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Low Shrinkage Mix Designs to Reduce Early Cracking of Concrete Bridge Decks

Study SD2018-04
Final Report

Prepared by
South Dakota School of Mines and Technology
Rapid City, SD 57701 **May 2021**

DISCLAIMER

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This work was performed under the direction of the SD2018-04 Technical Panel:

Darin Hodges .... Materials and Surfacing
Marc Hoelscher ....FHWA
Ryan Johnson..........................Operations Support
Steve Kamarainen...................... Rapid City Region
Steve Kerr ....Bridge Design
Aaron Litka.. Research
Bob Longbons .... Research
Margo McDowell..................................... Research
Josh Olson...................................Aberdeen Region
Darin Ormesher .... Research
Tom Strubel ....Bridge Design
Micah Howard ……………………….........Research

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16. Abstract

Concrete bridge decks in South Dakota have reduced services lives due to shrinkage cracking. This study evaluated the effects of varying concrete mix design parameters on shrinkage performance. Tested mix design changes include aggregate type (limestone and quartzite) and gradations (ASTM C33, Tarantula Curve, and 0.45 Power Curve), supplementary cementitious materials (fly ash), cementitious content, water-to-cementitious ratio, internal curing using saturated lightweight aggregates (expanded shale), and shrinkage reducing admixtures. These changes were evaluated for their effect on the shrinkage of paste, mortar, and concrete as measured by ASTM C1698 (autogenous shrinkage), ASTM C157 (drying shrinkage), and ASTM C1581 (restrained drying shrinkage). Fresh property tests, compressive strength, and electrical resistivity measurements were performed on each mix as well. A survey of state Department of Transportations revealed state-of-the-art practices on shrinkage reduction in bridge decks, including the use of admixtures, internal curing agents, and external curing methods. Experimental results indicate that the use of shrinkage reducing admixtures and saturated lightweight aggregates significantly reduced both autogenous and drying shrinkage by up to 84% and 40%, respectively, compared to the control mix. These changes also significantly increased the time to cracking as measured by the ring test. Other tested mix design changes did not significantly affect shrinkage performance compared to the control mix. All mixes met the design compressive strength of 5700 psi at 28 days, except for the mixes incorporating the high dosage of the shrinkage reducing admixture and the air entraining admixture. The durability performance of the concrete as measured by surface electrical resistivity (AASHTO T 358) was improved compared to the control by the majority of changed parameters. Recommended adjustments to the current bridge concrete mix used in South Dakota include the use of well-graded aggregate, a total cementitious materials content lowered to 615 lb/yd^3 including a 20% replacement of cement by weight with Class F fly ash, the use of a shrinkage reducing admixture at the recommended manufacturer dosage, and a 20% replacement by weight of fine aggregate with saturated lightweight aggregate. These mix design changes are anticipated to significantly reduce cracking caused by shrinkage in bridge decks.

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1.0 EXECUTIVE SUMMARY

1.1 Problem Description

Concrete bridge decks in South Dakota are not reaching their expected 20-year service life. Shrinkage is a major contributor to the observed early-age cracking in concrete. The focus of this study is on assessing the impacts of concrete mixture design on autogenous and drying shrinkage. However, it should be noted that construction practices, structural design, and curing of the concrete may also contribute to early deck cracking. This research identifies bridge deck mix designs that best control shrinkage, while maintaining sufficient strength, durability properties, and workability. Additionally, the best test method to qualify low shrinkage concrete was determined.

1.2 Literature Review

Shrinkage of concrete can result in cracking in restrained systems like bridge decks. Shrinkage in bridge decks can be controlled by minimizing cement content, using appropriate amounts of supplementary cementitious materials like fly ash, using quality aggregates with good gradation, using appropriate water-to-cement ratios, using saturated lightweight aggregates for internal curing, and using shrinkage controlling admixtures. A survey of state Department of Transportations revealed state-of-the-art practices on shrinkage reduction in bridge decks, including the use of admixtures, internal curing agents, and external curing methods.

1.3 Materials and Methods

The experimental plan tested a suite of concrete variables to measure their influence on shrinkage cracking including: 1) aggregate type (limestone and quartzite) and gradations (ASTM C33, Tarantula Curve, and 0.45 Power Curve), 2) supplementary cementitious materials (fly ash), 3) cementitious content, 4) water-to-cementitious ratio, 5) internal curing using saturated lightweight aggregates (expanded shale), and 6) shrinkage reducing admixtures. Three shrinkage tests were used to quantify these changes: 1) ASTM C1698 measured autogenous shrinkage on paste and mortars, 2) ASTM C157 measured drying shrinkage on concrete, and 3) ASTM C1581 measured restrained shrinkage and time to cracking for concrete (i.e., the ring test). Additionally, fresh concrete properties (i.e., setting time, air content, slump, density, temperature) and hardened concrete properties (i.e., compressive strength and surface electrical resistivity) were measured.

1.4 Results and Discussion

Experimental results indicate that the use of shrinkage reducing admixtures and saturated lightweight aggregates significantly reduced both autogenous and drying shrinkage by up to 84% and 40%, respectively, compared to the control mix. These changes also significantly increased the time to cracking as measured by the ring test. Other changed parameters including lowering the cement content, adjusting the fly ash content, use of optimized aggregate gradation, and altering the w/cm ratio also slightly improved autogenous and drying shrinkage performance compared to the control, but the shrinkage reduction was not statistically significant. All mixes met the design compressive strength of 5700 psi at 28 days, except for the mixes incorporating the high dosage of the shrinkage reducing admixture and the air entraining admixture. The durability performance of the concrete as measured by surface electrical resistivity was improved compared to the control by the majority of changed parameters. Compared to the current SDDOT A45 mix, the final mixes developed for improved shrinkage behavior used optimized aggregate gradation, a lower cementitious content, shrinkage reducing admixture, and saturated lightweight aggregate. This combination of changes in the mix design resulted in significantly lower autogenous and drying shrinkage, improved resistivity, and improved strength. The recommended mix designs also significantly increased the time to cracking as measured by the ring test.

1.5 Recommendations

1.5.1 Change the A45 mix design for improved shrinkage control

The SDDOT should change their current A45 mix design for bridge decks to include the following changes to improve early-age cracking performance of bridge decks: (1) use of optimized aggregate gradation (either meeting the 0.45 power curve or the tarantula curve), (2) a lower total cementitious material content (maximum of 615 lb/yd^3) with the replacement of 20% by mass of the cement with Class F fly ash, (3) use of SRA (dosage at the manufacturer recommended value), and, if available, (4) the use of saturated lightweight aggregate at a 20% by weight replacement of fine aggregate.

All four of these recommendations significantly improved the autogenous and drying shrinkage behavior of the paste, mortar, and concrete samples tested in this study. They are also feasible changes to implement at concrete batch plants across South Dakota.

1.5.2 Specify a drying shrinkage test of mix design qualification

The SDDOT should specify a drying shrinkage test and limit for mix design qualification for bridge decks.

SDDOT should implement either an ASTM C157 or equivalent AASHTO T 160 test for mix design qualification. This is in accordance with many state DOTs. As autogenous shrinkage and drying shrinkage values were strongly correlated, it is recommended that only drying shrinkage be used to assess shrinkage performance. The ring test (ASTM C1581) could also be used for acceptance as this is a better assessment of the performance of concrete in the field. However, the complexity of this test may inhibit its routine use.

Based on the final mixes, it is proposed for the SDDOT that the 28 day drying shrinkage limit using ASTM C157/AASHTO T 160 be set at a maximum of 285 $\mu\varepsilon$ (0.029%). This proposed limit is stricter than what is currently used by most state DOTs (DOT survey) but should produce better long-term results regarding concrete shrinkage. If a shorter curing time were used for this qualification test than shown in this research, a different limit may be more appropriate. A 56 day limit is likely unnecessary as performance did not change significantly between the two ages.

1.5.3 Consider specifying 56 day strength for Class C fly ash concrete

The SDDOT should consider specifying 56 day strength instead of 28 day strength for concrete mixes that use Class F fly ash.

Due to the lower observed strength in the final mixes and the required use of Class F fly ash in all bridge deck mixes for the SDDOT, it is recommended to allow for later age (56 day) strength acceptance criteria since fly ash tends to mostly react after 28 days, meaning mixes will gain strength at later ages. Alternatively, a lower strength value could be specified for 28 days, with the assumption that the concrete would reach the higher strength at a later age.

1.5.4 Implement additional strategies beyond mix design changes to reduce bridge deck cracking

Beyond changing the mix design requirements for bridge decks, the SDDOT should consider other known strategies for reducing shrinkage cracking.

Other strategies outside of the scope of this research including changes in bridge design (especially allowing more free movement at the abutments), improved construction practices, and strict curing regimes may also improve the shrinkage performance of bridge decks. More information on these additional strategies is provided in the report.

2.0 PROBLEM DESCRIPTION

Concrete bridge decks in South Dakota are not reaching their expected 20-year service life. These bridges often need to be repaired or receive an overlay only after 10 years. It is likely that this significant service life reduction is a direct result of early-age cracking. Bridge deck cracking increases the permeability of the concrete, allowing deleterious ions and moisture to penetrate quickly. This process can result in chemical and physical attack of the bridge deck, including corrosion of the rebar.

Shrinkage is a major contributor to the observed early-age cracking in concrete (Qiao et al.). Many forms of shrinkage can occur in concrete including plastic, chemical, autogenous, carbonation, drying, and thermal shrinkage. The focus of this study is on assessing the impacts of concrete mixture design on autogenous and drying shrinkage. However, it should be noted that construction practices, structural design, and curing of the concrete may also contribute to early deck cracking but are not the focus of this project.

This research will identify bridge deck mix designs that best control shrinkage, while maintaining sufficient strength, durability properties, and workability. Additionally, the research will identify the most reliable and efficient test methods to predict drying and autogenous shrinkage in concrete for future use by the South Dakota Department of Transportation (SDDOT). This will be accomplished using a set of experiments that test a suite of important variables such as: the use of lightweight aggregates, variation in aggregate type (limestone and quartzite), changes to aggregate gradations (ASTM C33, 0.45 Power curve and Tarantula curve), alterations to cementitious materials content, adjustments to supplemental cementitious materials (SCMs) contents, changes to water to cementitious materials (w/cm) ratios and adjustments to admixture dosages of an air entraining admixture (AEA), superplasticizer (SP), and a shrinkage reducing admixture (SRA). Three shrinkage tests can be used to quantify these changes: ASTM C 157 measures drying shrinkage on concrete, ASTM C 1698 measures autogenous shrinkage on paste and mortar, and ASTM C 1581 measures restrained shrinkage and is used to measure cracking tendency between the various concrete mix designs.

3.0 RESEARCH OBJECTIVES

<u>Objective 1. Evaluate and determine the best test methods to predict concrete shrinkage.</u>
Objective 1 was accomplished by a review of published data from a variety of sources including state DOTs, federal agencies, and literature in leading scientific journals. This work resulted in a better understanding of the state-of-the-art in testing methodology for predicting concrete shrinkage. A discussion with other state DOTs provided further insight on their strategies for shrinkage testing. Ultimately, this work helped determine how both the mix designs developed in Objective 2 and produced in the field will be best tested for shrinkage.

<u>Objective 2. Identify effective methods to reduce bridge deck shrinkage cracking by evaluating structural concrete mix designs.</u>
A suite of structural concrete mix designs was tested for shrinkage using the most effective methods identified in Objective 1. Variables to include in the mix design testing were determined from literature review and DOT interviews. Only locally-available materials were tested. Through evaluation of the data and the literature review, the most effective mix designs to prevent shrinkage were determined.

4.0 TASK DESCRIPTIONS

Work was performed to complete the two research objectives via the following 11 research tasks outlined in the RFP. Each of the 11 tasks is summarized herein with the plan to accomplish the respective task by focusing on meeting the two research objectives.

Task 1. Meet with the project's technical panel to review the project scope and work plan.
At the start of the project (April 15, 2019), the researcher met with the technical panel to discuss project scope, schedule, budget, and goals. This meeting included a review of the RFP and this proposal. This meeting clarified contractual obligations of SDDOT and South Dakota Mines for the project.

Task 2. Review and summarize literature on early deck cracking concentrating on mix design.
A three-month search of the cement and concrete literature was performed. The review included results of previous research studies on bridge deck cracking, methods to measure concrete shrinkage, and mix designs to prevent concrete shrinkage. Bridge deck cracking and concrete shrinkage measurement specifications used by other state DOTs and federal agencies were also examined. A brief introduction to some of the DOT studies was provided in the background information. A more in-depth evaluation of these studies was performed during this time.

Task 3. Based on the literature review, prepare an experimental testing plan that includes methods for testing shrinkage, workability, and strength and that considers the following factors in mix design:

- **a. limestone and quartzite aggregate**
- **b. lightweight supersaturated aggregate**
- **c. aggregate gradation**
- **d. cementitious materials**
- **e. cementitious admixtures (e.g. fly ash, silica slag, etc.)**
- **f. cement content**
- **g. water/cement ratio**
- **h. shrinkage-reducing admixtures**
- **i. other options identified in the literature review**

The best method to measure shrinkage of concrete mixtures for SDDOT was sought by evaluation of all current standard procedures including ASTM C596, ASTM C596, ASTM C157, ASTM C341, ASTM C1698, ASTM C1581, and the dual concentric ring test. A decision matrix was created that included ratings for cost, ease of operation, and effectiveness. Additionally, modified versions of these test methods were developed if warranted.

A chosen subset of these test methods was implemented to measure the shrinkage of the concrete mix designs in the experimental plan.

Materials were procured from SDDOT and local materials agencies. Materials characterization data was obtained from the material manufacturers.

In addition to shrinkage testing, mix designs were evaluated using compressive strength testing on mortars and concrete (ASTM C109 and ASTM C39) and by slump testing (ASTM C143) for workability measurements. Darwin et al. recommends the use of low-slump, moderate-strength concrete for low shrinkage, but this approach may not be adequate or desired for SDDOT bridge construction [Darwin 2010].

A thorough literature review determined the final experimental testing plan. However, some of the current understanding regarding the influence of the mix design factors on shrinkage behavior is listed below. Development of the mixture design testing plan involved varying the factors listed below between limits recommended in literature and by the DOT. Software was employed to develop a statistically significant design of experiments given the large number of variables.

Limestone and quartzite aggregate

Two coarse aggregate samples were used in this study provided by the SDDOT. It is known that to prevent shrinkage, the use of hard and stiff aggregates with low coefficients of thermal expansion and low absorption is recommended. Further, the volume of aggregates in the mix design should be as high as practical [Suits 2006].

Lightweight supersaturated aggregate

Guidance from NIST for the use of internal curing using lightweight aggregate was used to develop these mixes (http://ciks.cbt.nist.gov/lwagg.html). One lightweight aggregate was used in this study. In general, internal curing increases the maximum degree of hydration possible by providing extra curing water for hydration. Drying shrinkage is delayed and the concrete will have a greater tensile strength and subsequently, a lower tendency for drying shrinkage cracking. Lastly and most importantly, internal curing mitigates/minimizes autogenous shrinkage and related cracking/durability issues.

Aggregate gradation

Recommendations from the SDDOT study [SD2002-02] on optimization of aggregate gradation for structural concrete wereused as a starting point. This report recommended the use of the 0.45 power chart to develop optimize aggregate blends. However, more recent advances in aggregate optimization should be evaluated. For example, the Tarantula curve was evaluated as a potential method to optimize aggregate gradation (http://www.tarantulacurve.com/).

Cementitious materials

Type I/II and Type V cement were both included as these are commonly used by the SDDOT.

Cementitious admixtures (e.g. fly ash, silica slag, etc.)

Originally, the low-cracking high-performance concrete (LC-HPC) described in the literature review contained 100% cement [Darwin 2016]. This concrete design also recommended low cement paste contents, limits on aggregate properties, and lower concrete slumps. However, the inclusion of fly ash, slag, and fine silica was later found to improve cracking performance. Only Class F fly ash was considered for this study due to availability.

Cement content

Typically, lower amounts of cement in a concrete will reduce shrinkage because there is less paste available to shrink. Further, its heat of hydration is also reduced. A range of cement contents were tested to determine if the low cement contents recommended in LC-HPC (less than 540 lb/yd^3) is beneficial for shrinkage control using local cements.

Water/cement ratio

More water should be used to reduce autogenous shrinkage while less water should be used to reduce drying shrinkage. These conflicting recommendations make the selection of an appropriate w/c difficult. For this project a range of w/c from 0.38-0.42 was tested.

Shrinkage-reducing admixtures

These admixtures have been shown to be a useful tool to control cracking in bridge decks by the Virginia DOT when used in combination with lower cementitious contents (Nair 2016). Later in the experimental plan, shrinkage-reducing admixtures were added to certain mixes to assess their influence on shrinkage behavior.

Other options identified in the literature review

The significant variables known to control shrinkage are already listed above. However, any other variables found to influence shrinkage were considered in the development of the experimental design.

Mixes were developed using the SDDOT A45 concrete specifications as a baseline (see Table 1). A draft testing matrix is show below in Table 1. The final matrix was developed over the course of Task 3. Mixes were tested for 28-day strength (to reach 4500 psi), slump, and using two of the chosen shrinkage tests.

Table 1: Concrete Specifications for A45 Concrete

<table>
<tr><th>Minimum Cement Content[1] (lb/yd^3)</th><th>Max W/CM</th><th>Slump (in)</th><th>Entrained Air Content (%)</th><th>Miniumum Coarse Aggregate Content (%)</th><th>Minimum 28-Day Compressive Strength (psi)</th></tr>
<tr><td>650</td><td rowspan="2">0.45</td><td rowspan="2">1-4.5</td><td rowspan="2">5.0-7.5</td><td rowspan="2">55</td><td rowspan="2">4500</td></tr>
<tr><td>615 if well graded[2]</td></tr>
<tr><td colspan="6">[1]The maximum cementitious content including cement and SCMs shall be 800 lb/yd^3. Class F fly ash can replace between 20-25% percent by weight of cement</td></tr>
<tr><td colspan="6">[2]0.45 Power Gradation is used to conform to a well graded concrete mix</td></tr>
</table>

Table 2: Draft Testing Matrix

Sample #	Description	W/CM	Cement Type	Cement Content (lb/yd^3)	SCM Type	SCM % Replacement	Aggregate Type	Aggregate Content (%)	Aggregate Gradation	Admixtures
1	Baseline 1	0.45	Type I/II	650	N/A	N/A	Limestone	55	Standard	AEA,SP
2	Baseline 2	0.45	Type I/II	650	N/A	N/A	Limestone	55	0.45 Power	AEA,SP
3	Baseline 3	0.45	Type I/II	650	N/A	N/A	Quartzite	55	Standard	AEA,SP
4	Baseline 4	0.45	Type I/II	650	N/A	N/A	Quartzite	55	0.45 Power	AEA,SP
5	Change Gradation 1	0.45	Type I/II	650	N/A	N/A	Quartzite	55	Tarantula	AEA,SP
6	Change Gradation 2	0.45	Type I/II	650	N/A	N/A	Limestone	55	Tarantula	AEA,SP
7	Change Aggregate Content	0.45	Type I/II	650	N/A	N/A	Quartzite	70	0.45 Power	AEA,SP
8	Change Aggregate Content	0.45	Type I/II	650	N/A	N/A	Limestone	70	0.45 Power	AEA,SP
9	Lightweight Aggregate	0.45	Type I/II	650	N/A	N/A	Lightweight	55	0.45 Power	AEA,SP
10	Cement Content 1	0.45	Type I/II	450	N/A	N/A	Limestone	55	0.45 Power	AEA,SP
11	Cement Content 2	0.45	Type I/II	550	N/A	N/A	Limestone	55	0.45 Power	AEA,SP
12	Cement Content 3	0.45	Type I/II	750	N/A	N/A	Limestone	55	0.45 Power	AEA,SP
13	SCM 1	0.45	Type I/II	650	Fly Ash	20	Limestone	55	0.45 Power	AEA,SP
14	SCM 2	0.45	Type I/II	650	Fly Ash	30	Limestone	55	0.45 Power	AEA,SP
15	SCM 3	0.45	Type I/II	650	Fly Ash/Microsilex	20 + 5	Limestone	55	0.45 Power	AEA,SP
16	W/CM 1	0.4	Type I/II	650	N/A	N/A	Limestone	55	0.45 Power	AEA,SP
17	W/CM 2	0.43	Type I/II	650	N/A	N/A	Limestone	55	0.45 Power	AEA,SP
18	Shrinkage Reducing Admixture	0.45	Type I/II	650	N/A	N/A	Limestone	55	0.45 Power	AEA,SP, SRA
19	Final Mix Testing	Values adjusted to change variables that had greatest impact in reducing shrinkage								
20	Final Mix Testing	Values adjusted to change variables that had greatest impact in reducing shrinkage								
21	Final Mix Testing	Values adjusted to change variables that had greatest impact in reducing shrinkage								
22	Final Mix Testing	Values adjusted to change variables that had greatest impact in reducing shrinkage								

Task 4. Submit a technical memorandum and meet with the project's technical panel to present findings of Tasks 2-3.

A technical memorandum reporting the results of Tasks 2-3 was submitted on July 11, 2019. Findings from these tasks were presented to the project technical panel. The panel collaborated with the PI and graduate student to reach a finalized testing plan. A revised memo was submitted in August 2019.

Task 5. Upon panel approval of the technical memorandum, test a subset of the mix designs in the approved experimental testing plan to demonstrate adequate lab setup, procedure, staffing, and test sensitivity.

Using the recommendations from Task 3, eighteen approved mix designs were tested in accordance with the chosen test methods. The lab setup, procedure, and staffing, and test sensitivity were documented and shown to the technical panel. Test sensitivity was evaluated by conducting multiple trials of the same mix design and test procedure and comparing results.

Task 6. After completion of the subset testing, submit a technical memorandum and meet with the project's technical panel to present findings.

The PI and the graduate student submitted a technical memorandum presenting findings from Task 5 to the technical panel on September 14, 2020. Discussion on the results informed the selection of final fix designs to be tested in the lab.

Task 7. Upon panel approval of the technical memorandum, complete testing of the remaining mix designs.

Final mix designs were tested in accordance with recommendations from the technical panel.

Task 8. Analyze test results to identify effective methods to reduce bridge deck shrinkage cracking.

All collected data was analyzed using statistical methods to determine the significance of the impact of mix design parameters on shrinkage, strength, and workability performance. Using the results of this analysis in conjunction with literature review results, the most effective methods to measure concrete shrinkage and reduce concrete shrinkage cracking in bridge decks were determined and reported.

Task 9. Submit a technical memorandum and meet with the project's technical panel to present findings of Tasks 7-8 and solicit panel feedback.

The PI submitted a technical memorandum reporting the results of all mix design testing on January 25, 2021. Findings were presented to the technical panel. Discussion and analysis of these results informed recommendations included in the final report.

Task 10. In conformance with Guidelines for Performing Research for the South Dakota Department of Transportation, prepare a final report summarizing the research methodology, findings, conclusions, and recommendations.

A first draft of the final project report was submitted on April 12, 2021.

Task 11. Make an executive presentation to the South Dakota Department of Transportation Research Review Board at the conclusion of the project.

An executive presentation was delivered to SDDOT's Research Review Board on April 26, 2021. The principal investigator summarized the project's findings and presented recommended changes to SDDOT's A45 concrete mix design and qualification testing practices.

5.0 FINDINGS AND CONCLUSIONS

5.1 Literature Review

A literature review was conducted to evaluate the effect of individual components of the concrete mix on shrinkage performance, compare the current methods available to assess shrinkage performance, and analyze previous studies performed by other state DOT's. A nationwide survey of state DOT's current practices/ procedures on mitigating bridge deck shrinkage cracking, including material, test methods, and limits placed on associated standards was also conducted; full survey results are given in Appendix A.

5.1.1 Concrete Shrinkage

Portland cement concrete exhibits both elastic and viscous (time-dependent deformation) behavior, making it a viscoelastic material. Shrinkage of concrete contributes to its time-dependent deformation. Concrete undergoes many forms of shrinkage that have various underlying mechanisms. Regardless of the mechanism, if shrinkage strain is unrestrained, it will not develop stresses in the concrete. If the shrinkage is restrained, it will develop tensile stresses in the concrete. A concrete will undergo cracking when its internal tensile stress exceeds its tensile strength. These shrinkage cracks can compromise the long-term performance of the concrete.

There are six primary types of shrinkage that can be manifested in concrete (Mehta et al.):

1) Plastic – shrinkage strain associated with early moisture loss in plastic concrete
2) Chemical – shrinkage strain caused by volumetric change due to the reaction of water with cement
3) Autogenous – shrinkage strain caused by volumetric change due to self-desiccation when insufficient water is available for reaction with the cement
4) Carbonation – shrinkage strain resulting from the reaction of concrete with carbon dioxide in the air
5) Drying – shrinkage strain in hardened concrete caused by the loss of water in the hydrated cement paste (HCP) due to environmental conditions
6) Thermal – shrinkage strain caused by temperature changes (shrinkage due to lower temperatures)

The primary focus of this study is on measuring the autogenous and drying shrinkage behavior of concrete, selected by the SDDOT based on their field observations. The other types of shrinkage listed can also influence cracking in bridge decks but are not included in this research.

5.1.1.1 Autogenous Shrinkage

Autogenous shrinkage is caused by volumetric change due to self-desiccation when insufficient water is available for reaction with the cement paste (Mehta et al.). Self-desiccation is defined as "the reduction in internal relative humidity of a sealed system when empty pores are generated. This occurs when chemical shrinkage takes place at the stage where the paste matrix has developed a self-supportive skeleton, and the chemical shrinkage is larger than the autogenous shrinkage" (Persson et al.). Autogenous shrinkage in concrete causes tensile stresses in the cement paste due to aggregate or other forms of restraint (Lura).

Self-desiccation is most relevant in normal concrete with w/cm < 0.42 (Mehta et al.). In High Performance Concrete (HPC), with w/cm ≤ 0.40, the rate of hydration is significantly reduced due to self-desiccation (Persson et al.). Represented in Figure 1 are the resulting stresses formed around the empty pore spaces after the water has been consumed.

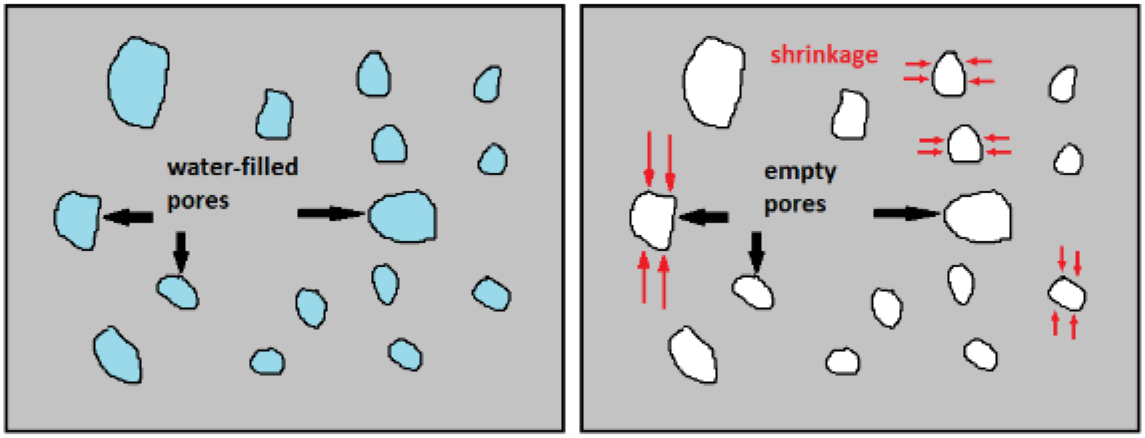


Figure 1: Visualization of Autogenous Shrinkage in Concrete

Directly related to autogenous shrinkage is chemical shrinkage, which manifests from the volumetric change due to hydration of cement with water. Chemical shrinkage causes a successive emptying of the pore structure and can lead to tensile stress in the pore solution through the formation of menisci at the air/pore solution interface. This is particularly problematic in concrete with low water to cementitious material ratios because of the lack of available water to satisfy the chemical reaction leading to bulk shrinkage of the concrete.

As the capillary tension increases, autogenous shrinkage of the matrix occurs, exclusive of chemical shrinkage. Changes in surface tension and disjoining pressure in the water/air menisci created in these capillary pores have also been proposed as mechanisms leading to this autogenous or self-desiccation shrinkage (Mehta et al.). The magnitude of stress is related to the size of the pores being emptied (i.e. related to initial w/cm and use of finely divided (SCMs)). As the pores are decreased in size the magnitude of stress is increased. Deformations produced during autogenous shrinkage may easily exceed 1000 µ-strain, which can lead to cracking if the member is restrained (Khairallah). The relationship of chemical and autogenous shrinkage to setting time is shown in Figure 2.

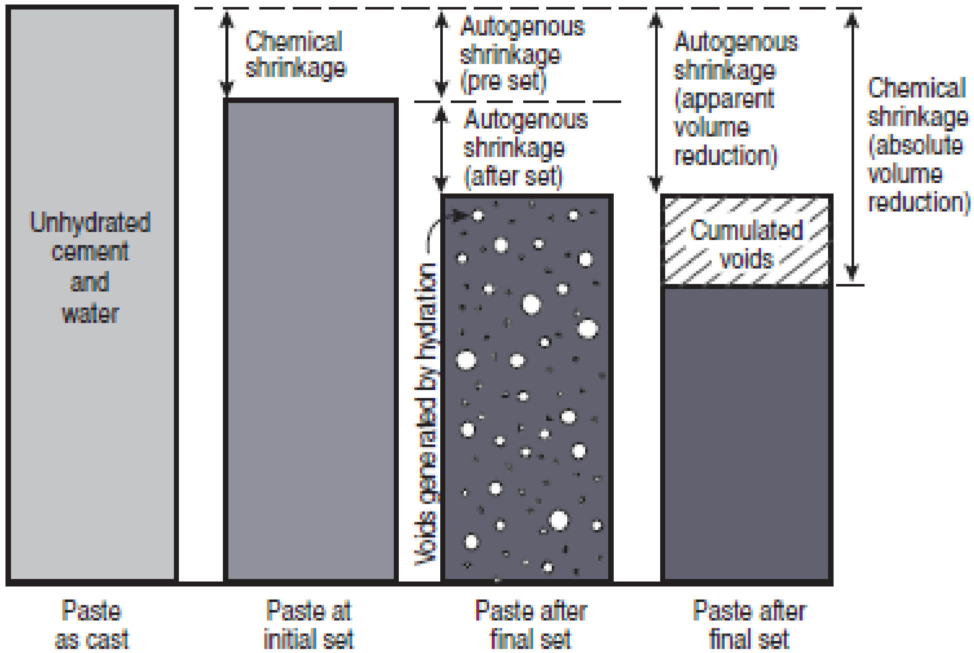


Figure 2: Shrinkage Related to Setting Time (Kosmatka et al.)

Traditional curing methods of water ponding are not effective against autogenous shrinkage, because the penetration of water from the external surface is limited. Self-desiccation can be limited or avoided by internal curing of the paste with water reservoirs (e.g., saturated lightweight aggregates or super absorbent polymers).

5.1.1.2 Drying Shrinkage

Drying shrinkage results from the movement and loss of water in hardened concrete due to environmental conditions (i.e., low external relative humidity) (Mehta et al.). This process results in new bonds forming in the calcium silicate hydrate (C-S-H) in the hydrated cement paste and an overall reduction in volume. Figure 3 shows how shrinkage will occur in concrete due to a reduction in relative humidity. There are three potential phenomena that are believed to contribute to drying shrinkage: (1) capillary stress, (2) disjoining pressure, and (3) changes in the surface free energy (Lindquist). These are related to the porosity and pore structure in the HCP, Van der Waals bonding in the C-S-H, the high surface area of the C-S-H, and the microporosity of the C-S-H (Han et al.) (Mehta et al.).

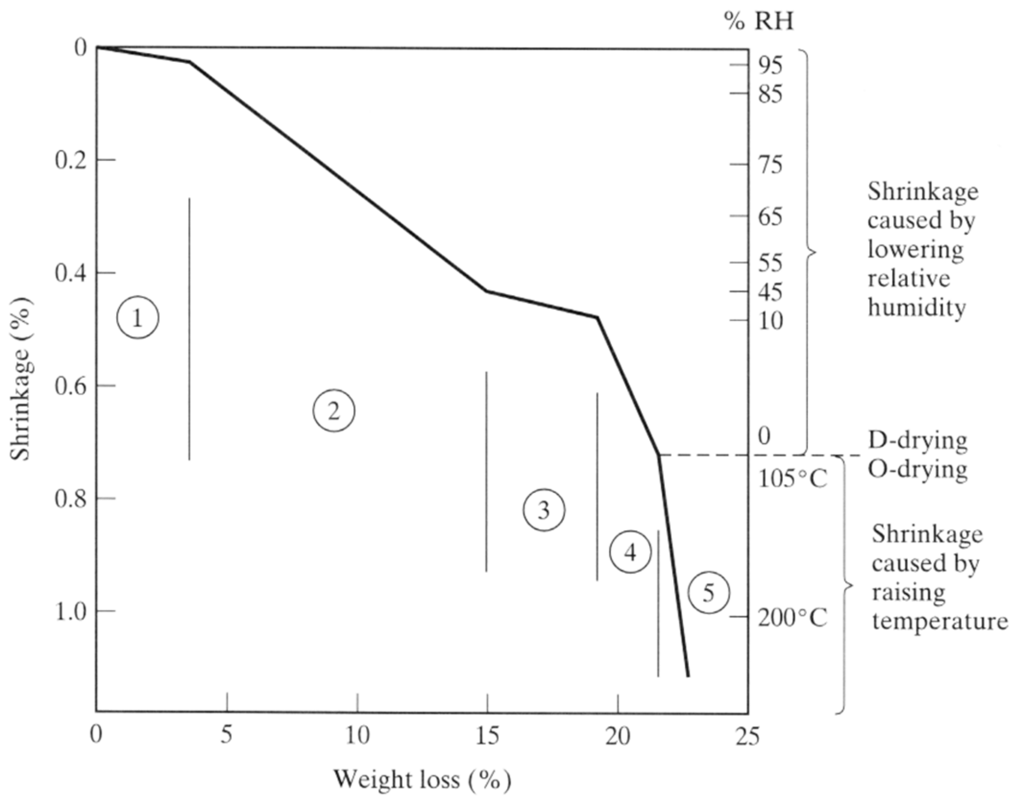


Figure 3: Shrinkage-water Loss Relationship for Cement Paste During Drying (Mehta et al.)

Inadequate allowance for drying shrinkage can lead to cracking. For example, joints are sawn into pavements to define where drying shrinkage cracks will form rather than allowing for random crack formation. These joints can then later be sealed to prevent water ingress.

5.1.2 Factors Affecting Autogenous and Drying Shrinkage

To develop concrete that can be subjected to large deformations without cracking, one must develop a concrete with high “extensibility”. In theory, concretes with a high degree of extensibility will have a low elastic modulus, high creep, and high tensile strength. Concrete with some of these properties may be less desirable for use in bridge decks. Still, in general low-strength concrete tends to have less cracking compared to high strength concrete due to these properties.

In more practical terms, general, cracking can be controlled in bridge decks using the following mix design rules of thumb (Suits et al.):

- Minimization of cement content
- Use of hard aggregates with a volume as high as practical with low coefficients of thermal expansion
- Use of lightweight aggregates for internal curing
- Use of fly ash or slag
- Use of shrinkage controlling admixtures

Autogenous shrinkage is particularly problematic in low w/c pastes (where w/c<0.36 to 0.42), where cements are finer, and where silica fume or metakaolin is used. To reduce autogenous shrinkage the following strategies are recommended:

- Use higher w/cm
- Eliminate silica fume or metakaolin
- Use coarser cement
- Use internal curing agents
- Use shrinkage reducing chemical admixtures

Drying shrinkage can be reduced by placing concrete with the lowest possible water content capable of achieving the desired mix design. Other recommended strategies to reduce drying shrinkage include the following:

- Use lower w/cm
- Use a larger fraction of aggregates and lower cement content
- Use stiffer aggregates

Reducing the excess water in the mixture can be achieved in part through choosing aggregates that are well-graded, have low-absorption, and have less surface texture. Addition of water added at the job site must also be prohibited (Rettner et al.). The following section highlights some of the factors affecting autogenous and drying shrinkage that were later addressed in this study.

5.1.2.1 Water to Cementitious Materials Ratio

When focusing on mitigating autogenous and drying shrinkage, adjusting the w/cm ratio has conflicting outcomes. Increasing the water content provides a higher likelihood that sufficient water will be available to complete the reaction with the cement, potentially eliminating autogenous shrinkage. On the other hand, increasing the water content will increase the strain caused by the loss of the absorbed water, raising the drying shrinkage potential. Concretes with high w/cm ratios (i.e., > 0.45) tend to have a high permeability, essentially reducing protection of reinforcing steel from chlorides, and they can show significant drying shrinkage (Khan).

The stoichiometric amount of water required for hydration of cement in a closed system corresponds to a w/cm ratio of 0.42. With a lower w/cm ratio, the lack of water stops cement hydration, leaving anhydrous cement particles in the hardened cement paste. If water is allowed to penetrate into the hardening cement paste (open system), the w/cm ratio needed to obtain full hydration is reduced to 0.36 (Lura). The C-S-H gel consumes the water expanding outward from the cement particles, creating the internal pore structure of the concrete. This process continues only if water (and cement) is available for the reaction. As stated earlier, concrete with w/cm ratios below 0.42 have an increased susceptibility to chemical and/or autogenous shrinkage cracking because of the reduced available water. On the other hand, excess water in the mix can evaporate at low atmospheric relative humidity, leading to greater drying shrinkage.

5.1.2.2 Cement Content

The cement content of a concrete mix can have a significant effect on its shrinkage performance. A smaller paste fraction decreases the potential amount of shrinkage in the concrete since only the paste undergoes volume change. During hydration at early ages, the cement paste is most susceptible to chemical and autogenous shrinkage. Crack surveys conducted in Kansas over a 10-year period suggested the bridges in their study should limit the total paste volume in the concrete, which is correlated to cement content, to less than 27% (Darwin et al.). Minnesota, Illinois, and Kansas reports along with research conducted by (Schmitt et al.) suggest maintaining a paste volume of 27% is optimal for HPC used on bridge decks.

The phase one results from a CODOT study recommended a cement content between 450-485 lb/yd^3 when blended with other SCMs for mitigating shrinkage. The mixes from this study that had the highest cracking resistance measured from the AASHTO T 334 ring test are listed in Table 3. Two significant correlations stemmed from the 30+ mixes in this study. First, increased cracking resistance was correlated with lower cement content with the paste volume below 27% and, second, lower concrete strengths (near 4000 psi) was correlated with lower shrinkage. In general, lower cement contents will also yield lower strengths.

Table 3: Summary of Highest Cracking Resistant Concrete Mixes from CODOT (Xi et al.)

		Mix 1	Mix 2	Mix 3	Mix 4
Cement content (lb/yd^3)		450	450	450	450
Class F fly ash lb/yd^3 (% of cement)		90 (20)	90 (20)	112.5 (25)	112.5 (25)
Silica Fume lb/yd^3 (% of cement)		18 (4)	18 (4)	18 (4)	18 (4)
W/(C+M)		0.37	0.41	0.37	0.41
Sand (lb/yd^3)		1480	1458	1450	1426
Gravel (lb/yd^3)		1595	1595	1595	1595
HRWR (oz/100 lb cement)		12	6.7	10	10
Micro Air (oz/100 lb cement)		5.64	5	3.36	1.34
Retarder (oz/100 lb cement)		3.75	3.75	3.75	2.65
Slump (inch)		3	2	1	2.5
Air content (%)		9	7	4.5	8
Permeability at 28 days (Coulomb)		2309 3352	4764 4123	3265	3115 3252
Permeability at 56 days (Coulomb)		1560	1430	1385 1578	2278 2339
First Cracking (days)		34	67	30	30
Compressive Strength (psi)	28 days	3837	3900	5573	3949
	56 days	3790	4326	6130	4570

Although a study on the influence of cement type on shrinkage is out of the scope of this study, Type-K cement has shown significant potential for mitigating early-age cracking. Type-K cement expands during early-age hydration producing compressive stresses in the concrete and reduces the onset of cracking in bridge decks (Rahman et al.). The cement type used in this study is limited to Type-I/II, which is commonly used in South Dakota for bridge decks.

5.1.2.3 Aggregate

One of the most important influences on shrinkage is aggregate. The aggregate restrains shrinkage of the cement paste. First, the use of hard aggregates (quartz, dolomite, and limestone as compared to sandstone) results in decreased shrinkage (Khan) Second, increasing the aggregate content reduces the paste volume and potential shrinkage. Aggregates provide restraint because they do not undergo volume changes due to changing moisture conditions. In general, shrinkage is reduced when concrete contains a coarse aggregate volume as high as is practical. Zhang et al. conducted laboratory experiments to study the effects of the coarse aggregate volume content on drying shrinkage. This study discovered that the increase of coarse aggregate from 50 to 70% reduced drying shrinkage by a factor of two with a w/c ratio of 0.43 (Zhang et al.).

Figure 4 shows the effects that increased coarse aggregate content has on drying shrinkage. The blue circles represent internal reinforcement and shows crack formation above the reinforcement in the concrete with the smaller coarse aggregate fraction as stated by (Alhmood et al.).

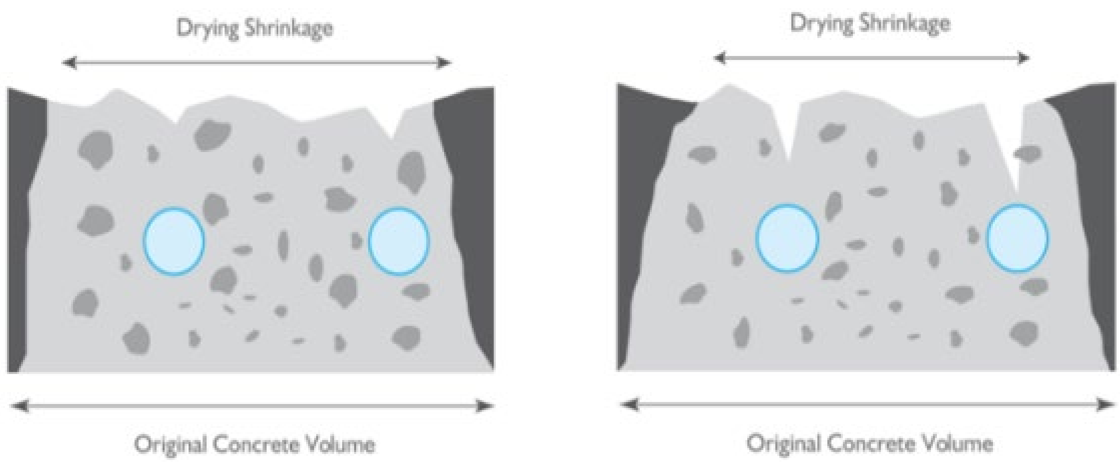


Figure 4: Reduction of drying shrinkage cracking over reinforcement with increased coarse aggregate (left) and increased cracking with lower coarse aggregate fraction (right)(Mohan)

5.1.2.3.1 Gradation Curves

One strategy to reduce the paste fraction of a concrete mix, and subsequently shrinkage, is to use an optimum gradation of aggregates. Both of the following gradation techniques can be used to blend different aggregates for an optimum maximum density.

5.1.2.3.1.1 0.45 Power Maximum Density Curve

The 0.45 power chart is a cumulative percent-passing grading curve in which the horizontal axis is marked off in sieve-opening sizes raised to the 0.45 power. The maximum density curve shown in Figure 5 appears as a straight diagonal line from zero to the maximum aggregate size for the mixture being considered. The 2015 SDDOT specification for roads and bridges allows the use of two curves for bridge deck concrete, with upper and lower limits for each sieve size as viewed in Table 4. A 2004 investigation conducted by the SDDOT assessing the applicability of using the 0.45 power chart for concrete concluded that “because of the intermediate particles, the concrete mix incorporating the 0.45 power chart gradations gave the best workable mix with the maximum strength” (Ramakrishnan).

Table 4: SDDOT Limits for Using the 0.45 Power Gradation Curve (Khan)

Sieve	1" 0.45 Power Gradation	
	Upper Limit	Lower Limit
1.5"	...	…
1"	100	92
3/4"	96	80
1/2"	81	65
3/8"	72	56
#4	55	39
#8	42	26
#16	33	17
#30	27	11

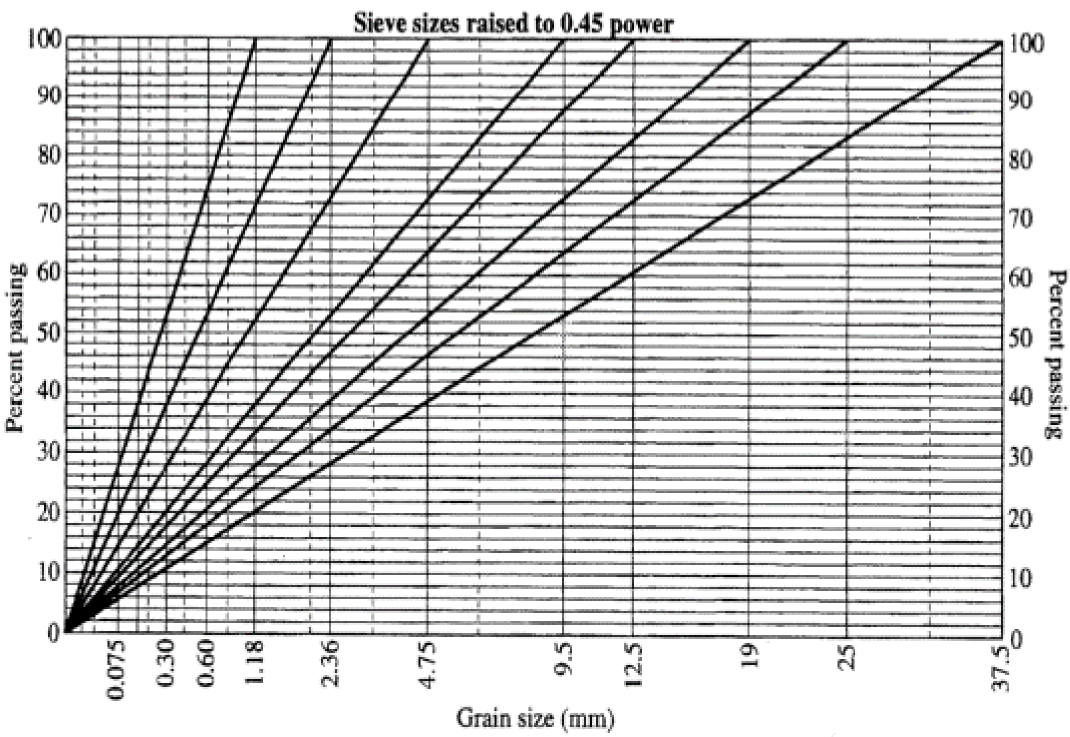


Figure 5: Maximum Density Curves for 0.45 Power Gradation Graph, Each Curve is for a Different Maximum Aggregate Size.

5.1.2.3.1.2 Tarantula Curve

The Tarantula Curve is a tool for proportioning an optimized combination of aggregate focused on maintaining the workability of the concrete mix (Cook et al.). Optimizing aggregate blends minimizes the paste content and provides a dense, workable, and easy to place concrete. The Tarantula Curve provides a recommended maximum limit and a suggested minimum limit for each sieve size as shown in Figure 6.

- The combined gradation must be within the boundary limits for each sieve size.
- The total volume of coarse sand (#8-30) must be a minimum of 15%.
- The total volume of fine sand (#30-200) must be within 25% and 34%.
- Limit the flat or elongated coarse aggregate to 15% or less at a ratio of 1:3 according to ASTM D4791.

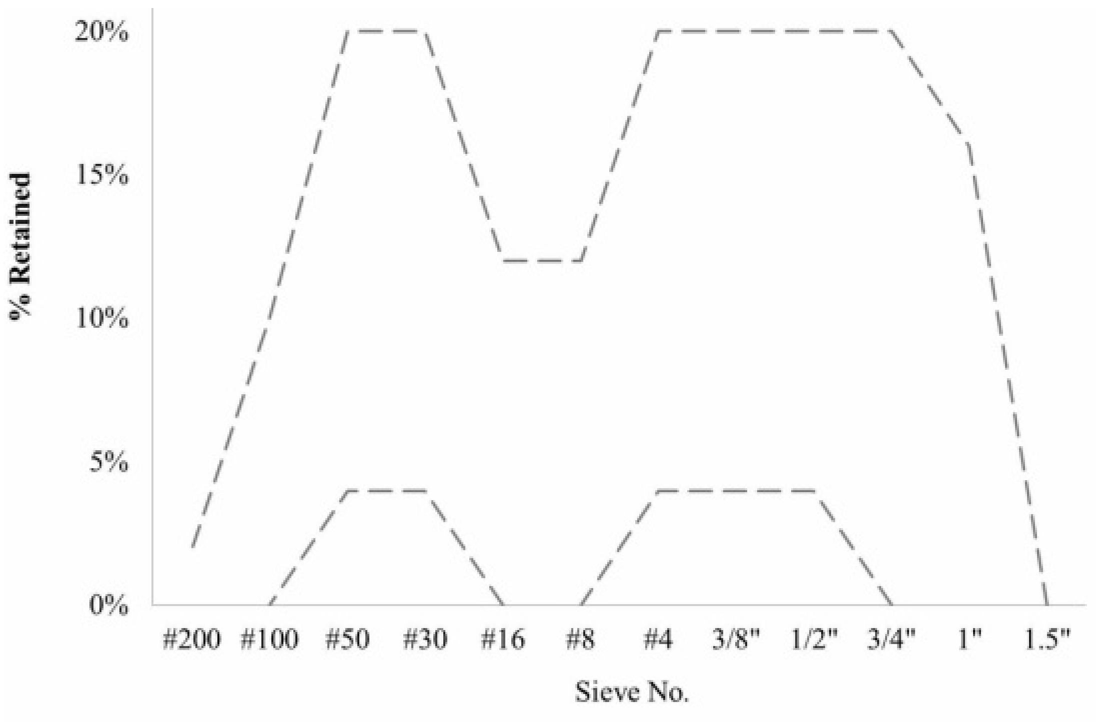


Figure 6: Minimum and Maximum Limits of Aggregate Gradation for the Tarantula Curve (Cook et al.)

5.1.2.3.2 Lightweight Aggregate

The largest amount of chemical/ autogenous shrinkage happens within the first few days of cement paste hydration. Internal curing agents provide additional 'curing water' to the paste without changing the design w/cm ratio (Yang et al.). Some example internal curing agents include superabsorbent polymers, lightweight aggregate (LWA), and wood-derived materials. The benefits from using internal curing include the following (Persson et al.):

1. Provides sufficient water to hydrate all the cement. In low w/c ratio mixes (under 0.43 and increasingly those below 0.40) replacing some of the sand with LWA supplies the additional water to the paste/mortar fractions.
2. Substantially eliminates autogenous shrinkage by supplying water, increasing the relative humidity and reducing self-desiccation potential.
3. Keeps the strength of the mortar and the concrete at early ages high enough to limit cracking due to internally and externally induced strains.

Several programs have investigated early-age shrinkage (autogenous, chemical, and drying) of HPC and mitigation with saturated LWA. The replacement of even a small volume of fine aggregate with saturated lightweight aggregate can reduce shrinkage. One study found that a 6% replacement of the fine aggregate with saturated LWA decreased autogenous shrinkage by 33% with insignificant impact on fresh concrete properties and strength. Another experimental program showed a 20% replacement drying and autogenous shrinkage without compromising 28 day compressive strength (D'Ambrosia et al.).

Autogenous shrinkage was practically eliminated by the use of wet LWA when a sufficient replacement of normal weight aggregate with pre-wetted LWA was used (Lura). For example, (Souslikov et al.) has shown that the addition of a small amount (less than 50 lb/yd^3) of saturated lightweight aggregate (pumice) containing about 50% volume porosity ranging in size from approximately 1/16 in. to 3/16 in. has been shown to reduce autogenous shrinkage with negligible influence on compressive strength (i.e. either no change or a reduction of 10%) (Souslikov et al.). Further, this technique allows the use of a low w/cm ratio because of the additional water supplied by the aggregates to the paste, which can produce a dense, crack-free microstructure, thus avoiding the detrimental effects of autogenous shrinkage (Henkensiefken et al.).

The internal curing process requires uniform spatial distribution of the 'water reservoirs' in the mixture. The distance of the saturated LWA from the point in the cement paste where the RH-drop takes place determines the efficiency of the internal curing. The estimated maximum transport distance of water, in low w/cm mixes, is a few hundreds of micrometers (Lura).

A study conducted in 2018 evaluated the effects of varying LWA replacement on autogenous shrinkage measured by ASTM C1698. The LWA replacement was tested at 0, 25, 50, 75, and 100%. For all three series, the 75% replacement at seven days produced an average microstrain of -11.1. The ternary blend containing 0.36 w/cm showed that replacement levels from 50 to 100% produced microstrain measurements from -44 to -11. The final series (0.42 w/cm) at seven days still produced minor expansion for the 75 and 100% replacement (10.7 and 51με), and only -11με for the 50% (Montanari et al.).

5.1.2.4 Supplemental Cementitious Materials

The use of SCMs in concrete can have several benefits: improved workability, reduction in water demand, and increased durability depending on the type of SCM used. This section is a brief overview of the use of fly ash and silica fume in concrete and their effects on shrinkage.

5.1.2.4.1 Fly Ash

The use of fly ash as a replacement of ordinary portland cement has been shown to affect the shrinkage properties of concrete. Benefits from fly ash usage include reduced water demand, a lower heat of hydration, and improved durability and workability. Typically, a Class F fly ash performs better than Class C regarding durability (Xi et al.). It also decreases autogenous shrinkage and increases the restrained shrinkage cracking age (Subramaniam et al.).

The National Institute of Standards and Technology (NIST) performed research on varying binder compositions to study the effects of LWA on internal curing. HPC mixtures with Class F fly ash had a coarser pore structure, leading to a more rapid transport of water, and showed less autogenous shrinkage than mixtures containing just silica fume and slag cement. NIST states that HPC mixes with fly ash benefit more from external curing, whereas mixes with just slag or silica fume benefit more from internal curing (D'Ambrosia et al.).

5.1.2.4.2 Silica Fume

Silica fume added to the cement will contribute to early strength at the cost of requiring additional water or the use of a high range water reducer. The use of silica fume will also reduce the permeability of concrete but increases capillary tension and contraction stress, creating a greater potential for autogenous shrinkage. Reducing the pore size also reduces the drying rate and overall volumetric change from drying shrinkage (Ozyildirim).

5.1.2.5 Shrinkage Reducing Admixtures

Another technology that has been developed to mitigate shrinkage are shrinkage reducing admixtures (SRAs). SRAs work by reducing the surface tension of pore water, and thereby decreasing the capillary stress and shrinkage induced by drying (Nair et al.) (Bentz). The reduction of surface tension plateaus when the SRA concentration reaches 10-15%, where the concentrations are based on the initial water to SRA replacement rates by mass and even lower when salts are present in the pore solution (Sant et al.).

5.1.3 Methods to Measure Autogenous and Drying Shrinkage

There are numerous tests to measure volumetric change in portland cement systems. Compiled here is a list of the most pertinent tests to measure volumetric change (or length change) mainly derived from autogenous and drying shrinkage:

- ASTM C1698 measures the autogenous strain of sealed cement paste and mortar for up to 28 days or longer if desired.
- ASTM C157 and AASHTO T 160 measures the length change over time of mortars and concrete conditioned either in water or air. For water stored specimens, readings are taken at 8, 16, 32, and 64 weeks; air stored specimen readings are at 4, 7, 14, and 28 days with long term measurements taken at 8, 16, 32, and 64 weeks.
- ASTM C596 measures the drying shrinkage of conditioned mortars specimens; comparator readings are the same as ASTM C157.
- ASTM C1581 and AASHTO T 334 use a steel ring test setup to determine the age at cracking of mortar and concrete under restrained shrinkage for a minimum of 28 days, unless cracking occurs prior.
- AASHTO T 363 is a dual concentric ring test used for evaluating residual stress development due to restrained volume change at specific temperatures. Forced thermal cycles are performed up to 7 days, then the temperature is decreased at 2°C/hr. to induce thermal cracking.

Table 5 shows a decision matrix developed to assess the available shrinkage tests. The numbers used in the matrix correspond to values of 1) low, 2) medium, and 3) high. Table 6 compares the aspects of the shrinkage tests used to develop the decision matrix. Colors correspond to equivalent/similar tests (i.e. blue-drying shrinkage, green-restrained shrinkage via single ring test, white-autogenous shrinkage, and grey-restrained/thermal shrinkage). The matrix revealed that the length-change autogenous shrinkage and drying shrinkage tests were the best candidates for the given criteria. Measuring the length change of hardened hydraulic cement mortar and concrete follows three different standards: ASTM C157, ASTM C596, and AASHTO T 160. C596 follows the C157 specification with a few exceptions: it 1) is specific to mortar containing hydraulic cement, 2) requires minimum of four test specimens per batch as compared to three with C157, and 3) allows a different curing method for low strength mortars. T160 and C157 are equivalent standards, with no other differences. The ASTM Standard is selected because of the multiple cross references amongst other ASTM Standards. C157 is chosen over C596 to evaluate drying shrinkage as it covers mortar and concrete.

A small handful of firms currently perform the ASTM C157 test for DOT mixes. In addition to American Engineering and Testing, C157 is performed by Braun Intertec and Terracon (both in Minnesota) and CTL (in Chicago).

Restrained shrinkage test AASHTO T 363 did not have any available test set-ups for purchase. One would have had to be fabricated at a cost exceeding $20,000 each, which did not fit within the budget for this research. ASTM C1581 was selected over AASHTO T 334 because the specimens are half the thickness (3" for T334 and 1.5" for C1581), which was anticipated to result in quicker turn around between tests.

Table 5: Decision Matrix Used to Evaluate available Tests

Test	Description	Cost	Testing Time	Complexity of Test	Quantity of Material	Total
ASTM C1698	Autogenous Shrinkage	2	2	1	1	6
ASTM C157	Drying Shrinkage	1	3	1	2	7
AASHTO T160	Drying Shrinkage	1	3	1	2	7
ASTM C596	Drying Shrinkage	1	2	1	2	6
ASTM C1581	Restrained Shrinkage	2	2	2	2	8
AASHTO T334	Restrained Shrinkage	2	2	2	3	9
AASHTO T363	Restrained Shrinkage	3	1	3	3	10

Table 6: Evaluation of Available Shrinkage Tests

Test	Description	Curing Conditions		Measuring Conditions			Cost
		Temp (C)	Humidity %	Temp (C)	Humidity %	Evaproation rate	$$$
ASTM C1698	Autogenous Shrinkage	23 ± 1	Not specified	23 ± 1	Not specified	Not specified	$5,000
ASTM C157	Drying Shrinkage	23 ± 2	>95%	23 ± 2	50±4	13 ± 5 ml /24 hr from 400ml Griffin low-form beaker filled to 3/4" from top	4 molds - $698 knurled studs - $144
AASHTO T160	Drying Shrinkage	23 ± 2	Submerged in lime-saturated water	23 ± 2	Submerged in lime-saturated water 50±4	13 ± 5 ml /24 hr from 400ml Griffin low-form beaker filled to 3/4" from top	4 molds - $698 knurled studs - $144
ASTM C596 same as 157 unless moist cured for first 3 days	Drying Shrinkage	23 ± 2	>95%	23 ± 2	50±4	13 ± 5 ml /24 hr from 400ml Griffin low-form beaker filled to 3/4" from top	4 molds - $698 knurled studs - $144
ASTM C1581	Single Ring Test	23 ± 2	Wet burlap	23 ± 2	50±4	Not specified but top of specimen is coated with paraffin wax	3 inner rings $375-620 3 outer rings $105-275
AASHTO T334	Single Ring Test	23 ± 2	Wet burlap	23 ± 1.7	50±4	Not specified but needs to be recorded	3 inner rings $375-620 3 outer rings $105-275
AASHTO T363	Dual ring test	23 ± 2	N/A	23 decreasing 2/hr until cracking	N/A	N/A	Invar Alloy (raw material) $19,850.00

5.1.4 Studies on High Performance Low Shrinkage Concrete

State DOTs have previously studied the influence of concrete mix design on controlling cracking in bridge decks. An analysis of bridge deck and roadway mix designs used by these State DOTs provides best practices used to mitigate shrinkage cracking. For reference, the standard concrete bridge deck mix design currently used by the SDDOT (A45) is shown in Table 7.

Table 7: Specifications for A45 Concrete

Minimum Cement Content[1] (lb/yd^3)	Max W/CM	Slump (in)	Entrained Air Content (%)	Minimum Coarse Aggregate Content (%)	Minimum 28-Day Compressive Strength (psi)
650 615 if well graded[2]	0.45	1-4.5	5.0-7.5	55	4500

[1]The maximum cementitious content including cement and SCMs shall be 800 lb/yd^3. Class F fly ash can replace between 20-25% percent by weight of cement

[2]0.45 Power Gradation is used to conform to a well graded concrete mix

The development of optimal concrete mix designs for bridge decks report by Xi et al. compiled a table (Table 8) of several mixes used across the United States for bridge decks. These mix designs were collected from technical papers published in the literature, not from specifications of the state DOT's (Xi et al.) and are used as a comparison to the A45 concrete mix specifications.

Table 8: Concrete Mix Designs Used by State DOTs for Bridge Decks (Xi et al.)

States	Cement	Fly Ash	Silica Fume	W/CM	28-Day Strength	Permeability	Air Content	Slump
	lb/yd^3	lb/yd^3	lb/yd^3		psi	Coul.	%	inch
Colorado Shing, P.B.et al, 1999)	660	-	50	0.35	5800	-	4-8	-
Colorado	615-660	<61-66	-	<0.44	4500	-	5-8	-
Illinois (Detwiler,1997)	630	-	70	0.31	6950 at 14d	540	6-8	-
New York (Alampalli,2000)	505	149	42	0.4	-	-	6.5	3-4
Washington (FHWA-RD-00-124)	660	75	-	0.39	4000 5300 at 56d	2800	6.0	-
Nebraska Beacham, M. W. (1999)	750	75	-	0.31	8000 at 56d	589 at 56d	6.0	-
Texas (Ralls, M. L., 1999)	382-610	88-131	-	0.31-0.43	4000	<2000	5-8	3-9
New Hampshire (Waszczuk, C. M. et al, 1999)	607	-	45	0.383	6000 7200 at 56d	<1000 at 56d	6-9	3-5
Virginia (FHWA-RD-00-123)	560	140	-	0.45	5000	2500	-	-

Similar to the A45 mix, these mixes use (1) pozzolanic materials (especially fly ash) and have (2) moderate air content (averaging 6.5%). However, in contrast to the A45 mix, these mixes use (1) different cement contents (382-750 lb/yd^3), (2) have different compressive strength values (4000-8000 psi), (3) have varying water-cementitious ratios (0.31-0.44), and (4) have a wide range of slump values (3-9 in.). Additional State DOT studies are reviewed in the following section.

5.1.4.1 Illinois

The Wacker Drive reconstruction project in Chicago used HPC to attain a longer service life, with the goal of 75-100 years. The selected mixture was a blend of Portland cement, Class F fly ash, slag cement, and silica fume. Minimum and maximum compressive strengths of 6,000 and 9,500 psi were specified at 28 days. To ensure workable concrete, the specified slump was 8 in. after the addition of high-range water-reducing admixture (HRWRA), and 4 in. 45 minutes after the addition of HRWRA. Initial set was not permitted for at least 3 hours (D’Ambrosia et al.).

The Illinois DOT laboratory evaluations demonstrated that higher strength mixtures with fly ash (approximately 20% replacement) and a lower cement paste content (26% to 29%) were better able to resist early temperature and shrinkage stresses. Other acceptance criteria for the Wacker drive project was: 2000 coulombs at 28 days (AASHTO T 277), a 90 day chloride penetration test at 0.5-1” : 0.03% (AASHTO T 259), scaling at 50 cycles (0-1 rating) (ASTM C672), and a 90 day limit on shrinkage of 600 microstrain (με) (ASTM C157) (Xi et al.).

5.1.4.2 Indiana

Field investigations performed at Purdue University examined cracking of bridge decks. They found that areas of high restraint displayed more cracking as well as areas of low humidity and high wind speed at the time of placement, whereas longer periods of wet curing lead to reduced cracking. This study identified that the best performance concrete mix contained 5% silica fume and 20% fly ash, while the remaining content was portland cement. It was also found that reducing the heat of hydration reduced the likelihood of thermal cracking (D’Ambrosia et al.).

5.1.4.3 New York State

In 2000, the state of New York conducted a study examining cracks in bridges that were recently constructed using HPC. Core samples from these decks found transverse cracking in the mortar fraction at early ages unrelated to the aggregate. It was concluded that larger temperature rises during the first day after pouring resulted in larger residual stresses when the concrete cooled and reached thermal equilibrium with the environment (D’Ambrosia et al.).

A study conducted by the University of Colorado in 2001 showed some of the requirements New York state places on HPC. Out of the states reviewed in the 2001 study, New York requires the highest compressive strength at 56 days of 10,150 psi. Other requirements are similar to that of Illinois and New Jersey following AASHTO T 161 (freeze/thaw cycles), AASHTO T 256 (chloride penetration), AASHTO T 160-97 (shrinkage) at 56 days less than 600 microstrain, and ASTM C672 (scaling). One additional requirement they place on HPC is ASTM C512 (creep) at 56 days of 60 MPa and a modulus of elasticity greater than 50 GPa (Xi et al.).

5.1.4.4 Kansas

Research conducted in the early 1980’s through the 1990’s found that most bridge deck cracking occurred at an early age but progressed throughout the life of the structure, and that higher quantities of cracks occurred from an increased water content, cement content, and paste volume. They suggest limiting the paste volume to 27% and imposing an upper bound on compressive strength at 5500 psi (Darwin et al. "Control of Cracking in Bridge Decks: Observations from the Field").

In 2002, laboratory tests were conducted evaluating the effects of water content, cement content, paste volume, and compressive strength requirements on cracking density of HPC used on bridge decks in Kansas. The results displayed in Table 9 show the detrimental effects of using higher quantities of these materials on crack density (Darwin et al. "Control of Cracking in Bridge Decks: Observations from the Field").

Table 9: HPC Mix Variables Evaluated for Monolithic Bridge Decks (Darwin et al. "Control of Cracking in Bridge Decks: Observations from the Field").

Adjusted Variables	Water Content (initial)	Water Content (final)	Cement Content (initial)	Cement Content (final)	Cement Paste Volume (initial)	Cement Paste Volume (final)	Compressive Strength (initial)	Compressive Strength (final)
-	lb/yd^3		lb/yd^3		%		psi	
-	248	278	603	639	27	29	4500	6500
Crack Density (ft/ft^2)	0.04	0.22	0.05	0.21	0.05	0.22	0.05	0.15

Mixes with reduced cementitious materials and cement paste content, lower maximum slump, and lower compressive strength all contribute to minimizing bridge deck cracking. Transverse cracks typically appear directly over and parallel to the top layer of reinforcing and perpendicular cracks, typically appear near the abutments (Alhmood et al.).

Two large pool-funded studies led by the Kansas DOT developed low-cracking high-performance concrete (LC-HPC) for use in bridge decks. The report recommended the use of only portland cement (no SCMs) with low cement paste contents, limits on aggregate properties, and lower concrete slumps (Darwin et al. "Construction of Crack-Free Bridge Decks").

5.1.4.5 Colorado

A project funded by the Colorado Department of Transportation (CODOT) produced recommendations for bridge deck concrete mixes limiting silica fume content to a maximum of 5% to prevent high early strength gain. Other recommendations included limiting the ambient temperature during placement to between 40-90°F with an evaporation limit below 0.2 lb/ft^2 for normal concrete and 0.10 lb/ft^2 for low w/cm mixes. The study stated that any deck constructed with silica fume or fly ash should receive seven days of moist curing (D’Ambrosia et al.). For HPC, Colorado requires a compressive strength at 56 days of 4500 psi, and the mix must not exhibit cracks before 14 days using the AASHTO T 334 (formerly PP 34) ring test (Xi et al.).

5.1.4.6 New Jersey

HPC used for bridge decks in New Jersey require a 4350-psi compressive strength for production and a 5365 psi 56 day compressive strength for laboratory testing. New Jersey imposes a maximum shrinkage at 56 days of 400-600 microstrain (ASTM C157) for precast/prestressed members but do not have a limit for bridge decks. Other acceptance criteria they follow is an 80% relative dynamic modulus for a freeze/thaw at 300 cycles (AASHTO T 161), an abrasion limit of 1 mm (ASTM C944) and a permeability limit of 1000 coulombs at 56 days (Xi et al.).

5.1.4.7 Minnesota

A study conducted by the Minnesota Department of Transportation analyzed 20 different bridges, finding correlations between ten variables leading to cracking of the bridge decks. One strong correlation identifies that "restraint cracking was observed consistently (and almost exclusively) on bridges with integral abutments" (Rettner et al.).

This study identified several key recommendations in the mix design for mitigating cracking potential: limiting the paste volume to 27% or less with an optimized w/cm between 0.38 and 0.42, reducing the "brittleness" of the deck overlay by reducing the design compressive strength to 4000 psi or less, using the largest practical aggregate size and well graded aggregate to reduce paste requirements, and avoiding the use of aggregate (especially sands) that increase water demand due to particle shape. The study also recommended using Type I, II, IP or IS cements, with the addition of 1-2% shrinkage-reducing admixture (Rettner et al.).

Other recommendations are placement when evaporation rate is <0.10 lb/ft^2/hr. and avoiding placement when winds are >15 mph. Placement is recommended when the air temperature range is 45-85^{o}F with a maximum temperature swing <50^o F. Rapid chloride permeability (ASTM C1202) must be less than or equal to 1500 coulombs at 56 days and maximum allowed shrinkage is 0.040% at 28 days in accordance with ASTM C157 (Rettner et al.). It should be noted that due to experience in the field, the 0.040% limit is under consideration to be lowered to 0.032. Concrete mixes are pre-tested for this limit and are not tested again after the bridge deck is poured. If no changes are made to a concrete mix and the placement meets the MNDOT requirements displayed in Table 10, the mix is certified for a period of five years and will not require new testing (Rettner et al.).

Table 10: Minnesota DOT Requirements for HPC Used on Bridge Decks (MNDOT).

W/CM	Target Air Content	Maximum % SCM (Fly Ash/Slag/Silica Fume/Ternary)	Slump	Minimum Compressive Strength (28-days)	Rapid Chloride Permeability	Shrinkage	Scaling	Freeze Thaw Durability
-	%	-	in	psi	Coulombs	%	50 cycles	300 cycles
0.40-0.45	6.5	30/35/5/40	4	4000	≤ 1500 at 56 days	0.04 at 28 days	≤ 1	> 90%

5.1.4.8 South Dakota

A SDDOT study (SD2005-11) (Patnaik) on the feasibility of implementing the LC-HPC developed by the Kansas DOT pooled studies in South Dakota indicated that these mix designs may not work as well in this region using SDDOT design and construction practices and local materials. The research recommended that there was no tangible benefit to switch to these mixes due to the increased costs without a reduction in crack density compared to the previous mix design. It is likely that the introduction of new technologies, including saturated LWA and shrinkage reducing admixtures, may improve performance and warrant further research in this present study.

5.1.5 DOT Survey

As part of the literature review, a survey on the current understanding of practices, procedures, and recommendations regarding shrinkage cracking mitigation in bridge decks was solicited from other states DOTs. 33 DOT agencies responded to the survey shown, as shown in Figure 7, and the full results can be found in Appendix A.

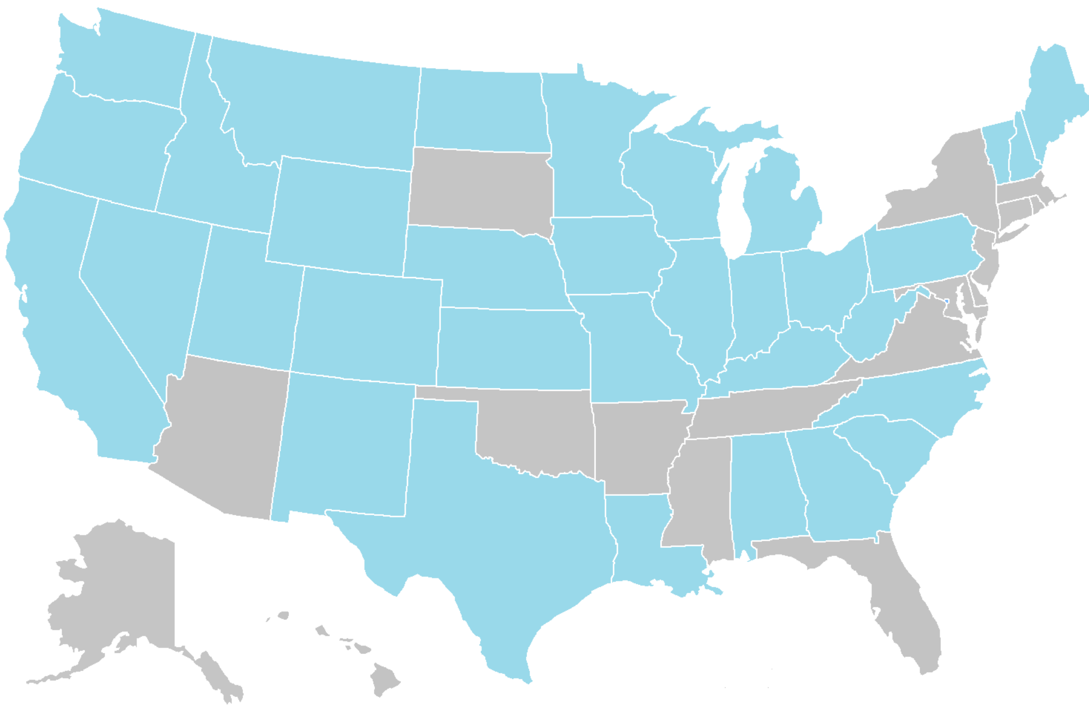


Figure 7: Representation of the responding states to the DOT Survey shown in blue

Agencies were asked to rate the following parameters on their effectiveness in controlling shrinkage: maximum compressive strength, maximum concrete temperature, placement time, admixtures, SCM content, evaporation retardants, cement content, w/cm ratio, slump, minimum curing times, curing methods, aggregate content, or other strategies. Options available for rating these items were, 1) not used, 2) ineffective, 3) slightly effective, 4) moderately effective, 5) highly effective, and 6) do not know. The responses to each of these items varied from state to state and may change as several have current/ongoing research on some of these topics.

Commonly only a minimum design compressive strength is specified for concrete mixes. When asked if these agencies specify a maximum compressive strength, 80% say that this parameter is not used. One state says this parameter is ineffective, yet two others report it is either highly or moderately effective for mitigating shrinkage. Maximum compressive strength values provided range from 4000 to 6500 psi; likewise, minimum values were also provided with 4000 psi at 14 days to 4500 psi at 28 days. Some DOT agencies are even offering incentives for targeting a strength below 5500 psi and achieving consistent strengths during production within ± 500 psi of the target strength.

The effectiveness of specifying maximum concrete temperature were split among the six available answers. There was a wide range of maximum temperatures specified from 50-90°F, but primarily between 80-90°F. Some of the provisions provided include: 60-90°F for normal structural concrete and reduced to 80°F for bridge decks, 90°F unless insulated forms are used then it is reduced to 80°F, and another reduces the maximum temperature from 90°F to 80°F when switching from normal to high performance concrete. Several report that after initial placement, the maximum concrete temperature during curing is not specified.

Nighttime concrete placement effectiveness was also not clear. Most of the provided feedback stated that this choice is left to the contractor to provide another option for meeting specified concrete temperature or evaporation at placement. Only two agencies say that it is required during summer months and a third reports it is not required but has been successful on a couple projects.

All agencies indicated that the use of admixtures was an effective strategy. The most common admixtures used are water reducers and superplasticizers in addition to retarders and hydration stabilizers. Shrinkage reducing admixtures are being used by some agencies and are being researched for use by several others, who are reporting success with their implementation.

Over 66% of the responses indicated that supplemental cementitious materials are effective for mitigating shrinkage. Fly ash, slag, and silica fume were the three most commonly reported SCMs, but metakaolin and Class N pozzolans have also been used. Replacement levels and binary/ternary blends vary greatly from the feedback. Fly ash and slag have similar reported replacement levels of cement by weight ranging from 10-40% (up to 50% for slag) and silica fume capping at 5%. Maximum SCM replacement levels specified vary from 10% to 70%. However, some agencies reported that the required SCMs provide little to no benefit regarding shrinkage.

Some agencies indicated that limiting total cementitious materials content was effective in reducing bridge deck shrinkage. Maximum total cementitious content ranged from 560-718 lb/yd^3. However, several of the agencies reported the maximums are unrelated to shrinkage and subsequently provided minimum requirements as low as 517 lb/yd^3.

Over 60% of the agencies indicated that evaporation retardants were either not used or had an unknown effect, but 37% marked that they are effective. A few states that allow their use have no limits, 4-5 have specific applications and associated curing processes, and another few states are considering eliminating them all together from their specifications because of historical misuse.

The agencies' view on the effectiveness of specifying a minimum or maximum w/c(m) was mixed. Values of specified ratios ranged from 0.32-0.5. One state has a 0.45 max unless latex or silica fume are used, in which case it is reduced to 0.40. Another provided varying limits based on aggregate shape at 0.381 for rounded and 0.426 for angular, and others specify their limits based on permeability or the class of concrete (limits not provided). There are states that do not specify a minimum or maximum, leaving it to the contractor to decide and have approved by the state.

Specifying a minimum or maximum slump was not generally thought to be an effective strategy for shrinkage. Typical values widely range between 1-3 in. to 9 in. Several states add 1-3 inches from their normal slump if admixtures are used (mainly water reducing admixtures).

Aggregate content (e.g., type, density, gradation) was reported as having a relatively low impact on shrinkage. The maximum size aggregate ranged from 1-2”. Optimized aggregate gradation is allowed (not required) by several states either by the Tarantula curve, Shilstone box, or COMPASS software, and one state offers incentives for using optimized aggregate gradations (OAG). A couple states, on the other hand, state that OAG are not used or have very limited use when application is for minimizing shrinkage.

Most agencies indicated that curing method and minimum curing time were both effective methods to mitigate shrinkage. A water curing method and 7-14 days of curing were most often specified. Certain states also use internal curing agents including expanded shale and clay with a range of 10-45% replacement of the fine aggregate (most used 30%).

The most common shrinkage test specified is ASTM C157/AASHTO T 160 for drying shrinkage. The limits placed by the states have a wide range of 0.03-0.45% (length change) which corresponds to ~294-441 microstrain at 28 days. None of the responses mentioned autogenous shrinkage or associated limits, but a small handful did mention the use of the restrained shrinkage test (ASTM C1581) stating the mix had to be crack free for a minimum of 28 days.

5.1.6 Summary

Overall, there have been many research studies on mitigating shrinkage in concrete. However, some of the recommended methods from these studies have not worked well when implemented in South Dakota. This could be a result of the local materials and local aggressive environment. Therefore, this research sought to study which best practices in concrete bridge mix designs will have the greatest impact on shrinkage reduction for the SDDOT using locally available materials and considering the local environment (e.g., using air entrainment for freeze-thaw mitigation). Recommendations for implementation will result from analysis of shrinkage, workability strength, and durability testing.

5.2 Materials and Methods

To develop a baseline concrete mix for comparison, a statistical analysis was performed on over 400 A45 concrete mixes previously used in South Dakota. Displayed in Table 11 is an analysis of the mixes separated by fly ash contents of 15, 20, and 25% by weight replacement of cement. Mixes containing 0% fly ash were not included in the analysis as the SDDOT has required a minimum 15% by weight fly ash content for over the last ten years.

Table 11: Variations of the A45 Concrete Mix Design Used by South Dakota

Mixes w/avg 100 lb/cyd fly ash (15%)						
Data Type	Cement (lb/yd^3)	Rock (lb/yd^3)	Sand (lb/yd^3)	Water (lb/yd^3)	% Air	W/CM
Average	557	1696	1220	263	6.5	0.40
Maximum	561	1724	1254	267	6.5	0.41
Minimum	554	1678	1192	260	6.5	0.40
Standard Deviation	4	18	31	3	0.0	0.00
Variance	52	1253	3731	40	0.0	0.00
1st Quartile	550	1615	1191	260	6.5	0.40
3rd Quartile	565	1680	1314	273	6.5	0.41
Mixes w/avg 130 lb/cyd fly ash (20%)						
Data Type	Cement (lb/yd^3)	Rock (lb/yd^3)	Sand (lb/yd^3)	Water (lb/yd^3)	% Air	W/C
Average	534	1699	1167	273	6.5	0.41
Maximum	546	1734	1191	279	6.5	0.42
Minimum	533	1676	1129	268	6.5	0.40
Standard Deviation	3	21	20	4	0.0	0.00
Variance	80	1657	1929	34	0.0	0.00
1st Quartile	524	1661	1156	260	6.5	0.40
3rd Quartile	528	1727	1200	276	6.5	0.42
Mixes w/avg 168 lb/cyd fly ash (25%)						
Data Type	Cement (lb/yd^3)	Rock (lb/yd^3)	Sand (lb/yd^3)	Water (lb/yd^3)	% Air	W/C
Average	504	1715	1164	262	6.5	0.39
Maximum	504	1715	1164	262	6.5	0.39
Minimum	504	1715	1164	262	6.5	0.39
Standard Deviation	0	0	0	0	0.0	0.00
Variance	0	0	0	0	0.0	0.00
1st Quartile	491	1715	1165	263	6.5	0.39
3rd Quartile	495	1715	1165	265	6.5	0.40

5.2.1 Concrete Mix Design Matrix

Based on the goal of this research (i.e., developing an optimum concrete mix that reduces shrinkage), recommendations from the literature review were used to develop the following testing plan. Tested changes to the baseline mix include aggregate type and gradation, cement content, SCM content, saturated LWA, w/cm ratio, and SRAs as described herein.

5.2.1.1 Aggregate

Both limestone and quartzite coarse aggregates were used for testing as they are the most common aggregates in South Dakota. Limestone was used as the baseline coarse aggregate for testing since the tests were performed near the quarry used by SDDOT. Silicious sand fine aggregate followed ASTM C33 gradation requirements for a standard curve as shown in Table 12. Coarse aggregate gradation followed a standard curve for 1" MSA (#57 viewed in Table 13). One mix (labeled "gradation") has an aggregate gradation that fits both the 0.45 power curve and the Tarantula curve as described in the next section.

Table 12: ASTM C33 Gradation Requirements for Fine Aggregates

Sieves Size	Percent Passing
3/8 in	100
No. 4	95 to 100
No. 8	80 to 100
No. 16	50 to 85
No. 30	25 to 60
No. 50	5 to 30
No. 100	0 to 10

Table 13: ASTM C33 Gradation Requirements for Coarse Aggregates

Size Number	Nominal Size (Sieves with Square Openings)	Amounts Finer than Each Laboratory Sieve (Square-Openings), Mass Percent													
		100 mm (4 in.)	90 mm (3½ in.)	75 mm (3 in.)	63 mm (2½ in.)	50 mm (2 in.)	37.5 mm (1½ in.)	25.0 mm (1 in.)	19.0 mm (¾ in.)	12.5 mm (½ in.)	9.5 mm (⅜ in.)	4.75 mm (No. 4)	2.36 mm (No. 8)	1.18 mm (No. 16)	300 µm (No.50)
1	3 1⁄2 to 1 1⁄2 in.	100	90 to 100	...	25 to 60	...	0 to 15	...	0 to 5	...	...	...	...	...	...
2	2 1⁄2 to 1 1⁄2 in.	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...	...
3	2 to 1 in.	...	...	...	100	90 to 100	35 to 70	0 to 15	...	0 to 5	...	...	...	...	...
357	2 in. to No. 4	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	...	0 to 5	...	...	...
4	1 1/2 to 3/4 in.	...	...	...	...	100	90 to 100	20 to 55	0 to 15	...	0 to 5	...	...	...	...
467	1 1⁄2 in. to No. 4	...	...	...	...	100	95 to 100	...	35 to 70	...	10 to 30	0 to 5	...	...	...
5	1 to 1⁄2 in.	...	...	...	...	...	100	90 to 100	20 to 55	0 to 10	0 to 5	...	...	...	...
56	1 to 3⁄8 in.	...	...	...	...	...	100	90 to 100	40 to 85	10 to 40	0 to 15	0 to 5	...	...	...
57	1 in. to No. 4	...	...	...	...	...	100	95 to 100	...	25 to 60	...	0 to 10	0 to 5	...	...
6	3⁄4 to 3⁄8 in.	...	...	...	...	...	...	100	90 to 100	20 to 55	0 to 15	0 to 5	...	...	...
67	3⁄4 in. to No. 4	...	...	...	...	...	...	100	90 to 100	...	20 to 55	0 to 10	0 to 5	...	...
7	1⁄2 in. to No. 4	...	...	...	...	...	...	...	100	90 to 100	40 to 70	0 to 15	0 to 5	...	...
8	3⁄8 in. to No. 8	...	...	...	...	...	...	...	...	100	85 to 100	10 to 30	0 to 10	0 to 5	...
89	3⁄8 in. to No. 16	...	...	...	...	...	...	...	...	100	90 to 100	20 to 55	5 to 30	0 to 10	0 to 5
9A	No. 4 to No. 16	...	...	...	...	...	...	...	...	...	100	85 to 100	10 to 40	0 to 10	0 to 5

Table 14 is the coarse aggregate gradation requirements for use in portland cement concrete specified by the SDDOT, listed in section 820 of the 2015 Standard Specifications for Roads and Bridges. Table 15 is the 2019 quality control testing report provided by Pete Lien & Sons of Rapid City, who are a local supplier of limestone aggregate, Table 15 shows that their aggregate conforms to ASTM C33 specification and SDDOT's specifications.

Table 14: SDDOT Standard for Concrete Aggregates (Khan)

Size #	Nominal Size Square Openings	1 1/2 inch	1 inch	3/4 inch	1/2 inch	3/8 inch	#4	#8
1	1 inch to #8	100	95-100		25-60		0-10	0-5[1]
1A	3/4 inch to #8		100	90-100		20-55	0-10	0-5[1]
3	3/4 inch to #8			100	97-100	40-90	5-20	0-5[1]
5	1/2 inch to #8			100	90-100	40-70	0-20	0-5[1]
15	1½ inch to #8	100	98-100	70-90		27-53	2-20	0-5[1]
[1]The combined mixture of fine and coarse aggregate shall be such that not more than 1.5% passes the #200 sieve. This limit shall not be more than 2.5% for Class M concrete.								

Table 15: 2019 Aggregate Quality Control Testing Results (Jacobson)

Sieve Size	**1 1/2 inch**	**1 inch**	**3/4 inch**	**1/2 inch**	**3/8 inch**	**#4**	**#8**	**#200**
1" Conc. Agg.	100	100	84	45	16	1	1	0.9
ASTM C33 Size 57	100	95-100	-	25-60	-	0-10	0-5	0-1.5
Sieve Size		**1/2 inch**	**3/8 inch**	**1/4 inch**	**#4**	**#8**	**#16**	**#200**
#8 Conc. Agg.		100	99	51	20	2	1.8	1.5
ASTM C33 Size #8		100	85-100	-	10-30	0-10	0-5	0-1.5

The mixes analyzed in Table 11 have a coarse aggregate content ranging from 55 to 60%. Three mixes tested lower cementitious materials content and, as a result, a larger aggregate fraction up to 72%.

5.2.1.2 Gradation Curves

Currently the A45 mix uses the ASTM C33 gradation for coarse and fine aggregates. The provisions provided allow for lower cement content to be used if the aggregates are well graded. The following two gradation techniques were both used to develop an aggregate gradation for this research. First, the 0.45 power chart is a cumulative percent-passing grading curve in which the horizontal axis is marked off in sieve-opening sizes raised to the 0.45 power. Second, the Tarantula Curve is a tool for proportioning aggregate focused on the workability of the concrete mix (Cook et al.). The aggregates used in this research were sieved and proportioned to meet the requirements for the 1" 0.45 power gradation curve and the Tarantula Curve, simultaneously. To accomplish this, a blend of #57 aggregate, #8 aggregate, and sand had to be produced as follows by weight percent (34% #57, 21% #8, and 45% sand). This blend also meets the minimum SDDOT A45 requirement for coarse aggregate percentage, which allows for the use of a lower cementitious content, as it is now a well graded blend. Figure 8 and Figure 9 show how this blend corresponds to the 0.45 power curve requirements from Figure 5 and the Tarantula Curve requirements from Figure 6.

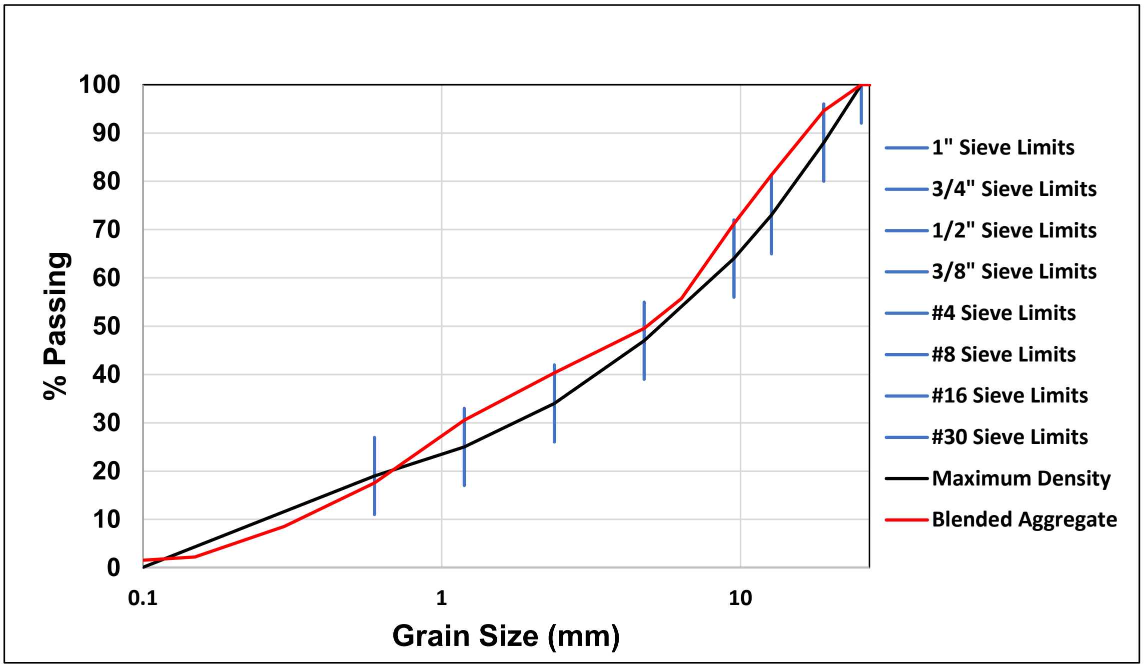


Figure 8: 0.45 Power Curve Blended Aggregate Gradation. Vertical Lines Represent Minimum and Maximum % Passing Allowed for Each Sieve Size

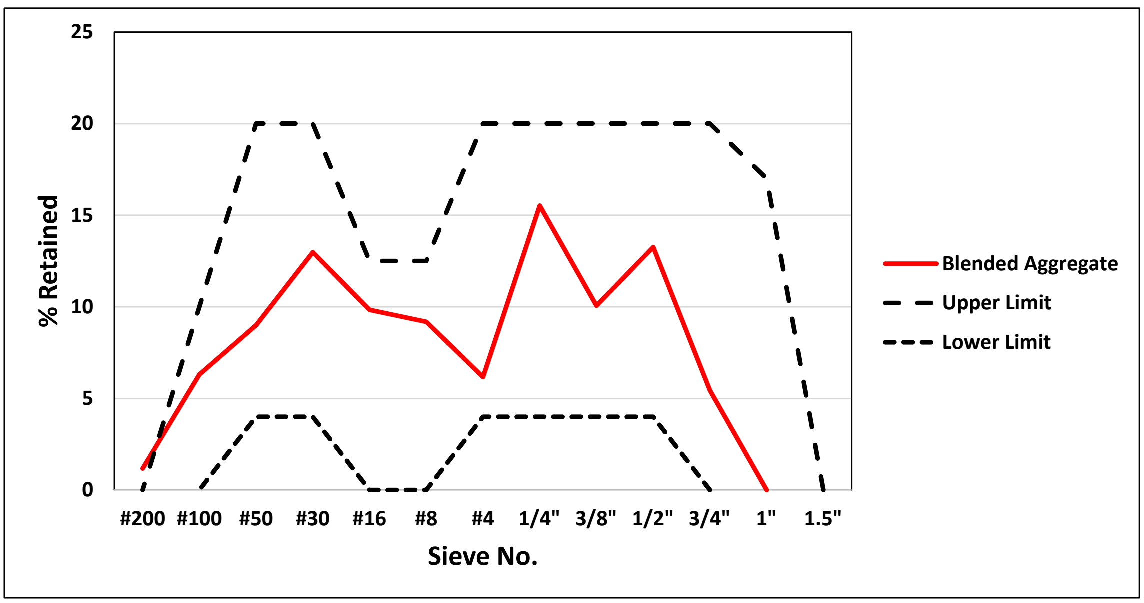


Figure 9: Tarantula Curve Blended Aggregate Gradation

5.2.1.3 Cement Content

The cement content of the baseline mix set for this research corresponds to the specifications of the A45 concrete at 650 lb/yd^3 (total cementitious materials), which is higher than the cement contents recommended in many previous studies for developing low shrinkage concrete mixes. As such, this research tested cementitious contents of 650, 613, 575, and 538 lb/yd^3, which reduced the paste volume from 31% down to 23%.

5.2.1.4 Supplemental Cementitious Materials

Class F fly ash was tested in all mixes with a 20% replacement level, based on the analysis from SDDOT and from the literature. One mix used a 25% replacement level testing at the lowest (615 lb/yd^3) cementitious materials content currently allowed by the SDDOT. 20% replacement is the minimum allowed content used on bridge decks allowed by MNDOT and a 20-25% replacement is the suggested level by the CODOT and VADOT. These levels also allow for a reduction in cement content to suggested levels from the CODOT. This research did not use silica fume in any of the testing mixes as it is not widely available for use in SD.

5.2.1.5 Lightweight Aggregate

Based on previous research, saturated fine LWA (expanded shale) was used in mixes as a partial replacement for the sand at 20, 40, and 60% by weight. In this study, this material will be called fine lightweight aggregate (FLA). The expanded shale used in the mortar mixes has an absorption capacity of 19.2% (ASTM C128) and a 72-hour absorption of 23.7% (ASTM C 1761). The porosity of this aggregate was 100% filled with water when used in the mortars. These testing values were chosen to establish limitations for replacement values with respect to eliminating autogenous shrinkage while not causing detrimental effects on compressive strength and fresh concrete properties.

5.2.1.6 Water to Cementitious Materials Ratio

The mix design analysis of SDDOT mixes (displayed in Table 11) shows a current range of 0.39 to 0.42 w/cm. These ranges are slightly different from those in the Colorado study (Xi et al.), but similar to Minnesota HPC requirements (Table 10) (MNDOT). A 2014 study conducted by the MNDOT also suggests limiting the paste volume to 27% or less and holding the w/cm ratio between 0.38 and 0.42. Based on this information, the baseline water to cementitious materials ratio selected was 0.40, which is the average w/cm currently used by SDDOT. The w/cm ratio was tested using a range from 0.38 to 0.42. This range should provide a sufficient assessment of its effect on shrinkage, in addition to its effects on other fresh and hardened concrete properties.

5.2.1.7 Shrinkage Reducing Admixtures

For the initial testing, three mixes contained an SRA replacement of 1.5 gal/yd^3 (two ea.) and one 3 gal/yd^3, which is the maximum and double the maximum dosage for the MasterLife SRA 035 admixture. It should be noted that shrinkage reducing admixtures used along with air entraining admixtures can reduce air-void stability. Superplasticizer was added to achieve desired slump between 1-4 inches, resulting in varying dosage amounts as compared to the paste and mortar mixes.

5.2.1.8 Final Design Matrix

Using these recommended mix design changes, eighteen mixes (displayed in Table 16) were tested to determine the variables that best mitigate shrinkage in concrete. Full material data sheets are in Appendix B. Highlighted in bold are the adjustments to each mix from the baseline with the superscript denoting the change. Note that air-entraining admixtures are not included in all tests due to their potential to significantly impact air contents, which would affect all measurements.

Table 16: Mix Design Matrix

Description	w/cm	Water	Cement	Fly Ash	Coarse Aggregate	Fine Aggregate	Paste Volume	Admixtures	SP Dosage	SRA Dosage	Theoretical Yield
	-	lb/yd³	lb/yd³	lb/yd³	lb/yd³	lb/yd³	%	type	fl oz/cwt	gal/yd³	ft³/yd³
Baseline w/o FA or SP	0.4	260	650	**0** 1*	1735	1421	28.2	-	0	0	27.0
Baseline w/o FA	0.4	260	650	0	1735	1421	28.2	**SP** 2*	6-20	0	27.0
DOT Baseline	0.4	260	520	130	1735	1396	29.1	SP	6-20	0	27.0
Baseline W/AEA	0.4	260	520	130	1735	1194	31.1	**AEA, SP** 3*	6-20	0	27.0
Baseline / Quartzite	0.4	260	520	130	**1735** 4*	**1349** 4*	29.5	SP	6-20	0	27.0
Gradation	0.4	260	520	130	**1735** 5*	**1396** 5*	29.1	SP	6-20	0	27.0
Cement Content 1	0.4	245	**490** 6*	122.5	1775	1430	26.8	SP	6-20	0	27.0
Cement Content 2	0.4	230	**460** 6*	115	1805	1473	24.6	SP	6-20	0	27.0
Cement Content 3	0.4	215	**430** 6*	107.5	1810	1540	22.5	SP	6-20	0	27.0
SCM 1	0.4	246	460	**155** 7*	1772	1421	27.0	SP	6-20	0	27.0
FLA Replacement 1	0.4	260	520	130	1735	**993/248** 8*#	30.6	SP	6-20	0	27.0
FLA Replacement 2	0.4	260	520	130	1735	**671/447** 9*#	31.9	SP	6-20	0	27.0
FLA Replacement 3	0.4	260	520	130	1735	**407/610** 10*#	33.1	SP	6-20	0	27.0
W/CM 1	**0.42** 11*	273	520	130	1735	1362	29.8	SP	6-20	0	27.0
W/CM 2	**0.38** 12*	247	520	130	1750	1415	28.3	SP	6-20	0	27.0
SRA 1	0.4	260	520	130	1735	1396	29.1	**SP, SRA** 13*	6-20	1.5	27.0
SRA 2	0.4	260	520	130	1735	1396	29.1	**SP, SRA** 14*	6-20	3	27.0
SRA 3	0.4	260	520	130	1735	1194	31.1	**AEA, SP, SRA** 15*	6-20	1.5	27.0
# Denotes quantity of fine aggregate and fine lightweight aggregate (fa/fLWA)											

1* - Change from the baseline by removing fly ash and SP.
2* - Change from baseline by removing fly ash but using SP.
3* - Change from baseline by adding an air-entraining admixture.
4* - Adjusting the aggregate from limestone to quartzite.
5* - Aggregate gradation using the 0.45 power curve/Tarantula Curve.
6* - Change cement content adjusting paste volume to 27%, 25%, and 23% on mixes 6-8.
7* - 25% replacement of cement content with Class F fly ash with total cementitious materials at 615 lb/yd^3.
8* - 20% replacement of fine aggregate with saturated lightweight aggregate
9* - 40% replacement of fine aggregate with saturated lightweight aggregate.
10* - 60% replacement of fine aggregate with saturated lightweight aggregate.
11* - W/cm ratio adjustment 0.42.
12* - W/cm ratio adjustment 0.38.
13* - Addition of 1.5 gal/yd^3 shrinkage reducing admixture.
14* - Addition of 3 gal/yd^3 shrinkage reducing admixture.
15* - Addition of 1.5 gal/yd^3 shrinkage reducing admixture and air entraining admixture.
Note: AEA and SP admixture quantities may be adjusted to meet air content and slump requirements.

The paste fraction determined from the concrete mixes in Table 17 were tested for autogenous shrinkage. Any mixes that only changed the cement to aggregate ratio or the aggregate content were excluded from this testing.

Table 18 presents the batch weights for the paste mixes that were tested. Although SP was not needed for workability of the paste and mortar mixes, it was added to these mixes to best match the concrete mixes where it is needed for some mixes to meet slump.

Table 17: Concrete Mix Designs Used for Autogenous Shrinkage Testing on Paste

Description	w/cm	Water	Cement	Fly Ash	Admixture	SP Dosage	SRA Dosage	AEA Dosage
	-	lb/yd^3	lb/yd^3	lb/yd^3	type	fl oz/cwt	gal/yd^3	fl oz/cwt
Baseline w/o FA or SP	0.40	260	650	0	-	-	-	-
Baseline w/o FA	0.40	260	650	0	SP	10	-	-
Baseline	0.40	260	520	130	SP	10	-	-
Baseline W/AEA	0.40	260	520	130	SP, AEA	10	-	4
SCM 1	0.40	246	460	155	SP	10	-	-
W/CM 1	0.42	273	520	130	SP	10	-	-
W/CM 2	0.38	247	520	130	SP	10	-	-
SRA 1	0.40	260	520	130	SP, SRA	10	1.5	-
SRA 2	0.40	260	520	130	SP, SRA	10	3	-
SRA 3	0.40	260	520	130	SP, SRA	10	1.5	4

Table 18: Batch Weights for Paste Mixes

Description	w/cm	Water	Cement	Fly Ash	AEA Admix	SP Admix	SRA Admix
	-	lb	lb	lb	mL	mL	mL
Baseline w/o FA or SP	0.40	0.988	2.470	0.000	0.0	0.0	0.0
Baseline w/o FA	0.40	0.988	2.470	0.000	0.0	12.0	0.0
DOT Baseline	0.40	0.988	1.976	0.494	0.0	6.0	0.0
Baseline W/AEA	0.40	0.988	1.976	0.494	3.0	6.0	0.0
SCM 1	0.40	0.988	1.847	0.622	0.0	5.5	0.0
W/CM 1	0.42	1.037	1.976	0.494	0.0	6.0	0.0
W/CM 2	0.38	0.938	1.976	0.494	0.0	6.0	0.0
SRA 1	0.40	0.988	1.976	0.494	0.0	6.0	13.0
SRA 2	0.40	0.988	1.976	0.494	0.0	6.0	45.0
SRA 3	0.40	0.988	1.976	0.494	3.0	6.0	13.0

The mortar fractions determined from the concrete mixes in Table 19 were tested for autogenous shrinkage. The fine lightweight aggregate (FLA) was used as an internal curing agent and is tested here at 20%, 40%, and 60% by weight replacement of the sand. Table 20 presents the batch weights for the mortar mixes that were tested.

Table 19: Mix Designs Used for Autogenous Shrinkage Testing on Mortar

Description	w/cm	Water	Cement	Fly Ash	Fine Agg.	Light Weight Agg.	Admixture	SP Dosage	SRA Dosage	AEA Dosage
	-	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	Type	fl oz/cwt	gal/yd^3	fl oz/cwt
Baseline w/o FA or SP	0.4	260	650	0	1396	0	-	-	-	-
Baseline w/o FA	0.4	260	650	0	1396	0	SP	18	-	-
DOT Baseline	0.4	260	520	130	1396	0	SP	18	-	-
Baseline W/AEA	0.4	260	520	130	1194	0	SP, AEA	18	-	4
FLA Replacement (20%)	0.4	260	520	130	993	248	SP	18	-	-
FLA Replacement (40%)	0.4	260	520	130	671	447	SP	18	-	-
FLA Replacement (60%)	0.4	260	520	130	407	610	SP	18	-	-

Table 20: Batch Weights for Mortar Mixes

Description	w/cm	Water	Cement	Fly Ash	AEA Admix	SP Admix	SRA Admix	Light Weight Agg.	Fine Agg.
	-	lb	lb	lb	mL	mL	mL	lb	lb
Baseline w/o FA or SP	0.40	0.988	2.470	0.000	0.0	0.0	0.0	0.000	1.989
Baseline w/o FA	0.40	0.988	2.470	0.000	0.0	13.0	0.0	0.000	1.989
DOT Baseline	0.40	0.988	1.976	0.494	0.0	11.0	0.0	0.000	1.989
Baseline W/AEA	0.40	0.988	1.976	0.494	2.0	10.5	0.0	0.000	1.989
FLA Replacement 1	0.40	0.988	1.976	0.494	0.0	10.5	0.0	0.398	1.591
FLA Replacement 2	0.40	0.988	1.976	0.494	0.0	10.5	0.0	0.796	1.193
FLA Replacement 3	0.40	0.988	1.976	0.494	0.0	10.5	0.0	1.193	0.796

The final concrete mix designs tested for drying shrinkage are shown in Table 21.

Table 21: Concrete Mix Designs Used for Testing Drying Shrinkage

Description	w/cm	Water	Cement	Fly Ash	Coarse Agg.	Fine Agg.	Light Weight Agg.	SP Dosage	SRA Dosage	AEA Dosage
	-	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	fl oz/cwt	gal/yd^3	fl oz/cwt
Baseline w/o FA or SP	0.4	260	650	0	1775	1450	0	0	0	0
Baseline w/o FA	0.4	260	650	0	1775	1450	0	10	0	0
Baseline	0.4	260	520	130	1735	1396	0	0	0	0
Baseline W/AEA	0.4	260	520	130	1735	1194	0	10	0	4
Baseline / Quartzite	0.4	260	520	130	1735	1349	0	5	0	0
Gradation 2	0.4	260	520	130	1041	1396	0	12	0	0
Cement Content 1	0.4	245	490	123	1775	1430	0	0	0	0
Cement Content 2	0.4	230	460	115	1805	1473	0	8	0	0
Cement Content 3	0.4	215	430	108	1810	1540	0	11	0	0
SCM 1	0.4	246	460	155	1772	1421	0	7	0	0
FLA Replacement 1	0.4	260	520	130	1735	993	248	4	0	0
FLA Replacement 2	0.4	260	520	130	1735	671	447	0	0	0
FLA Replacement 3	0.4	260	520	130	1735	407	610	0	0	0
W/CM 1	0.42	273	520	130	1735	1362	0	0	0	0
W/CM 2	0.38	247	520	130	1750	1415	0	8	0	0
SRA 1	0.4	260	520	130	1735	1396	0	0	1.5	0
SRA 2	0.4	260	520	130	1735	1396	0	0	3	0
SRA 3	0.4	260	520	130	1735	1194	0	0	1.5	2

5.2.1.9 Testing Sensitivity Analysis

The sensitivity of autogenous shrinkage testing as assessed by testing multiple batches of pastes and mortars. For the paste mixes, the following mixes were tested with two batches: Baseline w/o FA or SP, Baseline w/o FA, Baseline W/AEA, and SCM 1. The DOT Baseline paste mix was tested using five batches. For the mortar mixes, the following mixes were tested with two batches: Baseline w/o FA or SP, Baseline w/o FA, and FLA Replacement 3. All measured samples are included in the results presented in this study, and variation in sample size is factored into the statistical analysis.

5.2.2 Mixing procedure

The mixing procedure for the concrete batches was provided by SDDOT. It began by placing approximately 75% of the water and 100% of the coarse aggregate. Then the contents were mixed for 1-1.5 minutes. Once all the fine aggregate was added, contents were mixed for an additional 1-1.5 minutes. Afterward, all the cementitious materials were added along with the remaining water containing the liquid admixtures if used. Finally, the materials were mixed for 5 minutes, rested with the mixer covered for 3 minutes, and mixed again for another 5 minutes.

The coarse aggregate and a portion of the mixing water was combined at the beginning of the procedure because the moisture content of the coarse aggregate was consistently below the aggregate absorption capacity, and this process brings the aggregate closer to a saturated surface dry (SSD) condition. The bulk quantities of the coarse and fine aggregates were stored in an outdoor holding bin covered by a semi impermeable membrane, subjected to the thermal and humidity changes of South Dakota's climate. Quantities used for mixes were brought indoors and placed in sealed containers for a minimum of 24 hours to normalize to room temperature before a moisture content test was performed in accordance with ASTM C566 (Total Evaporable Moisture Content of Aggregate by Drying). Samples were weighed before and after a 24-hour period in a ventilated oven maintained at $110^{o}C$. Once the moisture content was determined, the mixing water was adjusted as well as the aggregate quantity, so the mixes still met theoretical yield using the procedure provided by SDDOT.

The total evaporable moisture content was calculated as follows:

$$p = 100\frac{W - D}{D} \qquad \text{Equation 1}$$

where:

p = total evaporable moisture content of the sample, percent
W = mass of original sample, lb
D = mass of dried sample, lb

Mixing water content was adjusted by multiplying the mass of the aggregate by the difference of absorption capacity. When the moisture content of the aggregate was below absorption capacity, water was added to the mix and vice versa when above.

$$W_{(adj.)} = M_{agg}\left(\frac{MC - A_c}{100}\right) \qquad \text{Equation 2}$$

where:

$W_{adj.}$ = mass of adjusted mixing water, lb
$M_{agg.}$ = mass of aggregate, lb
MC = moisture content of aggregate, percent
A_c = absorption capacity of aggregate, percent

Similarly, to ensure the batches meet yield requirements of ±2% by volume per SDDOT Standard Specification for Roads and Bridges, the aggregate weight was also adjusted by the moisture content.

$$Agg_{(cor.)} = Agg \mp (Agg(MC/100)) \qquad \text{Equation 3}$$

where:

$Agg_{cor.}$ = corrected aggregate weight, lb
Agg = aggregate weight as initially measured before moisture correction, lb
MC = moisture content of aggregate, percent

Note that if the aggregate moisture content is below its absorption capacity, the corrected aggregate weight will be lower than the original aggregate weight. Likewise, if the moisture content is greater than the aggregate's absorption capacity, the corrected aggregate weight will be greater than the original measured weight. An iterative process is required to converge the theoretical yield back to 27 ft^3/yd^3. A single iteration was used to converge on a yield that meets ± 2%. A full set of sample calculations for moisture content corrections for a concrete mix can be viewed in Appendix C.

5.2.3 Test Methods

The concrete mixes were tested for early-age and late-age properties including setting time, air content, slump, temperature, electrical resistivity, compressive strength, autogenous shrinkage, and drying shrinkage. Table 22 shows the testing schedule for the individual mixes. Not all samples were tested for autogenous shrinkage as the proposed changes to the mix did not affect the paste or mortar fractions tested.

Table 22: Testing Matrix for Experimental Mix Designs

Description	ASTM C39	ASTM C403	ASTM C138	AASHTO T358	ASTM C231	ASTM C157	ASTM C1698
	Compressive Strength	Setting Time	Density, Yield, Air-Content (G)	Electrical Resistivity	Air Content (P)	Length Change	Autogenous Shrinkage
Baseline w/o FA or SP	X	X	X	X	X	X	X (M&P)
Baseline w/o FA	X	X	X	X	X	X	X (M&P)
Baseline	X	X	X	X	X	X	X (M&P)
Baseline W/AEA	X	X	X	X	X	X	X (M&P)
Baseline / Quartzite	X	X	X	X	X	X	
Gradation 1	X	X	X	X	X	X	
Cement Content 1	X	X	X	X	X	X	X (P)
Cement Content 2	X	X	X	X	X	X	X (P)
Cement Content 3	X	X	X	X	X	X	X (P)
Change Aggregate Content	X	X	X	X	X	X	
Change Aggregate Content	X	X	X	X	X	X	
FLA Replacement	X	X	X	X	X	X	X (M)
FLA Replacement	X	X	X	X	X	X	X (M)
FLA Replacement	X	X	X	X	X	X	X (M)
SCM 1	X	X	X	X	X	X	X (P)
W/CM 1	X	X	X	X	X	X	X (P)
W/CM 2	X	X	X	X	X	X	X (P)
Shrinkage Reducing Admixture	X	X	X	X	X	X	X (P)
Shrinkage Reducing Admixture	X	X	X	X	X	X	X (P)
Shrinkage Reducing Admixture	X	X	X	X	X	X	X (P)
(M) = Mortar (P) = Paste							

5.2.3.1 Fresh Concrete Properties

Several fresh concrete properties were tested for comparison and determination of the quality of the mixes. The following is an overview of the properties selected for measurements.

5.2.3.1.1 Setting Time

Time of setting of concrete mixtures was measured by penetration resistance (ASTM C403 [mortar] & C191 [paste]). This test was conducted on all mixes to "determine the effects of variables, such as water content; brand, type and amount of cementitious material; or admixtures upon the time of setting of concrete". This test was required as the autogenous shrinkage test (ASTM C 1698) requires first measurements to be taken at the time of final set.

ASTM C191 (Time of Setting of Hydraulic Cement by Vicat Needle) Section 14 procedures were followed to determine the setting time by a manual Vicat needle apparatus shown in Figure 10.

Figure 10: Vicat Needle Apparatus

5.2.3.1.2 Air Content

Air content of freshly mixed concrete by the pressure method (ASTM C231) is applicable to concrete made with relatively dense aggregate particles and is exclusive of any air that may exist inside the voids within the aggregate particles. The gravimetric air content method (ASTM C138) determines the percentage by mathematical means. Both air content tests were applicable to this research, as the type, gradation, and aggregate content varied among most of the testing mixes. Determining the density (unit weight), yield, and air content (gravimetric) of concrete (ASTM C138) was used to evaluate consistency of mixing procedures and materials.

5.2.3.1.3 Slump/Temperature

Slump of hydraulic cement concrete (C143 ASTM) was used to determine the workability of the mix. Slump is also a standard of comparison consistently found in literature. Temperature of freshly mixes hydraulic cement concrete (C1064 ASTM) were recorded to evaluate the exothermic chemical reaction between the cement, SCMs, admixtures and water.

5.2.3.2 Hardened Concrete Properties

As part of current mix design qualifications and the potential for adjusting future standards such as the PP84 document (described in more detail in Section 5.2.4) the following sections describes the hardened concrete properties that were measured.

5.2.3.2.1 Surface Electrical Resistivity

Surface Electrical Conductivity of Hardened Concrete (AASHTO T 358) determines the bulk electrical conductivity of saturated specimens of hardened concrete to provide a rapid indication of the concrete's resistance to the penetration of chloride ions by diffusion. It was used to evaluate concrete mixture proportioning and can also aid in the design of cathodic protection systems.

Electrical resistivity is an indirect method of measuring the durability of concrete, primarily with respect to steel corrosion. It is found by measuring a concrete cylinder with a four-point Wenner probe. It represents the ability of a concrete to resist the ingress of chloride ions. A concrete with higher resistivity will theoretically be able to resist more chloride ions and thus have greater resistance against corrosion. The chloride penetrability levels established for standards based on electrical resistivity (AASHTO T 358) are shown in Table 23 below.

Table 23: Chloride Ion Penetrability Related to Resistivity Measurement

Surface Resistivity Test (4"x8" cylinder)	
Chloride Ion Penetration	kΩ-cm
High	<12
Moderate	12-21
Low	21-37
Very Low	37-254
Negligible	>254

The procedure for electrical resistivity described in AASHTO T 358 was used. Each concrete cylinder was measured a total of eight times (twice around the cylinder) on the lines drawn in Figure 11. Adjustment factors due to curing conditions must be applied after measurement. Section 5 of the standard states that curing in lime-saturated water reduces resistivity by 10 percent, thus the average readings from the set of cylinders are multiplied by 1.1 since this curing method was used for all samples.

Figure 11: Electrical Resistivity Meter and Sample Marking

5.2.3.2.2 Compressive Strength

Compressive strength of concrete cylinders was measured in accordance with (ASTM C39). Strength tests were performed at 28 and 56 days, using standard 4” by 8” cylinders. Three cylinders were tested at each of the time intervals. Represented in Figure 12 is one of the 4 x 8-inch cylinders tested for compressive strength.

Figure 12: 4" x 8”-Cylinder Mold Failure During Compression Testing

5.2.3.3 Autogenous Shrinkage

Autogenous strain of cement paste and mortar was determined by (ASTM C1698). Measuring the bulk strain of the cement paste in mixes with low w/c ratio is important for evaluating the risk of early-age cracking. Although this test is limited to the cement paste and mortar, it is the only test that isolates autogenous strain and is critical for evaluating the effects of internal curing from the addition of the saturated LWA.

Autogenous strain of paste and mortar mixes was tested in accordance with the procedures detailed in ASTM C 1698 (Autogenous Strain of Cement Paste and Mortar) (C1698 ASTM). Three samples were prepared for each mix and length measurements were taken at several ages: final set, 1, 3, 7, 14, and 28 days from time of initial mixing of cementitious materials and water. Mixing procedure for pastes are detailed in Section 7 and mortars in Section 8 of ASTM C305 (Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency) (C305 ASTM). The only deviation from the referenced mixing procedure concerned the mortars in Section 8.1.5. The mixing bowl is to be covered to minimize evaporation while allowing absorption of mixing water into the aggregate. A plastic sheet was used in place of a manufactured lid for the mixing bowl.

ASTM C192 allows external vibration by use of a vibrating table. Corrugated tubes are filled in a vertical position held in place by a fixture clamped to the vibrating table (Figure 13). The support tube described in ASTM C1698 was initially manufactured according to specs but suffered a catastrophic failure while being used to fill a sample. A steel fixture was subsequently manufactured which slightly resembles the support tube with minor modifications for durability purposes.

Figure 13: Support Fixture for Filling Corrugated Tube Molds

A trial batch of paste was mixed to test equipment, storage, and data collection procedures. This test demonstrated adequate data collection procedures and equipment functionality but showed an inherent flaw in sample storage, specifically in the time until final set of the mix. The initial samples were split in half as part of the inspection where evidence of bleeding was discovered from the discoloration of the paste. Section 8.1 of ASTM C 1698 states that bleeding has a minimal influence on test results but does allow for an apparatus to rotate the specimens at a rate of 1-3 revolutions per minute (rpm) for mixtures prone to bleeding. For consistency, all pastes and mortar mixes were rotated on an apparatus until final set shown in Figure 14 with a prescribed rotational speed near 3 rpm.

Figure 14: Machine Used to Rotate Samples Until Final Set was Reached

Section 9.2 (ASTM C1698) is used to determine the length of the paste/mortar sample independent of the mold, as shown in the equation below:

$$L_t = \frac{L_{ref}}{25.4mm} + R_t - \frac{2 * L_{plug}}{25.4mm}$$ Equation 4

where:

L_{ref} = length of reference bar, mm
R_t = reading of length gauge with specimen in the dilatometer, mm
L_{plug} = average length of end plugs, mm

The dial indicator as seen in Figure 15 measures in inches, where the dilatometer bench, reference bar, molds, and endcaps are all manufactured using the metric system, therefore the conversion of 25.4 mm/in was used to convert to the USCS system.

Figure 15: Dilatometer Bench Used to Measure Length of Paste and Mortar Samples

The autogenous strain of the samples (in microstrain) was calculated following equation two from Section 9.3 (ASTM C 1698) as shown below:

$$\varepsilon_{autogenous} = \frac{L_t - L_{t_{fs}}}{L_{t_{fs}}} * 10^6 \qquad \text{Equation 5}$$

where:

Lt = Length calculated from previous equation

Lt_{fs} = Length at time of final setting, when the first length measurement is performed, min

This test simultaneously measures chemical shrinkage, autogenous shrinkage, and drying shrinkage. It is impossible to separate chemical and autogenous shrinkage in this test as they are not independent of one another. The mass of the samples is also monitored, as a change in mass indicates a loss of moisture from the system resulting in drying shrinkage. One gram of mass change can result in 200µm/m and 80µm/m of additional strain for pastes and mortars, respectively (C1698 ASTM).

5.2.3.4 Drying Shrinkage

Length change of hardened hydraulic-cement mortar and concrete followed procedures outlined in (ASTM C157). This test measures the long-term unrestrained deformation of the specimens, determining the effect of the drying shrinkage of the concrete mixes. The length change is measured during curing and drying periods. Drying shrinkage is one of the key foci of this research, and for each mix, three specimens were cast in a 3" by 3" by 12" prism mold (used for 1" MSA).

Four 3" x 3" x 11.25" prism molds conforming to ASTM C 490 (Use of Apparatus for the Determination of Length Change of Hardened Cement Paste, Mortar, and Concrete) (C490 ASTM), and cast in accordance with ASTM C192 (Making and Curing Concrete Test Specimens in the Laboratory) (C192 ASTM) were used for determining drying shrinkage of concrete following ASTM C157 (Length change of Hardened Hydraulic-Cement Mortar and Concrete) (C157 ASTM) procedures. Section 9.2 of ASTM C157 allows for consolidation of concrete in molds by external vibration when slump determined by ASTM C143 (Slump of Hydraulic-Cement Concrete) (C 143 ASTM) is less than three inches. The first two batches made (mix 0 and mix 1) both had a slump of less than one inch allowing the use of a vibrating table.

Section 5.6.2 of ASTM C192 provides the required frequency for the vibrating table that was used (3600 vibrations per minute or 60 Hz); however, it does not provide a time interval for consolidation per lift. A trial batch of concrete was cast using the vibrating table to determine an appropriate time interval that provides proper consolidation without causing aggregate segregation. Durations of ~10, 20, 30, and 40 seconds of consolidation were tested at ~ 60 Hz and upon demolding the specimens, it was determined that 10-15 seconds per lift yielded a sufficient surface finish without separating the aggregates from the paste.

Immediately after casting the prism molds they were placed in a moist cabinet inside the curing room maintained at 23 ± 2°C at a relative humidity > 95% for 24 hours. After 24 hours, the specimens were demolded and placed in lime saturated water for 30 minutes to minimize variation in length due to variation in room temperature, then the initial length reading was taken using a H-3250D 10" effective length digital length comparator (Humboldt Manufacturing). The specimens were then placed back in the lime saturated water until they reached an age of 28 days (including the period in the molds). Once the curing period was finished, the specimens were stored according to Section 11.1.2 of ASTM C157 (air storage), and length measurements were taken at intervals of 4, 7, 14, 28, and 56 days as shown in Figure 16. Section 12.2 of ASTM C157 is used to determine the length change of the specimens any time after the initial comparator reading:

$$\Delta L_x = \frac{CRD - CRD_{initial}}{G} * 100 \qquad \text{Equation 6}$$

Where:

ΔL_x = length change of specimen at any age, %,

CRD = difference between the comparator reading of the specimen and the reference bar at any age

G = the gage length (10in [250mm])

Figure 16: ASTM C157 Drying Shrinkage Length Measurement

5.2.3.5 Restrained Shrinkage Test (Ring Test)

The single ring test is used to determine age at cracking due to induced tensile stress in concrete under restrained shrinkage and creep (ASTM C1581). It is an appropriate test to compare cracking tendency between mixes. It captures both the shrinkage and creep behavior of concrete. The test was performed on the three final mixes. Typically, when this test is specified the mix must be crack free for a minimum of 28 days to indicate it as low cracking potential.

Following ASTM C1581, concrete mixes were cast around steel rings and moist cured for 24 hours at 73.5°F ± 3.5 °F. Subsequently, the top surface of the specimen was coated with paraffin wax and the outer ring was removed (shown in Figure 17). The rings were then kept at a temperature of 73.5°F ± 3.5 °F and a relative humidity 50 ± 4% for the remainder of the testing. Strain gages were placed on the steel ring to measure changes in strain in the specimen over time. Unfortunately, the strain data was corrupted and could not be presented in this report. Therefore, cracking on the specimens was visually observed for the duration of the test.

Figure 17: ASTM C1581 Restrained Shrinkage Ring Test Setup

5.2.4 Mix Design Qualification

The results of these tests were compared to the working document AASHTO specification PP84-19 (Table 24). AASHTO PP84 covers elements of a concrete pavement mixture that considers and includes alternative performance characteristics for acceptance. It is intended to provide state highway agencies flexibility in their approach to the use of performance characteristics and includes a range of choices that can be selected to best fit the needs of an agency.

The specified shrinkage values in Table 24 were established from a Monte Carlo analysis. To develop the limits for drying shrinkage, a graphical approach was used (see Figure 18) assuming 60% restraint to simulate bridge decks, meaning that drying shrinkage was expected to contribute less than 60% of the stress in concrete. The unrestrained volume change determined from ASTM C157 at 91-days should result in a probability of cracking less than 5, 20, or 50%, corresponding to microstrain values of 360, 420, and 480.

Table 24: Section 6.4 AASHTO PP84 Specification, Limitations on Concrete

Reducing Unwanted Slab Warping and Cracking Due to Shrinkage					
Property	Specified Test	Specified Value		Mixture Qualification	Acceptance
Volume of Paste	-	25%		yes	no
Unrestrained Volume Change	ASTM C157	420 με	At 28 days	yes	no
Unrestrained Volume Change	ASTM C157	360, 420, 480 με	At 91 days	yes	no
Restrained Shrinkage	T 334	Crack Free	At 180 days	yes	no
Restrained Shrinkage	T 363	∑ < 60%	At 7 days	yes	no
Probability of Cracking	Appendix X1		As specified	yes	no
Quality Control Check	-			no	yes

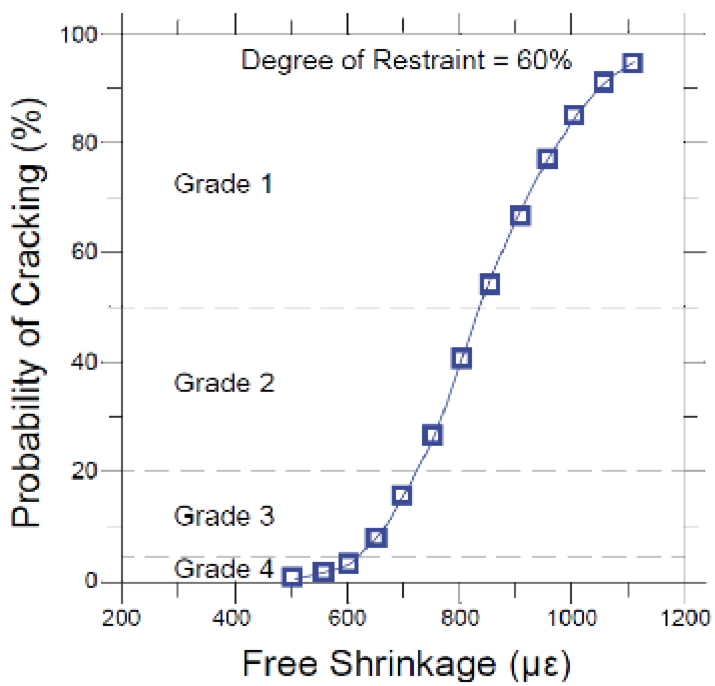


Figure 18: Graphical Approach Used to Determine Probability of Cracking From Drying Shrinkage (PP84)

5.3 Results and Discussion

In this section, autogenous and drying shrinkage results are presented for pastes, mortars, and concrete. Additionally, fresh and hardened concrete properties are reported. Analysis of the results reveal that certain mix design changes can reduce shrinkage while maintaining required workability, strength, and durability properties.

5.3.1 Paste Results

Figure 19 and Table 25 show the 28 day autogenous strain on the paste samples over 28 days of measurements. Throughout this section error bars on plots represent one standard deviation above and below the mean value. Figure 20 shows only the 28 day autogenous strain for comparison, and values are in descending order from left to right. In general, compared to the DOT Baseline, autogenous shrinkage was increased in mixes without fly ash and superplasticizer (combined), with air-entrainment, and with lower w/cm ratio. Autogenous shrinkage decreased with lower cement content and higher fly ash content (combined), no fly ash, higher w/cm ratio, and the inclusion of shrinkage reducing admixtures. Early age expansion was observed in certain paste samples with SRA.

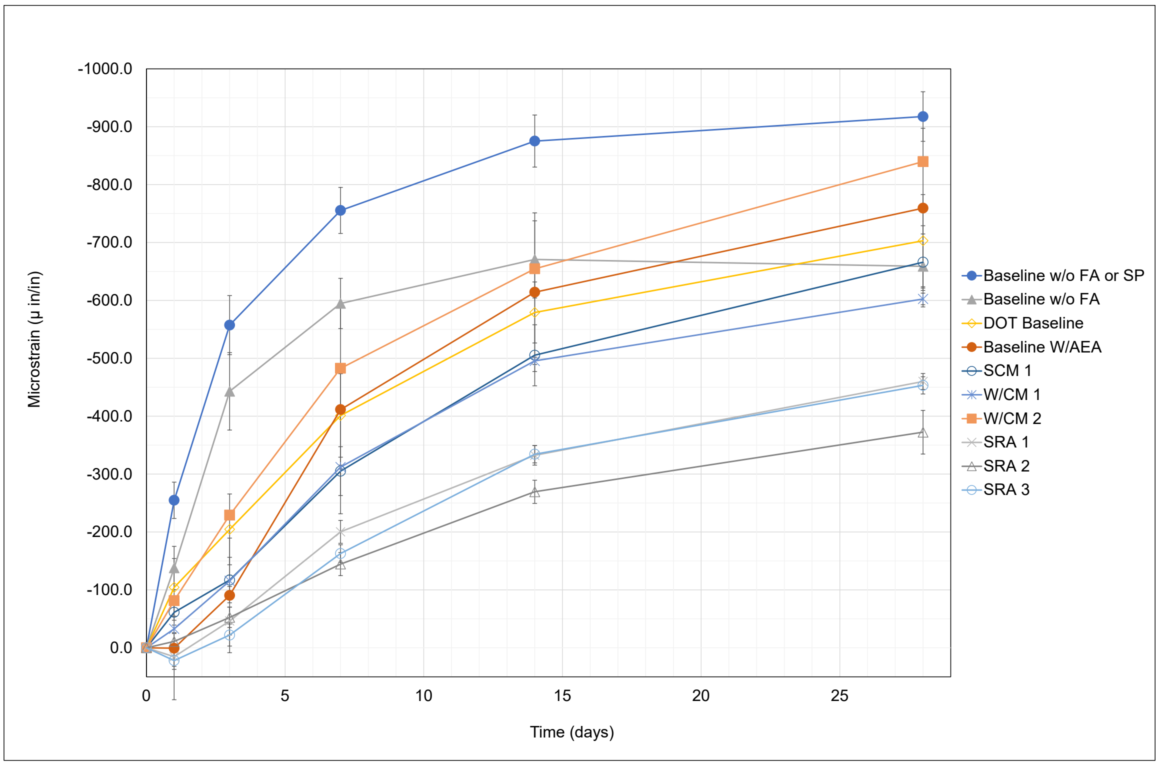


Figure 19: Time Dependent Autogenous Strain Deformation on Pastes

Table 25: 28 day Autogenous Shrinkage Results for Pastes

Mix Name	Data Type	0 days µ-in/in	1 days µ-in/in	3 days µ-in/in	7 days µ-in/in	14 days µ-in/in	28 days µ-in/in
Baseline w/o FA or SP	Average	0.0	-254.8	-557.4	-755.4	-875.1	-917.6
	STDEV	0.0	31.3	51.0	39.8	45.0	42.7
W/CM 2	Average	0.0	-81.6	-229.2	-482.7	-654.6	-839.8
	STDEV	0.0	4.1	4.2	7.8	5.0	2.4
Baseline W/AEA	Average	0.0	0.7	-90.5	-411.5	-614.2	-759.3
	STDEV	0.0	89.1	98.9	180.0	137.1	138.0
DOT Baseline	Average	0.0	-104.4	-204.6	-401.3	-579.2	-703.1
	STDEV	0.0	49.7	61.2	72.0	52.7	79.6
SCM 1	Average	0.0	-61.3	-117.1	-305.1	-505.3	-666.0
	STDEV	0.0	13.6	39.3	42.1	52.6	48.7
Baseline w/o FA	Average	0.0	-138.0	-443.0	-594.8	-670.8	-658.9
	STDEV	0.0	37.4	66.8	43.4	66.6	70.1
W/CM 1	Average	0.0	-32.7	-115.7	-312.2	-495.5	-602.5
	STDEV	0.0	6.6	9.8	3.4	6.4	10.0
SRA 1	Average	0.0	15.4	-46.3	-200.3	-332.4	-460.0
	STDEV	0.0	16.5	24.0	19.8	16.8	13.8
SRA 3	Average	0.0	22.0	-22.0	-162.8	-334.4	-453.2
	STDEV	0.0	15.3	19.0	15.1	15.0	14.9
SRA 2	Average	0.0	-11.0	-52.6	-144.6	-269.5	-372.4
	STDEV	0.0	13.7	17.4	19.9	20.0	37.7

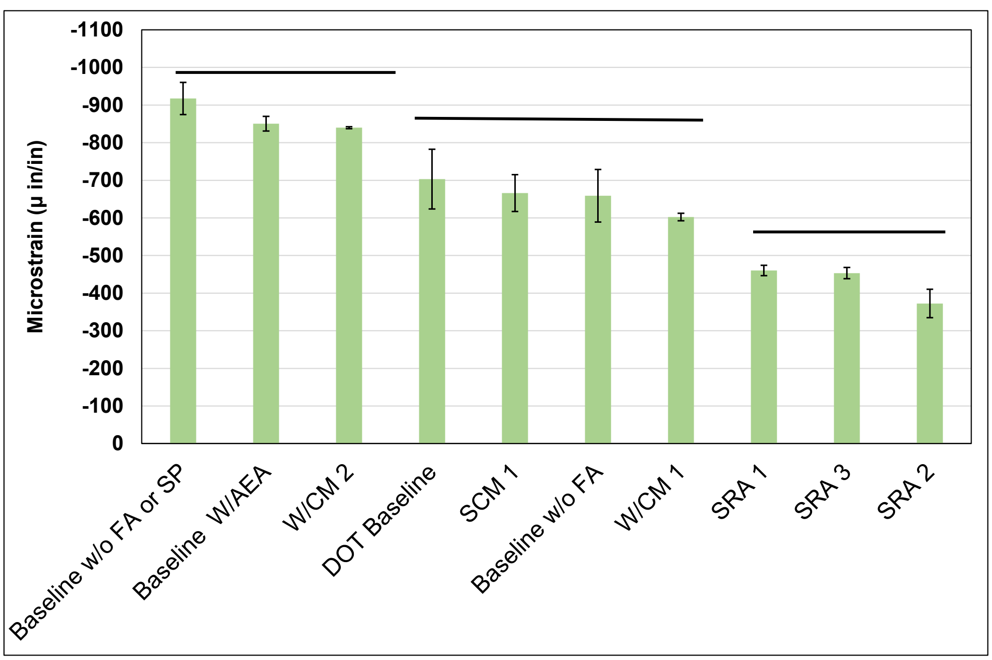


Figure 20: 28 day Autogenous Shrinkage on Paste Samples. Horizontal Bars Link Mixes That Are Not Significantly Different (Tukey-Kramer Test, P>0.05).

At 28 days, the autogenous shrinkage means were significantly heterogeneous (one-way ANOVA, F_9=42.8, P=2×10^{-16}). A Tukey-Kramer post-hoc test (see Table 26) revealed significant pairwise differences between the DOT baseline and the increase in shrinkage observed with the addition of AEA, the removal of FA and SP, and the lower w/cm=0.38 (P< 0.05). Further, significant pairwise differences exist between the DOT baseline and the decrease in shrinkage observed with the addition of both dosages of SRA with and without AEA (P< 0.05).

Table 26: Post-hoc Testing of 28 day Autogenous Shrinkage Means for Paste Samples Compared to the DOT Baseline

Mix Name	Percent Change in Mean Value (%)	Tukey-Kramer: P-value	Significant Difference (P<0.05)
Baseline w/o FA or SP	30.5	<0.001	Yes
Baseline W/AEA	21.0	<0.001	Yes
W/CM 2	19.4	0.01	Yes
SCM 1	-5.3	0.93	No
Baseline w/o FA	-6.3	0.83	No
W/CM 1	-14.3	0.16	No
SRA 1	-34.6	<0.001	Yes
SRA 3	-35.5	<0.001	Yes
SRA 2	-47.0	<0.001	Yes

A statistically significant decrease in autogenous shrinkage was only observed in paste mixes that included SRAs with and without air-entrainment. The higher dosage of SRA reduced shrinkage more than the lower dosage (47% vs. 35% reduction, respectively), but the difference in means between both dosages is not statistically significant, indicating that both dosages improve performance. Although the AEA increased shrinkage in the baseline, it appears that the AEA does not negatively affect autogenous shrinkage when used in combination with an SRA (see SRA 3 result). Both admixtures use the same mechanism of reducing the capillary tension of the pore water which ultimately reduces stress development in the concrete— AEA, in the plastic state, and SRA, in the plastic and hardened state (Pendergrass et al.). A reduced water content (w/cm=0.38) increased autogenous shrinkage as expected.

5.3.2 Mortar Results

Figure 21 and Table 27 show the 28 day autogenous strain on the mortar samples over 28 days of measurements. Figure 22 shows only the 28 day autogenous strain for comparison, and values are in descending order from left to right. In general, compared to the DOT Baseline, the removal of FA and SP slightly increased shrinkage while the addition of AEA and the removal of FA alone slightly decreased shrinkage. The addition of the saturated FLA lowered the autogenous shrinkage at all three replacement values, with the greatest reduction observed for the two highest replacement values. Early age expansion was not observed with the mortar specimens unlike the paste specimens.

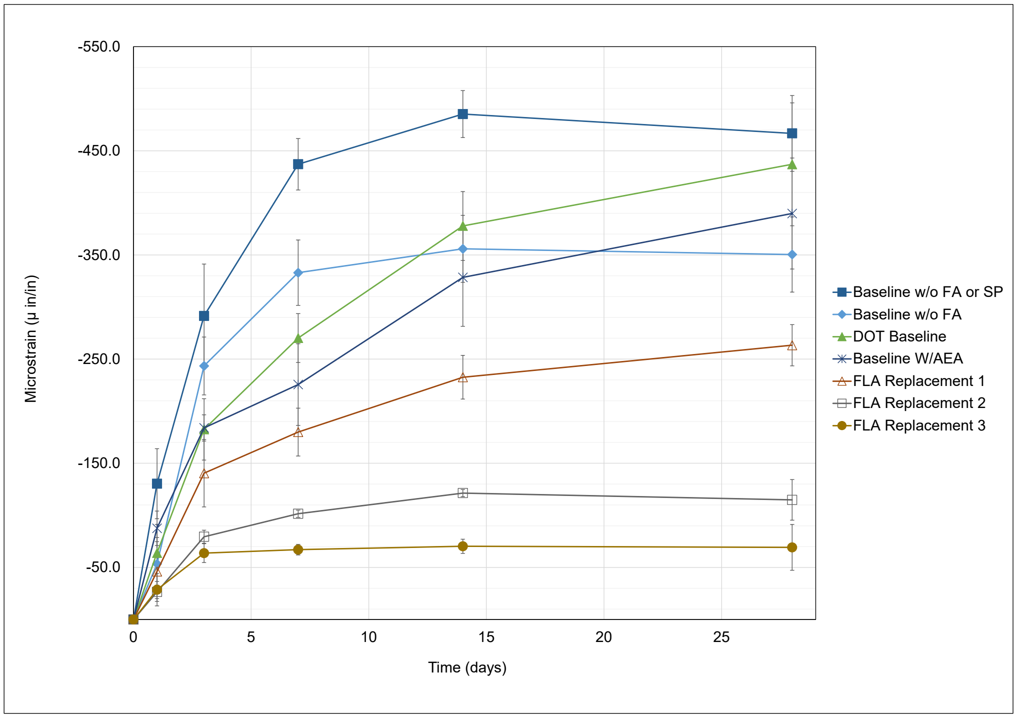


Figure 21: Time Dependent Autogenous Strain Deformation for Mortars

Table 27: 28 day Autogenous Shrinkage Results on Mortar Samples

Mix Name	Data Type	0 days μ-in/in	1 days μ-in/in	3 days μ-in/in	7 days μ-in/in	14 days μ-in/in	28 days μ-in/in
Baseline w/o FA or SP	Average	0.0	-130.4	-291.5	-437.1	-485.3	-466.8
	STDEV	0.0	33.6	49.8	24.7	22.5	36.4
DOT Baseline	Average	0.0	-63.9	-182.6	-270.3	-377.9	-437.1
	STDEV	0.0	27.4	29.5	23.5	33.0	59.0
Baseline W/AEA	Average	0.0	-87.6	-184.0	-225.6	-328.5	-389.8
	STDEV	0.0	16.5	12.6	39.2	47.0	53.3
Baseline w/o FA	Average	0.0	-53.4	-243.5	-333.0	-355.9	-350.5
	STDEV	0.0	25.3	27.8	31.4	32.1	36.2
FLA Replacement 1	Average	0.0	-46.1	-140.4	-179.9	-232.6	-263.4
	STDEV	0.0	28.7	32.4	22.9	21.0	19.8
FLA Replacement 2	Average	0.0	-26.5	-79.4	-101.5	-121.4	-114.8
	STDEV	0.0	6.5	6.3	3.5	3.4	19.5
FLA Replacement 3	Average	0.0	-28.6	-63.7	-67.0	-70.3	-69.2
	STDEV	0.0	15.4	9.0	5.1	6.8	22.0

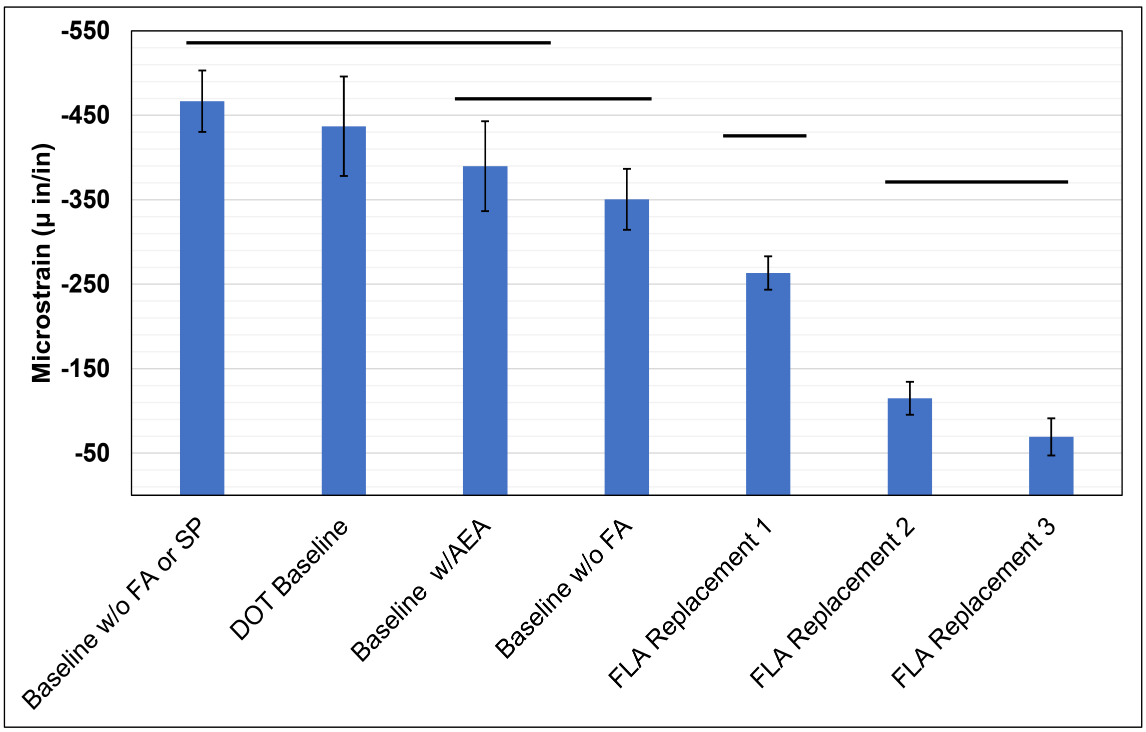


Figure 22: 28 day Autogenous Shrinkage on Mortar Samples. Horizontal Bars Link Mixes That Are Not Significantly Different (Tukey-Kramer Test, P>0.05).

At 28 days, the autogenous shrinkage means were significantly heterogeneous (one-way ANOVA, F_6=88.71, P=9.8×10^{-15}). A Tukey-Kramer post-hoc test (see Table 28) revealed significant pairwise differences between the DOT baseline and the decrease in shrinkage observed with the removal of FA and the addition of all three dosages of FLA (P< 0.05).

Table 28: Post-hoc Testing of 28 day Autogenous Shrinkage Means for Mortar Samples Compared to the DOT Baseline

Mix Name	Percent Change in Mean Value (%)	Tukey-Kramer: P-value	Significant Difference (P<0.05)
Baseline w/o FA or SP	6.8	0.90	No
Baseline W/AEA	-10.8	0.68	No
Baseline w/o FA	-19.8	0.03	Yes
FLA Replacement 1	-39.7	<0.001	Yes
FLA Replacement 2	-73.7	<0.001	Yes
FLA Replacement 3	-84.2	<0.001	Yes

A statistically significant decrease in autogenous shrinkage was observed in one mortar mix that removed FA and three others that included fly ash with saturated FLA at all replacement levels. The higher replacement levels of fine aggregate with saturated FLA (40% and 60%) resulted in greater shrinkage reduction. These results align with other research in this area (Montanari et al.). Although the 40% and 60% FLA replacement values reduced the shrinkage by nearly double that for the 20% replacement, these higher replacement values could potentially affect mechanical properties and complicate materials sourcing and batching logistics.

5.3.3 Concrete Results

This section presents fresh concrete properties, compressive strength, electrical resistivity, and drying shrinkage results for the concrete mixes. Fresh properties recorded for the concrete mixes including setting time, slump, wet unit weight, air content, and temperature are presented in Table 29. The average setting time for all mixes is 5 hr. 13 min. Slump for all mixes are within the SDDOT tolerance of 1-4 inches except for three mixes: (1) Baseline w/o FA or SP - low, (2) SRA 1-high, and (3) SRA 2-high. Baseline w/o FA or SP was expected to be low as fly ash and SP both contribute to improved workability. The higher slumps observed in the SRA mixes are likely due to two reasons: (1) the SRA lowers the surface tension of the water thus increasing slump and (2) the interaction between the SP and the SRA can be difficult to control.

The concrete mixes used for this testing were developed with an assumed 2.0% air content except for the two mixes that used AEA, which were developed with an assumed 6.5% entrained air content. Average air content for the mixes not using AEA is 2.7% (STDEV 0.7) and 2.5% (STDEV 0.6) when fly ash is included. A lower AEA dosage was required to achieve the target entrained air content when used in combination with SRA as shown in Table 21.

These concrete mixes were designed as normal weight concrete, which have a density that typically ranges from 145-150 lb/yd^3. The average density for the mixes not including the lightweight aggregate was 150.0 lb/yd^3 with a standard deviation of 2.2 lb/yd^3. The replacement of 20% and 40% of the fine aggregate with LWA reduces the density by 1.5% and 2.3% respectively, still within the range of normal weight concrete, but the 60% replacement of LWA reduced the density to 140.5 lb/yd^3 (6.3% reduction), slightly below what Mehta considers normal weight (Mehta et al.).

Laboratory conditions for mixing the concrete were consistent at 69 °F and a natural RH of 32-44%. As stated earlier, the materials were stored inside the lab except for the aggregates, which were brought inside and given 48 hours to normalize to room temperature. Aggregate temperature was not measured after the 48 hour wait. The addition of FA slightly raised the initial concrete temperature by an average of 4.4 °F. Having a lower cementitious materials content reduces the available materials for the subsequent exothermic chemical reactions, thus lowering the concrete temperature, as evident in a number of mixes (Gradation, Cement Content 1, Cement Content 2, and Cement Content 3).

Table 29: Fresh Concrete Properties

Name	Setting Time	Slump	Unit Weight (ρ)	Air Content	Concrete Temp.
	hr:min	in	pcf	%	°F
Baseline w/o FA or SP	-	0.75	146.7	3.8	72
Baseline w/o FA	-	1.50	151.0	3.8	70
DOT Baseline	4:29	3.75	151.2	2.0	76
Baseline W/AEA	5:39	2.75	144.9	6.9	78
Baseline / Quartzite	5:07	2.25	150.0	2.3	79
Gradation	5:29	3.75	151.4	2.9	72
Cement Content 1	6:09	1.50	152.6	1.5	70.5
Cement Content 2	6:06	3.25	150.2	2.8	72
Cement Content 3	4:56	1.75	151.4	2.6	74
SCM 1	5:13	1.75	153.0	3.3	75
FLA Replacement 1	5:05	2.75	147.7	3.4	73.5
FLA Replacement 2	5:19	3.75	146.5	2.1	75.5
FLA Replacement 3	4:09	3.00	140.5	3.3	75
W/CM 1	4:45	3.50	150.4	2.4	77
W/CM 2	4:34	3.00	151.2	2.6	79
SRA 1	5:28	4.75	150.4	2.0	75
SRA 2	5:53	6.75	148.6	2.1	74
SRA 3	5:11	3.75	147.1	6.5	80.5

Table 30 and Figure 23 show the 28 day and 56 day compressive strength results. Strength values in Figure 23 are arranged in descending order of 28 day strengths from left to right, which is the age at which the current SDDOT specification uses for acceptance. Specifically, the A45 bridge deck mix has a 28 day compressive strength minimum f'c = 4500 psi for structural design, but a materials design compressive strength minimum f'cr = 5700 psi. All mixes, except for two (SRA 2 and Baseline W/AEA), had mean strength values greater than 5700 psi, but both low strength mixes are still within 1-2 standard deviations from the limit. They also exceed the strength limit at 56 days as all mixes continued to increase in strength between these two ages.

For these two low strength mixes, the higher dosage of SRA and the addition of the AEA lowered their compressive strength approximately 1000 psi compared to the DOT baseline. However, SRA 3 meets the requirements with the lower dosage of SRA (1.5 gal/yd^3) and AEA combined. For concrete made with SRAs, water curing can sometimes inhibit strength gain, which may be the reason for the behavior observed here. Compared to the DOT Baseline, most mixes had a higher compressive strength at both ages. The highest strength mix at both ages removed fly ash, which is expected since low calcium Class F fly ash takes up to 2-3 months to begin reacting (Shearer et al.). The low dosage of SRA without AEA and all the saturated FLA mixes had increased strength compared to the control at 28 days indicating they do not detrimentally impact and can even improve concrete mechanical properties.

Table 30: 28 and 56 day Compressive Strengths

Name	28-Day Strength AVG	28-Day Strength STDEV	56-Day Strength AVG	56-Day Strength STDEV
	psi	psi	psi	psi
Baseline w/o FA	7865	82	8536	281
SCM 1	7312	623	8455	65
FLA Replacement 2	7166	82	8249	184
FLA Replacement 1	7213	185	8201	240
Cement Content 1	7277	230	8109	296
Baseline w/o FA or SP	7596	154	8105	329
Baseline / Quartzite	7202	269	8060	209
Gradation	7208	212	8030	287
Cement Content 2	6869	168	7939	92
Cement Content 3	6778	695	7872	214
FLA Replacement 3	7018	156	7862	90
W/CM 2	6841	193	7840	301
DOT Baseline	6842	366	7618	203
W/CM 1	6865	261	7373	97
SRA 1	7154	247	7296	336
SRA 2	5635	116	6585	142
SRA 3	5778	152	6187	189
Baseline W/AEA	5548	149	5832	456

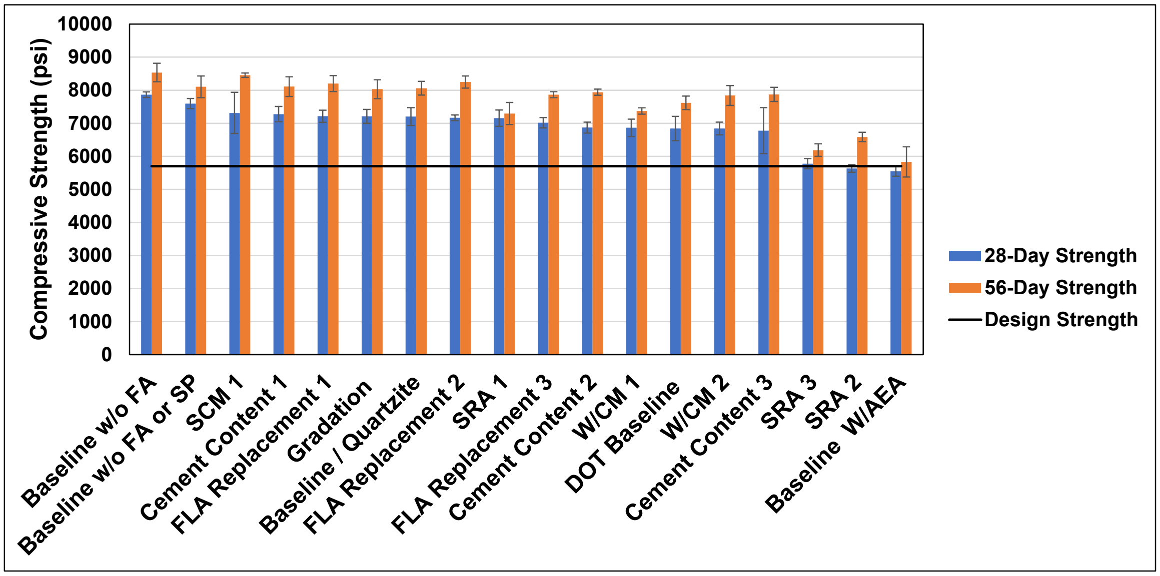


Figure 23: 28 and 56 day Concrete Compressive Strengths

The results listed in

Table 31 and displayed in Figure 24 show the surface electrical resistivity readings at 28 and 56 days. Resistivity values in Figure 24 are arranged in descending order of 56 day strengths from left to right to better capture the impact of the slow-reacting fly ash. Results are compared to Table 23, which provided the chloride penetrability limits from the AASHTO T 358 standard. All the 28 day readings are 8.0 kΩ-cm or less, which is categorized as high potential for chloride ion penetration (i.e., low resistivity). There is a noticeable jump in the 56 day readings in all the samples that contain fly ash due to their late-age reactivity.

Compared to the control, higher additions of the porous expanded shale, (FLA 2 and FLA 3), more fly ash with lower cement content (SCM 1), lower cement content (Cement Content 2), better aggregate gradation (Gradation), and a slightly higher w/cm ratio (W/CM 2) all improved to moderate potential for chloride ion penetration at 56 days. It is unexpected that the higher w/cm ratio mix showed improved performance, but it could be related to differences in sample preparation. SRA addition did not significantly change resistivity from the baseline although its combination with AEA slightly increased resistivity.

Table 31: 28 and 56 day Surface Electrical Resistivity Measurements

Name	28-day AVERAGE	28-day STDEV	56-day AVERAGE	56-day STDEV
	kΩ-cm	kΩ-cm	kΩ-cm	kΩ-cm
SCM 1	7.9	0.82	14.3	1.04
FLA Replacement 3	8.0	0.42	14.0	0.69
FLA Replacement 2	7.5	0.19	13.9	0.30
Cement Content 2	6.5	0.69	13.3	0.95
Gradation	7.7	0.49	12.9	0.82
W/CM 2	7.6	0.77	12.9	1.36
FLA Replacement 1	7.0	0.61	12.1	1.00
Cement Content 3	6.9	0.28	11.7	0.60
Baseline W/AEA	6.8	0.73	11.3	0.92
SRA 3	6.8	0.11	11.0	0.45
Cement Content 1	6.0	0.43	10.6	0.47
Baseline / Quartzite	5.8	0.23	9.8	0.18
W/CM 1	5.3	0.47	9.6	1.00
SRA 1	5.7	0.21	9.4	0.48
Baseline w/o FA	7.6	0.18	9.0	0.19
DOT Baseline	5.3	0.11	8.8	0.80
SRA 2	5.2	0.29	8.5	0.78
Baseline w/o FA or SP	5.0	0.42	6.6	1.15

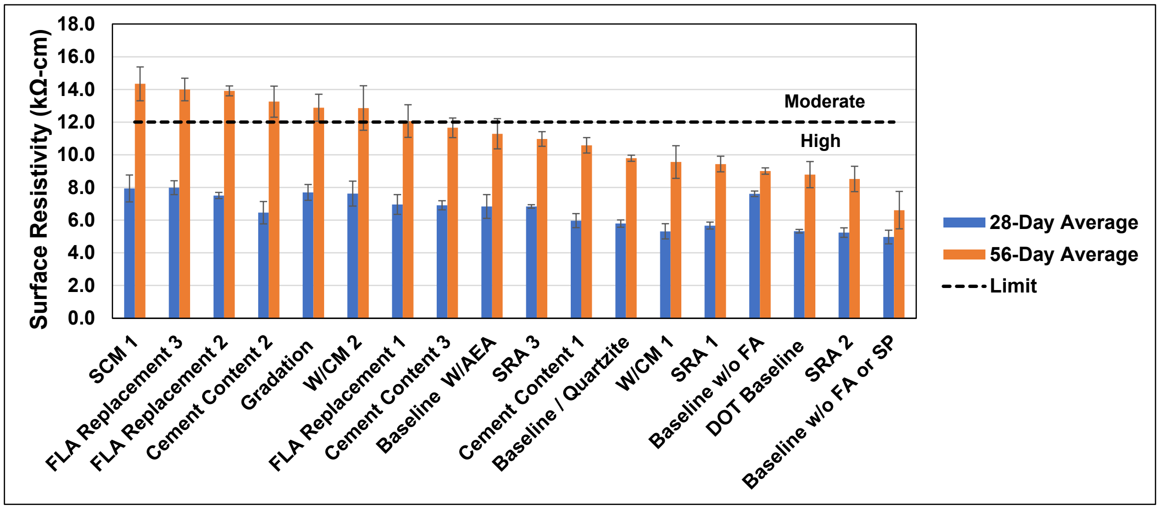


Figure 24: 28 and 56 day Surface Electrical Resistivity

Figure 26 and Table 32 show the 28 day drying shrinkage results on the concrete samples over 56 days of measurements. Figure 26 shows only the 28 day drying shrinkage strain for comparison, and values are in descending order from left to right. 28 day data is shown instead of 56 days since many DOTs use this age for qualification of mixes. Strains for all mixes were lower than the maximum 28 day limit established in AASHTO PP84 of 420 µ in/in. The DOT baseline mix had 24% less shrinkage than this limit, but it still does not perform well in the field. This indicates that this limit might not be applicable for these mix designs.

There was less overall variability in drying shrinkage results due to mix design changes compared to autogenous shrinkage. In general, compared to the DOT Baseline, reduced shrinkage was observed at 28 days due to the following changes: (1) lower cementitious content (with or without fly ash), (2) SRAs, especially at the higher dosage, (3) use of quartzite coarse aggregate, and (3) the use of saturated lightweight aggregate (FLA), especially at the highest replacement level (60%). The use of AEA and the removal of both FA and SP were the only changes that increased shrinkage compared to the control. Early age expansion was observed with some of the concrete specimens.

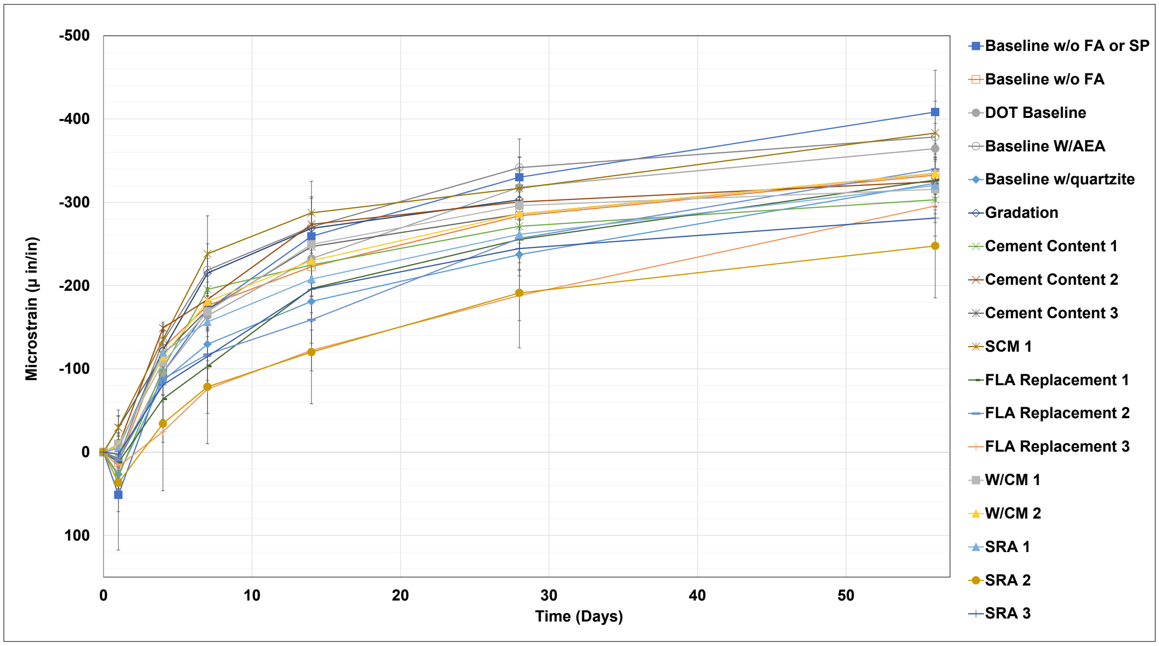


Figure 25: Time Dependent Drying Shrinkage Strain on Concrete Mixes

Table 32: 28 and 56 day Drying Shrinkage Results for Concrete Mixes

Name	Data Type	0 days µ in/in	1 days µ in/in	4 days µ in/in	7 days µ in/in	14 days µ in/in	28 days µ in/in	56 days µ in/in
Baseline w/o FA or SP	Average	0.0	51.3	-95.3	-171.1	-259.1	-330.1	-408.3
	STDEV	0.0	20.1	56.1	25.9	25.9	24.5	50.3
SCM 1	Average	0.0	-29.5	-135.1	-238.2	-287.3	-316.8	-383.2
	STDEV	0.0	21.2	9.4	45.6	37.9	36.9	28.7
Baseline W/AEA	Average	0.0	7.4	-132.7	-218.7	-270.3	-341.6	-378.5
	STDEV	0.0	12.4	23.5	31.6	36.4	34.6	43.0
DOT Baseline	Average	0.0	9.8	-95.4	-163.8	-232.3	-317.9	-364.4
	STDEV	0.0	23.9	14.7	12.3	25.8	24.6	30.3
FLA Replacement 2	Average	0.0	9.8	-88.0	-117.3	-158.9	-256.7	-339.8
	STDEV	0.0	41.5	27.7	30.9	28.1	29.3	30.4
W/CM 2	Average	0.0	-7.3	-114.9	-180.9	-229.8	-286.1	-335.0
	STDEV	0.0	25.7	31.3	23.3	42.7	35.2	29.2
Cement Content 3	Average	0.0	-29.3	-117.3	-171.0	-246.8	-285.9	-334.8
	STDEV	0.0	13.8	21.1	16.9	16.7	16.6	16.8
Baseline w/o FA	Average	0.0	12.2	-124.7	-176.1	-222.6	-283.7	-332.7
	STDEV	0.0	9.4	21.6	17.7	19.9	28.5	20.9
Gradation	Average	0.0	-4.9	-122.1	-215.0	-268.7	-302.9	-332.3
	STDEV	0.0	16.9	23.3	17.7	36.2	21.2	21.3
FLA Replacement 1	Average	0.0	12.3	-63.8	-103.1	-196.5	-255.4	-326.7
	STDEV	0.0	31.4	26.0	26.0	29.0	35.9	40.5
Cement Content 2	Average	0.0	-7.3	-149.0	-183.2	-273.5	-300.4	-324.9
	STDEV	0.0	12.3	4.9	12.3	13.9	16.7	9.4
Baseline / Quartzite	Average	0.0	26.9	-85.6	-129.6	-181.0	-237.2	-322.9
	STDEV	0.0	9.3	16.6	20.1	24.5	25.5	28.8
SRA 1	Average	0.0	-4.9	-119.8	-156.4	-207.8	-261.5	-320.2
	STDEV	0.0	18.7	9.3	17.8	20.1	16.7	29.2
W/CM 1	Average	0.0	-9.8	-107.6	-168.8	-249.5	-296.0	-315.6
	STDEV	0.0	13.8	13.8	21.7	20.5	34.3	34.3
Cement Content 1	Average	0.0	29.3	-100.2	-195.5	-224.8	-271.2	-303.0
	STDEV	0.0	8.0	16.7	0.1	13.8	14.7	8.0
FLA Replacement 3	Average	0.0	17.1	-24.4	-75.7	-122.1	-188.1	-295.6
	STDEV	0.0	28.1	12.6	29.1	24.6	30.2	20.0
SRA 3	Average	0.0	2.4	-80.7	-114.9	-195.5	-244.4	-281.1
	STDEV	0.0	9.4	12.4	14.7	8.1	11.4	21.8
SRA 2	Average	0.0	36.9	-34.2	-78.4	-120.1	-191.2	-247.6
	STDEV	0.0	80.7	80.6	68.3	62.0	66.0	62.4

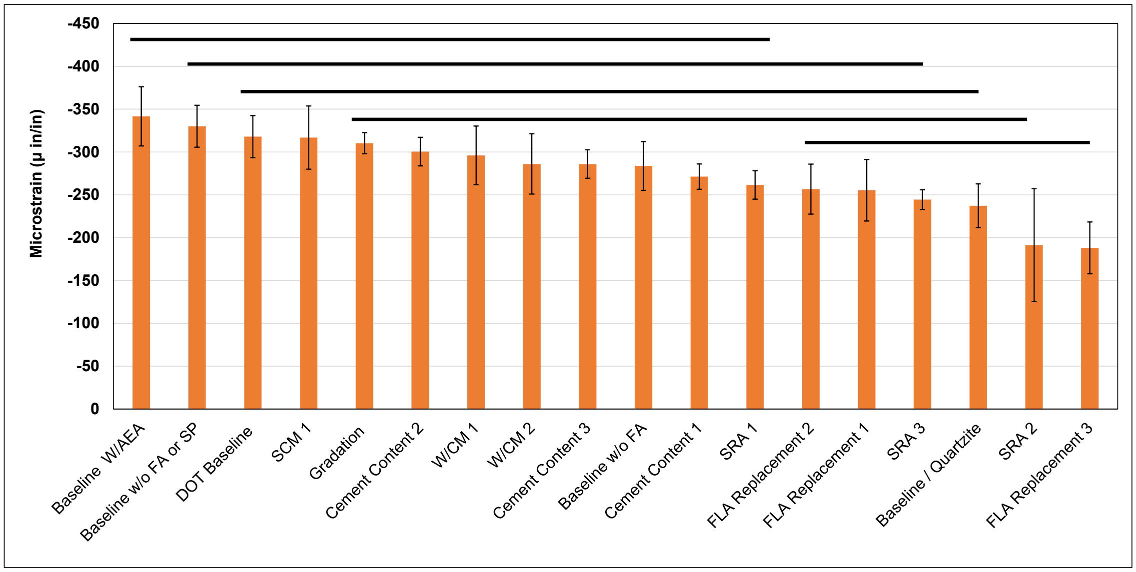


Figure 26: 28 day Drying Shrinkage Results for Concrete Mixes. Horizontal Bars Link Mixes That Are Not Significantly Different (Tukey-Kramer Test, P>0.05).

At 28 days, the drying shrinkage means were significantly heterogeneous (one-way ANOVA, F_{17}=7.89, P=2.3×10^{-9}). A Tukey-Kramer post-hoc test (see Table 33) revealed significant pairwise differences between the DOT baseline and the decrease in shrinkage observed with the use of quartzite coarse aggregate, the higher dosage of SRA (SRA 2), and the highest dosage of FLA (FLA Replacement 3) (P< 0.05).

Table 33: Post-hoc Testing of 28 day Drying Shrinkage Means for Concrete Samples Compared to the DOT Baseline

Mix Name	Percent Change in Mean Value (%)	Tukey-Kramer: P-value	Significant Difference (P<0.05)
Baseline W/AEA	7.4	0.99	No
Baseline w/o FA or SP	3.8	1.00	No
SCM 1	-0.3	1.00	No
Gradation	-4.7	1.00	No
Cement Content 2	-5.5	1.00	No
W/CM 1	-6.9	1.00	No
W/CM 2	-10.0	0.99	No
Cement Content 3	-10.1	0.99	No
Baseline w/o FA	-10.8	0.98	No
Cement Content 1	-14.7	0.76	No
SRA 1	-17.7	0.46	No
FLA Replacement 2	-19.3	0.32	No
FLA Replacement 1	-19.7	0.28	No
SRA 3	-23.1	0.09	No
Baseline / Quartzite	-25.4	0.04	Yes
SRA 2	-39.9	<0.001	Yes
FLA Replacement 3	-40.8	<0.001	Yes

The three statistically significant mix design changes observed at 28 days reduced drying shrinkage by 25%-41% compared to the control. Of these mixes, the highest SRA dosage and FLA dosage also performed best during autogenous shrinkage testing. Although the highest dosages of both SRA and FLA performed best, all dosages of SRA and FLA reduced drying shrinkage and the results were not significantly different from each other. This indicates that even the lower dosages for SRA and FLA would be effective strategies for reducing drying shrinkage compared to the DOT baseline (although the significance is lower). At 56 days, the higher dosages of SRA and FLA still perform best. The good performance at 28 days of the quartzite aggregate belies field evidence, which has shown more severe cracking present in bridge decks using the quartzite aggregates compared to limestone aggregates according to the SDDOT. But this cracking could be more likely related to other types of shrinkage including thermal shrinkage, because of quartzites' higher coefficient of thermal expansion (CTE) (Jensen et al.). Changes in cement content, fly ash dosage, gradation, and w/cm ratio reduced drying shrinkage compared to the control, but not in a statistically significant way.

5.3.4 Comparison of Drying Shrinkage and Autogenous Shrinkage Data

The drying shrinkage of the concrete is plotted versus the autogenous shrinkage of the paste fraction of each equivalent concrete mix for all measured ages in Figure 27. The coefficient of determination (R^2) of 0.77 indicates that there is a strong positive linear relationship between drying shrinkage and autogenous shrinkage values. This finding suggests that a specification only requiring drying shrinkage testing (which is more commonly measured) may be able to capture most autogenous shrinkage effects. However, in this study the autogenous test was able to better distinguish between the effects of mix design changes on shrinkage.

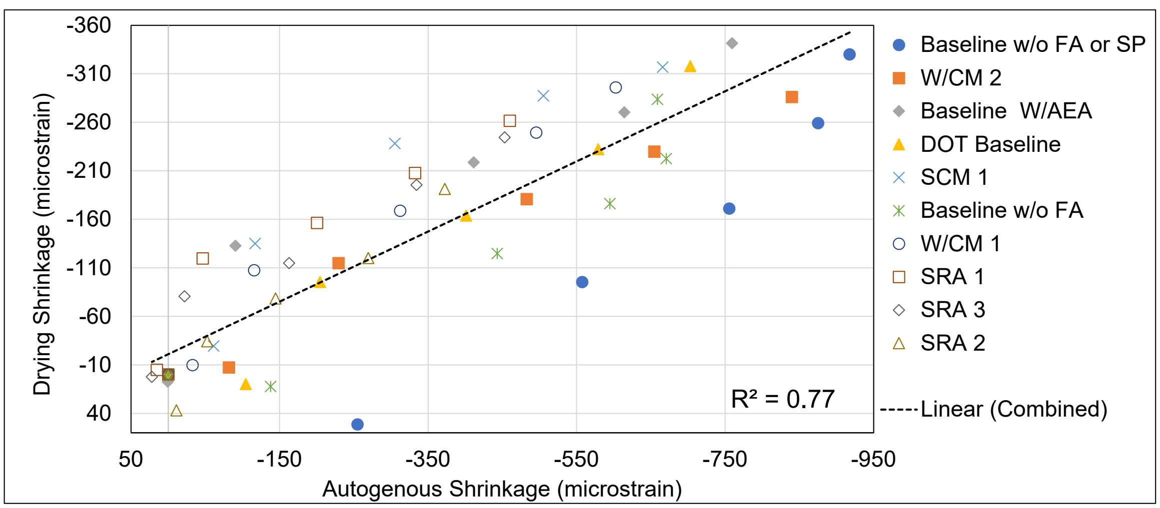
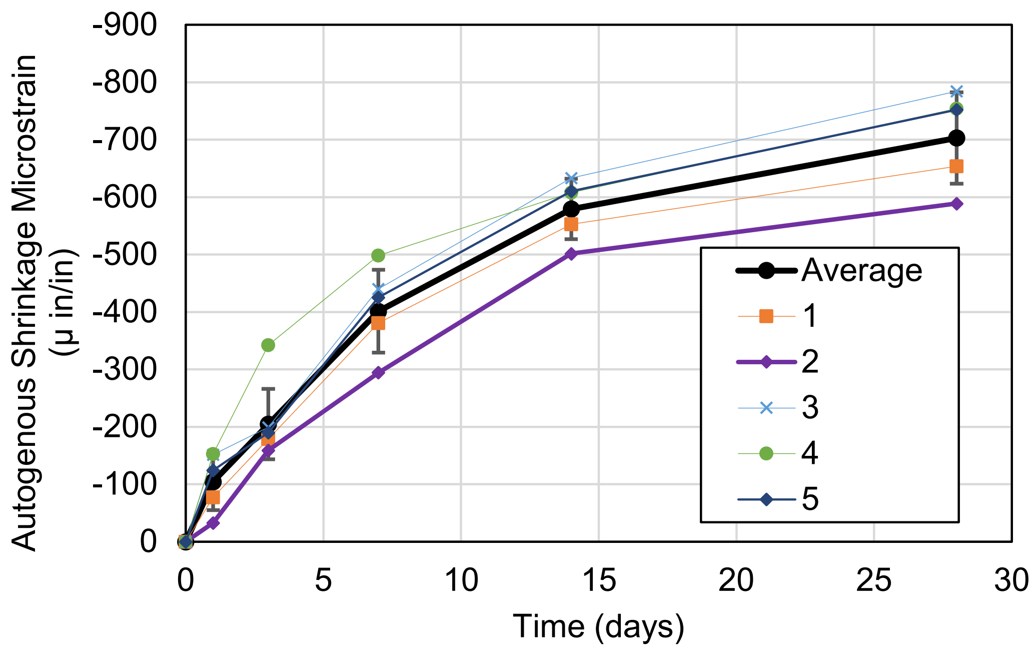


Figure 27: Drying Shrinkage Versus Autogenous Shrinkage for Like Mixes

5.4 Testing Sensitivity Analysis

An example of the sensitivity testing of the autogenous shrinkage results is presented in Figure 28 for the five DOT Baseline paste batches to assess the influence of batching, mixing, and sampling of the test specimens on measurements. The average shrinkage is shown for each of the five batches in addition to the overall average of all specimens (note that the error bar represents one standard deviation above and below the mean). It is apparent that no two tests yield the same shrinkage values, which is expected when testing a heterogeneous material like cement paste or concrete. At 28 days, the maximum difference between batches is 195 microstrain. Standard deviations found in literature for both drying and autogenous shrinkage are widespread and no specific limits were found. The spread in the data is captured in the overall standard deviation (80 microstrain) and factored into the statistical analysis. A limit had to be established for a basis of quality control, a standard deviation of 50 microstrain between samples from the same mix was chosen for both shrinkage tests (Khairallah) (Persson et al.), which is slightly exceeded here. Overall, the results indicate that while collecting shrinkage data the error tolerance must be set by the engineer and the data spread must be assessed using statistical methods when comparing the results of different mixes to account for the variability.

Figure 28: Autogenous Strain for Five DOT Baseline Paste Samples Assessing Test Sensitivity



5.5 Recommendations for Final Mix Testing

As a result of this testing, two final mix designs presented in Table 34 were recommended for use by the SDDOT and underwent further testing beyond the scope of this thesis. Superplasticizer and air-entraining admixtures were dosed as needed to meet slump and entrained air content, respectively. Major changes to the DOT Baseline mix included the following:

- Lower cementitious content (615 lb/yd^3) with 20% fly ash
- Use of SRA at lower dosage (max 1.5 gal/yd^3)
- Use of improved aggregate gradation (meets tarantula and 0.45 power curves)
- Use of saturated FLA at lower dosage (20% replacement of fine aggregate) – only in one mix

Table 34: Final Concrete Mix Designs for Testing

Sample	Description	w/cm	Water	Cement	Fly Ash	Coarse Aggregate	Intermediate Aggregate	Fine Aggregate	Light Weight Aggregate	Paste Volume	Coarse Aggregate Fraction	Admixtures	SP Dosage	SRA Dosage	AEA Dosage	Theoretical Yield
#			lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	lb/yd^3	%	%	type	fl oz/cwt	gal/yd^3	fl oz/cwt	ft^3/yd^3
1	DOT Baseline w/AEA	0.40	260	520	130	1720	0	1210	0	31.1	58.7	SP, AEA	as needed for 1-4" slump	0	as needed for 5-7.5% air	27.01
2	Final Mix	0.40	246	492	123	1395	395	1210	0	28.7	59.7	SP, AEA, SRA	as needed for 1-4" slump	1-1.5	as needed for 5-7.5% air	27.02
3	Final Mix w/LWA	0.40	246	492	123	1350	385	900	225	30.1	60.7	SP, AEA, SRA	as needed for 1-4" slump	1-1.5	as needed for 5-7.5% air	27.02

Below is the reasoning for each change:

1. A lower cementitious content was recommended because it showed slightly improved drying shrinkage performance compared to the baseline in addition to supporting evidence of this same effect from literature.
2. The use of Master Life SRA 035 dosed at the manufacturer recommended value of 1-1.5 gal/yd^3 was recommended due to its ability to reduce both autogenous and drying shrinkage. Although the higher dosage (3 gal/yd^3) performed slightly better, this dosage is not recommended due to the higher cost and potential interactions with other admixtures.
3. The improved aggregate gradation (i.e., a blend of 45% fine aggregate 21% intermediate (#8) and 34% coarse (#57) aggregate) meets both the 0.45 power curve and tarantula curve gradations. This gradation was recommended to improve the compressive strength of the concrete, which is needed to meet strength requirements for the lower cementitious content used in these mixes.
4. The use of saturated lightweight aggregate at a 20% by weight replacement of fine aggregate was recommended because it reduces both autogenous and drying shrinkage. Although higher replacement values improved performance more, the lowest replacement level was chosen to avoid other potential impacts of using the higher percentage replacement levels (i.e., changes in structural design, elastic modulus, batching issues, and material sourcing issues). A higher value could be used if these issues are not of concern.

These concrete mixes differ from the LC-HPC mixes used in the SD2005-11 bridge deck study in the following way:

- A higher cementitious content
- The use of fly ash
- A higher allowable slump
- The use of SRAs
- The use of saturated lightweight aggregate

5.6 Final Mix Design Results

This section presents fresh concrete properties, compressive strength, electrical resistivity, autogenous shrinkage, drying shrinkage, and ring test results for the two final recommended concrete mixes presented in Table 34. These are compared to the "DOT Baseline w/AEA" control mix originally presented in Table 16 with added air-entrainment to reach the target 5-7.5% air (see Table 34). Fresh properties recorded for the concrete mixes including setting time, slump, wet unit weight, air content, and temperature are presented in **Error! Reference source not found.**. The average setting time for all mixes is 6 hr. 10 min. Slump for all mixes are within the SDDOT tolerance of 1-4 inches and the average air content of the mixes is 6%. The average density for the mixes not including the lightweight aggregate is 148.6 lb/yd^3. The replacement of 20% of the fine aggregate with the LWA slightly reduced the density but it remained within the range of normal weight concrete.

Table 35: Fresh Concrete Properties for Final Mixes

Name	Setting Time	Slump	Unit Weight (ρ)	Air Content	Concrete Temp.
	hr:min	in	pcf	%	°F
DOT Baseline w/AEA	5:40	4.0	147.3	7	72.0
Final Mix	6:27	3.25	149.8	5	74.0
Final Mix w/LWA	6:24	3.0	141.5	6	73.5

Error! Reference source not found. and **Error! Reference source not found.** show the 28 day compressive strength results. The A45 bridge deck mix has a 28 day compressive strength minimum f'c = 4500 psi for structural design, but a materials design compressive strength minimum f'cr = 5700 psi. The baseline mix did not meet the 5700psi requirement, likely due to the addition of air entrainment. Only the "Final Mix" met the strength requirement, but the "Final Mix w/LWA" did have a higher mean strength than the baseline. In Table 30, the Baseline W/AEA only reached required strength after 56 days. Therefore, use of 56 day compressive strength approval instead may be warranted.

Table 36: Compressive Strength Values for Final Mixes

Name	28-Day Strength AVG	28-Day Strength STDEV
	psi	psi
DOT Baseline w/AEA	5160	90
Final Mix	6430	90
Final Mix w/LWA	5495	60

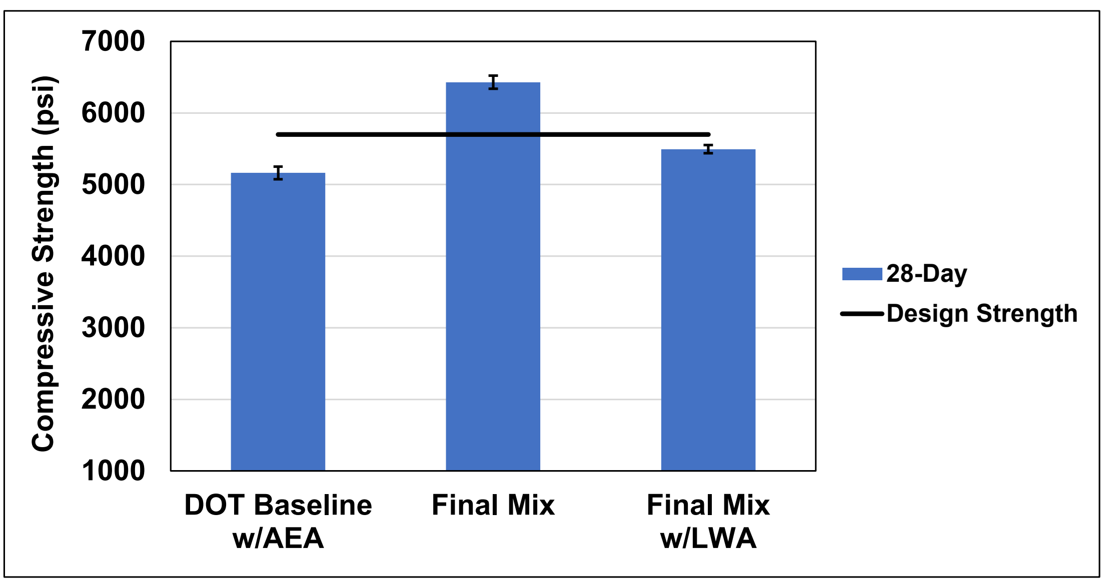


Figure 29: Compressive Strength for Final Concrete Mixes Compared to SDDOT Design Strength.

The results listed in **Error! Reference source not found.** and displayed in **Error! Reference source not found.** show the surface electrical resistivity readings at 28 days. Results are compared to Table 23, which provided the chloride penetrability limits from the AASHTO T 358 standard. All the 28 day readings are 9.5 kΩ-cm or less, which is categorized as high potential for chloride ion penetration (i.e., low resistivity). It is expected that this reading would improve at later ages. Both final mix designs have higher resistivity than the baseline, indicating lower permeability.

Table 37: 28 Day Surface Electrical Resistivity Readings for Final Concrete Mixes

Name	28-day AVG	28-day STDEV
	kΩ-cm	kΩ-cm
DOT Baseline w/AEA	6.0	0.23
Final Mix	9.3	0.03
Final Mix w/LWA	8.8	0.22

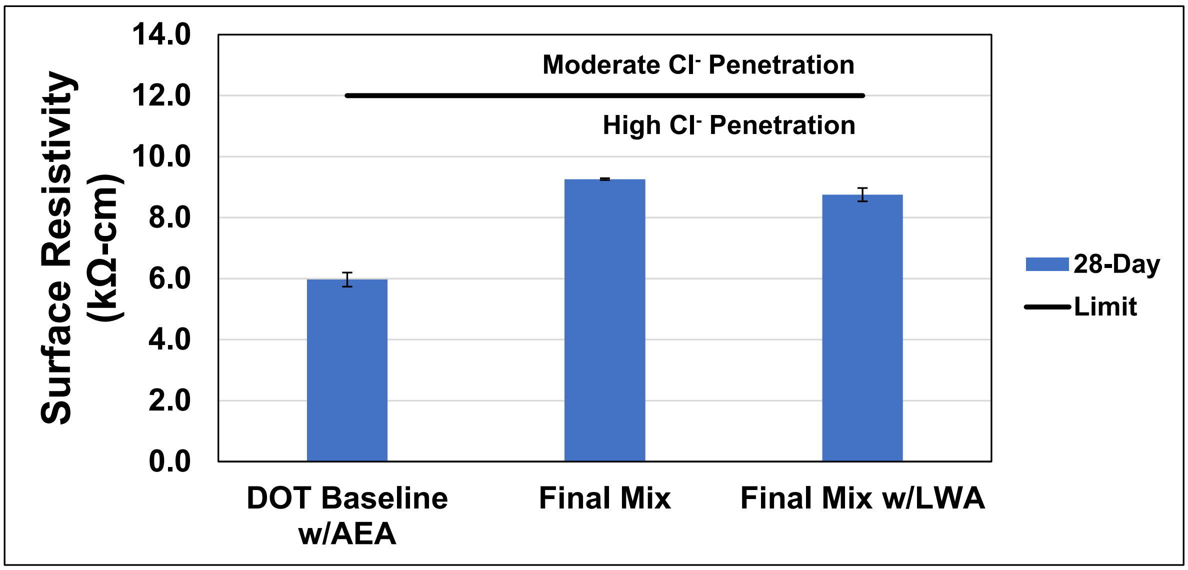


Figure 30: 28 Day Surface Electrical Resistivity Readings for Final Concrete Mixes

Error! Reference source not found. shows the 28 day autogenous strain on the mortar samples over 28 days of measurements. **Error! Reference source not found.** shows only the 28 day autogenous strain for comparison. Compared to the DOT Baseline, the addition of the SRA with the optimized aggregate reduced autogenous shrinkage by 29% and, when coupled with the saturated FLA, the autogenous shrinkage was reduced by 70%. Unlike the previous tests, early age expansion was observed on half of the individual samples, which can be attributed to the samples being wet sieved from the concrete mix instead of being mixed and proportioned as was done for the initial testing. Wet sieving out the mortar fraction provides a more accurate representation of the concrete mix design.

Table 38: Autogenous Shrinkage Strain for Mortar Wet Sieved from Final Concrete Mixes

Name	Data Type	0 days μ in/in	1 days μ in/in	4 days μ in/in	7 days μ in/in	14 days μ in/in	28 days μ in/in
DOT Baseline w/AEA	Average	0.0	-13.1	-35.8	-95.9	-154.5	-247.3
	STDEV	0.0	34.5	20.4	18.8	32.7	36.9
Final Mix	Average	0.0	-9.7	-65.2	-84.8	-125.6	-176.2
	STDEV	0.0	27.5	39.0	36.3	23.7	13.1
Final Mix w/LWA	Average	0.0	-9.8	-29.4	-31.0	-62.0	-75.1
	STDEV	0.0	22.3	26.4	24.7	15.7	11.5

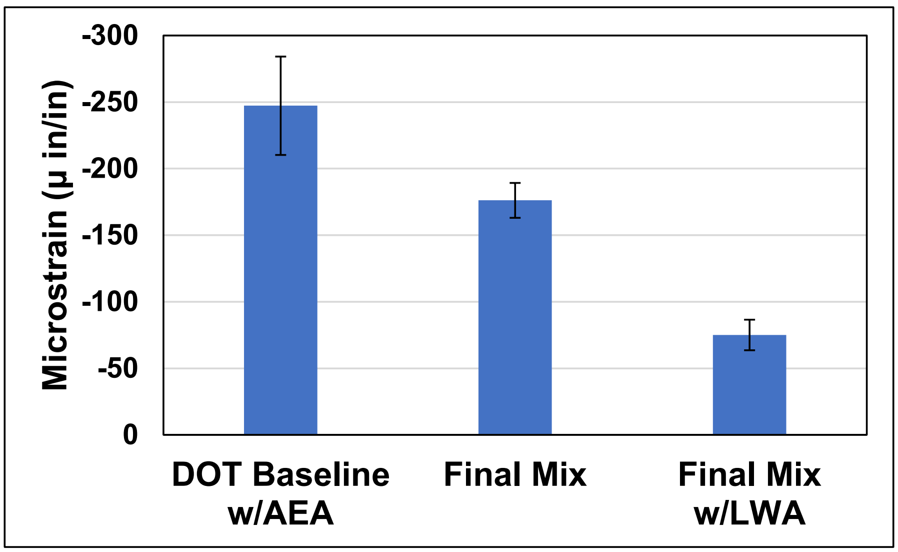


Figure 31: 28 Day Autogenous Shrinkage Strain on Mortar Wet Sieved from Final Concrete Mixes. All Mixes are Significantly Different (Tukey-Kramer Test, P<0.05).

At 28 days, the autogenous shrinkage means were significantly heterogeneous (one-way ANOVA, F_2=53.8, P=9.8×10^{-6}). A Tukey-Kramer post-hoc test (see Table 39) revealed significant pairwise differences between the DOT baseline w/AEA and the decrease in autogenous shrinkage observed with both final mixes (P< 0.05). Therefore, the changes made to the mix design resulted in a statistically significant decrease in observed autogenous shrinkage.

Table 39: Post-hoc Testing of 28 day Autogenous Shrinkage Means for Mortar Wet Sieved from Final Concrete Mixes Compared to the DOT Baseline w/AEA

Mix Name	Percent Change in Mean Value (%)	Tukey-Kramer: P-value	Significant Difference (P<0.05)
Final Mix	-28.7	0.005	Yes
Final Mix w/LWA	-69.6	<0.001	Yes

Error! Reference source not found. show the 0-56 day drying shrinkage results on the final concrete samples. **Error! Reference source not found.** shows only the 28 day drying shrinkage strain for comparison. 28 day data is shown instead of 56 days since many DOTs use this age for qualification of mixes. All mixes were lower than the maximum 28 day limit established in AASHTO PP84 of 420 µin/in.

Table 40: Drying Shrinkage Results for Final Concrete Mixes

Name	Data Type	0 days µ in/in	1 days µ in/in	4 days µ in/in	7 days µ in/in	14 days µ in/in	28 days µ in/in	56 days µ in/in
DOT Baseline w/AEA	Average	0.0	29.3	-107.5	-185.7	-254.1	-300.5	-342.1
	STDEV	0.0	8.0	28.7	28.6	23.8	22.8	17.4
Final Mix	Average	0.0	58.7	-17.1	-34.2	-80.7	-149.1	-185.8
	STDEV	0.0	8.0	25.7	24.6	28.1	35.1	39.9
Final Mix w/LWA	Average	0.0	14.7	-39.1	-48.9	-88.0	-200.5	-256.7
	STDEV	0.0	12.6	13.8	21.1	19.5	23.2	21.6

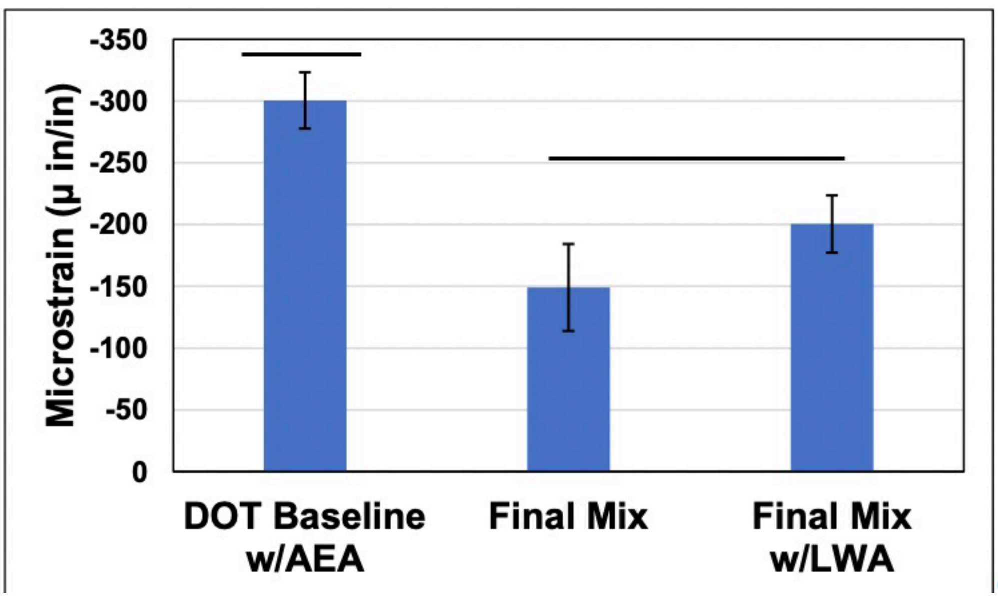


Figure 32: 28 Day Drying Shrinkage Results for Final Concrete Mixes. Horizontal Bars Link Mixes That Are Not Significantly Different (Tukey-Kraer Test, P>0.05).

At 28 days, the drying shrinkage means were significantly heterogeneous (one-way ANOVA, F_2=31.1, P=9.1×10^{-5}). A Tukey-Kramer post-hoc test (see Table 41) revealed significant pairwise differences between the DOT baseline w/AEA and the decrease in drying shrinkage observed with both final mixes (P< 0.05). Therefore, the changes made to the mix design resulted in a statistically significant decrease in observed drying shrinkage. Compared to the DOT Baseline, the addition of the SRA with the optimized aggregate reduced drying shrinkage by 50%, and when coupled with the saturated LWA, the drying shrinkage was reduced by 33%. This is opposite to the autogenous shrinkage results, but the two drying shrinkage means for the final mixes were not significantly different at 28 days.

Table 41: Post-hoc Testing of 28 day Drying Shrinkage Means Compared to the DOT Baseline w/AEA

Mix Name	Percent Change in Mean Value (%)	Tukey-Kramer: P-value	Significant Difference (P<0.05)
Final Mix	-50.4	<0.001	Yes
Final Mix w/LWA	-33.3	0.0016	Yes

The results of the restrained shrinkage test (i.e., the ring test) are presented in Table 42. The baseline mix cracked after 31 days, which barely passes the typically specified minimum age of 28 days for no observed cracking. The recommended mixes have remained uncracked after 130 and 180 days and measurements are still ongoing. The difference in uncracked days between the two mixes is a result of the timing of when the concrete mixes were cast. These results indicate that the recommended changes to the mix design have resulted in a significant improvement in cracking behavior. It should be noted that mixes with SRA's (especially with a minimum dosage of 1.5 gal/yd^3) may never exhibit cracking as measured by this test.

Table 42: Restrained Shrinkage (Ring Test) Results

Name	Number of Days Before Cracking
DOT Baseline w/AEA	31
Final Mix	Uncracked after 180 days
Final Mix w/LWA	Uncracked after 130 days

5.7 Conclusions

From this study, the following conclusions can be made regarding concrete bridge deck mix designs with improved shrinkage performance:

- Autogenous shrinkage was significantly reduced compared to a control with the use of all tested dosages of shrinkage reducing admixture (up to 47% at 28 days) and saturated lightweight aggregate as a partial replacement of fine aggregate (up to 84% at 28 days).
- Drying shrinkage was significantly reduced compared to a control with the use of the highest dosage of shrinkage reducing admixture and the highest dosage of saturated lightweight

aggregate (by 40% at 28 days for both). The lower dosages of SRAs and FLA also reduced drying shrinkage to a lesser extent. Quartzite aggregate significantly reduced drying shrinkage at 28 days, but not at 56 days.

- Other changed parameters including lowering the cement content, adjusting the fly ash content, using optimized aggregate gradation, and altering the w/cm ratio also slightly improved autogenous and drying shrinkage performance compared to the control, but the shrinkage reduction was not statistically significant.
- Concrete compressive strength for the majority of tested parameters was similar to the control at both 28 and 56 days, and most mixes met the 5700 psi strength requirement at 28 days. Most of the changed parameters improved surface electrical resistivity at 56 days compared to the control, including the use of FLA. The highest SRA dosage and the use of air-entrainment reduced compressive strength but did not significantly change electrical resistivity compared to the control.
- Compared to the current SDDOT A45 mix, the final mixes developed for improved shrinkage behavior used optimized aggregate gradation, a lower cementitious content, SRA, and FLA. This combination of changes in the mix design resulted in significantly lower autogenous and drying shrinkage, improved resistivity, and improved strength. The recommended mix designs also significantly increased the time to cracking as measured by the ring test.

Overall, these results indicate that the current SDDOT mix design can be modified to improve shrinkage performance as discussed in the Recommendations section.

6.0 RECOMMENDATIONS

6.1 Change the A45 mix design for improved shrinkage control

The SDDOT should change their current A45 mix design for bridge decks to include the following changes to improve early-age cracking performance of bridge decks: (1) use of optimized aggregate gradation (either meeting the 0.45 power curve or the tarantula curve), (2) a lower total cementitious material content (maximum of 615 lb/yd^3) with the replacement of 20% by mass of the cement with Class F fly ash, (3) use of SRA (dosage at the manufacturer recommended value), and, if available, (4) the use of saturated lightweight aggregate at a 20% by weight replacement of fine aggregate.

All four of these recommendations significantly improved the autogenous and drying shrinkage behavior of the paste, mortar, and concrete samples tested in this study. They are also feasible changes to implement at concrete batch plants across South Dakota.

6.2 Specify a drying shrinkage test of mix design qualification

The SDDOT should specify a drying shrinkage test and limit for mix design qualification for bridge decks.

SDDOT should implement either an ASTM C157 or equivalent AASHTO T160 test for mix design qualification. This is in accordance with many state DOTs. As autogenous shrinkage and drying shrinkage values were strongly correlated, it is recommended that only drying shrinkage be used to assess shrinkage performance. The ring test (ASTM C1581) could also be used for acceptance as this is a better assessment of the performance of concrete in the field. However, the complexity of this test may inhibit its routine use.

Based on the final mixes, it is proposed for the SDDOT that the 28 day drying shrinkage limit using ASTM C157/AASHTO T160 be set at a maximum of 285 με (0.029%). The limits placed for this test by other state DOTs have a wide range from 0.03-0.045% (length change) corresponding to ~294-441 microstrain at 28 days. The PP84 document falls within this range at 420 microstrain. The average drying shrinkage values for the SDDOT A45 mix measured from this research is 300 με (0.03%) at 28 days. At 28 days, the final mixes with improved shrinkage performance reached an average drying shrinkage value between 150-200 με (0.015-0.02%).

This proposed limit is stricter than what is currently used by most state DOTs (DOT survey) but should produce better long-term results regarding concrete shrinkage. If a shorter curing time were used for this qualification test than shown in this research, a different limit may be more appropriate. A 56 day limit is likely unnecessary as performance did not change significantly between the two ages.

6.3 Consider specifying 56 day strength for Class F fly ash concrete

The SDDOT should consider specifying 56 day strength instead of 28 day strength for concrete mixes that use Class F fly ash.

Due to the lower observed strength in the final mixes and due to the required use of Class F fly ash in all bridge deck mixes for the SDDOT, it is recommended to allow for later age (56 day) strength acceptance criteria since fly ash tends to mostly react after 28 days, and mixes will gain strength at later ages.

Alternatively, a lower strength value could be specified for 28 days, with the assumption that the concrete would reach the higher strength at a later age.

6.4 Implement additional strategies beyond mix design changes to reduce bridge deck cracking

Beyond changing the mix design requirements for bridge decks, the SDDOT should consider other known strategies for reducing shrinkage cracking.

Other strategies outside of the scope of this research including changes in bridge design (especially allowing more free movement at the abutments), improved construction practices, and strict curing regimes may also improve the shrinkage performance of bridge decks. Potential ideas for these additional strategies can be found in the DOT survey in Appendix A.

7.0 RESEARCH BENEFITS

This research resulted in a set of recommendations for SDDOT to specify changes to the current bridge concrete mix design to improve shrinkage cracking behavior. The most effective standard and limits for qualifying low shrinkage concrete mix designs for bridge decks were also recommended. Additional recommendations for specifying concrete strength at later ages and implementing other crack-control strategies were provided. This project also fully supported a graduate research student and increased the research capacity a South Dakota Mines.

The largest benefit of this research is the expected increase in the service life of bridge decks to at least meet their expected 20-year service life, but perhaps even exceed this service life. Significant cost savings will be seen if the need for an overlay can be delayed due to less early-age cracking. This benefit would be defined as the increase in the longevity of bridge due to proper mix design and testing as compared to a bridge that was designed without a low cracking mix design. An inventory of concrete placed using the new low shrinkage concrete mixes could be developed and tracked over the course of their lifetime to document their durability performance and compared against the performance of bridges made with the previous mix design specification. It is also predicted that maintenance costs will be reduced. Overall, this research will enable SDDOT to better control cracking on bridge decks and increase the service life of their transportation assets.

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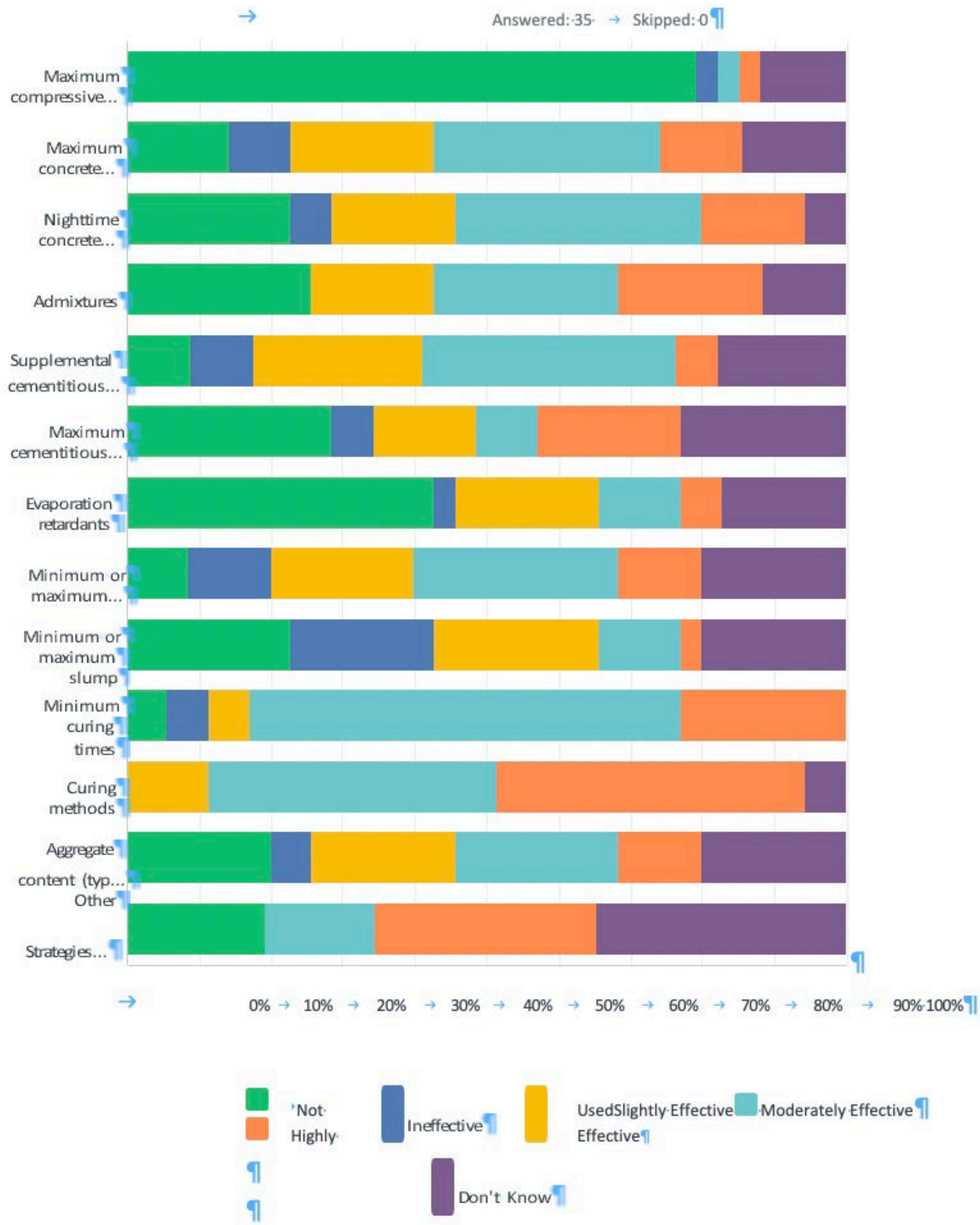
Appendix A: DOT Survey Questions and Results

Q3 What strategies has your agency used to mitigate concrete shrinkage in bridge decks? For each strategy used, please rate its effectiveness in reducing shrinkage. Please indicate "Not Used" for strategies your agency has not used. Please indicate "Don't Know" if you do not know whether a strategy was used or whether it was effective.



	NOT USED	INEFFECTIVE	SLIGHTLY EFFECTIVE	MODERATELY EFFECTIVE	HIGHLY EFFECTIVE	DON'T KNOW	TOTAL	WEIGHTED AVERAGE
Maximum compressive strength	79.41% 27	2.94% 1	0.00% 0	2.94% 1	2.94% 1	11.76% 4	34	0.27
Maximum concrete temperature	14.29% 5	8.57% 3	20.00% 7	31.43% 11	11.43% 4	14.29% 5	35	2.20
Nighttime concrete placement	22.86% 8	5.71% 2	17.14% 6	34.29% 12	14.29% 5	5.71% 2	35	2.12
Admixtures	25.71% 9	0.00% 0	17.14% 6	25.71% 9	20.00% 7	11.43% 4	35	2.16
Supplemental cementitious materials	8.82% 3	8.82% 3	23.53% 8	35.29% 12	5.88% 2	17.65% 6	34	2.25
Maximum cementitious materials content	28.57% 10	5.71% 2	14.29% 5	8.57% 3	20.00% 7	22.86% 8	35	1.81
Evaporation retardants	42.86% 15	2.86% 1	20.00% 7	11.43% 4	5.71% 2	17.14% 6	35	1.21
Minimum or maximum water-cement ratio	8.57% 3	11.43% 4	20.00% 7	28.57% 10	11.43% 4	20.00% 7	35	2.29
Minimum or maximum slump	22.86% 8	20.00% 7	22.86% 8	11.43% 4	2.86% 1	20.00% 7	35	1.39
Minimum curing times	5.71% 2	5.71% 2	5.71% 2	60.00% 21	22.86% 8	0.00% 0	35	2.89
Curing methods	0.00% 0	0.00% 0	11.43% 4	40.00% 14	42.86% 15	5.71% 2	35	3.33
Aggregate content (type, density, gradation, etc.)	20.00% 7	5.71% 2	20.00% 7	22.86% 8	11.43% 4	20.00% 7	35	2.00
Other Strategies (please describe below)	19.23% 5	0.00% 0	0.00% 0	15.38% 4	30.77% 8	34.62% 9	26	2.59

#	PLEASE DESCRIBE THE "OTHER STRATEGIES":	DATE
1	Fiber reinforcement (currently evaluating). Note: Many of these strategies are part of a comprehensive effort to provide quality concrete and to mitigate bridge deck cracking. It is difficult to assess the effectiveness of individual strategies.	8/7/2019 12:40 AM
2	Trials with SRA's and fibers in the near future	7/22/2019 6:04 PM
3	Evaporation rate cannot exceed 0.1 lb/ft^2/hr. when placing the deck and the ambient temperature cannot exceed 85 degrees F. Mix designs are well graded (1" NMAS) with strict deleterious material tolerances on the aggregates for chert, limonite, shale, etc. Evaporation retarders are not allowed as they are 9 parts water 1-part chemical when applied to the surface and only increases the w/cm ratio leading to weak paste that may lead to cracking, scaling, and other surface defects. Max slump is 6 inches when using superplasticizers in the mix. Curing is a double layer of burlap and plastic sheeting for 7 days minimum, followed by an application of curing compound. We are looking at internal curing with prewetted lightweight fine aggregate and	7/19/2019 11:48 AM

	have been successful with a handful of projects.	
4	tested in accordance w/ AASHTO T 160 as part of initial approval.	7/18/2019 4:49 PM
5	Polypropylene microfibers to reduce plastic shrinkage cracking. Polypropylene macro fibers to reduce drying shrinkage cracking/width of cracks - moderately effective	7/17/2019 11:20 PM
6	Polypropylene macro and microfibers	7/17/2019 4:06 PM
7	Fibers in the mix.	7/16/2019 12:58 PM
8	WSDOT uses a performance-based specification for qualification of the contractor's concrete mix design with a limit of 0.032% at 28 days per AASHTO T160.	7/15/2019 11:43 PM
9	We have a performance approach that has been successful in mitigating shrinkage. We require ASTM C 1581 and AASHTO T 160.	7/12/2019 8:28 PM
10	Use fibrillated fibers for silica fume overlays	7/12/2019 8:11 PM
11	Continuous misting and polyolefin fibers to prevent plastic shrinkage cracks along with minimum Shrinkage Reducing Admixture dosage and a 28 day shrinkage performance requirement.	7/12/2019 4:33 PM
12	KDOT has requirements for permeability. This requirement forces lower cement contents and lower water cement ratios. Thus, Lower Paste, less shrinkage. Also 14-day wet cure with a 7-day drying period.	7/11/2019 7:36 PM
13	Several placements with the inclusion of a lightweight sand for internal curing have shown such great promise that one of the local entities now require the use of Internal Curing for all structural concrete applications.	7/10/2019 9:00 PM
14	Maine is contemplating using additional strategies such as limiting compressive strength. Non-Shrink additives, Larger coarse aggregates. Internal curing. Optimized aggregate gradings.	7/10/2019 8:17 PM
15	Currently researching 'textured' epoxy-coated reinforcement.	7/10/2019 4:42 PM
16	We specified a maximum shrinkage requirement of 0.045% when tested according to ASTM C157 (28 day wet soak followed by 28 day air storage). We require macro fibers to mitigate plastic shrinkage cracking, all of them in the 5 lb/cy range. We also require 1.5" NMAS with a minimum combined coarse aggregate volume of 44% of the total CY design. We are in the early stages of specifying internally cured designs. We have tried it with positive results thus far.	7/10/2019 4:08 PM
17	For Deck and Paving require AASHTO T 277 moderate level, and ASTM C157 max 500 micro strain during mix design process.	7/10/2019 3:49 PM
18	Use of synthetic fibers.	7/10/2019 3:35 PM

Q4 Please describe the requirements and limits placed on each of the strategies your agency has used (from Question 3). For example, if your agency limits maximum compressive strength, please list the maximum value allowed such as 5000 psi.

Answered: 35 Skipped: 0

ANSWER CHOICES	RESPONSES	
Maximum compressive strength	57.14%	20
Maximum concrete temperature	82.86%	29
Nighttime concrete placement	82.86%	29
Admixtures	80.00%	28
Supplemental cementitious materials	85.71%	30
Maximum cementitious materials content	80.00%	28
Evaporation retardants	65.71%	23
Minimum or maximum water-cement ratio	88.57%	31
Minimum or maximum slump	85.71%	30
Minimum curing times	94.29%	33
Curing methods	100.00%	35
Aggregate content (type, density, gradation, etc.)	65.71%	23
Other Strategies (from Question 3)	48.57%	17

#	MAXIMUM COMPRESSIVE STRENGTH	DATE	
1	N/A	8/7/2019 12:40 AM	
2	Not used	7/31/2019 7:15 PM	
3	4,000 psi except for precast deck panels	7/26/2019 7:24 PM	
4	No maximum compressive strength specified	7/25/2019 3:58 PM	
5	No maximum at this point	7/22/2019 6:04 PM	
6	Incentive is offered for targeting a strength below 5,500 psi and achieving consistent strengths during production within +-500 psi of the target strength.	7/22/2019 3:34 PM	
7	n/a	7/22/2019 3:32 PM	
8	N/A, minimum requirement is 4500 psi	7/19/2019 11:48 AM	
9	n/a	7/17/2019 2:04 PM	
10	No maximum specified	7/16/2019 11:55 AM	

11	No requirement or limit.	7/15/2019 11:43 PM	
12	6500 PSI for silica fume	7/12/2019 8:11 PM	
13	NA	7/12/2019 4:33 PM	
14	N/A	7/11/2019 7:36 PM	
15	not used yet	7/10/2019 8:17 PM	
16	N/A	7/10/2019 7:41 PM	
17	n/a (minimum of 4000 psi @ 14 days)	7/10/2019 4:42 PM	
18	N/A	7/10/2019 4:08 PM	
19	N/A	7/10/2019 3:49 PM	
20	5500 psi	7/10/2019 2:37 PM	

MAXIMUM CONCRETE TEMPERATURE		DATE
1	90 deg F	8/7/2019 12:40 AM
2	90	8/2/2019 6:26 PM
3	The concrete mix temperature must not exceed 90 deg. Fahrenheit before placement in the forms.	7/31/2019 7:15 PM
4	90 degrees F @ time of placement	7/26/2019 7:24 PM
5	Maximum 85 deg. F	7/25/2019 3:58 PM
6	90 degrees when placed. No maximum during curing	7/22/2019 6:04 PM
7	80 degrees Fahrenheit	7/22/2019 3:34 M
8	90 deg at placement.	7/22/2019 3:32 PM
9	90 degrees Fahrenheit	7/19/2019 4:42 PM
10	95 degrees F, however most decks are done at night due to evaporation rate requirement of 0.1 lb/ft^2/hr.	7/19/2019 11:48 AM
11	90 degrees for bridge decks.	7/18/2019 4:49 PM
12	85 F	7/17/2019 11:20 PM
13	90F w evaporation rate control	7/17/2019 2:04 PM
14	90F	7/16/2019 11:55 AM
15	80 degrees max during placement (measured at the point of placement), no limit during the cure period.	7/15/2019 11:43 PM
16	85	7/12/2019 8:28 PM

17	80 F	7/12/2019 8:11 PM
18	Not related to deck crack prevention but 90 degrees F for all structure concrete	7/12/2019 4:33 PM
19	90 degrees	7/11/2019 7:36 PM
20	99F	7/10/2019 9:00 PM
21	85 for substructure and 75 for decks and concrete wearing surfaces	7/10/2019 8:17 PM
22	90 F	7/10/2019 7:41 PM
23	Standard = 90 F, HPC (high perf conc) = 80 F	7/10/2019 7:39 PM
24	90 F (80 F if using insulated forms to protect from cold temps)	7/10/2019 4:42 PM
25	Our normal structural concrete temp requirement is 60-90 degrees F, we reduce the maximum to 80 degrees F for bridge decks	7/10/2019 4:08 PM
26	50 to 80 decks, 50 to 90 paving	7/10/2019 3:49 PM
27	90 degrees	7/10/2019 3:35 PM
28	N/A	7/10/2019 2:37 PM
29	90	7/10/2019 2:21 PM

#	NIGHTTIME CONCRETE PLACEMENT	DATE
1	Allowed at contractor's option to meet temperature requirements	8/7/2019 12:40 AM
2	10 PM-8AM	8/2/2019 6:26 PM
3	Not used.	7/31/2019 7:15 PM
4	50 degrees F @ time of placement	7/26/2019 7:24 PM
5	Used when unable to comply with the maximum concrete temperature using different methods such as wetting the pile, adding ice, and adding chilled water	7/25/2019 3:58 PM
6	Required during summer months	7/22/2019 6:04 PM
7	not required, our maximum evaporation rate of 0.2 lb/ft2/hr. typically results in early morning or night placements of deck concrete	7/22/2019 3:34 PM
8	n/a	7/22/2019 3:32 PM
9	N/A	7/19/2019 11:48 AM
10		7/18/2019 4:49 PM
11	Concrete temperature limits force most contractors to pour decks at night or in the early AM during summer months.	7/17/2019 11:20 PM
12	Contractor option - mostly early morning, easier to get cooler concrete, more humidity, only if evaporation chart cannot be met, but perception is that it helps	7/17/2019 4:06 PM
13	A maximum 90-degree temperature for placement of concrete on bridge deck; therefore, the contractor will start early or place at night before the heat of the day.	7/16/2019 7:16 PM
14	When ambient temp is anticipated to be 85F or higher place concrete during the evening hours after temp cools of below 85F	7/16/2019 11:55 AM
15	Scheduling is the contractor's means and methods.	7/15/2019 11:43 PM
16	Maximum concrete temperature is 90 if the contractor elects for nighttime placement	7/12/2019 8:28 PM
17	Usually require placement between 12:00 am and 8:00 am. Depends on time of year and location.	7/12/2019 8:11 PM
18	NA	7/12/2019 4:33 PM

19	Not required but chosen frequently by contractor	7/11/2019 7:36 PM
20	Contractors use early morning placement, but mainly for their convenience	7/11/2019 2:51 PM
21	Contractors means and methods to control maximum concrete temperature.	7/10/2019 9:00 PM
22	Placement operations chosen by contractor during extreme hot weather	7/10/2019 8:17 PM
23	Currently after sunset. However, we are planning to revise it to permit placement to start late afternoon.	7/10/2019 7:41 PM
24	Used to minimize peak curing temps and to meet evaporation rate limits	7/10/2019 7:39 PM
25	Generally not required, but often opted for by the contractor to avoid exceeding max concrete temp spec.	7/10/2019 4:42 PM
26	We don't require the contractor to place at night. Some of them elect to but not for the purpose of mitigating cracking. In some cases, this has helped and in others it hasn't. I think to be effective you would have to do some sort of mockup to model the actual temperature development in the deck given local conditions. Then you would need to time the pour to coincide with the temperature increase in a forecasted period for the specific location. This would align the member with ambient temperature and minimize the differential temps in the deck. We haven't related our deck cracking issues to temperature differential so these measures have not been taken but might happen coincidentally.	7/10/2019 4:08 PM
27	This is not required but may be needed to meet the max temperatures above.	7/10/2019 3:49 PM
28	No requirements but has been done for a couple projects with some success	7/10/2019 2:37 PM
29	Left up to Contractor	7/10/2019 2:21 PM

#	ADMIXTURES	DATE
1	Meet AASHTO M194 for admixtures	8/7/2019 12:40 AM
2	SRA required in Silica Fume Modified Concrete	8/2/2019 6:26 PM
3	Water reducing admixture is required	8/1/2019 12:49 PM
4	Mix producers typically use water reducers to increase slump without having to add as much water, which can reduce shrinkage cracking.	7/31/2019 7:15 PM
5	fly ash, silica fume, metakaolin	7/26/2019 7:24 PM
6	Require a Type A water reducer to be used; do not require SRA's to be used	7/25/2019 3:58 PM
7	not required	7/22/2019 3:34 PM
8	n/a	7/22/2019 3:32 PM
9	N/A	7/19/2019 11:48 AM
10	Limited use of SRA but do appear to reduce cracking	7/17/2019 11:20 PM
11	WR, Retarders	7/17/2019 2:04 PM
12	Water Reducer and superplasticizers	7/16/2019 7:16 PM
13	Water reducing and retarding admixture if ambient above 71F	7/16/2019 11:55 AM
14	0.032% at 28 days under AASHTO T160 essentially requires the use of shrinkage reducing admixtures.	7/15/2019 11:43 PM
15	Most producers use shrinkage reducing admixture to meet the shrinkage test limits	7/12/2019 8:28 PM
16	NA	7/12/2019 8:11 PM
17	Shrinkage Reducing Admixture 3/4 Gal/CY minimum	7/12/2019 4:33 PM
18	Admixtures are allowed but mix must be prequalified with the admixtures in the mix	7/11/2019 7:36 PM
19	We are suing SRA to provide a maximum shrinkage number.	7/11/2019 2:51 PM
20	We have tried shrinkage reducing admixtures and had success with them	7/11/2019 2:21 PM
21	set retarder as needed for hot weather applications	7/10/2019 9:00 PM
22	Just normal retarders and hydration stabilizers along with HRWR	7/10/2019 8:17 PM
23	water reducing admixtures only	7/10/2019 7:41 PM
24	Shrinkage reducing admixtures have been shown in our research and field trials to be effective in mitigating cracking.	7/10/2019 4:42 PM
25	We require high range water reducer and set retarder. The high range water reducers limit the amount of water it takes to produce the needed slump for placement and the retarders keep the placed mixture plastic while most of the rest of the pour takes place so that settlement and deflective forces aren't placed on concrete in the early stages of hydration.	7/10/2019 4:08 PM
26	Not yet	7/10/2019 4:20 PM
27	Shrinkage Reducing Admixtures	7/10/2019 2:37 PM
28	The use of Shrinkage Reducing Admixtures have been used on a trial basis.	7/10/2019 2:21 PM

#	SUPPLEMENTAL CEMENTITIOUS MATERIALS	DATE
1	Require Class F Fly Ash (20-30%); allow substitution of Class N Pozzolan; Meet AASHTO M-295	8/7/2019 12:40 AM

2	20-25% class F replacement for ASR mitigation	8/2/2019 6:26 PM
3	Supplemental cementitious materials can be used, but we do not require them for bridge decks.	7/31/2019 7:15 PM
4	fly ash, silica fume, metakaolin	7/26/2019 7:24 PM
5	Require at least 15% of the cement be replaced	7/25/2019 3:58 PM
6	Up to 30% fly ash replacement; up to 50% slag replacement	7/22/2019 6:04 PM
7	Minimum of 15% Fly Ash or GGBFS are required along with 3-5% Silica Fume	7/22/2019 3:34 PM
8	20% minimum fly ash	7/22/2019 3:32 PM
9	Maximum 29% but normally 10% is used.	7/19/2019 4:42 PM
10	Slag cement is becoming more prevalent over fly ash due to supply.	7/19/2019 11:48 AM
11	Use fly ash quite often and generally think this has little benefit to cracking reduction	7/17/2019 11:20 PM
12	30/35/5/40 FA/Slab/SF/Ternary	7/17/2019 4:06 PM
13	Slag, Fly ash	7/17/2019 2:04 PM
14	25% Class F ash and slag	7/16/2019 7:16 PM
15	Contractor option	7/16/2019 11:55 AM
16	50% max by weight.	7/15/2019 11:43 PM
17	NA	7/12/2019 8:11 PM
18	Required but unrelated to deck crack prevention. See Standard Specifications.	7/12/2019 4:33 PM
19	SCMs are allow with varying maximum substitutions	7/11/2019 7:36 PM
20	We require a certain amount of fly ash or slag cement and silica fume. Fly ash and slag cement seem to help, but the silica fume may not	7/11/2019 2:21 PM
21	allow up to 70% replacement of portland cement content	7/10/2019 9:00 PM
22	Slag	7/10/2019 8:17 PM
23	In the past couple years, we have been requiring 25-40 percent replacement of the portland cement with slag cement or fly ash.	7/10/2019 7:41 PM
24	Max of 30% fly ash, slag or ternary	7/10/2019 7:39 PM
25	Shrinkage compensating materials (i.e., Type K) have been shown research in our research and field trials to be effective in mitigating cracking. Not sure we've seen a significant impact from other SCMs as they've become more commonly used over the years.	7/10/2019 4:42 PM
26	We use them in all bridge decks mainly to drive down permeability. It might have a side benefit of reducing the overall heat generation.	7/10/2019 4:08 PM
27	Not required but generally needed to meet the 2000 coulomb requirement of AASHTO T 277	7/10/2019 3:49 PM
28	30/35/5/40 Maximum % SCM (fly ash/slag/silica fume/ternary)	7/10/2019 3:35 PM
29	Slag/Fly Ash work well - Silica Fume pour	7/10/2019 2:37 PM
30	Contractor's choice.	7/10/2019 2:21 PM

	MAXIMUM CEMENTITIOUS MATERIALS CONTENT	DATE
1	N/A	8/7/2019 12:40 AM
2	710 lbs. for all mixes except latex-658 lbs.	8/2/2019 6:26 PM
3	718 lbs./cyd maximum. That amount is rarely used. 658 lbs./cyd is typical	8/1/2019 12:49 PM
4	Not used.	7/31/2019 7:15 PM
5	No maximum cementitious content specified	7/25/2019 3:58 PM
6	715 lbs.	7/22/2019 6:04 PM
7	564 lbs./cubic yard	7/22/2019 3:34 PM
8	615 to 660 lbs./cy	7/22/2019 3:32 PM
9	650 lbs./cu yd	7/19/2019 4:42 PM
10	N/A we have a minimum cementitious content of 520 lb/yd^3	7/19/2019 11:48 AM
11	max 700 lbs. cementitious/CY - Requirement is not for crack reduction	7/17/2019 11:20 PM
12	624	7/17/2019 2:04 PM
13	25% Class F ash and 38% Slag	7/16/2019 7:16 PM
14	This will be determined by the maximum water-cement ratio	7/16/2019 12:58 PM
15	No maximum specified	7/16/2019 11:55 AM
16	No requirement or limit.	7/15/2019 11:43 PM
17	NA	7/12/2019 8:11 PM
18	Unrelated to deck crack prevention but 800 #/cy max	7/12/2019 4:33 PM
19	Controlled by permeability requirements	7/11/2019 7:36 PM
20	We have a set cementitious material content of 658 lb/cy for our bridge deck mix	7/11/2019 2:21 PM
21	No maximum, but also there is no minimum cementitious content specified for LADOTD concrete applications.	7/10/2019 9:00 PM
22	660 total per cy including slag or fly ash	7/10/2019 8:17 PM
23	reduced the total cementitious materials content to 517 -658 lbs./cyd.	7/10/2019 7:41 PM
24	Standard = none, HPC = 540 lbs./cy	7/10/2019 7:39 PM
25	705 pcy, which probably is too high to be effective in limiting paste content (minimum cementitious content is 605 pcy, though we do allow 580 pcy to help limit paste content to 26% in our special provision for internal curing)	7/10/2019 4:42 PM
26	N/A	7/10/2019 4:08 PM

27	Decks 560 to 640 lbs. paving 517 to 611 lbs. cementitious	7/10/2019 3:49 PM
28	N/A	7/10/2019 2:37 PM

#	EVAPORATION RETARDANTS	DATE
1	Allowed but not desired; there are issues with using them correctly.	8/7/2019 12:40 AM
2	not to be used as a finishing aid	8/2/2019 6:26 PM
3	Frequently used, but often abused. INDOT is considering eliminating them for standard decks.	8/1/2019 12:49 PM
4	We require wet curing through the use of curing blankets.	7/31/2019 7:15 PM
5	liquid-applied evaporation reducers in our Spec.	7/26/2019 7:24 PM
6	Standard Specifications only allow use on silica fume bridge deck overlays	7/25/2019 3:58 PM
7	not required	7/22/2019 3:34 PM
8	n/a	7/22/2019 3:32 PM
9	Do not allow, only adds water to the surface. Only use is in emergency situation when plant or Bidwell break down. Contractor finishes the concrete and then applies the evap. retarder to "save" the concrete.	7/19/2019 11:48 AM
10	Apply in timely fashion as needed (not specifically required) - just an option	7/17/2019 11:20 PM
11	only used if burlap cannot be placed within 10 minutes - No finishing	7/17/2019 2:04 PM
12	None required	7/16/2019 11:55 AM
13	No requirement or limit.	7/15/2019 11:43 PM
14	NA	7/12/2019 8:11 PM
15	Not a standard practice. Continuous misting is required until wet cure blankets are applied.	7/12/2019 4:33 PM
16	Wet burlap applied within 15 minutes of placement. White poly to maintain moisture.	7/11/2019 7:36 PM
17	We are following CalTrans in the use of immediate application of curing compound, then wet cure, then more curing compound after 7 days of wet cure.	7/11/2019 2:51 PM
18	used when needed	7/10/2019 8:17 PM
19	N/A	7/10/2019 7:41 PM
20	n/a	7/10/2019 4:42 PM
21	N/A	7/10/2019 4:08 PM
22	required on decks and pavement	7/10/2019 3:49 PM
23	N/A	7/10/2019 2:37 PM

#	MINIMUM OR MAXIMUM WATER-CEMENT RATIO	DATE
1	Maximum w/c ratio = 0.42; part of optimized mix design.	8/7/2019 12:40 AM
2	0.40 max for silica fume and latex, 0.45 max for all other mixes	8/2/2019 6:26 PM
3	0.443	8/1/2019 12:49 PM
4	Typical max w/c ratio is 0.40.	7/31/2019 7:15 PM
5	0.45 max	7/26/2019 7:24 PM
6	Maximum w/cm ratio of 0.42	7/25/2019 3:58 PM
7	Max - 0.381 (rounded aggregates; 0.426 (angular aggregates)	7/22/2019 6:04 PM
8	0.42 to 0.45	7/22/2019 3:34 PM
9	maximum 0.45	7/22/2019 3:32 PM
10	Maximum 0.44 water-cement ratio	7/19/2019 4:42 PM
11	Max w/c ratio of 0.45	7/18/2019 4:49 PM
12	0.45 max - Should help reduce drying shrinkage	7/17/2019 11:20 PM
13	0.40 - 0.45	7/17/2019 4:06 PM
14	0.42 max	7/17/2019 2:04 PM
15	Maximum water-cement ratio varies by class of concrete. See section 520.1.2 of attached spec for ratio.	7/16/2019 12:58 PM
16	Maximum w/c - 0.42	7/16/2019 11:55 AM
17	No requirement or limit.	7/15/2019 11:43 PM
18	NA	7/12/2019 8:11 PM
19	Unrelated to deck crack prevention but parameters are in place that establish maximum water cementitious ratio on all structure concrete. See Standard Specifications.	7/12/2019 4:33 PM
20	Controlled by permeability requirements	7/11/2019 7:36 PM
21	We have a maximum w/c of 0.40 for our bridge deck mix	7/11/2019 2:21 PM
22	Max of 0.45	7/10/2019 9:00 PM
23	contractor sets w/c ratio max and is approved by the Department if within reason	7/10/2019 8:17 PM
24	Maximum w/c = 0.45	7/10/2019 7:41 PM
25	Max w/cm ratio = 0.45	7/10/2019 7:39 PM
26	0.32 - 0.44	7/10/2019 4:42 PM
27	We have a maximum w/cm ratio for permeability.	7/10/2019 4:08 PM
28	0.45 max. on decks 0.42 on pavement with incentive to go as low as 0.37	7/10/2019 3:49 PM
29	.42-.45	7/10/2019 3:35 PM
30	.5 Max	7/10/2019 2:37 PM
31	Max .445	7/10/2019 2:21 PM

#	MINIMUM OR MAXIMUM SLUMP	DATE
1	N/A -- Use a target slump specific to the mix design.	8/7/2019 12:40 AM
2	4-inch max for standard mixes, if admixtures are used then 6-inch max	8/2/2019 6:26 PM

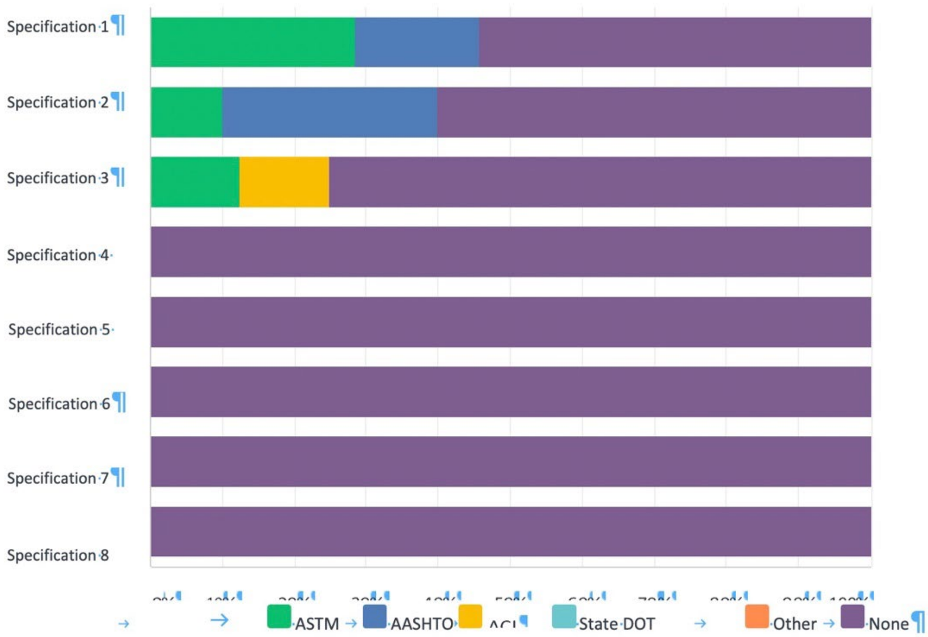
3	min 2" max 6"	8/1/2019 12:49 PM
4	Our max slump on bridge decks is 6 inches.	7/31/2019 7:15 PM
5	4.5" - 5.5"	7/26/2019 7:24 PM
6	Maximum slump of 6 inches	7/25/2019 3:58 PM
7	Max 3.5"	7/22/2019 6:04 PM
8	0-5" target slump, tolerance of +2" to -1.5" of targeted slump	7/22/2019 3:34 PM
9	n/a	7/22/2019 3:32 PM
10	1.0 to 3.0 inches	7/19/2019 4:42 PM
11	Slump range is 2 to 4 inches but may be increased to 6 inches with use of HRWR.	7/19/2019 11:48 AM
12	Max slump of 6" (with use of Type F admixtures)	7/18/2019 4:49 PM
13	3 to 5 1/2" -	7/17/2019 11:20 PM
14	5" with fibers, 4" without	7/17/2019 4:06 PM
15	4 inch with normal WR, 5 inch with mid-range WR	7/17/2019 2:04 PM
16	Slump 2-5 inches	7/16/2019 11:55 AM
17	3.5" max, of 5.5" max if a high range water reducer is used.	7/15/2019 11:43 PM
18	NA	7/12/2019 8:11 PM
19	Un related to deck crack prevention but minimum and maximum slump requirements are in the Standard Specifications for all structure concrete.	7/12/2019 4:33 PM
20	5 inch maximum but can be designated less	7/11/2019 7:36 PM
21	slump allowed up to 8 inches with use of HRWR	7/10/2019 9:00 PM
22	no slump spec	7/10/2019 8:17 PM
23	0-6 inch after introduction of mid-range water reducer. 0-7 inch after introduction of high range water reducer.	7/10/2019 7:41 PM
24	Max slump = 4"	7/10/2019 7:39 PM
25	2 - 7 inches when using a superplasticizer (2 - 4 in., if not)	7/10/2019 4:42 PM
26	We have maximums specified depending on what type of admixtures are used, this is mainly to prevent abuse.	7/10/2019 4:08 PM
27	5" max on decks	7/10/2019 3:49 PM
28	1-4"	7/10/2019 3:35 PM
29	Up to 9 in	7/10/2019 2:37 PM
30	2"-4"	7/10/2019 2:21 PM
#	MINIMUM CURING TIMES	DATE
1	14 days	8/7/2019 12:40 AM
2	5 days for paving and flatwork -wet or curing compound, 7 days for silica fume-curing compound and wet cure for 4 days, 5 days for latex modified concrete-3 wet and 2 dry	8/2/2019 6:26 PM
3	Seven-day wet cure	8/1/2019 12:49 PM
4	We require wet curing of bridge decks for a minimum of 7 days.	7/31/2019 7:15 PM
5	7 days of curing treatment	7/26/2019 7:24 PM
6	Minimum 7-day wet cure	7/25/2019 3:58 PM
7	7 days	7/22/2019 6:04 PM
8	96 hours	7/22/2019 3:34 PM
9	5 days	7/22/2019 3:32 PM
10	7 days	7/19/2019 4:42 PM
11	7-day wet cure, followed by liquid membrane curing compound application	7/19/2019 11:48 AM
12	7 days for bridge decks	7/18/2019 4:49 PM
13	8 to 10 days wet curing (10 with concrete containing SCMs)	7/17/2019 11:20 PM
14	7 days wet	7/17/2019 4:06 PM
15	7 days	7/17/2019 2:04 PM
16	10 days wet cure	7/16/2019 7:16 PM
17	Until specified compressive strength is obtained or Engineer may require 7 days	7/16/2019 11:55 AM
18	14 days min.	7/15/2019 11:43 PM
19	7 days	7/12/2019 8:28 PM
20	NA	7/12/2019 8:11 PM
21	Generally, 7 days water cure for structure concrete. See Standard Specifications.	7/12/2019 4:33 PM
22	14-day wet burlap cure with 7 day drying period under poly	7/11/2019 7:36 PM
23	We require minimum 7-day wet cure	7/11/2019 2:21 PM
24	7-day wet cure	7/10/2019 9:00 PM
25	Minimum 7-day wet cure with water	7/10/2019 8:17 PM
26	7-day continuous wet cure.	7/10/2019 7:41 PM
27	Standard = 7 days, HPC = 14 days	7/10/2019 7:39 PM
28	7 days	7/10/2019 4:42 PM
29	We currently specify 14 days continuous wet cure.	7/10/2019 4:08 PM
30	14-day wet cure followed by 3 days after PAMS cure	7/10/2019 3:49 PM
31	must be applied within 30 minutes after final strike off	7/10/2019 3:35 PM
32	10 days with no activity on deck	

33	5 days	7/10/2019 2:21 PM

#	CURING METHODS	DATE
1	Water cure plus curing compound	8/7/2019 12:40 AM
2	wet cure and/or PAMS curing compound	8/2/2019 6:26 PM
3	wet burlap, soaker hoses, covered with plastic sheeting	8/1/2019 12:49 PM
4	We require water foggers and curing blankets.	7/31/2019 7:15 PM
5	combination of water curing and curing compound	7/26/2019 7:24 PM
6	A dissipating curing compound is applied immediately after texturing; no more than 10 L.F. of textured surface can be exposed at any time	7/25/2019 3:58 PM
7	Wet Cure	7/22/2019 6:04 PM
8	Modified, see Modified Deck Cure attachment	7/22/2019 3:34 PM
9	wet cure or curing compound	7/22/2019 3:32 PM
10	wet burlap	7/19/2019 4:42 PM
11	double burlap soaker hose and white plastic secured so that it doesn't blow around. If done during cold weather, maintain 50-100-degree temperatures.	7/19/2019 11:48 AM
12	Moist curing (fog spraying, or saturated burlap). Inspectors monitor rate of evaporation using nomograph	7/18/2019 4:49 PM
13	Interim Cure + Wet mats covered with plastic sheeting. Early placement of curing is recommended.	7/17/2019 11:20 PM
14	presoaked burlap within 30 minutes of final strike-off	7/17/2019 4:06 PM
15	Wet burlap	7/17/2019 2:04 PM
16	wet cure and white pigment	7/16/2019 7:16 PM
17	7-day wet cure. See section of 520.3.10.1 of attached spec for ratio.	7/16/2019 12:58 PM
18	Application of curing compound the curing blankets or thickness of burlap keeping wet	7/16/2019 11:55 AM
19	Fogging for the initial cure; wet burlap or "Ultra-Cure"-type blankets for the final cure	7/15/2019 11:43 PM
20	Wet cure with cotton mats. The temperature of the curing water shall not be more than 20 °F cooler than the surface temperature of the concrete at the time the water and concrete come in contact.	7/12/2019 8:28 PM
21	NA	7/12/2019 8:11 PM
22	Water cure.	7/12/2019 4:33 PM
23	Wet Burlap	7/11/2019 7:36 PM
24	immediate curing compound application, then 7-day wet cure, then more curing compound.	7/11/2019 2:51 PM
25	Water cure with burlap	7/11/2019 2:21 PM
26	wet cure followed by pigmented curing compound	7/10/2019 9:00 PM
27	burlap and plastic	7/10/2019 8:17 PM
28	continuous wet cure, burlap, plastic sheeting, soaker hoses.	7/10/2019 7:41 PM
29	Continuous water cure (wet burlap + sprinklers, soaker hoses, etc.)	7/10/2019 7:39 PM
30	Wetted cotton blankets (covered with polyethylene sheeting or burlene), cellulose polyethylene blankets (e.g., UltraCure DOT), or synthetic fiber with polymer polyethylene blankets (e.g., ReliableCure VAB), all kept continuously wet with soaker hoses for the duration of curing	7/10/2019 4:42 PM
31	We specify a maximum allowable evaporation rate, fogging post bidwell prior to finishing, soaked burlap or polyproylene fabric within 20 minutes and 20 feet of the bidwell, continuous soaker hoses on top of that, plastic sheeting on top of that. Additional cure time if temperature drops below 45 degrees F.	7/10/2019 4:08 PM
32	see above	7/10/2019 3:49 PM
33	wet burlap	7/10/2019 3:35 PM
34	Always use wet burlap, haven't really tried anything else	7/10/2019 2:37 PM
35	AASHTO M 171	7/10/2019 2:21 PM
#	AGGREGATE CONTENT (TYPE, DENSITY, GRADATION, ETC.)	DATE
1	Use optimized (well-graded combined) gradation	8/7/2019 12:40 AM
2	44% max fines for all mixes except latex 50-60% fines	8/2/2019 6:26 PM
3	We have aggregate gradation requirements, but not for the reduction of shrinkage cracking	7/31/2019 7:15 PM
4	Standard Specifications allow the use of optimized mix designs; the decision to utilize an optimized mix design is made by the contractor	7/25/2019 3:58 PM
5	Not required. Incentive available for optimized gradations	7/22/2019 3:34 PM
6	n/a	7/22/2019 3:32 PM
7	limestone, dolomite, or gravels used in the mix in a well graded system (57s/8s/sand) using Tarantula curve or COMPASS software. Deleterious requirements are half of that for standard concrete production.	7/19/2019 11:48 AM

8	Very limited use of OAG but where used minimum cracking - OAG not typically required. Used more for cement/paste reduction.	7/17/2019 11:20 PM
9	Zone II Shilstone	7/17/2019 2:04 PM
10	Contractor option	7/16/2019 11:55 AM
11	1.5" nominal max. aggregate size.	7/15/2019 11:43 PM
12	Some producers have used internal curing to meet the shrinkage test limits	7/12/2019 8:28 PM
13	NA	7/12/2019 8:11 PM
14	Gradation parameters are in the Standard Specifications.	7/12/2019 4:33 PM
15	Require optimized aggregate gradations	7/11/2019 7:36 PM
16	combined aggregate gradation allowed, but not mandatory	7/10/2019 9:00 PM
17	Typical 3/4" stone, size 57 or 67 and also have used tarantula curve aggregate optimization. Gravity is typical 2.70 to 2.80	7/10/2019 8:17 PM
18	Optimized aggregate gradation (CF/WF) freeze thaw durable coarse and intermediate aggregate	7/10/2019 7:41 PM
19	Max nominal agg size = 1-1/2"	7/10/2019 7:39 PM
20	Limited field trials appear to show that internal curing with pre-wetted, expanded lightweight fine aggregates has some potential to improve performance of our decks	7/10/2019 4:42 PM
21	We specify 1.5" NMAS in all bridge decks to promote a well graded, dense aggregate structure. The larger top size aggregates also give us more abrasion resistance. We specify a minimum combined coarse aggregate volume of 44% of the design CY of concrete. This is a prescriptive measure taken many years ago to ensure we get more aggregate less paste. Pending the results of other performance specs initiated this requirement may go.	7/10/2019 4:08 PM
22	Use shilstone box on decks, and tarantula curve on pavement	7/10/2019 3:49 PM
23	Allow blended aggregates in performance specification	7/10/2019 2:37 PM
#	OTHER STRATEGIES (FROM QUESTION 3)	DATE
1	Synthetic Fiber Reinforcement -- 2 lb / cu yd fibrillated polypropylene fibers and 4 lb / cu yd macro synthetic fiber.	8/7/2019 12:40 AM
2	n/a	7/25/2019 3:58 PM
3	n/a	7/22/2019 3:32 PM
4	Maximum 28 day drying shrinkage: 0.04%.	7/18/2019 4:49 PM
5	1 1/2 lbs. microfibers/CY, 4 lbs. macro fibers/CY (drying shrinkage cracking)	7/17/2019 11:20 PM
6	Non-metallic fibers from APL	7/17/2019 4:06 PM
7	N/A	7/16/2019 11:55 AM
8	Use of a performance specification with a drying shrinkage limits has worked well to reduce (but not eliminate) transverse shrinkage cracking in bridge decks.	7/15/2019 11:43 PM
9	Net time to cracking shall not be less than 28 days when determined in accordance with ASTM C1581.Measured shrinkage shall not be greater than 0.030 percent after 21 days of air drying when determined in accordance with AASHTO T 160.	7/12/2019 8:28 PM
10	1.5 lb/cy fibrillated fibers	7/12/2019 8:11 PM
11	A minimum Shrinkage Reducing Admixture dosage 3/4 gal/cy and a 28 day shrinkage limit of .032% measured in accordance with AASHTO T160 using 4" X 4" prisms and an initial reading after 7 days of curing. See Standard Specifications.	7/12/2019 4:33 PM
12	Permeability requirements	7/11/2019 7:36 PM
13	IC lightweight aggregate to replace sand at an equivalent volume of 250 pounds per cubic yard of lightweight saturated fine aggregate.	7/10/2019 9:00 PM
14	'textured' epoxy-coated reinforcement is intended to behave more similarly to 'black' bar in that the bond between the bar and concrete will be better bonded. Early trials with pseudo-prototype 'textured' epoxy-coated reinforcement have been inconclusive so far; furthermore, research appears to show there are refinements needed before the technology is able to achieve desired results.	7/10/2019 4:42 PM
15	We specify a maximum shrinkage limit of 0.045% when tested at 28 day air storage according to ASTM C157. We require macro fibers around 5 lb/cy. We are currently in the early stages of requiring internally cured designs.	7/10/2019 4:08 PM
16	AASHTO T 277 2000 coulombs and ASTM C157 500 microstrain during mix design stage.	7/10/2019 3:49 PM
17	4 lbs. of synthetic fibers	7/10/2019 3:35 PM

Q5 What specifications does your agency use to test shrinkage in concrete used for bridge decks? For each specification, please identify: 1) the specifying organization (ASTM, AASHTO, ACI, etc.); 2) specification number/title; 3) specification test limits; 4) any changes your agency applies to the specification or test method. Please list all specifications that apply. If your agency has no specifications, please check "None" for Specification 1.



	ASTM	AASHTO	ACI	STATE DOT	OTHER	NONE	TOTAL	WEIGHTED AVERAGE
Specification 1	28.57% 10	17.14% 6	0.00% 0	0.00% 0	0.00% 0	54.29% 19	35	3.89
Specification 2	10.00% 1	30.00% 3	0.00% 0	0.00% 0	0.00% 0	60.00% 6	10	4.30
Specification 3	12.50% 1	0.00% 0	12.50% 1	0.00% 0	0.00% 0	75.00% 6	8	5.00
Specification 4	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 6	6	6.00
Specification 5	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 6	6	6.00
Specification 6	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 6	6	6.00
Specification 7	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 6	6	6.00
Specification 8	0.00% 0	0.00% 0	0.00% 0	0.00% 0	0.00% 0	100.00% 6	6	6.00

#	COMMENTS FOR "SPECIFICATION 1"	DATE
1	1/2: AASHTO T160 3: Max % shrinkage at 28 days = 0.035 4: No changes	8/7/2019 12:44 AM
2	for silica fume overlays only- C157-1.5 gal/cy dosage unless a lower dose shows shrinkage < 0.03%	8/2/2019 6:35 PM

3	ASTM C157 less than 0.04% at 28 days	7/26/2019 7:25 PM
4	.We currently do not evaluate the shrinkage properties of concrete mixes for approval	7/25/2019 3:58 PM
5	designs not meeting our Standard Specifications the following is required: "Include in the mix design shrinkage test results according to AASHTO T 160. The maximum allowed shrinkage for mix design acceptance is .0300% at 28 days."	7/22/2019 3:36 PM
6	of 0.04% shrinkage when exposed to drying at 7 days of age. Final reading is taken 28 days from start of drying (35 days from date of cast). Prisms are 3x3x11.75"	7/18/2019 4:58 PM
7	Required Hardened Fiber-Reinforced Concrete Properties Test Requirement Test Method Equivalent Flexural Strength Ratio (RDT,150): Minimum of 25% by ASTM C1609 Crack Reduction Ratio (CRR): Minimum reduction >85% by ASTM C1579	7/17/2019 5:40 PM
8	N/A	7/16/2019 11:57 AM
9	T160. 0.032% max at 28 days.	7/15/2019 11:43 PM
10	Net time to cracking shall not be less than 28 days when determined in accordance with ASTM C1581. Prior to batching for a test sample, all coarse aggregate particles exceeding ¾-inch shall be removed and replaced with an equal volume of minus ¾-inch graded material. This test shall be waived if the concrete mixture contains 605 lb/yd3 or less total cementitious material and a minimum dosage of 1.5 gal/yd3 of approved shrinkage reducing admixture (SRA).	7/12/2019 8:38 PM
11	T-160 use 4" X 4" prisms, initial reading taken after 7 days of curing. See Standard Specifications,Section 90-1.01D(3)	7/12/2019 4:38 PM
12	Shrinkage test ASTM C157, 4" cross section, 7 days wet, 28 days in 50% humidity, maximum 0.030% shrinkage, no fibers in shrinkage samples.	7/11/2019 3:06 PM
13	ASTM C157. Used for research purposes only in our internally cured concrete mix designs. We require air storage of specimens.	7/11/2019 2:27 PM
14	Special provision for shrinkage reducing admixture in bridge deck concrete: ASTM C 157, the concrete shrinkage shall not exceed -0.030% determined after 7 days of cure plus 28 days of drying	7/10/2019 5:03 PM
15	C157 was implemented about 3 years ago. A study done by Oregon State University suggested a limit of 0.045% with a wet cure of 14 day (to mimic current field curing requirements) followed by 28 day air storage. About 18 months ago we changed the wet cure period to the standard 28 day to align with industry standards at the request of the suppliers who are running the test for other work. We realize it's less conservative but within reason. We may reduce the acceptance limit pending the long-term results in practice and technological advances.	7/10/2019 4:35 PM
16	Shrinkage (Microstrain) – The maximum 28 day shrinkage based on ASTM C 157 air dried method of 500 microstrain. The DME/DMM has the option of accepting mix designs above the permeability or shrinkage limits if it is suspected that variation in the specimen curing or testing caused inconsistent test results.	7/10/2019 3:54 PM
17	C157 no greater than .040 at 28 days	7/10/2019 2:39 PM
18	AASHTO T 160, test limit of .032%, no changes	7/10/2019 3:41 PM

#	COMMENTS FOR "SPECIFICATION 2"	DATE
1.	Following seven-day initial cure, cure in relative humidity of 50% and test in accordance with AASHTO T 160	7/26/2019 7:25 PM
2	Shrinkage No greater than 0.040 percent at 28 days by ASTM C157	7/17/2019 5:40 PM
3	Measured shrinkage shall not be greater than 0.030 percent after 21 days of air drying when determined in accordance with AASHTO T 160. Specimens shall be wet cured for 7 days prior to air-drying. The initial reading for calculation of shrinkage shall be taken at the initiation of drying.	7/12/2019 8:38 PM

4	Specified maximum paste content of 30%, which includes cement, other cementitious, water and liquid admixtures.	7/11/2019 3:06 PM
5	Special provision for shrinkage compensating concrete: ASTM C 878, maximum restrained concrete prism expansion shall be a minimum of 0.05% and a maximum of 0.09%	7/10/2019 5:03 PM
6	Maximum Permeability – Design the concrete mixture to meet a target maximum permeability of 2000 coulombs after a 56 day curing period according to AASHTO T 277. The DME/DMM has the option of accepting mix designs above the permeability or shrinkage limits if it is suspected that variation in the specimen curing or testing caused inconsistent test results.	7/10/2019 3:54 PM

#	COMMENTS FOR "SPECIFICATION 3"	DATE
1	The "Rate of Evaporation Limitations" are detailed in ACI 305 - Hot Weather Concrete.	7/26/2019 7:25 PM
2	Required minimum of 1 lb of microfibers and 3 lbs. of macro fibers, ASTM D7508, microfibers shall be 0.5 to 2 inches in length, macro fibers shall be 1 to 2.5 inches in length.	7/11/2019 3:06 PM

#	COMMENTS FOR "SPECIFICATION 4"	DATE
	There are no responses.	

#	COMMENTS FOR "SPECIFICATION 5"	DATE
	There are no responses.	

#	COMMENTS FOR "SPECIFICATION 6"	DATE
	There are no responses.	

#	COMMENTS FOR "SPECIFICATION 7"	DATE
	There are no responses.	

#	COMMENTS FOR "SPECIFICATION 8"	DATE
	There are no responses.	

Q6 If your agency uses lightweight aggregate for internal curing, please provide details:

Answered: 23 Skipped: 12

ANSWER CHOICES	RESPONSES		
Type	95.65%		22
Content	60.87%		14
Method of Use	47.83%		11

#	TYPE	DATE
1	Expanded shale	8/1/2019 12:49 PM
2	n/a	7/25/2019 3:58 PM
3	Sand Lightweight - Research Project	7/22/2019 6:05 PM
4	Not Applicable	7/22/2019 3:36 PM
5	n/a	7/22/2019 3:32 PM
6	No real approved list yet, prewetted lightweight fine aggregate used for internal curing, must meet ASTM C330.	7/19/2019 12:51 PM
7	Have not used yet.	7/18/2019 4:58 PM
8	Experimental Project - expanded shale fine aggregate	7/17/2019 11:22 PM
9	trial projects only	7/17/2019 5:40 PM
10	N/A	7/16/2019 11:57 AM
11	ASTM C 1761	7/12/2019 8:38 PM
12	Expanded Shale	7/11/2019 7:39 PM
13	N/A	7/11/2019 3:06 PM
14	15% minimum absorption. This typically limits it to expanded shale or clay	7/11/2019 2:27 PM
15	Expanded shale, clay or slate is allowable	7/10/2019 9:02 PM
16	Expanded shale has been used but not for internal curing. We have used it for weight control on lift spans over water.	7/10/2019 8:21 PM
17	None	7/10/2019 7:42 PM
18	None	7/10/2019 7:42 PM
19	The lightweight aggregate shall be an expanded shale, expanded blast furnace slag, expanded slate, or expanded clay product according to ASTM C 1761.	7/10/2019 5:03 PM
20	Lightweight Fine Aggregate that meets ASTM C330 (Utelite out of Utah and Arcosa out of California are the two suppliers currently)	7/10/2019 4:35 PM
21	N/A The approved light weight aggregates we have are too low absorption for internal curing to work.	7/10/2019 3:54 PM
22	ASTM C1761 and ASTM C330	7/10/2019 3:41 PM

#	CONTENT	DATE
1	35%-45% of total volume	8/1/2019 12:49 PM
2	n/a	7/25/2019 3:58 PM
3	30% sand lightweight replacement	7/22/2019 6:05 PM
4	Not Applicable	7/22/2019 3:36 PM
5	7 lbs. per 100 lbs. cementitious. Still in research with this item.	7/19/2019 12:51 PM
6	10% of fine aggregate by weight	7/17/2019 11:22 PM
7	As needed to meet the shrinkage test limits. Typically, around 30% of fine aggregate	7/12/2019 8:38 PM
8	7% of mix water	7/11/2019 7:39 PM
9	Calculated in accordance with our SP, but at least 25% replacement of fine aggregate with lightweight fine aggregate	7/11/2019 2:27 PM
10	250 pcy of lightweight used to replace an equivalent sand volume	7/10/2019 9:02 PM
11	all of the coarse aggregate was replaced with lightweight	7/10/2019 8:21 PM
12	The pre-wetted lightweight aggregate shall replace a minimum 30 percent, by volume, of the normal weight fine aggregate	7/10/2019 5:03 PM
13	Determine fine aggregate replacement quantities according to subsection X1.3 of ASTM C1761, using an absorption value less than the average of a minimum of three representative samples from a lot of material to be used on the project.	7/10/2019 4:35 PM
14	can't be greater than 10% total volume of aggregate volume	7/10/2019 3:41 PM

#	METHOD OF USE	DATE
1	looking into it	8/2/2019 6:35 PM
2	INDOT built 5 decks as part of a research project between 2011-2016 for internally cured high-performance concrete. It is not currently standard practice.	8/1/2019 12:49 PM
3	n/a	7/25/2019 3:58 PM
4	prewetted lightweight fine aggregate	7/22/2019 6:05 PM
5	Not Applicable	7/22/2019 3:36 PM
6	Using in decks currently but looking to move into parapet and other items.	7/19/2019 12:51 PM
7	substitute with fine	7/17/2019 11:22 PM
8	Experimental only at this time but heavy interest.	7/11/2019 7:39 PM
9	Bridge deck mix	7/11/2019 2:27 PM
10	Structural concrete	7/10/2019 9:02 PM
11	LWFA is presaturated and replaces a portion of the sand so that it can provide more water for curing once it's placed.	7/10/2019 4:35 PM

Q7 Please list any other recommendations or practices from your agency for mitigating concrete shrinkage on bridge decks:

Answered: 15 Skipped: 20

#	RESPONSES	DATE
1	looking at requiring fogging for thin overlays	8/2/2019 6:36 PM
2	Wind break and fogging system on bridge decks and approach slabs.	7/26/2019 7:25 PM
3	See attached specification for Modified Deck Curing practices to reduce early age shrinkage. Link to research that led to modified deck curing practices: https://www.mdt.mt.gov/publications/docs/brochures/Forensic-Deck-Analysis-Report-2017-0421.pdf	7/22/2019 3:38 PM
4	Concrete shrinks. Use polyester polymer concrete or a hot applied waterproofing membrane with asphalt overlay.	7/22/2019 3:33 PM
5	None other than what's already been listed. Shrinkage cracks are thankfully not a prevalent issue to us (probably due to the extremely humid environment we live in year-round!)	7/18/2019 6:47 PM
6	ACI evaporation chart must be used to proceed and plan pour date. Decrease paste content by larger 1" to 1.25" rock seems a valid strategy. Set retarder for continuous span placements or integral end diaphragms.	7/17/2019 5:42 PM
7	Currently, the DOT has a 10-day wet cure for bridge decks.	7/16/2019 7:18 PM
8	We've been using fibers in the top of our buried approach slabs without a top mat of reinforcing to limit shrinkage cracks. We've started using fiber in the copings to see what effects that will have on mitigating cracks in them.	7/16/2019 12:58 PM
9	N/A	7/16/2019 11:57 AM
10	We've moved away from texturing/tining the concrete while in a plastic state, and now groove the concrete with diamond grinders after the cure period.	7/15/2019 11:46 PM
11	https://dschq.dot.ca.gov/OSCHQDownloads/misc/Control_Shrinkage_Cracking_ACI_CT.pdf	7/12/2019 5:20 PM
12	We try not to delay application of wet curing. We are also moving towards saw cut grooving so there are no delays in texturing the wearing surface. We are also trying diamond grinding as another method of texturing so curing can be applied sooner.	7/10/2019 8:25 PM
13	IDOT has been researching bridge deck cracking with a focus on mitigating shrinkage for nearly 10 years. Here are links to reports currently published: Phase I https://apps.ict.illinois.edu/projects/getfile.asp?id=3099 Phase II - https://apps.ict.illinois.edu/projects/getfile.asp?id=4980 Phase III will be complete by the end of 2020. Also, I will attach a 'process review' report from our IL FHWA division discussing IDOT bridge deck construction.	7/10/2019 5:03 PM
14	It is not just about shrinkage it is about permeability also. Before we required testing, we had permeabilities above 6000 coulombs and few SCMs were used. Now nearly all mixes have SCMs.	7/10/2019 3:58 PM
15	Limit compressive strength Use performance specifications and allow the industry to be creative.	7/10/2019 2:40 PM

Q8 Please upload any documentation that explains your agency's efforts to prevent and mitigate concrete shrinkage in bridge decks (file must be Microsoft Word [.doc or .docx] or Portable Document Format [.pdf] and less than 16MB in size)

Answered: 9 Skipped: 26

#	FILE NAME	FILE SIZE	DATE
1	SDDOT Bridge Deck Concrete Shrinkage Survey Attachment - UDOT Concrete Std Specs.pdf	235.7KB	NaN/NaN/0NaN NaN:NaN PM
2	RDT_03_004.pdf	1.5MB	NaN/NaN/0NaN NaN:NaN PM
3	MODIFIED BRIDGE DECK CONCRETE WATER CURE.pdf	86.8KB	NaN/NaN/0NaN NaN:NaN PM
4	CDOT Section 601 Structural Concrete Specification 2017.pdf	626.5KB	NaN/NaN/0NaN NaN:NaN PM
5	NHDOT Specification Section 520.pdf	1.1MB	NaN/NaN/0NaN NaN:NaN PM
6	WSDOT-747.1.pdf	1.4MB	NaN/NaN/0NaN NaN:NaN PM
7	Illinois Tollway High Performance Concrete for Bridge Decks.pdf	2.4MB	NaN/NaN/0NaN NaN:NaN PM
8	BridgeDeckCrackPreventionSSP.pdf	21.8KB	NaN/NaN/0NaN NaN:NaN PM
9	Bridge_Deck_Construction_Final_Report_and_Cover_Letter_6-3-2013.pdf	1.8MB	NaN/NaN/0NaN NaN:NaN PM

MASTER® BUILDERS SOLUTIONS | BASF We create chemistry

3

03 30 00	Cast-in-Place Concrete
03 40 00	Precast Concrete
03 70 00	Mass Concrete

MasterAir® VR 10

Vinsol-Resin Air-Entraining Admixture

Description

MasterAir VR 10 neutralized vinsol resin admixture is used for entraining air in concrete. It meets the requirements of ASTM C 260, AASHTO M 154, and CRD-C 13.

Applications

Recommended for use in:

- Concrete exposed to cyclic freezing and thawing
- Production of high-quality normal or lightweight concrete (heavyweight concrete normally does not contain entrained air)

Features

- Ready-to-use in the proper concentration for rapid, accurate dispensing

Benefits

- Increased resistance to damage from cyclic freezing and thawing
- Increased resistance to scaling from deicing salts
- Improved plasticity and workability
- Improved properties of mixtures used for making concrete block, concrete pipe and other precast products
- Reduced permeability – increased watertightness
- Reduced segregation and bleeding

Performance Characteristics

Concrete durability research has established that the best protection for concrete from the adverse effects of freezing and thawing cycles and deicing salts results from: proper air content in the hardened concrete, a suitable air-void system in terms of bubble size and spacing, and adequate concrete strength, assuming the use of sound aggregates and proper mixing, transporting, placing, consolidation, finishing and curing techniques. MasterAir VR 10 admixture can be used to obtain adequate freeze-thaw durability in a properly proportioned concrete mixture, if standard industry practices are followed.

Air Content Determination: The total air content of normal weight concrete should be measured in strict accordance with ASTM C 231, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method" or ASTM C 173/C 173M, "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method." The air content of lightweight concrete should only be determined using the Volumetric Method.

The air content should be verified by calculating the gravimetric air content in accordance with ASTM C 138/C 138M, "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete." If the total air content, as measured by the Pressure Method or Volumetric Method and as verified by the Gravimetric Method, deviates by more than 1.5%, the cause should be determined and corrected through equipment calibration or by whatever process is deemed necessary.

page 1 of 3

Guidelines for Use

Dosage: There is no standard dosage for MasterAir VR 10 admixture. The exact quantity of air-entraining admixture needed for a given air content of concrete varies because of differences in concrete making materials and ambient conditions. Typical factors that might influence the amount of air entrained include: temperature, cementitious materials, sand gradation, sand-aggregate ratio, mixture proportions, slump, means of conveying and placement, consolidation and finishing technique.The amount of MasterAir VR 10 admixture used will depend upon the amount of entrained air required under actual job conditions. In a trial mixture, use 0.25 to 4 fl oz/cwt (16-260 mL/100 kg) of cementitious materials. In mixtures containing water-reducing or set-control admixtures, the amount of MasterAir VR 10 admixture needed may be somewhat less than the amount required in plain concrete.

Due to possible changes in the factors that can affect the dosage of MasterAir VR 10 admixture, frequent air content checks should be made during the course of the work. Adjustments to the dosage should be based on the amount of entrained air required in the mixture at the point of placement. If an unusually high or low dosage of MasterAir VR 10 admixture is required to obtain the desired air content, consult your local sales representative. In such cases, it may be necessary to determine that, in addition to a proper air content in the fresh concrete, a suitable air-void system is achieved in the hardened concrete.

Dispensing and Mixing: Add MasterAir VR 10 admixture to the concrete mixture using a dispenser designed for air-entraining admixtures; or add manually using a suitable measuring device that ensures accuracy within plus or minus 3% of the required amount.

For optimum, consistent performance, the air-entraining admixture should be dispensed on damp, fine aggregate or with the initial batch water. If the concrete mixture contains lightweight aggregate, field evaluations should be conducted to determine the best method to dispense the air-entraining admixture.

Precaution

In a 2005 publication from the Portland Cement Association (PCA R&D Serial No. 2789), it was reported that problematic air-void clustering that can potentially lead to above normal decreases in strength was found to coincide with late additions of water to air-entrained concretes. Late additions of water include the conventional practice of holding back water during batching for addition at the jobsite. Therefore, caution should be exercised with delayed additions to air-entrained concrete. Furthermore, an air content check should be performed after post-batching addition of any other materials to an air-entrained concrete mixture.

Product Notes

Corrosivity – Non-Chloride, Non-Corrosive: MasterAir VR 10 admixture will neither initiate nor promote corrosion of reinforcing and prestressing steel embedded in concrete, or of galvanized floor and roof systems. No calcium chloride or other chloride-based ingredients are used in the manufacture of this admixture.

Compatibility: MasterAir VR 10 admixture may be used in combination with any BASF admixture, unless stated otherwise on the data sheet for the other product. When used in conjunction with other admixtures, each admixture must be dispensed separately into the concrete mixture.

Storage and Handling

Storage Temperature: MasterAir VR 10 admixture should be stored and dispensed at 35 °F (2 °C) or higher. Although freezing does not harm this product, precautions should be taken to protect it from freezing. If MasterAir VR 10 admixture freezes, thaw at 35 °F (2 °C) or above and completely reconstitute by mild mechanical agitation. Do not use pressurized air for agitation.

Shelf Life: MasterAir VR 10 admixture has a minimum shelf life of 18 months. Depending on storage conditions, the shelf life may be greater than stated. Please contact your local sales representative regarding suitability for use and dosage recommendations if the shelf life of MasterAir VR 10 admixture has been exceeded.

Safety: MasterAir VR 10 admixture is a caustic solution. Chemical goggles and gloves are recommended when transferring or handling this material. (See SDS and/or product label for complete information.)

Packaging

MasterAir VR 10 admixture is supplied in 55 gal (208 L) drums, 275 gal (1040 L) totes and by bulk delivery.

Related Documents

Safety Data Sheets: MasterAir VR 10 admixture

Additional Information

For suggested specification information or for additional product data on MasterAir VR 10 admixture, contact your local sales representative.

The Admixture Systems business of BASF's Construction Chemicals division is the leading provider of solutions that improve placement, pumping, finishing, appearance and performance characteristics of specialty concrete used in the ready-mixed, precast, manufactured concrete products, underground construction and paving markets. For over 100 years we have offered reliable products and innovative technologies, and through the Master Builders Solutions brand, we are connected globally with experts from many fields to provide sustainable solutions for the construction industry.

Limited Warranty Notice

BASF warrants this product to be free from manufacturing defects and to meet the technical properties on the current Technical Data Guide, if used as directed within shelf life. Satisfactory results depend not only on quality products but also upon many factors beyond our control. BASF MAKES NO OTHER WARRANTY OR GUARANTEE, EXPRESS OR IMPLIED, INCLUDING WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE WITH RESPECT TO ITS PRODUCTS. The sole and exclusive remedy of Purchaser for any claim concerning this product, including but not limited to, claims alleging breach of warranty, negligence, strict liability or otherwise, is shipment to purchaser of product equal to the amount of product that fails to meet this warranty or refund of the original purchase price of product that fails to meet this warranty, at the sole option of BASF. Any claims concerning this product must be received in writing within one (1) year from the date of shipment and any claims not presented within that period are waived by Purchaser. BASF WILL NOT BE RESPONSIBLE FOR ANY SPECIAL, INCIDENTAL, CONSEQUENTIAL (INCLUDING LOST PROFITS) OR PUNITIVE DAMAGES OF ANY KIND.

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BASF Corporation
Admixture Systems
www.master-builders-solutions.basf.us

United States
23700 Chagrin Boulevard
Cleveland, Ohio 44122-5544
Tel: 800 628-9990 ▪ Fax: 216 839-8821

Canada
1800 Clark Boulevard
Brampton, Ontario L6T 4M7
Tel: 800 387-5862 ▪ Fax: 905 792-0651

MASTER® BUILDERS SOLUTIONS | BASF We create chemistry

3	03 30 00	**Cast-in-Place Concrete**
	03 40 00	**Precast Concrete**
4	03 70 00	**Mass Concrete**
	04 05 16	**Masonry Grouting**

MasterGlenium® 3030

Full-Range Water-Reducing Admixture

Description

MasterGlenium 3030 ready-to-use full-range water-reducing admixture is a patented new generation of admixture based on polycarboxylate chemistry. MasterGlenium 3030 admixture is very effective in producing concretes with different levels of workability including applications that require the use of self-consolidating concrete (SCC). MasterGlenium 3030 admixture meets ASTM C 494/C 494M requirements for Type A, water-reducing, and Type F, high-range water-reducing, admixtures.

Applications

Recommended for use in:

- Concrete where high flowability, high-early and ultimate strengths and increased durability are needed
- Self-consolidating concrete
- Concrete where normal, mid-range, or high-range water-reduction is desired
- Concrete where normal setting times are required
- Strength-on-demand concrete, such as 4x4™ Concrete
- Pervious concrete
- Self-consolidating grout

Features

- Dosage flexibility for normal, mid- and high-range water reduction
- Reduced water content for a given slump
- Produces cohesive and non-segregating concrete mixture
- Increased compressive strength and flexural strength performance at all ages
- Providing faster setting times and strength development
- Enhanced finishability and pumpability

Benefits

- Providing economic benefits to the entire construction team through higher productivity and reduced variable costs

Performance Characteristics

The dosage flexibility of MasterGlenium 3030 admixture allows it to be used as a normal, mid-range and high-range water reducer.

Mixture Data: 600 lb/yd³ of Type I cement (360 kg/m³); slump, 8.5-9.25 in. (210-235 mm); non-air-entrained concrete; dosage rate adjusted to obtain 25-30% water reduction.

Setting Time

Mixture	Initial Set (h:min)	Difference (h:min)
Plain	4:24	–
Conventional high-range water-reducer	6:00	+ 1.36
MasterGlenium 3030 admixture	5:00	+0.36

Compressive Strength

Mixture	1 Day		7 Days	
	psi	MPa	psi	MPa
Plain	1700	12	4040	28
Conventional high-range water-reducer	3460	24	6380	44
MasterGlenium 3030 admixture	4120	28	7580	52

Slump Retention - in. (mm)

Mixture	Minutes		
	15	30	45
Plain	8.5 (215)	8.5 (215)	7.5 (200)
Conventional high-range water-reducer	8.5 (215)	4.25 (110)	3.5 (90)
MasterGlenium 3030 admixture	9.25 (235)	9.25 (235)	8.25 (210)

Rate of Hardening: MasterGlenium 3030 admixture is formulated to produce normal setting characteristics throughout its recommended dosage range. Setting time of concrete is influenced by the chemical and physical composition of the basic ingredients of the concrete, temperature of the concrete and ambient conditions. Trial mixtures should be made with actual job materials to determine the dosage required for a specified setting time and a given strength requirement.

Guidelines for Use

Dosage: MasterGlenium 3030 admixture has a recommended dosage range of up to 3 fl oz/cwt (195 mL/100 kg) for Type A applications, 3-6 fl oz/cwt (195-390 mL/100 kg) for mid-range use and up to 18 fl oz/cwt (1,170 mL/100 kg) for Type F applications. The dosage range is applicable to most mid- to high-range concrete mixtures using typical concrete ingredients. However, variations in job conditions and concrete materials, such as silica fume, may require dosages outside the recommended range. In such cases, contact your local sales representative.

Mixing: MasterGlenium 3030 admixture can be batched with the initial mixing water or as a delayed addition. However, optimum water reduction is generally obtained with a delayed addition.

Product Notes

Corrosivity – Non-Chloride, Non-Corrosive: MasterGlenium 3030 admixture will neither initiate nor promote corrosion of reinforcing steel embedded in concrete, prestressed concrete or of galvanized steel floor and roof systems. Neither calcium chloride nor other chloride-based ingredients are used in the manufacture of MasterGlenium 3030 admixture.

Compatibility: MasterGlenium 3030 admixture is compatible with most admixtures used in the production of quality concrete, including normal, mid-range and high-range water-reducing admixtures, air-entrainers, accelerators, retarders, extended set control admixtures, corrosion inhibitors, and shrinkage reducers.

Do not use MasterGlenium 3030 admixture with admixtures containing beta-naphthalene-sulfonate. Erratic behaviors in slump, slump flow, and pumpability may be experienced.

For directions on the proper evaluation of MasterGlenium 3030 admixture in specific applications, contact your local sales representative.

Storage and Handling

Storage Temperature: MasterGlenium 3030 admixture should be stored above freezing temperatures. If MasterGlenium 3030 admixture freezes, thaw at 45 °F (7 °C) or above and completely reconstitute by mild mechanical agitation. **Do not use pressurized air for agitation.**

Shelf Life: MasterGlenium 3030 admixture has a minimum shelf life of 12 months. Depending on storage conditions, the shelf life may be greater than stated. Please contact your local sales representative regarding suitability for use and dosage recommendations if the shelf life of MasterGlenium 3030 admixture has been exceeded.

Packaging

MasterGlenium 3030 admixture is supplied in 55 gal (208 L) drums, 275 gal (1040 L) totes and by bulk delivery.

Related Documents

Safety Data Sheets: MasterGlenium 3030 admixture

Additional Information

For additional information on MasterGlenium 3030 admixture or its use in developing concrete mixes with special performance characteristics, contact your local sales representative.

The Admixture Systems business of BASF's Construction Chemicals division is the leading provider of solutions that improve placement, pumping, finishing, appearance and performance characteristics of specialty concrete used in the ready-mixed, precast, manufactured concrete products, underground construction and paving markets. For over 100 years we have offered reliable products and innovative technologies, and through the Master Builders Solutions brand, we are connected globally with experts from many fields to provide sustainable solutions for the construction industry.

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BASF Corporation
Admixture Systems
www.master-builders-solutions.basf.us

United States
23700 Chagrin Boulevard
Cleveland, Ohio 44122-5544
Tel: 800 628-9990 ▪ Fax: 216 839-8821

Canada
1800 Clark Boulevard
Brampton, Ontario L6T 4M7
Tel: 800 387-5862 ▪ Fax: 905 792-0651

MasterLife® SRA 035

Shrinkage-Reducing Admixture

Description

MasterLife SRA 035 shrinkage-reducing admixture was developed specifically to reduce drying shrinkage of concrete and mortar, and the potential for subsequent cracking. MasterLife SRA 035 admixture functions by reducing capillary tension of pore water, a primary cause of drying shrinkage. MasterLife SRA 035 admixture will meet ASTM C 494/C 494M requirements for Type S, Specific Performance, admixtures.

Applications

Recommended for use in:

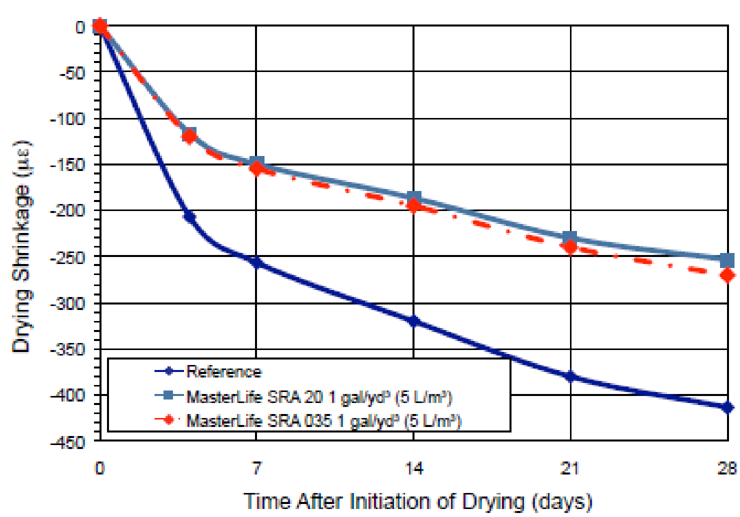
- Ready-mixed or precast concrete structures requiring shrinkage reduction and long-term durability
- Wet mix shotcrete

Features

- Reduces the capillary tension of pore water in cementitious mixtures
- Provides moderate to significant reductions in the drying shrinkage of cementitious mixtures
- Reduces stresses induced from one-dimensional surface drying in concrete slabs, walls and other elements

Benefits

- Reduces microcracking and drying shrinkage cracking in concrete, mortar and paste
- Minimizes curling in concrete slabs
- Improves aesthetics, watertightness and durability in concrete elements and structures
- Minimizes prestress loss in prestressed concrete applications



Performance Characteristics

MasterLife SRA 035 admixture does not substantially affect slump. MasterLife SRA 035 admixture may slightly increase bleed time and bleed ratio. MasterLife SRA 035 admixture may also delay time of set by 1-2 hours depending upon dosage and temperature. Compressive strength loss is minimal with MasterLife SRA 035 admixture. For air-entrained concrete applications, truck trial evaluations as detailed in the section titled "Compatibility" must be performed to verify that the specified air content can be achieved consistently. Therefore, contact your local sales representative when concrete treated with MasterLife SRA 035 admixture is being proposed for applications exposed to freezing and thawing environments.

Guidelines for Use

Dosage: Knowledge of the shrinkage characteristics of the concrete mixture proposed for use is required prior to the addition of MasterLife SRA 035 admixture. The dosage of MasterLife SRA 035 admixture will be dependent on the desired drying shrinkage and the reduction in drying shrinkage required. Therefore, it is strongly recommended that drying shrinkage testing be performed to determine the optimum dosage for each application and each set of materials. The typical dosage range of MasterLife SRA 035 admixture is 0.5 to 1.5 gal/yd^3 (2.5 to 7.5 L/m^3). However, dosages outside of this range may be required depending on the level of shrinkage reduction needed for a given application and because of variations in concrete materials, jobsite conditions and other factors. In such cases, contact your local sales representative for further guidance.

Dispensing and Mixing: MasterLife SRA 035 admixture may be added to the concrete mixture during the initial batch sequence or at the jobsite. The mix water content should be reduced to account for the quantity of MasterLife SRA 035 admixture used. If the delayed addition method is used, mixing at high speed for 3-5 minutes after the addition of MasterLife SRA 035 admixture will result in mixture uniformity.

Product Notes

Corrosivity: Non-Chloride, Non-Corrosive: MasterLife SRA 035 admixture will neither initiate nor promote corrosion of reinforcing steel, prestressing steel or of galvanized steel floor and roof systems. Neither calcium chloride nor other chloride-based ingredients are used in the manufacture of MasterLife SRA 035 admixture.

Compatibility: MasterLife SRA 035 admixture is compatible with all air entrainers, water-reducers, mid-range water-reducers, high-range water reducers, set retarders, accelerators, silica fume, and corrosion inhibitors. For air-entrained concrete applications, MasterAir® AE 200 admixture is the preferred air entrainer. The dosage of air entrainer must be established through truck trial evaluations. The trials should include a simulated haul time of at least 20 minutes to assess air content stability. MasterLife SRA 035 admixture should be added separately to the concrete mixture to ensure desired results.

Storage and Handling

Storage Temperature: MasterLife SRA 035 admixture is a potentially combustible material with a flash point of 198 °F (92 °C). This is substantially above the upper limit of 140 °F (60 °C) for classification as a flammable material, and below the limit of 200 °F (93 °C) where DOT requirements would classify this as a combustible material. Nonetheless, this product must be treated with care and protected from excessive heat, open flame or sparks. For more information refer to the Safety Data Sheet. MasterLife SRA 035 admixture should be stored at ambient temperatures above 35 °F (2 °C), and precautions should be taken to protect the admixture from freezing. If MasterLife SRA 035 admixture freezes, thaw and reconstitute by mild mechanical agitation. Do not use pressurized air for agitation.

Shelf Life: MasterLife SRA 035 admixture has a minimum shelf life of 12 months. Depending on storage conditions, the shelf life may be greater than stated. Please contact your local sales representative regarding suitability for use and dosage recommendations if the shelf life of MasterLife SRA 035 admixture has been exceeded.

Packaging

MasterLife SRA 035 admixture is available in 55 gal (208 L) drums, 275 gal (1040 L) totes and by bulk delivery.

Related Documents

Safety Data Sheets: MasterLife SRA 035 admixture

Additional Information

For additional information on MasterLife SRA 035 admixture, or its use in developing a concrete mixture with special performance characteristics, contact your local sales representative.

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Cleveland, Ohio 44122-5544
Tel: 800 628-9990 ■ Fax: 216 839-8821

Canada
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Brampton, Ontario L6T 4M7
Tel: 800 387-5862 ■ Fax: 905 792-0651

GCC

GCC of America
600 S. Cherry Street, Suite 1000, Glendale, CO 80246
Sales (303) 739-5900, Customer Service (800) 225-5422

MATERIAL CERTIFICATION REPORT

Plant:	Rapid City	**Cement Type:**	I/II, Low Alkali, GU
Address:	501 N. St Omge Street, Rapid City, SD 57702	**Date Issued:**	2-Dec-19
Contact:	Gail Amicucci	**Production Period:**	1-Nov-19
Phone:	(605) 721-7042	**To:**	30-Nov-19

STANDARD REQUIREMENTS ASTM C150/AASHTO M85/ASTM C1157

CHEMICAL			
Item	ASTM Test Method	ASTM C150 Spec. Limit	Test Result
SiO_2 (%)	C114	-	20.2
Al_2O_3 (%)	C114	6.0 max	4.4
Fe_2O_3 (%)	C114	6.0 max	3.5
CaO (%)	C114	-	64.0
MgO (%)	C114	6.0 max	1.1
SO_3 (%)	C114	3.0 max[A]	3.0
Loss On Ignition (%)	C114	3.5 max[B]	2.8
Na_2O (%)	C114	-	0.11
K_2O (%)	C114	-	0.67
Insoluble Residue (%)	C114	1.5 max	0.49
CO_2 (%)	C114	-	1.6
Limestone (%)	C150	5.0 max	4.2
$CaCO_3$ in Limestone (%)	C150	70 min	87
Inorganic Processing Addition	C150	5.0 max	-
Potential Phase Composition			
C_3S (%)	C150	-	56
C_2S (%)	C150	-	16
C_3A (%)	C150	8 max	6
C_4AF (%)	C150	-	11

PHYSICAL					
Item	ASTM Test Method	ASTM C150 Spec. Limit	ASTM C1157 Spec. Limit	Test Result	
Air Content (% vol)	C185	12 max	12 max	8	
Blaine Fineness (m^2/kg)	C204	260 min	-	420	
Residue 45 µm (No.325) Sieve (%)	C430	-	-	0.7	
Autoclave Expansion (%)	C151	0.80 max	0.80 max	0.00	
Compressive Strength				Mpa	psi
3 days, MPa (psi)	C109	12.0 (1740) min	13.0 (1890) min	24.8	3601
7 days, MPa (psi)	C109	19.0 (2760) min	20.0 (2900) min	33.5	4854
28 days, MPa (psi)[C]	C109	28.0 (4060) min	28.0 (4060) min	46.9	6807
Time of Setting, Initial Vicat (min)	C191	45 min / 375 max	45 min / 420 max	126	
Mortar Bar Expansion (%)	C1038	0.020 max	0.020 max	-0.001	

ADDITIONAL DATA					
Type	Limestone	Test Method	Base Phase Composition	ASTM Test Method	Test Result
SiO_2 (%)	2.4	Internal	C_3S (%)	C150	58
Al_2O_3 (%)	0.7	Internal	C_2S (%)	C150	16
Fe_2O_3 (%)	0.3	Internal	C_3A (%)	C150	6
CaO (%)	53.3	Internal	C_4AF (%)	C150	11
SO_3 (%)	0.1	Internal			

OPTIONAL REQUIREMENTS ASTM C150/AASHTO M85/ASTM C1157

CHEMICAL			
Item	ASTM Test Method	ASTM C150 Spec. Limit	Test Result
Equivalent Alkalies (%)	C114	0.60 max	0.55

PHYSICAL				
Item	ASTM Test Method	ASTM C150 Spec. Limit	ASTM C1157 Spec. Limit	Test Result
False Set (%)	C451	50 min	50 min	67

[A] It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020 % at 14 days.
[B] Loss on ignition, max: 3.0 % when limestone is not an ingredient; Loss on ignition, max: 3.5 % when limestone is an ingredient
[C] Test result of prior month

GCC of America Cement is warranted to conform at the time of shipment with current ASTM C150/AASHTO M85/ASTM C1157. No other warranty is made or implied. Having no control over the use of its cements, GCC of America does not guarantee finished work.

FMG ENGINEERING 3700 Sturgis Road, Rapid City, SD 57702 • fmgengineering.com • 605-342-4105

Pete Lien and Sons
Attn Laird Klippenstein:
PO Box 440
Rapid City, SD 57709-0440

January 10, 2019

RE: 2019 QUALITY CONTROL TESTING – **SIZE #8 CONCRETE AGGREGATE**
PETE LIEN & SONS QUARRY, RAPID CITY, SOUTH DAKOTA

Dear Mr. Klippenstein:

As requested, we performed testing on a sample of size #8 limestone concrete aggregate recently submitted to our laboratory from Pete Lien & Sons' Rapid City Quarry. The test results are as follows.

Standard Sieve Analysis

	Percent Passing By Weight						
Sieve Size:	1/2"	3/8"	1/4"	#4	#8	#16	#200
Size #8 Conc. Agg.:	**100**	**99**	**51**	**20**	**2**	**1.8**	**1.5**
ASTM C33 Size #8:	*100*	*85-100*	---	*10-30*	*0-10*	*0-5*	*0-1.5*

Clay Lumps and Friable Particles (ASTM C 142)
% Clay Lumps & Friable Particles: **0.1%**

Sodium Sulfate Soundness (ASTM C88, 5-Cycle)
Weighted Average Loss: **1.3%**

Lightweight Pieces (ASTM C123)
Lightweight Pieces: **None**

Los Angeles Abrasion (ASTM C131, Grading C)
Wear: **27%**

Specific Gravity & Absorption (ASTM C127)
Bulk Specific Gravity (Dry): **2.66**
Apparent Specific Gravity: **2.70**
Bulk Specific Gravity (SSD): **2.68**
Absorption: **0.6%**

Flat & Elongated Particles (SDDOT 212)
Weighted Average Flat & Elongated: **0%**

Bulk Density (ASTM 29)
Unit Weight: **97 pcf**

We trust this information is sufficient. Should you have any questions or need anything additional, please don't hesitate to contact us at your earliest convenience. *Thank you for the opportunity to be of service.*

Sincerely,
FMG Engineering

Kyle Jacobson

Civil Engineering
Geotechnical Engineering
Materials Testing Laboratory
Land Surveying
Environmental Services
Water Resources

180618.10 Pete Lien Size 8 Conc Rock

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January 10, 2019

Pete Lien and Sons
Attn Laird Klippenstein:
PO Box 440
Rapid City, SD 57709-0440

RE: 2019 QUALITY CONTROL TESTING – **ORAL SAND**
ORAL PIT, SOUTH DAKOTA

Dear Mr. Klippenstein:

As requested, we have performed quality control testing on a sample of concrete sand recently submitted to our laboratory from the Oral Sand Pit in South Dakota. The test results are as follows:

Standard Sieve Analysis

	Percent Passing By Weight								
Sieve Size:	3/8"	#4	#8	#16	#30	#50	#100	#200
Oral Concrete Sand:	**100**	**100**	**88**	**67**	**39**	**19**	**5**	**1.0**
Specs(ASTM C33):	*100*	*95-100*	*80-100*	*50-85*	*25-60*	*5-30*	*0-10*	*0-3*

		Specs. (ASTM C33)
Fineness Modulus (FM)		
Oral Sand:	**2.8**	*2.3 - 3.1*
Deleterious Materials		
Friable Particles (ASTM C142):	**0.2%**	*3.0% max*
Lightweight Particles (ASTM C123):	**0.0%**	*0.5% max*
Organic Impurities (ASTM C40):	**Standard**	*Standard or Lighter*
Finer than #200 mesh sieve (ASTM C117):	**1.0%**	*3.0% max.*
Soundness (ASTM C88, 5-cycle Sodium Sulfate)		
Weighted Average Loss:	**2.5%**	*10% Max*
Specific Gravity & Absorption (ASTM C 128)		
Absorption:	**1.2%**	
Specific Gravity (Bulk SSD):	**2.62**	
Fine Aggregate Angularity (AASHTO T 304)		
Oral Sand:	**40.8%**	

We trust this information is sufficient. Should you have any questions or need anything additional, please don't hesitate to contact us at your earliest convenience. *Thank you for the opportunity to be of service.*

Sincerely,
FMG Engineering

Kyle Jacobson

Civil Engineering
Geotechnical Engineering
Materials Testing Laboratory
Land Surveying
Environmental Services
Water Resources

180618.12 Pete Lien Oral Sand

FMG ENGINEERING 3700 Sturgis Road, Rapid City, SD 57702 • fmgengineering.com • 605-342-4105

Pete Lien and Sons
Attn Laird Klippenstein:
PO Box 440
Rapid City, SD 57709-0440

January 10, 2019

RE: 2019 QUALITY CONTROL TESTING – **1-INCH CONCRETE AGGREGATE**
PETE LIEN & SONS QUARRY, RAPID CITY, SOUTH DAKOTA

Dear Mr. Klippenstein:

As requested, we performed testing on a sample of 1" crushed limestone concrete aggregate recently submitted to our laboratory from Pete Lien & Sons' Rapid City Quarry. The test results are as follows.

Standard Sieve Analysis

	Percent Passing By Weight							
Sieve Size:	1 1/2"	1"	3/4"	1/2"	3/8"	#4	#8	#200
1" Conc.:	**100**	**100**	**84**	**45**	**16**	**1**	**1**	**0.9**
ASTM C33 Size 57:	*100*	*95-100*	---	*25-60*	---	*0-10*	*0-5*	*0-1.5*

Clay Lumps and Friable Particles (ASTM C 142)
% Clay Lumps & Friable Particles: **0.2%**

Sodium Sulfate Soundness (ASTM C88, 5-Cycle)
Weighted Average Loss: **1.0%**

Lightweight Pieces (ASTM C123)
Lightweight Pieces: **None**

Los Angeles Abrasion (ASTM C131, Grading B)
Wear: **27%**

Specific Gravity & Absorption (ASTM C127)
Bulk Specific Gravity (Dry): **2.67**
Apparent Specific Gravity: **2.71**
Bulk Specific Gravity (SSD): **2.68**
Absorption: **0.5%**

Flat & Elongated Particles (SDDOT 212)
Weighted Average Flat & Elongated: **0%**

Bulk Density (ASTM 29)
Unit Weight: **101 pcf**

We trust this information is sufficient. Should you have any questions or need anything additional, please don't hesitate to contact us at your earliest convenience. *Thank you for the opportunity to be of service.*

Sincerely,
FMG Engineering

Kyle Jacobson

Civil Engineering
Geotechnical Engineering
Materials Testing Laboratory
Land Surveying
Environmental Services
Water Resources

180618.02 Pete Lien 1-inch Conc Rock

FMG ENGINEERING 3700 Sturgis Road, Rapid City, SD 57702 • fmgengineering.com • 605-342-4105

Pete Lien and Sons
Attn: Laird Klippenstein
PO Box 440
Rapid City, SD 57709-0440

January 10, 2019

RE: 2019 QUALITY CONTROL TESTING – **3/4 -INCH CONCRETE AGGREGATE**
PETE LIEN & SONS QUARRY, RAPID CITY, SOUTH DAKOTA

Dear Mr. Klippenstein:

As requested, we performed testing on a sample of 3/4" crushed limestone concrete aggregate recently submitted to our laboratory from Pete Lien & Sons' Rapid City Quarry. The test results are as follows.

Standard Sieve Analysis — Percent Passing By Weight

Sieve Size:	1"	3/4"	1/2"	3/8"	#4	#8	#200
3/4" Concrete Agg.:	**100**	**95**	**44**	**27**	**4**	**1**	**0.8**
ASTM C33 Size 67:	*100*	*90-100*	--	*20-55*	*0-10*	*0-5*	*0-1.5*

Clay Lumps and Friable Particles (ASTM C 142)
% Clay Lumps & Friable Particles: **0.3%**

Sodium Sulfate Soundness (ASTM C88, 5-Cycle)
Weighted Average Loss: **1.0%**

Lightweight Pieces (ASTM C123)
Lightweight Pieces: **None**

Los Angeles Abrasion (ASTM C131, Grading B)
Wear: **27%**

Specific Gravity & Absorption (ASTM C127)
Bulk Specific Gravity (Dry): **2.67**
Apparent Specific Gravity: **2.71**
Bulk Specific Gravity (SSD): **2.68**
Absorption: **0.5%**

Flat & Elongated Particles (SDDOT 212)
Weighted Average Flat & Elongated: **0%**

Bulk Density (ASTM 29)
Unit Weight: **101 pcf**

We trust this information is sufficient. Should you have any questions or need anything additional, please don't hesitate to contact us at your earliest convenience. *Thank you for the opportunity to be of service.*

Sincerely,
FMG Engineering

Kyle Jacobson

Civil Engineering
Geotechnical Engineering
Materials Testing Laboratory
Land Surveying
Environmental Services
Water Resources

180618.09 0.75-inch Concrete Aggregate

LABORATORY TEST REPORT

WesTest
627 Sheridan Boulevard • Lakewood, CO 80214
303.975.9959 • office@westest.net

CLIENT: Trinity Expanded Shale & Clay
SOURCE: Realite
SAMPLED BY: Client
PROJECT: Realite Aggregate Testing

WesTest PROJECT NO.: 529817
REPORT DATE: April 28, 2017
REVISED REPORT DATE: June 28, 2017

MATERIAL DESCRIPTION	Lightweight Realite 3/8" Concrete Aggregate
DATE SAMPLED	February 2, 2017
SAMPLE LOCATION	Stockpile

Aggregate Physical Property and Quality Tests (ASTM C 330 Specifications)

ASTM C 136

SIEVE SIZE	% Passing	ASTM 9.5 mm to 2.36 mm Specification
1/2", 12.5 mm	100	100
3/8", 9.5 mm	89	80 - 100
# 4, 4.75 mm	12	5 - 40
# 8, 2.36 mm	2	0 - 20
# 16, 1.18 mm	1	0 - 10
# 30, 0.600 mm	1	
# 50, 0.300 mm	1	
# 100, 0.150 mm	1	
# 200, 0.075 mm	0.4	0 - 10

ASTM C 1761 Sect. 10, Absorption

Mass of Pycnometer filled with water (g) = 3243.2	
Mass of Test Specimen in the Wetted Surface Dry Condition (g) = 1500.0	
Mass of Pycnometer, Test Specimen, and Water (g) = 3915.2	
Mass of Oven Dry Specimen (g) = 1297.1	
72-Hour Absorption (%) = 15.6	**Specification =** 5% Min.
Relative Density (Oven Dry) = 1.81	

ASTM C 1761 Sect. 11, Desorption

Mass of Test Specimen in the Wetted Surface Dry Condition (g) = 23.3	
Mass of Test Specimen at Equilibrium (g) = 20.9	
Mass of Oven Dry Test Specimen (g) = 17.6	
Water Released at 94% Relative Humidity (%) = 13.64	
Desorption (%) = 87.4	**Specification =** 85% Min.

ASTM C 29, Bulk Density and Voids in Aggregate

Shoveling Method; Bulk Density = 53 pcf

Specification = 55 pcf Max.

ASTM C 142, Clay Lumps & Friable Particles

COARSE AGG. = 0.5%, Specification: 2.0% Max.

ASTM C 641
Stain Index = 0 Specification = 60 Max.
Iron Content = < 1
Iron Content Specification = Less than 1.5 mg/200 g of sample

ASTM C 114
Loss on Ignition = 0.26% Specification = 5% Max.

Comments:

WesTest
SPECIALISTS TO THE PAVING INDUSTRY

627 Sheridan Boulevard • Lakewood, CO 80214
P: 303.975.9959 • F: 303.975.9969
office@westest.net • www.westest.net

Trinity Expanded Shale & Clay
11728 Hwy. 93
Boulder, CO 80303

April 28, 2017
Revised: June 28, 2017

Attention: Mr. Mark Ewald

Subject: Laboratory Test Results
Lightweight Realite ASTM C 330 Aggregate Tests
Lightweight Realite 3/8" Concrete Aggregate
WesTest Project No. 529817

Gentlemen:

Included as Table 1 are the results of aggregate physical property and quality tests, done in general accordance with ASTM and AASHTO criteria, on concrete aggregate sampled from the above-referenced source on Feburary 2, 2017. The test results indicate the material meets the requirements of ASTM C 330, *Standard Specifications for Lightweight Aggregates for Structural Concrete.*

Included as Table 2 are the results of a laboratory trial mix study to determine the compressive strength, splitting tensile strength, and plastic properties of concrete. One air-entrained mix was proportioned with a cement content of 564 lbs./yd^3. Holcim Type I/II Cement was used for cementitious materials. Sika Air was used for the air-entraining admixtures. Compressive strength cylinders were cast for testing at 7, 28 and 56 days age. Splitting tensile strength specimens were cast for strength determination at 28 days age.

The aggregate used in the mix consisted of Aggregate Industries Platte Valley Pit ASTM C 33 fine aggregate and Lightweight Realite 3/8" concrete aggregate.

The concrete mix was proportioned in general accordance with American Concrete Institute procedures and ASTM C 330 Section 8.4.1. Outlined below is a summary of the materials and design criteria used for this mix:

CRITERIA	WESTEST MIX NO. 52981
CEMENT: Holcim Type I/II	564 lbs./yd^3
SLUMP (IN.)	3 – 3/4
AIR CONTENT (%)	6.50

Mix proportions, physical properties, compressive strength test results at 7, 28, and 56 days age and splitting tensile strength test results at 28 days age are included on Table 2.

Included as Figure 1 are the results of length change determination done in general accordance with ASTM C 157, *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete* as modified per ASTM C 330 Section 8.4.

The specimens were cured in a water bath until age 7 days and measured to determine the zero comparator reading. Drying shrinkage measurements taken at 7, 14, 21 and 28 days air storage, after the 7 day water bath cure, are included on Figure 1. Based on the test results of 0.015% shrinkage the mix design meets the specified maximum allowable shrinkage of 0.070%.

If you have any questions on the information presented, please contact us at your convenience.

Sincerely,
WesTest

Dylan A. Hullinger, P.E.

COLORADO LICENSED PROFESSIONAL ENGINEER 49996 6/28/17

Reviewed by:

Eric R. West, P.E.

WesTest **CONCRETE TRIAL MIX**

627 Sheridan Boulevard • Lakewood, CO 80214
303.975.9959 • office@westest.net

CLIENT: Trinity Expanded Shale & Clay
PROJECT No.: 529817

FINE AGGREGATE SOURCE
Aggregate Industries Platte Valley
ASTM C 33 Fine Aggregate
COARSE AGGREGATE SOURCE
Lightweight Realite 3/8" Concrete
Aggregate

MIX IDENTIFICATION NO.: 52981 DATE MADE: March 23, 2017

ASTM C 330, Section 8.4.1, Concrete Trial Mix,
4,000 psi Compressive Strength, 330 psi Splitting Tensile Strength

CONCRETE MIX INFORMATION

MIX PROPORTIONS	PER 1.01 CUBIC YARD	PER 1.01 CUBIC METER
CEMENT: Holcim Type I/II	564 lbs.	335 kg
AEA: Sika Air*	1	1
FINE AGG.: ASTM C 33 Fine Aggregate	1435 lbs.	851 kg
COARSE AGG.: 3/8" Concrete Aggregate	1030 lbs.	611 kg
WATER	304 lbs. (36.5 gal.)	180 kg (180 L)

Note: Aggregate weights are based on the aggregate being in the saturated, surface dry condition. Corrections must be made for aggregates that vary from these moisture conditions. *Information only, field adjust as necessary.

PHYSICAL PROPERTIES OF CONCRETE

UNIT WT. OF CONCRETE (ASTM C 138)	122.2 pcf	1957 kg/m³
YIELD (ASTM C 138)	27.27 ft.³	1.01 m³
SLUMP (ASTM C 143)	3 - 3/4"	95 mm
AIR CONTENT (ASTM C 173)	6.50%	6.50%
WATER/CEMENTITIOUS RATIO	0.54	0.54
TEMPERATURE	69 °F	21 °C

COMPRESSIVE STRENGTH OF TEST CYLINDERS (ASTM C 39), psi (MPa)

7 - Day	28 - Day	56 - Day
3740 (25.8)	5570 (38.4)	5960 (41.1)
4180 (28.8)	5410 (37.3)	6140 (42.3)
4140 (28.5)	5410 (37.3)	5960 (41.1)
AVERAGE 4020 (27.7)	**AVERAGE 5460 (37.6)**	**AVERAGE 6020 (41.5)**

SPLITTING TENSILE STRENGTH (ASTM C 496), psi (MPa)

28 - Day	
575 (4.0)	595 (4.1)
635 (4.4)	650 (4.5)
570 (3.9)	605 (4.2)
590 (3.9)	590 (4.2)
AVERAGE 600 (4.1)	

WesTest

COLORADO LICENSED
49996
PROFESSIONAL ENGINEER
6/28/17

MEASURED OVEN DRY DENSITY, pcf (ASTM C 567)
110.0

CALCULATED OVEN DRY DENSITY, pcf (ASTM C 567, 9.1)
109.5

CALCULATED EQUILIBRIUM DENSITY, pcf (ASTM C 567, 9.2)
112.5

Dylan A. Hullinger, P.E.

POPOUT MATERIALS (ASTM C 330, ASTM C 151)
NONE

TABLE 2

WesTest

627 Sheridan Boulevard • Lakewood, CO 80214
303.975.9959 • office@westest.net

LABORATORY TEST REPORT

Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete

ASTM C 157 As Modified per ASTM C 330 Section 8.4

REVISED REPORT DATE: June 28, 2017
CLIENT: Trinity Expanded Shale & Clay
REPORT DATE: April 28, 2017
PROJECT NO.: 529817
SAMPLE ID: 52981

DATE CAST: March 23, 2017
TYPE OF SPECIMEN: Concrete
CEMENT SUPPLIER, TYPE: Holcim Type I/II
FLY ASH SUPPLIER, CLASS: N/A
ADMIXTURES: Sika Air
SLUMP (IN.): 3 - 3/4
CONSOLIDATION METHOD: Rodding
CURING CONDITIONS
INITIAL: MOIST ROOM, ASTM C 511
7 DAY CURE: LIME-SATURATED WATER, 73±3 °F
AIR STORAGE: 32±2% RELATIVE HUMIDITY, 100±2 °F

SIZE OF SPECIMEN: 3"x3"x11"
COARSE AGGREGATE: Lightweight Realite 3/8" Concrete Aggregate
FINE AGGREGATE: Aggregate Industries Platte Valley Pit ASTM C 33 Fine Aggregate
TEMPERATURE (°F): 69

EFFECTIVE GAUGE LENGTH = 250 mm

DATE	3/24/17	3/31/17	4/7/17		4/14/17		4/21/17		4/28/17	
CURING	24 HR. INITIAL, 30 MIN. SOAK	7 DAY CURE	7 DAY CURE, 7 DAY AIR STORAGE		7 DAY CURE, 14 DAY AIR STORAGE		7 DAY CURE, 21 DAY AIR STORAGE		7 DAY CURE, 28 DAY AIR STORAGE	
READING DESCRIPTION	Initial	Zero	7 Days		14 Days		21 Days		28 Days	
Specimen	Comparator Reading	Comparator Reading	Comparator Reading	Length Change	Comparator Reading	Length Change	Comparator Reading	Length Change	Comparator Reading	Length Change
A	5.366	5.366	5.360	0.002%	5.346	0.008%	5.338	0.011%	5.338	0.011%
B	1.648	1.650	1.644	0.002%	1.624	0.010%	1.612	0.015%	1.612	0.015%
C	3.212	3.214	3.210	0.002%	3.190	0.010%	3.174	0.016%	3.168	0.018%
AVERAGE		3.410	3.405	0.002%	3.387	0.009%	3.375	0.014%	3.373	0.015%

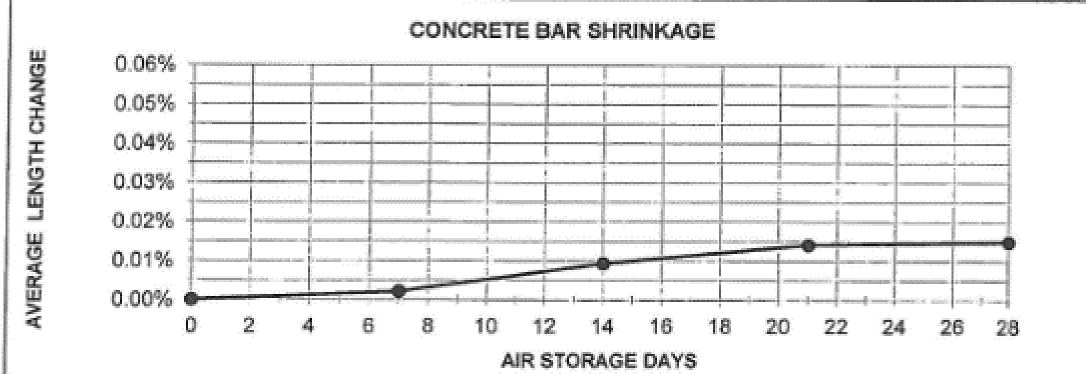


FIGURE 1

American Engineering Testing, Inc.
601 E. 48th St. N.
Sioux Falls, SD 57104
Phone: (605) 332-5371 | Toll Free: (800) 972-6364
Email: bcard@amengtest.com
www.amengtest.com

Material Test Report

Report No: MAT:19-01658-S7
Issue No: 1

Client: SPENCER QUARRIES **CC:**

Project: SPENCER QUARRIES PRODUCTION
SPENCER, SD
PO BOX 25

Job No: 32-02490

Date of Issue: 2/22/2019
Reviewed By: Scott Dumdei

Sample Details

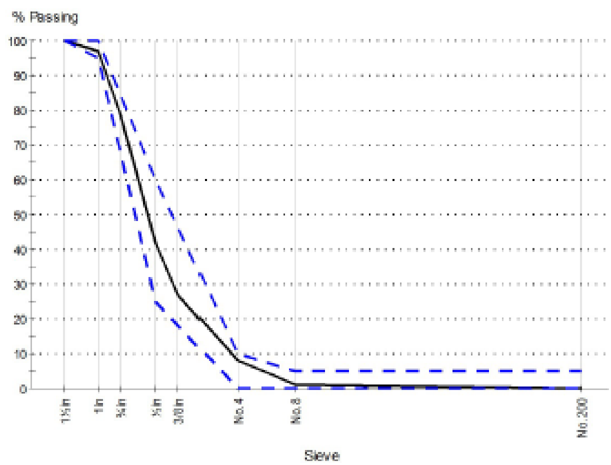
Sample ID	19-01658-S7
Field Sample ID	Class A Rock
Date Sampled	1/31/2019
Source	Spencer Quarries
Material	Class A Coarse Aggregate
Specification	C33 CA SIZE 57 (W/ #200)
Sampling Method	Sampled by Client
General Location	Spencer, SD
Location	Spencer Quarries
Date Submitted	2/22/2019

Other Test Results

Description	Method	Result	Limits
Mass of Test Sample (g)	ASTM C 123	1855.5	
Nominal Size of Aggregate (in)		1	
Type of Heavy Liquid		Zinc Chloride	
Heavy Liquid Specific Gravity		1.95	
Lightweight Particles (%)		0.0	
Date Tested		2/1/2019	

Particle Size Distribution

ASTM C 136, ASTM C 117



Date Tested: 2/1/2019
Tested By: Scott Dumdei

Sieve Size	% Passing	Limits
1½in (37.5mm)	100	100
1in (25.0mm)	97	95 – 100
¾in (19.0mm)	79	
½in (12.5mm)	42	25 – 60
3/8in (9.5mm)	27	
No.4 (4.75mm)	8	0 – 10
No.8 (2.36mm)	1	0 – 5
No.200 (75µm)	0	0 – 5

Comments

N/A

American Engineering Testing, Inc.
601 E. 48th St. N.
Sioux Falls, SD 57104
Phone: (605) 332-5371 | Toll Free: (800) 972-6364
Email: bcard@amengtest.com
www.amengtest.com

American Engineering Testing, Inc.

Material Test Report

Report No: MAT:19-01658-S7
Issue No: 1

Client: SPENCER QUARRIES **CC:**

Project: SPENCER QUARRIES PRODUCTION
SPENCER, SD
PO BOX 25

Job No: 32-02490

Date of Issue: 2/22/2019
Reviewed By: Scott Dumdei

Other Test Results

Description	Method	Result	Limits
Specific Gravity (OD)	ASTM C 127	2.63	
Specific Gravity (SSD)		2.64	
Apparent Specific Gravity		2.65	
Absorption (%)		0.3	
Density Determined Without First Drying?		No	
Additional Notes			
Date Tested		2/5/2019	
Nominal Aggregate Size (mm)	ASTM C 131	25.0	
Loss by Abrasion and Impact (%)		13	≤50
Grading Designation		B	
Date Tested		2/4/2019	
Bulk Density (lb/ft³)	ASTM C 29	101	
Bulk Density (SSD) (lb/ft³)		102	
Voids (%)		38	
Filling Procedure		Rodding	
Date Tested		2/5/2019	
Bulk Density (lb/ft³)	ASTM C 29	96	
Bulk Density (SSD) (lb/ft³)		96	
Voids (%)		42	
Filling Procedure		Shoveling	
Date Tested		2/5/2019	
Test Type	ASTM C 88	Coarse	
Preparation			
Solution Type		Sodium Sulfate	
Plus Number 4 (%)		92	
Total Weighted Coarse Loss (%)		0	
Date Tested		2/15/2019	
Retaining Sieve	ASTM D 5821	4.75mm	
Total Mass of Sample (g)		3500.0	
Fracture Criteria		1FF	
Fractured Particles (%)		100	
Method		Mass	
Date Tested		2/4/2019	

Comments

N/A

SPENCER QUARRIES, INC
Rock Gradation
25341 430th Ave. Spencer, S.D. 57374
Cell: 605-999-2590
Ph. 605-246-2344
Fax. 605-246-2362

Man Sand

2019

sieve size	15-Apr 1	23-Apr 2	3	4	5	6	7	8	9	10	11	12	13	AVG.	sieve size
2															2
1 1/2															1 1/2
1 1/4															1 1/4
1															1
3/4															3/4
5/8															5/8
1/2															1/2
3/8															3/8
1/4															1/4
#4	100	100	100	100	100	100	100	100	100	100	100	100	100	100	#4
8	93	91												92	8
10	88	84												86	10
16	76	66												71	16
20															20
30															30
40	52	39												45	40
50	36	28												32	50
80															80
100															100
200	1.0	1.3												1	200
L.L.															L.L.
P.I.															P.I.
+ 4 Lt.Wt.															+ 4 Lt.Wt.
- 4 Lt.Wt.															- 4 Lt.Wt.
% CRSH															% CRSH

CESARE, INC.
Geotechnical Engineers & Construction Materials Consultants

July 2, 2018

Mr. Mark Ewald
Trinity Lightweight LLC
11728 Highway 93
Boulder, CO 80303

Subject: Trinity Lightweight
ASTM C1761 Lightweight Fine Aggregate
Aggregate Qualification Testing
Lab ID F185061
Project No. 18.091

Dear Mr. Ewald:

This letter presents the results of laboratory tests performed on representative samples of the subject aggregate obtained from Trinity Lightweight facility in Boulder, Colorado. Samples were obtained and transported to Cesare, Inc.'s (Cesare) facilities by Trinity Lightweight representatives in May 2018. The following tests were performed in accordance with ASTM standard test methods (as modified by ASTM C1761, if applicable) and the results are presented in association with the relevant ASTM criteria:

1) Organic Impurities (ASTM C40)
2) Iron Staining Materials (ASTM C641)
3) Loss on Ignition (ASTM C114)
4) Clay Lumps and Friable Particles (ASTM C142)
5) Sieve Analysis (ASTM C136)
6) Loose Bulk Density (Dry) (ASTM C29)
7) Relative Density (Specific Gravity) (ASTM C128)
8) 72-hour Absorption and Desorption (ASTM C1761)

The results of testing indicate the material complies with the criteria presented for the requested testing. A summary of laboratory test results follows. Please contact us with any questions.

Sincerely,
CESARE, INC.

Ryan A. Zoetewey
Construction Materials Quality Assurance

Erin R. Arndt, P.E.
Senior Project Manager

BBR/ksm

Attachments

18.091 Trinity Lightweight Aggregate Qualification Letter ASTM C1761 Fine Aggregate 07.02.18

Corporate Office: 7108 South Alton Way, Building B • Centennial, CO 80112
Locations: Centennial • Frederick • Silverthorne • Crested Butte/Salida
Phone 303-220-0300 • www.cesareinc.com

CESARE, INC.

SUMMARY OF LABORATORY TEST RESULTS

Trinity Lightweight ESC - Boulder, CO

ASTM C1761 Lightweight Fine Aggregate

Lab ID F185061

Chemical Composition

Organic Impurities (ASTM C40)

Color Plate	ASTM C40
1	≤ Plate 3 (Standard)

Iron Staining Materials (ASTM C641)

Stain Index	ASTM C1761 Criteria
< 20	< 60

Loss on Ignition (ASTM C114)

% Loss	ASTM C1761 Criteria (%)
0.19	≤ 5

Physical Properties

Clay Lumps & Friable Particles (ASTM C142)

% dry mass	ASTM C1761 (%)
1	≤ 2

Loose Bulk Density (Dry) (ASTM C29)

Density (lb/ft^3)	ASTM C1761 (lb/ft^3)
57	≤ 70

Grading (ASTM C136)

Sieve size	Passing (%)	ASTM C1761 Table 1 Fine aggregate (%)
1/2 inch (12.5 mm)	100	
3/8 inch (9.5 mm)	100	100
#4 (4.75 mm)	100	65 to 100
#8 (2.36 mm)	92	
#16 (1.18 mm)	57	15 to 80
#50 (0.30 mm)	21	0 to 35
#100 (0.30 mm)	16	0 to 25
#200 (0.30 mm)	13.8	
Fineness Modulus	2.14	--

Specific Gravity and Absorption (ASTM C128)

Bulk specific gravity (oven dry)	1.64
Bulk specific gravity (SSD)	1.95
Apparent specific gravity	2.39
Absorption (%)	19.2

Absorption and Desorption (ASTM C1761 Section 10 and Section 11)

Property	Result	Criteria
72-hour Absorption	23.7	>5%
Desorption at 94% humidity	86.1	>85%

Aggregate Qualification Testing Summary C1761 Fine

BORAL RESOURCES

Materials Testing & Research Facility
2650 Old State Hwy 113
Taylorsville, GA 30178
770-684-0102

ASTM C618 / AASHTO M295 Testing of Coal Creek Station Fly Ash

Sample Date:	9/1 - 9/30/20	**Report Date:**	11/17/2020
Sample Type:	Monthly	**MTRF ID:**	2082CC
Sample ID:	MnDOT Split		

Chemical Analysis	**Results**		**ASTM Limit Class F / C**	**AASHTO Limit Class F / C**
Silicon Dioxide (SiO2)	51.30	%		
Aluminum Oxide (Al2O3)	15.02	%		
Iron Oxide (Fe2O3)	6.33	%		
Sum (SiO2+Al2O3+Fe2O3)	72.65	%	50.0 min	50.0 min
Sulfur Trioxide (SO3)	0.82	%	5.0 max	5.0 max
Calcium Oxide (CaO)	13.83	%	18.0 max / >18.0	18.0 max / >18.0
Magnesium Oxide (MgO)	4.35	%		
Sodium Oxide (Na2O)	3.73	%		
Potassium Oxide (K2O)	2.21	%		
Sodium Oxide Equivalent (Na2O+0.658K2O)	5.18	%		
Moisture	0.04	%	3.0 max	3.0 max
Loss on Ignition	0.16	%	6.0 max	5.0 max
Available Alkalies, as Na2Oe	1.88	%	Not Required	1.5 max* *when required by purchaser

Physical Analysis				
Fineness, % retained on 45-µm sieve	18.77	%	34 max	34 max
Fineness Uniformity	3.28	%	±5 max	±5 max
Strength Activity Index - 7 or 28 day requirement				
7 day, % of control	78	%	75 min	75 min
28 day, % of control	84	%	75 min	75 min
Water Requirement, % control	94	%	105 max	105 max
Autoclave Soundness	0.00	%	0.8 max	0.8 max
Density	2.60	g/cm3		
Density Uniformity	1.03	%	±5 max	±5 max

Christy Sieg
Lab Manager

AASHTO ACCREDITED

Appendix C: Concrete Mix Design Sample Calculations

Concrete mix aggregate moisture content adjustment process [Mix 1 Baseline w/o fly ash (FA)]

$C_{agg} := 125.43\ lb$ Initial weight of coarse aggregate

$F_{agg} := 102.46\ lb$ Initial weight of fine aggregate

$Cement := 43.459\ lb$ Weight of cement in mix

$Water := 17.3838\ lb$ Initial weight of mixing water

Determining moisture content of the coarse aggregate

$CA_{ssd} := 2.189\ lb$ weight of aggregate before drying in oven at 110 C

$CA_{od} := 2.186\ lb$ weight of aggregate after drying

$$MC_{CA} := \left(\frac{CA_{ssd} - CA_{od}}{CA_{od}}\right) \cdot 100 = 0.1372$$ Moisture content as a percentage

$$MC_{Ca} := \left(\frac{CA_{ssd} - CA_{od}}{CA_{od}}\right) = 0.001372$$ Moisture content as a decimal

Determining moisture content of fine aggregate

$FA_{ssd} := 2.062\ lb$ weight of aggregate before drying in oven at 110 C

$FA_{od} := 2.001\ lb$ weight of aggregate after drying

$$MC_{Fa} := \left(\frac{FA_{ssd} - FA_{od}}{FA_{od}}\right) = 0.03048$$ Moisture content as a decimal

$$MC_{FA} := \left(\frac{FA_{ssd} - FA_{od}}{FA_{od}}\right) \cdot 100 = 3.048$$ Moisture content as a percentage

Determining adjustment amount of mixing water based on MC of aggregates

$AC_{CAgg} := 0.005$ Absorption capacity of coarse aggregate

$AC_{FAgg} := 0.012$ Absorption capacity of fine aggregate

$CA_{free\_water} := \left(MC_{Ca} - AC_{CAgg}\right) \cdot C_{agg} = -0.455\ lb$

Moisture content of the coarse aggregate minus the absorption capacity times the initial weight of the aggregate

$FA_{free\_water} := \left(MC_{Fa} - AC_{FAgg}\right) \cdot F_{agg} = 1.894\ lb$

Moisture content of the fine aggregate minus the absorption capacity times the initial weight of the aggregate

$CA_{free\_water} + FA_{free\_water} = 1.439\ lb$

Weight of water that needs to be added or removed from batch water

$Free\_water_{CA} :=$ if $MC_{Ca} < AC_{CAgg}$
‖ "Add water to mix"
else if $MC_{Ca} > AC_{CAgg}$
‖ "Remove water from mix"

= "Add water to mix"

$Free\_water_{FA} :=$ if $MC_{Fa} < AC_{FAgg}$
‖ "Add water to mix"
else if $MC_{Fa} > AC_{FAgg}$
‖ "Remove water from mix"

= "Remove water from mix"

Mixing water corrected for aggregate moisture, adding water from coarse aggregate since its moisture content is lower than the absorption capacity and subtracting water from the fine aggregate since its moisture content is higher than the absorption capacity

$Water_{adj} := Water - CA_{free\_water} - FA_{free\_water} = 15.945\ lb$

Adjusting aggregate weight based on the moisture contents

$$C_{agg\_adjustment} := C_{agg} \cdot \left(\left(MC_{Ca} - AC_{CAgg} \right) \right) = -0.455\ lb$$

$$C_{agg\_adj} := C_{agg} + C_{agg\_adjustment} = 124.97\ lb$$

$$F_{agg\_adjustment} := F_{agg} \cdot \left(\left(MC_{Fa} - AC_{FAgg} \right) \right) = 1.894\ lb$$

$$F_{agg\_adj} := F_{agg} + F_{agg\_adjustment} = 104.35\ lb$$

$$Mix_{wt\_initial} := C_{agg} + F_{agg} + Cement + Water = 288.733\ lb$$

$$Mix_{wt\_final} := C_{agg\_adj} + F_{agg\_adj} + Cement + Water_{adj} = 288.733\ lb$$

Final mix design weights

$C_{agg\_adj} = 124.97\ lb$ $Water_{adj} = 15.945\ lb$

$F_{agg\_adj} = 104.35\ lb$ $Cement = 43.46\ lb$