are batched, they are often dry of saturation. Reasons for this include:

- Low relative humidity, high winds, and high summertime temperatures result in a very high rate of evaporation so the wetted aggregate surfaces dry out rapidly.
- The wetting process is non-uniform, with aggregates at the surface of the stockpile being wet but those inside the stockpile being dry.

It was simply stated, "poor stockpile management kind of sums up the situation" as it is impossible to saturate the aggregates in the field, and thus aggregates are batched with variable levels of saturation, and often dry, resulting in the cracking issue.

Another factor cited as a potential cause of cracking beyond aggregate saturation is the high daily temperature swings which can exceed 60 °F. It is especially acute when a rain storm comes in as it can result in a dramatic temperature decrease and cracking.

NDOT's specified compressive strength of 4,500 psi was also cited as a contributing factor, as it leads to over-design, which results in mixtures with very high cementitious materials content (normal is 8.5 sacks or 800 lbs/yd^3). This high paste content directly results in high shrinkage and cracking.

Aggregate cleanliness seems to be improving but is still potentially a problem. It was more of a problem in the past where dirty aggregates increased water demand and coated aggregates negatively affecting bond with the paste.

Even when clean, it was postulated that the mineralogy of some aggregates, notably the Martin Marietta aggregate, is such that hydrated cement paste will not bond well to it. The crushing process exposes large crystals on the aggregate surface that do not provide a good bonding surface or there is some other mechanism that interferes with the bond. The best aggregates from a bonding perspective have relatively high porosity including the All-Lite aggregate, which is considered by this laboratory to be one of the best. Yet these aggregates provide for the issues previously raised regarding stockpile management and uniformity in saturation.

It was felt that there is not a lot of control at the cement plant and that does result in variation, but that cement consistency appears to be improving.

Lately, there has been some ad hoc use of shrinkage reducing admixture (SRA), most notably on the Virginia Street Bridge. This was not part of the mixture design, but simply added.

The final comment reflected the beginning of the conversation, and that is that locally we have "learned to accept" bridge deck cracking.

4.3 NDOT Resident Engineer #1

This RE has worked on concrete bridge decks in Northern Nevada for around 16 years. In his opinion, water curing has not done much good in mitigating cracking as he can look under the wet curing blankets within a day or two of construction and observe that the cracking is already present.

Concrete bridge decks have always cracked. He has thought long and hard about the problem, but has not been able to identify any pattern regarding factors that might be contributing to the cracking. Asked whether he noticed a difference between steel or concrete girders, he did not seem to think it made a difference. A causative factor that he felt may be making cracking worse is if traffic is allowed on adjacent lanes during construction. He felt that the dynamic loading resulting in movement to the new deck at a young age that seemed to make the cracking worse. About the only factor that he had observed that may have reduced cracking is when the deck is small as he had experience in 2002 on a small deck off of I-80 near the Mustang exit that suffered little cracking. Based on this he felt that more jointing might help reduce cracking as the current designs do not provide any opportunity for the concrete to move as it shrinks.

He also singled out aggregates as a major contributor to deck cracking. He stated that stockpile management is horrible, and that the producers do not have enough room in their yards to stockpile sufficient aggregates for a given job. Thus the stockpile is continuously being replenished with aggregates that are not saturated resulting in batching of dry aggregates.

It was also stated that NDOT would benefit from moving to less prescriptive specifications and instead adopt performance-based specifications. As it is now, the contractors simply have to follow the specification and if something goes wrong, there is a dispute of who is to blame. Under a performance specification, the contractor would be instructed as to what is wanted and then would have to work to achieve the desired outcome.

4.4 NDOT Resident Engineer #2

This RE has worked for NDOT on concrete bridge decks for 23 years in Northern, Nevada. He stated that the evolution of curing practices has not really had much influence on the occurrence of cracking. The RE felt that curing must be done and has other positive impact but that cracking is still occurring even though multiple curing methods have been tried. He has observed cracking initiate before the curing is even applied and this suggests they are getting on too late. When asked about fogging, he stated that he has seen it done but to not much effect.

General feeling is that the environment is just too harsh; too evaporative and that no matter what is done, the decks are going to crack. As a result, he felt that it is best to just put a polymer concrete overlay on them all and be done with it.

The RE also identified stockpile management as a problem. No one really keeps the stockpiles uniformly wet and there is not enough room within most concrete producers' yards to be able to blend wet and dry materials within a stockpile. This results in variable moisture in the aggregate.

He mentioned that there was a study completed for NDOT by WJE in 2008 that studied the cause of cracking in two bridge decks. His recollection was that the results were inconclusive. A copy of the report was requested by NCE but never received.

4.5 Summary of Interviews

The interviews provided some insight into the perception of those dealing locally with concrete bridge decks regarding causation and potential areas of improvement. The following is a brief summary of major points:

- Bridge deck cracking continues to be a problem throughout Northern Nevada. Although the severity of the cracking appears to be diminished in recent construction, it is unclear whether that is an artifact of true improvement or simply a result of reduced age/loading.
- Changes to curing practices have had little effect on the occurrence of the cracking, which first appears very early on, even during the curing period.
- The major cause of cracking was attributed to poor stockpile management, particularly as reflected in non-uniformity in the moisture conditioning of the aggregates. This was cited as a particular problem for highly absorptive aggregates, which are being batched dry of SSD.
- Other aggregate issues were also cited, including poor aggregate-paste bond strength with aggregate dirtiness.

CHAPTER 5: PHASE II LABORATORY EXPERIMENTAL PLAN

5.1 Impetus and Scope

Based on the results of the literature review, visual assessments of several recently constructed bridge decks, and interviews with several local concrete experts and NDOT resident engineers, a strategy has emerged for conducting a controlled laboratory study to investigate material factors that are contributing to bridge deck cracking. As planned, the next phase of this broader study on bridge deck cracking is to conduct an 18-month laboratory study. The laboratory experimental plan, presented in this chapter, is developed to evaluate concrete mixture parameters that have been identified to affect concrete drying shrinkage as it specifically pertains to the materials and environmental conditions found across Northern Nevada. Other factors, including elements of bridge design and construction, will not be included in the Phase II laboratory investigation.

This initial laboratory plan will focus solely on mix design variables, such as aggregate type and gradation, rather than external construction variables such as curing and finishing practices. Likewise, many variables are presented for consideration and inclusion in the laboratory plan as well as many possible lab tests. This Phase II laboratory evaluation will consist of the following tasks:

- Task II-1: Selection of materials for use in the study – This task will finalize the materials to be included in the study including aggregates, cement, pozzolans, and admixtures. Further, any required treatments (e.g. cleanliness, level of saturation) of the materials will also be selected.
- Task II-2: Testing of initial mixtures – Initial testing will be conducted on a control and experimental mixtures to determine broad strategies that show promise in reducing shrinkage and restrained shrinkage cracking. The results of this initial testing will be used to hone in on specific mixtures for further investigation.
- Task II-3: Detailed testing of revised mixtures – A small number of mixtures will undergo more detailed testing to investigate specific properties that are increasing drying shrinkage cracking.
- Task II-4: Development of Phase III Research Plan – As the Phase II laboratory testing nears completion, a Phase III Research Plan will be developed which will focus on field trials and implementation.
- Task II-5: Phase II Report and approval of Phase III Research Plan – This task will provide the final report detailing the Phase II laboratory testing results and the Phase III Research Plan.

The following sections discuss the selection of materials to be considered in the Phase II study, the testing protocols to be applied, and some potential mixture combinations for the initial testing.

5.2 Proposed Variables of Construction

This laboratory investigation allows for the opportunity to investigate and isolate concrete mixture design factors, specifically related to conditions in Northern Nevada, that affect concrete drying shrinkage and cracking tendency. This includes investigating aggregates, cement, and supplemental materials specific to, and specified in, Nevada as well as using mixture design parameters common on Nevada DOT projects. Based on the literature review of other state DOTs, as well as a review of historical bridge records in Nevada, the following list of potential variables has been selected for this investigation:

- Aggregate source.
- Aggregate grading.
- Aggregate cleanliness.
- Aggregate level of saturation.
- Water-to-cementitious ratio.
- Cement content.
- Cement type.
- Pozzolans.
- SRA.
- Prewetted lightweight aggregate (PLWA)

5.2.1 Aggregate Source

From observations made when reviewing the current performance of selected Nevada bridge decks, it appeared that bridge decks made with certain aggregates performed better than others although the data was too limited to draw definitive conclusions. However, the varying coarse aggregate absorption values are a likely indicator of the performance of the aggregate which varied by source for the existing bridges investigated in this project. Higher absorption values, especially when aggregate is improperly saturated, can lead to excessive water being drawn from the paste matrix during curing, thus contributing to drying shrinkage cracking. Coarse aggregates, with varying absorption rates, from at least two different sources should be tested: one with absorption greater than four percent and one with an absorption capacity of approximately one percent.

5.2.2 Aggregate Grading

The practical benefits of a dense, optimized aggregate grading are largely two fold. First, optimization of the aggregate grading increases the total volume of aggregate in the concrete, reducing the required cementitious paste content. Concrete drying shrinkage is directly related to the paste content; therefore, reducing the overall paste content by increasing the volume of aggregate ultimately reduces the potential for drying shrinkage. Second, the aggregate itself provides physical restraint against drying shrinkage and therefore inclusion of more aggregate provides more restraint against shrinkage (Page and Page 2007). Generally, aggregate gradations can be divided into three categories: open-graded, dense-graded, and excessive fines. Direct, full contact between coarse aggregate particles, which occurs both in gap-graded and dense-graded mixtures, allows for full physical restraint against shrinkage. However, dense-grading fills the gaps between the larger sized aggregate with smaller sized aggregate particles, ultimately reducing the required amount of cement paste (Atkins 1997).

The Nevada DOT *Standard Specifications for Road and Bridge Construction* provides the required aggregate grading for concrete mix designs. However, the requirements as presented can lead to considerable variation in aggregate grading. There are many different methods of evaluating the nature of the aggregate grading, but for concrete mixture design, the three of the most common methods are the 0.45 power chart, a coarseness factor-workability factor chart, and a modified-percent-passing chart (see Cool et al. 2015).

The 0.45 power chart examines aggregate grading by plotting the percent retained against sieve size, raised to the 0.45 power. A common tool used in understanding asphalt gradations, in the 0.45 power curve a dense, optimized grading aligns closely with a straight line drawn from the maximum aggregate size through the origin. This is shown in figure 1 as the solid gray line. Greatly deviating above this line indicates a fine aggregate grading where greatly deviating below the line indicates a coarse aggregate grading. Figure 5-1 illustrates three possible aggregate gradings that are all acceptable under the Nevada DOT specifications: a fine grading, a coarse grading, and an optimized grading. It can be seen that both of the extreme gradations deviate from the central, target line, despite all falling within NDOT gradation specifications. A gradation that does not cross the maximum density line will not have sufficient space for the cementitious materials and would not be proposed.

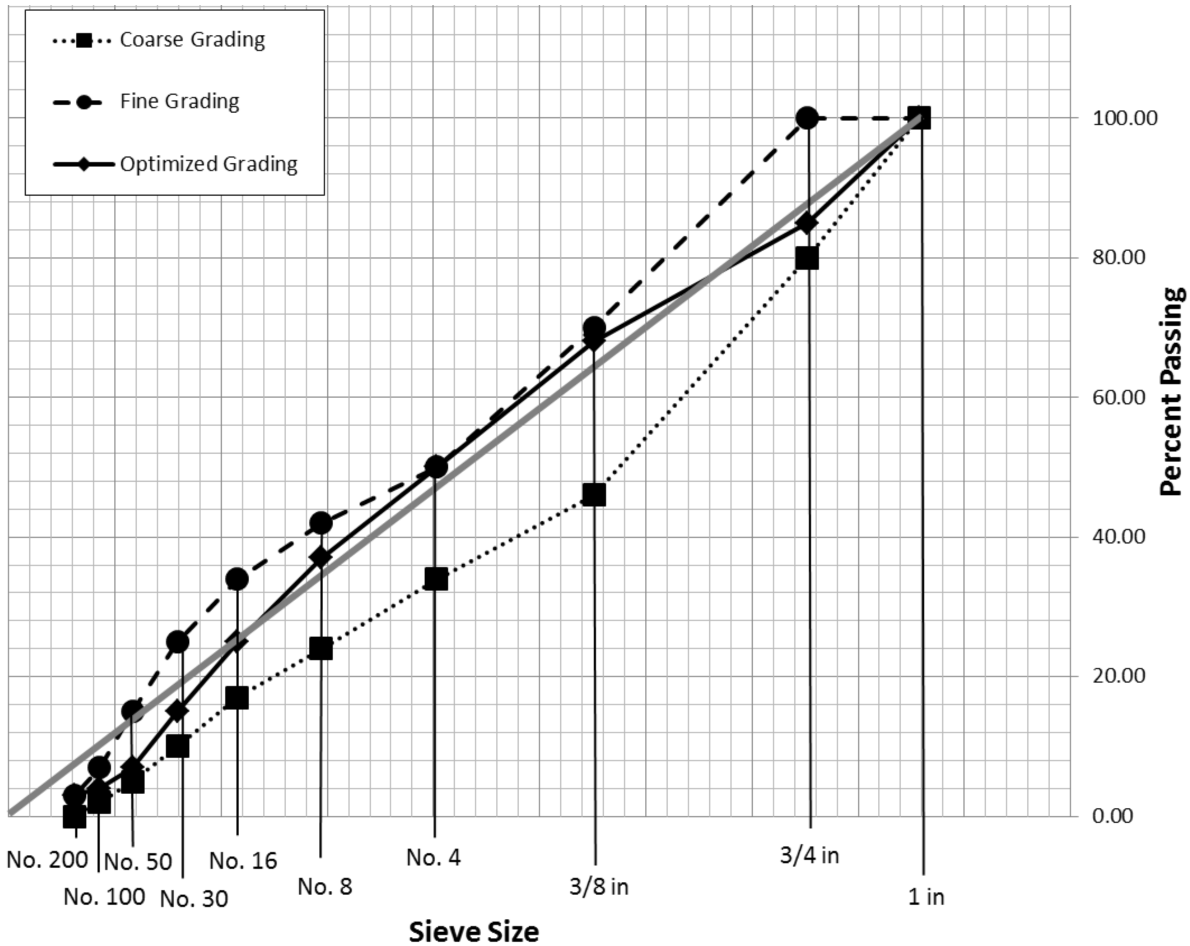


Figure 5-1. Range of acceptable aggregate gradings within NDOT specifications plotted on a 0.45 power chart.

The coarseness factor-workability factor chart plots the coarseness factor against the workability factor for a given gradation. The coarseness factor (CF) is the percent of the combined aggregate that is retained on the No. 8 sieve that is also retained on the 3/8 inch sieve whereas the workability factor (WF) is the percent of the combined aggregate that passes the No. 8 sieve. The CF and WF are plotted to see where the grading lies within the five zones of the coarseness factor-workability factor chart as presented in Figure 5-2. Zone II is considered the dense, optimal grading zone, and is thought to be most desirable for paving grade mixtures. Further optimization can be found in sub-zone II-A. It is seen in Figure 5-2 that the NDOT fine and optimized gradings fall within the desirable Zone II, with the optimized grading being very close to the sub-zone II-A. The NDOT coarse grading falls within Zone V: Rocky.

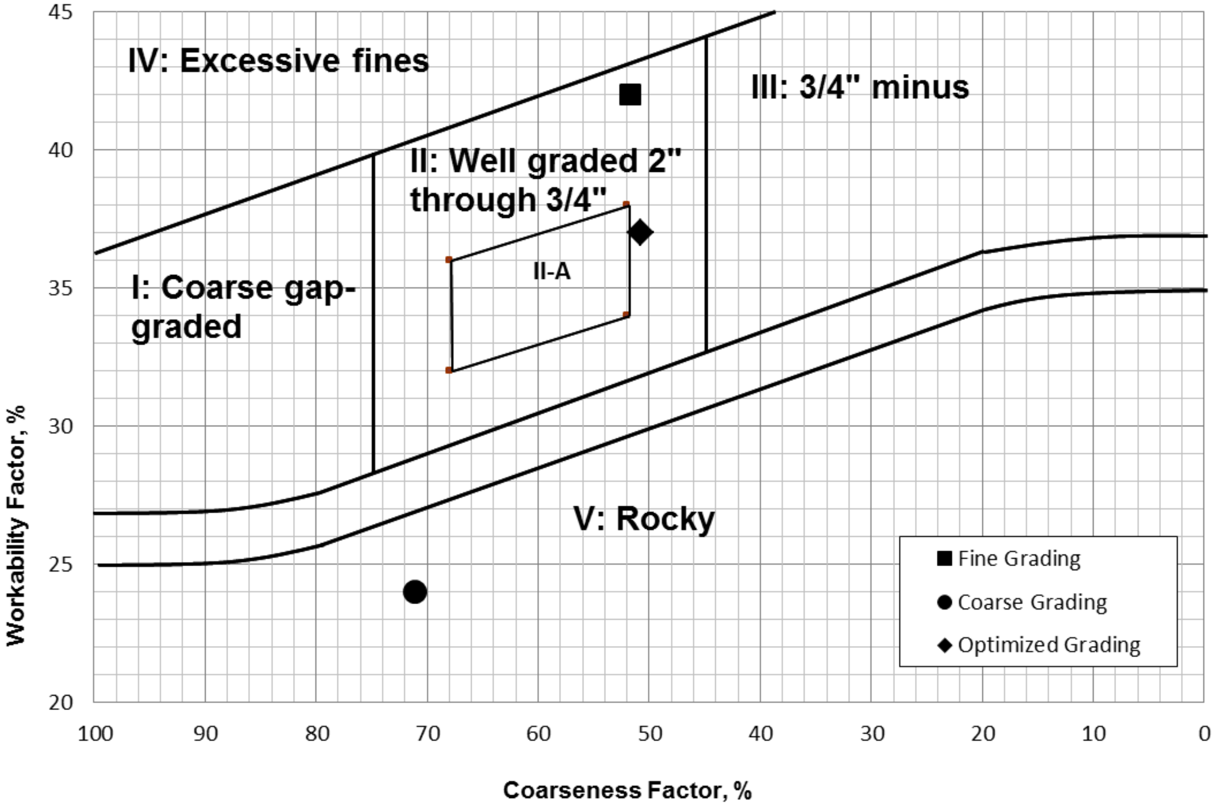


Figure 5-2. Coarseness factor-workability factor chart showing NDOT Gradations.

Recently, efforts focused on proper grading of concrete aggregates for use in bridge decks has resulted in the development of the modified-combined grading percent retained chart, also known as the Tarantula Curve (Cook et al. 2015). An optimal grading should fall within the bands in order to achieve multiple mixture parameters related to workability, pumpability, finishability, and strength. It can be seen in Figure 5-3 that both the fine and the coarse gradings exceed the recommended boundaries outlined in the chart; however, the optimized gradation falls within the prescribed boundaries.

In addition to the grading for the combined aggregate, Cook et al. (2015) also provide the following guidance on the desirable grading for fine and coarse sand:

- Fine sand: Sum of No. 30 through No. 200 sieves between 25 and 40 percent.
- Coarse sand: Sum of No. 8 through No. 30 greater than 20 percent.

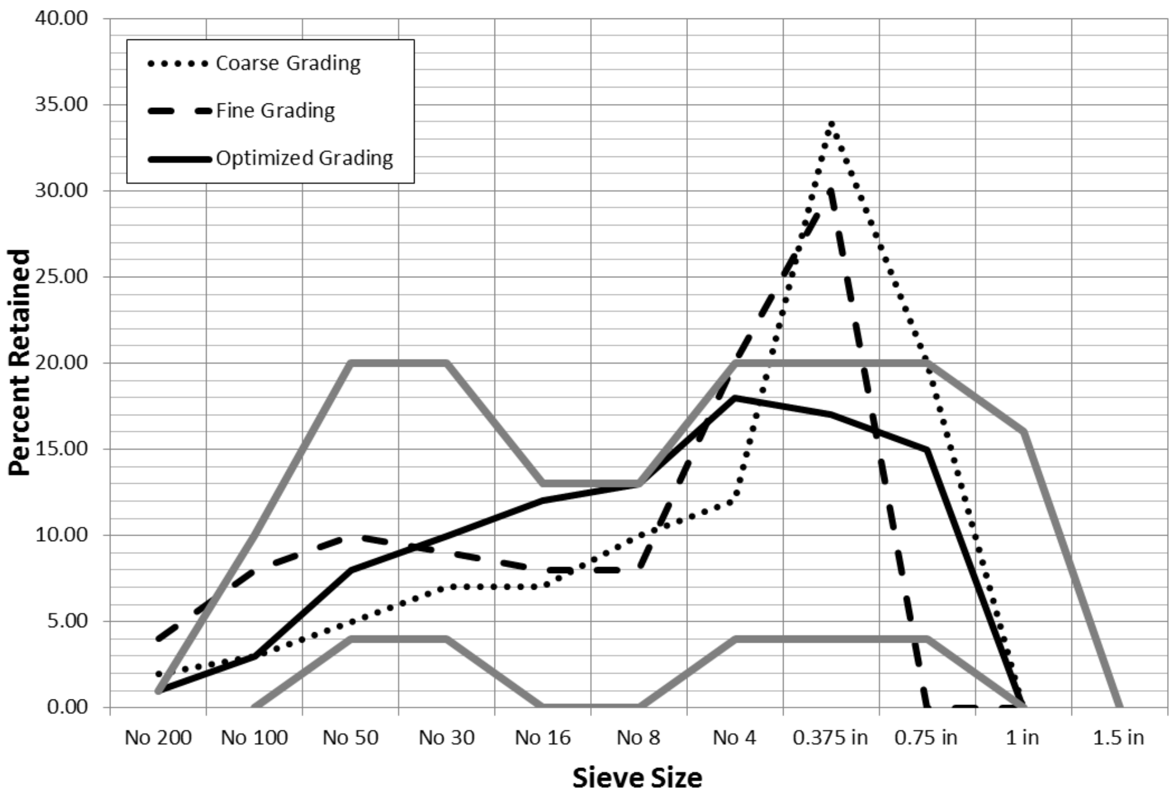


Figure 5-3. Modified percent passing chart based on Cook et al. 2015.

This analysis reveals that the aggregate grading can vary substantially within the current Nevada DOT specifications. An aggregate grading that is near the specification boundaries may be a consideration in drying shrinkage as it may require more cement paste content compared to a grading in the middle of the grading band. To evaluate this factor, mixtures should be investigated made with a historic average grading within the NDOT specification requirements and with an optimized grading within the NDOT specification requirements.

5.2.3 Aggregate Cleanliness

Aggregate cleanliness is another factor that is potentially contributing to the concrete drying shrinkage cracking. Fine materials present on the coarse aggregate, if loosened from the surface during mixing, will provide an additional source of fines that would increase water demand and correspondingly shrinkage. Further, coatings that remain adhered to the aggregate surface may negatively impact the bond at the aggregate-paste interface, compromising strength. While somewhat difficult to quantify, this variable is considered important to the performance of the concrete bridge decks. The laboratory study would allow for comparison of coarse aggregate that are meticulously cleaned according to a detailed washing procedure to coarse aggregates batched as obtained from the aggregate stockpile without washing.

5.2.4 Aggregate Level of Saturation

Concrete aggregates should not be batched drier than saturated-surface dry (SSD) conditions, especially if the aggregates are highly absorptive (absorption greater than 2.5 percent) as this can contribute greatly to early-age shrinkage. It was noted during the interviews that moisture content of aggregates at batching was often dry of SSD due to difficulties in keeping aggregate stockpiles uniformly wet during times of high production. Such aggregates will draw in water during mixing, transport, placing, finishing, and throughout the early curing period, potentially resulting in early shrinkage cracking. Therefore, this variable will be investigated by batching aggregates allowed to air dry in laboratory ambient conditions (the moisture condition will be measured), and then batched dry of SSD as well as aggregate batched at or above SSD after 7 days of soaking (moisture condition will be measured prior to batching).

5.2.5 Total Water Content

It is known that the total water content in a concrete mixture directly affects the drying shrinkage potential of concrete. This relationship is represented in Figure 5-4 (Kostmatka 2002), which shows a distinctly linear relationship between ultimate drying shrinkage and total water content.

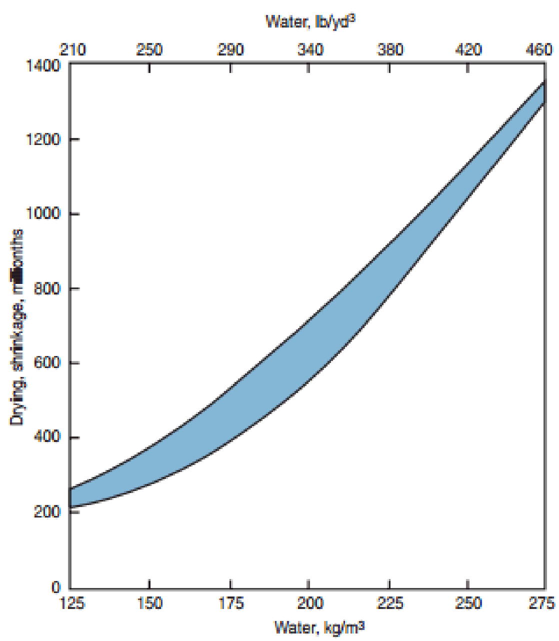


Figure 5-4. Effect of water content on drying shrinkage of concrete (Kostmatka and Wilson 2011).

Two primary factors control the total water content in a concrete mixture: the water-to-cementitious materials ratio (*w/cm*) and the cementitious materials content. With regards to *w/cm*, the 2014 Nevada DOT *Standard Specifications* limit the maximum *w/cm* to 0.4. To investigate the impact of *w/cm*, similar mixture should be made with *w/cm* of 0.35 and 0.40.

The second factor to consider is reducing the cementitious materials content to the lowest practical level. This will not only reduce the overall paste content, which should be a maximum of 27 percent by volume (Araiza et al. 2011), but will also reduce the heat of hydration which will also reduce shrinkage (Schmeckpeper and Lecoultre 2008). For the initial mixtures, the limits within the NDOT standard specifications should be tested, ranging from 564 lbs/yd^3 to 752 lbs/yd^3. In the latter part of the study, mixtures with even lower cementitious materials content, on the order of 500 lbs/yd^3 could be tested based on D'Ambrosia et al. (2013)

5.2.6 Cementitious Materials

The cementitious materials used in NDOT's Northern Nevada bridge deck concrete are composed of portland cement and pozzolans.

5.2.6.1 Cement Type. There are primarily two sources of cement available and both should be included in the laboratory evaluation: Type II cement supplied by Lehigh Hansen (source: Redding, CA) and Type II cement supplied Nevada Cement (source: Fernley, NV). The fineness of the cement will be noted and compared to historical records to evaluate how it may have changed with time.

5.2.6.2 Pozzolan Type. The 2014 NDOT *Standard Specifications* require a minimum of 20 percent pozzolan addition by mass of cement. There are primarily two sources of pozzolans that are widely available in Northern Nevada and should be tested in the laboratory evaluation: ASTM C618 Class N natural pozzolan (supplied by Nevada Cement, Fernley, NV) and ASTM C618 Class F fly ash (supplied by Headwaters Resources from the Jim Bridger Plant, Point of Rocks, WY).

5.2.7 Shrinkage Reducing Admixture Dosage

Shrinkage reducing admixtures (SRAs) are considered a viable method to reduce the early drying shrinkage in concrete (Qiao et al. 2010, Bentz et al. 2012, Chaunsali et al. 2013, D'Ambrosia et al. 2013). The most recent research on the use of SRAs in Virginia confirms this earlier work (Nair et al., 2016A). It is therefore recommended that mixtures be tested with and without SRA.

5.2.8 Prewetted Lightweight Aggregate

It has been shown that a source of internal water available for curing can support cement hydration and partially mitigate shrinkage (D'Ambrosia et al. 2013). The most common approach to providing this source of water is through partial replacement of some of the fine aggregate with prewetted lightweight fine aggregate (PLWA) having a specific void structure that will only release water one the concrete has set and a capillary pore system has begun to develop. It is recommended that mixtures be prepared both with and without PLWA. The most recent research on the use of PLWA in Virginia confirms this earlier work (Nair et al., 2016B). It is therefore recommended that mixtures be tested with and without PLWA, noting that local availability may be an issue for practical application in the future, although the overall volume used is relatively small.

5.3 PROPOSED LABORATORY TESTS

Following the identification of important variables, testing will be conducted to assess the primary factors under investigation, including shrinkage and strength, as well as other factors identified in previous projects as outlined in the literature review. The testing will identify the positive contribution of tactics engaged to reduce shrinkage as well as possible negative side to ensure that the concrete mixtures ultimately developed provide a broad-range of desirable attributes.

Based on the work conducted in this study, it is proposed that the following laboratory tests are conducted in Phase II.

5.3.1 Tests of Constituent Properties

All aggregates, cementitious materials, and admixtures should be obtained meeting the requirements of the NDOT *2014 Standard Specifications for Road and Bridge Construction*. Each should be in compliance with specification requirements as would be done if they were to be used on an NDOT bridge project. This would include, but not limited to:

- Aggregate grading (ASTM C136/C117)
- Clay lumps and friable material (ASTM C142 and Nev. T490)
- Coal and lignite (ASTM C123)
- LA Abrasion (ASTM C131)
- Specific gravity and absorption (ASTM C127 & C128)
- Cleanness for coarse aggregate (Nev. T228)
- Sand equivalent for fine aggregate (ASTM D2419/Nev. T227)
- Durability index for fine aggregate (ASTM D3744)
- Organic impurities for fine aggregate (ASTM C40)
- Uncompacted void content for fine aggregate (ASTM C1252 Method C)
- Sulfate soundness (ASTM C88)
- Unit weight (ASTM C29)
- Cement test report (mill certification) (ASTM C150)
- Pozzolan test report (ASTM C618)
- Admixture certification (ASTM C494)

In addition to this standard certification and testing, the following should be completed:

- A modified “loss by wash” should be conducted on all aggregate sources that will undergo “rigorous washing.” Wash water should be filtered to collect the fines for possible later analysis.

- Long term soaking of the aggregate should be conducted to determine additional water uptake beyond the standard 24 hour soak.
- Additional analytical testing may be conducted on cementitious materials if deemed necessary to evaluate chemistry and mineralogy.

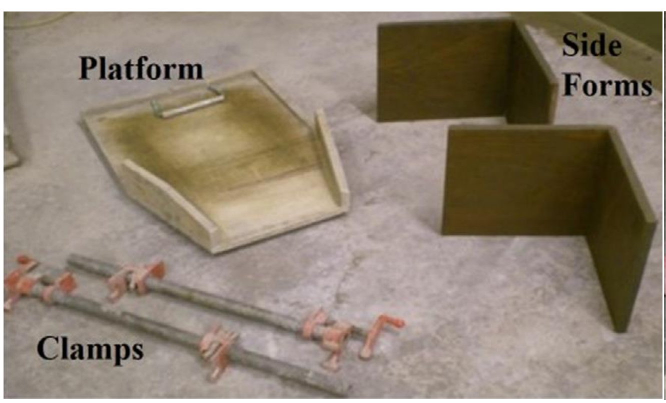
5.3.2 Tests on Fresh Concrete

Standard testing should be conducted on all fresh concrete mixtures. This will include tests described in the following subsections.

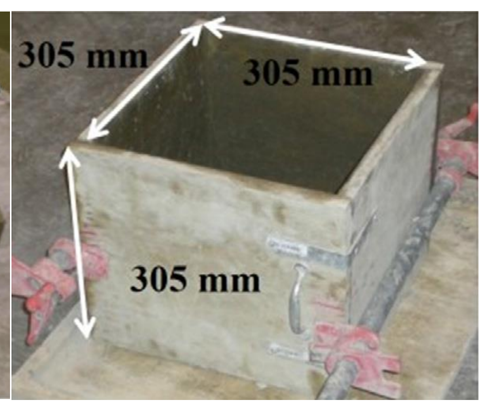
5.3.2.1 ASTM C143: Slump Test. The concrete slump should be measured in accordance with ASTM C143, *Standard Test Method for Slump of Hydraulic-Cement Concrete*. The target slump will be 4 inches, which is the maximum allowed for a Class EA Modified Concrete as set in the 2014 NDOT *Standard Specifications for Road and Bridge Construction*.

5.3.2.2 Box Test. The Box Test should be used to assess workability. It is designed to assess the ability of the concrete mixture to consolidate under vibration yet be stiff enough to maintain a straight edge after vibration passes (Cook et al., 2013; Cook et al., 2014). This test assesses whether or not the concrete can be readily fluidized through vibration to ensure consolidation while maintaining a vertical edge without slumping once vibration is complete.

The Box Test is very simplistic in concept. It consists of a platform, two right-angled side forms, and two clamps that form a "box" having a 1 ft^3 volume as shown in Figure 5-5. Concrete is uniformly placed into the box to a depth of 9.5 inches and an internal electric vibrator (set at 12,500 vpm) is lowered into the center of the box for three seconds and then raised out of the box over a period of three seconds.



(a)



(b)

Figure 5-5. Box Test components (a) and assembled box (b) (Cook et al., 2014).

Immediately after vibration, the clamps are detached and the side forms removed exposing the vertical edges of the concrete. A qualitative assessment of the degree of consolidation is then made for each vertical side using rankings based on the percent overall surface voids as shown in Figure 5-6. Edge slumping is also measured using a straight edge placed at a corner and measuring the length of the highest extruding point.

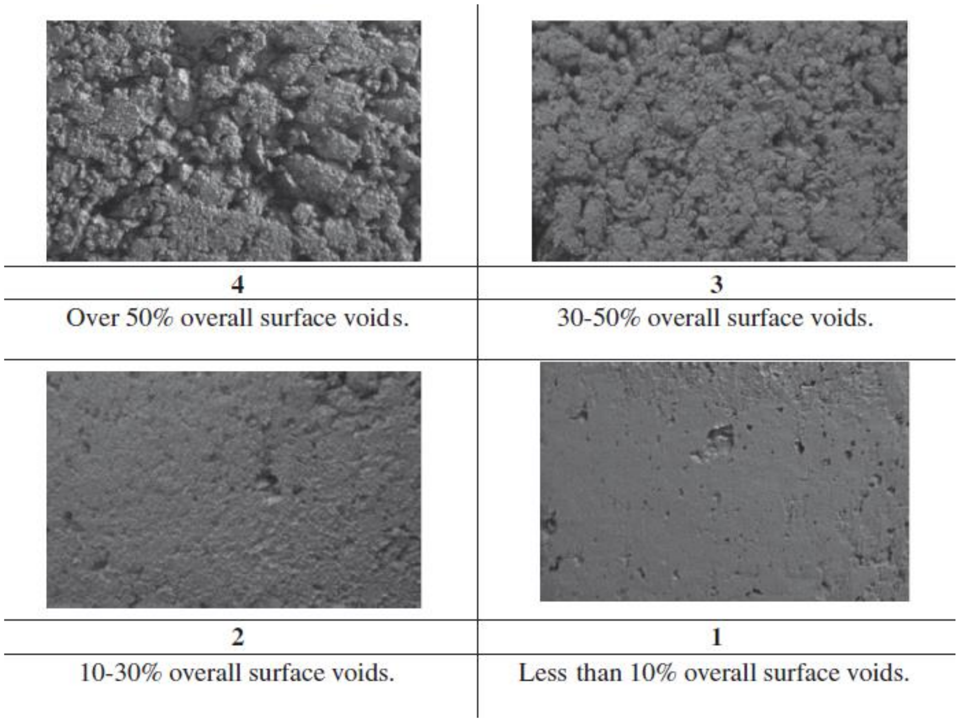


Figure 5-6. Surface void ranking based on percent overall surface voids (Cook et al., 2014).

As reported in Cook et al., 2013 and Cook et al., 2014, the test method was validated over a range of concrete mixtures in the laboratory with multiple evaluators and it was found to be an excellent test to assess the workability of concrete under vibration.

5.3.2.3 ASTM C403: Set Time. The concrete set time should be measured in accordance with ASTM C403, *Standard Test Method for Time of Setting of Concrete Mixtures by Penetration Resistance*. It is not required by Nevada DOT specifications but a commonly cited negative side effect of using SRAs is a decrease in set time. The inclusion of this test would allow for further investigation of this potential side effect of SRAs as well as the impact of other constituents.

5.3.2.4 ASTM C231: Air Content Determined by Pressure Method

The air content of the fresh concrete should be determined in accordance with ASTM C231. *Standard Test Method for Air Content of Freshly Mixed Concrete by Pressure Method*. The target air will be 6.0 percent, in the mid-range of the allowable 4 to 7 percent for Class EA Modified Concrete specified in the 2014 NDOT *Standard Specifications for Road and Bridge Construction*.

5.3.2.5 ASTM C173: Air Content Determined by Rollometer. The air content of the fresh concrete should also be determined in accordance with ASTM C173, *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method* (Rollometer method) as this method is recommended for high absorption aggregates. The target air will be 6.0 percent, in the mid-range of the allowable 4 to 7 percent for Class EA Modified Concrete specified in the 2014 NDOT *Standard Specifications for Road and Bridge Construction*.

5.3.2.6 ASTM C138: Unit Weight. The unit weight of the fresh concrete should be determined in accordance with ASTM C138, *Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete.* This will provide a check with the air determined via other means as well as a way to track factors that influence unit weight.

5.3.2.7 AASHTO TP 118: Super Air Meter (SAM) Test. Additionally, the air-void system should be characterized using AASHTO TP 118, *Provisional Standard Method of Test for Characterization of the Air-Void System of Freshly Mixed Concrete by the Sequential Pressure Method* is based on ASTM C231 (Ley and Tabb 2013, Welchel 2014). Instead of using a single testing pressure as is used in AASHTO T 152, the SAM meter uses sequential pressures to determine the volume of air and air-void distribution. To date, the results of the SAM test (the SAM Number) have been shown to correlate to hardened air void analysis (ASTM C457) and rapid freeze-thaw testing (ASTM C666, *Standard Method of Test for Resistance of Concrete to Rapid Freezing and Thawing*) for over 400 concrete mixtures and the method is being investigated for implementation in 25 U.S. states, two Canadian provinces and by 17 different DOTs. The SAM test is conducted on fresh concrete. It can be part of the mixture proportioning process as well as used as a quality control tool during actual construction. The acceptance criterion for the SAM test is as follows (Ley and Weiss 2015):

- Total air content should be greater than 4 percent.
- If the SAM Number is less than 0.20 psi, the concrete is acceptable.
- If the SAM Number is between 0.20 psi and 0.25 psi, methods to increase air content in subsequent delivered concrete must be implemented.
- If the SAM Number is greater than 0.25 psi, the concrete should be rejected.

5.3.3 Tests of Hardened Concrete

5.3.3.1 ASTM C39: Compressive Strength. The compressive strength test for hardened concrete should be measured in accordance with ASTM C39, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens*. Strengths will be obtained at 7, 14, and 28 days. Typically, NDOT has targeted a compressive strength between 4,000 and 5,000 psi at 28 days for bridge deck concrete. Considerable work has been done to suggest that less might actually be more, with Caltrans research (Araiza et al 2011) suggesting specifying a minimum compressive strength of 3,600 psi and a maximum strength of 4,500 psi to minimize cracking.

5.3.3.2 ASTM C157: Free Shrinkage. The free concrete shrinkage of concrete should be measured in accordance with ASTM C157, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*. The 2014 NDOT *Standard Specifications for Road and Bridge Construction* specify a maximum shrinkage of 0.06 percent at 56 days for SA concrete; a requirement that will be used as a guideline for the mixtures investigated in this project. Generally, this test is considered the standard test for measuring concrete drying shrinkage, but because it is unrestrained, it is not necessarily a good measure of cracking tendency.

5.3.3.3 ASTM C1581: Restrained Shrinkage. It is currently proposed that the restrained concrete shrinkage will be assessed through ASTM C1581, *Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Restrained Shrinkage.* This test will be the primary method of comparing restrained shrinkage performance between the mixtures in this laboratory study. The restrained shrinkage test provides a more realistic performance expectation for bridge deck concrete, which would more accurately experience restrained shrinkage rather than free shrinkage due to structural constraints of a bridge deck. During the design of Kansas DOT low cracking, high performance concrete, it was found that restrained shrinkage should be measured in addition to free shrinkage for better overall insight into cracking tendency (Yuan 2011, D'Ambrosia et al. 2013). The net time to cracking should exceed 28 days. It is noted that a dual ring restrained shrinkage test is currently undergoing standardization and will likely be available for consideration as an alternative test method (Schlitter et al. 2010).

5.3.3.4 ASTM C1202: Rapid Chloride Penetration Testing. A rapid indication of the concrete's resistance to chloride ion penetration should be made in accordance with ASTM C1202, *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. This test is commonly used by State DOTs, and is in the 2014 NDOT *Standard Specifications for Road and Bridge Construction* with a limit not to be exceeded of 2000 coulombs at 56 days.

5.3.3.5 AASHTO T 358: Surface Resistivity. The surface resistivity of the concrete should be assessed in accordance with AASTHO T 358, *Standard Method of Test for Surface Resistivity Indication of Concrete's Ability to Resist Chloride Ion Penetration*. While ASTM C1202 is still frequently used to provide a baseline for chloride penetrability measurements of concrete, surface resistivity provides a reliable and repeatable alternative. Further, as resistivity testing is nondestructive, tested specimens can subsequently be used in other tests (e.g., compressive strength). Table 1 provides the typical correlations that have been observed between ASTM C1202 and AASHTO T 358. Further, when specimens are properly conditioned, the resistivity can be coupled with an assessment of the pore solution chemistry derived from the cement and SCM mill certificates to estimate the Formation Factor which is a direct measurement of the pore volume and connectivity of the concrete.

5.4 EXPERIMENTAL APPROACH

The concrete mixture variables that could be investigated in the Phase II laboratory evaluation are summarized in Table 5-1. It is noted that if all combinations of concrete mixtures were made at two levels, the total number of mixtures would be 210 or 1024 mixtures if a full factorial design were implemented. This level of testing is not feasible within the time and resources available, nor is it necessary. Instead, an approach is to be used where 20 initial mixtures are made and subject to limited testing as shown in Table 5-2. Based on the results of this testing, six revised mixtures will be selected for more detailed testing as shown in Table 5-2.

Table 5-1. Summary of potential variables and levels to be investigated in Phase II laboratory evaluation.

Variable	Level 1	Level 2
Aggregate Source	Typical Low Absorption (LA)	Typical High Absorption (HA)
Aggregate Grading	Optimized (AOP)	Historic Average (AHA)
Aggregate Cleanliness	Washed (W)	Unwashed (UW)
Aggregate Saturation	SSD (SSD)	Dry of SSD (Dry)
w/cm	0.35 (0.35)	0.40 (0.40)
Cementitious Content	564 lbs/yd^3 (564)	752lbs/yd^3 (752)
Cement Type	Nevada Cement (NC)	Lehigh Redding (LR)
Pozzolan Type	Class N (PN)	Class F (PF)
SRA	Yes (SRA)	No (No SRA)
PLWA	Yes (PLWA)	No (No PLWA)

Note: Labels in parenthesis used to identify mixtures in experimental matrix.

Table 5-2. Summary of test methods for initial and revised, as indicated.

Test Method	**Initial Mixtures**	**Revised Mixtures**
Constituent Properties	✓	✓
Fresh Concrete		
Slump	✓	✓
Box Test	✓	✓
Set Time		✓
Air (Pressure Method)	✓	✓
Air (Rollometer)		✓
Unit Weight	✓	✓
Air (SAM)		✓ (Optional)
Hardened Concrete		-
Compressive Strength	✓	✓
Free Shrinkage	✓	✓
Restrained Shrinkage		✓
RCPT		✓(Optional)
Resistivity	✓	✓
Modulus of Elasticity		✓
Petrographic Analysis		✓ (Optional)

5.4.1 Initial Mixtures

It is anticipated that 20 concrete mixtures will be prepared and tested in accordance with the test methods described in Table 5-2 for initial mixtures. A preliminary testing matrix is represented in Table 5-3.

5.4.2 Revised Mixtures and Detailed Testing

The objective of the preliminary mixtures is to narrow the number of revised mixtures down to six mixtures. These six with be the same as six mixtures made in the initial testing of the 20 mixtures, thus adding replication for all of the previous tests conducted. This will help to establish repeatability as well as add in the more advanced test methods including the ASTM C1581 restrained shrinkage testing. It is hoped through this additional testing that relationships can be established between the simpler tests and more advanced test that can be used for specification development in Phase III of this broader study. Ultimately, these results could be used to revise standard specifications and special provisions for Nevada DOT bridge decks and eventually reduce the overall incidence of shrinkage cracking.

Table 5-3. Preliminary testing matrix for 20 initial mixtures.

Mix No.	**Agg. Src.**	**Agg. Grd.**	**Agg. Cln.**	**Agg. Sat.**	**w/cm**	**Cem. Cnt.**	**Cem. Typ.**	**Poz. Typ.**	**SRA**	**PLWA**
1	LA	AOP	UW	SSD	0.35	564	NC	PN	NO	NO
2	LA	AOP	UW	SSD	0.35	564	NC	PN	YES	NO
3	LA	AOP	UW	SSD	0.35	564	NC	PN	NO	YES
4	LA	AOP	UW	SSD	0.35	752	NC	PN	NO	NO
5	LA	AOP	UW	SSD	0.35	752	NC	PN	YES	NO
6	LA	AOP	W	SSD	0.35	564	NC	PN	NO	NO
7	LA	AOP	W	SSD	0.35	752	NC	PN	NO	NO
8	LA	AOP	UW	SSD	0.35	564	LR	PF	NO	NO
9	LA	AOP	UW	SSD	0.35	752	LR	PF	NO	NO
10	LA	AOP	UW	SSD	0.40	564	NC	PN	NO	NO
11	LA	AOP	UW	SSD	0.40	752	NC	PN	NO	NO
12	LA	AHA	UW	SSD	0.35	752	NC	PN	NO	NO
13	LA	AHA	UW	SSD	0.35	752	NC	PN	YES	NO
14	LA	AHA	UW	SSD	0.40	752	NC	PN	NO	NO
15	HA	AOP	UW	SSD	0.35	564	NC	PN	NO	NO
16	HA	AOP	UW	SSD	0.35	752	NC	PN	NO	NO
17	HA	AOP	UW	SSD	0.35	752	NC	PN	YES	NO
18	HA	AOP	UW	DRY	0.35	564	NC	PN	NO	NO
19	HA	AOP	UW	DRY	0.35	752	NC	PN	NO	NO
20	HA	AOP	UW	DRY	0.35	752	NC	PN	YES	NO

CHAPTER 6: CONCLUSIONS

6.1 Summary of Research Need

There is broad recognition that early-age cracking of HPC bridge decks continues to be a problem nationwide. The cracking is largely attributed to restraint, as many HPC mixtures suffer high drying shrinkage and poor resistance to cracking. To address this, there has been a movement toward adoption of concrete mixtures possessing adequate strength and reduced permeability, but are also less prone to shrinkage and cracking. Since adopting the use of HPC, NDOT has noted that random cracking continues to plague some newly constructed concrete bridge decks. These cracks require expensive and unsightly crack sealing, which is of unproven effectiveness in the long term. In cases of extreme cracking, polyester overlays are used to seal the entire deck at great expense. National research efforts and findings provide valuable insights into the cause of cracking and potential solutions, but fall short of directly addressing NDOT's needs as they do not reflect Nevada's unique climatic conditions (most notably the low relative humidity), material sources, industry practices, and state of concrete technology.

The overall objective of mitigating early-age bridge deck cracking in Nevada will be achieved through a three phase research program; the results of the first phase, Phase I, being reported in this document. Phase I includes a synthesis of state, regional, and national knowledge and practice on factors contributing to early-age HPC bridge deck cracking, assessment of recently constructed bridges in Northern Nevada, interviews with local concrete technologists, and a Phase II research plan for conducting the next phase of the research program. Given the Phase I results, presented herein, NDOT has a better understanding of the issues causing cracking of HPC bridge decks and a Phase II laboratory research plan for the collection of test data and development of test methods for a Nevada solution.

6.2 Literature Review Findings

Early-age restraint cracking of concrete bridge decks is a widely reported problem, not only in Nevada and other states with similar arid climates, but throughout the United States. The cause of the problem can largely be separated into three general categories: 1) material and mixture design, 2) construction practices and ambient conditions, and 3) structural design factors. This study is focused on the first two categories and does not consider the third category.

With respect to materials and mixture design, the overwhelming conclusion is that the shrinkage of the concrete mixture, especially at early-ages, must be reduced while the concrete's resistance to cracking must be increased. Multiple strategies are available to reduce shrinkage, including reducing the volume of cementitious paste (accomplished by increasing the volume of aggregate through optimized aggregate grading), using PLWA to provide a source of internal water for distributed curing, and the use of SRAs (often found to be very effective although resulting in a decrease in compressive strength and potentially negative impact on the entrained air-void system). Improved construction practices focus on close monitoring of ambient conditions (temperature and humidity) to reduce thermal stress and avoid highly evaporative conditions and the early application of wet curing that is maintained for a minimum of 7 days.

The current Nevada specifications have evolved over the last 15 years and are a step in the right direction, but are lacking in provisions that actually assess the characteristics of the concrete mixtures most closely linked to shrinkage and cracking tendency. The next step to improve current practice will be to execute a rigorous, well-designed laboratory experiment using local materials that assesses the properties of concrete mixtures that are related to early-age restraint cracking.

6.3 Field Evaluation of Existing Bridges

To evaluate the performance of bridge decks constructed using recent and current NDOT specifications, seven bridges under NDOT jurisdiction on the US 395/I-580 corridor were visited in the greater Carson City, Nevada area. In addition to these NDOT bridge decks, three other recently constructed local bridge decks were visited in the Reno-Sparks area. The visual inspection results were evaluated in combination with mixture design records and construction history to develop a profile of each bridge in an attempt to identify key factors contributing to the observed performance.

Multiple factors contribute to concrete bridge deck cracking. Concrete mixture constituents and proportions impact the drying shrinkage potential of the concrete, which in turn induces stress due to restraint that may result in cracking. Unfortunately, the data available on the bridge decks evaluated is insufficient to draw any definitive conclusions regarding the relationship between mixture constituents and the occurrence of bridge deck cracking in recently constructed bridge decks in Northern Nevada.

Cracking appears to be more apparent on older decks, but these decks have been subjected to more years of use and it is impossible to determine if the reduction in cracking observed in newer decks will become worse in time. And for the most part, the older decks are more heavily trafficked as well. Of course an exception is the two newer decks observed that are part of the SE Connector. Although these were constructed within the last two years and have seen little to no traffic, the cracking observed is fairly extensive. The NDOT decks with the least amount of cracking were made with the Martin Marietta Spanish Springs aggregate, but again these were some of the newest, least trafficked decks. All of the decks observed are suffering some degree of cracking, with the exception of the recently cast deck on the Virginia Street Bridge in Reno. Cracking may develop in time, but it appears initially that the SRA resulted in a deck that is relatively crack free just after construction. This is an important observation given the fact that visible cracking on other bridge decks was reported during removal of the curing blankets.

6.4 Interview Summary

In addition to discussing bridge deck cracking with the NDOT project team members, experienced concrete technologists at two concrete materials laboratories located in the Reno area and two NDOT resident engineers (RE's) were interviewed separately to ascertain their observations regarding bridge deck cracking in Northern Nevada.

The interviews provided insight into the perception of those dealing locally with concrete bridge decks regarding causation and potential areas for improvement. The following is a brief summary of major points:

- Bridge deck cracking continues to be a problem throughout Northern Nevada. Although the severity of the cracking appears to be diminished in recent construction, it is unclear whether that is an artifact of true improvement or simply a result of reduced age/loading.
- Changes to curing practices have had little effect on the occurrence of the cracking, which appears very early on, even during the wet curing period.
- The major cause of cracking was attributed to poor stockpile management, particularly as reflected in non-uniformity in the moisture conditioning of the aggregates. This was cited as a particular problem for highly absorptive aggregates, which are often batched dry of SSD.
- Other aggregate issues were also cited, including poor aggregate-paste bond strength with aggregate dirtiness.

6.5 Phase II Laboratory Experimental Plan

Based on the results of the literature review, visual assessments of several recently constructed bridge decks, and interviews with individuals experienced in local bridge deck construction, a strategy has been developed for conducting a Phase II laboratory study to investigate material factors that are contributing to bridge deck cracking. The next phase of this broader study on bridge deck cracking would be to conduct the 18-month laboratory study described in chapter 5, which will evaluate concrete mixture parameters that have been identified to affect concrete drying shrinkage as it specifically pertains to the materials and environmental conditions found across Northern Nevada. Other factors, including elements of bridge design and construction, will not be included in the Phase II laboratory investigation.

6.5.1 Scope

The Phase II laboratory plan will focus solely on mix design variables, such as aggregate type and gradation, rather than external construction variables such as curing and finishing practices. Many variables are considered for inclusion in the laboratory plan as well as many possible lab tests. In total, the Phase II laboratory evaluation will consist of the following five tasks:

- Task II-1: Selection of materials for use in the study.

- Task II-2: Testing of initial mixtures.
- Task II-3: Detailed testing of revised mixtures.
- Task II-4: Development of Phase III Research Plan.
- Task II-5: Phase II Report and approval of Phase III Research Plan

6.5.2 Variables

This laboratory investigation allows for the opportunity to investigate and isolate concrete mixture design factors, specifically those related to conditions in Northern Nevada, that affect concrete drying shrinkage and cracking tendency. This includes investigating aggregates, cement, and supplemental cementitious materials specific to, and specified in, Nevada as well as using mixture design parameters common on Nevada DOT projects. Based on the literature review and interviews with local concrete technologists, the following list of potential variables is recommended for this investigation:

- Aggregate source.
- Aggregate grading.
- Aggregate cleanliness.
- Aggregate level of saturation.
- Water-to-cementitious ratio.
- Cement content.
- Cement type.
- Pozzolan type.
- SRA.
- Prewetted lightweight aggregate (PLWA)

Following the identification of important variables, testing will be conducted to assess the primary factors under investigation, including shrinkage and strength, as well as other factors identified in previous projects as outlined in the literature review. The testing will identify the positive contribution of tactics engaged to reduce shrinkage as well as possible negative side to ensure that the concrete mixtures ultimately developed provide a broad-range of desirable attributes.

6.5.3 Recommended Laboratory Tests

Based on findings of this research project, the following list of potential laboratory tests to include is given in this section, including the standard specifications, where applicable.

6.5.3.1 Tests of Constituent Properties. All aggregates, cementitious materials, and admixtures will be obtained meeting the requirements of the 2014 NDOT *Standard Specifications for Road and Bridge Construction*. Each will be in compliance with specification requirements as would be done if they were to be used on an NDOT bridge project. The testing conducted would include, but not limited to:

- Aggregate grading (ASTM C136/C117)
- Clay lumps and friable material (ASTM C142 and Nev. T490)
- Coal and lignite (ASTM C123)
- LA Abrasion (ASTM C131)
- Specific gravity and absorption (ASTM C127 & C128)
- Cleanness for coarse aggregate (Nev. T228)
- Sand equivalent for fine aggregate (ASTM D2419/Nev. T227)
- Durability index for fine aggregate (ASTM D3744)
- Organic impurities for fine aggregate (ASTM C40)
- Uncompacted void content for fine aggregate (ASTM C1252 Method C)
- Sulfate soundness (ASTM C88)
- Unit weight (ASTM C29)
- Cement test report (mill certification) (ASTM C150)
- Pozzolan test report (ASTM C618)
- Admixture certification (ASTM C494)

In addition to this standard certification and testing, the following will be completed:

- A modified "loss by wash" will be conducted on all aggregate sources using a rigorous washing. Wash water will be filtered to collect the fines for possible later analysis.
- Long term soaking of the aggregate will be conducted to determine additional water uptake beyond the standard 24 hour soak.
- Additional analytical testing may be conducted on cementitious materials if deemed necessary to evaluate chemistry and mineralogy.

6.5.3.2 Recommended Tests on Fresh Concrete. The following provides a list of recommended tests on fresh concrete:

- ASTM C143: Slump Test
- Box Test
- ASTM C403: Set Time
- ASTM C231: Air Content Determined by Pressure Method
- ASTM C173: Air Content Determined by Rollometer
- ASTM C138: Unit Weight
- AASHTO TP 118: Super Air Meter (SAM) Test

6.5.3.3 Recommended Tests of Hardened Concrete. The following provides a list of recommended tests of hardened concrete:

- ASTM C39: Compressive Strength.
- ASTM C157: Free Shrinkage.

- ASTM C1581: Restrained Shrinkage.
- ASTM C1202: Rapid Chloride Penetration Testing.
- AASHTO T 358: Surface Resistivity.
- ASTM C469: Modulus of Elasticity.
- ASTM C856: Petrographic Analysis.

6.5.4 Experimental Approach

A proposed experimental approach was presented based on a partial factorial experimental design, of which the variables are presented in the previous Chapter. If a full factorial design was carried out, it would include 1024 mixtures. This level of testing is not feasible within the time and resources available, nor is it necessary. Instead, an approach is suggested where 20 initial mixtures are made and subjected to limited testing and, based on the results of this testing, six revised mixtures will be selected for more detailed testing to complete the Phase II experimental plan.

It is hoped through the Phase II experimental plan proposed herein, relationships can be established between the simpler tests and more advanced tests that can be used for specification development in Phase III of this broader research study. Ultimately, these results could be used to revise standard specifications and special provisions for Nevada DOT bridge decks and eventually reduce the overall incidence of shrinkage cracking.

CHAPTER 7: REFERENCES

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