Development of Specifications for a Crack Resistant Bridge Deck Concrete

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ABSTRACT
Within the past five years, the Colorado Department of Transportation (CDOT) has experienced a continued problem with cracking of bridge decks. In 2003, CDOT implemented the concrete mixture design Class H into the CDOT Standard Specification for Road and Bridge Construction. Class H was developed to provide crack resistant concrete structures and was intended to be used in the construction of bridges and other concrete structures. Recently, the CDOT has noticed cracking in several bridge decks using this concrete specification. This paper includes the design and testing of eleven concrete mixtures in an effort to create a more crack resistant concrete and improve the current specification. The concrete mixtures were designed with water-to-cementitious material’s ratio (w/cm) amounts and cement content both above and below the current specifications. In addition, the design approach was intended to investigate the effect of individual and multiple supplemental cementitious materials replacement levels and aggregate and cement type on the fresh and hardened concrete properties: restrained shrinkage strain, compressive strength, rate of strength gain, freeze/thaw durability, and permeability. A national state Department of Transportation (DOT) survey was conducted to determine other DOT’s current and past research involving crack resistant concrete as well as comments regarding their own specifications currently used for bridge decks. A more crack resistant concrete mixture was developed through this study. The primary recommendations from this research were: increase the maximum allowable w/cm, decrease the cementitious content, increase the percent of allowable fly ash, and include a shrinkage reducing admixture.
INTRODUCTION
If concrete cracks during the early stages after placement, it immediately begins to degrade the structure. Preventing the early age cracking of concrete is especially important to the Colorado Department of Transportation (CDOT). It is the CDOT’s responsibility to maintain a safe network of roads, bridges, and highways throughout the State of Colorado. From public safety to keeping an efficient budget, a durable low cracking potential concrete is very effective in accomplishing both of these objectives. A cracked bridge deck not only diminishes the integrity of the structure but jeopardizes the safety of the travelling public. Substantial damage to the structures integrity begins to occur when cracking in the deck surface allows water to penetrate to the reinforcing steel. The resulting corrosion of steel reinforcement shortens the life span of the bridge and increases maintenance costs while the bridge is in service. These factors are unfavorable, specifically to the DOT.

Winter conditions in Colorado create the need for increased de-icing salt on the road surface to ensure the safety of the traveling public. The increased amounts of deicing chemicals accelerate the corrosion process when melting snow transports the chlorides through the small cracks to the steel reinforcement.

Research has been underway to investigate several factors contributing to the problems surrounding early age cracking in concrete. The CDOT currently has a specification for a low cracking concrete used for bridge decks; Class H concrete. Current specifications require fresh and hardened concrete properties of the concrete to fall within a specific range. While the current Class H specification is an improvement over previously designed bridge deck concrete, the need for enhancement still exists.

The primary objective of this research is to examine and modify the current specification to reduce the cracking tendency of CDOT’s bridge deck concretes. It is believed that the current specifications are creating favorable scenarios for early age cracking. The rate of strength gain, magnitude of ultimate strength, permeability, restrained shrinkage strain, and freeze/thaw durability were tested for each of the designed mixtures and their effects on early age cracking examined. Specifically, eleven, low cracking potential, concrete mixtures were designed, batched, and tested for this study. Fresh and hardened concrete properties were examined and their individual effect on concrete cracking analyzed.

The primary benefit gained from this research is that the CDOT is in a better position to design and construct crack resistant bridge decks and other concrete structures. Results from this study provided valuable information that allowed the CDOT to modify their specifications for future construction. Ancillary benefits from this research include a cost savings to the CDOT. Developing a crack-resistant concrete benefits the CDOT by providing for longer lasting concrete structures and reducing the annual costs to maintain these pavement structures.

BACKGROUND
Transverse cracks are one of the most prominent defects facing many bridge decks. These cracks will typically develop during the early age of newly constructed bridge decks (1). Within the past three decades, the bridge engineering society has made substantial efforts to reduce and even eliminate bridge deck cracking. An investigation by the Federal Highway Administration in 1997 revealed that bridge decks in the State of
Colorado were experiencing cracking problems (2). As a result of this study, several new concrete mixture designs such as Class D, Class DT, and Class SF were implemented in the design of bridge decks. Though these mixtures reduced the size and number of cracks, some deck cracking problems still existed. A research study was undertaken and reported in the document “Development of Optimal Concrete Mix Designs for Bridge Decks.” In this research, nineteen mixture designs were evaluated for their effectiveness in improving concrete durability. Conclusions made from this study include:

- The cement content for the mixtures was reduced from above 600 lb/cy to less than 500 lb/cy.
- The chloride permeability was drastically reduced. Rapid Chloride Permeability Test readings at 56 days of age were reduced from 6000 Coulomb to less than 2000 Coulomb.
- A range in the amount of each material was established to meet the specific need of the CDOT project.
- Data indicated that Class F fly ash produced better durability results than Class C fly ash.

Ultimately, two mixture designs were recommended to the CDOT. The mixtures were for summer and winter usage. The cement content for these mixtures ranged from 465 lb/cy to 485 lb/cy. In addition, Class F fly ash ranging from 20% to 25% was incorporated into the mixture.

A more extensive study on Colorado bridge decks was published in March 2003 (3). The objectives of this study were twofold. First, the extent and causes for bridge deck cracking was investigated. Secondly, concrete material properties, construction practices, and design specifications where examined as to possible causes for bridge deck cracking. A literature review within this study concluded that cracking in early age bridge decks is a result of material, design, construction, and environment. High early age shrinkage was found to be a major cause for this cracking problem. In addition, the structural design had a direct role in cracking as well. Cracks were typically noticed above girders and piers. Placement and curing can have a significant role in cracking, primarily plastic shrinkage cracking.

The Class H concrete mixture was discussed in this study and included in the CDOT standard specifications. Recommendations regarding materials, design factors, and construction practices were included in the Final Report. Cement and silica fume content, water/cement ratio, and the rate of strength gain were key recommendations regarding materials included in the report.

**LITERATURE REVIEW**

*Design Mixture Factors Affecting Cracking in Concrete*

**Supplementary Cementitious Materials**

Substitution of cement with silica fume produces a denser concrete matrix. It results in a more rapid rate of hydration, which is accompanied by a higher heat of hydration and increased early strength development (4). A higher heat of hydration results in higher thermal stresses and reduced bleeding, making concrete more prone to plastic shrinkage (3). Another study by Bissonnette et al (5) claims silica fume is not beneficial in concrete for reducing cracking. Bissonnette et al concluded that the presence of silica fume in
concrete results in increased long term shrinkage. However, the resulting early age increase in shrinkage leads to significant cracking because the tensile strength is so low at early ages (5). Whiting et al suggest not exceeding 6% silica fume replacement of portland cement because it begins to have an adverse effect on shrinkage and cracking (6).

Research concerning the replacement of portland cement with fly ash in a concrete mixture returned contradicting results. Class F and class C fly ash replacement is a very effective method of slowing the rate of C-S-H growth. It reduces early age strength gain and early concrete temperatures while achieving the same or higher ultimate strength (3). Atis and Cabrera reported a decrease in drying shrinkage with the use of fly ash (7). Some studies say both Class C and Class F fly ash replacement in concrete increase drying shrinkage and results in increased early cracking with decreased development of tensile strength (1). The research studied in the literature review is tough to decipher; fly ash replacement have mixed results. Its reduction in the rate of stiffness development is helpful in reducing its potential for cracking (4). While the reports are contradictory, the majority of the literature suggests fly ash is beneficial with regards to concrete shrinkage.

**Water to Cementitious Materials Ratio (w/cm)**

It is generally accepted that drying shrinkage increases significantly as the water content increases. ACI 224 Report states that for a typical concrete specimen, 134 kg/m$^3$ (225 lbs/yd$^3$) water content results in a drying shrinkage of approximately 300 micro strains. In addition, it states that drying shrinkage increases at a rate of 30 micro strain per 5.9 kg/m$^3$ (10 lbs/yd$^3$) increase in water content. An increase in water content showed increased drying shrinkage of approximately 75 micro-strains, indicating that with respect to transverse cracking, mix water content alone was not the significant difference in the performance of bridge decks (8). Similar articles report concrete with a w/cm greater than 0.45 tend to have high porosity and can exhibit substantial drying shrinkage, which results in reduced protection of the reinforcing steel from chlorides (4).

**Cement Content and Type**

Concrete made with higher cement content and a low w/cm is more susceptible to cracking than concrete with low cement content and higher w/cm (3). Xi et al research and other literature suggest limiting cement content to 470 lbs/yd$^3$ (279 kg/m$^3$) and a cement paste volume less than 27.5% can significantly reduce cracking. Proper measures must be taken for concrete made with increased cement content or it can significantly increase cracking (4). Deshpande et al (9) reported the greatest shrinkage occurred in the concrete with a w/c equal to 0.40 (the lowest w/c) and a 60% (lowest) aggregate content. Shrinkage was lowest in the concrete with a w/c equal to 0.40 and having the highest aggregate content of 80%.

Burrows (10) reports that cracking in bridge decks increased in 1973 when the building code increased 28-day compressive strength requirements from 20.7MPa (3000psi) to 31.0MPa (4500psi). The increase in the rate of strength gain causes concrete to become more brittle and likely to crack. Burrows points out that in 1966 Virginia increased its 28-day compressive strength requirements from 20.7MPa (3000psi) to 31.0MPa (4000psi). It was at this time when bridge deck cracking increased from 11% to
29%. Xi et al suggest using Type II cement and avoiding finely ground cement and/or Type III cement (10). Cements with high alkali content, high C₃S and C₃A contents, low C₄AF, and high fineness have an increased development of strength and are therefore more likely to crack. This is another reason the transportation research circular raises caution in using Type III cement for bridge decks (4).

Brewer and Burrows (11) tested three cement clinkers ground to finenesses ranging from 1200 to 2700 cm.² (186 to 419 in.²), in 300 cm.² /g increments. They performed tests similar to ASTM C 1581 but using an apparatus created before the standard was adopted by ASTM. They also performed unrestrained shrinkage tests on mortar bars. Restrained shrinkage tests showed concrete made with coarse-ground cement resisted cracking longer than the more finely-ground cement concrete.

Admixtures
Water reducing admixtures are often used in concrete to increase workability while maintaining a low w/cm, resulting in higher concrete strength. A lower w/cm will result in reduced drying and plastic shrinkage. ACI 212 Committee Report gives detailed information concerning set retarders and set accelerators. Set retarders are sometimes used in bridge deck applications because they offer delayed set times. These retarders allow for continuous placement of bridge decks making the deck less susceptible to cracking due to deflection of the formwork during placement. The delayed set time is also accompanied by lower temperatures during hydration which help reduce cracking due to thermal stresses (4).

Shrinkage reducing admixtures (SRAs) are a new product currently undergoing testing and research. They work by reducing the surface tension of the concrete water which reduces internal stresses thus lowering long-term shrinkage. Concrete in the 50% humidity range develop significant capillary stresses which develop into cracks. SRAs reduce these stresses enough to reduce shrinkage cracking. There has been a significant amount of research on SRAs in laboratory trials; however, limited research was found in which SRAs were incorporated in bridge decks.

Internal Curing Using Light Weight Aggregate
The use of new presoaked lightweight aggregate (LWA) in high performance concrete (HCC) is becoming more common. The aggregate internally cures the concrete as a result of being soaked before batching and contributes to the hydration process instead of absorbing water from the concrete mixture. Research conducted by Cusson and Hoogeveen (12) found that free shrinkage test results prove that as the LWA content increased in the concrete mixtures the autogenous shrinkage decreased. Cusson and Hoogeveen’s research shows how effective internal curing is against shrinkage and tensile stress in concrete, especially high performance concrete. Their results prove the effect of LWA sand replacement on strain and stress reductions. Their data indicates that a 25% LWA concrete could possibly eliminate autogenous shrinkage and tensile stress. Significant swelling did occur in the 20% LWA concrete. As a result, it is not recommended to use more than a 25% LWA concrete because of the possibility of excess swelling (12).
STATE DOT SURVEY FINDINGS
A national survey of state Departments of Transportation was conducted with the objective of obtaining additional information that may aid in the improvement of the current CDOT specification for structural bridge deck concrete. A web-based survey was used to formulate the questionnaire and analyze the responses. A 38% response rate was obtained for the State DOT survey. Responses were received from 19 of the 50 State DOT’s, for a 38% return rate. Multiple state DOT’s provided more than one response. Most of the two-respondent states included responses from both the Materials and Bridge Engineer. The survey returned a total 28 responses.

A majority of respondents, 95.0%, replied that their state does experience bridge deck cracking. Transverse deck, full width cracking is most common and was noted to occur at early ages in many states. The majority of responses identified curing to be the primary cause of cracking. After curing, mixture design, placement, rate of strength gain, and use of admixtures were ranked most to least influential in causing cracks, respectively. Settlement and early-age thermal cracking were mentioned as causes for deck cracking. A majority of states, 42.9%, reported achieving ultimate strength at 7 days. Respondents representing 35.7% claim to achieve ultimate strength at 28 days. A majority of Respondents, 93.8%, replied that their state does not perform AASHTO T334. Many agree that shrinkage is an important issue contributing to cracking; however do not perform any shrinkage measuring tests. Half of the respondents report cement content as the major contributor to bridge deck cracking with respect to mixture design, while 37.5% report the cause to be the w/cm. A common adjustment made by many states is the cement content. Reductions in cement content were mentioned. An approach taken by the Minnesota DOT was to reduce the permeability of the concrete with lower paste contents and higher percentages of SCM's. However, their latest designs involve 100% portland cement. The concern of the Minnesota DOT is that the use of supplementary cementitious materials (SCM's) result in lower tensile strengths in the first several days resulting in concrete unable to resist restraint cracking. Only 21.4% of the responses indicated using shrinkage-reducing admixtures in their states bridge deck concrete. The Michigan DOT abandoned a project involving SRAs claiming it repeatedly “knocked the air out.” Ohio and New York are two of only several states currently utilizing this shrinkage compensating cement. One problem concerning Type K cement is predicting the amount of expansion that will occur. The majority of the respondents, 84.6%, reported having never used shrinkage-compensating cement in their bridge decks. Silica fume was chosen by most respondents as the cause of increased cracking. Blast furnace slag and water reducing admixtures were also selected numerous times. Louisiana suspects they are having problems with the compatibility of materials such as cement, admixtures, and fly ash within their mixture. Set retarders and shrinkage-reducing admixtures were chosen least among the provided choices. Some respondents claim that blast furnace slag and water-reducing admixtures proved beneficial in reducing cracking in bridge decks. In addition, some states claim silica fume to be beneficial against cracking. The Iowa DOT reported having lower shrinkage when slag and Class C fly ash were used as a ternary blend. A majority of respondents, 78.6%, selected 0.40 < w/cm < 0.45 as the range for the maximum allowable w/cm for their State DOT’s concrete bridge deck mixtures.
Curing is mentioned by many respondents to contribute significantly to bridge deck cracking. A significant number of respondents, 81.8%, reported changes in their state’s curing practices of bridge deck concrete. A common response was that an increase in moist-cure (wet cure) times from 7 to 14 days was beneficial. Another is the application of wet burlap within 30 minutes after placement. The Michigan DOT specifies strict fogging, burlap, soaker hose systems for a continuous 7 day wet cure, but reports that enforcement of these specifications is inconsistent. In addition, it was noted that monitoring concrete temperature and protection of the concrete during its early plastic state are essential in minimizing concrete cracking.

In summary, several factors such as cement content and concrete curing were noted as being influential factors resulting in concrete cracking of bridge decks for several DOTs. Reduction in the total cementitious content and 14 day cure times are a few adjustments to the mixture design and curing practices made by State DOTs. Further, many DOTs do not perform shrinkage evaluation tests of any kind on their current bridge deck mixtures.

**EXPERIMENTAL PLAN**

Ultimately, eleven mixtures were developed and tested during this research study. See Table 1. A primary objective was to reduce the early age strength gain. This was accomplished by adjusting the w/cm, cementitious content of the mixture, and percent of pozzolan replacement. In addition, the use of coarse-ground cement was incorporated into several mixture designs.

<table>
<thead>
<tr>
<th>Mix #</th>
<th>Mixture ID</th>
<th>w/cm</th>
<th>Cementitious Content</th>
<th>Type of Cement</th>
<th>%FA</th>
<th>%BFS</th>
<th>%SF</th>
<th>ADMIX.</th>
<th>Air Content (%)</th>
<th>Paste Vol.</th>
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<td>640</td>
<td>Type II</td>
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<td>0.28</td>
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<td>580</td>
<td>Type II</td>
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<td>3</td>
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<td>640</td>
<td>Class G Oil Well Cement (Coarse Grained Cement)</td>
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<td>4</td>
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<td>0.42</td>
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<td>Type II</td>
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<td>611</td>
<td>Type II</td>
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<td>SRA</td>
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<td>11</td>
<td>0.42/6.0/II(NORM.WT.)</td>
<td>0.42</td>
<td>564</td>
<td>Type II</td>
<td>30</td>
<td>6.5</td>
<td>0.25</td>
<td></td>
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</table>

**Table 1 Mixture Design Matrix**

Within the eleven concrete mixture designs are two Class H control mixtures, per current CDOT Structural Concrete Specifications. One mixture contains the highest allowable percentage replacement of portland cement with fly ash and silica fume (and lowest allowable w/cm) and the other with the lowest allowable percentage replacement of cement with the same (and highest allowable w/cm). All of the mixtures take into account aggregate content, effective replacement percentages of portland cement with supplementary cementitious materials, chemical admixtures, and varying w/cm. An air-
entraining agent (AEA) was used to increase durability of the concrete. Air content within these concrete mixtures was expected to coincide with the required percentages per CDOT structural concrete specifications.

**Mixture Design and Materials**

**Cement Type**

Two types of cement were used in this research study. Colorado produced Holcim Type II portland cement was used in the fabrication of several concrete mixtures. In addition, coarse-grained cement supplied by GCC Dacotah Cement from Rapid City, South Dakota, was utilized for two mixtures. This type of cement is a Class G, Oil-well cement. Calcium silicate compounds and other calcium compounds containing iron and aluminum make up the majority of this product. The most notable difference between the two cements is the Blaine fineness. The Blaine fineness for each are 420m²/kg and 325m²/kg for the Type II and Class G cements respectively. In addition, the three day compressive strength for the Type II cement is 28.7MPa (4170psi) and 11.1MPa (1613psi) for the Class G cement. Additional physical and chemical properties for the two cements are published by Cavaliero and Durham (13).

Mixtures #1 (0.38-6.8-FA20-SF5-II) and #3 (0.38-6.8-FA20-SF5-G) are CDOT control mixtures and have identical mixture proportions and w/cm equal to 0.38; however, Mixture #3 is made using the Class G, oil-well cement which is more coarsely ground than Type II cement. Mixture #2 (0.42/6.2/FA16/SF3.5/II) and Mixture #4 (0.42/6.2/FA16/SF3.5/G) are the other CDOT control mixtures but Mixture #4 is again made using the Class G, oil-well.

**Supplementary Cementitious Materials**

Mixture #5 (0.44/6.5/FA30/II), Mixture #6 (0.44/6.5/FA30/SF5/II), and Mixture #7 (0.44/6.5/BFS50/II) have the same w/cm (0.44) but each introduces varying amounts of cement replacement with supplementary cementitious materials; 30% Class F fly ash alone, 30% Class F fly ash and 5% silica fume, and a mixture containing only 50% blast furnace slag. The 30% replacement of cement with Class F fly ash in Mixture #5 exceeds the current allowable CDOT Class H specification replacement percentage of 20%.

**Chemical Admixtures**

Mixture #8 (0.44-6.0-FA30-SRA-II) and Mixture #9 (0.44-6.0-FA30-RET-II) are identical in mixture proportions but each incorporates the use of a chemical admixture. Both mixtures exceed current allowable CDOT Class H and HT specification replacement percentages by having a 30% percent replacement of cement with Class F fly ash. Mixture #8 (0.44-6.0-FA30-SRA-II) utilizes a SRA to help reduce and control the development of shrinkage strain. SRAs are used in the field to help control shrinkage strain development. The SRA used in this research was the Master Builders- Tetraguard and the maximum suggested dosage rate of 1.5gal/yd³ was incorporated. Mixture #9 (0.44-6.0-FA30-RET-II) utilizes a set retarder admixture. These admixtures are often used in the field to delay set time when temperatures are high or traffic delays delivery of fresh concrete. The set retarder was a Master Builders- Pozzolith 100XR and an average dosage of 3 ounces per one hundred pounds of cementitious materials in the mixture.
Aggregate Type
Mixture #10 (0.42-6.0-II-L.W.A) is a 100% portland cement mixture made with a substitution of normal weight sand with 250lbs./yd.\(^3\) of light weight, fine-aggregate. The aggregate was pre-conditioned (pre-soaked) to a moisture content (MC.) of approximately 18%. This was an exceptionally high MC for aggregate but is done so with the intent of internally cure the concrete. The aggregate releases internal water for use in hydration of cement particles over time. Results were expected to be most significant at 56-days of age. Mixture #11 (0.42-6.0-II-Norm.Wt.) was a control mixture for comparison with the lightweight aggregate concrete mixture. Mixture proportions are identical to Mixture #10 (0.42-6.0-II-L.W.A).

Testing Program
Fresh and hardened concrete tests were performed on all mixtures. The fresh concrete properties at the time of batching included slump, unit weight, air content, and temperature. Hardened concrete properties tests included compressive strength at 1, 3, 7, 28, and 56 days of age, rapid chloride ion penetrability at 28 and 56 days of age, freeze-thaw durability beginning at 28 days of age, and restrained “ring” shrinkage until cracking.

EXPERIMENTAL TEST RESULTS
The fresh and hardened concrete properties were tested to evaluate the effects of cement content and type, supplementary cementitious materials type and content, chemical admixtures, water-to-cementitious ratio, and aggregate type on the concrete performance.

Fresh Concrete Properties
Fresh concrete properties for the eleven design mixtures are listed in Table 2. Slump values were increased slightly with the use of Class G, coarse-ground cement. In addition, an increase in slump was also observed when the percentage of cement replacement with fly ash was increased beyond the current replacement levels.

<table>
<thead>
<tr>
<th>Mixture Identification</th>
<th>Slump (in.)</th>
<th>Air Content (%)</th>
<th>Unit Weight (lbs./ft.(^3))</th>
<th>Ambient Temp. (°F)</th>
<th>Concrete Temp. (°F)</th>
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<td>0.38/6.8/FA20/SF5/II</td>
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<td>9.5</td>
<td>137.2</td>
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<td>60</td>
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<td>4.5</td>
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<td>3.5</td>
<td>146.4</td>
<td>72</td>
<td>68</td>
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<td>2.8</td>
<td>147.4</td>
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<td>71</td>
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<td>71</td>
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<tr>
<td>0.42-6.0-II (L.W.A)</td>
<td>2.5</td>
<td>7.5</td>
<td>138.6</td>
<td>72</td>
<td>72</td>
</tr>
<tr>
<td>0.42-6.0-II (Normal Wt.)</td>
<td>2.0</td>
<td>7.5</td>
<td>143.0</td>
<td>66</td>
<td>69</td>
</tr>
</tbody>
</table>
The air content of the mixtures varied between mixtures. The Class G cement didn’t seem to have an effect on air content at w/cm of 0.38. However, at w/cm of 0.42 the air content greatly increased with the Class G cement concrete mixture. A constant AEA dosage rate was utilized. The use of chemical admixtures greatly reduced air content. The shrinkage reducing admixture reduced the air content within the concrete significantly. This phenomenon has been experienced by other DOTs and was noted in the DOT survey conducted by the authors. Increased percent cement replacement with SCMs increased the workability of the mixtures. When necessary, careful addition of HRWRA extended mixing times. Increased time in the mixer deflates the mixture and results in a decreased air content. The set retarder increased air content slightly with only an average recommended dosage rate. Unit weight for all eleven mixtures varied due to the fluctuation in air content. When the design “predicted” unit weight was adjusted for the measured “actual” air content, the revised unit weight was reasonably close to the measured value.

Hardened Concrete Properties
The compressive strength, permeability, freeze-thaw durability and restrained shrinkage of the eleven mixtures were measured to aid in the revision of the current Class H bridge deck concrete specification. The primary objective was to maintain the required level of strength and permeability as required by the current specification and produce a concrete mixture with decreased cracking tendency.

Compressive Strength
The air content for the mixtures varied from the design of 6.5%. Various air contents resulted from the use of chemical admixtures, supplementary cementitious materials contents, and the resulting mixing times necessary to achieve adequate workability of the mixture. The compressive strength and the air content are inversely proportionate; as air content increases compressive strength decreases. In fact, the compressive strength of concrete is decreased 5% for each 1% increase in air content (14). In order to compare the compressive strengths of the mixtures more appropriately, the strengths were normalized to account for the difference in the measured air content and the designed air content (6.5%). Figure 1 shows the normalized compressive strengths for the eleven mixtures.

When normalized for air content, all eleven mixtures achieved the current CDOT Class H specification requiring 4500psi (31.0MPa) at 56-days of age. When examining cement type, the coarse ground cement was more effective at reducing early rate of strength gain as compared to the companion mixtures made with Type II portland cement. This was beneficial as the CDOT had observed a rapid strength gain in many of their field placements of the Class H concrete in recent years.

An increase in the allowable Class F fly ash content from 22% to 30% of cementitious materials was shown to meet the current CDOT compressive strength requirement at 56 days of age. In addition, the increase in the fly ash content reduced early rate of strength gain with slightly higher rates between 28 and 56 days of age when compared to mixtures meeting the upper and lower limits of the specification. Blast furnace slag was found to be particularly effective in developing strength reaching a 56 day strength of 5930psi (40.9MPa).
Mixture 0.44-6.0-FA30-RET-II, slowed strength gain during the first twenty-four hours, but had comparable strengths up to 56 days of age. The shrinkage reducing admixture mixture demonstrated slow strength gain developing a 56 day compressive strength slightly greater than the required.

The internally cured light-weight aggregate mixture had lower strengths through 7 days of age when compared to the normal-weight aggregate mixture; however, surpassed the normal-weight aggregate mixture at 28 and 56 days of age.

**Permeability**

The permeability of concrete develops at various rates and to different magnitudes depending upon the w/cm, cementitious content, and quantity and types of SCMs it contains. Current CDOT Class H and HT specifications require the 56-day permeability not to exceed 2,000 coulombs, or a chloride ion penetrability rating of “low.” The results for all eleven mixtures are shown in Figure 2.

The eleven mixtures tested in this study produced low-to-very low permeability at 56 days of age. The cement study produced mixed results. The coarse grained cement reduced the permeability when compared to the mixture with Type II portland cement at the low w/cm (0.38); however, experienced increased permeability at the higher w/cm (0.42). The increased fly ash content (up to 30%) demonstrated a decrease in permeability between 28 to 56 days of age. In addition, the blast furnace slag mixture demonstrated exceptional permeability with a very low classification at 56 days of age. Though the set retarder and shrinkage reducing admixture mixtures experienced moderate
permeability at 28 days of age, 56 day results were measured below the 2000 Coulomb requirement. Similarities were observed between the light-weight and normal-weight aggregate mixtures. Results for the two mixtures were approximately identical at both 28 and 56 days of age.

**FIGURE 2 Rapid Chloride Ion Penetrability Tests at 28 and 56 Days**

**Freeze-Thaw Durability**
The ability of concrete to resist freeze/thaw cycles translates to durability. A more durable concrete will better resist the harmful effects caused by freeze/thaw cycles. The freeze/thaw resistance test chosen for this research is the ASTM C 666 Procedure A (AASHTO T 161). The results from the freeze-thaw study are shown in Table 3.

**TABLE 3 Freeze-Thaw Durability Test Results**

<table>
<thead>
<tr>
<th>Mixture Number</th>
<th>Mixture Identification</th>
<th># of Cycles</th>
<th>Durability Factor</th>
<th>Air Content %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.38/6.8/FA20/SF5/II</td>
<td>316</td>
<td>101.8</td>
<td>103.3</td>
</tr>
<tr>
<td>2</td>
<td>0.42/6.2/FA16/SF3.5/II</td>
<td>316</td>
<td>106.3</td>
<td>104.3</td>
</tr>
<tr>
<td>3</td>
<td>0.38/6.8/FA20/SF5/G</td>
<td>308</td>
<td>84.8</td>
<td>79.7</td>
</tr>
<tr>
<td>4</td>
<td>0.42/6.2/FA16/SF3.5/G</td>
<td>313</td>
<td>96.0</td>
<td>96.1</td>
</tr>
<tr>
<td>5</td>
<td>0.44/6.5/FA30/II</td>
<td>313</td>
<td>92.2</td>
<td>89.0</td>
</tr>
<tr>
<td>6</td>
<td>0.44/6.5/FA30/SF5/II</td>
<td>308</td>
<td>92.4</td>
<td>86.7</td>
</tr>
<tr>
<td>7</td>
<td>0.44/6.5/BFS50/II</td>
<td>308</td>
<td>72.0</td>
<td>73.9</td>
</tr>
<tr>
<td>8</td>
<td>0.44/6.0-FA30-SRA-II</td>
<td>60</td>
<td>11.3</td>
<td>11.2</td>
</tr>
<tr>
<td>9</td>
<td>0.44/6.0-FA30-RET-II</td>
<td>330</td>
<td>105.2</td>
<td>104.6</td>
</tr>
<tr>
<td>10</td>
<td>0.42-6.0-II (L.W.A)</td>
<td>310</td>
<td>90.1</td>
<td>90.8</td>
</tr>
<tr>
<td>11</td>
<td>0.42-6.0-II (Normal Wt)</td>
<td>310</td>
<td>88.6</td>
<td>86</td>
</tr>
</tbody>
</table>
As expected, the air content had the greatest influence on the freeze-thaw durability of the concrete mixtures. Mixture 0.44-6.0-FA30-SRA-II produced the lowest durability factor with an average value of 11.3. This is the result of a low air content (2.8%). Mixtures 0.38/6.8/FA20/SF5/G, 0.44/6.5/FA30/II, and 0.44/6.5/BFS/II demonstrated good durability factors even with low air contents. This is primarily the result of the low-to-very low permeability they exhibited. All mixtures with the exception of the shrinkage reducing admixture mixture produced durability factors in excess of 60, with values greater considered acceptable.

**Restrained Shrinkage Test Results**

The method used for this study to measure restrained shrinkage was the restrained ring shrinkage test (ASTM C 1581, AASHTO PP34). Current CDOT Class H and HT specifications require concrete mixtures to not crack before 14 days of age. Tests were typically run for 28 to 30 days, and in some cases, 50 plus days. Concrete mixtures were compared on the basis of their individual strain development and magnitude at the time the test was discontinued. A summary of the results from the shrinkage study is listed in Table 4. Mixture 0.44-6.0-FA-SRA-II produced a concrete with the lowest ultimate shrinkage with rings that did not crack. The coarse ground cement was found to reduce the maximum strain; however, the mixtures cracked at an earlier age than their companion mixtures with Type II cement. An increase in the fly ash content to 30% was found to be beneficial in reducing shrinkage with mixtures that excluded silica fume performing better. The light-weight aggregate mixture behaved similar to its companion mixture cracking at approximately the same age and slightly less microstrain.

<table>
<thead>
<tr>
<th>Mixture Identification</th>
<th>Crack at 14-Days</th>
<th>Ring Status &amp; Age at Max. Strain (Days)</th>
<th>Maximum Strain (microstrain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.38/6.8/FA20/SF5/II</td>
<td>No</td>
<td>Ring 1 _39 days</td>
<td>-127</td>
</tr>
<tr>
<td>0.42/6.2/FA16/SF3.5/II</td>
<td>No</td>
<td>Ring2 _29days</td>
<td>-112</td>
</tr>
<tr>
<td>0.38/6.8/FA20/SF5/G</td>
<td>No</td>
<td>Ring1 _16.5 days</td>
<td>-89</td>
</tr>
<tr>
<td>0.42/6.2/FA16/SF3.5/G</td>
<td>No</td>
<td>Ring1 _24days</td>
<td>-94</td>
</tr>
<tr>
<td>0.44/6.5/FA30/II</td>
<td>No</td>
<td>Rings Did Not Crack</td>
<td>-103</td>
</tr>
<tr>
<td>0.44/6.5/FA30/SF5/II</td>
<td>No</td>
<td>Ring 1 _31days</td>
<td>-96</td>
</tr>
<tr>
<td>0.44/6.5/BFS50/II</td>
<td>No</td>
<td>Ring 1 _32days</td>
<td>-113</td>
</tr>
<tr>
<td>0.44-6.0-FA30-SRA-II</td>
<td>No</td>
<td>Rings Did Not Crack</td>
<td>-73</td>
</tr>
<tr>
<td>0.44-6.0-FA30-RET-II</td>
<td>No</td>
<td>Rings 1&amp;2 _36 days</td>
<td>-125</td>
</tr>
<tr>
<td>0.42-6.0-II (L.W.A)</td>
<td>No</td>
<td>Ring 1 _32.5days</td>
<td>-125</td>
</tr>
<tr>
<td>0.42-6.0-II (Normal Wt.)</td>
<td>No</td>
<td>Ring 1&amp;2 _34 days</td>
<td>-134</td>
</tr>
</tbody>
</table>

**REVISION OF CRACK RESISTANT CONCRETE SPECIFICATION**

Recommended adjustments to the CDOT Class H structural concrete specification as a result of this study included an increase in the maximum allowable w/cm from 0.42 to 0.44, an increase in the allowable cement replacement with Class F fly ash from 20 to
30%, and a decrease in the cementitious content to 564 lb/cy. The Class H bridge deck concrete specification was revised in 2011 based upon these recommendations. See Table 5.

### TABLE 5 Class H Structural Concrete Revision

<table>
<thead>
<tr>
<th>Standard Year</th>
<th>Concrete Class</th>
<th>Required Field Compressive Strength (psi)</th>
<th>Cementitious Materials Content: Minimum or Range (lb/cy)</th>
<th>Air Content: % Range (Total)</th>
<th>Water/Cementitious Materials Ratio: Maximum or Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-2011</td>
<td>H</td>
<td>4500 at 56 Days</td>
<td>580 to 640</td>
<td>5 - 8</td>
<td>0.38 - 0.42</td>
</tr>
<tr>
<td>2011</td>
<td>H</td>
<td>4500 at 56 Days</td>
<td>500 to 640</td>
<td>5 - 8</td>
<td>0.42 - 0.44</td>
</tr>
</tbody>
</table>

The major changes to the specification included a reduction in the minimum cementitious materials content, an increase in the allowable fly ash content, the optional use of silica fume and an increase in the maximum w/cm. In addition, an added requirement is the use of wet curing during winter construction.

**CONCLUSION**

A total of eleven concrete mixtures were examined in this study to examine mixture characteristics in an effort to modify the current bridge deck concrete specification. The major findings from this study include:

- A lower w/cm resulted in higher early compressive strengths and rates of strength and strain development.
- Increasing the w/cm to 0.44 and Class F fly ash replacement levels up to 30% was beneficial in controlling strength gain.
- A lower cementitious content mixture with increased w/cm and fly ash replacement proved to be beneficial.
- Class G, coarse-ground cement was beneficial to strain and strength at the higher w/cm of 0.42 and low cementitious materials content. At lower w/cm of 0.38 the cement behaved similarly to the companion concrete mixture using Type II cement, developing strain and strength at an average rate.
- A high dosage rate of a shrinkage reducing admixture is extremely beneficial in controlling both the development rate and ultimate strain of the mixture, while maintaining adequate development of ultimate strength at all ages; however, air content was greatly affected.

**ACKNOWLEDGEMENT**

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**REFERENCES**


