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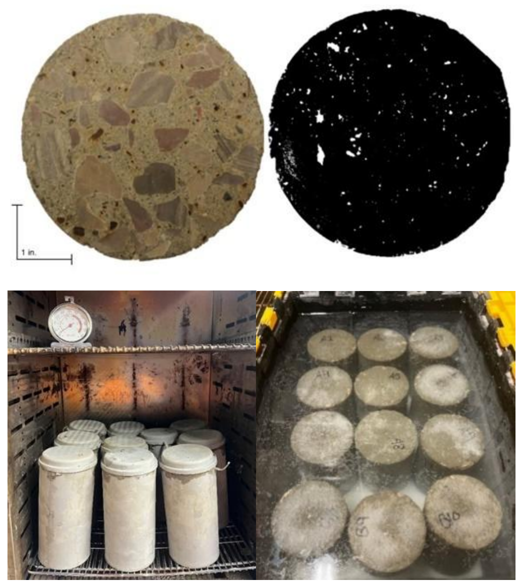

Investigation of Poor Compressive Strength and Performance of A45 Structural Concrete Mixes

Study SD2022-03

Final Report

Prepared by

South Dakota School of Mines and Technology

Rapid City, SD 57701

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This work was performed under the direction of the SD2022-03 Technical Panel:

Thad Bauer .... Research

Hadly Eisenbeisz .... Bridge Design

John Gerlach .... Operations

Darin Hodges .... Materials and Surfacing

Micah Howard .... Materials and Surfacing

Keld Ditlev .... SDRMCA

Jay Larson .... Operations

Jill Rotherham .... SDSM&T

Chris Shearer .... SDSM&T

Jason Smith .... Operations

Kirk Van Roekel .... FHWA

Andy Vandel .... Research

Steve Weisz .... Operations

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16. Abstract

In the five years leading up to the 2022 construction season, the South Dakota Department of Transportation (SDDOT) observed an increasing failure rate for their A45 structural concrete mixes, with mixes failing to meet the 4500psi compressive strength requirement. The sources of low compressive strength concrete tests identified by SDDOT were investigated through a literature review, a statistical analysis, a review of historical test data, interviews with concrete technicians, and a survey to concrete suppliers and other state DOTs. The effects of changing water content, air content, materials, curing conditions, and processing variables were assessed on concrete by measuring fresh properties, compressive strength, and bulk resistivity. Furthermore, a forensics and petrographic assessment was performed on cored samples for low strength concrete in the field. Correlations were found between increased air contents and higher ambient temperatures and increased strength failures when analyzing historical data. Interviews with SDDOT technicians found discrepancies between practice and specification in the areas of testing frequency, the transportation and handling of cylinders, and fresh concrete cylinder temperature control. Field testing revealed higher curing temperatures than allowed by specification. A nationwide DOT survey concluded that while there is not a single perceived reason for their low strength issues, specimen handling and extreme temperatures appear to be significant contributors. Experimental results showed that significantly lower compressive strengths were correlated with higher air content, higher curing temperatures, retempering at high temperatures, higher w/cm, and the use of a different coal ash. Changing these variables, especially in combination, resulted in 28-day compressive strengths lower than 4500psi indicating that the current A45 structural concrete specification can result in strength failures. Bulk resistivity of the concrete was less affected by these changing variables. The specifications should be updated to address issues including re-qualifying mix design strengths for higher air contents and incentivizing lower air contents on hot days, better quality control for batch plant and in-field concrete adjustments and fresh concrete curing procedures, changing the acceptance procedure for 28-day strength to require three cylinders, and more strictly enforcing and changing the mix design qualification procedures.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

TABLE OF ACRONYMS

Acronym	Definition
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AEA	Air Entraining Admixture
ASR	Alkali Silica Reactivity
ASTM	American Society for Testing and Materials
DOT	Department of Transportation
f'c	Compressive Strength of Concrete
HRWR	High Range Water Reducer
ITZ	Interfacial Transition Zone
MnDOT	Minnesota Department of Transportation
MSTR	Minimum Sample and Test Requirement
NDOT	Nebraska Department of Transportation
PCC	Portland Cement Concrete
PCN	Project Control Number
pcy	Pounds per Cubic Yard
PI	Principal Investigator
PLC	Portland Limestone Cement
psi	Pounds per Square Inch
QC	Quality Control
RFP	Request for Proposal
SDDOT	South Dakota Department of Transportation
SCM	Supplementary Cementitious Materials
SEM	Scanning Electron Microscope
STDEV	Standard Deviation
W/CM	Water Cementitious Ratio

1.0 EXECUTIVE SUMMARY

1.1 Problem Description

Structural concrete mixes in recent years have not met specified compressive strengths. In particular, the A45 structural concrete mixes (which require a compressive strength of 4500 psi at 28-days) have had numerous low strength measurements categorized as “remove and replace”. This has increased the risk for the SDDOT on future projects. It has also increased the risk for contractors and concrete producers, who have noted that maintaining and achieving quality concrete performance has been difficult using the prescriptive A45 specification. However, the exact cause of these low strength and poor performance mixes remains a mystery. It has been speculated that they could be a result of materials issues (e.g, cement, fly ash, admixtures, aggregates, etc.) or could be due to mix designs that are not valid for the currently used materials. Furthermore, the processing of the concrete including batching, delivery, placement, and curing methods could also be contributing factors to the issue. The handling of cylinders and testing methods for strength also potentially influence strength results. The potential issues causing low strength are wide ranging, but this investigation was able to determine the major contributing factors. This research worked to systematically determine the cause or causes of the low strength that has been frequently observed by the SDDOT.

1.2 Literature Review, Historical Data Analysis, and Surveys

Low strength of concrete cylinders can be caused by many factors including water cementitious ratio, admixture type, cementitious material type, fresh concrete and curing temperatures, and handling and testing procedures among other reasons. An analysis of historical SDDOT strength data from the past six years revealed that certain concrete producers, materials suppliers (sand and admixture sources), higher fresh concrete and ambient temperatures, and higher air content in the concrete were correlated with more strength failures. Interviews with six technicians based throughout the state provided insight into how the test cylinders are prepared and tested. Discrepancies between practice and specification included testing frequency using time intervals instead of specified concrete volumes, temperature control during fresh concrete curing, and transportation handling including vibration control. A survey sent to SDDOT concrete suppliers produced limited results with only two suppliers responding. These two suppliers acknowledged low strength testing issues but were unsure as to the cause. A national survey of DOTs indicated that while most agencies experience occasional low strength tests, no other responding DOT is overly concerned nor has experienced similar low strength issues at the same magnitude as SDDOT. The survey concluded that while there is not a single targeted reason for low strength issues, specimen handling and extreme temperatures appear to be a large contributor to low strength tests.

1.3 Materials and Methods

The experimental plan tested a suite of concrete variables to measure their influence on compressive strength including: 1) w/cm ratio, 2) entrained air content, 3) fresh concrete temperature, 3) curing temperature, 4) aggregate moisture content adjustment, 5) retempering, and 6) different materials. Additionally, fresh concrete properties (i.e., setting time, air content, slump, unit weight) and bulk electrical resistivity were measured.

1.4 Results and Discussion

Changing certain mix designs and processing variables, especially in combination, resulted in 28-day compressive strengths lower than 4500 psi indicating that the A45 mix design has the potential to result in strength failures. Air content significantly reduced compressive strength especially at the upper allowed limit of 8%. The use of a higher w/cm and a different coal ash also significantly reduced strength while using different aggregate and admixture combinations increased strength. This finding highlights the impact of materials and mix design on strength. An investigation into SDDOT concrete cylinder's initial curing temperatures found that the temperature within the curing cooler was higher than allowed by SDDOT specification for every sample monitored. A high curing temperature for the cylinders resulted in significant strength reduction for a range of mix designs highlighting the importance of standardizing curing conditions for fresh concrete and improving quality control of these conditions to properly assess strength. Fresh concrete made at high temperatures or with retempering alone did not appear to significantly change strength values, but the combination of the two did result in a significant strength reduction. Bulk resistivity of the concrete was less affected by these changing variables. A forensics analysis for low strength concrete in the field indicated that high air content and large air voids on the surface of the aggregates might have been a cause of the strength failure. However, these results were not corroborated by a petrographic examination conducted by a separate lab, which found that an elevated water-cementitious materials ratio was the reason for the low strength.

1.5 Recommendations

Based on the experimental results in combination with the literature review, historical data analysis, and surveys, it is recommended that the SDDOT:

1.5.1 Change the SDDOT Standard Specification for Roads and Bridges to re-qualify mix designs for higher air contents and incentive lower entrained air contents

The SDDOT should update the SDDOT Standard Specification for Roads and Bridges to (1) re-qualify mix designs such that the air content of each trial batch shall be +1.0% to -0.5% of the maximum specified value of 8% and (2) incentivize concrete producers to target air contents lower than 7%, especially on hot days with air temperatures greater than 80 °F.

1.5.2 Implement improved quality control measures for batch plant and in-field concrete adjustments and fresh concrete curing procedures

The SDDOT should improve the quality control measures in the SDDOT Standard Specification for Roads and Bridges to (1) change the curing method for cylinders in the first 24 hours to maintain temperatures between 60-80 °F, (2) prohibit retempering of concrete if the air temperature is forecast to be above 80 °F, (3) for retempered mixes, ensure that on-site water additions are recorded to verify maximum w/cm are not exceeded and verify additional mixing requirements are met, and (4) implement improved quality control guidelines for concrete producers on aggregate moisture content adjustments.

1.5.3 Change the acceptance procedure for 28-day compressive strength

The SDDOT should update the SDDOT Standard Specification for Roads and Bridges for 28-day compressive strength qualification to require the average of three consecutive strength tests to be equal or exceed the f'c requirement (4500psi) and no individual strength test can fall below the f'c by more than 500 psi.

1.5.4 Modify and strictly enforce Section 460.3 in the SDDOT Standard Specification for Roads and Bridges regarding mix design qualification

The SDDOT should ensure that the mix design qualification procedures provided in the SDDOT Standard Specification for Roads and Bridges are strictly enforced. Furthermore, these procedures could be modified to (1) require a bi-annual mix design qualification, (2) add 56-day compressive strength testing, and (3) require mix designs that have failed strength more than once in the field over a period (e.g., three months) to be re-qualified.

(Note to technical panel: we request guidance on this section since we don't know how strictly this portion of the specification is enforced).

The recommended specification changes should reduce the number of strength failures observed by SDDOT. Statistically there will still be strength failures even if these recommendations are implemented. Otherwise, the concrete will be overdesigned for strength, which is not desirable for numerous reasons including higher cost, reduced sustainability, and potential durability issues.

2.0 PROBLEM DESCRIPTION

Structural concrete mixes in recent years have not met specified compressive strengths. In particular, the A45 structural concrete mixes (which require a compressive strength of 4500 psi at 28-days) have had numerous low strength measurements categorized as “remove and replace”. This has increased the risk for the SDDOT on future projects. It has also increased the risk for contractors and concrete producers, who have noted that maintaining and achieving quality concrete performance has been difficult using the prescriptive A45 specification.

However, the exact cause of these low strength and poor performance mixes remains a mystery. It has been speculated that they could be a result of materials issues (e.g, cement, fly ash, admixtures, aggregates, etc.) or could be due to mix designs that are not valid for the currently used materials. Furthermore, the processing of the concrete including batching, delivery, placement, and curing methods could also be contributing factors to the issue. The handling of cylinders and testing methods for strength also potentially influence strength results.

The potential issues causing low strength are wide ranging, but this investigation should be able to determine the major contributing factors. This research will work to systematically determine the cause or causes of the low strength that has been frequently observed by the SDDOT. The results of this research will result in changes to the specifications to prevent this issue from happening in the future.

3.0 RESEARCH OBJECTIVES

Objective 1. Determine the factors contributing to the significant increase in instances of below-specification strength A45 structural concrete observed in recent construction years.

Objective 1 was accomplished by a review of published data and interviews from a variety of sources including SDDOT, other state DOTs, contractors, concrete producers, technicians, and literature in leading scientific journals. This informed the experimental testing plan, which entailed both laboratory testing of variables of interest and a petrographic analysis on concrete core samples. The primary factors that contributed to the below specification strength were identified from this process.

Objective 2. Recommend changes to current practice (handling, placement, testing, mix design) to reduce future instances of below-specification strength A45 structural concrete following placement in the field.

Following the completion of Objective 1, recommended changes to the current practice were provided for SDDOT to implement with the goal of reducing future low strength failures of A45 structural concrete. The changes were based on the results of the data review and experimental components of this research project.

4.0 TASK DESCRIPTIONS

Work was performed to complete the two research objectives via the following 12 research tasks outlined in the RFP. Each of the 12 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 (September 15, 2022), the researcher met with the technical panel to discuss the project scope, schedule, budget, and goals. This meeting included a review of the RFP and this proposal. This meeting clarified the contractual obligations of SDDOT and South Dakota Mines for the project.

Task 2. Review and summarize literature on factors contributing to proper concrete strength development, and report on any known mechanisms that may inhibit the achievement of specified concrete strength, where they result from materials and mix design; the field conditions in which concrete is prepared, placed and cured; or other factors.

An extensive search through cement and concrete literature was performed. The review included results of previous research studies on how different concrete attributes or mechanisms were observed to cause low strength results. This included curing temperature, curing methods, mix design variations, field conditions, testing, and handling. Previous SDDOT research on the influence of air-entraining admixtures on strength properties was also reviewed.

Task 3. Develop respective survey instruments for distribution to surrounding state DOTs, South Dakota concrete producers, and testing firms to (a) collect information on their experiences with below strength structural concrete; (b) compare surrounding state DOTs' structural concrete mix designs, allowed materials, testing/acceptance practices, and required compressive strengths to those of SDDOT; and (c) understand the extent to which failures observed by contractors have been isolated to SDDOT projects.

In collaboration with SDDOT, a survey was sent to all 50 state DOTs and some Canadian agencies as well to gather insights on whether they have experienced similar low strength concrete. Questions on their specific mix designs, required compressive strengths, and any observed strength failures were also asked. Twenty-two DOTs and one Canadian agency responded. The questions and their answers can be found in Appendix E. An anonymous survey was also sent out to multiple DOT concrete producers throughout South Dakota to receive feedback on their experiences with below strength structural concrete, quality control protocols, and potential strategies for reduction of failed tests. Two producers responded and their answers can also be found in Appendix E.

Task 4. Collect and analyze SDDOT project data associated with instances of below specification strength A45 structural concrete.

The SDDOT provided project data of every project from 2017-2022 that had at least one failed cylinder batch. Through various data analysis methods, numerous parameters were compared to their corresponding concrete batch test to determine how that parameter historically affected concrete strength. The parameters that correlated with low compressive strength were noted for potential attributes to test during lab testing.

Task 5. Prepare and present to the project's technical panel a technical memorandum summarizing the literature review, survey results, and review of SDDOT project data; and reporting any likely factors contributing to the observed low A45 structural concrete compressive strengths.

A technical memorandum reporting the results of Tasks 2-4 was submitted on August 9, 2023. Findings from these tasks were presented to the project technical panel on August 17, 2023. The panel collaborated with the PI and graduate student to discuss the results of the literature review and SDDOT historical data analysis. A revised memo was submitted in March 2024.

Task 6. Develop a laboratory testing plan that (a) uses petrographic analysis and other characterization techniques to examine concrete cores (including those from below strength SDDOT projects) to seek a root cause of poor structural concrete strength and (b) evaluates structural concrete compressive strength and durability as a function of the variables of interest identified in the literature review, survey, and analysis of past project data (e.g., material types, mix design variables, construction practices, curing methods, field conditions, cylinder test procedures).

Based upon findings from Task 1-5, a laboratory testing plan to further investigate the low strength issues was completed. This involved a two-pronged approach: (1) analyzing concrete cores from poor structural concrete strength projects and (2) evaluation of concrete compressive strength and durability in the lab.

Task 7. Prepare and present to the project's technical panel a technical memorandum detailing the laboratory testing plan developed in Task 6.

The PI and the graduate student submitted the initial mix designs based on the findings of Task 6 to the technical panel on January 22, 2024. A presentation and discussion of the proposed mix designs and testing plan occurred on February 26, 2024. This informed the selection of final mix designs to be tested in the lab. A revised and finalized second technical memorandum was submitted to the panel on March 7, 2024.

Task 8. Upon panel approval of the test plan, conduct lab testing, leveraging any early findings to select SDDOT projects from the present construction season for inclusion in lab testing (via mix design or testing of core samples from the field).

The finalized 13 mix designs were tested in accordance with recommendations from the technical panel.

Task 9. Prepare and present to the project's technical panel a technical memorandum summarizing the results of the Task 8 lab testing.

The third technical memorandum reporting the lab testing results was submitted on July 5, 2024. Findings were presented to the project technical panel on July 8, 2024. All collected data was analyzed using statistical methods to determine the significance of the impact of mix design parameters on the concrete’s 7-, 14-, and 28-day compressive strength. Using the results of this analysis in conjunction with literature review results, the concrete attributes that affected the compressive strength most were determined and reported. A revised memo was submitted on August 12, 2024.

Task 10. Recommend changes to SDDOT practice to reduce instances of below specification structural concrete strength.

The PI submitted the final report, which reported the recommended changes to SDDOT, on June 1, 2025.

Task 11. 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 June 1, 2025.

Task 12. 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 SDDOTs Research Review Board on January 29, 2025. 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

5.1.1 Strength Affecting Parameters

The compressive strength of concrete is an important measured property that must satisfy structural engineering requirements. It is also used as an indicator of the quality of a concrete mix. The factors that control the compressive strength of hardened portland cement concretes are numerous and can be seen in Table 1. Fundamentally, concrete strength is inversely proportional to the porosity of the matrix. Therefore, any factors that can affect concrete porosity will affect compressive strength. These factors are described throughout this section. Concrete is also a composite material, which is a synthesis of multiple materials with different strength properties. The weakest phase within the composite material will influence its overall strength. With the use of quality aggregates, the cement paste, as well as the interfacial transition zone (ITZ) between the paste and the aggregate, are usually the phases that primarily determine strength properties (Mehta and Monteiro, 2014).

Table 1: Parameters affecting concrete strength

Parameter	Strength Affecting Factors
Water/Cementitious Ratio	• Most significant strength affecting parameter • Increased w/cm ratios result in increased porosity of the cement paste and the ITZ between the matrix and the aggregate, lowering the strength
Degree of Hydration (Curing Time, Temp., Humidity)	• Longer curing periods result in higher strength • Higher curing temperatures have mixed results on early- and late-age strength gain
Air Content (Entrapped or Entrained)	• Increases porosity which decreases strength • Can result in air void clustering at aggregate interface
Aggregate	• Aggregate porosity, size, shape, surface texture, grading, and mineralogy all affect strength although to a lesser extent compared to other parameters. For example, flat and elongated particles are easily fractured and can affect water demand. Further, the grading of an aggregate can increase or decrease the paste demand and workability of the mix affecting water demand.

Parameter	Strength Affecting Factors
Cement Type	A variety of cement exists to target specific cement goals/requirements and have differing strength effects: • Type IL – Portland-Limestone Cement • Type I – General Purposes • Type II – Moderate Sulfate Resistance • Type III – High Early Strength • Type IV – Low Heat of Hydration • Type V – High Sulfate Resistance
Admixtures	• Varies depending on the admixture, which can result in either an increase or decrease in strength
Capillary Porosity	• Inversely proportional to strength
Loading Parameters	• Rate of stress application will also affect strength
Dimension of Test Specimen	• Inversely proportional to a cylinder's height/diameter ratio
Geometry of Test Specimen	• Cubes have a higher compressive strength than cylinders made of same mix
Other	• Bleeding characteristics • Degree of consolidation • Chemical interaction between the aggregate and cement paste • Moisture state • Coal ash properties • Handling of samples

Influence of Concrete Materials and Mix Design on Compressive Strength

The common material components of concrete include cement, coal ashes, water, coarse aggregate, fine aggregate, and a range of admixtures (i.e., air-entrainment, water reducers, set modifiers, and many others). Table 2 displays the specifications for these components as found in the SD Standard Specifications for Roads and Bridges. The cement type will directly affect strength development, and the introduction of Class F coal ash tends to reduce early-age strength. Although aggregates are typically not the source for low strength, their characteristics such as size, gradation, morphology, mineralogy, and texture can influence strength. For example, previous research for SDDOT by this research team noted that using the 0.45 power curve for gradation resulted in higher strength concrete (SD2018-04 Report, 2021).

Table 2: South Dakota accepted materials adopted from (SD Specifications, 2015)

Material	Section	Criteria
Cement	750	Portland Cement: - Type II cement shall be used, unless otherwise specified - Shall conform to AASHTO M 85 - Shall not have more than 0.60% Alkalis Portland-Pozzolan Cement: - Shall conform to AASHTO M 240 Type IL - When Type II cement is specified, it must meet MS requirements of AASHTO M 240 - When Type V cement is specified, it must meet HS requirements of AASHTO M 240
Fine Aggregate	800	- Shall consist of natural sand or other inert materials with similar characteristics - Fine aggregate from different sources shall not be mixed or stored in the same pile or used alternately in the same class of construction or mix - Max amount of all deleterious substances (specified in section) shall not exceed 2.0% by dry weight - Section includes additional sodium sulfate soundness test specifications - Section includes additional organic impurities specifications - Section includes additional Alkali-Silica Reactivity (ASR) specifications - Section includes additional gradation specifications - Section includes additional uniformity of grading specifications
Coarse Aggregate	820	- Shall consist of ledge rock - For Class A, coarse aggregate shall conform to the gradation requirements of Size #1, #15, or #20 as indicated on the mix design - Max amount of all deleterious substances (specified in section) shall not exceed 2.0% by dry weight - Percentage of wear, LA abrasion test, shall not be more than 40% by weight - Section includes additional sodium sulfate soundness test specifications - Section includes additional gradation specifications - The maximum amount of flat and elongated particles shall not exceed 10%
Water	790	- Shall be clean and free of oil, salt, acid, alkali, sugar, vegetation, effluent from sewage, or other substances - Total solids shall not exceed 50,000 parts per million

Material	Section	Criteria
Admixtures	751 and 752	Air-Entraining Admixtures: - 100% Vinsol Resin Based or listed on the Department's Approved Products List - Shall conform to AASHTO M 154 modified to: when entrained 5-7% air, the compressive strength at 7 days must be not less than 90% of the standard Chemical Admixtures - Shall conform to AASHTO M 194 - Shall be a non-chloride based material containing less than 1% chloride ion by weight of admixture
Curing Materials	821	Curing Blankets - Burlap cloth made from jute or kenaf shall conform to AASHTO M 182 - White Non-woven Polypropylene Geotextile Fabric may be used when in accordance to parameters listed in section Polyethylene Sheeting - Must be durable enough to withstand the intended job use - White is the standard but black can be used during cool weather Liquid Membrane Forming Compounds for Curing Concrete - Shall be either white pigmented (shall conform to ASTM C309 Type 2) or linseed oil base emulsion (shall conform to modified ASTM C309 Type 2 as laid out in section) Storage - Shall be stored at temperatures above 35°F

Material	Section	Criteria

Coal Ash	753	- Shall be from a base loaded electric generating plant using a single coal source
		- Limestone injection process using plants are not acceptable
		- Fly ash from the start up and shut down of the plant shall not be used
		Class C Coal Ash:
		- Shall conform to AASHTO M 295
		- Only allowed in grout for pavement jacking, undersealing, or when specified
		Class F, Modified Coal Ash:
		- Shall conform to AASHTO M 295 Class F including optional requirements expect as modified as follows:
		  - Loss on Ignition: 2.0% Maximum
		  - Moisture Content: 2.0% Maximum
		  - Available Alkalis as Na_2O: 1.5% Maximum
		- The silicon dioxide (SiO_2) shall be at least 40.0% by dry weight of the total coal ash composition
		- The total of silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) plus iron oxide (Fe_2O_3) shall be at least 66.0% by dry weight of the total coal ash composition

The quality of the mixing water can also influence concrete strength, particularly when impurities exist that cause the water to be acidic, alkaline, or salty. Furthermore, the use of admixtures can increase or decrease strength. For example, air-entrainment significantly reduces strength by directly increasing porosity. The rule of thumb is that a 1% increase in air content reduces the compressive strength (f'_c) by 5%. There can also be deleterious interactions between any of these materials, which has been an issue for the SDDOT in the past. For example, coal ash can interact with admixtures and reduce strength relative to a control. This can be seen specifically with Type V cement reacting with some water reducers affecting setting and strength gain parameters.

The mix design plays a large role in strength development. Perhaps the water-cementitious ratio (w/cm) has the greatest influence on strength, with lower water contents relative to cementitious materials resulting in higher strength if the mix remains workable. Furthermore, the blend of cementitious content and the ratio of paste to aggregate can also be influencing factors. The prescriptive nature of the A45 specifications as seen in Table 3 may result in mix designs that are not compatible with current materials to meet intended design objectives including strength. The mix design shown here is the current mix design specification for SDDOT's A45 concrete. This was updated on September 7th, 2022. Table 4 shows this prior mix design criteria. Some other DOTs use a less prescriptive approach to concrete specifications that allow producers to develop more adaptable mix designs. For example, Louisiana DOT follows a more performance- based approach in its concrete specification that does not prescribe a minimum or maximum cementitious or aggregate content. Rather they have

28-day strength requirements for a range of structural class mixes between 4500-10000 psi using a range of maximum w/cm ratios and slump values (Louisiana Specification, 2016).

Table 3: Concrete specification for A45 concrete (adapted from Supplemental Specification, 2022)

Minimum Cement Content[1] (lb/yd^3)	Max w/cm[3]	Slump[4] (in.)	Entrained Air Content[5] (%)	Minimum Coarse Aggregate Content[6] (%)	Minimum 28-day Compressive Strength (psi)
600	Field max. listed on mix design	1-5.5	5.0-8.0	50	4500
575 if well graded[2]	Field max. listed on mix design	1-5.5	5.0-8.0	50	4500

[1]The maximum cementitious content (total cement, coal ash, and other cementitious admixture) content will be 800 pounds per cubic yard. The Contractor will substitute a portion of the cement with Class F modified coal ash in accordance with Section 605 for all concrete used in bridge decks, bridge sidewalks, and barrier curbs. The amount of cement to be replaced will be 20% to 25% by weight. The ratio of substitution of coal ash to cement will be 1:1 by weight.

[2]Well graded concrete mixes are those mixes conforming to the aggregate gradation shown in Chart A for size #15 coarse aggregate or Chart B for size #20 coarse aggregate. Size #20 coarse aggregate will only be allowed when specified in the plans.

[3]The mix design will establish a maximum w/cm material ratio, which will not exceed 0.45.

[4]The slump of concrete used in bridge decks and bridge sidewalks poured with the bridge deck will be maintained between 2 and 4 inches at the time of placement. The slump of concrete used in cantilevered bridge deck sidewalks poured separately from the bridge deck will be maintained between 2 and 5½ inches at the time of placement.

[5]Concrete used in bridge decks, bridge sidewalks, and barrier curbs will contain 5.5% to 7.5% entrained air.

[6]The minimum coarse aggregate content is determined by the percent weight of the total aggregates.

Table 4: A45 mix design prior to 2022 update (adapted from South Dakota Specification, 2015)

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	0.45	1-4.5	5.0-7.5	55	4500
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 coal ash can replace between 20-25% by weight of cement

[2]0.45 power gradation is used to conform to a well graded concrete mix

Influence of Concrete Processing on Compressive Strength

The processing of the concrete including batching, delivery, placement, and curing methods also significantly affects the compressive strength. If batching at the plant does not match the intended mix design or if the delivery of the concrete is lengthy or experiences high temperatures, it could result in changes to strength. An example of this is when a mix must be retempered upon arrival to the job site. Retempering is when a portion of the mix's water is withheld during initial mixing at the concrete plant and then incorporated into the mix when at the job site. This can help with workability if the job site location is far from the concrete plant. However, incorrectly adjusting the water content for the moisture state of the aggregates can also result in workability and strength issues. Placement practices including using pumps or other methods to deliver concrete and consolidation techniques (e.g., vibration) will also impact in situ strength.

The concrete mixing procedure also determines the overall concrete quality and can affect its strength. For concrete completely mixed in the truck, the mixing rate is recommended to be kept within 70-100 revolutions at mixing speed (Structures Construction Manual, 2021). Concrete that is under mixed can cause segregation due to not being thoroughly combined which leads to low strength concrete. If it is over mixed, the percent of entrained air is reduced while the temperature of the concrete is raised. Additionally, overmixing reduces slump, increases water demand, and ultimately leads to lower strength. The concrete is also recommended to be placed and screeded within certain time frames as shown in Table 5 as provided in the Structures Construction Manual. If any of these listed times are exceeded, it is recommended that the load be rejected.

Table 5: Time limits for placing and screeding concrete

Condition	Temperature	Discharge Rate	Screed Time
Agitated/mixed in hauling units	Above 80°F	Within 45 min.	Within 60 min.
Agitated/mixed in hauling units	Below 80°F	Within 90 min.	Within 105 min.
Not agitated/mixed in hauling units	Above 80°F	Within 30 min.	Within 45 min.
Not agitated/mixed in hauling units	Below 80°F	Within 45 min.	Within 60 min.

Curing methods for concrete depend on several factors including materials, construction methods, placement conditions, and the intended purpose for the concrete. Normally, curing is performed by covering concrete with sheets or wet burlap depending on the setting characteristics or by applying curing compounds. The SDDOT states that the concrete surface shall be continuously kept wet, and the burlap or other curing material cannot cause discoloration or damage to the concrete surface. The main parameters that influence curing include time, humidity, and temperature. Concrete generally exhibits increased strength with time up to a certain age. Typically, most of a concrete's strength gain occurs prior to 90 days with often minimal changes after 90 days. Higher humidity during curing also significantly improves strength properties at early- and late-ages. A concrete's final strength can be expected to be greater if the samples were cured in a moist state for the first seven days versus only curing in a non humid state. Additionally, the strength often increases the longer the samples are cured in a moist curing environment. Lastly, cement hydration is slower when the concrete temperature is lower. It has also been observed that higher casting and curing temperatures results in higher early-age strength, but lower late-age strength.

Influence of Handling and Testing on Compressive Strength

Proper handling of concrete cylinders from the fresh to hardened state and the usage of the correct testing protocol is vital for accurately assessing the compressive strength for a batch of concrete. If not, the test results may not represent the in situ concrete strength properties. If the concrete cylinders are not prepared, stored, cured, and transported using appropriate procedures, it can significantly impact strength properties. For example, further consolidation and potential segregation can occur in cylinders with wet concrete during movement and storage.

Concrete strength is not an intrinsic material property because it strongly depends on the testing method. In the US, concrete strength is primarily tested in uniaxial compression using the standard test protocol described in ASTM C39 (2021), which allows for direct comparison of strength properties. The uniaxial compressive strength

results are influenced by specimen size, geometry, moisture state, and the stress rate. A cylinder's height to diameter ratio is the most significant of these factors. Specimens with height/diameter (h/d) ratios less than 1.5 can significantly increase compressive strength. A 4"x8" cylinder is expected to have an approximately 5% higher relative strength than a 6”x12” cylinder. Cylinders that are air dried tend to have 20-25% higher compressive strength compared to wet samples. Lastly, a higher stress loading rate will yield a higher compressive strength. Therefore, the ASTM C39 standardizes all these parameters, but if the standard is not properly followed the results could impact strength measurements.

ACI 214R-11 states that the causes that lead concrete cylinders to not meet strength requirements can be separated into two primary categories: (1) batch-to-batch or (2) within-batch variations. Batch-to-batch variations result from changes in each batch’s mix design which can include differences in ingredient proportions, mixing, transporting, placement, and curing. Within-batch variations result from sampling differences over how the individual samples are prepared, cured, handled, and tested.

Table 6 is adapted from Chapter 3 of the ACI 214R-11 and further explores each of these variations. Most of the conditions for the batch-to-batch variations were discussed previously, and the environments surrounding the within-batch variations will be explored in a later section.

Table 6: Principal sources of strength variation (adapted from ACI, 2011)

Within-Batch Variations	Batch-to-Batch Variations
Improper sampling from the batch sample. Variations due to fabrication techniques: • Substandard conditions • Incorrect tools • Poor quality, damaged, or distorted molds • Nonstandard molding and consolidation • Incorrect handling of fresh test samples Differences in curing: • Delays in beginning initial curing • Temperature variation • Variable moisture control • Nonstandard initial curing • Delays in bringing cylinders to the laboratory • Rough handling of cylinders in transport • Improper final curing Variations in sample testing: • Uncertified tester • Specimen surface preparation • Inadequate or uncalibrated testing equipment • Nonstandard loading rate • Poor record keeping	Variations in characteristics and proportions of ingredients: • Aggregates • Cementitious materials (including pozzolans) • Admixtures Changes in w/cm caused by: • Poor control of water • Variation of aggregate stockpile moisture conditions • Variable aggregate moisture measurements • Retempering Variations in mixing, transporting, and sampling: • Mixing time and speed • Distance between plant and placement • Road conditions • Failure to obtain a representative sample from the batch Variations in placing, and consolidation:* • Chute, pump, or buggy • Internal/external vibration • Different operators Variations in concrete temperature and curing:* • Time of year • Ambient humidity • Wind speed

*Applies to in-place strength of the structure.

Influence of Curing Temperature on Compressive Strength

The curing temperature of concrete can have both short-term and long-term effects on the strength of concrete. In this project, strength failures were primarily observed during the summer construction season at hotter temperatures, which will be the focus of this section. The American Concrete Institute (ACI) defines hot weather as any combination of high air temperature, low relative humidity, and wind velocities that can lead to abnormal concrete temperatures (ACI, 2020). In general, hot weather can lead to an increased slump loss, increased plastic-shrinkage cracking, decreased setting time, increased mixing water requirement for a given consistency, and it can create difficulty in maintaining air contents in an air-entrained mixture. Concrete that is cured at higher temperatures can develop higher early-age strength (prior to 28-days), but at later ages the strength is typically lower than if it were cured at a lower temperature (Mehta and Monteiro, 2014). However, if the temperature is too high there can be a decrease in strength even by 28-days. For example, it was found that if the initial 24-hr curing temperature is 100˚F, the 28-day strength may be 10-15% lower than if cured at the standard 60-80˚F (ACI, 2020).

One study analyzed the compressive strength of different concretes when mixed, placed, and cured at various temperatures from 25-120˚F and found that for Type I and II cements, the optimal casting and curing temperature during the early life (<1 month) of the concrete was 55˚F when assessing the impact on strength at later ages (>1 year). Tables 7 - 12 show the compressive strengths of concrete cast and cured at different temperatures. At 1-, 3-, and 7-days, the compressive strength increased with an increase in initial casting and curing temperatures. However, at 28-days, 3 months, and 1 year the strengths were found to be considerably lower at elevated cast and curing temperatures compared to samples cast and cured at 73˚F. Additionally, as the temperature increased, more air-entraining admixture was needed to maintain a constant amount of entrained air in the concrete mix (Klieger, 1958).

Fresh concrete can be cooled down by either using cooled mixing water or replacing the water with shaved or chipped ice. Due to the ice's ability to absorb heat, replacing the mixing water with ice is the most effective way to lower the concrete temperature. To cool the concrete during initial field curing of cast cylinders, cold water can be placed within the cooler if the cylinders are sealed to ensure water will not interact with the concrete. Additionally, technologies could be implemented such as curing storage devices that regulate the temperature to ensure the curing temperature stays within a specified range.

Table 7: Compressive strengths (psi) of concrete and percentage difference than 73°F cured compressive strength value with Type I cement fabricated and cured at different temperatures (adapted from Klieger, 1958)

Fabrication and curing temperature, deg. F, first 7-days	Moist curing time at fabrication temperature (1-Day)	Moist curing time at fabrication temperature (3-days)	Moist curing time at fabrication temperature (7-Days)
73	1150	2600	4060
90	1490 (30%)	3090 (19%)	4160 (2%)
105	1850 (61%)	3200 (23%)	3850 (-5%)
120	2040 (77%)	2840 (9%)	3440 (-15%)

Table 8: Compressive strengths (psi) of concrete and percentage difference than 73°F cured compressive strength value with Type II cement fabricated and cured at different temperatures (adapted from Klieger, 1958)

Fabrication and curing temperature, deg. F, first 7-days	Moist curing time at fabrication temperature (1-Day)	Moist curing time at fabrication temperature (3-Days)	Moist curing time at fabrication temperature (7-Days)
73	990	2180	3680
90	1250 (26%)	2720 (25%)	3900 (6%)
105	1500 (52%)	3070 (41%)	4420 (20%)
120	1950 (97%)	3060 (40%)	3930 (7%)

Table 9: Compressive strengths (psi) of concrete and percentage difference than 73°F cured compressive strength value with Type I cement fabricated and cured at different temperatures and 100 percent relative humidity (adapted from Klieger, 1958)

Fabrication and curing temperature, deg. F, first 7-days	Moist curing time at fabrication temperature (28-Days)	Moist curing time at fabrication temperature (3 Months)	Moist curing time at fabrication temperature (1 Year)
73	5440	6000	6450
90	4820 (-11%)	5460 (-9%)	6320 (-1.6%)
105	4200 (-23%)	4920 (-18%)	5820 (-9.3%)
120	4080 (-25%)	4320 (-28%)	5410 (-16%)

Table 10: Compressive strengths (psi) of concrete and percentage difference than 73°F cured compressive strength value with Type II cement fabricated and cured at different temperatures and 100 percent relative humidity (adapted from Klieger, 1958)

Fabrication and curing temperature, deg. F, first 7-days	Moist curing time at fabrication temperature (28-Days)	Moist curing time at fabrication temperature (3 Months)	Moist curing time at fabrication temperature (1 Year)
73	5230	6570	7620
90	5190 (-0.8%)	6090 (-7.3%)	6400 (-16%)
105	4990 (-4.6%)	5760 (-12%)	6490 (-15%)
120	4720 (-9.8%)	5300 (-19%)	5630 (-26%)

Table 11: Compressive strengths (psi) of concrete and percentage difference than 73°F cured compressive strength value with Type I cement fabricated and cured at different temperatures and 50 percent relative humidity (adapted from Klieger, 1958)

Fabrication and curing temperature, deg. F, first 7-days	Moist curing time at fabrication temperature (28-Days)	Moist curing time at fabrication temperature (3 Months)	Moist curing time at fabrication temperature (1 Year)
73	5700	6190	6270
90	5380 (-5.6%)	5710 (-7.8%)	5640 (-10%)
105	4700 (-18%)	5600 (-9.5%)	5690 (-9%)
120	4340 (-24%)	5020 (-19%)	5030 (-20%)

Table 12: Compressive strengths (psi) of concrete and percentage difference than 73°F cured compressive strength value with Type II cement fabricated and cured at different temperatures and 50 percent relative humidity (adapted from Klieger, 1958)

Fabrication and curing temperature, deg. F, first 7-days	Moist curing time at fabrication temperature (28-Days)	Moist curing time at fabrication temperature (3 Months)	Moist curing time at fabrication temperature (1 Year)
73	5840	6460	6160
90	5470 (-6.4%)	5880 (-9%)	5780 (-6%)
105	5570 (-4.6%)	5850 (-9.4%)	5880 (-5%)
120	5040 (-14%)	5690 (-12%)	5620 (-8%)

5.1.2 Statistical Analysis

The statistical methods used to determine minimum strength requirements for concrete indicate there will always be a small percentage of failing tests. The U.S. standards, including provisions provided by ACI, are based on statistical methods which account for the probability of 10% of individual compressive strength tests not meeting the required specified compressive strength, f'_c. While perhaps alarming, lowering this failure rate would be economically and sustainably unreasonable. A concrete mix would need to be designed for a strength at least three standard deviations greater than the desired f'_c to ensure zero failing individual strength tests. This would subsequently require the mix to drastically raise in price due to the additional cement and other additives needed to achieve this. It has been determined that this probability balances these criteria fairly against other vital factors such as safety, constructability, and resistance factors in design. Table 13 provides the acceptable distribution of expected low strength tests for various testing frequencies.

Table 13: Expected number of compressive strength test results less than f'_c (adapted from Klinger, 2022)

Volume of Placed Concrete	Minimum Number of Tests	Minimum Number of Tests	Expected Number of Tests Less Than f_c'	Expected Number of Tests Less Than f_c'
(yd^3)	One per 150 yd^3 (ACI 318-19, ACI 301-20)	One per 100 yd^3	One per 150 yd^3 (ACI 318-19, ACI 301-20)	One per 100 yd^3
1,000	7	10	1	1
10,000	70	100	7	10
50,000	334	500	34	50
100,000	667	1000	67	100

ACI 214R-11, the Guide to Evaluation of Strength Test Results of Concrete, provides insight into the industry's practice of statistical analysis. Each mix design should have a specified desired strength, testing frequency, and a permitted tolerance. This tolerance accounts for the random variation that can always occur, and thus the document states that it is impractical to specify an absolute minimum strength due to this. The ACI 214R-11 assumes the compressive strength tests follow a normal distribution which aligns with the assumption that a well monitored concrete mix will produce tests that tend to cluster along the average strength. A normal distribution adheres to the data set having 68.27% of its data falling between one standard deviation (σ) from the mean (μ) and 95.45% within two standard deviations. Assuming every concrete mix will follow this behavior, it can be expected that there will be some percentage of tests that will fall below the set concrete compressive strength, f'_c. Therefore, to meet the statistically based strength requirements set by any mix design, the minimum required average strength of the concrete, f'_{cr}, needs to exceed f'_c. Table 14 can be found in the ACI 214R-11 and displays this relationship between a higher established f'_{cr} with the expected percentage of individual low strength tests. ACI 214R-11 provides more instruction on deciding the variation between the f'_{cr} and f'_c based on the acceptable allowance of failures permitted (ACI, 2011).

Table 14: Expected percentages of individual tests lower than f'_c (adapted from ACI, 2011)

Average Strength, f'_{cr}	Expected % of Low Tests	Average Strength, f'_{cr}	Expected % of Low Tests
$f'_c + 0.10\sigma$	46.0	$f'_c + 1.60\sigma$	5.5
$f'_c + 0.50\sigma$	30.9	$f'_c + 2.00\sigma$	2.3
$f'_c + 0.70\sigma$	24.2	$f'_c + 2.20\sigma$	1.4
$f'_c + 0.80\sigma$	21.2	$f'_c + 2.30\sigma$	1.1
$f'_c + 1.00\sigma$	15.9	$f'_c + 2.50\sigma$	0.6
$f'_c + 1.30\sigma$	9.7	$f'_c + 2.80\sigma$	0.25
$f'_c + 1.50\sigma$	6.7	$f'_c + 3.00\sigma$	0.13

ACI 318-19 states that for a mix to be acceptable, the average of any three consecutive strength tests needs to equal or exceed the f'_c and no strength test can fall below the f'_c by more than 500 psi if that mix is to have a strength of 5000 psi or less (ACI, 2022). If it is greater than 5000 psi, no test can be below $0.10f'_c$. ACI 301-20 states there is a 1% probability that strength tests will fail the above criteria when following the process of determining the required average strength, f'_{cr}, using standard deviation data.

SDDOT mainly references ACI codes and manuals for guidance related to this topic. The SDDOT Standard Specifications for Roads and Bridges states that "the mix design shall be based on obtaining an average concrete compressive strength 1200 psi above the specified minimum 28-day compressive strength". This is likely to result in a higher f'_{cr} value than when using standard deviation data, but it would depend on the variation in the data. Table 15 shows the expected number of individual low strength tests compared to the actual number of observed individual low strength tests over the year 2022 for certain projects. This is assuming the f'_{cr} of 5700 psi (i.e., 4500 psi + 1200 psi) value is similar to that found using standard deviation data, resulting in a 10% failure rate for individual compressive strength tests. Some of the projects fall within the expected range, but a few projects have a higher failure rate indicating there are other contributing factors.

Table 15: 2022 Observed vs. expected number of failed tests

Project Control Number	Number of Tests Conducted	Observed Number of Failed Tests	Expected Number of Failed Tests (10%)
020V	18	1	2
076A	8	1	1
04F0	4	2	1
04KT	6	1	1
02EC	9	3	1
027K	52	7	5

SDDOT does not use an average of three cylinders for strength acceptance or standard deviation data in determination of required strength, so a direct comparison of expected failures is not achievable. Further, data analyzed from SDDOT in this report does not encompass all the DOT projects conducted or cylinders tested over that period; rather the data set only includes the projects that had at least one failing cylinder during its duration. Therefore, it's unknown if the strength failures are higher than expected when analyzing all projects combined. The testing frequencies used to determine these standard statistics also differ from SDDOT practices.

5.1.3 1997 SDDOT Research Study on Low Strength

The 1997 SDDOT construction season had similar low strength issues that results in a research study on the topic. During that study, cement type/quality, dirty rock, mix design being too harsh, air entraining admixtures, high water-cementitious ratios, high air contents, temperature, and concrete mixing time were the factors selected as potential causes. Through field data compilation, various laboratory testing, petrographic, and scanning electron microscopy (SEM), as well as gathering information from surrounding DOTs, it was concluded that the low strength issue was caused by synthetic or non-vinsol resin air entraining admixtures (AEA) (Ashworth et. al., 2000). It was found that the non-vinsol resin AEA's interacted with the low alkali cements being used that led to the formation of air clusters in the mixture as well as non-uniform cement paste at the aggregate interface. When comparing a low strength sample to a high strength sample using a SEM microscope, the low strength sample had large significant air voids throughout the sample with very little uniform paste. While the high strength sample still had some small voids throughout the sample, they were less frequent and considerably smaller than the low strength sample.

The combination of this nonuniformity and air clusters resulted in weak bonding at the aggregate-paste interface which is what caused the low strength in the concrete, especially at high air contents. There was a clear negative correlation between the compressive strength vs. air content for the mixes made and analyzed during that study.

As the result of this research, it was suggested to exclusively use vinsol resin-based AEA's for all structural and paving concrete mixtures. SDDOT then implemented Section 751 in their Standard Specifications for Roads and Bridges which reads:

> "Air-entraining admixtures for concrete shall be one hundred percent vinsol resin based or one of the products as listed on the Department's Approved Products List for all air-entraining admixtures and shall conform to the requirements of AASHTO M 154, except as modified below:
>
> Concrete having sufficient air-entraining admixture added to entrain 5 to 7% air shall have compressive strength at the age of 7 days of not less than 90% of the standard. The standard shall consist of a concrete of equal cement content, equal consistency, and of the same aggregates in adjusted proportions, but without the addition of an air-entraining admixture." (SD Specifications, 2015)

5.1.4 SDDOT Handling/Traveling/Testing Procedures

Beyond the parameters discussed in the previous section, the methods of cylinder production, handling, transportation, and testing can also have a significant impact on results. These types of variability in the sample fall under the within-batch variations discussed previously in ACI 214. The processes laid out in this section reflect the verbiage within various SDDOT manuals on the procedure of how to sample, cure, handle, transport, and test the cylinders.

SDDOT requires all personnel who test these cylinders be certified, at minimum, as an ACI Concrete Field-Testing Technician – Grade I and to have taken the SDDOT+ course on the DOT procedures in LMS (Materials Testing & Inspection Certification Program, 2022). While the Materials Testing & Inspection Certification Program Manual provides different requirements for the temporary and seasonal personnel who might have to conduct the assembly and testing of the concrete cylinders, it states that the Certified Technician on the project "assumes all responsibility for the accuracy of the test data". Therefore, there is a clear standard placed on the individuals conducting this work to be correctly trained to ensure proper consistency and repeatability of the cylinder's results.

At each sampling occurrence, a minimum of four concrete cylinders will be made. One cylinder for the 28-day break, a backup 28-day break, and two early break cylinders which are recommended for testing at 7- and 14-days (RSTC, 2022). Minimum Sample and Test Requirements (MSTR) states that a set of cylinders is to be made "per 200 yd^3 of concrete, per day for each class of concrete from each plant" (MSTR, 2022). The MSTR also specifies that for bridge decks the frequency should be "1 per 100 yd^3 of concrete per day". ACI 318-19 states that a sample shall be taken in accordance with the following three conditions: (1) at least once a day, (2) once for each 50 yd^3 of concrete, or (3) once for each 5000 ft^2 of surface area for slabs or walls. It also states that if the total concrete volume provides fewer than five tests for a mixture, then test specimens should be taken from five randomly selected batches or each batch if fewer than five batches. Strength tests are not required if the total concrete volume is less than 50 yd^3.

The actual procedure of gathering the concrete samples from the site is described in SD 402 (SD 402, 2020). This manual states that all concrete used for testing should be gathered within 15 minutes. Tests for slump, air content, temperature, and unit weight needs to begin within 5 minutes of this process starting. By the end of these 15 minutes, all necessary tests should be completed, and the formation of the testing cylinders should be started. During this entire process, the concrete should be protected from the sun, wind, other sources of rapid evaporation and overall contamination. Table 16 includes details of gathering the samples from the different types of concrete mixers.

Table 16: Sampling for various mixers (SD 402, 2020)

Type of Concrete Mixer	Sampling Process
Stationary and Continuous Mixers	• Pass a receptable completely through the discharge stream or divert the stream completely into a wheelbarrow/ container. • Do not obtain samples from the very first or last part of discharge.
Revolving Truck Mixers	• Wait to get sample until all water and admixtures have been incorporated. • Pass a receptable completely through the discharge stream or divert the stream completely into a wheelbarrow/ container. • Do not obtain samples from the very first or last part of discharge. • Regulate the discharge of the batch by the rate of reduction of the drum and not by the size of the opening.
Dump Trucks or Open Top Truck Mixers	• Discharge the contents of the truck and collect the sample from at least 5 different locations of the pile. • PCC paving train operations shall be obtained from at least 5 different locations immediately ahead of the paver.
Pumps	• Take the sample from the discharge end of the pump. • Collect the sample from at least 5 different locations of the pile. • Discharge shall not be directly into a sampling bucket. • Sample shall be taken at same location where discharge is being incorporated into the structures. • Pump should not be shut off or angle of discharge changed.

The making and curing of the concrete cylinders are described in SD 405 and can be summarized in Figure 1 below. The 28-day cylinder and its back up will be cast using a metallic 6”x12” mold while the early break cylinders can be cast using either 6”x12” or 4”x8” plastic or metallic molds. Typically, these early breaks are cast using plastic 4”x8” molds. The larger molds will consist of the concrete being added in three layers and two layers for the smaller molds. Each layer will be rodded 25 times in accordance with ACI testing standards.

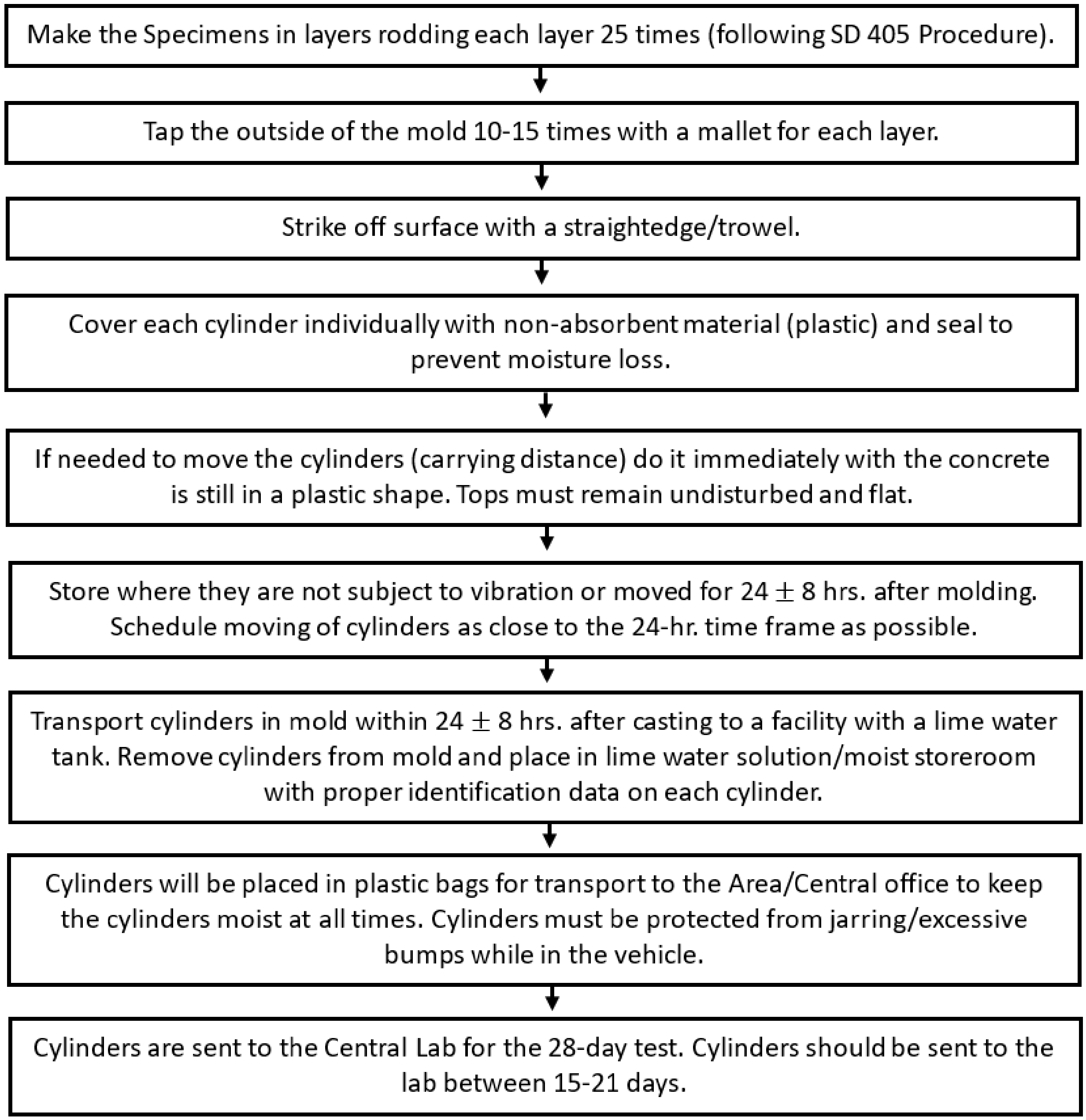


Figure 1: Making and curing procedure (SD 405, 2021)

The technicians are to ensure that the cylinders do not experience excess vibration, direct sunlight/radiant heating/radiant cooling, and that the cylinder temperature remains between 60-80°F. Excess vibration can be checked by driving a 2” x 2” stake into the ground and placing a glass of water on top of it. If the water ripples, the vibration is too much and the cylinders should be moved to control the ambient temperature and the sunlight, the cylinders are placed in a well-insulated cooler that may be propped open during hot days. Additionally, the cooler could be placed in a shady area/temperature-controlled building, or the cylinders could be wrapped in wet burlap and white or clear plastic. Ice or water can be placed in the cooler along with the cylinders to keep them cool. It must be ensured that the concrete cannot come in direct contact with the ice or water, therefore at least ½" from the top of the cylinders should be exposed. To control temperatures during colder weather, the cylinders should be placed in a well-insulated cooler and in a temperature-controlled building if possible. Cylinders can be wrapped in wet burlap and black plastic or placed alongside freshly laid concrete under an insulating material to utilize its heat. However, the cylinders must remain free from vibration (SD 405, 2021).

During transportation from the site to the regional office and from the regional office to the central office, the cylinders must be protected from jarring or excessive bumps. Transportation can be performed by placing the cylinders in a bed of sand. Excess vibration during transportation could result in fractures or microcracking in the cylinders, which may cause them to fail at a lower strength. Any mishandling of the cylinders or issues during the processing (i.e., curing problems, excessive temperatures, dryness, etc.) should be noted in DOT-23. Once at the office, the cylinders should be placed in either a lime water curing tank or a moist room. If a curing tank is used, it should have a one teaspoon to one gallon concentration of lime (calcium hydroxide) to water and maintain a temperature between 70-77°F. This should be stirred daily. A moist room should maintain a temperature of 70-77°F and a relative humidity of not less than 95% (SD 405, 2021).

The testing procedure for the compressive strength tests are explained in SD 420. It states that the 28-day test should be performed as soon as practicable or within 20 hours of the 28th day. As such, the 28-day test will be sent to the central office for testing between 15-21 days. If the 14-day early break test fails to meet strength, the backup 28-day cylinder will be sent with the original (SD 420, 2020). South Dakota's Standard Specification for Roads and Bridges provides more detail on the process of passing/failing cylinders but is summarized in Figure 2.

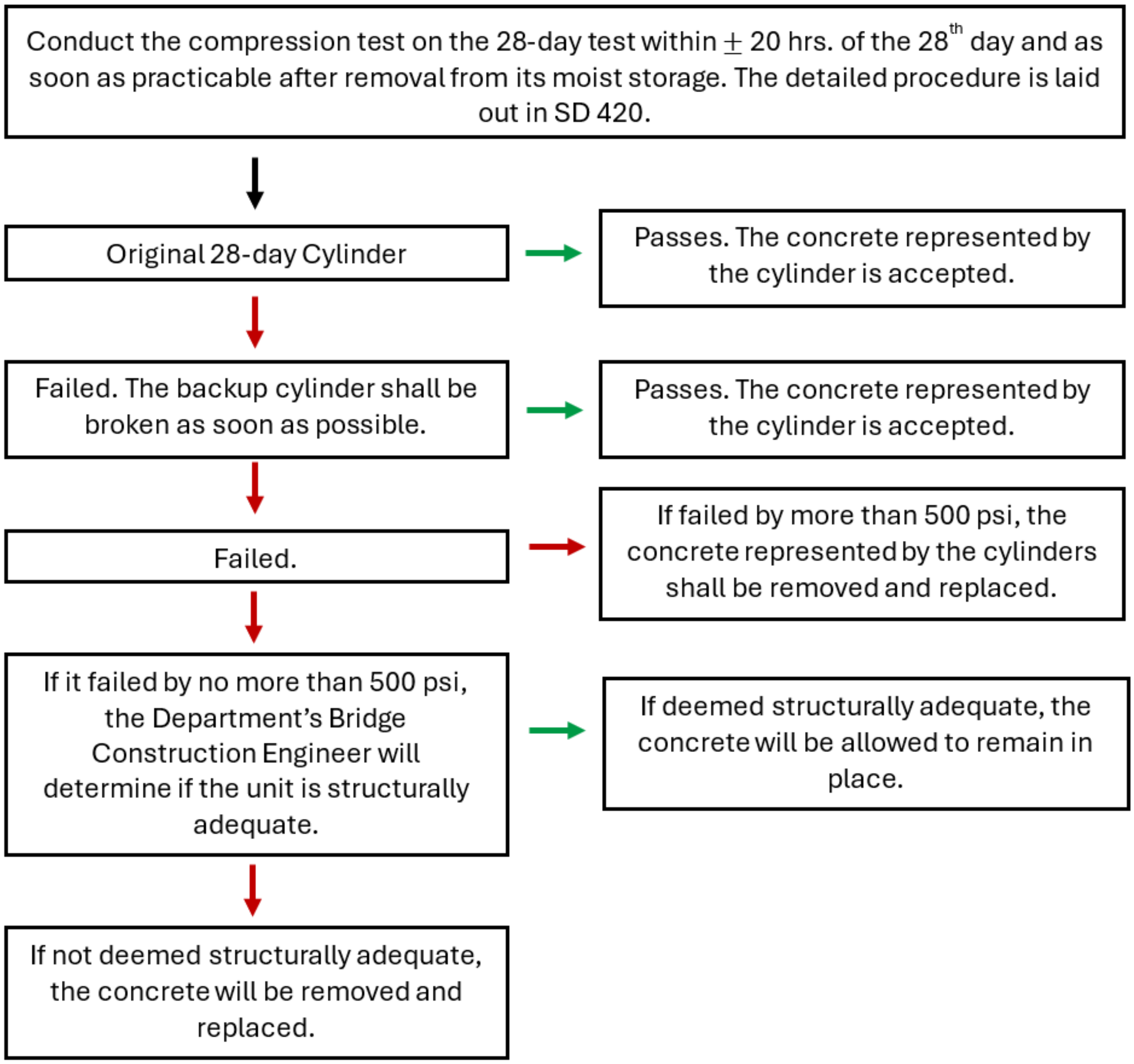


Figure 2: Testing procedure (SD Specifications, 2015)

A core of the concrete can be requested if the compressive strength results fail or are suspected to be invalid for some reason (e.g., damaged cylinder, malfunction, or unrepresentative of the in-place concrete) or the contractor disputes the accuracy of the test. The coring procedure should be in accordance with AASHTO T24 and its analysis process is similar to that of the cylinders. The average compressive strength of three cores collected per concrete batch is used for acceptance. If the average compressive strength is greater than the specified 28-day strength, 4500 psi in this case, the concrete will be accepted. If the average strength is less than the specified strength but within 500 psi, the SDDOT's Bridge Construction Engineer will determine if the unit is still structurally sound. If it is, the concrete will remain in place with a penalty placed on the contractor. If it is not deemed structurally sound, the concrete will have to be removed and replaced. If the average compressive strength is more than 500 psi below the specified strength, the concrete will need to be removed and replaced (South Dakota Specification, 2015).

5.1.5 Surrounding State Specifications

A comparison of the surrounding states DOT's specifications and procedures were gathered and summarized in Appendix A. Since South Dakota and all the surrounding states rely heavily on AASHTO specifications, many of the basic requirements are similar. However, differences were found in the mix design components of the specifications along with variations of acceptable temperature ranges for fresh concrete and field curing conditions. Furthermore, all but one of the surrounding state DOTs require at least an average of three cylinders for strength acceptance.

Minnesota's DOT has strict phrasing of their temperature specifications, so a representative in their research division was contacted to provide further clarification. This technician explained that their procedure is to place the concrete cylinders within a cooler but then also surround the cylinders with water from the ready-mix truck that brings the concrete. The cooler is filled to a level that reaches about an inch from the top of the cylinder. This practice is used during hot weather when the exterior temperatures is greater than 80˚F. The water's temperature throughout the process is not monitored, and he claimed there have not been any seepage issues. The technician said they too had major strength issues with their testing cylinders before making this change around 2016. He estimated their strength issues have improved at least 50% since implementing this statewide change. Alternatively, if the work site is within 15 minutes of an office, they will transport the concrete to that office so the cylinders can be made and cured in the office. Since there is a strict time constraint of 15 minutes, this does not happen frequently but is a practice they follow when applicable.

A Nebraska DOT research project conducted in 2020 corroborated that placing the testing cylinders in water resulted in higher compressive strength values. This research study compared different curing methods used by the NDOT and evaluated them to determine which practice would be best for extreme hot and cold weather conditions (Heyen & Halsey, 2020). For hot weather conditions, eight curing methods were tested and the results can be seen in Figure 3 and Table 17. As can be seen, the curing condition was found to have a significant effect on the compressive strength of a sample. The method that resulted in the highest compressive strengths was when the cylinders were placed in a cooler filled with water. The Nebraska DOT recommended that water should be used in the coolers for hot weather conditions when the outside ambient temperature is above 80˚F for several days in a row. They also specified the water should cover at least 75% of the concrete cylinder.

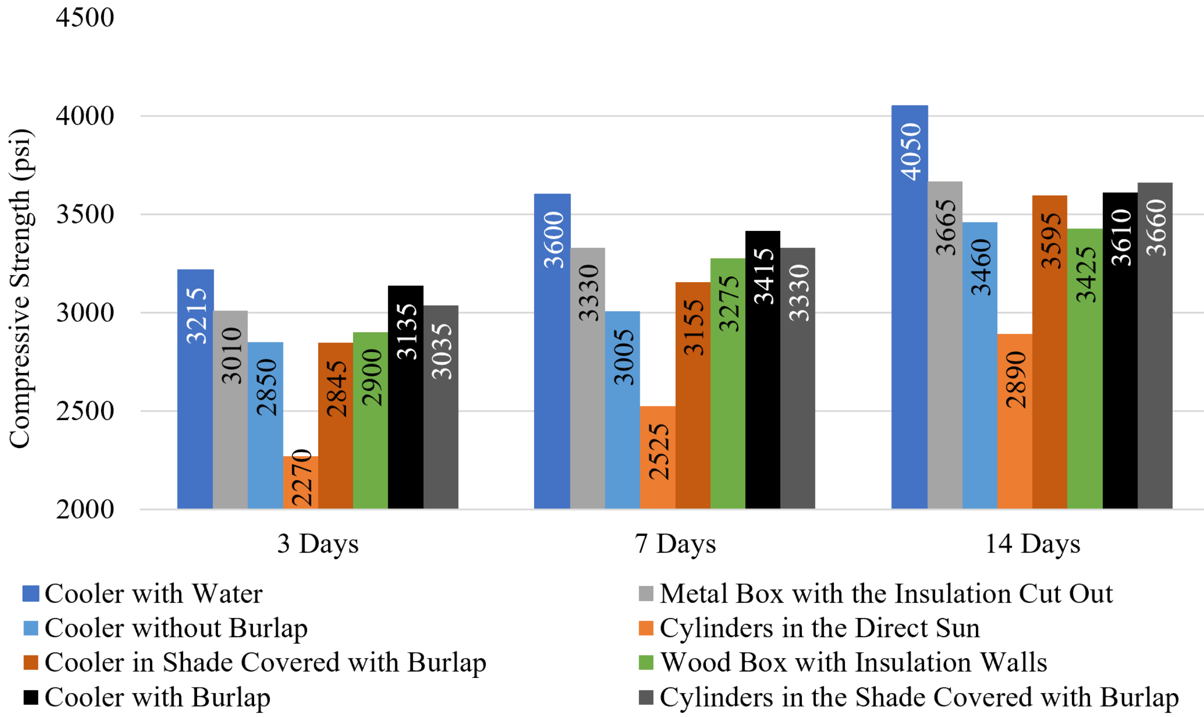


Figure 3: Nebraska DOT hot weather results (adapted from Heyen & Halsey, 2020)

Table 17: Summary of the data from Figure 3

Curing Condition	3 Day Compressive Strength (psi)	7 Day Compressive Strength (psi)	14 Day Compressive Strength (psi)
Cooler with Water	3215	3600	4050
Metal Box with the Insulation Cut Out	3010	3330	3665
Cooler without Burlap	2850	3005	3460
Cylinders in the Direct Sun	2270	2525	2890
Cooler in Shade Covered with Burlap	2845	3155	3595
Wood Box with Insulation Walls	2900	3275	3425
Cooler with Burlap	3135	3415	3610
Cylinders in the Shade Covered with Burlap	3035	3330	3660

5.2 Methods and Materials

This section will describe the procedures on how each portion of this research was conducted. First, historical SDDOT data was analyzed and a survey to the national DOTs and regional SD material suppliers were sent and collected. From this information, a further investigation in temperature led to utilizing SmartRock sensor technology to monitor temperatures in the field for a new project in Sioux Falls, SD.

From these sections, the testing parameters for the experimental portion of the research project were derived. Concrete slices from three of the lab created concrete mixes and cores from a nearby SDDOT project were also analyzed. The results of these works can be found in the next section.

5.2.1 South Dakota Historical Project Data

The first step in understanding why the SDDOT had issues with their compressive strength was to examine the concrete and projects that were low performing. The SDDOT sent over project data for every project (48 total projects) that had at least one failed cylinder test from 2017-2022. As discussed in the previous section, the testing frequency varied so each project had different numbers of testing batches depending on project size. Each batch had at least four cylinders to be tested at the required testing dates. The SDDOT provided excel sheets for every project that had all its project data, fresh concrete properties, and compressive strengths. It is important to note that most of the information provided was before the updated mix design specification and therefore adheres to the old specifications shown previously in Table 4. The researchers only wanted to incorporate the testing batch's final compressive strength. A 28-day cylinder that had a compressive strength of 4500 psi or higher passed. A test was only classified as failing if the oldest tested cylinder per test batch did not meet the strength limit. This approach was chosen since an additional cylinder is often tested at 28-days or a later age after a failed 28-day test, which can be used for acceptance. The data set was organized in a way that ensured no overlapping failing test data (i.e., not counting the same batch more than once if it failed at 28-days and passed at a later age). This resulted in a total of 1019 batches. These batches were separated and analyzed by their fresh concrete properties (air content, slump, concrete temperature) and environmental factors (i.e., project location, daily temperatures) along with material suppliers, types, and sources.

5.2.2 Core Investigation

Of the failed 1019 testing batches, 33 of them were cored. These cored batches were separated from the excel sheets and analyzed separately in the same ways as the whole historical set. These cores were also compared against their failed 28-day counterparts to see the differences between the testing cylinders and the in situ concrete.

5.2.3 Technician Interviews

To supplement the recorded historical data, a better understanding of how the concrete is handled in the field was gathered through technician interviews. Six technicians from across the state were interviewed about their experiences and the entire journey of the concrete from arriving to the site to being tested at the central office. These interviews were conducted primarily over Zoom with one being in person in Rapid City, SD. The questions asked during these interviews can be found in Appendix B.

5.2.4 SDDOT Concrete Supplier and National DOT Survey

A survey was created and distributed to all the National DOTs to assess their experiences with failures for this type of concrete. Additionally, one was sent to regional concrete suppliers. The goal was to get feedback from those who make the concrete to get their perspectives of the concrete mix design and the performance from their point of view. Both surveys were distributed by the SDDOT. The questions and responses received can be found in Appendix E.

5.2.5 In Field Curing Temperature Assessment

The SD 405 manual states that "the temperature surrounding the cylinders should be maintained as closely as practical between 60˚F and 80˚F" during field curing and then between 70˚F and 77˚F once the cylinders are in a regional lab's moist cure room (SD 405, 2021). However, the coolers that are used for curing the concrete samples are not monitored by SDDOT for the first 24 hours. To assess if this requirement is satisfied in the field, the temperature was monitored within the coolers at the top (lid) and bottom (floor), within the concrete cylinders, and the ambient condition outside the cooler using SmartRock data technology for seven different cylinder testing batches. These seven samples were poured throughout September 2023 and the coolers were separated by two conditions: the cooler's lid was (1) closed or (2) cracked open. The SmartRock sensors were placed within the coolers used by the SDDOT in a way that the sensors were not in contact with any surface. Figure 4 and Figure 5 show one of these coolers full of specimens (Figure 4) and the cracked open condition (Figure 5). Two 4"x8" cylinders and two 6"x12" cylinders are typically held in the cooler at a time. To gather the following data, an additional 6"x12" cylinder was included for concrete temperature measurements. Note that the cooler used here is not representative of all the different coolers used by SDDOT across the state.

Figure 4: Cooler with concrete cylinder samples and sensors

Figure 5: Cracked open cooler with exterior sensor

5.2.6 Concrete Mix Designs

Eighteen mix designs were chosen to address potential factors resulting in low strength issues. Type IL Portland-limestone cement (PLC) was used for all mixes to simulate future mix designs used by SDDOT (ASTM C595). Class F coal ash was used for all mix designs as this is the most common coal ash used by the SDDOT. Tap water was used for all mixes. The fine and coarse aggregates for all but the two low strength mix designs were locally sourced in Rapid City, SD and stored outside. The material data sheets for all materials used can be found in Appendix C.

Prior to mixing, the aggregates were brought indoors and covered for a minimum of 24 hours before the moisture content was measured so the aggregates could reach room temperature. Twenty-four hours before mixing the batch, a moisture content test was completed in accordance with ASTM C566. A small amount of both types of aggregate were weighed before and after being placed in an oven at 110˚C for 24 hours. These weights were used to determine the moisture content of the aggregates to adjust the water and aggregate contents in the mixes to ensure the correct w/cm ratio. For mixing, 75% of the water and all the coarse aggregates for the mix was placed in the Multiquip MC64SE mixer and mixed for 1-1.5 minutes. The fine aggregates were added next and then the mixture was once again mixed for 1-1.5 minutes. Then, the cementitious materials (PLC cement and Class F coal ash) and the remaining 25% water was incorporated into the mix and mixed for five minutes. After the five minutes of mixing, the batch sat in the mixer covered for three minutes and then mixed for a final five minutes.

All mixes were cured in lime water after the initial 24-hour cure. Figure 6 shows the lime water containers and how the cylinders were oriented within them. The lime water was stirred daily. The cylinders remained in the lime water until each testing age was met and were kept at a temperature between 70-77˚F. Table 18 shows the mix designs and the targeted testing parameters.

Figure 6: Lime water containers

Table 18: Mix designs and their targeted testing parameters

Batch Description	Targeted Testing Parameters
Baseline	None
0.45 w/cm	High w/cm Ratio
100˚F Curing Temp	High Curing Temp.
100˚F Curing Temp/Hot Concrete	High Curing Temp., Hot Concrete/Aggregate
115˚F Curing Temp	High Curing Temp.
5% Air Content	None
5% Air Content/Retempering	Retempering/Long Hauls
8% Air Content	High Air Content
8% Air Content/100˚F Curing Temp	High Curing Temp., High Air Content
8% Air Content/Hot Concrete/Retempering	High Curing Temp., High Air Content, Hot Concrete/Aggregate, Retempering/Long Hauls
Low Strength Mix Design A	High Air Content, Retempering/Long Hauls
Low Strength Mix Design B	High Air Content, Retempering/Long Hauls
Worst Case Scenario Mix Design	High Curing Temp., High Air Content, Hot Concrete/Aggregate, Not Adjusting for Moisture Content in Aggregates, Retempering/Long Hauls

The baseline mix design with a coal ash replacement content of 20% by weight of cement was developed during a previous SDDOT research project (Simonton, 2021). In that study, a statistical analysis was performed on over 400 A45 concrete mixes previously used to develop the mix design. The average compressive strength of these mixes was greater than 4500 psi.

To address w/cm variability, the baseline mix was replicated but with 0.45 w/cm ratio instead of 0.4. To assess temperature effects, the baseline mix design was cured at three different temperatures for the first 24 hours. The baseline was cured at 70˚F, and the two others were cured at elevated temperatures based on the collected SmartRock temperature data. One mix was cured at 100˚F for 24 hours. The other was cured at 115˚F for the first 12 hours and then cured at room temperature (70-77˚F) for the remaining time with an average temperature of approximately 92.5˚F. The maximum temperature that was recorded by the SmartRock sensors during the month of September within the cooler was 99.2˚F, so it can be expected the cylinders initially cure at temperatures even higher than these during midsummer. As such, the 100˚F initial curing temperature was determined. To capture the effects of curing at a peak high temperature, 115˚F was chosen due to the SmartRock analysis combined with a lower temperature to simulate day and night curing. Figure 7 shows how this elevated curing was achieved. The oven used is heated through natural convection. The oven was heated to the appropriate temperature hours before placing the cylinders in it. The cylinders were spaced apart so none of the cylinders were touching to ensure the cylinders were uniformly heated.

Figure 7: Cylinder configuration in oven

To test for the combined effect of a higher fresh concrete temperature in addition to a high ambient curing temperature, one mix was heated to 90˚F prior to forming the testing cylinders and cured at the elevated temperature 100˚F. The concrete reached this temperature in the laboratory by heating the aggregate and water prior to being incorporated in the mix. The coarse aggregate was heated to 150˚F for at least 24 hours before mixing. The moisture content was still found for this mix to ensure proper w/cm ratio was achieved.

To further explore the effect of air content on strength for the A45 mix, a 5% and 8% air content was targeted to represent the allowable range from the SDDOT specification. To achieve this, the addition of an air entraining admixture was used. An additional 8% air content batch was cured at 100˚F instead of 70˚F to couple the parameters of high air content and high curing temperature. All other mixes had no entrained air content to ensure lower variability in strength results. A 2% entrapped air content was assumed for these mixes.

The DOT research panel also wanted to explore a worst-case scenario where multiple parameters were tested. One mix design was made to simulate pouring on a hot day that had a long haul with the concrete also having a high air content, high w/cm ratio, underwent retempering, and not being properly adjusted for the aggregate's moisture content. This mix followed the same procedures of heating the concrete to 90˚F as the "100˚F Curing Temp/Hot Concrete" mix and was also cured at 100˚F. To simulate a long haul/retempering, the mix remained in the mixer for 45 minutes with it being remixed for one minute every five minutes. The 45 minutes concluded with five minutes of mixing. This differs from the SDDOT's requirement of constant agitation while hauling, but the lab used for this research was not equipped to have continuous mixing.

The rate at which the researcher's mixer agitated the material was at a higher frequency than what a concrete truck maintains while hauling, so this interval mixing was believed to be a suitable replication. To further simulate the effects a hot summer day might have on the concrete, this mix was also not adjusted to account for coarse and fine aggregates that had a moisture content less than the saturated surface dry (SSD) condition. Once retempering was completed, more water was added to the mix to reach a desired workability. Given the other parameters being tested, the amount of water used resulted in a water cement ratio higher than 0.40. The air entrainer was used to achieve an air content of 8%.

To attempt to isolate the effects of retempering, an additional 5% air content mix was made. This batch replicated the 5% air content mix design with the added steps of retempering laid out above. Initially, enough water to make the mix have a w/cm ratio of 0.38 was added and then just before the final two minutes of mixing, the remaining water was added to the concrete. Additionally, a batch with an 8% air content was retempered and cured at a higher curing temperature (100 ˚F). The aggregate for this mix was also heated to simulate it being a hot concrete mix. Heating the aggregate and retempering followed the same procedures previously discussed.

The next two mix designs replicated two batches that were two historical mix designs that produced low strengths. The first replicated the mix design with project number 07N9. This mix design was proposed by the SDDOT panel and used fine aggregate from Fine Aggregate Source E, coarse quartz aggregate from Coarse Aggregate Source B Pit 1, and two admixtures: an air entrainer and a water reducer. The second mix was chosen by the researchers. This mix used fine aggregate from Fine Aggregate Source A Pit 3, coarse quartz aggregate from Coarse Aggregate Source B Pit 1, and two admixtures: an air entrainer and a water reducer. Similar mixes (04K0 and 04HN) had high failing rates for both Concrete Supplier B and G. The fine aggregate and admixtures used in this mix appeared to have the highest failure rates from the historical data.

Two batches of coal ash were procured during this experimental process. While their properties were very similar, there was an observed difference in strength performance. Therefore, two baseline mixes are included throughout this report so a proper comparison could be made. The data sheets for both coal ashes and all other materials used can be found in Appendix C. Also, a second 8% air content batch was made using the second batch of coal ash for comparison. Furthermore, the two low strength mix designs were doubled so each mix could be cured both at room temperature and 100 ˚F to assess the impacts of high temperature curing on other mixes. Lastly, the high air content mixes were over-yielded due to the extra volume of air as shown in Table 19. To test for this variability, an additional mix was made in which the fine aggregate volume was reduced by the same volume as the added air content of 8% to keep the theoretical yield at 27ft^3/yd^3. This mix is labeled as 8% Air Content/Adjusted Aggregate mix, and it has a reduced fine aggregate content of 1116 pcy instead of 1396 pcy.

The full mix design information for all the mixes is listed below in Table 19.

Table 19: Mix designs

Description	Curing Temp. (˚F)	w/cm	Water (lb/yd^3)	Cement (lb/yd^3)	Coal Ash (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	Air Content (%)	Theoretical Yield (ft^3/yd^3)
Baseline***	70	0.4	260	520	130	1735	1396	2%	27
0.45 w/cm	70	0.45	292.5	520	130	1735	1396	2%	27.5
100˚F Curing Temp	100	0.4	260	520	130	1735	1396	2%	27
100˚F Curing Temp/Hot Concrete *	100	0.4	260	520	130	1735	1396	2%	27
115˚F Curing Temp	115/70	0.4	260	520	130	1735	1396	2%	27
5% Air Content	70	0.4	260	520	130	1735	1396	5%	27.9
5% Air/Retempering	70	0.4	260	520	130	1735	1396	5%	27.9
8% Air Content***	70	0.4	260	520	130	1735	1396	8%	28.7
8% Air Content/100˚F Curing Temp	100	0.4	260	520	130	1735	1396	8%	28.7
8% Air Content/Adjusted Aggregate	100	0.4	260	520	130	1735	1116	8%	27
8% Air Content/Hot Concrete/Retempering*	100	0.4	260	520	130	1735	1396	8%	28.7
Low Strength Mix Design A**	70	0.4	262	520	135	1810	1097	8%	27.6
Low Strength Mix Design B**	70	0.4	262	520	135	1755	1149	8%	27.9
Worst Case Scenario Mix Design*	100	0.4	260	520	130	1735	1396	8%	28.7

* Concrete is heated to 90˚F

** Mix Design will incorporate admixture combination and sourced aggregate from a chosen historical mix design. A duplicate batch will also have a 100˚F curing temperature.

***Mix design has two batches with different coal ash batches

Table 20 shows the types and amounts of all the admixtures used in each concrete mix. The addition of the air entrainers had a variable effect on fresh air content for different mixes which resulted in a spread of doses. The two hot concrete mixes required at least three times higher air entrainer dosage than their room temperature counterparts. The admixtures were incorporated into the mix per manufacturer recommendation. Air entrainer 1 was added to the mix with the first part of water (75% of the total water). Air entrainer 2 was added to the fine aggregate and both water reducers were added to the last 25% of water incorporated in the mix.

Table 20: Admixture amounts in concrete mixes

Batch Description	Admixture (fl. oz./cwt) Air Entrainer 1	Admixture (fl. oz./cwt) Air Entrainer 2	Admixture (fl. oz./cwt) Water Reducer 1	Admixture (fl. oz./cwt) Water Reducer 2
8% Air Content*	1.7	-	-	-
8% Air Content/100˚F Curing Temp*	1.7	-	-	-
5% Air Content	0.9	-	-	-
5% Air Content/Retempering	1.0	-	-	-
8% Air Content	1.8	-	-	-
8% Air Content/Adjusted Aggregate	2.0	-	-	-
8% Air Content/Hot Concrete/Retempering	5.6	-	-	-
Low Strength Mix Design A	-	2.0	-	2.0
Low Strength Mix Design A/100˚F Curing Temp	-	2.0	-	2.0
Low Strength Mix Design B	-	1.4	7.0	-
Low Strength Mix Design B/100˚F Curing Temp	-	1.4	7.0	-
Worst Case Scenario Mix Design	7.6	-	-	-

*Designates mixes using first coal ash batch

Three concrete mixes were meant to simulate hot concrete and were heated prior to consolidating the cylinders. Through the procedure laid out above, Table 21 reports the temperatures of each of these mixes throughout the mixing process. The first temperature was taken after the initial five minutes of mixing once all the material had the chance to be incorporated. The second temperature was taken after the three minutes of rest and last five minutes of mixing (if not undergoing the retempering procedure). The last temperature was the temperature of the concrete when the cylinders were being cast. The temperatures were taken with a digital thermometer. All three heated mixes were within the 90˚F temperature limit set by the SDDOT.

Table 21: Recorded temperatures of the hot concrete batches

Batch Description	Temperature After Mixture is Incorporated (˚F)	Temperature After 10 Minutes of Mixing (˚F)	Temperature During Casting Cylinders (˚F)
100˚F Curing Temp/Hot Concrete*	94	92	90
8% Air Content/Hot Concrete/Retempering	99	96	89
Worst Case Scenario Mix Design	97	96	87

*Designates mixes using first coal ash batch

5.2.7 Cylinder Tests

The fresh and hardened properties of the concrete mixes were tested according to their respective ASTM or AASHTO specifications as described below.

Slump

The slump of hydraulic cement concrete (ASTM C143) was used to determine the workability of the mix. In accordance with the SDDOT specifications, a slump of within 1-5.5 inches was targeted to meet SDDOT specification.

Air Content

The air content of freshly mixed concrete was measured by the pressure method (ASTM C231). This pressure method for determining air content 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.

Compressive Strength

The compressive strength of concrete cylinders was measured in accordance with ASTM C39. Strength tests were performed at 7-, 14-, and 28-days using standard 4” by 8” cylinders. Three cylinders were tested at each of these time intervals. The SDDOT uses 6”x12 “cylinders for approval, but due to lab limitations this size of cylinders could not be made for this study.

Electrical Resistivity

The bulk resistivity of the concrete cylinders was measured in accordance with ASTM C1876-19. The cylinders were tested for electrical resistivity at 7-, 14-, and 28-days before being tested for their compressive strength. Each cylinder was tested twice, with the cylinder being flipped after the first reading. The recorded value was the average of these two readings. The chloride penetrability levels established for standards based on electrical resistivity are shown in Table 22. Figure 8 shows the test setup using the Porceq Resipod device.

Table 22: Chloride ion penetrability related to 28-day bulk electrical resistivity measurement for a 4”x8” cylinder (Eid, 2023)

Chloride Ion Penetration	kΩ-cm
High	< 4
Moderate	4-8
Low	8-16
Very Low	16-190
Negligible	>190

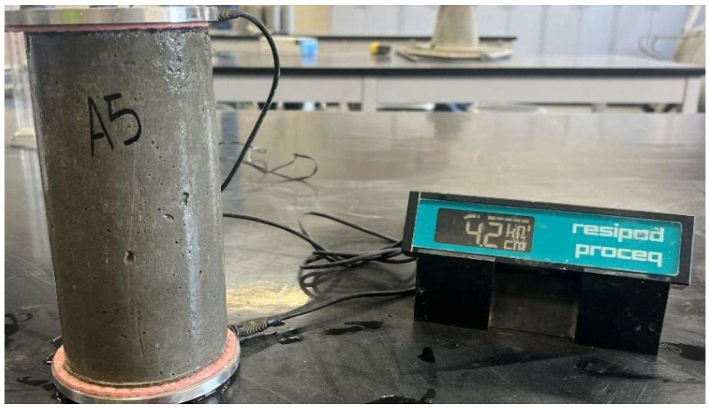


Figure 8: Bulk resistivity testing

Concrete Forensic and Petrography Analysis

A forensic analysis was conducted on low strength concrete samples from a recently constructed box culvert. This culvert failed its strength test and needed to be cored. Samples of these cores were sent to be analyzed by SDSMT. These cores were analyzed alongside three cylinders from different batches made in the lab by the researchers. The three batches were the baseline mix with no added air entrainment, a 5% air content mix, and an 8% air content mix. The cores and cylinders were cut into approximately one-inch-thick slices using a wet tile saw. The cut surfaces were then sanded until smooth. Pictures were then taken of the entire cross-section of the cylinder. Furthermore, microscopic images were collected on magnified features of interest. The air voids in the cylinders were estimated by measuring the air void surface area on one cut face. To perform this test, the samples were prepared by darkening the face of the sample with a black marker. Talc powder was then spread along the surface filling any voids. The talc powder was then wiped away carefully to ensure the voids were still filled but the surface was clean. Pictures of the prepared samples were then taken and analyzed using ImageJ software. Using image analysis, the percent area of the surface that is white was calculated and used as a proxy for air content.

Two cores were also sent for professional petrographic examination performed by MJ2 consulting. One core represented the “Good” (strength passing) sample and the other “Bad” (strength failing) concrete from the same culvert project.

5.3 Results and Discussion

In this section, the results of the analysis of historical and core data are presented. Additionally, the results of the surveys, interviews, and supplemental SmartRock technology investigations are also included. This section will end with the findings of the experimental portion of the research project.

5.3.1 SDDOT Historical Concrete Data

The SDDOT provided project data from the last six years for every project that had at least one compressive strength test that did not meet strength requirements. As such, the following analysis is not representative of the entirety of the SDDOT's projects from the last six years. The percentages referenced throughout this section are based solely on the total number of test cylinders for projects that had at least one failing test.

The overall 2017-2022 pass rate of the analyzed samples from projects with a failed cylinder was 91%. Table 23 shows how this compares to the individual year rates. The data in this table coincides with the SDDOT's anecdotal evidence that low strength issues had seemingly gotten worse over the years. Next, the dataset was sorted to identify the passing rates by month and county as shown in Figure 9 and Table 24, and Figure 10 and Table 25, respectively. The summer months of June-August had the most failures. Furthermore, three counties had the highest failure rates in this data set: Buffalo, Bon Homme, and Charles Mix. The majority of failed cylinders had strengths within 500 psi of the 4500 psi limit (i.e., 4000-4500 psi). According to ACI 318-19 strength acceptance criteria, no strength test can fall below the f'_c by more than 500 psi, which occasionally occurred in this sample set.

Table 23: Yearly pass/fail rates

Year	Passing Rate	Fail Rate
2017	95%	5%
2018	94%	6%
2019	94%	6%
2020	92%	8%
2021	86%	14%
2022	89%	11%

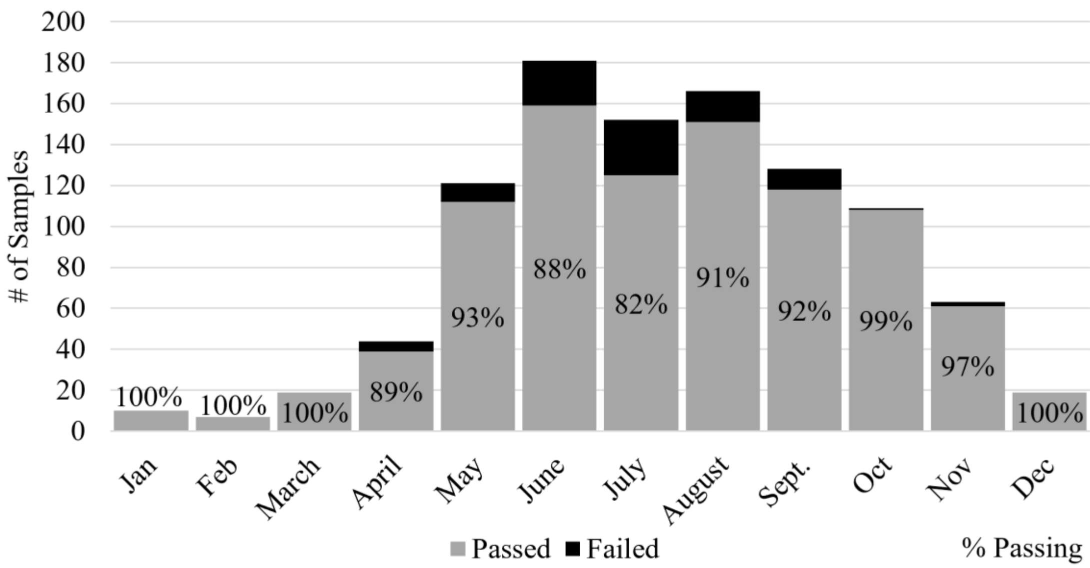


Figure 9: Historical monthly pass/fail rates

Table 24: Summary of the data from Figure 9

Month	Number of Samples	Number of Passing Samples	Passing Rate	Number of Failed Samples	Failed Rate
January	10	10	100%	0	0%
February	7	7	100%	0	0%
March	19	19	100%	0	0%
April	44	39	89%	5	11%
May	121	112	93%	9	7%
June	181	159	88%	22	12%
July	152	125	82%	27	18%
August	176	151	91%	25	9%
September	128	118	92%	10	8%
October	109	108	99%	1	1%
November	63	61	97%	2	3%
December	19	19	100%	0	0%

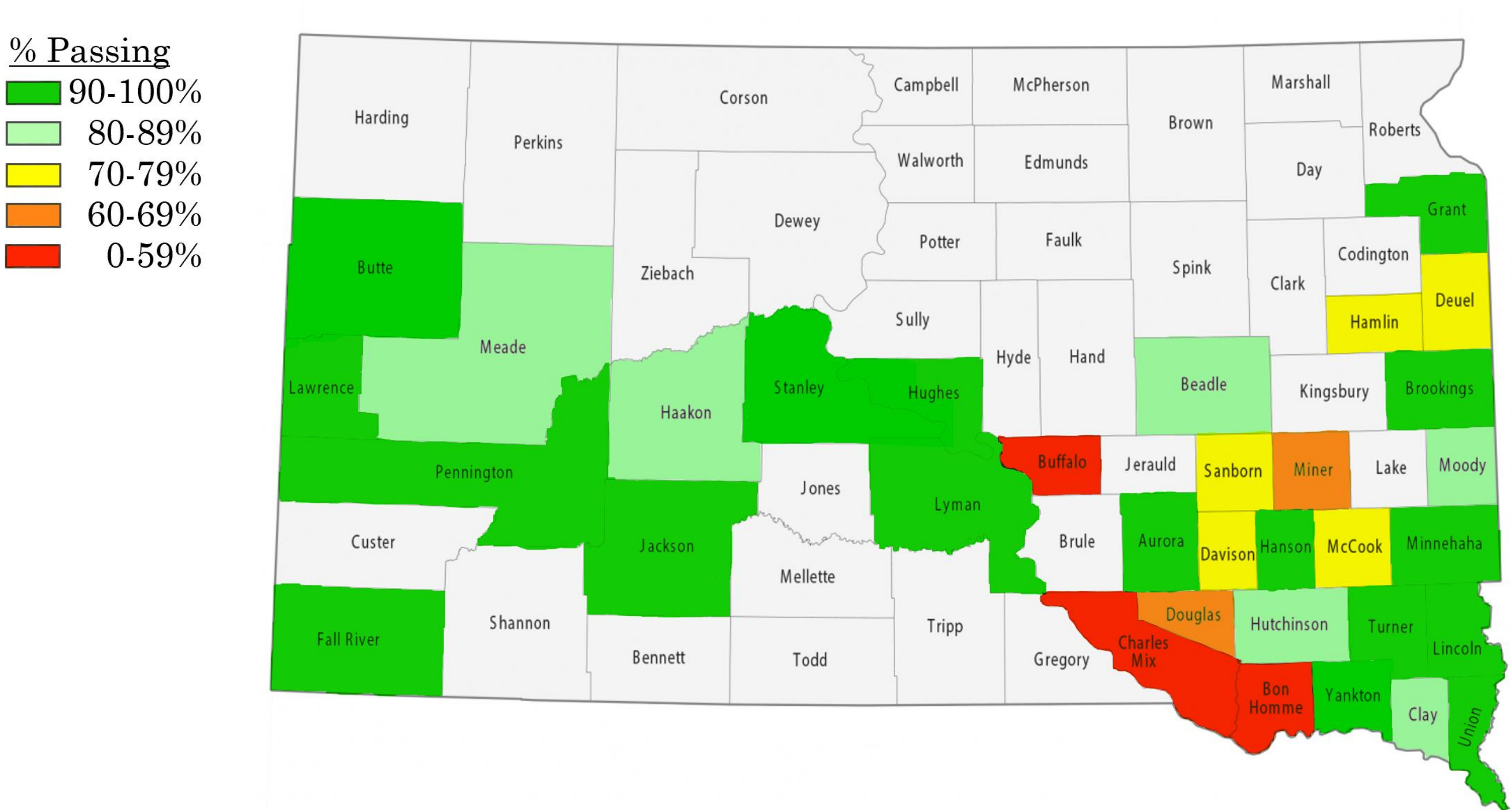


Figure 10: County passing rates for concrete compressive strength tests

Table 25: Summary of the data from Figure 10

Percent Passing	Counties
90-100%	Aurora, Brookings, Butte, Fall River, Grant, Hanson, Hughes, Jackson, Lawrence, Lincoln, Lyman, Minnehaha, Pennington, Stanley, Turner, Union, Yankton
80-89%	Beadle, Clay, Haakon, Hutchinson, Meade, Moody
70-79%	Davison, Deuel, Hamlin, McCook, Sanborn
60-69%	Douglas, Miner
0-59%	Bon Homme, Buffalo, Charles Mix
No Data	Bennett, Brown, Brule, Campbell, Clark, Codington, Corson, Custer, Day, Dewey, Edmunds, Faulk, Gregory, Hand, Harding, Hyde, Jerauld, Jones, Kingsbury, Lake, Marshall, McPherson, Mellette, Perkins, Potter, Roberts, Shannon, Spink, Sully, Todd, Tripp, Walworth, Ziebach

Next, various mix design data was analyzed to identify any parameters that correlated with low strength occurrences. The first parameter that had a slight correlation with low strength was the percent air in the concrete (see Figure 11, Figure 12, and Table 26). (A summary of the data in Figure 11 is found in Appendix H Table 90.) To present the passing rates of each air content in a concise way, Figure 12 shows the data when grouped in increments of 0.5%. Each group (4.5-4.9%, 5-5.4%, 5.5-5.9%, etc.) had its own passing rate based off the individual occurrences found within each increment. The passing rates tended to decrease as the air content increased. It appears that passing rates significantly decreased for concrete batches with air contents greater than 7%.

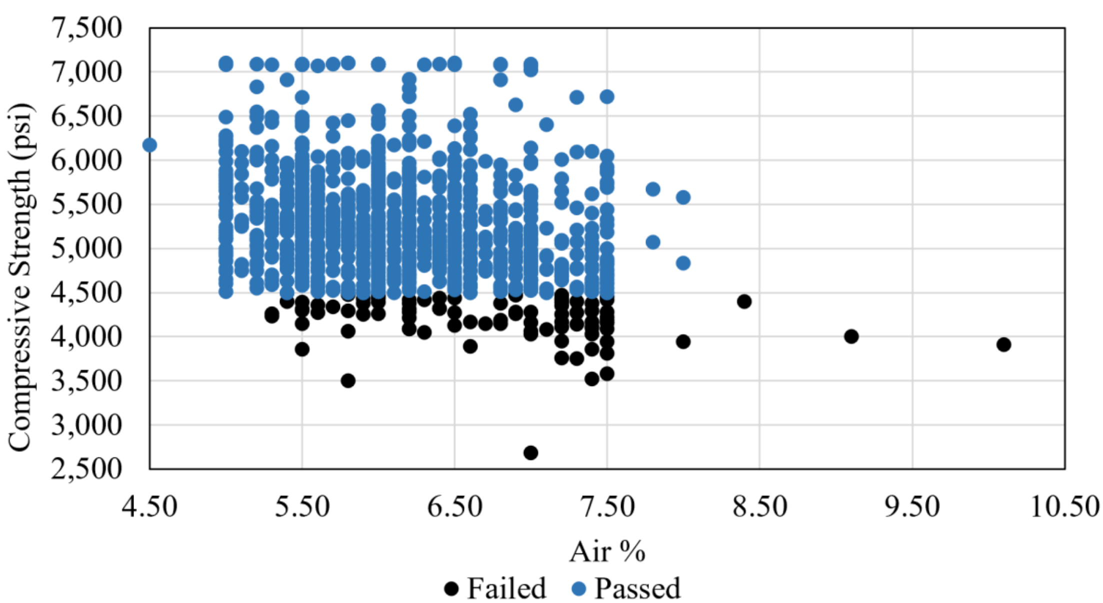


Figure 11: The historical compressive strength vs. air content

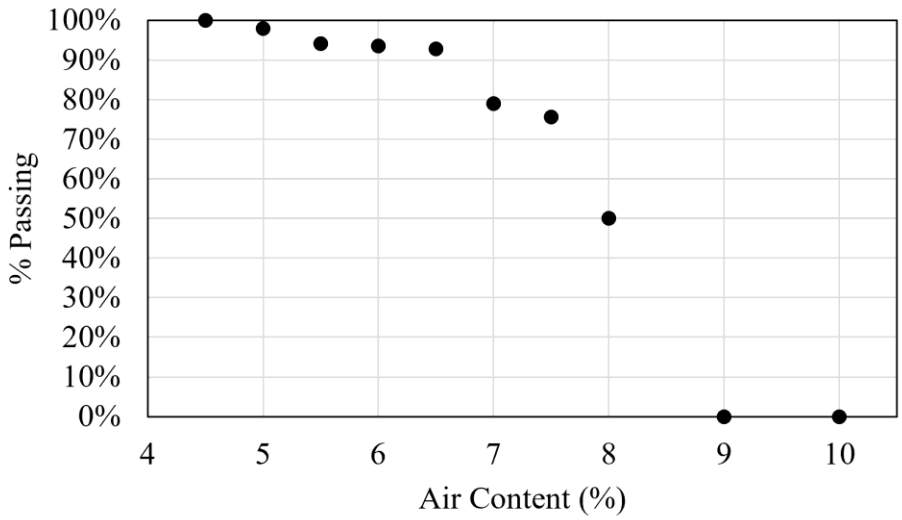


Figure 12: The historical influence air content had on the passing rate of compressive strength of concrete cylinders

Table 26: Summary of the data from Figure 12

Air Content (%)	Passing (%)
4.5	100
5.0	98
5.5	94
6.0	94
6.5	93
7.0	79
7.5	76
8.0	50
9.0	0
10.0	0

Figure 13 shows the relationship between concrete temperature and compressive strength. (A summary of the data in Figure 13 is found in Appendix H Table 90.) Figure 14 and Table 27 bin the data into 5 °F increments and shows the passing rate decreased as the temperature increased. Concrete temperatures above 75°F exhibit higher failure rates. The ambient temperature for the dates each of the batches were made was also collected using Weather Underground to determine the daily high and average temperatures (Weather Underground, 2023). The compressive strength data is plotted vs. average daily temperatures in Figure 15 and the 5 °F binned data are shown in Figure 16 and Table 28. (A summary of the data in Figure 15 is found in Appendix H Table 90.) The compressive strength data is plotted vs. daily high temperatures in Figure 17. (A summary of the data in Figure 17 is found in Appendix H Table 90.) Additionally, the passing rates using 5 °F binned data are shown in Figure 18 and Table 29. Like the concrete temperature trend, there was a decrease in passing rate as the average and high temperature increased with some anomalous data at lower temperatures. From the data, it appears that failure rates increase above 50°F average daily temperature and above 60°F daily high temperatures. The highest failure rates are observed when ambient temperatures are above 80°F. This correlation was also observed with the concrete's temperature. No significance was found when a multivariable regression was performed on the air content with the various temperature variables (concrete, average daily, and daily high).

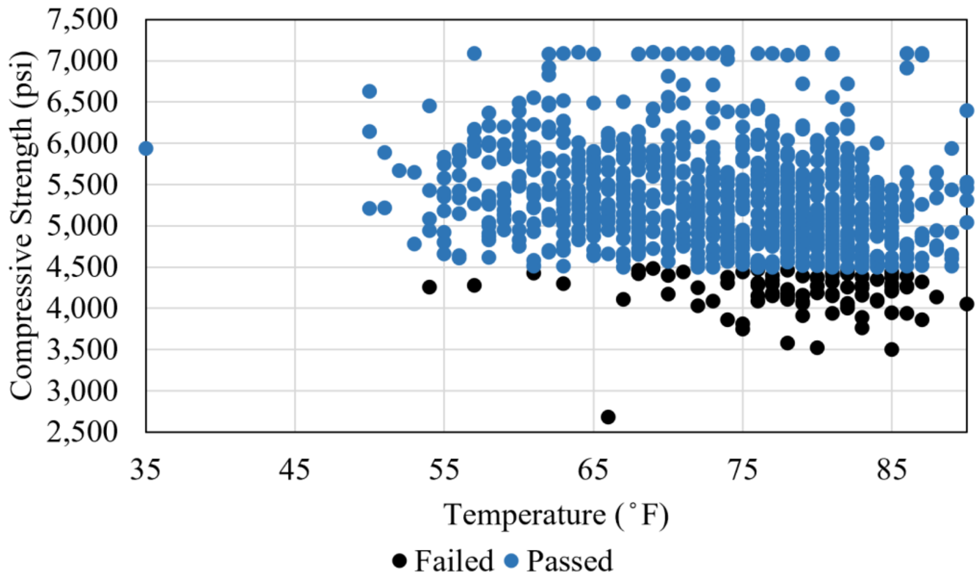


Figure 13: Historical compressive strength vs. concrete temperature

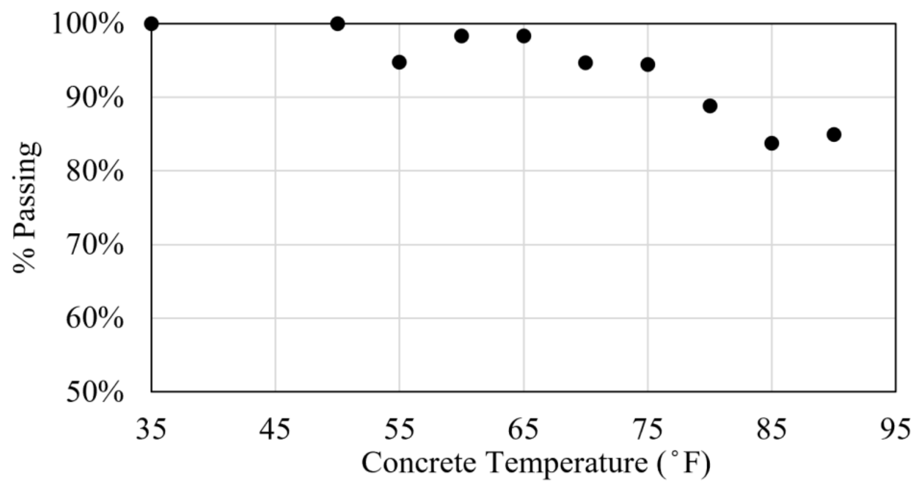


Figure 14: The historical influence of concrete temperature on the passing rate of concrete compressive strength cylinders

Table 27: Summary of the data from Figure 14

Concrete Temperature (˚F)	Passing (%)
35	100
50	100
55	95
60	98
65	98
70	95
75	94
80	89
85	84
90	85

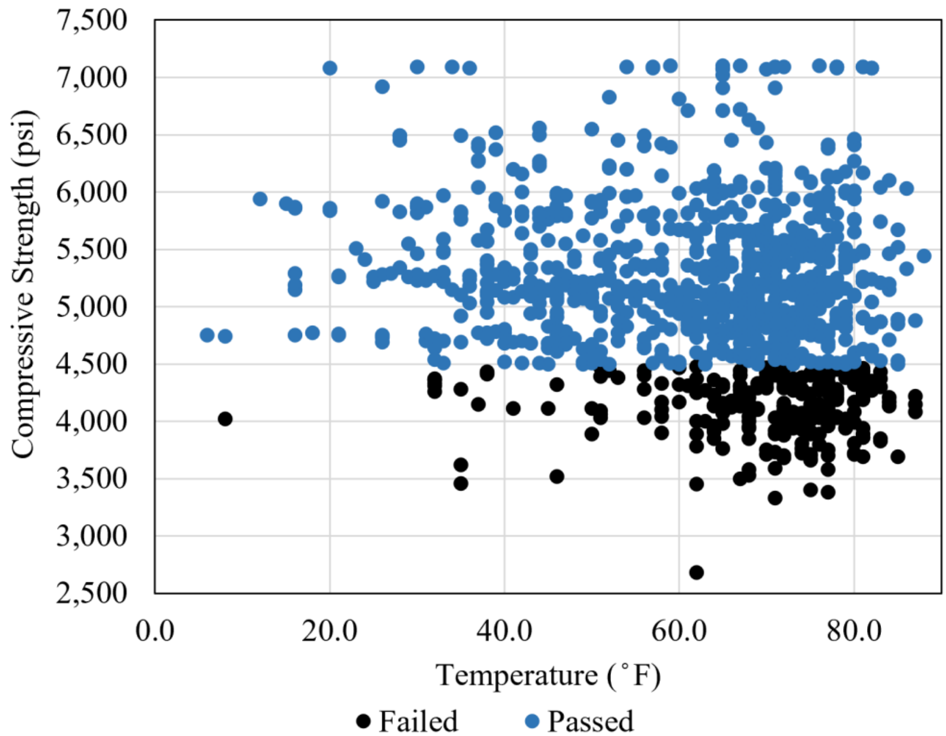


Figure 15: Historical compressive strength vs. average daily temperature

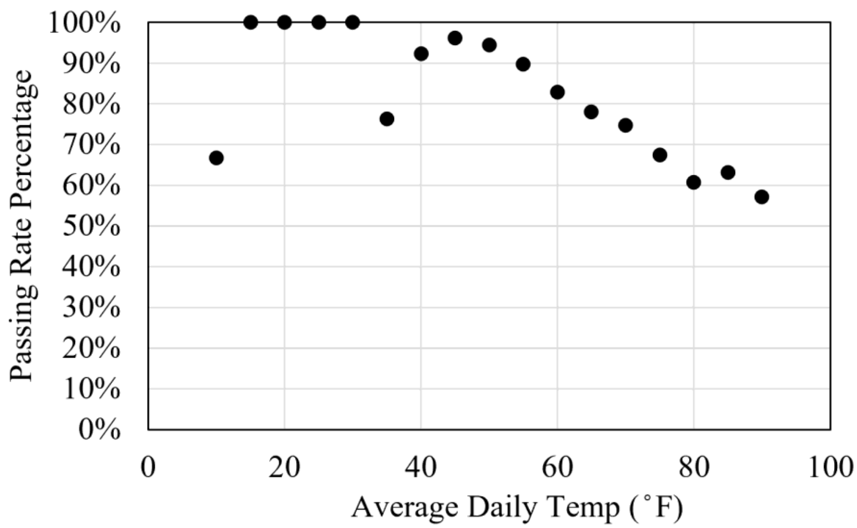


Figure 16: The historical influence of average daily temperature on the passing rate of concrete compressive strength cylinders

Table 28: Summary of the data from Figure 16

Average Daily Temp (˚F)	Passing (%)
10	67
15	100
20	100
25	100
30	100
35	76
40	92
45	96
50	94
55	90
60	83
65	78
70	75
75	67
80	61
85	63
90	57

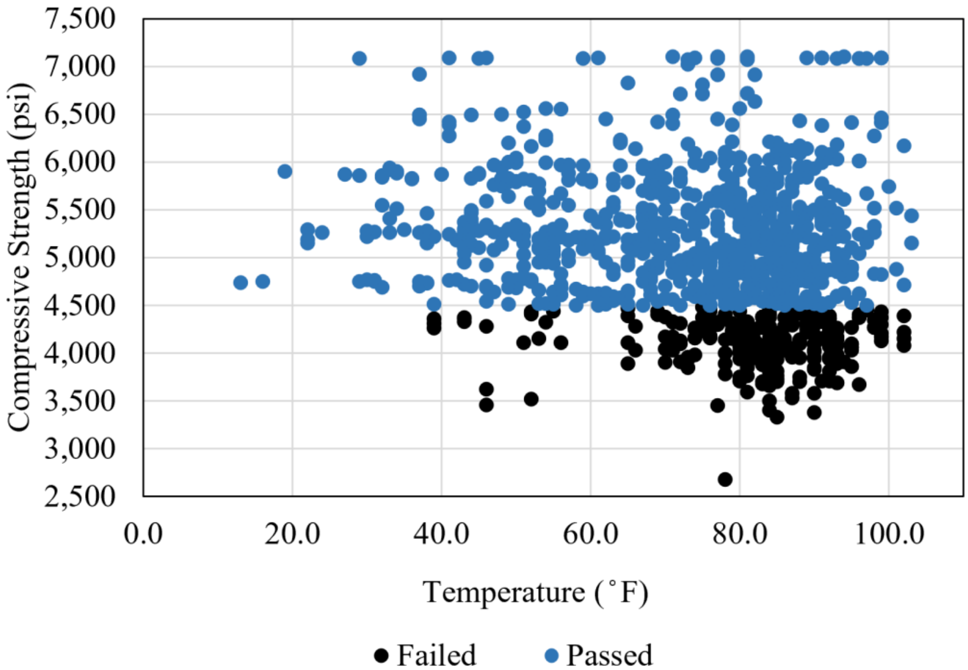


Figure 17: The historical influence of daily high temperature on the passing rate of concrete compressive strength cylinders

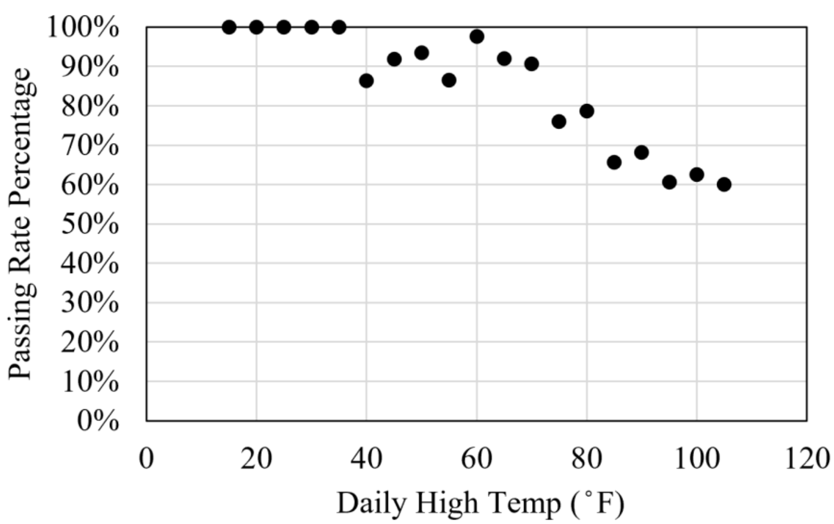


Figure 18: The historical influence of daily high temperature on the passing rate of concrete compressive strength cylinders

Table 29: Summary of the data from Figure 18

Daily High Temp (˚F)	Passing (%)
15	100
20	100
25	100
30	100
35	100
40	86
45	92
50	93
55	86
60	98
65	92
70	91
75	76
80	79
85	66
90	68
95	61
100	63
105	60

Figure 19 and Table 30 show the pass/fail numbers for the mixes that omitted and included coal ash as a partial substitute for cement. It appears that the use of coal ash did not have a significant impact on strength failure for this data. Some mixes had batches with both coal ash and no coal ash (intermixed) which is represented as the “Mixed Fly Ash Mixes”. The no-coal ash mixes had a higher fail rate, but in general represented a much lower fraction of the overall mix designs.

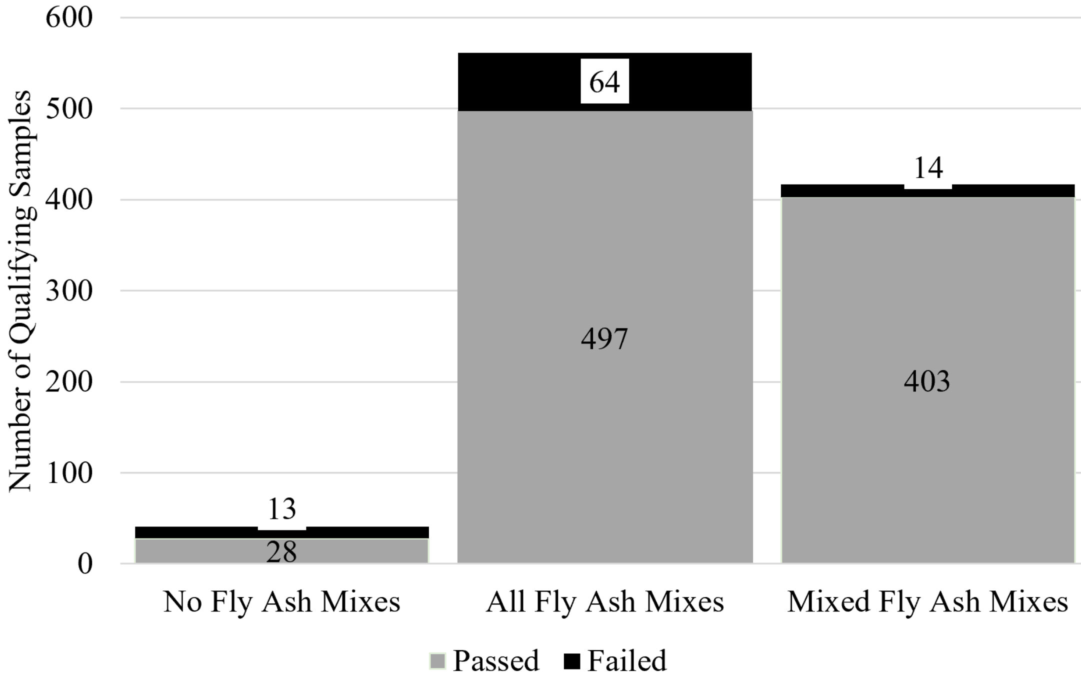


Figure 19: Coal ash pass/fail numbers

Table 30: Summary of the data from Figure 19

Mix Classification	Number of Specimens	Number of Specimens Passing	Percent of Specimens Passing	Number of Specimens Failing	Percent of Specimens Failing
No Fly Ash	41	28	68%	13	32%
All Fly Ash	561	497	89%	64	11%
Mixed Fly Ash	417	403	97%	14	3%

No strong correlations were found with slump and unit weight. Appendix D shows additional plots correlating slump and unit weight parameters to compressive strength and passing rates. Unit weight and air content are negatively correlated. As such, lower unit weight mixes generally had higher failure rates.

The impact of material suppliers, types, and sources were also assessed. Report cards were created to indicate each supplier's passing rate in the given data set. Once again, this data does not represent all SDDOT batches of concrete, but rather only those with at least one failed cylinder. Table 31 shows the various concrete supplier's report cards. Concrete Supplier N has the lowest passing rate but also had a low number of samples. Table 32 and Table 33 shows the passing rates of different coal ash and cement types. Of the cements used in the failed batches, Cement Source B Type 2 and Cement Source C Type 2 showed the lowest passing rates, but both still pass above 80%. Table 34 and Table 35 display all the sources for fine and coarse aggregates along with their corresponding passing rates. There does not appear to be any major outliers with a high number of samples other than the Fine Aggregate Source A Pit 3, which exhibited the lowest pass rate.

Table 36 is the admixture report card and includes all the admixture combinations that were used in the projects included in the dataset. There is a correlation with low passing rates of admixture combinations and concrete suppliers who also had lower passing rates. Some most frequently used admixtures had relatively high passing rates since they were used throughout the state in most mix designs. Others were among the admixture combinations that had lower passing rates. No admixture combination with a large sample size had very low passing rates. Correlations with this data and other parameters could be influencing these results so it is unknown if these suppliers and/or materials are the sole cause of the low strength results.

Table 31: Concrete supplier report card

Concrete Supplier	# of Samples	% Passing
Concrete Supplier A	33	97%
Concrete Supplier B	59	97%
Concrete Supplier C	23	96%
Concrete Supplier D	440	94%
Concrete Supplier E	26	92%
Concrete Supplier F	10	90%
Concrete Supplier G	187	89%
Concrete Supplier H	97	89%
Concrete Supplier I	26	89%
Concrete Supplier J	52	83%
Concrete Supplier K	34	74%
Concrete Supplier L	15	73%
Concrete Supplier M	10	63%
Concrete Supplier N	7	43%

Table 32: Coal ash type report card

Coal Ash Source	# of Samples	% Passing
Coal Ash Source A Type 1	59	97%
Coal Ash Source B	26	94%
Coal Ash Source A Type 2	934	92%

Table 33: Cement source report card

Cement Source	# of Samples	% Passing
Cement Source A Type 1	4	100%
Cement Source A Type 2	30	98%
Cement Source B Type 1	520	89%
Cement Source C Type 1	125	87%
Cement Source C Type 2	33	84%
Cement Source B Type 2	307	81%

Table 34: Fine aggregate sources report card

Fine Aggregate Source	# of Samples	% Passing
Fine Aggregate Source A Pit 1	33	97%
Fine Aggregate Source B Pit 1	76	96%
Fine Aggregate Source B Pit 2	21	95%
Fine Aggregate Source C Pit 1	386	92%
Fine Aggregate Source D Pit 1	50	91%
Fine Aggregate Source C Pit 2	56	90%
Fine Aggregate Source D Pit 2	170	89%
Fine Aggregate Source E	153	86%
Fine Aggregate Source B Pit 3	28	84%
Fine Aggregate Source F	12	75%
Fine Aggregate Source A Pit 2	2	75%
Fine Aggregate Source A Pit 3	23	65%

Table 35: Coarse aggregate sources report card

Coarse Aggregate Source	# of Samples	% Passing
Coarse Aggregate Source A Pit 1	23	96%
Coarse Aggregate Source B Pit 1	21	95%
Coarse Aggregate Source B Pit 2	17	94%
Coarse Aggregate Source C	503	92%
Coarse Aggregate Source D	220	91%
Coarse Aggregate Source A Pit 2	10	90%
Coarse Aggregate Source E	187	89%
Coarse Aggregate Source B Pit 3	38	87%

Table 36: Historical admixture combination report card

Concrete Suppliers	Admixture Combinations	# of Samples	% Passing
Concrete Supplier B	Admixture Combination A	8	100%
Concrete Supplier G	Admixture Combination B	7	86%
Concrete Supplier J	Admixture Combination C	8	88%
Concrete Supplier A	Admixture Combination D	33	97%
Concrete Supplier K	Admixture Combination E	9	67%
Concrete Supplier H	Admixture Combination F	7	86%
Concrete Supplier H	Admixture Combination G	35	94%
Concrete Supplier L	Admixture Combination H	2	50%
Concrete Supplier N	Admixture Combination I	7	43%
Concrete Supplier L	Admixture Combination J	11	82%
Concrete Supplier J and L	Admixture Combination K	35	86%
Concrete Supplier J	Admixture Combination L	9	100%
Concrete Supplier M and J	Admixture Combination M	4	75%
Concrete Supplier I and H	Admixture Combination N	28	86%
Concrete Supplier D	Admixture Combination O	1	0%
Concrete Supplier D and H	Admixture Combination P	9	89%
Concrete Supplier C	Admixture Combination Q	23	96%
Concrete Supplier E	Admixture Combination R	18	94%
Concrete Supplier E	Admixture Combination S	8	88%
Concrete Supplier B	Admixture Combination T	51	96%
Concrete Supplier G	Admixture Combination U	15	60%
Concrete Supplier G	Admixture Combination V	15	93%
Concrete Supplier M	Admixture Combination W	8	50%
Concrete Supplier K	Admixture Combination X	25	76%
Concrete Supplier D	Admixture Combination Y	133	89%
Concrete Supplier I	Admixture Combination Z	12	92%
Concrete Supplier D	Admixture Combination AA	160	96%
Concrete Supplier D	Admixture Combination BB	120	98%
Concrete Supplier H	Admixture Combination CC	32	94%
Concrete Supplier F	Admixture Combination DD	10	90%

The analysis of the historical data showed a strong correlation between compressive strength and both temperature and air content. When the concrete reached 75°F the overall cylinder passing rate started to decrease below 90%. The air content had a steep decrease in passing rate when the concrete had an air content of 6.5% or higher. Additionally, there were some material combinations or suppliers that were also found to have a lower passing rate.

5.3.2 Core Investigation Results

Concrete core compressive strength data was analyzed to investigate any potential differences between the tested cylinders and the in situ concrete they represent. Since it is typically at the contractor's discretion whether to core or not when both acceptance cylinders fail, cores are not always collected when there is a failed cylinder test for a batch. If the contractor chooses to core, three cores are taken from the area deemed to correlate with the failed testing cylinders and the three cores are averaged to get a final compressive strength. Of the 172 failed batches, there were only 33 instances where a coring was utilized. Overall, the cores had a 61% passing rate with 13 of the 33 cores failing. Table 37 and Table 38 shows the comparison between average acceptance cylinder data from two cylinders and compressive strength data from the cores for batches that failed and passed, respectively. For the failed cores, the cores had an average compressive strength only 1% higher than the average cylinder strength. The passing cores had 27% higher average strength compared to the average cylinder strength. Table 39 shows the average ambient temperatures and most frequent concrete parameters observed for the cores. Within parentheses after each listed parameter is the number of observed occurrences for that criterion.

Table 37: Failed core strength data and differences

Failed Specimen	Avg. 28-day Cylinder Compressive Strength (psi)	Avg. Core Compressive Strength (psi)	Core Strength (psi)	Difference (%)
F1	3890	2680	-1210	-31%
F2	4190	3950	-240	-6%
F3	3955	3760	-195	-5%
F4	4250	4130	-120	-3%
F5	4090	4030	-60	-1%
F6	3820	3810	-10	-0.3%
F7	3990	4160	170	4%
F8	3890	4100	210	5%
F9	3660	3890	230	6%
F10	4030	4380	350	9%
F11	3845	4420	575	15%
F12	3540	4280	740	21%
Average	3929	3966	37	1%
Standard Dev.	204	456	494	13%

Table 38: Passed core strength data and differences

Passed Specimen	Avg. 28-day Cylinder Compressive Strength (psi)	Avg. Core Compressive Strength (psi)	Core Strength (psi)	Difference (%)
P1	4180	4760	580	14%
P2	4125	4780	655	16%
P3	4075	4840	765	19%
P4	3925	4700	775	20%
P5	4115	4980	865	21%
P6	3930	4850	920	23%
P7	4060	4990	930	23%
P8	4210	5190	980	23%
P9	4170	5280	1110	27%
P10	3725	4760	1035	28%
P11	3570	4600	1030	29%
P12	4020	5230	1210	30%
P13	3680	4820	1140	31%
P14	3530	4650	1120	32%
P15	3895	5140	1245	32%
P16	4255	5690	1435	34%
P17	4070	55`30	1460	36%
P18	3690	5220	1530	41%
P19	4135	5940	1805	44%
P20	3915	5790	1875	48%
Average	3957	5001	1044	27%
Standard Dev.	228	308	269	7%

Table 39: Cored concrete observances

Parameter	Failed Core	Passed Core
Average Daily Avg. Temp.	69˚F	64˚F
Average Daily High Temp.	82˚F	76˚F
Concrete Supplier	Concrete Supplier D (4)	Concrete Supplier C (11)
Fine Aggregate Source	Fine Aggregate Source E (6)	Fine Aggregate Source C Pit 1(6)
Coarse Aggregate Source	Coarse Aggregate Source B (7)	Coarse Aggregate Source C (12)
Portland Cement	Cement Source B Type 1 (7)	Cement Source B Type 2 (12)
Admixture Combination	Admixture Combination K (4)	Admixture Combination Y (6)

It is difficult to make a direct comparison between the acceptance cylinders to their cored counterpart. The cores are tested at ages sometimes a month or older compared to the cylinder, giving the core more time to mature. Additionally, it is unlikely the cored sample will consist of the same concrete batch that the cylinder's concrete is representing. In the context of these limitations, the data suggests that in situ concrete strength was more often stronger on average than the test cylinder cast to represent it.

5.3.3 Technician Interview Analysis

After the analysis of the historical data, a better understanding of the procedures of casting, transporting, and testing the cylinders that occur in the field was desired. This information was gathered through interviews with six technicians spread amongst the Rapid City, Sioux Falls, Mitchell, and Yankton areas. While most of the six technicians walked through the process as required by the manual, the following discrepancies were noted:

- Testing frequency differed from the manuals. Instead of a per volume of concrete sampling frequency, they each expressed a time frame for when cylinders would be made for strength acceptance. A consensus was that, at a minimum, a set of cylinders would be made every two hours for concrete paving or every one hour for structural or bridge decks.
- Curing of cylinders on site did not have strict temperature control. Many technicians noted they do not measure temperature in the curing coolers to ensure they are within specified limits.
- Transportation of the cylinders is not in a manner that is protected from jarring/excessive bumps. The cylinders are mostly placed on a pallet with no vibration protection.

These noted discrepancies informed the development of the experimental testing matrix. The technicians were also asked if they had any opinions on the cause of low strength cylinders. Some said they were unsure what was causing it, but those who did provide their insight all believed it had something to do with the concrete materials, with an emphasis on the cement type.

5.3.4 SDDOT Concrete Supplier and National DOT Survey Analysis

The perspectives of the concrete suppliers on low strength issues were collected through a survey. Only two suppliers completed the survey. The survey questions and the full results of the survey can be found in Appendix E.

Both suppliers had supplied the SDDOT with concrete mixes in the last five years that had cylinders not meet their specified strength. One supplier stated that they were never able to figure out the cause of the issues, but that it suddenly resolved. Their issues occurred over the Covid-19 pandemic so they conjectured that it may have been caused by staffing shortages. The second supplier chose water/cementitious ratio, curing method, concrete temperature, air content, supplementary cementitious material source, retempering, specimen handling and testing procedures as the potential affecting factors. Both suppliers said none of their clients other than the SDDOT had test batches that did not meet strength requirements.

One supplier did have a response when asked if they had any recommendations to reduce low strength concrete issues related to SDDOT projects. They said “utilizing concrete cylinders that are 4x8 can be handled and stored easier. Breaking 28-day test cylinders at a local lab and not transporting to Pierre for verification. The DOT needs to adopt testing concrete at the back of the truck and not at point of placement with pump. In many occasions we are seeing higher air content than what is required due to the effects of the pump to the concrete.” Finally, both suppliers were asked if they had any other comments to provide the research team. One thought it would be helpful if the DOT would allow them to use a set retardant without special provisions which could potentially help keep the w/cm ratio lower, retemper the concrete, and increase strength. The other supplier stated that they have produced A-45 mixes on projects not for the SDDOT and they have had no issues reaching strength. They also stated that they have tested concurrently with the SDDOT and had the same low-test results.

A 17-question survey was sent to all 50 DOTs along with a couple of Canadian departments to gain insight on their structural mix designs as well as any low strength issues (see Appendix E for survey questions). Twenty-two DOTs from around the country responded to the survey with one Canadian response. All six of the states that border South Dakota responded to the survey. Full results of the survey can be found in Appendix E.

The responses were broad when responding to how many different cast-in-place structural concrete mix designs each DOT had used in the last five years. Seven DOTs listed fewer than fifteen while four DOTs stated they used thousands of mix designs. The minimum specified strength requirements for those mixes were also varied, but 67% of the responses had a 4000 psi minimum. Minimum values up to 10000 psi were also reported. All the responders who answered at what age the cylinders are tested chose 28-days, with 17% also including 56-day testing as a common project requirement.

Seventy-four percent of the DOTs stated that within the last five years some cast-in-place structural concrete mixes had field tests that did not meet strength requirements. When asked on average how many low strength field test batches per year occur, all responses stated it was a very rare occurrence with 31% stating occurrences around 10-20 per year, 31% said 1-3, and 19% said less than 1%. To compare, the SDDOT had 28 failed test batches last year. Only 11% of those who had experienced low strength tests said they noticed an increase in mixes not meeting strength within the last two years, which is a phenomenon recently experienced by SDDOT.

The next questions were asking the opinions of the responder on what caused their low strength outcomes. Table 40 reflects the answers that were provided when asked which factors the responders believed led to low strength tests. The cylinder's curing method and handling procedures were the most popular answers. When asked to provide any additional clarification for the above factors, most emphasized the importance of properly handling the cylinders in extreme weather conditions. Poor field curing/handling, cement source, and the learning curve of using Type IL cement were additional factors listed that affected the cylinders strength. Kansas DOT also explained that some of their issues stemmed from chemical admixture interactions.

Table 40: DOT survey response to "Which factors cause low strength outcomes?"

Strength Affecting Factors	Response
Specimen Handling Procedures	56%
Curing Method	50%
Air Content	44%
Lack of Quality Control	39%
Water/Cementitious Ratio	33%
Aggregates Source	22%
Concrete Temperature	17%
Cement Source	17%
Supplementary Cementitious Material Source	17%
Retempering	17%
Mix Design	11%
Specimen Testing Procedures	11%
Humidity	6%
Admixtures	6%
Cold/Hot weather protection not being implemented.	6%
Chemical Admixture Interaction when incorrect batch procedure is used - i.e. adding AEA with PLS in headwater, and then adding water at the job.	6%
Moisture intrusion into portland Cement storage silo	6%
Variability in the production of concrete	6%

Not getting wash water out before batching.	6%
Pump truck operator adding water	6%
High SCM dosage rates	6%

The responses when providing recommendations to reduce low strength concrete issues or other information the respondents wanted to share are shown below in Table 41. Additionally, Kansas DOT noted that they are currently evaluating a tool called the Pheonix to be deployed into the field to measure the concrete's w/cm ratio. Wyoming DOT stated they are trying to implement a stricter w/cm ratio specification to stop suppliers from trying to compensate for previous low strength projects by increasing the cement content of the next mix design, which is increasing the cost of the mix for the state while not providing a consistent positive result.

Table 41: DOT survey response to "Recommendations to reduce low strength concrete issues."

State	Recommendation
Missouri	Missouri DOT allows high range water reducer (HRWR) to be added at the job site. It is critical to check the air after adding the HRWR as it can generate air. We had a few projects where the air content was checked prior to adding the HRWR but was not checked after adding the admixture. The air content can be well over 8 percent.
Michigan	Control w/cm and cure properly
North Dakota	Utilize maturity to verify, assure cylinders are treated properly, and test project level cement supplies.
Delaware	Concrete curing temperature, dirty aggregate and air content
Louisiana	We require curing boxes that are temperature controlled to alleviate issues associated with extremely high temperatures in the summertime.
Utah	A good QC process catches most issues before the concrete is poured.
Massachusetts	Follow ACI 318 recommendations on all structural concrete design, testing, protection, etc.
Kansas	Get a Go Pro on a stick and check trucks for onboard water after wash out. Monitor fin wash down time to be less than 1 min. (1 min with a standard garden hose = 5 gallons of water). Use correct batch procedure. Actually measure stockpile moistures and use correct specific gravities on mix design. DO NOT ADD ADDITIONAL WATER AT THE JOB if any plasticizing admixture is used in the mix.
Rhode Island	The mixes we get tend to be overdesigned because of the way we accept material. It's cheaper for the producers to go high on the strength, rather then risk a reduced pay factor. We are currently working on a PWL spec that will reduce the need to overdesign (which creates its own issues). Note that we do have low breaks on some of our Class XX (4000 psi) mixes. But those are rare (<1%/yr)

State	Recommendation
Rhode Island	and are generally because some producers don't use pozzolans (smaller outfits that have trouble setting up batching equipment for the materials). We would put them out of business for State work if we required pozzolans for that class and having limited options (RI is small), that doesn't make sense for us. XX is used for less demanding applications like commercial driveways and footings. All higher strength mixes require pozzolans.
Alaska	For the few concrete plants that operate with minimum QC State DOTs should consider adding an annual plant inspection. Require NRMCA Plant Certification
Montana	Making sure they provide trial batch data for proposed mix designs and ensuring the field is verifying the design matches the approved design for proportioning and materials.
Colorado	More quality control at the batch plant. We have seen better results on pavement when the contractor took ownership of QC in an effort to earn incentive payments for strength and consistency. We have a few low strength field cylinder test per year. We maybe thought with our change to PEM that lower cement contents could increase the number of low breaks. Most ready mixed suppliers still stick to their old tried and true mixes which are overdesigned by at least 15%. We do allow coring to dispute cylinder strength. Generally with cylinders that are up to 500 psi below required strength, the cores show a higher strength and meet the minimum. Coring on lower strengths generally validate the low cylinder strength. We have had more issues with flexural strength on pavements, but think its a testing issue.
Minnesota	For some mixes, either lower the 28-day strength requirement or move final acceptance for strength out to 56 days. MnDOT often sees low strengths on a project level, not so much a mix design level. We have on occasion seen that at a few plants and we then require the Producer to make an adjustment to the mix design which usually involves adding 5-10 pounds of cement. Other than HPC bridge deck, SCC and mass concrete mixes, MnDOT doesn't require trial batching or mix verification prior to use of the mix designs unless the Producer wants to use more than 15% fly ash. MnDOT standard designed mixes for many years contained 15% fly ash so when we transitioned to Contractor designed mixes, we felt it was pretty low risk to not require trial batching for 15% max fly ash mixes.
South Carolina	The handling of the cylinders is important, especially when using 4X8 cylinders.
Iowa	It seems that the Type IL cements with high replacement of slag and fly ash have shown reduced strengths, but still meeting design strength.

Focusing on the six states that surround SD instead of all the respondents did not produce a different interpretation of the overall survey. The responders did not notice an increase in low strength tests over the last two years, and they attributed specimen handling procedures to be the leading causing factor of low strength. Air content and w/cm ratio followed as the second and third leading cause. Additional factors for low strength included curing issues, extreme temperatures, cement sources, and a lack of supplier quality control. Both the North Dakota DOT and Montana DOT respondents included testing the cement supplies or verifying mix design batches in the field to potentially remedy the issue.

Ultimately, this survey showed that while no DOT that responded was as urgently concerned about low strength cylinders as SDDOT, they did note that it happens occasionally. It is evident that many factors were observed to potentially affect cylinder strength for the various DOTs, however handling/curing of the cylinders specifically during extreme temperatures emerged as a leading cause of low strength issues.

5.3.5 In Field Curing Temperature Results

The temperature of the ambient conditions, the curing container environment, and concrete cylinders from seven concrete pours batched throughout September 2023 in Sioux Falls, SD were recorded using SmartRock technology. Four cylinder sample sets were measured in the closed cooler condition while three were measured in the cracked open condition. Figure 20 shows the temperature progression of the outside temperature, two measured cooler inside temperatures (lid and floor), and the concrete cylinder temperature for the sample with the hottest observed exterior and cylinder temperatures. Figure 21 shows the same data for the hottest observed cooler temperature. Both were observed in the closed cooler condition. Summary tables for the data in Figure 20 and Figure 21 can be found in Appendix H in Table 91 and Table 92. The other five cylinder data sets can be seen in Appendix F.

Table 42 and Table 43 show the recorded minimum and maximum values for each of the four readings for all seven samples and the average cooler temperature. A varied temperature differential exists between the inside and outside of the cooler and with the concrete cylinder temperature.

Table 44 shows the recorded overall minimum and maximum readings for the closed and cracked open cooler data sets. In general, maximum observed temperatures in the coolers and cylinders were only slightly lower for the closed cooler compared to the cracked open cooler. Minimum temperatures were higher for the closed coolers, however that could be a result of the higher outside minimum temperatures. For reference, the average initial fresh concrete temperature for the closed samples was 72.1°F and for the cracked open samples was 70.4°F.

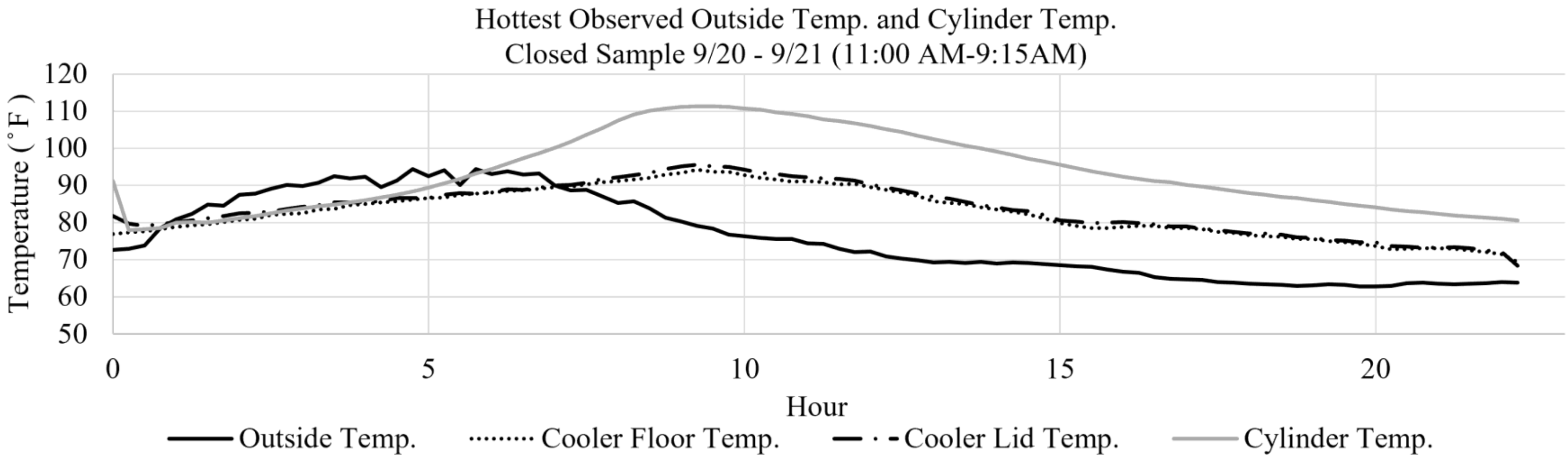


Figure 20: Closed SmartRock sample 9/20-9/21

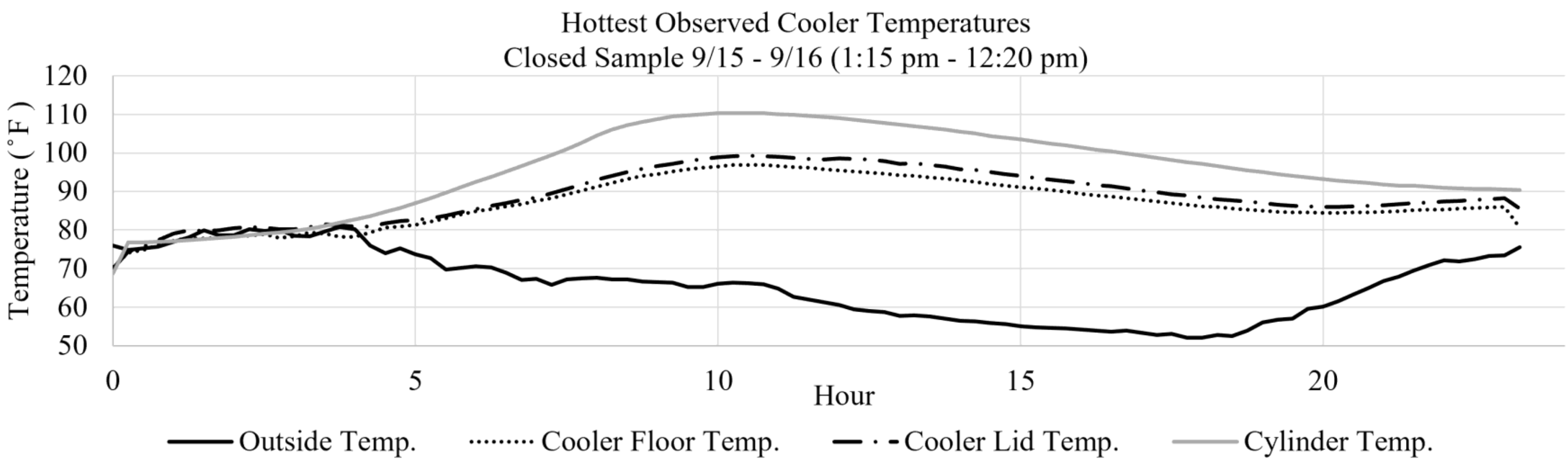


Figure 21: Closed SmartRock sample 9/15-9/16

Table 42: Smart Rock closed cooler sample minimum and maximum values

Sample Dates	Stat	Outside Temp. (˚F)	Floor Temp. (˚F)	Lid Temp. (˚F)	Avg. Cooler Temp. (˚F)	Cylinder Temp. (˚F)
9/12 – 9/13 6:38 a.m. – 7:08 a.m.	Min.	52.4	52.6	51.3	52.0	53.4
9/12 – 9/13 6:38 a.m. – 7:08 a.m.	Max.	80.0	86.4	89.0	87.7	96.1
9/15 – 9/16 1:08 p.m. – 12:23 p.m.	Min.	52.2	70.4	70.0	70.2	68.8
9/15 – 9/16 1:08 p.m. – 12:23 p.m.	Max.	80.8	96.9	99.2	98.1	110.2
9/20 – 9/21 10:53 a.m. – 9:08 a.m.	Min.	62.7	69.5	68.3	68.9	77.9
9/20 – 9/21 10:53 a.m. – 9:08 a.m.	Max.	94.4	94.2	95.5	94.9	111.3
9/27 – 9/28 9:08 a.m. – 4:23 p.m.	Min.	55.2	64	63.7	63.9	67.3
9/27 – 9/28 9:08 a.m. – 4:23 p.m.	Max.	85.6	90	92.0	91.0	101.0

Table 43: Smart Rock cracked cooler sample minimum and maximum values

Sample Dates	Stat	Outside Temp. (˚F)	Floor Temp. (˚F)	Lid Temp. (˚F)	Avg. Cooler Temp. (˚F)	Cylinder Temp. (˚F)
9/8 – 9/9 9:38 a.m. – 7:08 a.m.	Min.	63.7	68.2	71.4	69.8	71.5
9/8 – 9/9 9:38 a.m. – 7:08 a.m.	Max.	90	94.7	96.9	95.8	108.7
9/14 – 9/15 7:23 a.m. – 8:53 a.m.	Min.	60.4	60.4	61.4	60.9	59.0
9/14 – 9/15 7:23 a.m. – 8:53 a.m.	Max.	89.4	88.4	88.2	88.3	106.4
9/19 – 9/20 10:23 a.m. – 9:23 a.m.	Min.	61.4	66.9	66.8	66.9	72.1
9/19 – 9/20 10:23 a.m. – 9:23 a.m.	Max.	87.1	91.0	91.8	91.4	110.4

Table 44: Recorded minimum and maximum SmartRock data

Stat	Outside Temp. (°F)	Floor Temp. (°F)	Lid Temp. (°F)	Cylinder Temp. (°F)
Closed Cooler Min.	52.2	52.3	51.3	53.4
Closed Cooler Max.	94.4	96.9	99.2	111.3
Cracked Cooler Min.	60.4	61.6	61.4	59.0
Cracked Cooler Max.	90.0	94.7	96.9	110.4

Table 45 shows the calculated average temperature differentials for the maximum observed temperatures between: (1) the cooler temp and the outside temperature, (2) the cylinder temperature and the outside temperature, and (3) the cylinder temperature and the cooler temperature. The minimum and maximum differences between maximum observed temperatures are also reported. The closed samples have a higher average maximum temperature differential between the cooler and outside temperature (an increase of 4.7 ˚F). However, the differential between the cylinder and outside/cooler temperature was higher for the cracked samples.

Table 45: Differentials observed from maximum SmartRock data

Stat	Cooler Temp. - Outside Temp. (°F)	Cylinder Temp. – Outside Temp. (°F)	Cylinder Temp. – Cooler Temp. (°F)
Closed Cooler Avg.	7.7	12.8	11.8
Closed Cooler Min.	0.4	9.7	8.4
Closed Cooler Max.	17.3	17.1	16.5
Cracked Cooler Avg.	3.0	17.1	16.7
Cracked Cooler Min.	-1.1	14.0	12.9
Cracked Cooler Max.	5.8	19.4	19.0

The average increase in the maximum temperature inside the cooler compared to the outside temperature was 7.7° F and 3.0° F for the closed and cracked samples, respectively. Likewise, the average increase in the maximum temperature inside the cylinders compared to the outside temperature was 12.8° F and 17.1° F for the closed and cracked samples, respectively.

The hottest day last year in Sioux Falls, SD occurred on July 26^{th} reaching 104 ˚F (Sioux Falls Weather, 2023). Therefore, it can be estimated from the average maximum temperature increase that the cooler on such a day could theoretically reach 111.7 ˚F if closed or 107 ˚F if cracked. Furthermore, it can be estimated from the average maximum temperature increase that the cylinders on such a day could theoretically reach 116.8 ˚F if closed or 121.1 ˚F if cracked, assuming a similar fresh initial cylinder temperature (i.e., between 70.4°F -72.1°F). If the worst case scenario was considered by taking the maximum observed difference, the cooler on such a day could theoretically reach 121.3°F if closed or 109.8 ˚F if cracked.

For further comparison, the average temperature and average temperature differential data for the entire period was analyzed. Table 46 shows the average outside, cooler, and cylinder temperatures for all samples for the entire period. Table 47 shows the calculated average temperature differentials between: (1) the cooler temp and the outside temperature, (2) the cylinder temperature and the outside temperature, and (3) the cylinder temperature and the cooler temperature. The average difference and the minimum and maximum differences over the entire period are reported. From this data, there is a more pronounced difference between the closed and cracked samples, with the closed samples having a higher temperature differential between the cooler and outside temperature (an increase of 9.2˚F) and between the cylinder and outside temperature (an increase of 7.5°F). The differential between the cylinder and cooler temperature was slightly higher for the cracked samples. Note that when there were no cylinders in the coolers, the closed coolers were an average of 4.8˚F hotter than the average recorded outside temperature. Therefore, the heat of hydration of the cylinders increased the cooler temperature by an average of 9.1˚F.

Table 46: SmartRock data average values

Stat	Outside Temp. (˚F)	Cooler Temp. (˚F)	Cylinder Temp. (˚F)
Closed Cooler Avg.	68.3	82.2	88.8
Cracked Cooler Avg.	73.7	78.4	86.8

Table 47: SmartRock data average differences

Stat	Cooler Temp. – Outside Temp. (˚F)	Cylinder Temp. – Outside Temp. (˚F)	Cylinder Temp. – Cooler Temp. (˚F)
Closed Cooler Avg.	13.9	20.6	6.6
Closed Cooler Min.	-6.1	-7.3	-1.9
Closed Cooler Max.	28.3	39.4	18.2
Cracked Cooler Avg.	4.7	13.1	8.4
Cracked Cooler Min.	-8.5	-10.9	-5.7
Cracked Cooler Max.	13.9	30.45	18.4

The hottest day last year in Sioux Falls, SD occurred on July 26th reaching 104˚F with a low of 75˚F with an average daily temperature of 85˚F (Sioux Falls Weather, 2023). Using this average temperature as the basis, it can be estimated from the average temperature increase that the average temperature in the cooler on such a day could theoretically be 98.9˚F if closed or 89.7˚F if cracked. Furthermore, it can be estimated from the average temperature increase that the average cylinder temperatures on such a day could theoretically be 105.6˚F if closed or 98.1˚F if cracked, assuming a similar fresh initial cylinder temperature (i.e., between 70.4°F -72.1°F).

Overall, this data shows that the cylinder curing conditions for the first 24 hours were not kept between the specified 60-80˚F. It is unknown if the temperatures in the coolers are representative of the temperatures of the poured in situ concrete on these hot days. Furthermore, the relative humidity inside the coolers was not monitored and may also not match in situ conditions. If not, the cylinders may not represent in situ strength. The differing curing conditions and the heat of hydration of the poured in situ concrete, which would likely be higher compared to the cylinders due to the relative increased size of the poured elements, could also be affecting strength development. Regardless, improvements can be made to field curing conditions.

5.3.6 Fresh Concrete Data

Table 48 shows the fresh concrete data recorded for each batch. All slumps were within the SDDOT required range of 1-5.5 in. and all but one mix with entrained air also fell within the acceptable range of 5.0-8.0%. The mix design that fell outside of this range was the worst-case scenario mix which was designed to have a high air content and to test all parameters, so a higher than acceptable air content was deemed acceptable. The worst-case scenario mix design followed the procedure of retempering but instead of only adding enough water to make it workable up to the limit of 0.4 like the other mixes, this mix did not have a limit. Sufficient water was added to make the concrete workable with a similar consistency to other mixes that were not heated resulting in an actual w/cm of 0.43. As Table 48 shows, the various testing parameters did seem to affect the slump. The average slump for all mixes was 3.1 inches. Also, while air contents of 5% and 8% were targeted, the actual air contents did not hit this exactly but were near these values.

Table 48: Fresh concrete data

Batch Description	Slump (in.)	Unit Weight (ρ) (pcf)	Air Content (%)
Baseline 1*	2.25	155.3	1.3
0.45 w/cm*	3.50	152.4	1.0
100˚F Curing Temp*	2.25	155.3	1.3
100˚F Curing Temp/Hot Concrete*	1.00	153.2	1.6
115˚F Curing Temp*	1.50	153.9	1.5
8% Air Content*	2.50	142.3	7.8
8% Air Content/100˚F Curing Temp*	2.50	142.3	7.8
Baseline 2	3.00	151.4	1.8
5% Air Content	3.00	147.0	5.1
5% Air Content/Retempering	4.50	143.7	5.4
8% Air Content	3.50	141.7	7.0
8% Air Content/Adjusted Aggregate	4.00	141.9	7.2
8% Air Content/Hot Concrete/Retempering	2.50	140.5	8.0
Low Strength Mix Design A	3.50	140.5	7.4
Low Strength Mix Design A/100˚F Curing Temp	3.50	140.5	7.4
Low Strength Mix Design B	4.50	140.1	7.5
Low Strength Mix Design B/100˚F Curing Temp	4.50	140.1	7.5
Worst Case Scenario Mix Design	4.25	133.2	10.0

*Designates mixes using first coal ash batch

5.3.7 Compressive Strength Results

Table 49 shows the 28-day compressive strength data for each cylinder tested and the batch average strength and standard deviation. Eight of the eighteen mixes had an average compressive strength less than 4500 psi. The mixes lower than 4500 psi had a combination of high air content and a high curing temperature. Furthermore, the second batch of coal ash that was used resulted in significantly lower concrete strength. Only mixes using this second batch of coal ash produced batches less than the 4500 psi limit. In this study, it is perhaps more prudent to observe how changes in the mix designs and processing affect strength rather than the nominal strength value. Thus, the next sections compare the groups of mixes based on various testing parameters including air content, mix design, high curing temperature, hot concrete, and retempering. In accordance with SDDOT specifications (SD 420), all reported strengths throughout this section were rounded to the nearest 10 psi.

Table 49: 28-day compressive test results (psi)

Batch Description	1st Cylinder	2nd Cylinder	3rd Cylinder	Average	Standard Deviation
Baseline 1*	6880	6790	7290	6990	270
0.45 w/cm*	5970	6260	6060	6100	150
100˚F Curing Temp*	5790	5960	6160	5970	180
100˚F Curing Temp/Hot Concrete*	6320	5830	5920	6020	260
115˚F Curing Temp*	5790	5760	6100	5880	190
8% Air Content*	4550	5180	5470	5070	470
8% Air Content/100˚F Curing Temp*	3890	4460	4440	4260	320
Baseline 2	5750	6320	5870	5980	300
5% Air Content	5570	4860	4910	5110	400
5% Air Content/Retempering	4690	4700	4350	4580	200
8% Air Content	3710	4140	3700	3850	250
8% Air Content/Adjusted Aggregate	3890	3860	4080	3940	120
8% Air Content/Hot Concrete/Retempering	3120	2970	3470	3190	260
Low Strength Mix Design A	4000	4680	4160	4280	360
Low Strength Mix Design A/100˚F Curing Temp	3300	3360	3230	3300	70
Low Strength Mix Design B	5200	5120	4950	5090	130
Low Strength Mix Design B/100˚F Curing Temp	4430	3870	4340	4210	300
Worst Case Scenario Mix Design	2150	2410	2140	2230	150

*Designates mixes using first coal ash batch

The Effect of Air Content

Table 50 and Figure 22 show the 7, 14, and 28-day average compressive strengths for five mixes with varied air content including the two baseline mixes, a 5% air content mix, and two 8% air content mixes. For both groups, when looking at the baselines and the mixes with entrained air, the compressive strengths decreased as the air content increased. This observation corresponds with the known negative correlation between air content and strength. For all results, the compressive strength generally increased with age, with 7-day and/or 14-day strength many times reaching similar strengths to

28-day strength. Therefore, the early-age testing performed by SDDOT is a good method to detect potential low strength issues prior to the 28-day test.

Table 51 shows the results from a Tukey-Kramer post-hoc test on the 28-day mean data. Post-hoc testing is used to determine whether independent groups have statistically significant differences. This test assumes the study consists of independent samples, follows a normal distribution of the data, and has equal variance of the subgroup data. This test shows there was a statistically significant pairwise difference between the compressive strengths of the two baseline mix designs compared to the same mixes with increased air contents. An 8% air content resulted in a reduced compressive strength between 28-36% lower than the control, compared to the 15% reduction observed for the 5% air content. For Baseline 2, the increase from 5% to 8% air changed the batch from passing to failing the 4500 psi strength limit.

Table 50: Compressive strength results for air content mixes (psi)

Batch Description	Air Content (%)	7-Day Avg.	7-Day St. Dev.	14-Day Avg.	14-Day St. Dev.	28-Day Avg.	28-Day St. Dev.
Baseline 1*	1.3	5740	330	6390	150	6990	270
8% Air Content*	7.8	4180	580	4680	590	5070	470
Baseline 2	1.8	5050	270	5400	290	5980	300
5% Air Content	5.1	4540	370	4880	70	5120	400
8% Air Content	7.0	3170	130	3660	300	3850	260

*Designates mixes using first coal ash batch

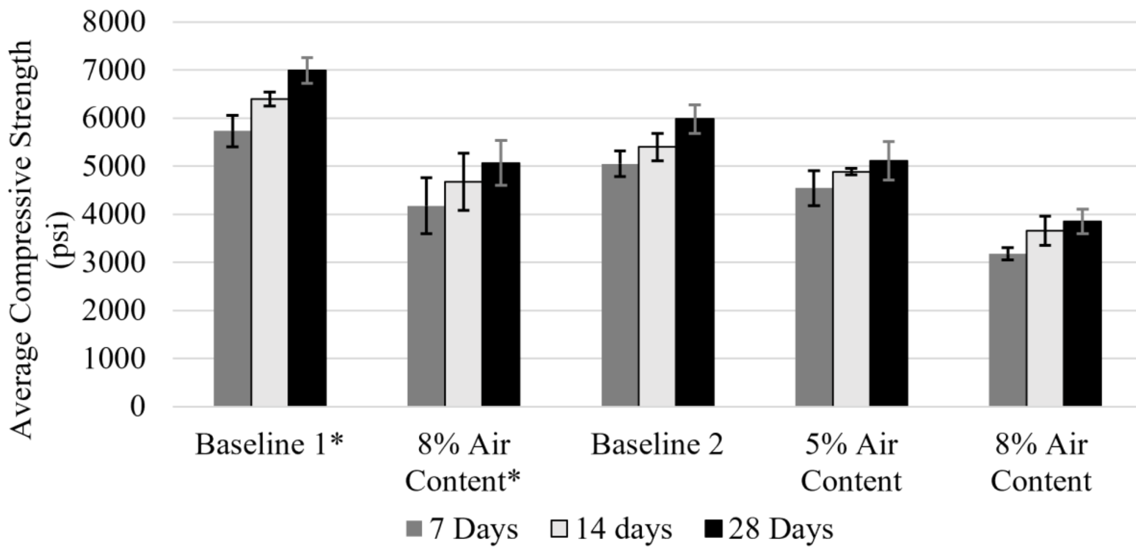


Figure 22: Compressive strength results for air content mixes

Table 51: Post-hoc testing of 28-day mean compressive strengths for air content mixes

Batch Description	Percent Change in Mean Value (%)	Tukey-Kramer: P-Value	Significant Difference (P < 0.05)
Baseline 1*	-	-	-
8% Air Content*	-27.5	0.0035	Yes
Baseline 2	-	-	-
5% Air Content	-14.5	0.0377	Yes
8% Air Content	-35.6	0.0005	Yes

The Effect of Mix Design

Table 52 and Figure 23 show the compressive strengths of the mixes that had varied mix designs. Table 53 shows the results of the Tukey-Kramer post-hoc test for these mixes. The use of a different coal ash and the increase in w/cm from 0.4 to 0.45 both independently resulted in a large reduction in compressive strength. This indicates that changing the cementitious material source can have a significant impact on strength and may warrant a new mix design qualification. In a recent report conducted for NCHRP, similar strength differences were observed for a variety of different tested coal ashes (Shearer et al., 2024). It is possible that testing strength at a later age such as 56-days would result in higher strength values depending on the rate of pozzolanic reactivity for the two different coal ash sources used in this study. These results also highlight the influence of the range of allowable w/cm ratios in the SDDOT specification (dependent on project but not more than 0.45) on potential strength values.

To account for the overyielding that occurred in the air-entrained mixes, another mix with a reduced fine aggregate content was created and called 8% Air Content/Adjusted Aggregate. Results show that making this adjustment did not have a significant impact on 28-day strength when comparing the 8% mix to the same mix with reduced aggregate content. When calculating the actual yield for the non-adjusted 8% air mix, the total cementitious content was theoretically 617 pcy instead of 650 pcy. Note that the 5% air mix would be between 617-650 pcy depending on the actual air content. This is still within the range of the SDDOT specifications, which allows for a cementitious content as low as 600 pcy content without the use of well-graded sand. This research indicates that the lower cementitious content did not significantly change compressive strength.

When comparing mixes made with the lowest strength performing aggregate and admixture combinations (Low Strength Mix Design A and B), both mixes exhibited increased 28-day compressive strength, with mix design B having significantly higher strength. This indicates that the use of these aggregates and admixtures improved strength in lab testing rather than decreased strength as observed in the field. It can be deduced that other factors might have been the cause of the low observed strength. For example, the concrete producers for these concrete mixes had some of the highest failure rates so their practices might have influenced strength more than the materials. One potential cause could be inconsistent or incorrect moisture content adjustments for the aggregate. The batch tickets did not indicate that the field moisture content of the aggregate was being measured and factored into the mix design calculations. However, this could have been completed off the record.

Lastly, the worst-case scenario mix design had a significant 42% reduction in 28-day compressive strength compared to the companion 8% air mix. The combination of high air content, high w/cm ratio, high curing temperature, hot concrete, retempering, and not adjusting for aggregate moisture content synergistically resulted in the lowest strength mixture that was tested. This emphasizes that low strength results in the field are likely a result of more than one issue, but rather a combination of multiple factors such as high air content with hot concrete.

Table 52: Compressive strength results for the varied mix designs (psi)

Batch Description	7-Day Avg.	7-Day St. Dev.	14-Day Avg.	14-Day St. Dev.	28-Day Avg.	28-Day St. Dev.
Baseline 1*	5740	330	6390	150	6990	270
Baseline 2	5050	270	5400	290	5980	300
0.45 w/cm*	4920	650	5820	310	6100	150
8% Air Content	3170	130	3660	300	3850	260
8% Air Content/Adjusted Aggregate	3050	240	3240	170	3940	120
Low Strength Mix Design A	3570	170	3850	240	4280	350
Low Strength Mix Design B	4090	170	4340	280	5090	130
Worst Case Scenario Mix Design	1710	50	1980	100	2240	150

*Designates mixes using first coal ash batch

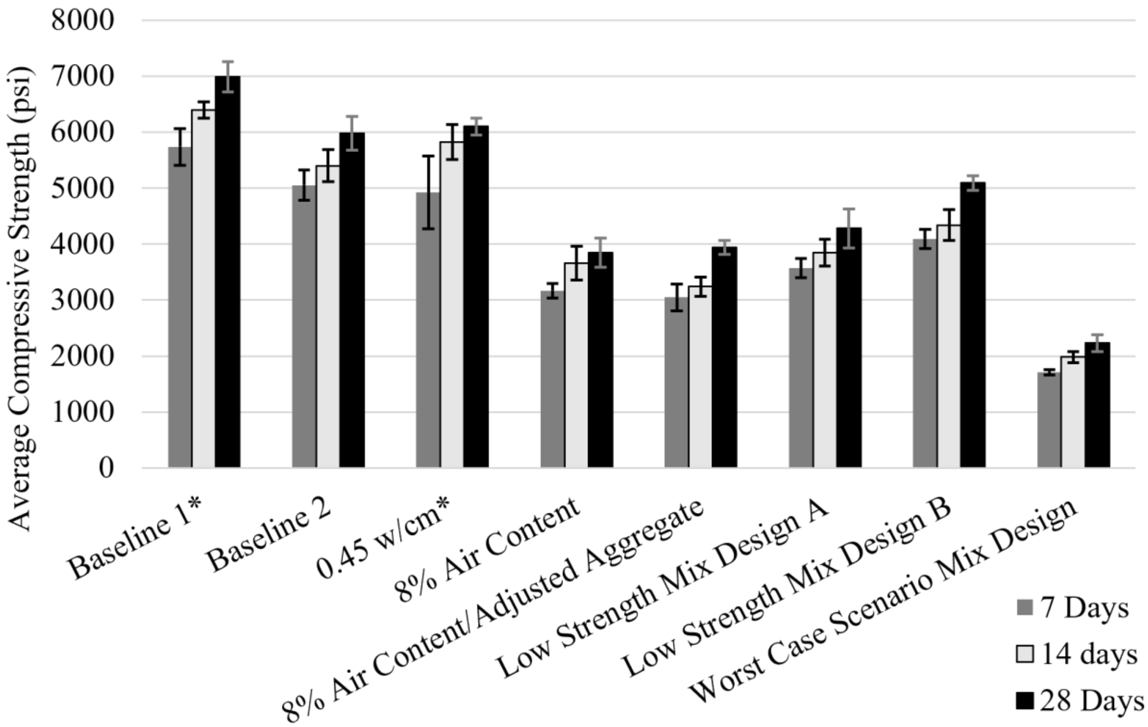


Figure 23: Compressive strength results for the varied mix designs

Table 53: Post-hoc testing of 28-day mean compressive strengths for the varied mix designs

Batch Description	Percent Change in Mean Value (%)	Tukey-Kramer: P-Value	Significant Difference (P < 0.05)
Baseline 1*	-	-	-
Baseline 2	-14.4%	0.0060	Yes
0.45 w/cm*	-12.7%	0.0107	Yes
8% Air Content	-	-	-
8% Air Content/Adjusted Aggregate	2.4%	0.9835	No
Low Strength Mix Design A	11.2%	0.1960	No
Low Strength Mix Design B	32.2%	0.0003	Yes
Worst Case Scenario Mix Design	-42.0%	0.00003	Yes

The Effect of a High Curing Temperature

Four mixes tested the correlation between compressive strength and increased initial curing temperature. These four mixes were cast from the same batch of concrete with one cured at room temperature and the other cured at 100˚F for the first 24 hours. These four batches are therefore identical to each other and have no variances in air content, admixture dosages, or w/cm ratios. Table 54 and Figure 24 show the compressive strength results for these batches. On average, curing the cylinders at 100˚F for the first 24 hours decreased the 28-day compressive strength by 962 psi or 18%.

Table 54: Compressive strength results for high curing temperature mixes (psi)

Batch Description	7-Day Avg.	7-Day St. Dev.	14-Day Avg.	14-Day St. Dev.	28-Day Avg.	28-Day St. Dev.
Baseline 1*	5740	330	6390	150	6990	270
100˚F Curing Temp*	5010	90	5260	280	5970	180
115˚F Curing Temp*	5060	130	5540	160	5880	190
8% Air Content*	4180	580	4680	590	5070	470
8% Air Content/100˚F Curing Temp*	3830	210	4000	530	4260	320
Low Strength Mix Design A	3570	170	3850	240	4280	350
Low Strength Mix Design A/100˚F Curing Temp	2710	200	3200	200	3290	60
Low Strength Mix Design B	4090	170	4340	280	5090	130
Low Strength Mix Design B/100˚F Curing Temp	3290	250	3740	180	4210	300

*Designates mixes using first coal ash batch

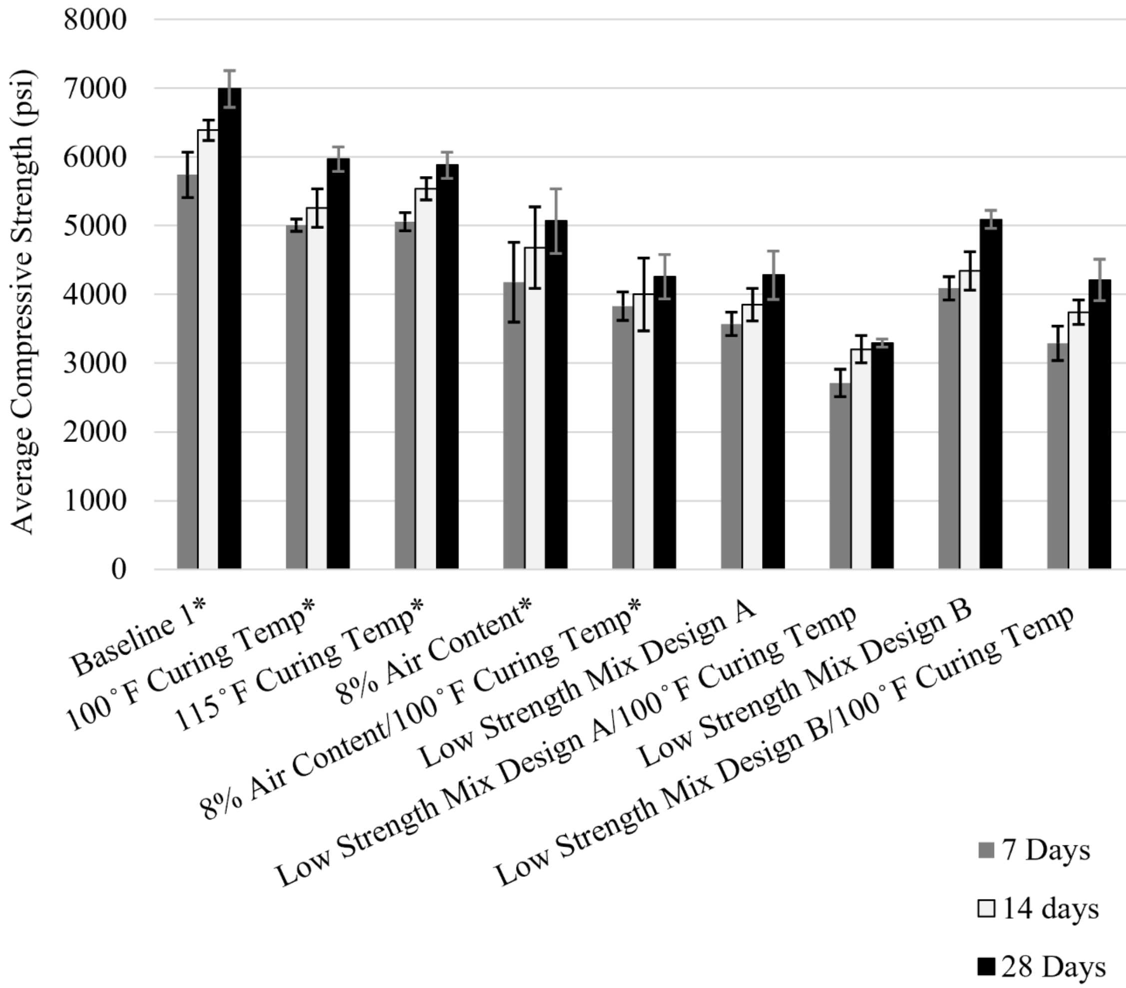


Figure 24: Compressive strength results for high curing temperature mixes

Table 55 shows the post-hoc test results which show that all the reductions in strength were significant except the 8% air content/100˚F Curing Temp* mix. Lastly, the 115˚F Curing Temp*, which was batched separately from Baseline 1*, represented a two-step temperature curing of 115˚F for 12 hours and 70˚F for 12 hours. This resulted in a similar strength reduction to 100˚F curing for 24 hours. Overall, these findings show that high curing temperatures have a significant negative impact on strength. However, more research is needed to determine if the cast-in-place in situ concrete temperatures are higher or lower than the observed cylinder temperatures on hot days.

Table 55: Post-hoc testing of 28-day mean compressive strengths for high curing temperature mixes

Batch Description	Percent Change in Mean Value (%)	Tukey-Kramer: P-Value	Significant Difference (P < 0.05)
Baseline 1*	-	-	-
100˚F Curing Temp*	-14.6%	0.0029	Yes
115˚F Curing Temp*	-15.8%	0.0019	Yes
8% Air Content*	-	-	-
8% Air Content/100˚F Curing Temp*	-15.9%	0.0714	No
Low Strength Mix Design A	-	-	-
Low Strength Mix Design A/100˚F Curing Temp	-23.0%	0.0092	Yes
Low Strength Mix Design B	-	-	-
Low Strength Mix Design B/100˚F Curing Temp	-17.2%	0.0097	Yes

The Effect of Hot Concrete

Two concrete mix pairs show the difference between pouring on a mild temperature day and on a hot day. The concrete temperature for the 100˚F Curing Temp/Hot Concrete* and 8% Air Content/Hot Concrete/Retempering were 90˚F and 89˚F respectively. Table 56 and Figure 25 show the compressive strengths of these four mixes. Table 57 shows the post-hoc test results. The data shows that the change in strength for the 100˚F Curing Temp/Hot Concrete* mix was not statistically significant, but a significant reduction was observed for the 8% Air Content/Hot Concrete/Retempering mix. Therefore, the combination of retempering a hot concrete batch had a much greater effect on strength than the hot concrete alone.

Table 56: Compressive strength results for the hot concrete mixes (psi)

Batch Description	7-Day Avg.	7-Day St. Dev.	14-Day Avg.	14-Day St. Dev.	28-Day Avg.	28-Day St. Dev.
100˚F Curing Temp*	5010	90	5260	280	5970	180
100˚F Curing Temp/Hot Concrete*	5550	340	6090	80	6030	260
8% Air Content	3170	130	3660	300	3850	260
8% Air Content/Hot Concrete/Retempering	2710	400	3100	350	3180	260

*Designates mixes using first coal ash batch

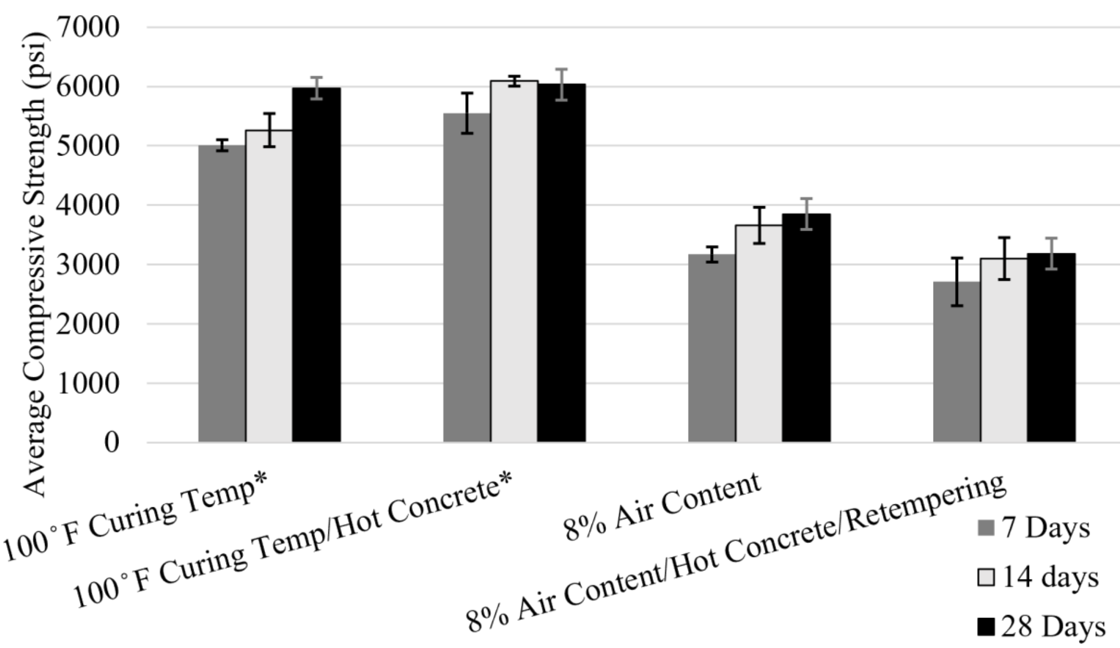


Figure 25: Compressive strength results for the hot concrete mixes

Table 57: Post-hoc testing of 28-day mean compressive strengths for the hot concrete mixes

Batch Description	Percent Change in Mean Value (%)	Tukey-Kramer: P-Value	Significant Difference (P < 0.05)
100˚F Curing Temp*	-	-	-
100˚F Curing Temp/Hot Concrete*	0.9%	0.7871	No
8% Air Content	-	-	-
8% Air Content/Hot Concrete/Retempering	-17.2%	0.0329	Yes

The Effect of Retempering

Retempering the concrete reduced compressive strength. Table 58 and Figure 26 show the two mixes that underwent the retempering procedure along with their respective control batches at both 5% air content and 8% air content. Table 59 shows the post-hoc test results which show retempering by itself did reduce the 28-day compressive strength by over 10%, but the results were not significant. However, when retempering was coupled with hot fresh concrete, the strength reduction was greater and significant. Retempering many times occurs on hot days, so the combination of these two effects is common.

Table 58: Compressive strength results for the retempered mixes (psi)

Batch Description	7-Day Avg.	7-Day St. Dev.	14-Day Avg.	14-Day St. Dev.	28-Day Avg.	28-Day St. Dev.
5% Air Content	4540	370	4880	70	5120	400
5% Air Content/Retempering	3850	200	3800	190	4580	200
8% Air Content	3170	130	3660	300	3850	260
8% Air Content/Hot Concrete/Retempering	2710	410	3100	350	3180	260

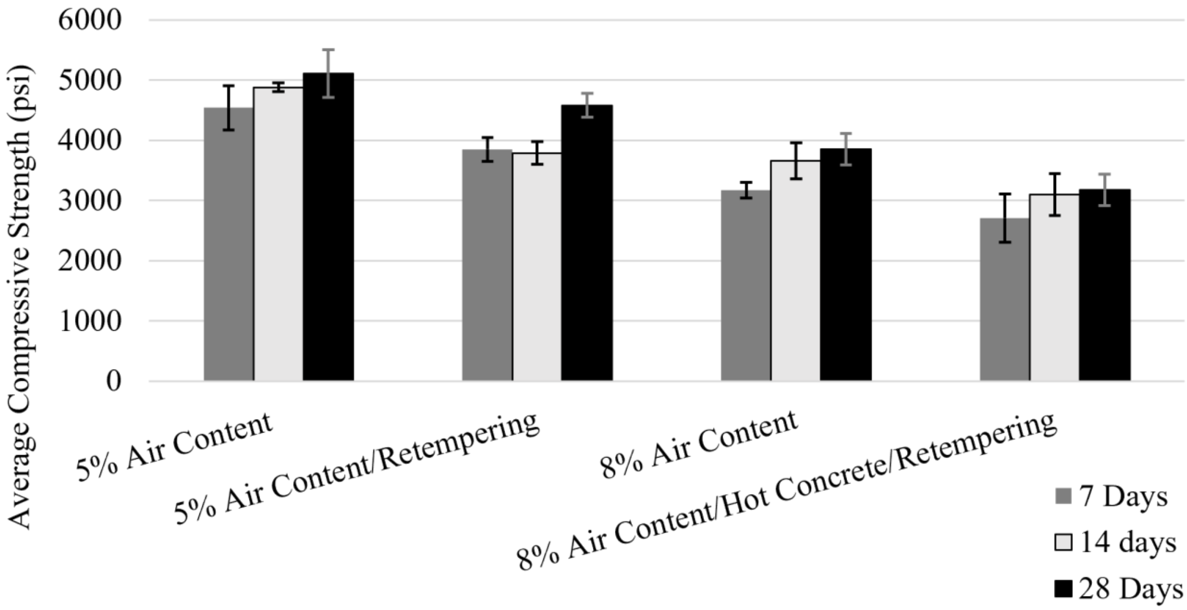


Figure 26: Compressive strength results for the retempered mixes

Table 59: Post-hoc testing of 28-day mean compressive strengths for the retempered mixes

Batch Description	Percent Change in Mean Value (%)	Tukey-Kramer: P-Value	Significant Difference (P < 0.05)
5% Air Content	-	-	-
5% Air Content/Retempering	-10.4%	0.1057	No
8% Air Content	-	-	-
8% Air Content/Hot Concrete/Retempering	-17.2%	0.0329	Yes

The Effect of the Order of Cylinder Testing

The compressive strengths of three cylinders in order of testing for select batches at 7-,14-, and 28-day testing are shown in Table 60. The batches were chosen for having at least one cylinder with a strength less than 4500psi. If one cylinder is used for acceptance, the order of cylinder testing for these batches would determine whether the concrete would pass or fail. SDDOT testing guidelines permit a second cylinder to be tested if the first cylinder does not meet strength. For many of these samples, the concrete would be accepted by testing either one or two cylinders and, for most of the batches, that acceptance outcome matches the acceptance if the average of three cylinders were used instead. However, for some of the batches the current SDDOT procedure does not match the three-cylinder average outcome. Three batches (F, I, and K) would be accepted when the three-cylinder average is lower than f’c. It is also possible that two low strength cylinders could initially be tested, but the average of three would be greater than f'c. However, this scenario was not observed with these batches. These results indicate that additional cylinder testing for acceptance is warranted.

Table 60: Compressive strength (psi) in order of cylinder testing for select batches

Batch	1st Cylinder	2nd Cylinder	3rd Cylinder	Average	St. Dev.
A	4670	4078*	4875	4540	410
B	4030*	4800	5200	4680	590
C	4460*	4660	5460	4860	520
D	4670	4120*	4820	4540	370
E	4200*	5430	5140	4920	640
F	3540**	4670	4320*	4180*	580
G	4180*	4530	4910	4540	370
H	4750	4790	4290*	4610	280
I	4570	4200*	4280*	4350*	200
J	4690	4700	4350*	4580	200
K	4000*	4680	4160*	4280*	360

* indicates <f'c; **Indicates cylinders that fall below f'_c by more than 500 psi

5.3.8 Bulk Resistivity Results

Bulk electrical conductivity of hardened concrete (ASTM C1876-19) 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 fluids and dissolved aggressive ions. This test is an indirect method to determine a concrete's resistance to steel corrosion. Concrete with higher resistivity will theoretically be able to resist more chloride ions and thus provide greater resistance against steel corrosion. Table 61 and Figure 27 show the bulk resistivity values measured at each testing age for all the mixes. For most mixes, bulk resistivity did not significantly increase between 7- and 14-days, but more significant increases were observed between 14- and 28-days especially for the second batch of coal ash. This could indicate that the coal ash might be initiating pozzolanic reaction by 28-days. All 18 mixes were classified with a 'moderate' resistivity rating by 28-days, which is in the range of 4-8 kΩ. Based on previous research using Class F coal ash, the bulk resistivity would likely significantly increase at later ages (>56 days) due to the continuation of the pozzolanic reactivity.

Table 61: Bulk resistivity results (kΩ)

Batch Description	7-Day Avg.	7-Day St. Dev.	14-Day Avg.	14-Day St. Dev.	28-Day Avg.	28-Day St. Dev.
Baseline 1*	4.50	0.43	4.40	0.18	5.13	0.23
0.45 w/cm*	3.70	0.18	3.97	0.08	4.15	0.15
100˚F Curing Temp*	4.23	0.18	4.23	0.15	5.02	0.33
100˚F Curing Temp/Hot Concrete*	4.78	0.13	5.15	0.30	5.52	0.39
115˚F Curing Temp*	5.08	0.71	5.20	0.58	5.23	0.46
8% Air Content*	3.77	0.10	4.05	0.36	4.58	0.15
8% Air Content/100˚F Curing Temp*	3.87	0.29	3.83	0.03	4.53	0.45
Baseline 2	3.22	0.14	3.40	0.20	4.62	0.10
5% Air Content	3.87	0.12	4.25	0.13	4.77	0.33
5% Air Content/Retempering	3.28	0.03	3.35	0.28	4.38	0.08
8% Air Content	3.55	0.26	3.57	0.21	4.47	0.24
8% Air Content/Adjusted Aggregate	3.45	0.09	3.63	0.12	4.65	0.36
8% Air Content/Hot Concrete/Retempering	3.15	0.13	3.15	0.13	4.97	0.45
Low Strength Mix Design A	3.88	0.14	3.93	0.06	5.58	0.29
Low Strength Mix Design A/100˚F Curing Temp	4.13	0.16	4.48	0.10	6.70	0.09
Low Strength Mix Design B	3.35	0.00	3.77	0.06	5.12	0.03
Low Strength Mix Design B/100˚F Curing Temp	3.63	0.06	4.32	0.21	6.28	0.34
Worst Case Scenario Mix Design	3.18	0.08	3.33	0.20	4.35	0.18

*Designates mixes using first coal ash batch

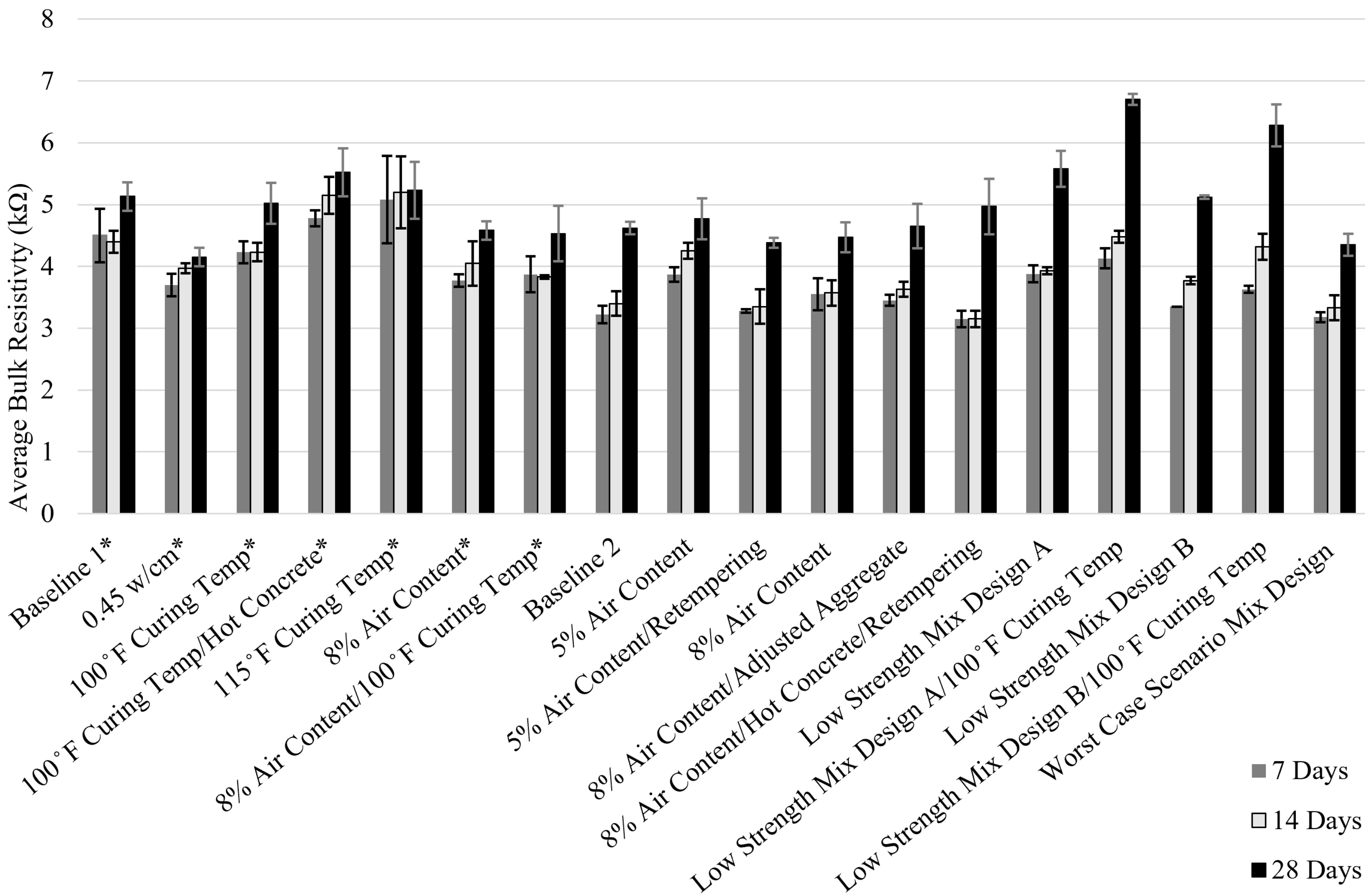


Figure 27: Bulk resistivity results

Overall, differences between the 28-day bulk resistivities for mixes were minimal especially compared to differences observed for compressive strength. The mixes containing the second coal ash batch had a larger increase in resistivity between the 14- and 28-day testing. Therefore, the two batches had varied reactivities potentially from a difference in fineness. Increasing the concrete's air content had mixed results. When comparing the two 8% air contents with their respective baselines, bulk resistivity decreased indicating improved durability. However, the 5% air content bulk resistivity increased compared to the control. Altering the mix design of the concrete showed little effect on bulk resistivity. The 0.45 w/cm* and worst-case scenario mix design both had higher w/cm ratios compared to the baselines, but both had lower resistivity values.

When assessing the impact of curing temperature, there was little correlation with bulk resistivity. The baseline cured at 100 ˚F had a lower bulk resistivity than when cured at room temperature, while curing it at 115 ˚F increased the measurement. However, the highest two measurements were the two low strength designs when cured at a higher temperature. Since a higher curing temperature does not seem to have a strong correlation to an increase in bulk resistivity, except for the low-strength mix, it is likely a result of the material differences for these mixes. Retempering had an inconclusive effect as retempering the 5% air content lowered the bulk resistivity while retempering the 8% air content raised it. These results indicate the tested changes in parameters had mixed results overall on the bulk resistivity at these ages. Later-age testing might result in more conclusive differences between the mixes.

5.3.9 Concrete Forensic Analysis

The tested samples' fresh air content, hardened air void content (denoted as area of voids) and measured 28-days compressive strength are shown in Table 62. After comparing the three DOT samples against the Baseline 1*, 5% Air Content Mix, and 8% Air Content Mix* samples, it was found that the air content of at least one of the cored failed cylinders was abnormally high. While this is not a statistically significant method to measure the air void content, it enables a quick comparison between specimens. Using image analysis, the percent area of the polished core surface that was white was calculated and used as a proxy for air content. Other features of the failed cores did not appear to be significantly different compared to the lab-made specimens.

Table 62: Area of voids for the concrete cylinder samples

Batch Description	Fresh Concrete Air (%)	Area of Voids (%)	28-Day Compressive Strength (psi)
Baseline 1*	1.3	1.2	6990
5% Air Content	5.1	1.6	5110
8% Air Content*	7.8	1.9	5070
DOT Sample A	6.2*	1.6	4030*
DOT Sample B	6.2*	3.5	4030*
DOT Sample C	6.2*	1.9	4030*

*A direct connection between these measured properties with the cored samples provided is unknown.

The DOT samples from the box culvert were all produced using one mix design but likely made from different batches of concrete. Only one fresh air content and one failing compressive strength value was provided to represent all the cored samples. However, it is unknown whether all the cored samples were associated with the low strength failure. The analysis suggests that Samples A and C were within the same range of air content as the lab made samples. However, Sample B was found to have nearly double the air content of the remining cylinders. Images of all the cylinders before and after processing are shown in Figure 28 to Figure 34.

In DOT Sample B, there are several large air voids located adjacent to the coarse aggregates as shown in Figure 32 and Figure 33. These voids might be associated with entrapped air. No clustering of entrained air was observed unless the entrained air coalesced into these larger air voids prior to hardening. Regardless, these large voids can significantly weaken the bond between the aggregate and the paste at the interfacial transition zone. This would result in an overall reduction in composite compressive strength. The cause of the large air voids is unknown from this analysis. It could be related to poor workability and placement of the concrete at that location. It could also be a result of high air entrainment content for the concrete at that location.

Figure 28: SDSMT Sample: Baseline 1*

Figure 29: SDSMT Sample: 5% Air Content

Figure 30: SDSMT Sample: 8% Air Content*

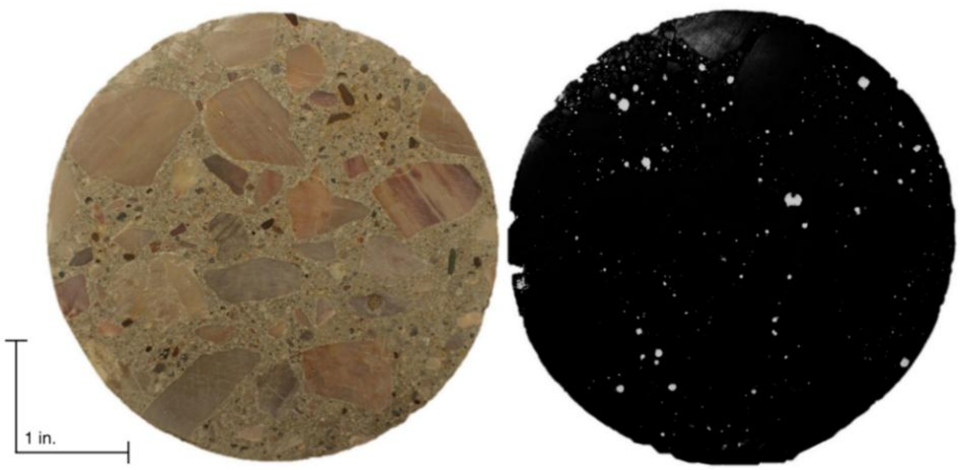


Figure 31: DOT Sample A

Figure 32: DOT Sample B

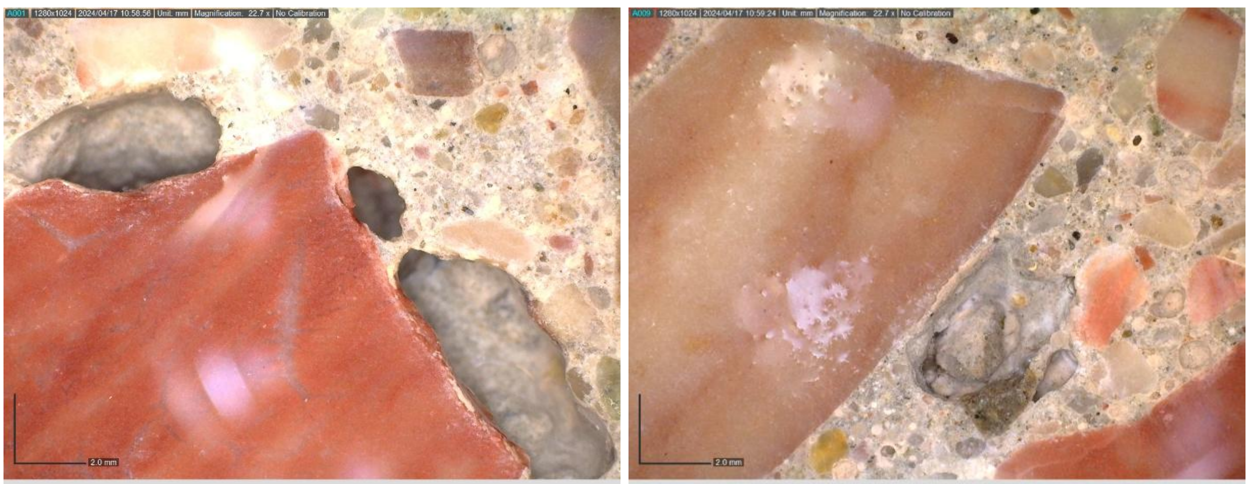


Figure 33: Zoomed in view of large air voids surrounding aggregate in DOT Sample B. The air voids are the darkened areas next to the red/pink aggregate.

Figure 34: DOT Sample C

5.3.10 Petrographic Examination

The petrographic examination performed on two core samples from the same box culvert project is shown in Appendix G. One core represented the “Good” (strength passing) sample and the other “Bad” (strength failing) concrete from the same project with the same mix design. The examination did not find an elevated hardened air content in either of the cores analyzed unlike the forensic analysis performed at South Dakota Mines. It is possible that a different portion of the core was analyzed, or the South Dakota Mines results were not statistically significant. Rather, the petrographic results indicated that the “lower-than-expected compressive strength of the concrete represented by the “Bad” sample is attributed to an elevated water-cementitious materials ratio (w/cm). Petrographic examination could not definitively identify the source of excess water leading to the overall elevated w/cm in the “Bad” concrete. However, the observed variability in properties and w/cm through the concrete suggests incomplete incorporation of mix water. Furthermore, the batch tickets indicate significant underbatching of water at the ready-mix plant. Thus, the variable and overall elevated w/cm may be the result of on-site water additions to the concrete. Only a few of the provided tickets note the water amounts added on-site. For many of the batches, the amount of water added on site and the total amount of water in the as-placed concrete are not clear. It is possible that some additions exceeded the amount withheld. Additionally, if on-site water additions were not adequately mixed, significant variability, as observed in the “Bad” concrete, could result.”

5.4 Conclusion.

The sources of low compressive strength concrete tests identified by SDDOT was investigated through a literature review, a statistical analysis, a review of historical test data, interviews with concrete technicians, and a survey to concrete suppliers and other DOTs. The effects of changing water content, air content, materials, curing conditions, and processing variables were assessed on concrete by measuring fresh properties, compressive strength, and bulk resistivity. Furthermore, a forensics and petrographic assessment was performed on cored samples for low strength concrete in the field. The results are as follows:

- Low strength of concrete cylinders can be caused by many factors including water cementitious ratio, admixture type, cementitious material type, fresh concrete and curing temperatures, and handling and testing procedures among other reasons.
- An analysis of historical SDDOT strength data from the past six years revealed that certain concrete producers, materials suppliers (sand and admixture sources), higher fresh concrete and ambient temperatures, and higher air content in the concrete were correlated with more strength failures.
- Analyzing the historical cored data compared to test cylinders found that the in situ concrete strength was more frequently stronger than the representative test cylinder.
- Interviews with six technicians based throughout the state provided insight into how the test cylinders are prepared and tested. Discrepancies between practice and specification included testing frequency using time intervals instead of specified concrete volumes, temperature control during fresh concrete curing, and transportation handling including vibration control.
- A survey sent to SDDOT concrete suppliers produced limited results with only two suppliers responding. These two suppliers acknowledged low strength testing issues but were unsure as to the cause.
- A national survey of DOTs indicated that while most agencies experience occasional low strength tests, no other responding DOT is overly concerned nor has experienced similar low strength issues at the same magnitude as SDDOT. The survey concluded that while there is not a single targeted reason for low strength issues, specimen handling and extreme temperatures appear to be a large contributor to low strength tests.
- An investigation into SDDOT concrete cylinder's initial curing temperatures found that the temperature within the curing cooler was higher than allowed by SDDOT specification for every sample monitored.
- Changing certain mix designs and processing variables, especially in combination, resulted in 28-day compressive strengths lower than 4500 psi indicating that the A45 mix design has the potential to result in strength failures.
- Air content significantly reduced compressive strength especially at the upper allowed limit of 8%.
- The use of a higher w/cm and a different coal ash also significantly reduced strength while using different aggregate and admixture combinations increased

strength. This finding highlights the impact of materials and mix design on strength. Based on these results, more frequent mix design qualification could be warranted to address these issues on an individual basis.

- A high curing temperature for the cylinders resulted in significant strength reduction for a range of mix designs highlighting the importance of standardizing curing conditions for fresh concrete and improving quality control of these conditions to properly assess strength.
- Fresh concrete made at high temperatures or with retempering alone did not appear to significantly change strength values, but the combination of the two did result in a significant strength reduction.
- All mix designs had a moderate bulk resistivity rating by 28-days with no significant patterns observed between changes in the concrete and the resulting measurements.
- A forensics analysis on low strength concrete in the field indicated that high air content and large air voids on the surface of the aggregates might have been a cause of the strength failure. However, these results were not corroborated by a petrographic examination conducted by a separate lab, which found that an elevated water-cementitious materials ratio was the reason for the low strength.

6.0 RECOMMENDATIONS

Based on the experimental results in combination with the literature review, historical data analysis, and surveys, it is recommended that the SDDOT:

6.1 Change the SDDOT Standard Specification for Roads and Bridges to re-qualify mix designs for higher air contents and incentive lower entrained air contents

The SDDOT should update the SDDOT Standard Specification for Roads and Bridges to (1) re-qualify mix designs such that the air content of each trial batch shall be +1.0% to -0.5% of the maximum specified value of 8% and (2) incentivize concrete producers to target air contents lower than 7%, especially on hot days with air temperatures greater than 80 °F.

Both historical data and experimental testing showed strong evidence that strength is reduced because of higher air content. Historical data shows that there was a reduction in passing rates for batches of concrete with air contents above 7%. For two different batches of concrete tested experimentally, 7-8% entrained air reduced 28-day compressive strength by 28%-36% compared to a non-entrained control. Experimental data also showed that an increase in air content for the same mix from 5% to 7% reduced 28-day compressive strength by over 20% when cured at room temperature. Most of the historical concrete batches that did not pass strength were within the range of 3500-4500psi at 28-days. For a 4500psi concrete, a 20% reduction in strength would result in 3600psi, which is within the observed failure range.

The experimental results also showed that low strength results are likely a result of more than one issue, but rather a combination of multiple factors such as high air content and hot concrete. For example, curing cylinders at 100 °F for the first 24 hours decreased the 28-day compressive strength by 18% on average in addition to strength reductions from air content. For the 2024 season, data pertaining to fifteen strength failures were provided for analysis. Eleven of those failures had air contents above 7%. Three out of the remaining four failed samples with air contents lower than 7% were cast on days with air temperatures above 80 °F. The highest historical failure rates were also observed when ambient temperatures reached above 80°F.

A recent update to the specifications increased the maximum allowable air contents to 8% from 7.5%. To accommodate this change, the concrete producer must provide evidence through mix design qualification using local materials and admixtures that strength requirements will be met at air contents up to 8%. Current trial batching requirements in the SDDOT Standard Specification for Roads and Bridges require that "the air content of each trial batch shall be +0.5% to -1.0% of the maximum specified". This could be modified to "the air content of each trial batch shall be **+1.0%** to **-0.5%** of the maximum specified" and strictly enforced to retest all mixes at a maximum of 8% air content. Otherwise, existing mix designs that have not been tested at the increased air content level should have a reduced maximum air content of 7.5% as originally specified.

Additionally, it may be specified that if the air temperature is forecast to be above 80 °F, the air content limit must be lowered to 7%. If a reduced maximum specification limit is not a viable option, it is recommended to instead financially or otherwise incentivize concrete producers to achieve air contents at or below 7%, especially if the air temperature is forecast to be above 80 °F.

6.2 Implement improved quality control measures for batch plant and in-field concrete adjustments and fresh concrete curing procedures

The SDDOT should improve the quality control measures in the SDDOT Standard Specification for Roads and Bridges to (1) change the curing method for cylinders in the first 24 hours to maintain temperatures between 60-80 °F, (2) prohibit retempering of concrete if the air temperature is forecast to be above 80 °F, (3) for retempered mixes, ensure that on-site water additions are recorded to verify maximum w/cm are not exceeded and verify additional mixing requirements are met, and (4) implement improved quality control guidelines for concrete producers on aggregate moisture content adjustments.

Experimental results showed that the combination of high air content, high w/cm ratio, high curing temperature, hot concrete, retempering, and not adjusting for aggregate moisture content synergistically resulted in the lowest strength mixture that was tested. The strength reduction for this combination was greater than any one factor tested independently. Therefore, improving the quality control of these factors will reduce the likelihood of these “worst case scenario” batches of concrete in the field. High air content and high w/cm ratio are addressed in the first and last recommendation. High curing temperatures, hot concrete, retempering, and aggregate moisture content adjustments are addressed in this recommendation.

High Curing Temperatures and Hot Concrete

Concrete that is cast and cured at higher temperatures can develop higher early-age strength (prior to 28-days), but at later ages the strength is typically lower than if it were cast and cured at a lower temperature. Historical data indicates that strength failure rates increased when the average daily temperature was above 50 °F and the daily high temperatures were above 60°F. The highest failure rates were observed when ambient temperatures reach above 80 °F.

Experimental results indicated that 28-day compressive strength did not decrease when concrete was cast at the upper 90 °F limit specified by SDDOT compared to a control cast at 70 °F when both were cured at an elevated temperature of 100 °F. Therefore, there is no recommendation to change the fresh concrete temperature limits. However, the combination of retempering a hot concrete batch significantly reduced concrete strength as discussed in the next section.

It is recommended that improved quality control measures are implemented to ensure that fresh concrete cylinders are cured within the SDDOT specified temperature range (60–80 °F) in the field. Smartrock data showed that for a variety of different concrete batches, cylinder curing conditions for the first 24 hours were not kept between the specified 60-80 °F. This was corroborated by technicians throughout the state who noted they do not measure temperature in the curing coolers to ensure they are within specified limits. For the curing coolers tested in this study, measured ambient temperatures within the coolers reached a maximum of 98 °F. Extrapolating from this data, it can be estimated that on the hottest day of the year in Sioux Falls, SD in 2023, the average temperature in the cooler could theoretically reach 98.9 ˚F if closed or 89.7 ˚F if cracked and the maximum concrete temperature in the cooler could theoretically reach 111.7 ˚F if closed or 107 ˚F if cracked.

Experimental results found that high curing temperatures have a significant negative impact on 28-day compressive strength. On average, curing the cylinders at 100 ˚F for the first 24 hours decreased the 28-day compressive strength by 18%, which mirrors previous findings by others (ACI, 2020). In addition to affecting hydration kinetics, there could be some potential moisture loss through evaporation in the cylinders at these high temperatures in low humidity environments.

There are a variety of potential solutions to maintain the specified temperatures in the cylinder curing boxes. For example, a commercially available concrete curing box that maintains the internal environment at a set temperature could be used. A study by Nebraska DOT found that the most effective method of curing in hot weather was to submerge the fresh cylinders in water in the curing chamber such that the water covers at least 75% of the concrete cylinder (Heyen & Halsey, 2020). Preferably, the cylinders would be submerged such that only 0.5”-1” of the top of the cylinder is exposed. This would be a cost-effective solution and mix water from the concrete trucks could be used to fill the containers if it is a suitable temperature. Temperatures above 80 °F were measured in the coolers even on days with a maximum temperature of 80 °F due to the heat of hydration of the concrete. Therefore, it is recommended to specify this curing condition if the air temperature is forecast to be above 70 °F or an even lower temperature limit.

Future research is recommended to compare how important concrete properties including the relationship between temperature, humidity, and compressive strength development compare between testing cylinders and the situ concrete especially on hot days. Coring data suggests that in situ concrete strength was more often stronger on average than the test cylinders cast to represent it, but other factors may contribute to these results. This future research could result in improved concrete testing protocols to better represent cast-in-place concrete. Additionally, testing different curing methods to understand which practices result in the most effective temperature regulation of the cylinders could be a future research topic.

Retempering

Section 460.3 in the SDDOT Standard Specification for Roads and Bridges states that additional water may be added to structural concrete after completion of the original mixing if the slump, entrained air, and w/cm specifications are met. The batch needs to be mixed with an additional 30 revolutions at mixing speed. Experimental results showed that strength reduction was greatest when retempering concrete was coupled with hot fresh concrete. Retempering commonly occurs on hot days, so the combination of these two effects is common. It is recommended that retempering mixes with water be discouraged, if not prohibited, on hot days if the air temperature is forecast to be above 80 °F. The petrographic examination identified an elevated overall water-to-cementitious ratio in a failed core sample. It further found variable paste properties likely due to incomplete incorporation of mix water. This could be a result of significant underbatching of water at the ready-mix plant, lack of documentation of the water amounts added on-site which could have exceeded the amount withheld, and lack of adequate mixing after on-site water additions. Therefore, an added specification provision to record on-site water additions and verify additional on-site mixing is recommended. Also, concrete producers should be encouraged to modify concrete rheological properties through the addition of admixtures in the field instead of mix water especially on hot days when the fresh concrete temperature is expected to be near the 90˚F limit specified by SDDOT.

Aggregate Moisture Content Adjustments

Replicating two of the lowest strength-performing mix designs from the field in the laboratory resulted in some unexpected results; these mixes demonstrated increased strengths compared to a control. The concrete producers for these concrete mixes had some of the highest failure rates so their practices might have influenced strength more than the material properties. One potential cause could be inconsistent or incorrect moisture content adjustments for the aggregate. The batch tickets did not clearly indicate that the field moisture content of the aggregate was being factored into the mix design calculations. However, this could have been completed off the record.

Regarding aggregate moisture content corrections, Section 460.3 in the SDDOT Standard Specification for Roads and Bridges states that “batching equipment shall be automatic or a Department inspector shall be present during batching operations”. For computerized batching equipment, the ticket should show how the mix designs are adjusted for aggregate moisture content. However, the specifications do not state how this information will be provided for manual batching equipment or how frequently aggregate moisture contents need to be measured either manually or automatically by moisture probes.

Improved quality control guidelines should be written for concrete producers on aggregate moisture content adjustments that include (1) required method and frequency of measuring aggregate moisture contents and (2) plant certification on a semi-annual basis from SDDOT personnel or an outside certification agency to ensure aggregate moisture content adjustments are accurate.

6.3 Change the acceptance procedure for 28-day compressive strength

The SDDOT should update the SDDOT Standard Specification for Roads and Bridges for 28-day compressive strength qualification to require the average of three consecutive strength tests to be equal or exceed the f'c requirement (4500psi) and no individual strength test can fall below the f'c by more than 500 psi.

Section 460.3 in the SDDOT Standard Specification for Roads and Bridges states that only one cylinder is required to accept a batch of concrete if it reaches a strength equal to or greater than 4500psi at 28-days. If it is below strength, a backup cylinder can be used for acceptance if it reaches a strength equal to or greater than 4500psi at 28-days. The Department's Bridge Construction Engineer can determine if a low compressive strength not less than 500psi from f'c is structurally adequate. If the average compressive strength of the 28-day and the backup cylinder compressive strength is more than 500 psi below the specified 28-day compressive strength, the concrete represented by the cylinders shall be removed and replaced.

Experimental testing determined that the current SDDOT testing procedure is not always statistically representative of the batch strength. That is, for some of the batches the current SDDOT procedure does not match the three-cylinder average outcome. At least three tested batches at the 4500psi threshold would be accepted using the SDDOT procedure but would not be accepted using the three-cylinder average. It is also possible that two low strength cylinders could initially be tested, but the average of three would be greater than f'c. However, this scenario was not observed in this study. These results indicate that additional cylinder testing for acceptance is warranted to provide greater confidence in the testing results. Furthermore, many of the surrounding state DOTs require three cylinders for acceptance.

To improve the statistical significance of compressive strength testing results, it is recommended that the number of tested cylinder samples should be increased to three at 28-days. Following ACI guidance, for qualification the average of three consecutive strength tests needs to equal or exceed the f'_c and no individual strength test can fall below the f'_c by more than 500 psi if that mix is to have a strength of 5000 psi or less. Using this approach, the order of cylinder testing would not influence the outcome.

6.4 Modify and strictly enforce Section 460.3 in the SDDOT Standard Specification for Roads and Bridges regarding mix design qualification

The SDDOT should ensure that the mix design qualification procedures provided in the SDDOT Standard Specification for Roads and Bridges are strictly enforced. Furthermore, these procedures could be modified to (1) require a bi-annual mix design qualification, (2) add 56-day compressive strength testing, and (3) require mix designs that have failed strength more than once in the field over a period (e.g., three months) to be re-qualified.

The available material supply and mix design parameters are highly variable for many concrete producers used by the SDDOT. Cement and coal ash suppliers or types can change at any time. Even cementitious materials and aggregates from existing sources can change composition and properties. Additionally, w/cm can be variable for a given mix since only a maximum w/cm of 0.45 is specified. Experimental results indicated that for the mixes tested, the use of a different coal ash from the same source and the increase in w/cm from 0.4 to 0.45 both separately resulted in a large reduction in 28-day compressive strength. Furthermore, data from a recent NCHRP report by these authors showed a large spread in compressive strength is possible with different coal ash sources used in the same concrete mix (Shearer et al., 2024). Experimental results also found that the use of different aggregate and admixture combinations increased strength compared to a control. Overall, these findings highlight the significant impact of materials and mix design on strength.

Section 460.3 in the SDDOT Standard Specification for Roads and Bridges states that “satisfactory performance of the proposed concrete mix design shall be verified by laboratory tests on trial batches” and that “a concrete mix design previously used will be considered in compliance with the mix design requirements provided…the mix design, including all material and admixtures, are identical to those previously used and tested”. A new cement, coal ash, or admixture source can be currently considered “identical” to a previous source. For example, the transition from ASTM C150 to ASTM C595 cements did not require re-qualification by the SDDOT through trial batching based on a number of factors. This research indicated that changes in material sources can significantly change concrete strength. Therefore, it is recommended that the specification be more strictly followed in that changes in material and admixture sources for previously tested mix designs require laboratory trial batch testing since they are not “identical”. If this approach is too conservative, trial batching could be recommended for mixes that do not meet strength in the field after changing source materials.

Furthermore, three modifications could be made to these specifications. First, a bi-annual mix design qualification could be required to identify any changes in mix design properties if material characteristics have changed but are not reported. Second, a 56-day strength measurement could be added for mixes with coal ash. Although 56-day strength data was not collected in this project, previous research has shown that SDDOT mixes with coal ash continue to gain strength at later ages (Simonton, 2021). This data could be used to potentially accept mixes with slower concrete strength development at 56-days instead of 28-days. Third, if a previously qualified mix design has more than one failure within a given timeframe such as a period of three months, the mix design will be required to be trial batched again and re-qualified.

Summary

The recommended specification changes should reduce the number of strength failures observed by SDDOT. Statistically there will still be strength failures even if these recommendations are implemented. Otherwise, the concrete will be overdesigned for strength, which is not desirable for numerous reasons including higher cost, reduced sustainability, and potential durability issues.

7.0 RESEARCH BENEFITS

This research will result in a set of recommendations for SDDOT that would determine and prevent the causes of low strength failures. This is a high priority issue, because below specification concrete is a major time, energy, and cost sink for all agencies involved in a project. Achieving better concrete performance reduces costs, minimizes risk, and maintains on-time construction schedules. The timely resolution of the problem will have great benefit to SDDOT, the taxpayers of South Dakota, and the public who use these roads every day.

This project also supported student research and increased the research capacity at South Dakota Mines. Overall, this research will enable SDDOT to achieve better-quality transportation assets.

8.0 REFRENCES

ACI 214R-11 Guide to Evaluation of Strength Test Results of Concrete. (2011). ACI.

ACI 301-20: Specifications for Concrete Construction. (2020). ACI.

ACI 305R-20: Guide to Hot Weather Concreting. (2020). ACI.

ACI 318-19 Building Code Requirements for Structural Concrete . (2022). ACI.

Ashworth, E., Cross, W., Duke, E., Kellar, J., & Johnston, D. (2000). Investigation of Low Compressive Strengths of Concrete in Paving, Precast and Structural Concrete, SD98-03. South Dakota DOT.

ASTM C39 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. (2021). ASTM.

Concrete Manual. (1975). U.S. Bureau of Reclamation.

Eid, M. (2023, September 13). Understanding concrete electrical resistivity and its relationship with rapid chloride permeability. Giatec Scientific Inc. https://www.giatecscientific.com/education/understanding-concrete-electrical-resistivity-and-its-relationship-with-rapid-chloride-permeability/

Elwell, D., & Fu, G. (1995). (rep.). Compression Testing of Concrete: Cylinders vs. Cubes (Vol. Special Report 119).

Heyen, W., & Halsey, L. (2020). Influence of Curing Conditions on Concrete Specimens (Cylinders) in Hot and Cold Weather in the Field. NDOT Materials & Research Investigation .

Klieger, P. (1958). Effect of mixing and curing temperature on concrete strength. ACI Journal Proceedings, 54(6), 1063–1081. https://doi.org/10.14359/11495

Klinger, J., Lobo, C. L., Connolly, E. F., & Suprenant, B. A. (2022). Expect Compressive Strength Test Results Less Than Specified Strength on Every Project. Concrete International, 37–43.

Kosmatka, S. H., Kerkhoff, B., & Panarese, W. C. (2011). Design and Control of Concrete Mixtures. Portland Cement Association.

Materials Testing & Inspection Verification Program Manual . (2022). South Dakota DOT.

Mehta, P. K., & M., M. P. J. (2014). Concrete: Microstructure, properties, and materials. McGraw-Hill Education.

Minimum Sample and Test Requirements (MSTR) . (2022). South Dakota DOT.

Portland Cement Concrete Level 1 Instruction Manual. (2022). Iowa DOT.

Required Samples, Tests, and Certificates (RSTC). (2022). South Dakota DOT.

SD 402 : Method of Sampling Fresh Concrete . (2020). South Dakota DOT.

SD 405: Method of Making and Curing Concrete Specimens in the Field for Compression and Flexural Tests . (2021). South Dakota DOT.

SD 408: Method of Test for Temperature of Freshly Mixed Portland Cement Concrete . (2016). South Dakota DOT .

SD: 420 Method of Test for Determining Compressive Strength of Concrete . (2020). South Dakota DOT.

Shearer, C. R., Burris, L., Hooton, R. D., & Suraneni, P. National Academies of Sciences, Engineering, and Medicine. (2024). Use of Marginal and Unconventional-Source Coal Ashes in Concrete. Washington, DC: The National Academies Press.

Simonton, E., & Shearer, C. R. (2020). Low Shrinkage Mix Designs to Reduce Early Cracking of Concrete Bridge Decks, SD2018-04. South Dakota DOT.

Simonton, E. (2021). Low Shrinkage Mix Designs to Reduce Early Cracking of Concrete Bridge Decks (thesis).

Sioux Falls Weather in 2023. (n.d.). https://www.weatherunderground.com

Standard and Supplemental Specifications for Road and Bridge Construction. (2020). Montana DOT.

Standard Specifications for Highway and Bridge Construction. (2015). Iowa DOT.

Standard Specifications for Road and Bridge Construction. (2020). North Dakota DOT.

Standard Specifications for Road and Bridge Construction. (2021). Wyoming DOT.

Standard Specifications for Roads and Bridges South Dakota Department of Transportation. (2015). South Dakota DOT.

Standard Specifications for Roads and Bridges. (2016). Louisiana DOT.

Structures Construction Manual. (2021). South Dakota DOT.

Supplemental Specifications to 2015 Standard Specifications for Roads and Bridges. (2022). South Dakota DOT.

U.S. Bureau of Reclamation . (1975). (rep.). Concrete Manual (pp. 574–575).

Appendices

Appendix A: Surrounding State Specification Comparison

North Dakota Specifications:

- Mix Design
  - Provide concrete that is air entrained.
  - Divided into three classifications:
    - Class AAE: Cementitious material content per CY = 600-650 and a max w/cm ratio of 0.44. Reaches a compressive strength of 3000 psi after 7-days.
    - Class AE: Cementitious material content per CY = 550-600 and a max w/cm ratio of 0.47. Reaches a compressive strength of 3000 psi after 7-days.
    - Class ASE: Cementitious material content per CY = 575-625 and a max w/cm ratio of 0.40. Reaches a compressive strength of 3000 psi after 30 hours.
  - Cement
    - Portland Cement that meets the requirements of AASHTO M 85, Type II; or
    - Blended Hydraulic Cement that meets the requirements of AASHTO M 240, Type IL(MS).
  - Coal Ash
    - Must meet the requirements of AASHTO M 295, Class F with a few modifications
    - May replace cement on a 1:1 ratio, up to a maximum of 29 percent by weight.
  - Admixtures
    - Air-entraining admixtures must meet requirements of AASHTO M 154
    - Chemical admixtures must meet the requirements of AASHTO M 194 and classified as Type A under ASTM C 494
- Sampling
  - Testing Frequency
    - Slump, air content, and unit weight tests will occur every 2,000 S.Y. of concrete.
    - Cast one set of specimens every 250 cubic yards of concrete or a minimum of one set per day per AASHTO T 23
  - After mixing, maintain the concrete temperature between 50°F and 90°F until placement.
  - Maintain the concrete surface temperature between 40 - 90°F for the duration of the curing period.
  - Slump for Structural concrete must be between 1.0-4.0 inches.
  - Supply concrete with an air content between 5.0 and 8.0 percent of the volume of the concrete at the time of placement.

    - • Average of two cylinders are used for strength acceptance.
- Handling/Transportation
    - Transportation:
        - Specimens must be cured and protected prior to transportation.
        - Specimens shall not be transported until at least 8 hours after final set.
        - Specimens must be cushioned to prevent damage from jarring.
        - In cold weather, the specimens shall be protected from freezing.
        - Prevent moisture loss by either wrapping in plastic or wet burlap; surrounding with wet sand; or using tight-fitting plastic caps on plastic molds.
        - Transportation time shall not exceed four hours.

Wyoming Specifications

- Mix Design
    - Mix Design
        - 3 classes (2 @ 4000 psi, 1 @ 3500)
        - Mix design is prescriptive in nature like SD
- Sampling
    - Maintain concrete at temperatures of 60 - 90°F
    - Average of four and three cylinders are used for strength acceptance for structural concrete and PCC pavement, respectively.
- Handling/Transportation
    - Use a concrete plant with sufficient capacity and hauling vehicles to ensure continuous concrete delivery at the rate required for uninterrupted placement and without allowing intervals between batches longer than 20 minutes.

Montana Specifications

- Mix Design
- Sampling
    - Prepare test cylinders according to MT 101 and AASHTO R 60, and test for compressive strength according to AASHTO T 22
    - Frequency: Every 2,500 S.Y. of concrete pavement but not less than two sets per day.
    - Cure test cylinders under the same conditions as the area they represent.
    - Average of three cylinders are used for strength acceptance.
- Handling/Transportation
    - Specimens shall not be transported until at least 8 hours after final set
    - Protect the specimens from jarring, extreme changes in temperature, freezing and moisture loss during transportation
    - Place specimens in sturdy boxes surrounded by a suitable cushioning material to prevent damage

    - Prevent moisture loss during transportation by wrapping the specimens in plastic or wet burlap and by surrounding them with wet sand or sawdust or using tight-fitting plastic caps for plastic molds.

Minnesota Specifications

- Mix Design
    - Cements
        - MN has approved all cement types utilized by SD in this report
    - Coal Ash
        - MN has approved all coal ash sources utilized by SD in this report
    - Admixtures
        - Type AEA - Air Entrainment
        - Type A - Water Reducing and Mid Range Water Reducing – 6
        - Type B - Retarding/Hydration Stabilizer – 2
        - Type C - Accelerating – 2
        - Type D - Water Reducing and Retarding – 1
        - Type E - Water Reducing and Accelerating – 1
        - Type F - Water Reducing, High Range – 4
        - Type G - Water Reducing, High Range and Retarding – 1
        - Type S - Specific Performance - 4
- Sampling
    - When making the test specimens:
        - Place molds on a level, firm foundation in a sheltered place where they can remain undisturbed and protected from direct sunlight and the concrete is maintained at temperatures of 60 - 80°F for the initial 16-48 hours.
        - The supporting surface on which specimens are stored shall be level to within ¼ in. per ft.
        - If specimens cannot be molded at the place where they will receive initial curing, immediately after finishing move the specimens to an initial curing place for storage.
        - If concrete temperatures are outside the range of 60 - 80°F, or a casting site is not available in the immediate proximity of the work, transport the sampled concrete to a casting location where the specimens will remain at 60 - 80°F undisturbed for the initial 16-48-hour period. Re-mix by hand shoveling prior to casting the test cylinder.
    - Prevent/Control moisture loss by:
        - Placing the specimen in an insulated box/coolers containing moisture
        - Covering with polyethylene sheeting or bags
        - Covering with a minimum of 4 thickness of wet burlap
        - Covering with waterproof paper
        - Placing caps on molds
    - Average of three cylinders are used for strength acceptance.
- Handling/Transportation

    - Collect and transport concrete cylinders from the initial cure site:
        - Transport cylinders to the “intermediate” or “final” curing site 16-24 hours after final finishing.
        - High Early concrete mixes are to be transported to the “intermediate” or “final” curing site 12-24 hours after final finishing.
    - Transporting test cylinders to the laboratory:
        - Transport standard strength test specimens with the cylinder mold covers affixed.
        - During transportation of cylinders, protect with a suitable cushioning material to prevent damage from jarring During cold weather, protect the cylinders from freezing with suitable insulation material.
        - Transport the cylinders to the laboratory with securely placed tight fitting plastic caps on plastic molds, wrapping the specimens in plastic, wet burlap, or by surrounding them with sand to prevent moisture loss. In no case shall the transportation time exceed 4 hours.

Iowa Specifications

- Mix Design
    - Air entraining agent must comply with AASHTO M 154 and not contain more than 1.0% chloride ions
    - Coal ash must meet the requirements of AASHTO M 295 and the maximum allowable substitution rate is 20%. Available alkalis is not to exceed 1.50%
- Sampling
    - Target slump to be between 1-3 in.
    - Do not place concrete when the ambient temperature is 40°F or less
    - Placed concrete should have a temperature between 45-80°F
    - Cylinders must be protected against moisture loss. This can be done by covering them with wet burlap and placing a plastic sheet over the burlap
    - Average of three cylinders are used for strength acceptance.
- Handling/Transportation
    - When handling and transporting cylinders, they should be protected from moving around and impacts of any type

Appendix B: SDDOT Technician Interview Questions

Tech Interview Questions

1. Explain the typical process of making, handling, transporting, and testing the cylinders from start to finish. Please be as detailed as possible.
2. Potential follow-up questions based on level of detail of initial explanation:
    a. How many cylinders per batch to you make (Testing Frequency)? In what molds?
    b. Are you ACI certified? What certifications do you have?
    c. How do you typically cure the cylinders? How is that curing adjusted for hot and cold temperatures. How is it adjusted for humidity?
    d. How long are the cylinders left sitting outside on average?
    e. How are they secured in the truck while transporting?
    f. Is there a typical time of day when the cylinders are tested?
    g. Who has custody of the cylinders from start to finish? Are others able to handle the cylinders that are not certified?
    h. What is your course of action when cylinders pass or do not pass the strength requirement?
3. What was your training process for making, handling, transporting, and testing cylinders?
4. How often are you observed or retrained on this process?
5. Have you seen any technicians making, handling, transporting, or testing cylinders differently than you or out of typical protocol?
6. Potential follow-up questions:
    a. What are some different methods used to cure the cylinders especially during hot or cold days? At what temps do you start implementing these tactics?
    b. How have you seen cylinders transported to the laboratory for testing?
    c. Have you ever seen a cylinder damaged during transportation, but still used for testing?
    d. Do you note if something occurred out of typical protocol or is it just dismissed without noting?
    e. Lime Water?
    f. So the cylinders get transported how many times?

Appendix C: Material Data Sheets

Cement

GCC

600 S. Cherry Street, Suite 1000, Glendale, CO 80246
Customer Service (800) CALL GCC / (800) 225-5422

MATERIAL CERTIFICATION REPORT

Plant: Rapid City
Address: 501 N. St Onge Street
Rapid City, SD 57702
Contact: Gail Amicucci
Phone: (605) 721-7042

Cement Type: ASTM C595 IL(10) HS MH
ASTM C1157 GU HS MH
Date Issued: 1-Feb-24
Production Period: 1-Jan-24
To: 31-Jan-24
Lot Number: 2024-01

GCC RAPID CITY IS AN AASHTO R-18 CERTIFIED FACILITY

STANDARD REQUIREMENTS ASTM C595/AASHTO M 240/ASTM C1157

CHEMICAL

Item	ASTM Test Method	ASTM C595 IL Spec. Limit	Test Result
SiO_2	C114	A	19.3
Al_2O_3 (%)	C114	A	4.2
Fe_2O_3 (%)	C114	A	3.1
CaO (%)	C114	A	63.4
MgO (%)	C114	A	1.1
SO_3 (%)	C114	3.0 max[B]	2.9
Loss On Ignition (%)[C]	C114	10.0 max	5.2
Equivalent Alkalis of Portland Cement (%)	C114	A	0.56

PHYSICAL

Item	ASTM Test Method	ASTM C595 IL Spec. Limit	ASTM C1157 Spec. Limit	Test Result	
Blaine Fineness (m^2/kg)	C204	A	A	439	
Residue 45 µm (No. 325) Sieve (%)	C430	A	A	3.0	
Density (g/cm^3)	C188	A	A	3.09	
Air Content of Mortar (volume %)	C185	12 max	12 max	7	
Time of Initial Setting / Vicat (minutes)	C191	45 min / 420 max	45 min / 420 max	134	
Compressive Strength					
3 Days, MPa (psi)	C109	13.0 (1890) min	13.0 (1890) min	27.5	(3990)
7 Days, MPa (psi)	C109	20.0 (2900) min	20.0 (2900) min	36.7	(5330)
28 Days, MPa (psi)[D]	C109	25.0 (3620) min	28.0 (4060) min	43.3	(6290)
Mortar Bar Expansion C1038 (%)	C1038	0.020 max	0.020 max	-0.002	

PHYSICAL OPTIONAL

Item	ASTM Test Method	ASTM C595 Spec. Limit	ASTM C1157 Spec. Limit	Test Result
Early Stiffening, Final Penetration (%)	C451	A	50 min	71

REQUIREMENTS OF LIMESTONE FOR USE IN BLENDED CEMENTS

LIMESTONE

Item	ASTM Test Method	ASTM C595 Spec. Limit	Test Result
$CaCO_3$ in Limestone (%)	C150	70 min	91

PHYSICAL REQUIREMENTS FOR SPECIAL PROPERTIES ASTM C595/ASTM C1157

SPECIAL PHYSICAL REQUIREMENTS

Item	ASTM Test Method	High Sulfate Resistance (HS)	Moderate Heat of Hydration (MH)	Test Result	
Sulfate Resistance[E]					
Expansion at 180 Days (%)	C1012	0.05	A	0.03	
Heat of Hydration[F]					
3 Days, kJ/kg (cal/g)	C1702	A	335 (80) max	280.6	(63)

[A] Not applicable
[B] It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020 % at 14 days.
[C] This alternative analysis has been qualified in accordance with ASTM C114 and meets requirements of Table 1
[D] Test result of prior month
[E] ASTM C1012 Sulfate Resistance Testing has been performed at CTLGroup, an AASHTO R-18 certified facility.
[E] A cement meeting high sulfate (HS) resistance also meets the specification of moderate sulfate (MS) resistance.
[F] ASTM C1702 Heat of Hydration has been performed by GCC Pueblo Cement Plant, an AASHTO R-18 certified facility.

GCC cement is warranted to conform at the time of shipment with current ASTM C595/AASHTO M 240/ASTM C1157. No other warranty is made or implied. Having no control over the use of its cements, GCC does not guarantee finished work. GCC is not responsible for any additives not stated in this Material Certification Report.

Baseline 1 Coal Ash

HEADWATERS 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: 4/10 - 4/17/17 **Report Date:** 5/26/2017
Sample Type: 3200-ton **MTRF ID:** 923CC
Sample ID:

Chemical Analysis	Results		ASTM Limit Class F/C	AASHTO Limit Class F/C
Silicon Dioxide (SiO2)	52.27	%		
Aluminum Oxide (Al2O3)	15.95	%		
Iron Oxide (Fe2O3)	5.76	%		
Sum (SiO2+Al2O3+Fe2O3)	73.98	%	70.0/50.0 min	70.0/50.0 min
Sulfur Trioxide (SO3)	0.62	%	5.0 max	5.0 max
Calcium Oxide (CaO)	13.03	%		
Magnesium Oxide (MgO)	4.43	%		
Sodium Oxide (Na2O)	2.49	%		
Potassium Oxide (K2O)	2.44	%		
Sodium Oxide Equivalent (Na2O+0.658K2O)	4.10	%		
Moisture	0.03	%	3.0 max	3.0 max
Loss on Ignition	0.08	%	6.0 max	5.0 max
Available Alkalies, as Na2Oe	1.50	%	Not Required	1.5 max*

*when required by purchaser

Physical Analysis	Results		ASTM Limit Class F/C	AASHTO Limit Class F/C
Fineness, % retained on 45-µm sieve	21.03	%	34 max	34 max
Fineness Uniformity	1.64	%	±5 max	±5 max
Strength Activity Index - 7 or 28 day requirement				
7 day, % of control	85	%	75 min	75 min
28 day, % of control	93	%	75 min	75 min
Water Requirement, % control	95	%	105 max	105 max
Autoclave Soundness	0.03	%	0.8 max	0.8 max
Density	2.53			
Density Uniformity	0.44	%	±5 max	±5 max

Headwaters Resources certifies that pursuant to current ASTM C618 protocol for testing, the test data listed herein was generated by applicable ASTM methods and meets the requirements of ASTM C618.

Doug Rhodes, CET
Facility Manager

AASHTO R18

Baseline 2 Coal Ash

ECOMATERIAL TECHNOLOGIES

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

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

Sample Date: 12/1 - 12/31/23
Sample Type: Monthly
Sample ID: MnDOT Split

Report Date: 2/20/2024
MTRF ID: 46CC

Chemical Analysis	Results		ASTM Limit Class F / C	AASHTO Limit Class F / C
Silicon Dioxide (SiO2)	52.86	%		
Aluminum Oxide (Al2O3)	15.65	%		
Iron Oxide (Fe2O3)	5.43	%		
Sum (SiO2+Al2O3+Fe2O3)	73.94	%	50.0 min	50.0 min
Sulfur Trioxide (SO3)	0.73	%	5.0 max	5.0 max
Calcium Oxide (CaO)	12.94	%	18.0 max / >18.0	18.0 max / >18.0
Magnesium Oxide (MgO)	4.08	%		
Sodium Oxide (Na2O)	3.88	%		
Potassium Oxide (K2O)	2.28	%		
Total Alkali (Sodium Oxide Equivalent)	5.4	%		
Moisture	0.02	%	3.0 max	3.0 max
Loss on Ignition	0.10	%	6.0 max	5.0 max
Available Alkalies, as Na2Oe	1.83	%	Not Required	1.5 max*

*when required by purchaser

Physical Analysis	Results		ASTM Limit Class F / C	AASHTO Limit Class F / C
Fineness, % retained on 45-µm sieve	21.54	%	34 max	34 max
Fineness Uniformity	0.5	%	±5 max	±5 max
Strength Activity Index - 7 or 28 day requirement				
7 day, % of control	83	%	75 min	75 min
28 day, % of control	99	%	75 min	75 min
Water Requirement, % control	89	%	105 max	105 max
Density, ASTM C604	2.51	g/cm3		
Density Uniformity	3.5	%	±5 max	±5 max

Tyler Lambert
QA Manager

AASHTO ACCREDITED

Standard Fine Aggregate

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

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

Standard Coarse Aggregate

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

Low Performing Mix Coarse Aggregate (A and B)

American Engineering Testing, Inc.
Sioux Falls
601 E. 48th St. N.
Sioux Falls, SD 57104
(605) 332-5371
www.teamAET.com

Material Test Report

Report No: MAT:AET-149332-S2
Issue No: 1

Client:	Spencer Quarries, Inc	**CC:**	
Project:	Spencer Quarry Annual Quality Checks		
	Spencer SD		
Job No:	P-0020820		

Date of Issue: 3/11/2024
Reviewed By: Scott Dumdei

Sample Details

Sample ID	AET-149332-S2
Field Sample ID	Class A Concrete Rock
Date Sampled	2/26/2024
Source	Spencer Quarries
Material	Class A Coarse Aggregate
Specification	SDDOT COARSE AGG FOR CONCRETE (SIZE 1)
Sampling Method	Sampled by Client
General Location	Spencer, SD
Location	Spencer Quarry, Sampled by Client
Date Submitted	3/11/2024

Particle Size Distribution

Method: ASTM C 136, ASTM C 117

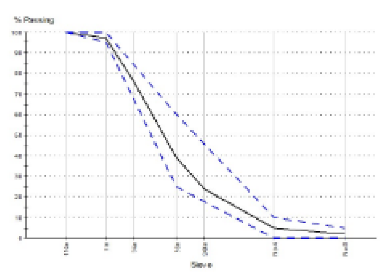
Date Tested: 3/11/2024
Tested By: Paul DeWeese

Sieve Size	% Passing	Limits
1½in (37.5mm)	100	≥100
1in (25.0mm)	97	95 – 100
¾in (19.0mm)	76	
½in (12.5mm)	39	25 – 60
3/8in (9.5mm)	24	
No.4 (4.75mm)	5	0 – 10
No.8 (2.36mm)	2	0 – 5

Other Test Results

Description	Method	Result	Limits
Mass of Test Sample (g)	ASTM C 123	3201.1	
Nominal Maximum Size (in)		1	
Type of Heavy Liquid		Zinc Chloride	
Heavy Liquid Specific Gravity		1.970	
Lightweight Particles (%)		0.0	
Shale Particles (%)		0.0	
Coal and Lignite Particles (%)		0.0	
Deleterious Substances (%)		0.0	
Chert Particles (%)		0.0	
Date Tested		3/11/2024	
Specific Gravity (OD)	ASTM C 127	2.621	
Specific Gravity (SSD)		2.628	
Apparent Specific Gravity		2.639	
Absorption (%)		0.3	
Density Determined Without First Drying?		No	
Additional Notes			
Date Tested		3/11/2024	
Bulk Density (lb/ft³)	ASTM C 29	105	
Voids (%)		36	
Filling Procedure		Rodding	
Date Tested		3/11/2024	
Bulk Density (lb/ft³)	ASTM C 29	100	
Voids (%)		39	
Filling Procedure		Shoveling	
Date Tested		2/26/2024	
Test Type	ASTM C 88	Coarse	
Preparation		Freshly Prepared	
Solution Type		Sodium Sulfate	
Plus Number 4 (%)		95	
Total Weighted Coarse Loss (%)		0	

Chart



Comments

N/A

Low Performing Mix Coarse Aggregate (A and B)

American Engineering Testing, Inc.
Sioux Falls
601 E. 48th St. N.
Sioux Falls, SD 57104
(605) 332-5371
www.teamAET.com

Material Test Report

Report No: MAT:AET-149332-S2
Issue No: 1

Client: Spencer Quarries, Inc
CC:

Project: Spencer Quarry Annual Quality Checks

Spencer SD
Job No: P-0020820

Date of Issue: 3/11/2024
Reviewed By: Scott Dumdei

Sample Details

Sample ID	AET-149332-S2
Field Sample ID	Class A Concrete Rock
Date Sampled	2/26/2024
Source	Spencer Quarries
Material	Class A Coarse Aggregate
Specification	SDDOT COARSE AGG FOR CONCRETE (SIZE 1)
Sampling Method	Sampled by Client
General Location	Spencer, SD
Location	Spencer Quarry, Sampled by Client
Date Submitted	3/11/2024

Other Test Results

Description	Method	Result	Limits
Date Tested		3/11/2024	

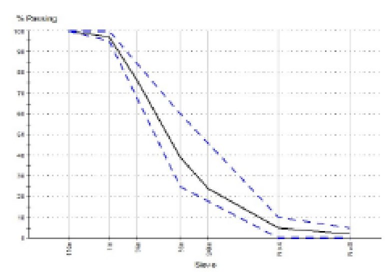
Particle Size Distribution

Method: ASTM C 136, ASTM C 117

Date Tested: 3/11/2024
Tested By: Paul DeWeese

Sieve Size	% Passing	Limits
1½in (37.5mm)	100	≥100
1in (25.0mm)	97	95 – 100
¾in (19.0mm)	76	
½in (12.5mm)	39	25 – 60
3/8in (9.5mm)	24	
No.4 (4.75mm)	5	0 – 10
No.8 (2.36mm)	2	0 – 5

Chart



Comments

N/A

Low Performing Mix A Fine Aggregate

AMERICAN ENGINEERING TESTING, INC.

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:19-02305-S1
Issue No: 1

Client: WAGNER BUILDING & SUPPLY CO INC **CC:**

Project: PREVAILING WIND PROJECT
CHARLES MIX, BON HOMME & HUTCHINSON COUNTIES

Job No: 32-20221

Date of Issue: 3/19/2019
Reviewed By: Adam Johnson
Senior Engineering Technician

Sample Details

Sample ID	19-02305-S1
Field Sample ID	Concrete Sand
Date Sampled	3/13/2019
Source	Ravina Sand Pit
Material	Concrete Sand
Specification	C33 Fine Aggregate
Sampling Method	Field
General Location	Ravina Sand Pit
Location	Wagner, South Dakota
Date Submitted	3/13/2019

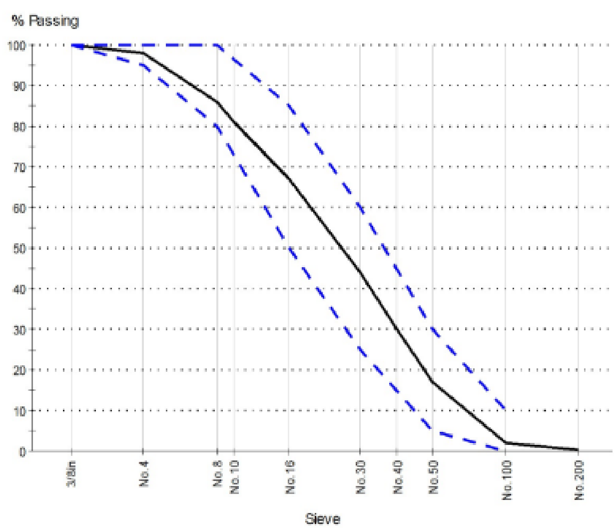
Other Test Results

Description	Method	Result	Limits
Specific Gravity (OD)	ASTM C 128	2.610	
Specific Gravity (SSD)		2.624	
Apparent Specific Gravity		2.646	
Absorption (%)		0.523	
Additional Notes			
Fineness Modulus	ASTM C 136, ASTM C 117	2.86	

Particle Size Distribution

Method: ASTM C 136, ASTM C 117

Date Tested: 3/14/2019
Tested By: Adam Johnson



Sieve Size	% Passing	Limits
3/8in (9.5mm)	100	100
No.4 (4.75mm)	98	95 – 100
No.8 (2.36mm)	86	80 – 100
No.10 (2.0mm)	81	
No.16 (1.18mm)	67	50 – 85
No.30 (600µm)	44	25 – 60
No.40 (425µm)	30	
No.50 (300µm)	17	5 – 30
No.100 (150µm)	2	0 – 10
No.200 (75µm)	0.3	

Comments

N/A

Low Performing Mix B Fine Aggregate

OCT-12-99 09:55 PM DOT WINNER 8420810 P.01

SOUTH DAKOTA DEPARTMENT OF TRANSPORTATION - TESTING SECTION April 1995

CLASS A 45 (4500 PSI) AIR-ENTRAINED CONCRETE MIX DESIGN - Sources WEST of the Missouri River. WEST A 45
(Material variation may require adjustment of proportions) 6.0% air used for calculations
Aggregate Weight is saturated surface-dry basis Page 5

MIX No.	Aggregate Sources		Aggregate Properties Fine Mod.	Sp. Gr.	% Abs	Portland Cement Used	Agg. Lbs.	Quanities per Cubic Yard. Percent Fine Agg	Water Gals.	Lbs.	Cement cwt.	W/C by Weight
105-45-81	Opperman Sand Gregory, SD	(Fine)	2.60	2.62	0.6	Dacotah	1189	40.5	32.6	272		
	Hills Materials Co. Hot Springs, SD	(Coarse)	7.04	2.67	0.5	Type I-II	1723				6.70	0.406
104-45-79	Opperman Sand Gregory, SD	(Fine)	2.75	2.61	0.6	Dacotah	1192	40.5	31.8	265		
	Lien, Pete & Sons Rapid City, SD	(Coarse)	6.85	2.58	0.4	Type I-II	1753				6.65	0.398
116-45-81	Opperman Sand Gregory, SD	(Fine)	2.60	2.62	0.6	Dacotah	1094	40.0	31.3	261		
	Oral Pit Winner, SD	(Coarse)	6.97	2.36	2.6	Type I-II	1642				6.70	0.390
116-45-82	Opperman Sand Gregory, SD	(Fine)	2.53	2.62	0.6	Dacotah	1156	39.5	31.6	264		
	Spencer Quarries, Inc. Spencer, SD	(Coarse)	6.91	2.63	0.4	Type I-II	1769				6.60	0.400

Appendix D: Additional Historical Project Data

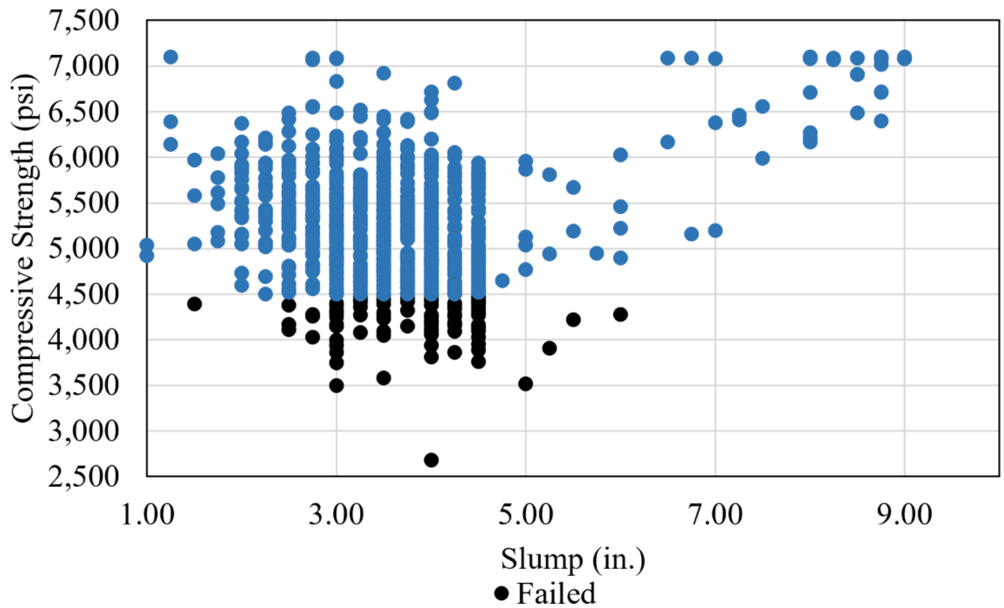


Figure 35: Historical compressive strength vs. slump

A summary of the data in Figure 35 is found in Appendix H Table 90.

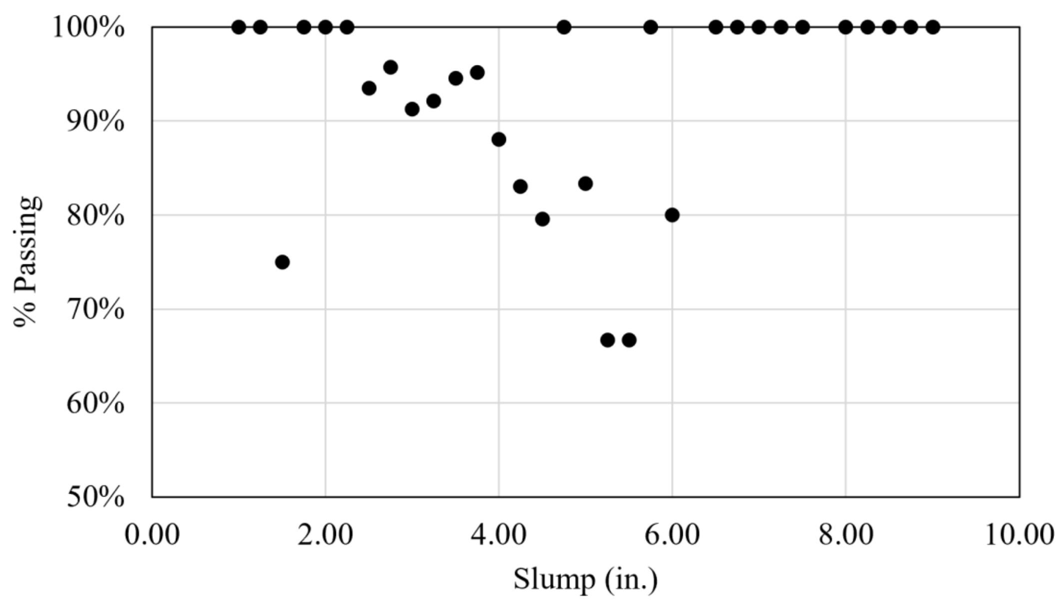


Figure 36: The historical influence of slump on % passing

Table 63: Summary of the data from Figure 36

Slump (in.)	Passing (%)	Slump (in.)	Passing (%)
1.00	100	5.25	67
1.25	100	5.50	67
1.50	75	5.75	100
1.75	100	6.00	80
2.00	100	6.25	No data
2.25	100	6.50	100
2.50	93	6.75	100
2.75	96	7.00	100
3.00	91	7.25	100
3.25	92	7.50	100
3.50	95	7.75	No data
3.75	95	8.00	100
4.00	88	8.25	100
4.25	83	8.50	100
4.50	80	8.75	100
4.75	100	9.00	100
5.00	83	-	-

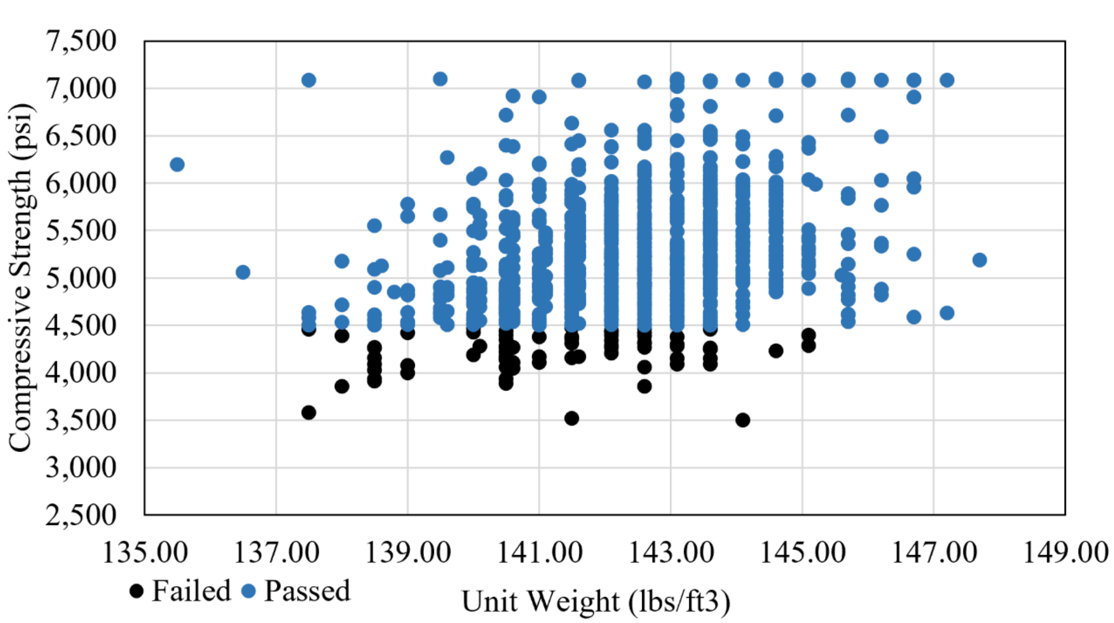


Figure 37: Historical compressive strength vs. unit weight

A summary of the data in Figure 37 is found in Appendix H Table 90.

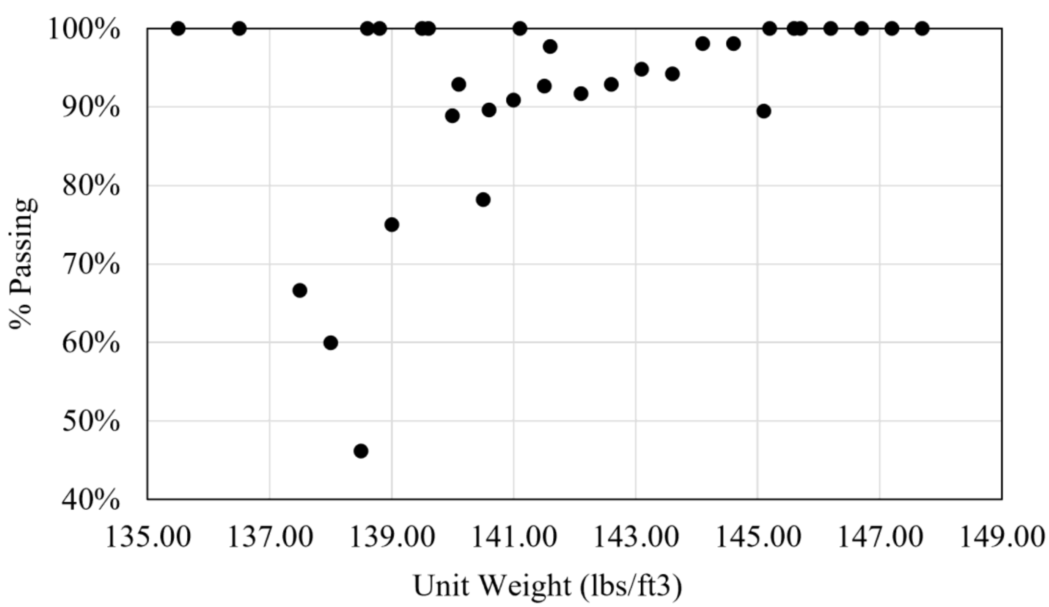


Figure 38: The historical influence of unit weight on % passing

Table 64: Summary of the data from Figure 38

Unit Weight (lb/ft3)	Passing (%)	Unit Weight (lb/ft3)	Passing (%)
135.50	100	141.50	93
136.50	100	141.60	98
137.50	67	142.10	92
138.00	60	142.60	93
138.50	46	143.10	95
138.60	100	143.60	94
138.80	100	144.10	98
139.00	75	144.60	98
139.50	100	145.10	89
139.60	100	145.20	100
140.00	89	145.60	100
140.10	93	145.70	100
140.50	78	146.20	100
140.60	90	146.70	100
141.00	91	147.20	100
141.10	100	147.70	100

Appendix E: SDDOT Concrete Supplier and DOT Surveys

Table 65: Supplier 1 SDDOT Concrete Supplier Survey Response

Question	Response
Has your company supplied any cast-in-place structural concrete mixes for SDDOT in the past 5 years that had field test batches not meet strength specifications? If not, go to Question 4.	Yes
If so, what factors do you believe led to the low strength outcomes?	Water/Cementitious Ratio, Curing Method, Concrete Temperature, Air Content, Supplementary Cementitious Material Source, Retempering, Specimen Handling Procedures, Specimen Testing Procedures
Provide additional clarification on any of the above factors.	Skipped
Have you supplied cast-in-place structural concrete mixes for clients other than SDDOT that had field test batches not meet strength specifications in the past 5 years?	No
Provide additional clarification for other instances where strength specifications were not met for clients other than SDDOT.	Skipped
Do you have any recommendations to reduce low strength concrete issues related to SDDOT projects?	Utilizing concrete cylinders that are 4x8 can be handled and stored easier. Breaking 28 day test cylinders at a local lab and not transporting to Pierre for verification. The DOT needs to adopt testing concrete at the back of the truck and not at point of placement with pump. In many occasions we are seeing higher air content than what is required due to the effects of the pump to the concrete.
Please provide any other relevant information about your experience with low strength concrete.	It would be helpful if the state agencies would allow for use of a set retardant without special provisions. These are used commonly across the industry and would help keep wc lower, retempering of concrete, and increased strength would be seen.

Table 66: Supplier 2 SDDOT Concrete Supplier Survey Response

Question	Response
Has your company supplied any cast-in-place structural concrete mixes for SDDOT in the past 5 years that had field test batches not meet strength specifications? If not, go to Question 4.	Yes
If so, what factors do you believe led to the low strength outcomes?	we could never pin point the problem and we never changed anything and it suddenly went away but it was also during covid so there was defiantly a help shortage.
Provide additional clarification on any of the above factors.	Skipped
Have you supplied cast-in-place structural concrete mixes for clients other than SDDOT that had field test batches not meet strength specifications in the past 5 years?	No
Provide additional clarification for other instances where strength specifications were not met for clients other than SDDOT.	Skipped
Do you have any recommendations to reduce low strength concrete issues related to SDDOT projects?	No
Please provide any other relevant information about your experience with low strength concrete.	We have supplied a-45 for other contractors on county bridges where the dot was not involved and used the exact same mix design and actually poured with in the same work week and had a low strength from the dot but a good strength from the 3rd party testing company with a significant difference and the test were close to the same results. We also used an a-45 mix for a water treatment plant last year and just called it a 4500psi mix and we had extremely high breaks through the whole job with some breaks over 6000psi. I have also tested side by side the dot and made cylinders out of the same concrete and have had the same results as the dot so our situation I cant honestly pin point the problem.

Table 67: South Carolina Response to DOT Survey

Question	Response
Provide your name	Caleb Gunter
Provide your email	guntercb@scdot.org
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	Probably hundreds. Each producer designs their own mixes and submits them for our review. Typically, most structural concrete is 4000 psi, however.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	I don't know, but it's not a large percentage in my view. Our mix design requirements (minimum cement content) are pretty conservative.
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Same answer as #9.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Curing Method, Specimen Handling Procedures, Other (I think that the variability in the production of concrete has led to some of the failures through the years)

Question	Response
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	Yes, the handling of the cylinders is important, especially when using 4x8 cylinders
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 68: Canadian Agency Response to DOT Survey

Question	Response
Provide your name	Allan Hegedus
Provide your email	allan.hegedus@gov.sk.ca
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	Pile concrete, deck concrete, precast mix
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3500 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches do not meet strength specifications?	No
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches do not meet strength specifications?	Skipped
On average, how many low strengths field test batches per year occur for all cast-in-place structural concrete mixes?	Skipped
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	Skipped
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	Skipped

Question	Response
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Skipped
What factors do you believe led to the low strength outcomes?	Skipped
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 69: Alaska Response to DOT Survey

Question	Response
Provide your name	Richard Giessel
Provide your email	richard.giessel@alaska.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	~15
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi, 5000 psi, 8000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	1
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Very few
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi

Question	Response
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Lack of quality control, Other (moisture intrusion into Portland Cement storage silo)
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	Yes, require NRMCA Plant Certification
Please provide any other relevant information about your experience with low strength concrete.	For the few concrete plants that operate with minimum QC State DOTs should consider adding an annual plant inspection.

Table 70: Kansas Response to DOT Survey

Question	Response
Provide your name	Dan Wadley
Provide your email	Dan.Wadley@ks.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	hundreds...
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	https://www.ksdot.gov/Assets/wwwksdotorg/bureaus/burConsMain/specprov/2015/401.pdf It depends on the grade of concrete specified - see Eqn. A and B.
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)

Question	Response
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	at least 10
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	at least 10 over the last 2 years
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Yes
What factors do you believe led to the low strength outcomes?	Water/Cementitious Ratio, Air Content, Admixtures Chemical Admixture interaction when incorrect batch procedure is used - i.e. adding AEA with PLS in headwater, and then adding water at the job. Not getting wash water out before batching. Pump truck operator adding water. All of these things spike the air, which further reduces f'c in addition to the reduction from adding more water.
Provide additional clarification on any of the above factors.	Chemical reps are telling producers they can add AEA and PLS (often polycarboxylates) to batch water... this causes an reaction that reduces the effectiveness of both products, and in some cases can lead to air void clustering if additional job water is added at the site, because there is now more AEA in the mix than is needed, and some of it can be latently activated during pumping. Grinding aids are also a concern in the new 1L cements, but typically they knock down the air.

Question	Response
Do you have any recommendations to reduce low strength concrete issues?	Get a Go Pro on a stick and check trucks for onboard water after wash out. Monitor fin wash down time to be less than 1 min. (1 min with a standard garden hose = 5 gallons of water). Use correct batch procedure. Actually measure stockpile moistures and use correct specific gravities on mix design. DO NOT ADD ADDITIONAL WATER AT THE JOB if any plasticizing admixture is used in the mix.
Please provide any other relevant information about your experience with low strength concrete.	We are currently evaluating the Pheonix as a tool to deploy in the field to measure job w/cm ratio's. This will help.

Table 71: Massachusetts Response to DOT Survey

Question	Response
Provide your name	Jason Robertson, Richard Mulcahy
Provide your email	mailto:jason.robertson@dot.state.ma.us, Richard.mulcahy@dot.state.ma.us
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	a. We approve over 1100 mix designs each years with different suppliers, materials, quantities, and dosages. We have 1 mix type for structural concrete but have varies strengths. Attached is our specs just revised this year.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi, 5000 psi, 6500 psi, 8000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	7, 28, 56 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years had field test batches not meet strength specifications?	a. Unknown but rare. We typically don't get low breaks but when we do the 56 days typically meet the 28 day requirement. So I would say less than 1 percent.

Question	Response
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	a. Unknown but rare. We typically don't get low breaks but when we do the 56 days typically meet the 28 day requirement. So I would say less than 1 percent.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi, 5000 psi, 6500 psi, 8000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	7, 28, 56 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Curing Method, Concrete Temperature, Cold weather and hot weather protection not being implemented
Provide additional clarification on any of the above factors.	a. MassDOT mix designs are vetted prior to construction and approved on a yearly bases most issues with strength are workmanship issues and not protecting during extreme temps.
Do you have any recommendations to reduce low strength concrete issues?	follow ACI 318 recommendations on all structural concrete design, testing, protection, etc.)
Please provide any other relevant information about your experience with low strength concrete.	follow ACI 318 recommendations on all structural concrete design, testing, protection, etc.)

Table 72: Wyoming Response to DOT Survey

Question	Response
Provide your name	Whitney Wise
Provide your email	whitney.wise@wyo.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	213 total. We average about 42 new mix designs per year, mixes are allowed to be used for 2 years.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3500 psi, 4000 psi, 6000 psi, 6000 psi only applies to silica fume modified mixes
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	We don't really do field test batches. We've had a few isolated mixes that we see a few low strength results on.
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	10-20 placements per year don't meet strength.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 and 56 days If it fails at 28-days we will hold a cylinder back for 56-day testing
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Water/Cementitious Ratio, Curing Method, Humidity, supplementary Cementitious Material Source, Specimen Handling Procedures

Question	Response
Provide additional clarification on any of the above factors.	Specimens are kept on the job site for 24-hours and occasionally get knocked over or frozen/cooked depending on the time of year.
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	Many of our suppliers still try to compensate for low strength on previous projects by increasing the cement content of the next mix design. This doesn't always work and just adds cost for us. I'm trying to implement a stricter spec on w/cm ratio, so we'll see how that goes. Please reach out if you have more questions!

Table 73: Indiana Response to DOT Survey

Question	Response
Provide your name	Michael Nelson
Provide your email	mnelson@indot.in.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	INDOT structural mixes are generically Class B, Class A or Class C
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3000 psi, 3500 psi, 4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days Design strength is 28 days, but acceptance can be anytime once 28-day strenth is verified
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	No
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Skipped

Question	Response
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Skipped
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	Skipped
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	Skipped
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Skipped
What factors do you believe led to the low strength outcomes?	Skipped
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 74: Utah Response to DOT Survey

Question	Response
Provide your name	Jason Richins
Provide your email	Jtrichins@utah.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	Over 1000 in the last two years.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi, 5000 psi, 6000 psi, As required by the design
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Many but we don't have an easy way to track that.

Question	Response
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	I don't currently have a way to see that information.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi, 5000 psi, 6000 psi, All have been low at times. We are not aware of one particular strength
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Mix Design, Air Conent, Aggregates Source, Specimen handling Procedures, Specimen Testing Procedures, Lack of Quality Control, Hard to tie it to just one cause
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	A good QC process catches most issues before the concrete is poured.
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 75: Iowa Response to DOT Survey

Question	Response
Provide your name	Todd Hanson
Provide your email	todd.hanson@iowadot.us
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	5 to 7
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi, 4500 psi, 5000 psi

Question	Response
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28, 56 days (56 days are allowed for higher replacement HPC mixes
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	No (if no, proceed to question 16)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Skipped
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Skipped
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	Skipped
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	Skipped
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Skipped
What factors do you believe led to the low strength outcomes?	Skipped
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	No

Question	Response
Please provide any other relevant information about your experience with low strength concrete.	Iowa DOT projects have not had any issues meeting design strength. There have been issues on commercial projects. We have seen some strengths lower than usual. It seems that the Type IL cements with high replacement of slag and fly ash have shown reduced strengths, but still meeting design strength.

Table 76: Rhode Island Response to DOT Survey

Question	Response
Provide your name	Michael D Sock
Provide your email	michael.sock@dot.ri.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	Roughly 30, but each production plant mix design has to be approved, even if the mix design is the same.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi, 5000 psi, 6000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days, 56 days, most mixes are 28 days, but mass concrete mixes are 56 due to high pozzolans percentages
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	No (if no, proceed to question 16)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Skipped
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Skipped

Question	Response
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	Skipped
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	Skipped
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Skipped
What factors do you believe led to the low strength outcomes?	Skipped
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	The mixes we get tend to be overdesigned because of the way we accept material. It's cheaper for the producers to go high on the strength, rather then risk a reduced pay factor. We are currently working on a PWL spec that will reduce the need to overdesign (which creates its own issues). Note that we do have low breaks on some of our Class XX (4000 psi) mixes. But those are rare (<1%/yr) and are generally because some producers don't use pozzolans (smaller outfits that have trouble setting up batching equipment for the materials). We would put them out of business for State work if we required pozzolans for that class and having limited options (RI is small), that doesn't make sense for us. XX is used for less demanding applications like commercial driveways and footings. All higher strength mixes require pozzolans.

Table 77: Louisiana Response to DOT Survey

Question	Response
Provide your name	Tyson Rupnow
Provide your email	tyson.rupnow@la.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	Depends upon what you mean by different. . . We have 6 different Types of Structural Concrete not counting the precast ones. From those we have probably 3000 approved mix designs for use.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4500 psi, 6000 psi, 8500 psi, 10000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28, 56 days (varries- early form removal)
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	very very few (2 maybe)
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	2-3 per year
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4500 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Curing Method, Specimen Testing Procedures
Provide additional clarification on any of the above factors.	Skipped

Question	Response
Do you have any recommendations to reduce low strength concrete issues?	we generally do not have issues, but we require curing boxes that are temperature controlled to alleviate issues associated with extremely high temperatures in the summertime.
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 78: New York Response to DOT Survey

Question	Response
Provide your name	Jonathan Kunin
Provide your email	jonathan.kunin@dot.ny.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	It is diffcult to pinpoint, we have several prescriptive classes of concrete and are moving towards performance engineered mixes. Several design/build projects have also done performance engineered mixes. For generic structural concrete, I would say there are 6 prescriptive mixes. If you add in performance mixes, it is probably over 20.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3000 psi, Currently it is 3000 psi but we are moving to 4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	I would guess all 6 have at some point

Question	Response
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Hard to guess, I might not be made aware of all of them. Probably more than 10 but less than 30.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	3000 psi, 4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days, 56 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Curing Method, Concrete Temperature, Lack of Quality Control
Provide additional clarification on any of the above factors.	I would say most of our low cylinder breaks could be traced back to questionable storage of the cylinders in cold weather.
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	I would say the other problem with low breaks, that is much rarer than cold weather, is dirty aggregate.

Table 79: Georgia Response to DOT Survey

Question	Response
Provide your name	Jason Waters
Provide your email	jwaters@dot.ga.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	5
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3000 psi, 3500 psi, 4000 psi, 4500 psi, 5000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days

Question	Response
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	39
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	N/A
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	3000 psi, 3500 psi, 4000 psi, 4500 psi, 5000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Water/Cementitious Ratio, Aggregate Source, Cement Source, Supplementary Cementitious Material Source, Retempering, Specimen Handling Procedures, Lack of Quality Control
Provide additional clarification on any of the above factors.	N/A
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	N/A

Table 80: Nebraska Response to DOT Survey

Question	Response
Provide your name	Kellie Troxel
Provide your email	kellie.troxel@nebraska.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	1
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3500 psi, 4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	Typically 3 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	1
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	There were 14 in the last year.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	3500 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Water/Cementitious Ratio, Air Content, Specimen Handling Procedures

Question	Response
Provide additional clarification on any of the above factors.	Nebraska typically doesn't investigate low strength concrete. It happens from time to time, but it is rare The contractor is responsible for the concrete. In certain locations, the contractor would be asked to core the structure to verify compressive strength.
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 81: Delaware Response to DOT Survey

Question	Response
Provide your name	Brian L Johnson
Provide your email	mailto:brianx.johnson@state.de.us
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	5
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4500 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	0
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	0

Question	Response
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4500 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Curing Method, Air Content, Aggregates Source
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	Concrete curing temperature, dirty aggregate and air content
Please provide any other relevant information about your experience with low strength concrete.	high air content and dirty aggregate

Table 82: North Dakota Response to DOT Survey

Question	Response
Provide your name	TJ Murphy
Provide your email	tjmurphy@nd.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	10+ Most stock mixes from ready mix suppliers.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3000 psi, 5000 psi, Depends on the element Ranges from 3-7.5 K psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days, There are constraints on form removal and opening to traffic but if needed 56 days can be used. Most mixes area meeting in 7-28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)

Question	Response
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Multiple elements have had some form of low strength, in most cases destructive testing proved the low break to be tied to cylinder miss handling. The inplace PCC was at the design strength.
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Minimal, 1 to 2 per season.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	5000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Cement Source, Specimen Handling Procedures
Provide additional clarification on any of the above factors.	As noted cylinder conditioning has resulted in some low breaks do to over heated cylinders. We have also seen cement source or "load" being the root cause of low field breaks
Do you have any recommendations to reduce low strength concrete issues?	Utilize maturity to verify, assure cylinders are treated properly. Test project level cement supplies.
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 83: Arkansas Response to DOT Survey

Question	Response
Provide your name	David Henning
Provide your email	david.henning@ardot.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	probably well over 200
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3500 psi, 4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	No (if no, proceed to question 16)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Skipped
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Skipped
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	Skipped
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	Skipped
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Skipped
What factors do you believe led to the low strength outcomes?	Skipped
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	No

Question	Response
Please provide any other relevant information about your experience with low strength concrete.	My answers reflect field test batches. I am not aware of any failing test batches-but these would result in a mix design not being approved for use on our projects. We experienced very limited failures of concrete strength acceptance tests in the field-probably less than 3-5 per year and these are typically attributed to the delivery of the wrong mix to a project or a mechanical issues at the batch plant.

Table 84: Illinois Response to DOT Survey

Question	Response
Provide your name	James Krstulovich
Provide your email	james.krstulovich@illinois.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	1,439 (but how much these designs truly differ from each other in terms of cementitious content, w/cm, etc. would be an undertaking to determine)
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3500 psi, 4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	14 days (massive pours, i.e., least dimension of 5 ft, sometimes allow up to 56 days)
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	160 had instances when they didn't meet strength, but only a handful of mixes appear to have not been able to meet strength as designed.

Question	Response
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	0.8-0.9% of the time on average. 2018: 73/8263; 2019: 62/8340; 2020: 73/9200; 2021: 50/7760; 2022: 67/4918 (but you can probably see that we look to still be waiting on a number of reports to be filed for '22)
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	3500 psi, 4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	14
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	Yes
What factors do you believe led to the low strength outcomes?	Mix Design, Cement Source, Supplementary Cementitious Material Source, Specimen Handling Procedures
Provide additional clarification on any of the above factors.	I wouldn't say that the transition to Type IL cement has caused even a majority of the issues, but I do think there has been a learning curve associated with its use. I also suspect that we're seeing a lot of inexperienced technicians now handling specimens.
Do you have any recommendations to reduce low strength concrete issues?	No
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 85: Michigan Response to DOT Survey

Question	Response
Provide your name	John Belcher
Provide your email	belcherj@michigan.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	2 Primary and dozens of unique
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3500 psi, 4500 psi, These are the standards with unique mixes going higher
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	No (if no, proceed to question 16)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Not many
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	1 to 2
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	3500 psi, 4500 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Curing Method
Provide additional clarification on any of the above factors.	Poor field curing resulted in coring to validate strength.
Do you have any recommendations to reduce low strength concrete issues?	Control w/cm and cure properly.
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 86: Missouri Response to DOT Survey

Question	Response
Provide your name	Brett S Trautman
Provide your email	brett.trautman@modot.mo.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	The Missouri DOT has 4 types of structural concrete mix designs: 1) Class B, 2) Class B-1, 3) Class B-2, and 4) Class Modified B-2. Over the past 5 years, we have approved approximately 1200 mix designs for cast-in-place structural concrete.
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3000 psi, 4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	The Missouri DOT experiences low strength issues on about 5 to 10 structural mixes a year. This translates to about 25 to 50 mixes over the past 5 year.
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	On the average, the Missouri DOT has about 20 samples that experience low strength issues each year.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	3000 psi, 4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No

Question	Response
What factors do you believe led to the low strength outcomes?	Curing Method, Concrete Temperature, Air Content, Retempering, Specimen Handling Procedures, Lack of Quality Control
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	MoDOT allows high range water reducer (HRWR) to be added at the job site. It is critical to check the air after adding the HRWR. Some HRWR will generate air. We had a few projects where the air content was checked prior to adding the HRWR but was not checked after adding the admixture. The air content can be well over 8 percent.
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Table 87: Minnesota Response to DOT Survey

Question	Response
Provide your name	Maria Masten
Provide your email	maria.masten@state.mn.us
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	7
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	3000 psi, 4000 psi, 5000 psi, Sometimes there are project specific strength requirments that are higher but it is typically 4000 psi for all structural mixes except for piling is 3000 psi and cofferdam, rock sockets and drilled shafts are 5000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days, We use 28 days for all strength acceptance, however if high SCM mixes do not make strength at 28 days we extend out to 56 days and evaluate the results

Question	Response
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	We typically do not see strength issues with the structural mix designs that contain 15% fly ash substitution but as I said above mix designs that have 25-30% fly ash and or slag sometimes do not meet 28 day strengths.
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Less than 1%
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Air Content, Specimen Handling Procedures, High SCM dosage rates

Question	Response
Provide additional clarification on any of the above factors.	Skipped
Do you have any recommendations to reduce low strength concrete issues?	For some mixes, either lower the 28 day strength requirement or move final acceptance for strength out to 56 days
Please provide any other relevant information about your experience with low strength concrete.	MnDOT often sees low strengths on a project level, not so much a mix design level. We have on occasion seen that at a few plants and we then require the Producer to make an adjustment to the mix design which usually involves adding 5-10 pounds of cement. Other than HPC bridge deck, SCC and mass concrete mixes, MnDOT doesn't require trial batching or mix verification prior to use of the mix designs unless the Producer wants to use more than 15% fly ash. MnDOT standard designed mixes for many years contained 15% fly ash so when we transitioned to Contractor designed mixes, we felt it was pretty low risk to not require trial batching for 15% max fly ash mixes.

Table 88: Colorado Response to DOT Survey

Question	Response
Provide your name	Eric Prieve
Provide your email	eric.prieve@state.co.us
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	100+
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT?	4000 psi, 4500 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)

Question	Response
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	5-10, just in the Denver metro area, unknown for rural areas as they perform the testing and are not required to notify the central lab.
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	2-3, same comments as #9
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4500 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes? (Select all that apply)	Water/Cementitious Ratio, Air Content, Aggregates Source, Lack of Quality Control
Provide additional clarification on any of the above factors.	moisture content of aggregates and gradation changes
Do you have any recommendations to reduce low strength concrete issues?	More quality control at the batch plant. We have seen better results on pavement when the contractor took ownership of QC in an effort to earn incentive payments for strength and consistency.

Question	Response
Please provide any other relevant information about your experience with low strength concrete.	We have a few low strength field cylinder test per year. We maybe thought with our change to PEM that lower cement contents could increase the number of low breaks. Most ready mixed suppliers still stick to their old tried and true mixes which are overdesigned by at least 15%. We do allow coring to dispute cylinder strength. Generally with cylinders that are up to 500 psi below required strength, the cores show a higher strength and meet the minimum. Coring on lower strengths generally validate the low cylinder strength. We have had more issues with flexural strength on pavements, but think its a testing issue.

Table 89: Montana Response to DOT Survey

Question	Response
Provide your name	Wesley Dess
Provide your email	wdess@mt.gov
How many different cast-in-place structural concrete mix designs have been used by your state DOT in the past 5 years?	Roughly 42 Class Structure designs have been used not including class deck or class structure low slump for decks
What are the minimum specified strength requirements of the cast-in-place structural concrete mixes used by your DOT? Check all that apply.	4000 psi
At what testing age(s) are the minimum strength of cast-in-place structural concrete mixes specified?	28 days
Have any cast-in-place structural concrete mixes used by your DOT in the past 5 years had field test batches not meet strength specifications?	Yes (if yes, proceed to next question)

Question	Response
How many of the cast-in-place structural concrete mix designs used by your state DOT in the past 5 years (identified in Question 5) had field test batches not meet strength specifications?	Roughly 12 individual times class structure failed strength requirements in the last 3 years. Most all were on separate projects with different suppliers and not one mix design failed repeatedly
On average, how many low strength field test batches per year occur for all cast-in-place structural concrete mixes?	Roughly 3-6 a year based on historical information for the past 3 years.
What minimum specified strength requirement(s) of the cast-in-place structural concrete mix(es) used by your DOT have resulted in low strength field test batches?	4000 psi
At what testing age(s) have the cast-in-place structural concrete mix(es) resulted in low strength field test batches?	28 days
Have you noticed an increase in cast-in-place structural concrete mixes not meeting strength specifications within the last 2 years relative to previous years?	No
What factors do you believe led to the low strength outcomes?	Water/Cementitious Ratio, Air Content, Curing Method, Retempering, Specimen Handling Procedures, Lack of Quality Control
Provide additional clarification on any of the above factors.	Higher air content appears to be the most common reason for the failures, Feel lack of quality control by the suppliers has played a part as well as curing and handling issues.
Do you have any recommendations to reduce low strength concrete issues?	Making sure they provide trial batch data for proposed mix designs and ensuring the field is verifying the design matches the approved design for proportioning and materials.
Please provide any other relevant information about your experience with low strength concrete.	Skipped

Appendix F: Additional SmartRock Data

Summary tables for the data in Figures 39-43 can be found in Appendix H in Tables 93-97.

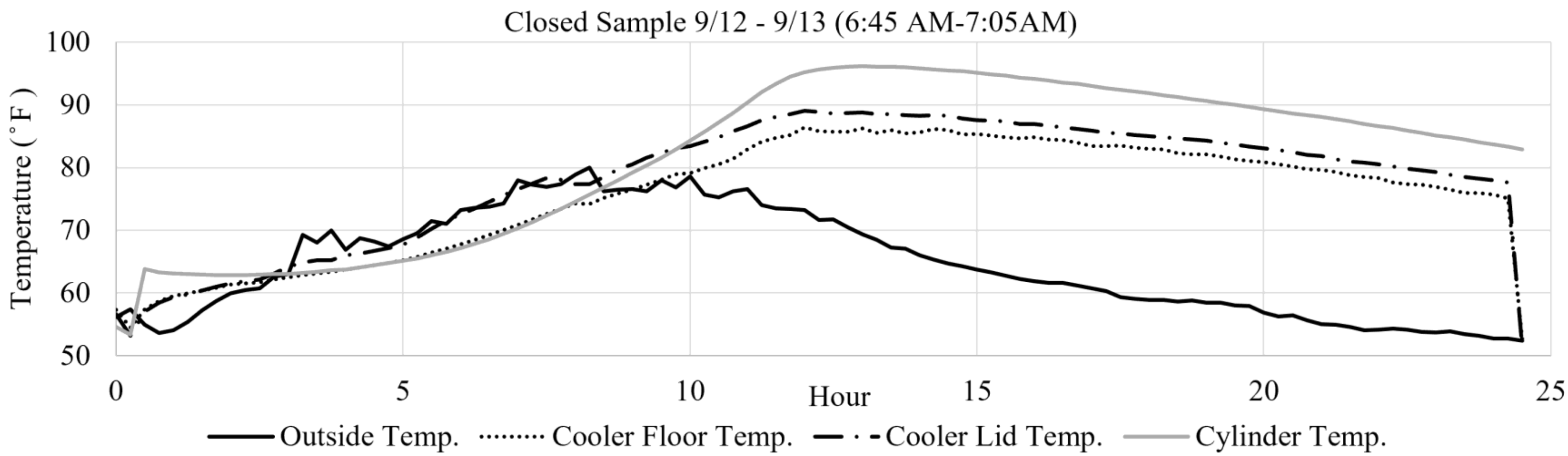


Figure 39: Closed SmartRock Sample 9/12-9/13

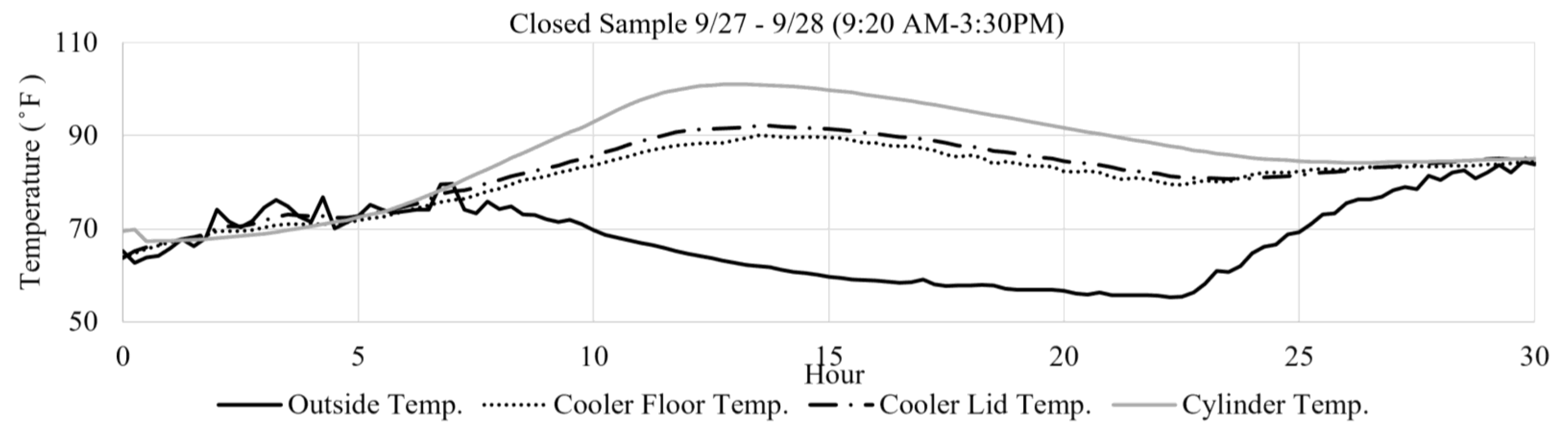


Figure 40: Closed SmartRock Sample 9/27-9/28

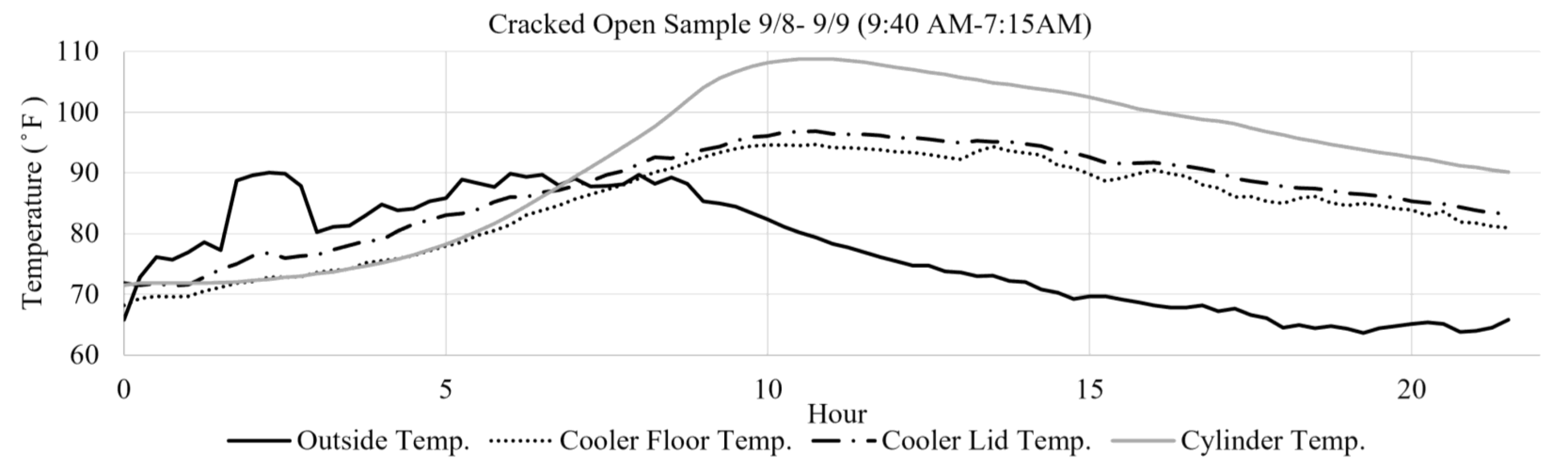


Figure 41: Cracked Open SmartRock Sample 9/8-9/9

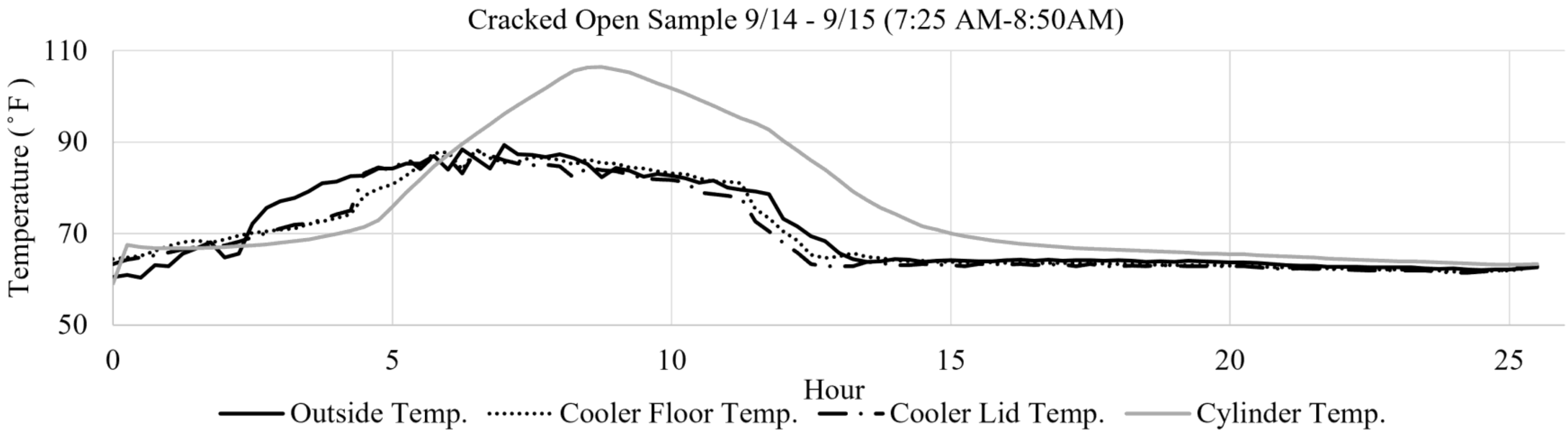


Figure 42: Cracked Open SmartRock Sample 9/14-9/15

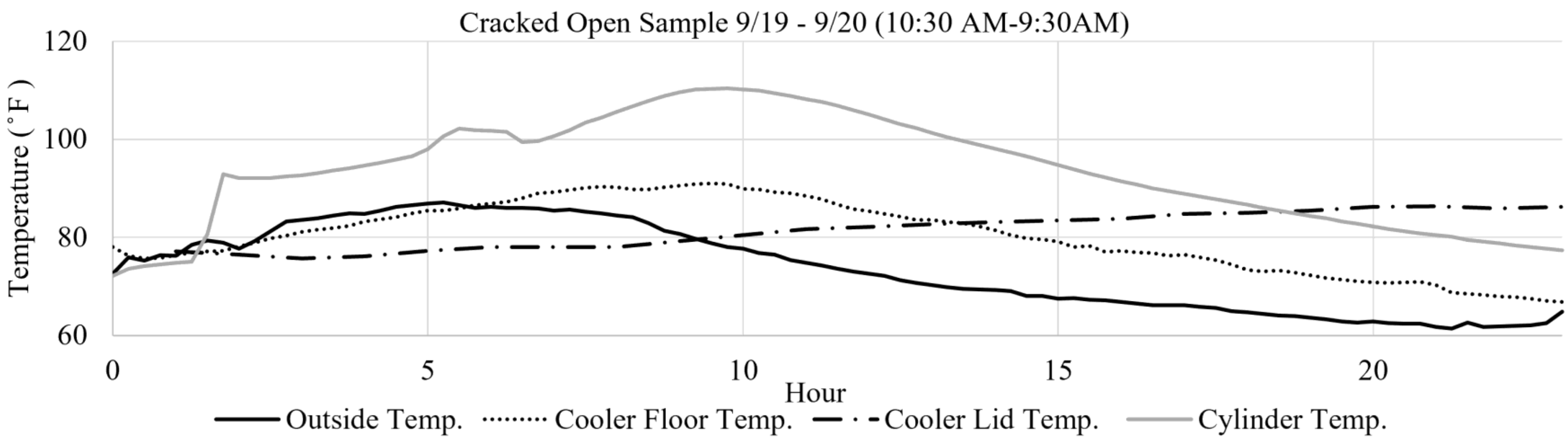


Figure 43: Cracked Open SmartRock Sample 9/19-9/20

Appendix G: Petrographic Examination

MJ2 CONSULTING

April 18, 2025

Dr. Christopher Shearer
South Dakota Mines
501 E. Saint Joseph St.
Rapid City, South Dakota 57701

Email: chris.shearer@sdsmt.edu
Phone: 605-219-8263

Petrographic Examination of Core Samples from Concrete Box Culvert—
Comparative Evaluation due to Low Concrete Strength, Meade County, South Dakota
MJ2 No. 2024.0166.1

Dear Dr. Shearer,

Two sets of concrete core samples, identified as "Good" and "Bad" (Figures 1 and 2), were received by MJ2 Consulting, PLLC (MJ2) on November 22, 2024. The samples reportedly represent the floor of a concrete box culvert placed in September 2022 in Meade County, South Dakota. Based on provided information, samples from the concrete represented by the *Bad* sample set achieved lower-than-expected compressive strength. Samples from a different batch of concrete on the same project, represented by the *Good* sample set, attained the expected strength. An initial visual assessment reportedly found high air content in the lower strength samples.

Petrographic examination (ASTM C856) of the provided samples was requested to evaluate the concrete properties and identify potential features which may have contributed to lower-than-expected compressive strength test results for the concrete represented by the *Bad* sample set. Each of the submitted sample sets included two core segments; one segment from each set (Figures 3 and 4) was selected by MJ2 for the examination.

Document Review

Project documents provided to MJ2 include concrete mixture information, quality control test reports for the box culvert project, and ready-mix batch tickets for the date of the floor placement (September 8, 2022). Review of these documents indicated the following relevant information:

- The concrete has a specified 28-day compressive strength of 4,500 psi. Details from the approved concrete mixture are reproduced in Table 1 on the following page.
- The batch tickets indicate that varying amounts of water, ranging from 30.4 to 80.8 gallons, were withheld from the ready-mix trucks at the batch plant. Given the load sizes, this amounts to 25.3 to 67.3 lbs. of water per cubic yard of concrete. Field additions of water are noted on only a few tickets.
- Quality control test reports for the date of the floor placement indicate that fresh air content measurements were within the specified limits of 5.0 to 7.5%. Tested cylinders from that day achieved an average compressive strength of 4,060 psi at 28+ days. Test results for drilled core samples also indicated low strength.

Table 1 – Concrete Mix Design, PCN: 021G, 07VR, 08QQ (Class A45)
Pete Lien & Sons, Inc., Mix # P01-902-45-20.F1

Material	Type/Source	Quantities, lbs/yd^3
Cement	Type I/II GCC Dacotah Cement, Rapid City, SD	487
Fly ash	Class F ECO Material, Coal Creek, ND	163
Fine aggregate 1	Natural sand Pete Lien & Sons Oral Pit, Fall River County, SD	572
Fine aggregate 2	Manufactured sand Pete Lien & Sons Quarry, Pennington County, SD	572
Coarse aggregate 1	Limestone ledge rock, size #1 Pete Lien & Sons Quarry, Pennington County, SD	1,412
Coarse aggregate 2	Limestone ledge rock, size #8 Pete Lien & Sons Quarry, Pennington County, SD	409
Water	City of Rapid City, SD	260
Admixtures	NRWR, Sika Plastocrete 250	1.0 - 3.0 oz./cwt
	MRWR, Sika Sikament 686	1.0 - 5.0 oz./cwt
	AEA, Sika AER-C	0.25 - 8.0 oz./yd^3
	Retarder, Sika Sikatard 440	0 - 6.0 oz./cwt
Air content		6.5%
Water-cementitious materials ratio (w/cm)		0.40

Summary of Findings

Based on examination of the selected core segments, lower-than-expected compressive strength of the concrete represented by the *Bad* sample is attributed to an **elevated water-cementitious materials ratio (w/cm)**. Paste within this concrete is non-uniform, exhibiting variable physical properties and microstructure. The overall w/cm is estimated to be greater than that of the *Good* concrete and exceeds the design w/cm.

Examination Results

– Concrete represented by the examined core segments exhibits similar constituents and overall composition. The concrete consists of crushed carbonate rock coarse aggregate, and siliceous and carbonate sand fine aggregate in a hardened paste of portland cement and fly ash (Figures 5 to 7).

- The coarse aggregate is crushed rock composed of limestone and dolomitic limestone. Observed maximum aggregate size is 0.9 in. Particles are generally uniformly distributed in the *Bad* core; distribution is somewhat non-uniform through the depth of the *Good* core.
- The fine aggregate consists of sand-sized particles of limestone, quartz and quartzite, granite and other igneous rocks, feldspar, iron oxides, chert, sandstone, shale, and other rocks and minerals. Distribution of particles is generally uniform.
- The cementitious paste contains a relatively large volume of cement-sized carbonate fragments (Figure 6b). These particles are likely limestone fines originating with the crushed rock coarse aggregate and manufactured sand fine aggregate. However, a portion may represent an interground limestone addition to the cement.

– Physical properties and microstructural characteristics of the cement paste are summarized in Table 2 on the following page.

- Observed properties are slightly variable in the *Good* core.
- Properties are significantly more variable within the *Bad* core. Under magnification, the paste exhibits a mottled appearance with localized areas of lighter colored paste and darker colored paste. Areas with darker color generally exhibit better physical properties than areas with lighter color. Variability is also observed within the paste microstructure; some regions exhibit significantly greater volumes of residual cementitious particles than other areas (Figure 7).
- The w/cm of the *Bad* core is thus variable over small areas. Overall, the properties and characteristics of the *Bad* core suggest a higher w/cm than estimated for the *Good* core.

– The concrete is air entrained based on the abundance of small, spherical voids in the paste matrix.

- As indicated in Table 2, the total air content is estimated to be slightly higher in the *Bad* core compared to the *Good* core, but is still within the specified limits for the concrete.
- Minor clustering of voids is observed within both cores (Figure 8). The degree of clustering does not appear severe enough to significantly affect the compressive strength of the concrete.

– Depth of paste carbonation is relatively shallow along the top surface of each core (Figure 9), but is overall slightly deeper in the *Bad* core.

Table 2 – Observed properties of examined core segments

Sample	**“Good”**	**“Bad”**
Paste color	medium gray-beige; slightly darker in uppermost ~0.2 in.	mottled light beige to medium-dark beige-gray; overall, light-medium gray-beige
Paste hardness	moderately hard to locally hard	variable, ranges from moderately soft to moderately hard
Paste luster	subvitreous	subvitreous
Paste absorbency	moderate to moderately low	variable, ranges from moderately high to moderately low
Paste-aggregate bond	moderately tight to tight	moderately tight
Calcium hydroxide*	7 to 10%	somewhat variable, 9 to 12% overall
Residual cement*	8 to 11%	variable, 6 to 9% overall
Residual fly ash*	18 to 22%	variable, 14 to 18% overall
Estimated w/cm	0.35 to 0.45	variable, 0.40 to 0.50 overall
Air content	estimated 4 to 6%	estimated 5 to 7%
Depth of carbonation	negligible to 0.08 in. at top surface	0.04 to 0.12 in. at top surface

* Visually estimated by volume of cementitious paste.

Discussion

The examined concrete does not appear to deviate from the provided concrete mixture information in relation to overall composition and constituents. The coarse aggregate is crushed limestone with an observed top size of 0.9 in.; this complies with top size requirements for the South Dakota DOT Size #1 designation. Observed properties and constituents of the fine aggregate are consistent with a blend of natural and manufactured sand. The concrete contains portland cement and fly ash, and is air entrained.

Features of the air-void systems in the examined samples do not suggest that the low strength of the *Bad* concrete is related to elevated air content or harmful clustering of entrained air voids. The estimated air contents do not exceed the specified maximum of 7.5%, and observed clustering is minor.

The w/cm of the *Good* concrete is estimated at 0.40 ±0.05 and is, thus, generally in line with the w/cm indicated by the concrete mixture information.

Paste of the *Bad* concrete exhibits significant variability in physical properties, microstructure, and w/cm. Small pockets of weak paste with significantly elevated w/cm are distributed throughout the concrete. These would have a significant effect on load transfer and reduce the overall compressive strength of the material. To allow for comparison between samples and to the mix design, the overall w/cm of the *Bad* concrete is estimated at 0.45 ±0.05. This increase in w/cm compared to the *Good* concrete, and the concrete mixture design, is significant enough to account for the approximate 500 psi deficit in compressive strength indicated by the quality control test results for cylinders cast on the date of the floor placement.

Petrographic examination could not definitively identify the source of excess water leading to the overall elevated w/cm in the *Bad* concrete. However, the observed variability in properties and w/cm through the concrete suggests incomplete incorporation of mix water. Furthermore, the batch tickets indicate significant underbatching of water at the ready-mix plant. Thus, the variable and overall elevated w/cm may be the result of on-site water additions to the concrete. Only a few of the provided tickets note the water amounts added on-site. For many of the batches, the amount of water added on site and the total amount of water in the as-placed concrete are not clear. It is possible that some additions exceeded the amount withheld. Additionally, if on-site water additions were not adequately mixed, significant variability, as observed in the *Bad* concrete, could result.

Methods of Test

The examination was performed in accordance with ASTM C856-20, "Standard Practice for Petrographic Examination of Hardened Concrete." The provided samples were visually inspected and photographed as received. A slice was cut longitudinally from the selected core segments and one of the resulting sides of each slice was ground (lapped) to produce a smooth, flat, semi-polished surface. Lapped and freshly broken surfaces of the concrete were examined using a stereomicroscope at magnifications up to 45X.

For thin-section study, a small rectangular block was cut from the central portion of each selected core segment, and one side of each block was lapped to produce a smooth, flat surface. The blocks were cleaned and dried, and the prepared surfaces were mounted on ground glass microscope slides with epoxy. After the epoxy hardened, the thickness of each mounted block was reduced to approximately 20 µm (0.0008 in.). The resulting thin sections were examined using a polarized-light (petrographic) microscope at magnifications up to 400X to study aggregate and paste mineralogy and microstructure.

Estimated water-cementitious materials ratio (w/cm) is based on observed concrete and paste properties including, but not limited to: 1) relative amounts of residual (unhydrated and partially hydrated) portland cement clinker particles and supplementary cementitious materials, such as ground slag or fly ash; 2) amount and size of calcium hydroxide crystals; 3) paste hardness, color, and luster; 4) paste-aggregate bond; and 5) relative absorbency of paste as indicated by the readiness of a freshly fractured surface to absorb applied water droplets.

Depth and pattern of paste carbonation was determined by application of a pH indicator solution (phenolphthalein) to freshly cut and fractured concrete surfaces. The solution imparts a deep magenta stain to high pH, non-carbonated paste. Carbonated paste does not change color.

Full results and observations from the examination are provided in the attached petrographic data sheets.

Closing

The observations and interpretations presented in this report are based on the performed examination of the submitted concrete samples and information available at the time of the examination. MJ2 reserves the right to modify interpretations if further testing is performed on the samples, additional samples are examined, or other relevant information becomes available at a later date.

The samples will be retained for 30 days and then disposed. If you wish to have the samples returned, please contact me at your earliest convenience to make arrangements.

MJ2 appreciates the opportunity to be of service to you. If you have any questions, please feel free to contact me by phone or email.

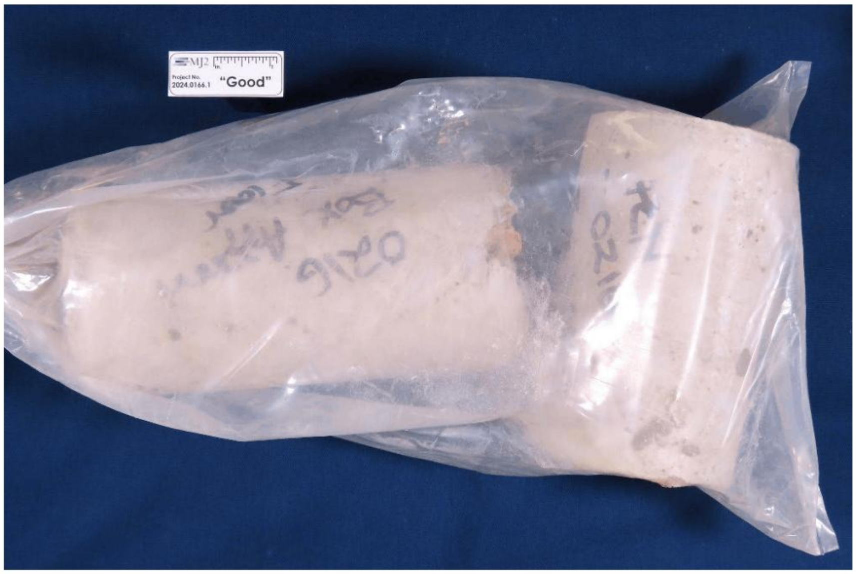
Sincerely,

MJ2 Consulting, PLLC

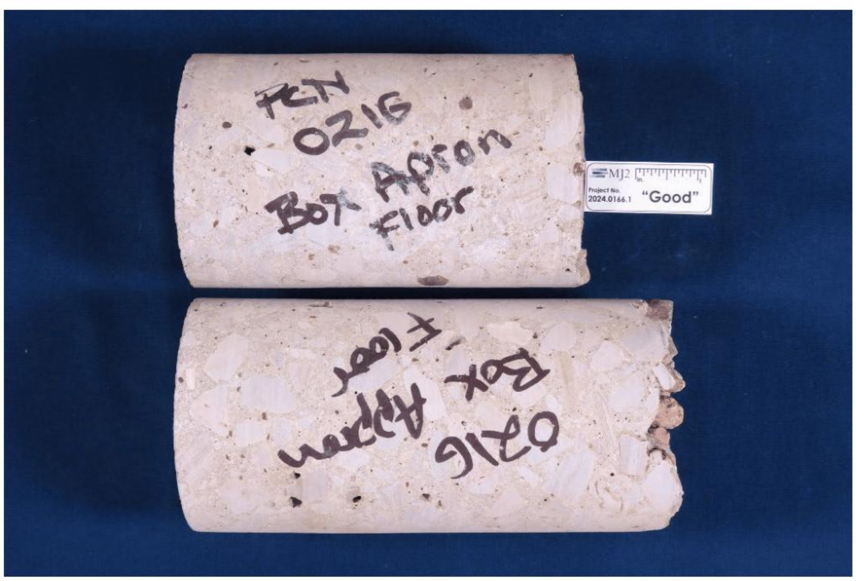
Victoria A. Jennings

Victoria Jennings
Senior Petrographer
Vicki@MJ2consulting.com
Cell: 773-659-9711

Attachments: Figures, Petrographic Data Sheets

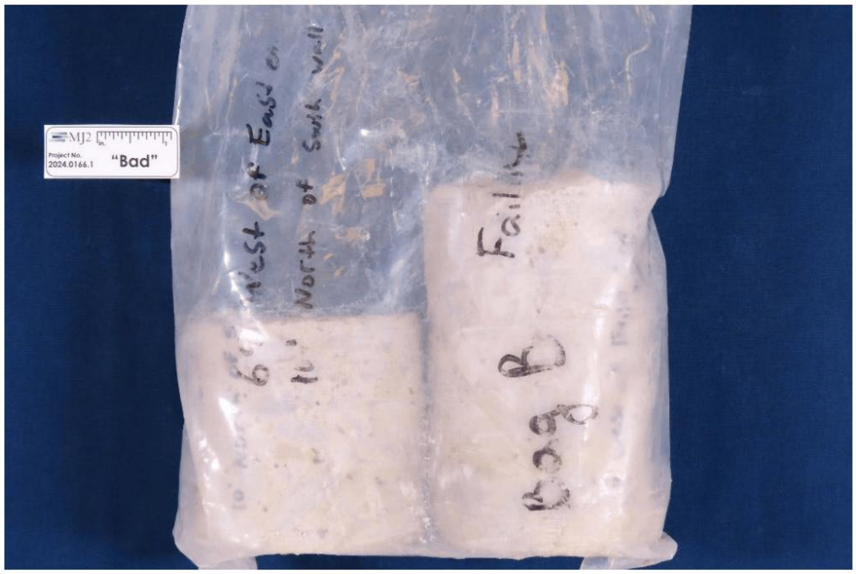


1a Bagged sample.

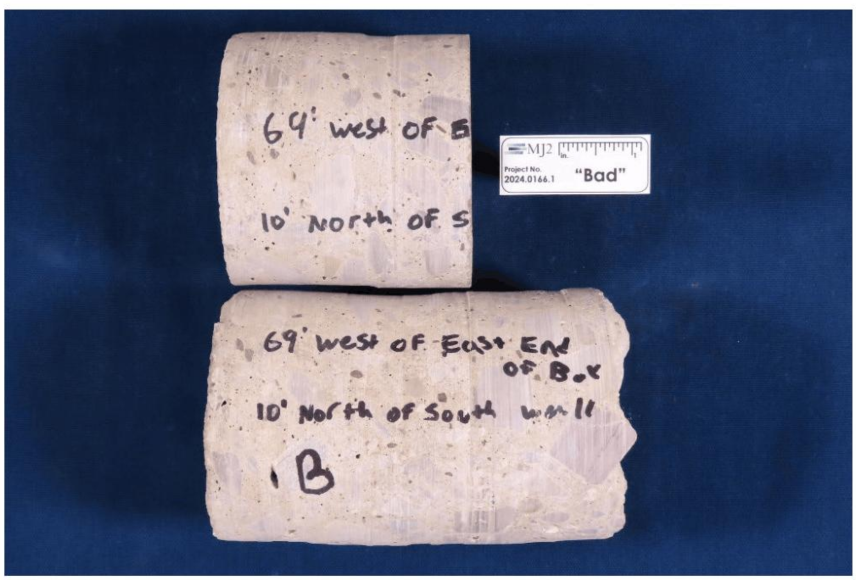


1b Side views of unbagged sample segments.

Figure 1 – "Good" sample set, as received in laboratory.

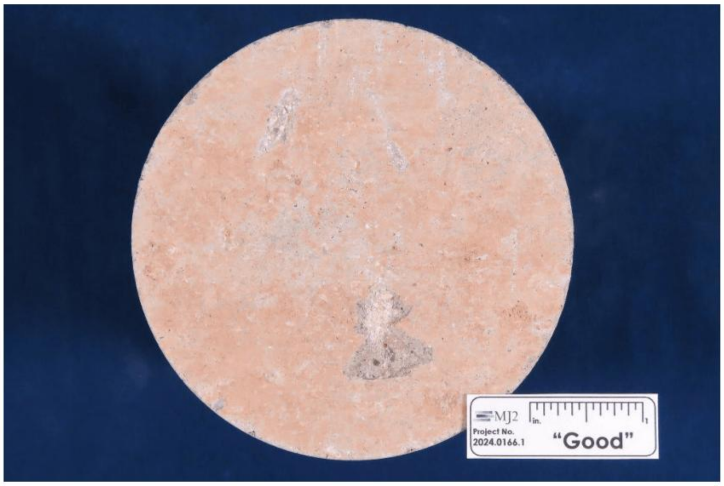


2a Bagged sample.



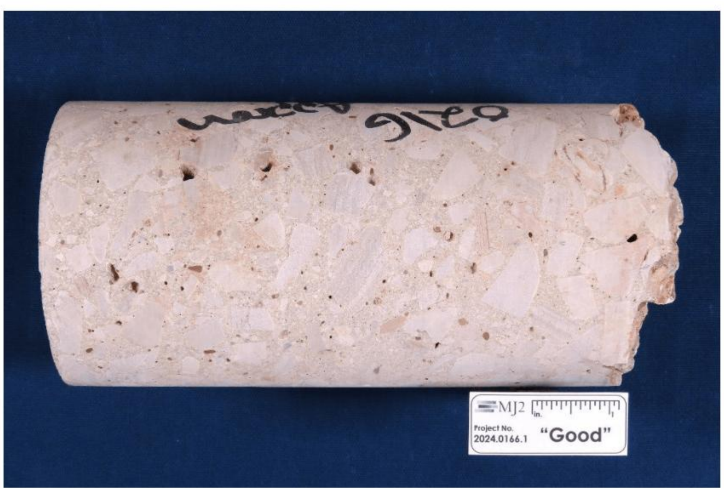
2b Side views of unbagged sample segments.

Figure 2 – "Bad" sample set, as received in laboratory.



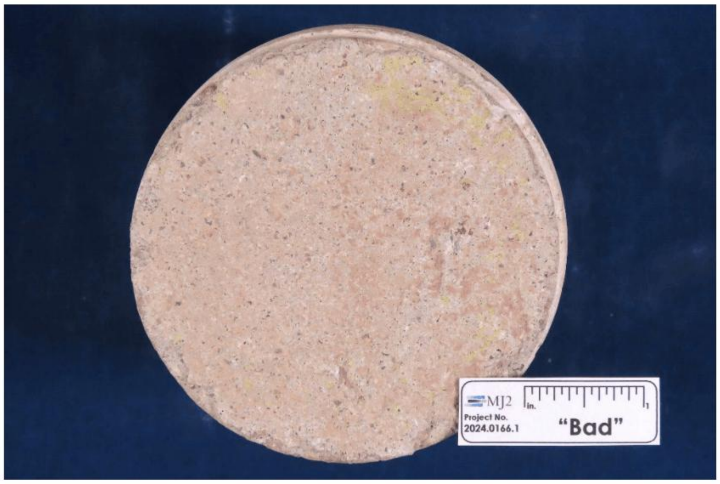
3a. Top surface.

3b. Bottom surface.

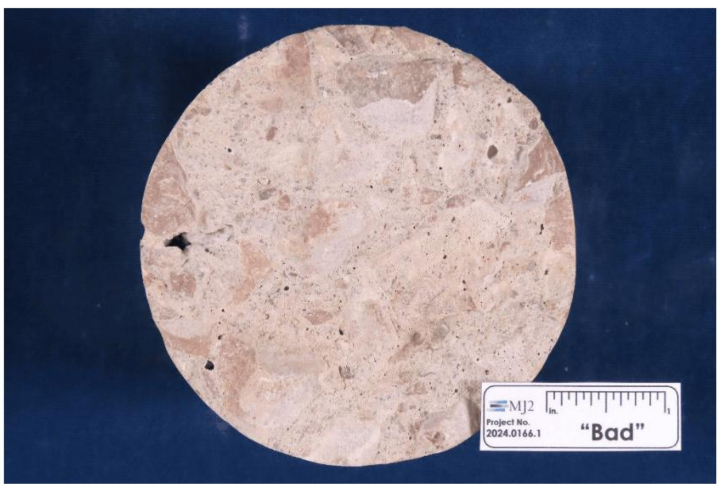


3c. Side view, top end at left.

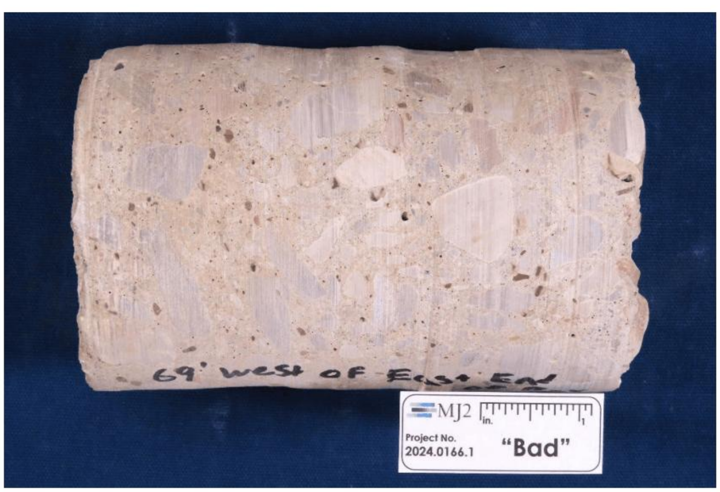
Figure 3 – Core segment from *Good* sample set selected for examination.



4a. Top surface.

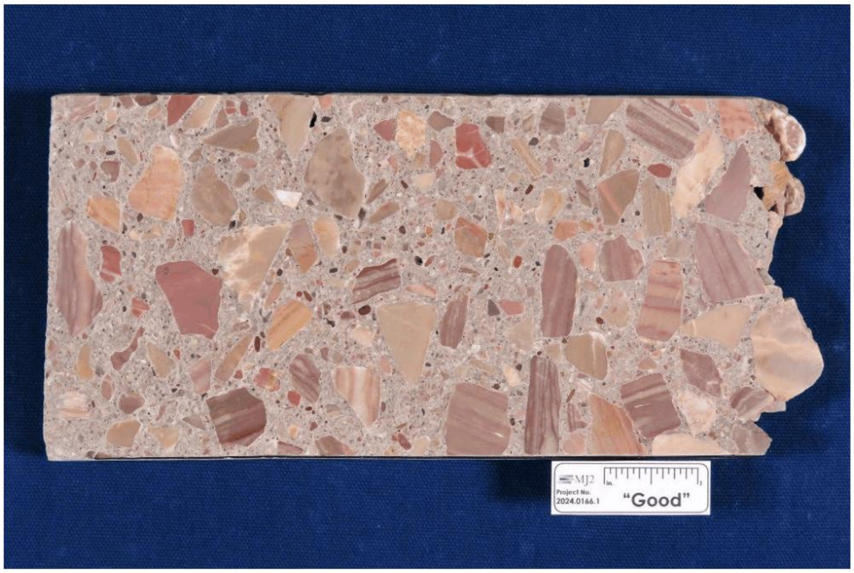


4b. Bottom surface.

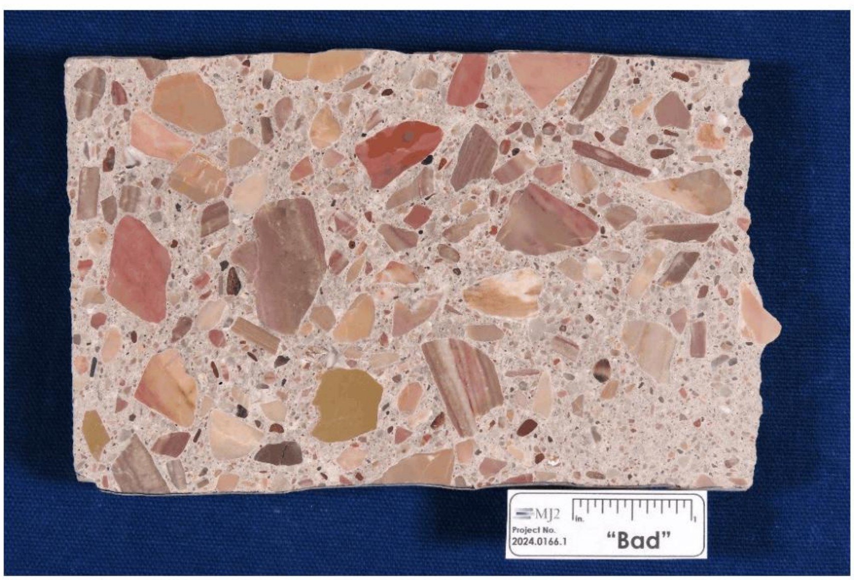


4c. Side view, top end at left.

Figure 4 – Core segment from *Bad* sample set selected for examination.

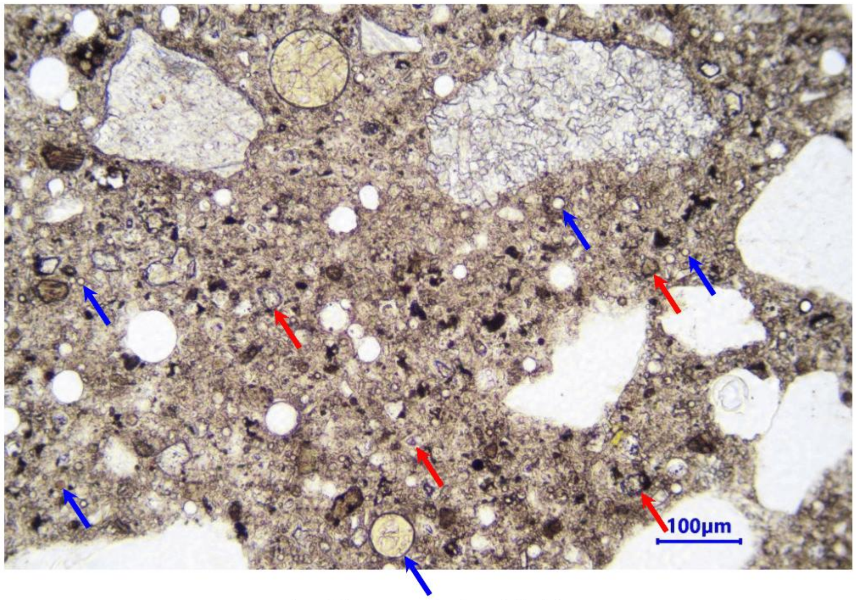


5a *Good* core.

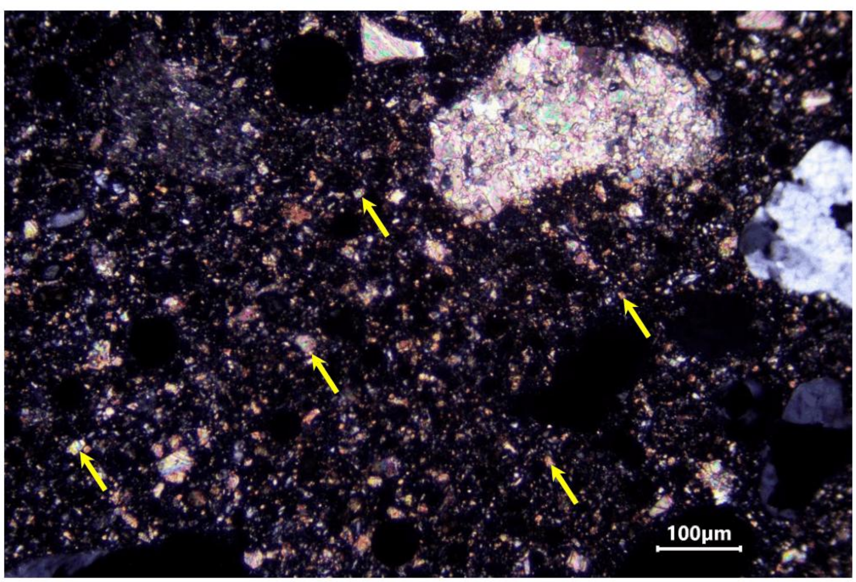


5b *Bad* core.

Figure 5 – Lapped longitudinal cross-sections of examined core segments, top ends at left.

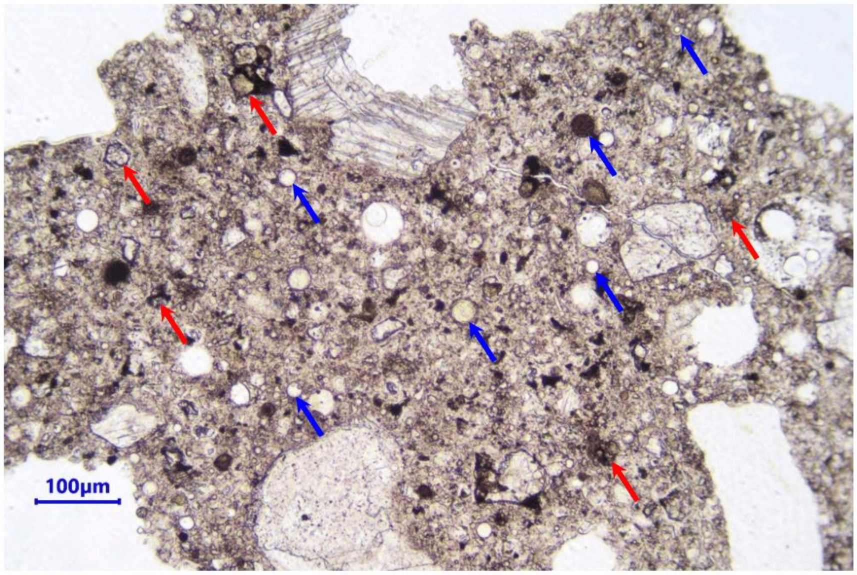


6a Plane-polarized light.

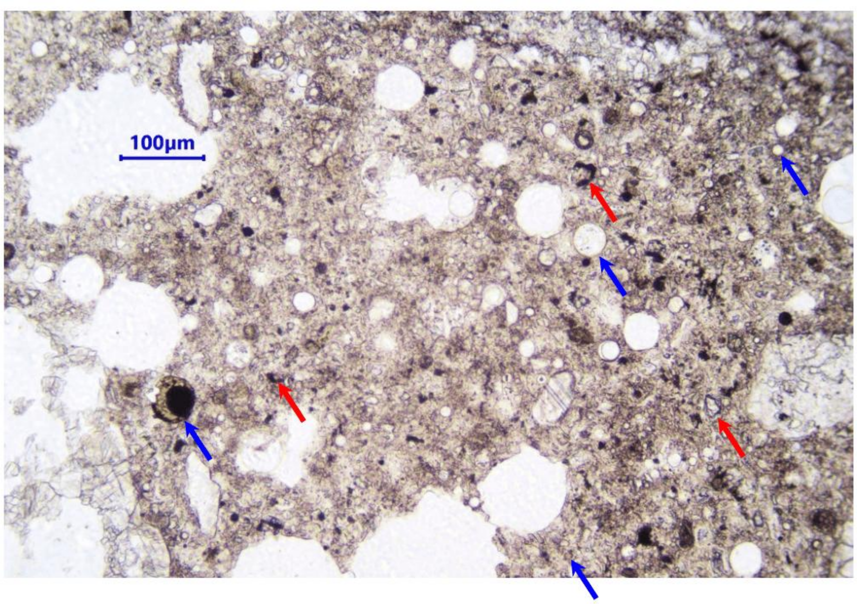


6b Cross-polarized light.

Figure 6 – Transmitted light photomicrographs of concrete of *Good* core in thin section. Red arrows indicate residual particles of portland cement, while blue arrows designate residual fly ash spheres within paste matrix. Yellow arrows indicate cement-sized carbonate fragments. Images show the same field of view under different lighting conditions.

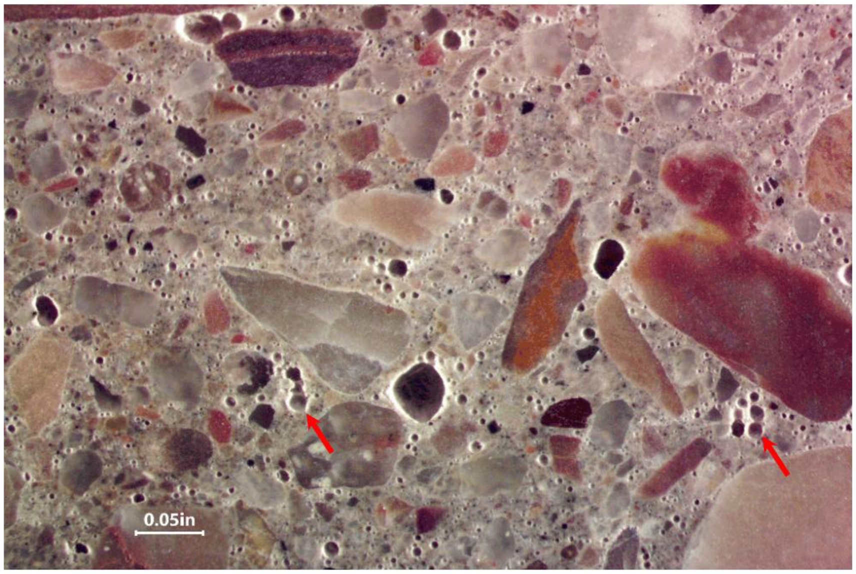


7a Area with greater volume of residual cementitious materials and lower w/cm.

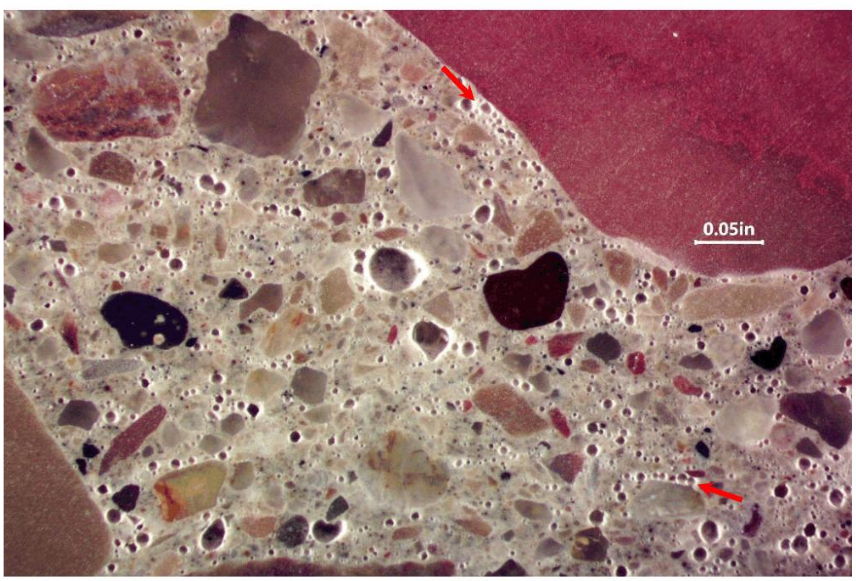


7b Area with lower overall volume of residual cementitious materials and higher w/cm.

Figure 7 – Transmitted light photomicrographs of concrete of *Bad* core in thin section, plane-polarized light. Images show areas with varying volumes of residual portland cement particles (red arrows) and residual fly ash spheres (blue arrows), and variable w/cm.

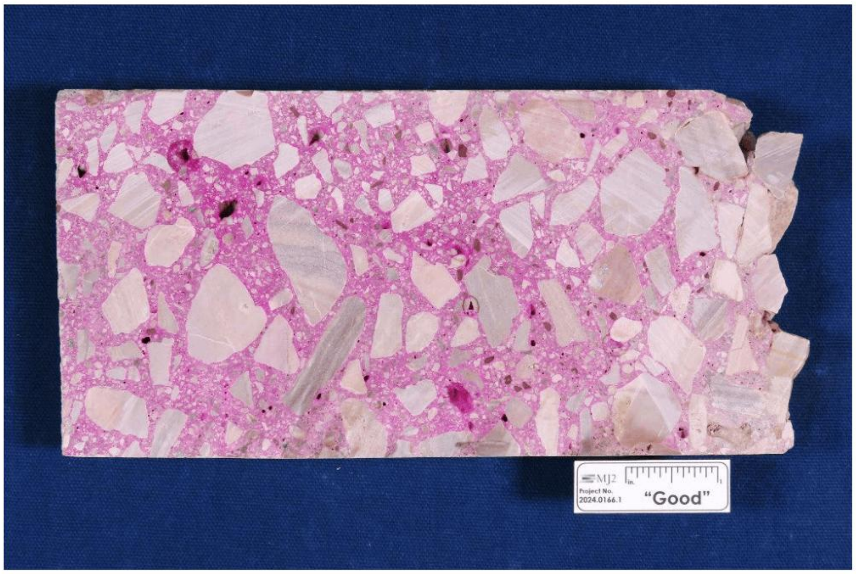


8a *Good* core.

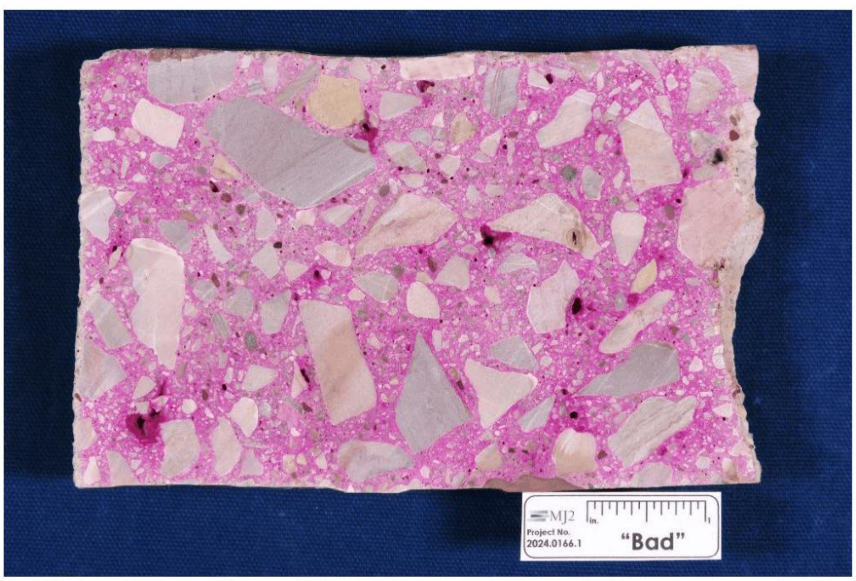


8b *Bad* core.

Figure 8 – Magnified views of lapped cross-sections of core samples showing air-void systems within concrete. Arrows indicate small clusters of entrained air voids.



9a *Good* core.



9b *Bad* core.

Figure 9 – Saw-cut cross-sections of core samples, stained with pH indicator (phenolphthalein) solution. The solution imparts a magenta stain to high-pH, non-carbonated paste. Carbonated paste does not change color.

PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C856

STRUCTURE: Concrete box culvert | DATE RECEIVED: November 22, 2024

LOCATION: Meade County, SD | EXAMINED BY: V. Jennings

SAMPLE

Identification: "Good"

Dimensions: Core diameter is 100 mm (3.9 in.). Core length is 185 to 205 mm (7.3 to 8.1 in.); full floor thickness.

Top Surface: Generally flat, and slightly rough concrete surface exhibits lightly textured finish. Surface is shallowly chipped in a couple localized areas, and is otherwise lightly coated with orange-brown powder.

Bottom Surface: Rough and highly irregular with coarse subbase particles embedded into underside of concrete.

Cracks, Joints, Large Voids: Core exhibits a few coarse, irregular voids measuring up to 13 mm (0.5 in.) across. No cracks or joints observed.

Reinforcement: None in core segment.

AGGREGATES

Coarse: Crushed rock composed of limestone and dolomitic limestone.

Fine: Sand-sized particles comprised of limestone, quartz and quartzite, granite and other igneous rocks, feldspar, iron oxides, chert, sandstone, shale, and other rocks and minerals.

Gradation & Top Size: Visually appears evenly graded to an observed top size of 22 mm (0.9 in.).

Shape, Texture, Distribution: Coarse– angular to sub-angular, and equant to elongate, with somewhat rough, irregular surfaces. Distribution is somewhat non-uniform; relative volume of coarse particles increases with depth into core. Fine– angular to sub-rounded, and equant to oblong; distribution is generally uniform.

PASTE

Color: Medium gray-beige. Slightly darker in uppermost approximate 5 mm (0.2 in.).

Hardness: Moderately hard to locally hard.

Luster: Subvitreous.

Absorbency: Slightly variable, ranging from moderate to moderately low; water droplets applied to surfaces of freshly fractured concrete are absorbed slightly quickly to slowly by paste.

Paste-Aggregate Bond: Moderately tight to tight; surfaces of freshly fractured concrete extend through a slight majority of aggregate particles.

Air Content: Estimated 4 to 6%. Concrete is air entrained based on abundance of small, spherical voids in paste matrix. Minor clustering of voids locally occurs within body of paste.

Depth of Carbonation: Negligible to 2 mm (0.08 in.) at top surface.

Calcium Hydroxide*: Estimated 7 to 10% comprised of fine to medium, tabular crystals distributed throughout paste and along periphery of aggregate particles.

Residual Portland Cement Clinker Particles*: Estimated 8 to 11%.

Supplementary Cementitious Materials*: Estimated 18 to 22% residual fly ash.

Secondary Deposits: None observed.

ESTIMATED WATER-CEMENTITIOUS MATERIALS RATIO: Moderately low (0.35 to 0.45).

MICROCRACKING: A couple vertical microcracks extend from core top surface to depths up to 4 mm (0.16 in.). Randomly oriented, and occasionally interconnected, microcracks are common in body of concrete.

MISCELLANEOUS: Paste contains a relatively large volume of cement-sized carbonate fragments. These particles are likely limestone fines originating with the crushed rock aggregate; a portion may also represent an interground limestone addition to the cement.

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*percent by volume of paste

PETROGRAPHIC EXAMINATION OF HARDENED CONCRETE, ASTM C856

STRUCTURE: Concrete box culvert	DATE RECEIVED: November 22, 2024

LOCATION: Meade County, SD	EXAMINED BY: V. Jennings

SAMPLE

Identification: “Bad”

Dimensions: Core diameter is 94 mm (3.7 in.). Core length is 140 to 152 mm (5.5 to 6.0 in.); partial floor thickness.

Top Surface: Slightly rough and uneven concrete surface exhibits moderately textured, possibly broomed, finish. Tops of several sand particles are exposed on otherwise paste-rich surface. Surface paste is light-medium gray-beige in color and moderately hard. Small amounts of orange-brown powder locally coat surface.

Bottom Surface: Rough, broken concrete fractured both around and through aggregate particles.

Cracks, Joints, Large Voids: Core exhibits a couple coarse voids measuring up to 8 mm (0.3 in.) across. No cracks or joints observed.

Reinforcement: None in core segment.

AGGREGATES

Coarse: Crushed rock composed of limestone and dolomitic limestone.

Fine: Sand-sized particles comprised of limestone, quartz and quartzite, granite and other igneous rocks, feldspar, iron oxides, chert, sandstone, shale, and other rocks and minerals.

Gradation & Top Size: Visually appears evenly graded to an observed top size of 20 mm (0.8 in.).

Shape, Texture, Distribution: Coarse– angular to sub-angular, and equant to elongate, with somewhat rough, irregular surfaces; distribution is generally uniform. Fine– angular to sub-rounded, and equant to oblong; distribution is uniform.

PASTE

Color: Generally mottled between light beige and medium-dark beige-gray; overall, appears light-medium gray-beige.

Hardness: Variable, ranging from moderately soft to moderately hard.

Luster: Subvitreous.

Absorbency: Variable, ranging from moderately high to moderately low; water droplets applied to surfaces of freshly fractured concrete are absorbed somewhat quickly to somewhat slowly by paste.

Paste-Aggregate Bond: Moderately tight; surfaces of freshly fractured concrete extend through a slight majority of aggregate particles.

Air Content: Estimated 5 to 7%. Concrete is air entrained based on abundance of small, spherical voids in paste matrix. Concrete exhibits minor clustering of voids, mainly within body of paste and occasionally along periphery of aggregate particles.

Depth of Carbonation: 1 to 3 mm (0.04 to 0.12 in.) at top surface.

Calcium Hydroxide*: Somewhat variable through paste; locally estimated as low as 6% and as high as 14%. Overall, estimated 9 to 12%, comprised of fine to medium, tabular crystals.

Residual Portland Cement Clinker Particles*: Variable through paste; locally estimated as low as 3% and as high as 12%. Overall estimated 6 to 9%.

Supplementary Cementitious Materials*: Variable through paste; locally estimated as low as 9% and as high as 23%. Overall estimated 14 to 18%.

Secondary Deposits: None observed.

ESTIMATED WATER-CEMENTITIOUS MATERIALS RATIO: Variable through paste. Overall, moderately low to moderate (0.40 to 0.50).

MICROCRACKING: One microcrack extends vertically from top surface through full depth of core segment, passing around aggregate particles. A couple other vertical microcracks extend from core top surface to depths up to 6 mm (0.24 in.). Randomly oriented, and occasionally interconnected, microcracks are common in body of concrete.

MISCELLANEOUS: Paste contains a relatively large volume of cement-sized carbonate fragments. These particles are likely limestone fines originating with the crushed rock aggregate; a portion may also represent an interground limestone addition to the cement.

---

*percent by volume of paste

Appendix H: Supplemental Tables

Table 90: Summary of the data from Figures 11, 13, 15, 17, 35, and 37

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2361788	7.0	4.0	No Data	66	2,680	62	78
2371245	7.4	4.5	139.5	82	3,330	71	85
No Data	7.5	3.5	137.5	78	3,380	77	90
2353821	6.6	4.5	139.5	83	3,400	75	84
No Data	7.5	3.3	138.5	89	3,450	62	77
2363037	7.0	4.3	138.0	57	3,460	35	46
2372698	5.8	3.0	144.1	85	3,500	67	84
2371306	7.4	5.0	141.5	80	3,520	46	52
2371306	7.4	5.0	141.5	80	3,530	68	87
2357363	9.1	3.0	138.5	82	3,580	68	87
No Data	7.5	3.5	137.5	78	3,580	77	90
2377981	7.0	2.8	140.5	82	3,590	71	81
2363037	7.0	4.3	138.0	57	3,620	35	46
2353821	6.6	4.5	138.5	83	3,660	75	84
2372698	5.8	3.0	143.6	85	3,670	75	96
2347741	7.2	4.5	140.5	82	3,680	72	83
No Data	7.5	3.3	139.0	89	3,690	85	93
2351486	5.6	4.5	142.1	81	3,690	81	93
2320288	7.4	4.0	138.5	88	3,700	77	88
2358781	6.6	4.3	141.0	79	3,700	75	85
2347741	7.2	4.5	140.5	82	3,700	72	83
No Data	7.5	4.5	139.5	77	3,710	75	91
2328457	7.5	4.0	138.0	75	3,710	80	92
No Data	7.3	3.0	135.0	75	3,710	70	80
2290803	7.5	4.0	139.6	74	3,720	74	85
2327810	7.4	4.5	138.0	84	3,720	80	92
2371245	7.4	4.5	140.5	82	3,730	71	85
2320288	7.4	4.0	138.0	88	3,750	77	88
No Data	7.3	3.0	134.5	75	3,750	70	80
2328547	7.1	3.3	139.0	79	3,760	65	81
2351388	7.2	4.5	No Data	83	3,760	74	85
2361788	7.0	4.0	139.5	66	3,780	62	78
2376260	7.5	4.5	140.0	82	3,800	76	84
2296135	7.5	4.0	138.5	84	3,810	74	85
2328457	7.5	4.0	No Data	75	3,810	80	92
2291377	7.5	4.0	139.0	71	3,830	83	90
2277198	6.8	4.5	139.5	85	3,850	83	90
2328884	7.3	4.0	139.0	80	3,850	64	73
2372686	7.5	4.3	140.0	79	3,850	68	81
2274274	5.5	3.0	142.6	87	3,860	81	95

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2280577	7.4	4.3	138.0	74	3,860	81	95
2280577	7.4	4.3	141.5	74	3,880	72	83
2350619	7.5	4.5	140.0	83	3,880	72	84
2311271	7.2	2.5	139.6	67	3,890	50	65
2320684	6.0	3.0	144.1	80	3,890	71	81
2361788	7.0	4.0	No Data	66	3,890	62	78
2376260	7.5	4.5	140.0	82	3,890	76	84
2351486	5.6	4.5	145.1	81	3,890	81	93
2353821	6.6	4.5	140.5	83	3,890	75	84
2367755	7.2	2.5	141.5	70	3,900	58	70
2278700	7.4	4.3	140.0	81	3,910	64	72
2341721	10.1	5.3	138.5	79	3,910	75	94
2316762	7.0	4.0	139.0	79	3,920	71	81
2328457	7.5	4.0	138.0	75	3,930	64	73
2351388	7.2	4.5	138.5	83	3,930	74	85
2322376	6.8	3.8	142.1	85	3,940	68	80
2277198	6.8	4.5	139.5	85	3,940	73	83
2272908	6.8	4.0	140.5	80	3,940	81	90
2344391	7.5	3.0	140.5	86	3,940	79	92
2355882	8.0	4.0	138.5	81	3,940	79	92
2380307	6.0	3.8	143.6	78	3,950	72	88
2348333	7.2	4.5	No Data	85	3,950	68	82
2320703	6.3	3.5	141.1	90	3,960	77	87
2328642	7.5	4.0	138.5	76	3,960	64	73
2348674	7.4	4.3	139.5	83	3,960	72	90
2351779	5.6	4.3	142.1	82	3,960	77	92
2350466	5.8	4.0	142.6	79	3,970	72	81
2322885	6.4	4.5	139.6	82	3,980	74	83
2276020	5.8	4.5	141.5	77	3,980	72	87
2349346	7.0	3.3	139.0	79	3,980	65	74
2351388	7.2	4.5	137.5	83	3,980	74	85
2350619	7.5	4.5	No Data	83	3,990	72	84
2344270	7.4	3.0	140.5	81	3,990	80	93
2357363	9.1	3.0	139.0	82	4,000	68	82
No Data	7.4	4.5	138.5	72	4,000	73	83
No Data	No Data	No Data	141.5	No Data	4,000	63	80
2361788	7.0	4.0	139.5	66	4,000	62	78
2279034	7.0	4.0	140.5	82	4,010	75	85
2322201	5.8	3.8	140.1	78	4,020	8	80
2370573	6.1	4.5	142.6	88	4,020	79	90
No Data	5.9	3.3	141.5	70	4,020	75	85
2377981	7.0	2.8	138.5	82	4,030	71	81
2379601	6.2	4.3	142.6	84	4,030	72	90
No Data	7.5	3.5	140.0	76	4,030	56	66

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
No Data	7.4	4.5	No Data	72	4,030	78	86
2328642	7.5	4.0	No Data	76	4,030	76	95
2338932	6.2	3.5	144.1	73	4,030	51	71
2372274	6.3	3.8	142.6	81	4,040	68	82
2367755	7.2	2.5	No Data	70	4,040	58	70
2316762	7.0	4.0	No Data	79	4,040	78	86
2322615	6.4	3.8	145.7	81	4,040	75	82
2320703	6.3	3.5	140.6	90	4,050	77	87
2350466	5.8	4.0	142.6	79	4,060	72	81
2327810	7.4	4.5	138.0	84	4,060	76	95
2328884	7.3	4.0	No Data	80	4,060	76	95
2338932	6.2	3.5	No Data	73	4,060	51	71
2279034	7.0	4.0	140.5	82	4,060	74	81
2268483	6.9	4.0	141.5	75	4,070	74	81
2372370	5.4	4.0	145.7	85	4,070	65	80
2351779	5.6	4.3	142.6	82	4,070	77	92
2328547	7.1	3.3	139.0	79	4,080	65	81
No Data	5.6	4.5	141.5	85	4,080	73	83
2344270	7.4	3.0	No Data	81	4,080	80	93
2375999	7.5	5.5	140.5	85	4,080	87	102
2379601	6.2	4.3	143.6	84	4,090	72	90
No Data	7.4	4.5	138.0	72	4,090	75	85
2275070	7.2	4.0	140.0	83	4,090	75	85
2328642	7.5	4.0	138.5	76	4,090	76	95
2338932	6.2	3.5	143.1	73	4,090	51	71
2350619	7.5	4.5	140.0	83	4,090	72	84
2277554	7.3	4.5	140.0	88	4,090	76	93
2287064	6.5	4.5	140.5	68	4,100	58	72
2327810	7.4	4.5	No Data	84	4,100	76	95
2348674	7.4	4.3	140.0	83	4,100	72	90
2343073	7.3	4.5	142.6	77	4,100	69	88
2343240	7.4	4.0	141.0	78	4,100	77	92
2370380	6.8	3.0	145.1	77	4,110	41	51
2311271	7.2	2.5	140.6	67	4,110	50	65
2363500	5.9	4.0	141.5	64	4,110	45	56
2355882	8.0	4.0	138.0	81	4,110	69	88
2343240	7.4	4.0	141.0	78	4,110	77	92
2298995	6.5	4.5	140.6	82	4,120	66	81
2323818	6.5	4.5	No Data	78	4,130	72	84
2323818	6.5	4.5	138.5	78	4,130	72	84
2290803	7.5	4.0	141.6	74	4,130	72	88
2358781	6.6	4.3	141.0	79	4,130	75	85
2322557	6.2	4.0	142.6	85	4,130	84	99
2278700	7.4	4.3	140.5	81	4,130	64	72

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2348333	7.2	4.5	139.5	85	4,130	68	82
2354518	5.5	4.5	141.0	74	4,130	67	81
2275819	5.6	3.3	141.5	80	4,140	64	78
2274274	5.5	3.0	141.5	87	4,140	72	88
2375097	6.7	3.0	140.5	81	4,140	76	86
2277554	7.3	4.5	140.5	88	4,140	76	93
2298995	6.5	4.5	141.1	82	4,150	77	91
No Data	7.5	4.5	139.5	77	4,150	75	91
2370380	6.8	3.0	143.6	77	4,150	37	53
2366898	6.2	3.0	141.5	76	4,150	67	79
2375097	6.7	3.0	140.5	81	4,150	76	86
2375999	7.5	5.5	No Data	85	4,150	87	102
2371329	5.5	3.8	143.1	76	4,150	67	79
2316762	7.0	4.0	138.5	79	4,160	65	74
2320091	7.2	3.3	139.0	85	4,160	65	74
2341536	6.5	3.3	142.1	71	4,160	67	76
2350619	7.5	4.5	No Data	83	4,160	72	84
2372686	7.5	4.3	141.5	79	4,160	68	81
2367755	7.2	2.5	141.0	70	4,170	58	70
No Data	6.6	4.3	141.6	78	4,170	66	76
2349141	6.4	3.0	142.6	87	4,170	60	71
2322557	6.2	4.0	No Data	85	4,170	84	99
2344270	7.4	3.0	140.5	81	4,170	80	93
2376971	6.9	4.0	140.0	86	4,170	66	76
2291377	7.5	4.0	140.6	71	4,180	66	76
2299240	7.0	4.5	140.1	86	4,190	78	85
2272908	6.8	4.0	140.0	80	4,190	81	90
2276161	7.5	4.3	No Data	77	4,190	67	79
2322746	6.0	1.5	141.6	86	4,200	78	85
2322376	6.8	3.8	140.1	85	4,210	68	80
2299240	7.0	4.5	139.6	86	4,210	78	85
2322557	6.2	4.0	142.1	85	4,210	84	99
2375999	7.5	5.5	140.5	85	4,220	87	102
2376971	6.9	4.0	No Data	86	4,220	81	89
2354518	5.5	4.5	No Data	74	4,220	67	81
2354040	7.5	4.5	140.0	83	4,230	78	92
2370225	5.3	3.5	144.6	78	4,230	64	75
2366898	6.2	3.0	No Data	76	4,230	67	79
2371329	5.5	3.8	No Data	76	4,230	67	79
No Data	6.9	2.8	140.1	83	4,240	74	84
2332916	7.4	4.3	140.0	63	4,240	75	82
2355056	5.3	4.3	143.1	82	4,240	78	93
2366904	6.0	4.0	142.6	69	4,250	62	75
2275070	7.2	4.0	143.6	83	4,250	81	89

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2340918	5.9	3.0	143.6	72	4,250	62	74
2348333	7.2	4.5	139.0	85	4,250	68	82
2354234	5.7	4.3	142.6	77	4,250	77	89
2355056	5.3	4.3	No Data	82	4,250	78	93
No Data	6.9	2.8	No Data	83	4,260	74	84
2311474	6.0	2.8	138.5	54	4,260	32	39
2340918	5.9	3.0	143.1	72	4,260	62	74
2340918	5.9	3.0	No Data	72	4,260	62	74
2376971	6.9	4.0	140.5	86	4,260	81	89
2355056	5.3	4.3	143.6	82	4,260	78	93
2322885	6.4	4.5	139.0	82	4,270	74	83
No Data	5.6	4.5	142.6	85	4,270	73	83
No Data	No Data	No Data	142.1	No Data	4,270	63	80
2320686	6.5	3.3	140.6	86	4,270	81	92
2328884	7.3	4.0	138.5	80	4,270	76	95
2274738	7.2	4.5	140.0	84	4,270	82	98
2281377	5.2	3.5	143.6	74	4,270	82	98
2376619	7.4	3.0	144.6	85	4,270	67	84
2354040	7.5	4.5	139.5	83	4,280	78	92
No Data	7.5	3.5	140.5	76	4,280	56	66
No Data	7.4	3.8	139.0	77	4,280	74	86
No Data	6.6	4.3	No Data	78	4,280	74	86
No Data	6.9	2.8	140.1	83	4,280	74	84
2363037	7.0	4.3	No Data	57	4,280	35	46
2343075	6.2	6.0	143.1	83	4,280	67	84
2276020	5.8	4.5	142.1	77	4,290	72	87
2272989	5.4	2.8	142.6	80	4,290	70	80
2320091	7.2	3.3	No Data	85	4,290	70	80
2372095	7.0	4.5	139.0	77	4,290	77	90
2376619	7.4	3.0	145.1	85	4,290	69	81
2371511	7.2	4.5	140.5	81	4,300	83	99
2301545	7.5	4.0	139.0	77	4,300	69	83
2312667	6.9	4.0	141.1	70	4,300	70	83
2367101	5.5	3.5	143.1	63	4,300	72	90
2322746	6.0	1.5	No Data	86	4,300	65	77
2341536	6.5	3.3	No Data	71	4,300	67	76
2371329	5.5	3.8	143.6	76	4,300	67	79
2354234	5.7	4.3	No Data	77	4,300	77	89
2311638	7.5	4.5	137.5	68	4,310	61	72
2351318	5.8	3.5	142.1	82	4,310	76	87
2311474	6.0	2.8	No Data	54	4,310	32	39
2366898	6.2	3.0	142.6	76	4,310	67	79
2354518	5.5	4.5	141.5	74	4,310	67	81
2322201	5.8	3.8	139.6	78	4,320	65	77

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
No Data	7.2	2.3	140.0	78	4,320	73	81
2349141	6.4	3.0	142.6	87	4,320	60	71
2347393	5.5	3.5	142.1	83	4,320	80	92
2322615	6.4	3.8	142.6	81	4,320	46	54
2381401	6.6	4.5	142.6	70	4,330	58	71
2343641	6.6	3.5	139.0	87	4,330	69	81
2320686	6.5	3.3	No Data	86	4,330	32	43
2367269	6.2	4.5	142.6	68	4,330	70	91
2367101	5.5	3.5	No Data	63	4,340	72	90
2354234	5.7	4.3	142.1	77	4,340	77	89
2357166	6.4	3.5	144.1	78	4,340	72	89
2363609	7.4	3.0	141.0	78	4,350	72	89
2274738	7.2	4.5	140.5	84	4,350	82	98
2275819	5.6	3.3	141.5	80	4,360	64	78
2344391	7.5	3.0	140.0	86	4,360	72	92
2272760	6.9	3.3	141.5	82	4,360	32	43
2311474	6.0	2.8	138.0	54	4,360	32	39
2347393	5.5	3.5	No Data	83	4,360	80	92
2323818	6.5	4.5	137.0	78	4,370	72	84
2371511	7.2	4.5	No Data	81	4,370	83	99
2271757	6.2	4.5	140.5	79	4,370	80	96
2291371	6.0	4.0	140.6	77	4,370	73	86
2364862	7.5	3.5	141.5	71	4,370	72	92
2366904	6.0	4.0	No Data	69	4,370	62	75
No Data	7.2	4.5	138.5	79	4,370	32	43
2331226	6.2	4.0	141.0	80	4,380	80	83
2331226	6.2	4.0	141.0	80	4,380	80	83
2373832	8.4	4.3	141.5	81	4,380	81	96
No Data	7.2	4.5	No Data	79	4,380	74	91
2273113	7.2	4.0	142.1	83	4,380	80	83
2320686	6.5	3.3	140.6	86	4,380	74	91
2324002	6.8	3.0	141.5	85	4,380	74	91
2366198	5.9	4.5	141.5	63	4,380	53	70
2367269	6.2	4.5	No Data	68	4,380	70	91
2320117	5.9	2.5	143.1	74	4,380	70	83
2348674	7.4	4.3	No Data	83	4,380	72	90
2372191	5.4	3.3	143.6	82	4,380	79	91
2311638	7.5	4.5	No Data	68	4,390	77	87
No Data	7.2	4.5	138.0	79	4,390	80	89
No Data	6.6	4.3	142.1	78	4,390	80	89
2366210	7.2	4.5	141.0	76	4,390	51	65
2322746	6.0	1.5	142.6	86	4,390	80	89
2347393	5.5	3.5	142.6	83	4,390	80	92
2342264	7.4	3.5	141.0	67	4,390	81	102

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2373832	8.4	4.3	140.5	81	4,400	81	96
2351318	5.8	3.5	No Data	82	4,400	76	87
2324002	6.8	3.0	No Data	85	4,400	75	84
2366903	5.4	3.0	144.6	70	4,400	67	78
2366903	5.4	3.0	No Data	70	4,400	67	78
2366903	5.4	3.0	145.1	70	4,400	67	78
2318928	6.4	4.0	142.1	75	4,400	56	69
2343073	7.3	4.5	142.1	77	4,400	71	84
2324002	6.8	3.0	141.5	85	4,410	75	84
2363386	5.9	4.0	141.5	61	4,410	38	52
2372274	6.3	3.8	142.6	81	4,420	71	88
2320091	7.2	3.3	139.0	85	4,420	75	84
2367269	6.2	4.5	142.6	68	4,420	70	91
2376260	7.5	4.5	No Data	82	4,420	70	87
2363386	5.9	4.0	No Data	61	4,420	38	52
2371511	7.2	4.5	140.0	81	4,430	83	99
2276211	6.0	3.5	141.5	85	4,430	81	91
2363386	5.9	4.0	142.1	61	4,430	38	52
2370225	5.3	3.5	144.6	78	4,440	71	88
2366644	6.5	2.8	142.6	59	4,440	52	55
2341536	6.5	3.3	142.1	71	4,440	67	76
2318928	6.4	4.0	142.1	75	4,440	56	69
2378850	5.5	4.3	143.1	82	4,440	71	80
2276211	6.0	3.5	140.5	85	4,440	81	91
2370116	5.1	2.8	144.1	75	4,450	78	97
2311638	7.5	4.5	137.5	68	4,460	81	91
2380307	6.0	3.8	143.6	78	4,460	72	88
2316344	6.1	4.0	141.1	65	4,460	70	84
2305106	6.0	4.0	139.6	86	4,470	79	90
2368026	6.6	3.5	140.5	73	4,470	60	76
2272760	6.9	3.3	142.6	82	4,470	70	84
2366210	7.2	4.5	140.0	76	4,470	51	65
2372570	7.0	3.0	142.1	81	4,480	78	97
2366904	6.0	4.0	143.6	69	4,480	62	75
2351318	5.8	3.5	141.5	82	4,480	76	87
2309049	6.4	3.8	No Data	65	4,490	79	90
2276914	5.2	3.5	143.6	86	4,490	79	90
2296135	7.5	4.0	138.5	84	4,500	52	61
2368026	6.6	3.5	141.5	73	4,500	60	76
2372692	5.9	4.0	142.6	83	4,500	85	97
2365776	7.5	3.5	141.0	67	4,500	45	58
2367445	6.1	2.3	142.6	72	4,500	60	72
No Data	7.1	4.3	137.5	76	4,500	49	67
2341999	5.9	3.8	142.6	76	4,500	73	86

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2334482	5.8	3.0	143.1	81	4,500	69	80
2372191	5.4	3.3	143.6	82	4,500	79	91
2375478	5.4	3.0	143.6	77	4,500	63	76
2305106	6.0	4.0	139.6	86	4,510	59	78
2368028	5.0	4.3	143.6	73	4,510	57	65
No Data	7.4	3.8	139.0	77	4,510	44	55
2323663	6.3	3.0	139.6	89	4,510	50	62
2323547	6.0	3.8	142.1	83	4,510	60	76
2321141	6.0	4.3	144.1	85	4,510	78	88
2332916	7.4	4.3	140.0	63	4,510	76	91
2362150	6.8	3.8	141.5	61	4,510	42	49
2376628	5.6	3.5	143.6	81	4,510	33	39
2272688	5.8	3.0	142.6	79	4,520	75	85
2279049	6.2	4.0	140.0	83	4,520	60	79
2317264	5.9	3.0	142.6	87	4,520	49	53
2363336	5.8	3.0	141.5	61	4,520	40	54
2321155	5.7	2.5	141.6	80	4,520	80	91
2355018	5.8	4.5	140.0	80	4,520	79	90
2372095	7.0	4.5	140.5	77	4,520	77	90
No Data	6.9	4.3	141.0	75	4,530	68	80
2272764	6.5	4.0	141.0	85	4,530	83	92
2318149	7.3	4.5	138.0	81	4,530	75	89
2327029	7.0	4.5	139.0	83	4,530	77	89
2378850	5.5	4.3	143.7	82	4,530	85	95
2296129	7.1	4.0	140.6	81	4,540	73	83
2371011	7.0	3.3	143.6	77	4,540	32	46
No Data	7.4	4.5	139.0	72	4,540	71	84
No Data	7.3	4.5	145.7	76	4,540	71	84
2365859	5.8	3.0	142.1	75	4,540	51	69
2271757	6.2	4.5	142.1	79	4,550	71	84
2367207	5.2	3.5	143.6	75	4,550	72	90
No Data	6.5	3.3	141.0	84	4,550	72	86
2319312	7.5	2.5	140.1	76	4,550	71	84
2359766	6.0	3.5	140.5	75	4,550	74	87
2345493	6.8	3.0	143.1	80	4,550	50	63
2293308	7.3	4.0	138.5	75	4,560	71	84
2376551	6.9	4.0	142.6	75	4,560	67	78
2256650	7.0	3.8	140.0	78	4,560	71	84
2268483	6.9	4.0	142.1	75	4,560	63	71
2275851	6.0	2.8	140.5	77	4,560	67	80
2278505	6.6	3.5	140.0	79	4,560	71	84
2279018	5.7	4.3	142.6	84	4,560	74	81
2334664	7.0	3.0	143.1	77	4,560	69	84
2369352	5.8	4.5	142.6	70	4,570	58	70

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2270637	6.8	2.8	141.0	74	4,570	69	81
2350440	5.6	4.5	142.1	77	4,570	66	81
2273859	5.6	3.5	142.1	83	4,570	82	90
2286297	6.5	4.5	139.5	61	4,580	68	75
2296133	6.5	3.8	140.6	83	4,580	71	80
2276018	6.8	4.3	140.0	76	4,580	72	87
No Data	5.5	3.0	143.6	72	4,580	69	86
2342368	5.9	3.8	141.5	75	4,580	67	81
2339665	7.4	3.8	137.5	67	4,580	50	64
2275414	5.5	4.3	143.1	83	4,580	73	82
2277786	7.0	4.3	141.5	81	4,590	69	74
No Data	6.0	4.0	141.5	78	4,590	74	89
No Data	6.6	4.0	146.7	74	4,590	65	76
2367211	5.3	3.5	143.6	72	4,590	80	93
2376622	5.6	4.0	143.1	84	4,590	50	63
No Data	7.5	3.3	No Data	89	4,600	62	78
2316562	5.0	3.5	140.6	83	4,600	80	93
No Data	6.5	2.0	143.1	86	4,600	50	59
2363609	7.4	3.0	142.1	78	4,610	51	68
2371166	5.2	3.5	145.7	78	4,610	46	56
2272768	7.4	3.0	140.5	87	4,610	67	75
2329200	7.5	4.3	138.5	74	4,610	69	90
2366389	6.5	2.8	141.0	56	4,610	46	56
2279032	6.2	2.5	142.6	83	4,610	71	81
2323083	6.0	4.0	144.1	82	4,610	69	84
No Data	6.1	4.0	140.0	86	4,620	65	73
2295999	6.4	3.8	140.6	80	4,620	58	61
2364227	5.6	4.3	145.7	73	4,620	67	78
2376697	6.2	3.8	141.0	85	4,620	64	75
2378850	5.5	4.3	143.6	82	4,620	72	84
2343979	6.5	4.5	139.5	75	4,620	82	96
2362986	5.6	3.8	142.6	58	4,620	46	60
2299351	5.4	4.0	142.1	84	4,630	50	62
2327782	6.4	4.0	139.5	84	4,630	81	94
2349346	7.0	3.3	140.5	79	4,630	65	74
2354918	5.5	4.5	147.2	83	4,630	49	65
2370286	7.2	4.3	139.5	75	4,640	64	77
2366252	7.0	3.3	140.5	56	4,640	45	55
No Data	5.3	3.8	142.6	83	4,640	69	82
2318604	6.5	3.5	140.6	75	4,640	56	75
2338324	6.1	3.8	141.5	65	4,640	32	47
2280754	7.0	4.0	140.5	82	4,640	69	79
No Data	7.0	4.0	137.5	83	4,640	70	85
2339698	7.0	22.0	139.0	67	4,640	46	59

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2344063	6.0	3.3	143.6	81	4,640	56	74
2322551	6.1	3.8	139.6	89	4,650	77	87
2371245	7.4	4.5	No Data	82	4,650	71	85
2380618	7.5	4.8	142.1	68	4,650	64	74
2349834	7.0	4.5	142.1	81	4,650	50	65
2355302	5.0	3.5	143.1	86	4,650	64	77
2273429	6.0	3.5	142.1	82	4,650	69	79
2307376	5.6	3.8	142.6	66	4,660	56	75
2366559	6.6	3.0	140.5	55	4,660	50	53
2361553	6.2	4.0	140.5	67	4,670	47	58
2281283	5.5	3.5	142.1	74	4,670	77	87
2363382	6.6	3.0	143.1	72	4,670	50	68
2287064	6.5	4.5	140.5	68	4,680	45	56
2333070	7.2	4.0	139.5	70	4,680	43	50
No Data	6.0	3.0	142.1	78	4,680	45	56
2267129	7.5	4.5	142.6	62	4,680	40	46
2364227	5.6	4.3	145.1	73	4,680	67	78
2301555	6.9	3.8	140.1	74	4,690	26	32
No Data	7.2	2.3	140.5	78	4,690	73	81
No Data	5.9	3.3	142.1	70	4,690	35	49
2353474	6.2	3.3	141.5	82	4,690	41	46
2278020	6.1	3.5	144.1	78	4,690	77	87
2290803	7.5	4.0	No Data	74	4,700	42	50
2273113	7.2	4.0	140.5	83	4,700	31	44
No Data	5.9	3.5	142.6	73	4,700	69	85
2312820	7.5	3.5	141.1	62	4,700	33	37
2366198	5.9	4.5	141.5	63	4,700	53	70
2363238	5.3	3.3	143.1	63	4,700	33	46
2370573	6.1	4.5	141.5	88	4,710	79	90
2321655	5.8	2.5	142.1	79	4,710	72	84
2332920	6.8	3.8	141.5	65	4,710	68	79
2375992	6.2	3.8	143.1	82	4,710	84	102
2377104	6.2	4.0	142.6	79	4,710	69	74
2372570	7.0	3.0	142.6	81	4,720	48	56
No Data	7.5	3.5	140.0	82	4,720	72	84
No Data	7.0	4.3	143.1	68	4,720	32	43
No Data	7.1	3.3	139.0	78	4,720	38	50
2368903	5.5	3.3	143.6	69	4,720	56	78
2322091	6.8	4.3	138.0	73	4,720	72	86
2377615	7.2	4.5	140.5	79	4,720	71	77
No Data	6.5	3.8	141.6	80	4,730	26	38
2367432	6.0	2.0	142.6	75	4,730	65	83
2334288	6.0	3.0	142.6	74	4,730	62	77
2371968	5.0	4.5	143.6	86	4,740	76	91

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2279615	7.0	3.0	140.0	83	4,740	8	13
No Data	6.7	3.5	141.5	75	4,740	65	76
No Data	6.4	3.5	140.6	79	4,740	26	38
2296126	5.1	3.5	141.6	82	4,750	6	16
2364862	7.5	3.5	142.1	71	4,750	46	52
No Data	6.6	3.8	141.6	77	4,750	21	29
2346515	5.5	3.3	143.1	80	4,750	73	90
2380204	5.9	4.0	142.6	86	4,750	64	72
2321581	5.7	3.5	140.6	80	4,750	75	87
2346501	7.0	4.0	140.5	82	4,750	51	67
2276914	5.2	3.5	143.6	86	4,750	26	37
2279030	6.1	4.0	142.6	75	4,750	16	31
2346502	5.6	2.8	144.1	82	4,750	75	89
2363375	6.2	3.0	141.5	60	4,750	38	52
2320288	7.4	4.0	No Data	88	4,760	77	88
2291377	7.5	4.0	No Data	71	4,760	21	31
2272247	5.8	3.3	141.5	77	4,760	31	41
2301753	7.1	3.8	140.1	80	4,760	77	88
2277221	6.0	3.0	142.6	85	4,770	40	52
2376579	7.2	5.0	141.0	81	4,770	67	78
No Data	7.1	3.5	140.5	72	4,770	72	86
No Data	5.0	4.3	143.1	85	4,770	74	83
2272989	5.4	2.8	143.1	80	4,770	18	30
No Data	7.3	4.5	140.1	72	4,770	37	50
No Data	6.5	3.8	142.1	80	4,770	38	42
2338602	6.1	4.3	142.1	63	4,770	53	76
2346953	6.7	2.8	141.5	74	4,770	57	68
2379217	6.9	3.0	141.5	74	4,770	66	76
2348625	5.4	3.8	145.7	80	4,770	77	90
2357166	6.4	3.5	143.1	78	4,770	64	78
2322885	6.4	4.5	No Data	82	4,780	74	83
2290789	5.6	3.5	141.6	76	4,780	39	49
No Data	7.3	4.5	140.0	77	4,780	75	83
2283196	6.8	3.8	139.5	53	4,780	47	51
2379004	6.8	4.3	140.5	86	4,780	72	86
2256648	6.0	3.3	140.0	76	4,790	62	77
No Data	6.4	3.8	140.6	79	4,790	68	82
No Data	6.0	2.5	142.6	80	4,790	77	90
2379625	7.0	3.5	140.0	82	4,790	65	79
2256654	6.7	3.5	140.5	77	4,800	61	68
2369544	7.4	3.0	142.6	75	4,800	75	94
No Data	7.0	4.3	141.6	68	4,800	75	86
2311934	6.0	2.8	142.1	68	4,800	59	77
2363261	6.2	4.0	141.0	55	4,800	40	51

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2290349	5.5	3.5	143.1	72	4,810	75	91
2278726	6.3	2.5	143.1	78	4,810	72	81
2372346	5.2	3.5	145.7	81	4,820	79	88
2291371	6.0	4.0	141.6	77	4,820	79	91
2306134	6.4	4.0	140.6	74	4,820	70	78
2370116	5.1	2.8	146.2	75	4,820	72	86
No Data	6.2	3.5	140.5	81	4,820	69	81
2278500	6.2	3.0	142.6	78	4,820	79	95
No Data	6.6	3.0	139.6	80	4,820	70	78
2355838	7.5	3.0	141.5	75	4,820	68	81
2341838	7.2	4.0	139.0	74	4,820	46	63
2279532	5.4	4.5	143.1	76	4,820	70	88
2347741	7.2	4.5	No Data	82	4,820	72	83
2338652	7.5	2.8	141.5	70	4,820	82	99
2321629	5.9	3.0	141.1	85	4,830	75	86
2370295	6.4	3.3	142.6	70	4,830	71	87
2307874	7.5	4.5	139.0	60	4,830	63	79
2333077	7.0	3.5	139.5	71	4,830	66	78
2355707	8.0	2.8	142.1	80	4,830	75	98
2360373	5.4	3.0	144.1	79	4,830	69	81
2272761	6.4	3.5	141.5	80	4,830	74	82
2366195	5.9	2.8	141.5	58	4,830	54	68
2363500	5.9	4.0	141.5	64	4,830	45	56
2347222	5.6	4.0	143.6	87	4,830	75	89
2322376	6.8	3.8	No Data	85	4,840	68	80
2333450	6.8	3.5	141.5	67	4,840	73	87
2381401	6.6	4.5	142.6	70	4,840	58	71
2320112	5.2	3.0	143.6	78	4,840	61	67
2275788	5.5	4.0	142.1	80	4,840	76	85
2358090	6.4	4.0	143.1	80	4,840	69	81
2301545	7.5	4.0	138.8	77	4,850	85	93
2334555	6.5	3.0	142.1	68	4,850	68	72
No Data	7.5	4.5	No Data	77	4,850	75	91
2374476	6.0	4.3	141.5	76	4,850	82	93
2272154	6.2	3.0	140.0	79	4,850	68	72
2381060	7.0	4.5	144.6	70	4,850	67	76
2272008	6.5	4.5	141.0	78	4,860	74	85
No Data	6.9	3.5	141.1	74	4,860	67	78
No Data	6.5	4.0	140.1	81	4,860	74	85
2355319	5.0	4.0	142.6	83	4,860	78	88
2361878	5.7	4.5	140.5	68	4,860	61	74
2302590	6.5	3.0	140.6	78	4,870	74	85
2305434	6.8	4.0	139.6	73	4,870	83	90
2376575	7.5	4.0	141.5	76	4,870	67	78

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2343641	6.6	3.5	139.0	87	4,870	79	92
No Data	7.0	3.0	140.5	75	4,870	69	80
No Data	6.4	4.0	140.6	81	4,870	83	90
2275336	6.0	4.0	141.5	87	4,870	83	90
2275338	6.8	4.0	140.5	84	4,870	74	85
No Data	6.2	3.0	142.1	58	4,870	68	83
2316344	6.1	4.0	140.6	65	4,870	83	90
2352471	7.5	3.8	140.0	82	4,880	87	101
2297324	6.8	3.8	140.1	83	4,880	78	87
2304947	6.5	3.5	141.1	80	4,880	78	87
2372370	5.4	4.0	146.2	85	4,880	75	93
2364227	5.6	4.3	144.6	73	4,880	75	94
2352951	6.4	4.5	140.5	79	4,880	78	89
2323914	5.5	3.8	143.6	84	4,880	53	63
2353068	6.6	4.0	142.1	84	4,880	78	91
2305206	6.5	3.8	141.1	80	4,890	85	95
2324273	5.9	3.5	143.1	79	4,890	71	85
2309053	6.2	3.8	140.1	70	4,890	85	95
2371317	5.8	3.5	142.6	75	4,890	72	85
2272762	5.7	4.0	143.6	75	4,890	78	87
2352586	6.2	4.0	140.5	76	4,890	79	94
2377301	6.0	3.0	142.6	79	4,890	67	78
2277650	5.5	3.5	143.6	83	4,890	79	90
2348953	6.0	4.3	143.1	81	4,890	64	69
2349987	6.2	3.5	145.1	75	4,890	62	73
2294310	6.9	6.0	139.6	83	4,900	81	95
2301495	6.3	3.0	141.6	75	4,900	81	95
2333075	7.1	3.8	139.5	70	4,900	71	84
2270810	5.3	3.0	143.1	87	4,900	73	84
No Data	7.4	4.5	138.5	64	4,900	72	83
2356124	6.2	3.0	144.6	77	4,900	69	84
2294312	5.3	3.8	142.6	85	4,910	72	82
2368394	6.1	3.3	142.6	58	4,910	57	68
2274272	6.0	3.0	142.1	87	4,910	73	81
No Data	6.4	3.0	141.1	82	4,910	71	81
2344323	6.2	3.5	142.1	79	4,910	81	94
2268334	7.0	4.5	139.5	63	4,910	73	83
2370158	5.6	3.8	143.6	76	4,910	75	94
2328190	7.0	3.0	140.5	78	4,910	46	51
2367804	6.5	4.5	141.0	72	4,910	72	89
2378486	6.0	4.0	142.1	83	4,910	70	80
2380603	5.5	4.0	145.7	71	4,910	69	84
2282863	7.1	3.3	141.5	55	4,920	75	85
2296001	5.0	4.3	142.6	77	4,920	65	76

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2312461	6.0	4.3	141.6	68	4,920	51	65
2317039	5.9	4.5	141.6	83	4,920	75	85
2320969	5.6	1.0	142.6	89	4,920	69	83
2363043	6.0	3.0	141.5	73	4,920	35	46
2370024	5.7	3.0	142.6	75	4,920	62	69
2348260	6.0	3.8	142.6	82	4,920	72	84
2338717	6.5	2.8	143.6	69	4,930	68	83
No Data	7.0	4.5	141.0	69	4,930	62	73
2267047	7.3	2.8	142.6	61	4,930	78	86
2355407	6.4	3.3	143.1	78	4,930	72	87
2355988	6.2	3.5	144.6	76	4,930	71	86
2322063	5.0	3.5	141.6	83	4,940	79	90
2301571	6.2	3.5	142.6	79	4,940	78	86
2275072	6.0	4.0	140.5	81	4,940	78	86
2374045	6.8	5.3	141.5	88	4,940	60	71
2322094	6.0	4.0	140.1	78	4,940	72	86
2305458	6.7	4.5	141.6	69	4,940	61	79
2281377	5.2	3.5	143.1	74	4,940	71	80
2362964	5.4	3.8	142.6	54	4,940	43	55
2376573	6.0	3.8	142.6	75	4,950	67	78
2381278	6.6	5.8	142.6	66	4,950	54	62
2273060	5.0	3.8	143.1	78	4,950	71	76
No Data	5.9	3.5	142.6	78	4,950	60	75
No Data	7.0	4.3	140.0	74	4,950	69	81
No Data	6.1	4.3	142.6	73	4,950	69	80
2279619	6.8	4.0	140.0	74	4,950	74	84
2366410	6.8	3.5	142.6	60	4,950	38	43
2265800	6.0	3.8	142.6	64	4,950	73	84
2267159	6.9	4.0	141.5	65	4,950	72	78
2363526	6.3	3.0	141.5	59	4,950	44	53
2341483	6.3	2.8	141.5	74	4,950	64	69
2324892	6.0	2.8	144.1	79	4,950	46	54
2369354	5.2	4.5	143.6	74	4,960	56	65
2270320	6.8	2.8	142.1	78	4,960	64	73
2314032	6.5	3.5	140.6	67	4,960	51	57
2316565	5.6	4.0	141.6	74	4,960	75	90
2377869	6.3	3.5	144.6	80	4,970	65	72
2282673	6.4	3.0	143.1	71	4,970	64	73
2362470	6.1	4.5	143.1	73	4,970	72	86
2347550	5.0	4.0	143.1	74	4,970	69	84
2369694	6.5	3.5	141.5	73	4,970	59	74
2348898	5.6	3.0	144.6	85	4,980	70	78
No Data	5.5	4.5	142.1	68	4,980	63	76
2354270	7.0	3.5	144.1	79	4,980	76	88

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2342264	7.4	3.5	141.5	67	4,980	69	80
2256645	5.5	3.5	141.5	79	4,990	74	81
No Data	5.4	3.0	145.7	84	4,990	74	89
2301651	6.0	3.0	142.6	79	4,990	63	76
2276913	5.5	3.0	143.6	81	4,990	74	81
2358632	5.0	3.3	144.6	82	5,000	79	93
2314738	5.8	3.0	140.6	58	5,000	62	75
2361871	7.5	3.5	141.0	65	5,000	66	81
No Data	5.0	4.0	141.5	72	5,000	53	73
2279530	6.0	3.3	141.5	79	5,010	68	76
2275921	6.5	3.5	142.6	77	5,010	66	75
2296124	6.0	3.0	141.1	84	5,020	68	76
2276146	6.4	2.3	144.1	84	5,020	69	79
2320684	6.0	3.0	141.1	80	5,020	68	76
2372680	6.2	3.5	142.6	83	5,030	76	94
2356814	6.0	3.5	144.1	81	5,030	66	76
No Data	5.6	2.8	142.1	63	5,030	50	57
No Data	6.6	2.8	141.6	70	5,030	74	85
2367783	5.9	4.5	145.6	72	5,030	36	51
2366469	5.2	4.5	142.6	61	5,030	44	55
2342704	6.4	3.5	143.1	72	5,030	65	80
No Data	5.3	1.0	144.6	90	5,040	82	93
2364638	6.0	3.3	143.1	76	5,040	58	70
2371889	6.3	3.5	141.5	79	5,040	68	87
2270530	5.7	2.8	142.6	77	5,040	74	85
2366407	5.8	2.3	142.6	58	5,040	38	43
2367890	5.4	2.5	144.6	74	5,040	69	86
2261948	6.5	4.0	143.1	70	5,040	75	85
No Data	5.6	2.5	142.1	82	5,040	76	90
2319897	6.2	5.0	141.6	78	5,040	67	80
2346088	5.8	3.3	143.1	81	5,040	64	74
2281738	5.5	4.3	143.6	68	5,040	60	67
2379634	6.9	4.5	141.0	77	5,040	82	96
No Data	5.6	1.5	145.1	70	5,050	48	61
No Data	5.9	4.3	142.1	66	5,050	75	85
2281912	6.2	3.0	141.5	67	5,050	77	85
2316991	6.3	2.0	142.6	73	5,050	61	76
2282175	6.4	3.5	141.5	65	5,050	55	61
2276904	5.3	3.5	145.1	85	5,050	66	80
2324413	7.0	3.5	143.6	78	5,050	46	54
2363700	7.4	2.3	141.0	74	5,060	71	90
2364908	7.4	3.5	136.5	65	5,060	58	70
No Data	6.7	2.3	140.5	82	5,060	69	81
No Data	6.0	2.8	141.6	68	5,060	71	77

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2320310	7.2	3.5	143.6	83	5,060	71	77
2365088	7.8	4.0	142.6	80	5,070	66	80
2366644	6.5	2.8	142.6	59	5,070	52	55
2342556	6.3	3.3	141.5	63	5,070	68	75
2277654	6.1	2.5	143.6	84	5,070	46	54
2379159	5.9	3.0	143.6	83	5,070	67	78
2368311	7.0	4.3	143.1	62	5,070	49	61
2360388	5.5	3.0	144.1	81	5,080	64	81
2282383	6.5	4.0	140.5	54	5,080	55	66
2333446	6.9	4.0	139.5	63	5,080	55	66
2376577	6.3	4.0	142.6	80	5,080	67	78
2256642	6.1	4.0	142.6	79	5,080	55	66
2362079	7.3	4.3	140.5	69	5,080	64	77
No Data	5.7	1.8	144.1	66	5,080	53	70
2281259	5.8	3.5	142.6	81	5,080	55	66
2368932	6.0	3.5	142.6	65	5,080	59	69
2282330	6.5	4.0	141.5	64	5,080	50	54
2329351	6.0	3.3	144.1	65	5,080	41	47
2334376	6.2	3.5	143.1	78	5,080	40	47
2363553	6.4	4.0	141.5	69	5,090	44	53
No Data	5.7	2.8	143.1	66	5,090	43	59
2312178	7.2	3.3	138.5	63	5,090	61	77
2351897	7.0	3.5	140.5	79	5,090	76	90
No Data	7.2	3.5	141.6	72	5,090	80	90
2379050	6.8	3.0	142.6	82	5,090	68	83
2280503	5.2	2.5	144.1	77	5,100	55	66
2333083	6.6	3.3	142.1	70	5,100	55	66
2334673	6.5	3.5	140.5	69	5,100	35	45
2366412	6.6	3.0	142.6	60	5,100	38	43
2317746	5.9	3.3	141.6	78	5,100	63	83
2344280	6.3	3.0	141.0	84	5,100	73	84
2281621	5.7	4.0	143.6	60	5,100	80	95
2323917	7.0	3.8	142.6	81	5,100	46	55
2289394	7.0	4.0	140.6	66	5,110	55	66
2306585	6.9	4.0	139.6	64	5,110	57	65
No Data	5.0	4.5	142.6	72	5,110	69	82
No Data	5.2	3.0	143.6	62	5,110	50	53
2320105	5.5	2.5	144.1	77	5,110	72	86
2355496	5.0	4.3	142.6	77	5,110	68	78
2375743	6.5	3.5	142.6	80	5,110	73	87
2381662	5.9	4.5	144.6	70	5,120	60	75
No Data	6.3	2.5	141.5	72	5,120	55	60
2366416	5.7	2.5	143.6	64	5,120	38	43
2370096	5.7	3.0	143.6	72	5,120	64	75

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2367548	6.7	4.5	141.5	68	5,120	68	80
2380919	5.0	3.8	144.6	86	5,120	78	91
2335102	6.4	3.3	145.1	65	5,130	38	44
2359893	6.3	3.5	143.6	71	5,130	49	67
2364825	6.7	3.0	138.6	68	5,130	42	54
No Data	7.4	3.3	140.5	71	5,130	57	71
2273369	6.0	3.5	142.6	81	5,130	62	86
2363365	5.8	4.3	142.1	59	5,130	54	69
2341674	6.5	3.0	140.0	74	5,130	48	54
2275238	5.7	3.0	143.6	81	5,130	77	91
2380991	6.2	3.5	141.5	78	5,130	57	68
2380320	6.5	5.0	141.5	74	5,130	67	81
2377871	5.0	2.8	145.1	84	5,140	75	83
2277198	6.8	4.5	No Data	85	5,140	45	48
2278453	6.5	3.0	143.1	74	5,140	45	48
2313226	6.0	3.0	142.1	62	5,140	39	44
2363753	5.9	3.8	142.1	67	5,140	56	75
2317884	6.1	3.5	142.1	72	5,140	64	81
2320601	6.2	2.0	143.1	76	5,140	65	79
2323459	5.5	3.5	143.6	80	5,140	67	81
No Data	6.9	3.8	140.1	79	5,140	76	87
No Data	6.2	4.0	142.1	82	5,140	76	87
2375629	5.8	3.5	143.6	78	5,140	75	92
2271502	5.6	3.5	142.6	74	5,150	34	38
2269969	5.8	4.5	142.1	77	5,150	34	38
2372612	5.8	2.8	143.6	80	5,150	84	103
2378619	6.0	4.0	145.7	79	5,150	16	22
No Data	5.2	2.8	143.6	84	5,150	71	81
2363574	5.5	3.5	143.1	56	5,150	45	51
2380826	6.6	3.0	142.6	79	5,150	77	87
2361643	6.6	3.5	140.5	67	5,150	49	67
2376634	5.7	3.0	142.1	78	5,160	74	91
2341165	7.0	4.5	141.5	71	5,160	79	97
2320110	5.3	1.8	144.8	75	5,160	76	85
2346755	5.9	2.0	142.6	83	5,160	68	83
2323553	5.8	3.0	144.6	82	5,160	53	61
2378710	7.0	6.8	143.6	77	5,160	43	54
2247382	5.9	3.0	143.6	66	5,180	44	57
2267525	6.8	4.0	141.5	68	5,180	36	42
No Data	6.3	3.0	143.1	66	5,180	53	71
No Data	7.0	4.0	140.0	82	5,180	55	66
2274359	5.3	1.8	143.6	83	5,180	44	57
2315043	7.5	3.5	138.0	74	5,180	57	59
2378381	5.6	3.8	142.6	82	5,180	72	81

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2380407	5.0	3.8	144.1	78	5,180	70	87
2366595	5.5	2.8	141.5	55	5,180	44	55
2359858	5.7	4.5	145.1	72	5,180	70	78
2299240	7.0	4.5	No Data	86	5,190	49	67
2286762	5.6	3.5	147.7	63	5,190	47	59
2333737	6.8	3.5	141.0	66	5,190	47	59
No Data	5.6	3.0	142.6	83	5,190	50	53
2376993	6.5	5.5	144.6	85	5,190	16	22
2316567	5.6	4.0	141.1	81	5,190	75	90
2362915	5.4	3.5	143.1	59	5,190	46	59
2304250	5.3	3.8	143.6	73	5,190	59	65
2320112	5.2	3.0	143.3	78	5,190	61	67
2292789	6.2	4.0	140.6	75	5,200	50	67
No Data	6.4	3.0	141.1	81	5,200	50	53
2341158	6.3	2.3	142.1	68	5,200	84	97
2278128	6.3	4.5	143.1	80	5,200	69	83
2375922	7.0	7.0	143.1	81	5,200	50	62
2334175	6.9	4.0	141.0	50	5,210	50	67
No Data	7.3	3.8	143.6	71	5,210	43	58
2366419	5.8	2.8	143.1	65	5,210	38	43
2282663	5.8	4.0	143.1	64	5,210	46	56
2343231	5.7	3.3	141.5	79	5,210	83	97
No Data	6.0	3.5	142.1	86	5,210	78	89
2355830	5.0	3.5	143.6	79	5,210	77	85
2293789	5.3	3.5	143.6	85	5,220	33	39
2333067	6.0	3.3	142.6	73	5,220	25	30
2283121	6.1	2.8	142.1	51	5,220	43	59
2335990	6.0	3.0	143.1	61	5,220	40	54
2371095	6.0	4.0	142.6	74	5,220	68	82
2273115	6.2	2.5	142.1	84	5,220	33	39
2312880	5.3	3.8	141.6	61	5,220	48	60
2378104	5.4	3.8	143.6	83	5,220	70	87
2348560	5.6	3.0	143.1	84	5,220	70	86
2374296	6.5	3.0	141.5	79	5,220	81	94
2350409	5.8	4.3	142.6	82	5,220	71	81
2351486	5.6	4.5	No Data	81	5,220	81	93
2351020	6.1	6.0	143.6	84	5,220	49	63
2270998	6.9	4.0	141.5	75	5,230	30	51
2338430	5.9	3.3	144.1	73	5,230	52	73
2364476	6.9	4.5	142.6	71	5,230	31	43
No Data	6.2	4.0	142.1	73	5,230	51	62
No Data	5.5	4.0	142.6	79	5,230	67	81
No Data	7.1	2.5	143.1	73	5,230	73	86
2346534	6.5	3.5	141.5	75	5,230	68	84

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2278700	7.4	4.3	No Data	81	5,230	74	92
No Data	5.8	2.8	142.6	75	5,230	81	88
2381475	7.0	4.3	144.6	72	5,230	52	68
2336655	5.5	3.0	144.6	61	5,240	36	48
2319689	5.8	2.5	141.6	86	5,240	31	41
2344555	5.5	3.5	143.6	73	5,240	82	96
2363694	5.0	3.0	143.6	66	5,240	41	50
2341530	6.0	3.3	142.1	67	5,250	63	70
2369968	6.0	4.3	142.6	71	5,250	64	74
2280848	5.1	3.0	146.7	81	5,250	78	93
2374730	6.2	3.5	142.1	79	5,250	76	88
2365270	6.0	3.0	145.1	72	5,260	52	68
No Data	6.2	3.0	141.5	58	5,260	25	33
No Data	5.7	3.3	141.0	63	5,260	29	37
2359802	6.0	2.5	141.0	75	5,260	75	93
2282883	6.4	3.0	142.6	66	5,260	21	24
2344600	6.5	4.0	142.1	79	5,260	81	98
No Data	6.6	3.5	141.1	87	5,260	71	83
2282006	7.5	4.0	140.0	64	5,270	36	47
2271617	5.9	3.5	141.5	77	5,270	32	43
2277604	5.5	3.0	142.1	84	5,270	21	31
No Data	5.4	3.5	141.6	64	5,270	36	44
2362645	5.3	3.5	142.6	57	5,270	47	54
2322201	5.8	3.8	No Data	78	5,280	65	77
2289556	5.3	3.5	141.6	59	5,280	39	45
2271336	6.0	3.3	142.6	75	5,280	26	30
2309046	6.1	3.5	142.1	63	5,280	30	38
2360702	5.6	2.5	141.5	72	5,280	64	82
2273678	5.3	3.3	142.6	79	5,290	27	35
No Data	5.1	3.8	144.6	69	5,290	40	49
2371149	5.8	3.8	144.1	79	5,290	16	22
No Data	5.1	3.0	144.6	76	5,290	70	83
2343530	6.2	4.5	143.1	78	5,290	64	77
2349529	6.1	3.3	143.1	81	5,290	41	51
2357770	5.4	2.3	145.1	79	5,300	33	43
2321204	5.5	2.5	143.6	82	5,300	76	86
2312414	6.6	2.5	140.6	65	5,300	40	55
2319167	5.7	2.5	141.1	78	5,300	40	49
2321754	5.9	4.0	142.1	81	5,300	68	88
2351745	6.8	3.0	143.1	90	5,310	54	69
2337985	5.7	3.8	144.6	58	5,310	38	46
2269465	5.1	2.5	145.1	74	5,320	38	46
2367137	5.7	2.8	142.6	71	5,320	71	89
2325058	6.0	3.5	141.5	77	5,320	70	80

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2369093	5.5	2.8	142.6	68	5,320	58	69
2371636	5.4	3.5	144.6	78	5,330	71	85
2301500	6.3	3.5	141.6	84	5,330	58	72
2355789	6.5	3.5	143.1	81	5,330	46	67
2331635	6.7	3.0	140.5	68	5,330	62	82
2369660	7.5	3.5	142.6	72	5,330	43	68
2319663	6.2	2.8	141.6	82	5,330	56	69
2340318	5.6	3.3	142.6	67	5,330	86	98
2361418	6.0	2.8	140.5	71	5,330	56	69
2248702	6.8	4.3	140.5	63	5,340	46	62
No Data	6.0	3.5	141.5	64	5,340	40	50
2339792	5.5	2.8	144.1	56	5,340	52	68
No Data	5.4	2.0	143.6	85	5,340	79	91
2365634	7.0	4.0	143.1	70	5,340	28	46
2375809	5.2	3.5	146.2	88	5,340	45	56
2283557	7.0	2.8	140.5	55	5,350	56	71
2282781	5.3	3.5	142.6	63	5,350	66	81
2319383	5.7	2.3	143.1	84	5,350	63	74
2320194	5.9	3.5	141.6	78	5,350	65	77
2380965	5.5	3.8	143.6	65	5,350	73	93
2334181	6.5	3.3	141.5	58	5,360	61	69
No Data	6.1	2.8	143.1	80	5,360	68	80
2246012	5.5	3.8	144.1	61	5,360	69	83
No Data	5.6	3.0	145.7	79	5,360	65	71
2309049	6.4	3.8	No Data	65	5,360	61	69
2313946	6.0	2.0	143.6	74	5,360	57	70
2292563	6.0	3.5	142.6	75	5,370	55	61
2334415	5.6	3.0	143.6	68	5,370	64	75
2338076	5.8	3.0	143.6	72	5,370	38	44
No Data	5.5	2.8	143.1	63	5,370	55	61
2366425	6.6	2.8	142.6	59	5,370	38	43
2274599	5.2	2.5	144.1	83	5,370	55	61
2322333	6.0	2.3	142.1	73	5,370	71	81
2316779	5.6	3.5	144.1	76	5,370	65	81
2340001	5.5	2.8	142.6	69	5,370	79	94
2277152	5.0	2.5	146.2	86	5,370	73	91
2310527	5.8	3.8	143.1	62	5,380	58	65
2274112	5.0	2.5	142.6	84	5,380	58	65
2379747	5.4	4.0	144.1	76	5,380	66	75
2289560	6.0	3.5	141.1	67	5,390	77	92
No Data	5.7	3.0	142.1	61	5,390	72	88
2311852	5.0	2.5	144.6	63	5,390	48	64
2363863	5.8	2.3	145.1	73	5,400	38	44
2361503	6.1	4.5	139.5	55	5,400	51	64

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2376192	7.4	4.3	142.1	74	5,400	79	91
2333752	6.8	3.5	142.6	64	5,410	77	91
2336935	5.8	2.8	143.6	62	5,410	24	33
2320105	5.5	2.5	142.6	77	5,410	72	86
2299208	6.2	3.5	141.6	80	5,420	65	74
2368030	6.7	4.3	142.6	67	5,420	68	86
2347592	5.0	2.0	145.1	75	5,420	70	84
2281254	5.8	3.5	142.6	75	5,420	76	86
2316926	5.2	3.5	142.6	78	5,420	69	82
2366106	5.7	3.8	142.1	56	5,420	51	67
2276288	5.3	3.8	144.6	82	5,420	69	87
2297936	5.6	3.0	142.6	80	5,430	65	77
2334183	6.8	3.3	142.1	62	5,430	71	81
2335339	6.9	3.5	145.1	62	5,430	71	81
2335341	6.9	3.5	141.5	54	5,430	68	77
No Data	6.3	2.3	142.6	83	5,430	68	80
2286893	6.8	4.5	140.6	66	5,440	80	89
2302168	5.6	4.0	141.1	85	5,440	74	89
2309886	6.9	4.0	141.6	61	5,440	79	89
No Data	7.0	3.0	140.6	72	5,440	79	89
2276292	5.7	3.8	144.1	80	5,440	80	89
No Data	No Data	No Data	144.1	No Data	5,440	74	84
2312877	5.8	2.5	142.6	64	5,440	48	60
No Data	7.5	4.5	140.6	84	5,440	75	84
2345671	5.5	4.0	144.1	89	5,440	88	103
2292145	6.2	3.8	142.6	72	5,450	72	80
2365691	6.2	2.5	142.6	59	5,450	52	62
2333081	6.4	3.3	142.1	70	5,460	84	93
2360772	5.5	3.3	143.6	79	5,460	30	38
2369785	5.8	3.0	142.6	71	5,460	65	74
2273110	5.5	3.0	143.6	84	5,460	71	84
2378355	5.9	6.0	145.7	90	5,460	43	68
2347606	7.3	3.0	141.5	78	5,460	68	84
2286356	5.2	4.0	143.6	67	5,470	81	92
2300502	6.2	3.5	140.1	83	5,470	81	89
No Data	6.6	3.3	142.1	68	5,470	62	73
No Data	6.8	3.0	140.6	65	5,470	81	92
2356457	6.8	3.0	142.6	79	5,470	33	44
2309749	5.5	2.8	141.1	60	5,480	81	92
2265996	6.0	3.5	143.6	63	5,480	81	92
2343832	6.4	3.3	142.1	82	5,480	71	82
2281435	6.5	2.8	142.6	68	5,480	54	67
2286363	5.8	3.8	143.1	67	5,490	81	92
2310802	6.2	4.0	141.6	66	5,490	81	92

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2358128	5.4	1.8	143.6	76	5,490	64	79
2360937	5.3	3.0	144.6	77	5,490	33	44
2256660	6.0	3.5	142.1	75	5,500	73	82
2271004	5.0	3.0	144.1	76	5,500	79	91
No Data	5.5	2.8	143.6	65	5,500	58	70
2352781	5.2	4.0	143.6	70	5,500	62	68
2362497	5.4	3.8	142.6	57	5,500	43	53
2314602	5.4	4.0	144.1	74	5,500	74	90
2280196	5.2	3.5	144.6	81	5,500	65	81
2361747	7.0	4.0	140.0	66	5,500	54	73
2364019	6.2	3.3	143.6	73	5,510	23	34
2277662	5.4	2.0	145.1	86	5,510	79	91
No Data	6.0	2.8	142.6	84	5,510	75	91
No Data	5.5	2.5	142.6	88	5,510	75	91
2302172	6.1	3.3	142.6	78	5,520	65	75
2333740	6.4	3.5	142.6	60	5,520	70	80
2335835	6.3	3.3	142.1	65	5,520	74	86
2314754	5.4	4.0	143.6	73	5,520	75	86
2280756	6.4	3.8	142.6	79	5,520	77	98
2381169	7.2	4.0	140.5	70	5,520	53	67
2347477	5.6	2.0	144.6	78	5,520	85	101
2303866	5.6	3.0	142.1	77	5,530	70	80
No Data	5.6	2.8	142.6	78	5,530	70	80
No Data	5.9	3.3	141.6	79	5,530	72	82
2379180	5.2	3.0	143.6	90	5,530	73	82
No Data	5.2	2.8	144.6	84	5,530	74	88
2381305	6.4	4.5	142.6	65	5,530	55	63
2351779	5.6	4.3	No Data	82	5,530	77	92
2327010	6.2	3.3	141.5	77	5,540	76	86
2375433	5.5	4.0	142.1	78	5,550	68	82
2364749	6.6	3.5	138.5	72	5,550	29	32
2323926	6.0	3.0	141.5	82	5,550	74	84
2361645	6.1	3.0	143.6	65	5,550	47	57
2256638	5.5	3.8	142.1	83	5,560	72	82
No Data	5.8	3.0	142.6	62	5,560	71	83
2320632	5.9	2.8	141.6	80	5,560	75	86
2342849	5.8	3.3	142.6	76	5,560	71	85
2380711	5.7	3.0	143.6	75	5,560	70	83
2302170	6.5	3.8	140.1	83	5,570	72	82
2363739	5.5	2.8	144.6	67	5,570	38	52
No Data	6.5	3.5	142.1	73	5,570	68	80
2325666	6.0	3.3	142.6	77	5,570	68	78
2319408	5.4	3.0	143.6	74	5,570	73	91
2293781	5.5	2.5	143.6	80	5,580	69	80

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2273327	5.0	1.5	144.6	79	5,580	72	82
2265755	8.0	3.5	142.6	64	5,580	70	83
2371141	5.4	4.0	144.6	74	5,580	45	63
2326020	5.8	3.5	142.1	80	5,580	77	86
2366564	5.1	2.3	144.6	55	5,580	51	55
No Data	7.0	2.8	140.6	80	5,580	72	83
2362875	6.0	3.0	143.6	62	5,580	37	53
2378580	5.6	2.3	144.1	81	5,590	65	77
2366014	7.0	2.8	141.0	73	5,590	33	46
No Data	5.5	3.0	143.6	77	5,590	69	83
2319266	6.2	3.0	143.6	73	5,590	62	76
No Data	6.5	3.0	141.6	80	5,590	73	80
2286261	7.0	4.5	141.0	67	5,600	68	77
2305102	6.5	4.0	140.6	79	5,600	65	77
2333746	6.5	3.5	143.1	69	5,600	68	77
2266852	5.9	3.3	143.1	60	5,600	68	77
2302176	5.6	3.5	141.6	78	5,610	65	77
No Data	6.2	1.8	141.0	82	5,610	75	86
2267551	5.4	4.3	142.1	56	5,610	65	77
2322124	5.4	3.0	144.6	77	5,610	78	94
2302174	5.9	3.5	142.1	76	5,620	65	77
2366593	7.4	3.3	144.1	74	5,620	49	70
2261771	6.2	4.0	141.5	81	5,620	68	76
2320628	5.8	2.5	142.6	80	5,620	75	86
2335701	6.0	3.3	143.1	70	5,630	70	79
No Data	6.6	4.0	141.5	79	5,630	69	86
2357049	6.2	3.5	143.6	76	5,630	74	83
2361406	7.0	3.8	142.6	71	5,640	62	71
2305938	6.8	4.0	140.6	71	5,640	70	79
2362159	5.5	3.8	142.6	64	5,640	42	49
2259174	6.8	4.0	142.6	74	5,650	70	79
No Data	5.5	2.8	144.1	78	5,650	65	77
No Data	5.5	2.0	142.1	88	5,650	70	80
No Data	7.2	4.3	139.0	82	5,650	80	93
2266166	7.0	2.8	141.5	67	5,650	66	74
2266167	7.0	3.8	140.5	53	5,650	66	74
2266425	6.5	3.0	141.5	64	5,650	66	74
2274352	5.5	2.8	143.1	86	5,650	70	79
No Data	6.0	2.8	141.6	63	5,650	69	80
2285923	6.6	4.0	142.1	64	5,660	67	78
2286231	5.9	4.5	142.1	71	5,660	66	78
2323938	6.6	3.3	141.0	78	5,660	74	84
2304431	5.0	4.3	144.1	65	5,660	61	71
No Data	6.2	3.0	140.1	76	5,660	68	77

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
No Data	5.4	3.0	144.6	81	5,660	70	80
2334179	6.6	3.3	143.1	66	5,670	69	80
2268935	5.1	2.3	144.1	70	5,670	67	78
2283198	6.6	3.3	139.5	52	5,670	65	68
No Data	6.0	3.0	142.6	77	5,670	60	73
2344847	5.5	2.0	143.6	73	5,670	85	97
2341799	7.8	5.5	142.6	65	5,670	38	56
2334185	6.9	3.5	142.6	65	5,680	61	69
No Data	5.6	4.5	143.1	61	5,680	57	68
2311855	5.2	2.5	143.1	68	5,680	59	77
2277888	5.1	2.8	144.1	76	5,680	63	70
2354040	7.5	4.5	No Data	83	5,690	78	92
2318794	6.4	3.5	142.1	70	5,690	73	87
2363555	6.5	3.5	143.6	70	5,700	44	53
2364254	5.6	3.3	144.6	72	5,700	53	78
No Data	5.0	2.3	144.6	78	5,700	57	67
2285920	6.2	4.0	142.1	64	5,710	77	84
2286419	6.0	3.8	143.1	69	5,720	70	79
2302165	5.5	3.0	143.1	82	5,730	70	79
2310308	6.8	4.3	141.6	65	5,730	70	83
2266216	5.0	3.0	144.1	65	5,730	70	83
2379291	7.5	4.5	140.0	72	5,740	83	100
2284939	6.1	3.0	143.1	55	5,750	80	87
2292935	7.5	3.3	143.1	77	5,750	70	83
2362124	5.4	3.0	142.6	61	5,750	40	48
2303869	6.0	3.5	141.6	76	5,760	80	87
2364381	5.7	2.0	144.6	61	5,760	35	47
2363240	6.4	4.5	142.1	68	5,760	45	63
2363549	5.6	3.0	143.6	66	5,770	44	53
No Data	6.4	3.3	140.0	81	5,770	75	91
2363961	5.0	2.3	146.2	58	5,770	50	69
2284352	No Data	No Data	140.0	No Data	5,780	64	79
2309751	6.4	3.0	139.0	56	5,780	64	79
No Data	6.2	3.5	141.6	62	5,780	64	79
2320110	5.3	1.8	143.6	75	5,780	76	85
2285698	6.0	4.5	141.5	70	5,790	56	68
No Data	5.5	3.3	143.6	82	5,790	71	83
2282003	7.2	4.0	141.5	63	5,790	54	65
No Data	6.1	4.5	142.1	56	5,790	59	69
2265750	6.2	2.5	144.1	65	5,790	59	69
2266732	5.8	3.5	143.6	69	5,790	71	82
2280627	6.2	3.0	143.1	80	5,790	46	50
2358781	6.6	4.3	No Data	79	5,790	47	60
2362164	5.6	3.0	143.6	64	5,790	42	49

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2301493	6.4	3.5	142.1	79	5,800	46	50
2259050	6.2	4.0	143.6	75	5,800	63	72
No Data	5.5	3.3	144.6	82	5,800	67	84
2286163	6.2	4.5	142.6	67	5,810	61	72
2335652	6.2	3.3	142.1	65	5,810	45	52
2381876	6.0	5.3	144.6	69	5,810	47	60
2363468	5.0	3.3	144.6	59	5,810	46	57
2341167	6.3	4.5	142.6	73	5,810	78	87
2280885	5.4	2.5	143.6	81	5,820	44	59
2286264	5.6	3.5	142.6	62	5,820	61	72
2335563	6.4	4.5	141.5	68	5,820	35	51
No Data	6.6	4.5	140.5	65	5,820	57	63
2258624	5.4	3.0	143.1	82	5,820	61	72
2260568	6.5	3.5	142.1	75	5,820	30	36
2275611	5.5	3.8	142.1	83	5,820	44	59
No Data	5.6	2.5	143.1	82	5,820	65	79
2286758	6.9	3.5	143.6	69	5,830	28	36
2363795	5.4	2.0	143.6	61	5,830	51	70
2264160	6.0	3.5	141.5	70	5,830	35	44
2266488	6.8	3.5	143.1	59	5,830	40	48
2280886	6.2	4.3	142.6	79	5,830	71	85
2362147	5.0	2.8	144.6	55	5,830	42	49
No Data	5.1	2.0	145.7	78	5,840	76	89
2266909	6.0	2.8	143.6	60	5,840	20	32
2376080	5.0	3.5	143.6	77	5,840	72	88
2245866	7.5	4.0	141.0	59	5,860	20	32
2264841	5.5	2.8	142.1	67	5,860	16	29
2286422	5.6	4.0	143.6	71	5,870	31	40
2310769	6.0	4.0	142.1	68	5,870	16	27
2251237	6.2	4.0	140.5	78	5,870	30	45
2374803	6.5	5.0	144.1	81	5,870	66	78
2271151	5.0	2.0	144.1	83	5,880	30	45
2281998	7.5	3.5	141.5	64	5,880	30	34
2364190	6.2	3.8	143.6	65	5,880	46	72
2312793	5.5	2.3	142.6	60	5,880	39	57
2356598	5.3	4.5	144.6	81	5,880	77	88
2366008	5.5	2.0	144.1	56	5,880	46	69
2358547	5.3	4.3	144.6	73	5,890	70	82
2323945	5.5	3.5	143.6	78	5,890	71	84
2381670	5.5	2.5	145.7	51	5,890	62	83
2310718	6.0	4.0	142.6	65	5,900	15	19
2284353	5.7	3.5	143.6	60	5,900	30	34
2365763	5.5	2.0	144.1	57	5,900	51	68
2337642	6.2	2.5	143.6	69	5,910	50	69

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2313610	5.5	2.0	143.6	56	5,920	26	33
2357742	7.5	3.8	141.5	68	5,920	68	80
2364202	5.5	25.0	142.6	61	5,920	50	69
2364064	6.0	2.3	144.1	67	5,930	51	67
2319050	5.4	3.0	144.6	77	5,930	75	90
2298995	6.5	4.5	No Data	82	5,940	39	48
2246710	6.6	4.0	141.0	35	5,940	12	33
2266740	5.4	2.8	142.6	70	5,940	73	86
2318528	5.5	2.3	143.6	80	5,940	80	88
No Data	6.5	2.8	142.1	89	5,940	64	68
No Data	6.8	4.0	141.6	61	5,950	76	88
No Data	5.4	2.5	143.1	73	5,950	77	89
2286454	7.0	5.0	No Data	67	5,960	54	64
2257334	5.5	4.0	142.6	77	5,960	54	59
2340573	5.5	25.0	143.1	75	5,960	54	67
2363667	6.0	3.5	146.7	71	5,960	64	75
No Data	5.1	1.5	144.6	60	5,970	46	57
No Data	5.5	3.0	144.1	71	5,970	55	69
2336564	5.4	2.5	144.1	57	5,970	33	47
2266217	6.2	3.0	143.1	58	5,970	47	56
2266765	5.8	4.0	144.1	66	5,970	46	57
2357758	5.7	3.0	143.6	75	5,990	65	74
2280574	5.9	3.5	141.5	76	5,990	52	54
2306502	5.0	3.8	145.2	59	5,990	46	50
2376203	6.7	4.0	143.6	81	5,990	79	91
2338706	7.0	7.5	141.0	71	5,990	60	78
2258838	5.2	4.3	144.1	81	6,000	64	70
No Data	5.8	3.0	143.1	84	6,000	77	86
2362161	5.5	3.0	143.1	66	6,000	42	49
No Data	7.2	3.8	142.1	80	6,010	65	70
2281991	6.4	3.0	142.6	64	6,010	80	96
2379693	6.5	4.0	144.6	81	6,010	66	78
2314231	5.3	3.5	144.6	58	6,010	79	96
2367983	5.9	2.8	142.6	63	6,010	65	82
2266854	5.9	3.0	142.1	66	6,020	71	84
2257628	6.4	4.0	140.5	75	6,030	86	93
2381691	6.0	6.0	146.2	68	6,030	62	78
2292940	5.7	3.3	144.1	80	6,040	69	79
2268715	5.2	1.8	145.1	76	6,040	67	76
No Data	5.6	1.8	143.6	78	6,040	83	92
2364371	5.9	2.0	143.6	57	6,040	37	50
2342621	7.5	4.3	140.0	67	6,050	71	85
2364067	5.5	3.5	146.7	68	6,050	63	80
2314851	5.8	3.0	143.6	72	6,080	75	92

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2361609	7.3	3.8	143.1	71	6,090	71	85
2309747	5.0	3.0	142.6	66	6,090	75	88
2266990	5.2	2.8	142.6	60	6,090	67	78
2281356	6.0	3.0	143.1	70	6,090	64	74
2303872	5.1	3.0	143.1	77	6,100	84	91
No Data	7.4	3.0	140.1	76	6,100	64	78
No Data	6.6	2.5	142.6	66	6,120	77	87
2266918	6.5	3.8	143.6	62	6,130	78	86
2282000	7.0	3.5	142.6	63	6,140	71	85
2314548	6.0	2.3	141.6	68	6,140	58	66
2313805	5.5	1.3	143.6	50	6,140	77	89
2363546	5.3	2.3	143.6	57	6,160	42	52
2285490	4.5	8.0	144.6	57	6,170	71	85
No Data	6.1	2.0	143.6	81	6,170	74	88
2357018	6.2	6.5	142.6	79	6,170	81	102
2358632	5.0	3.3	144.6	82	6,180	79	93
2250932	5.5	3.0	143.1	82	6,190	71	85
2267013	6.0	3.0	144.6	71	6,190	71	85
No Data	5.5	3.0	143.1	79	6,190	64	73
2310972	5.5	4.0	141.6	75	6,200	71	85
2248031	6.0	4.0	141.0	62	6,200	54	64
2364725	6.0	3.0	135.5	59	6,200	41	49
No Data	5.0	2.3	144.6	82	6,210	70	79
2283450	6.2	3.3	141.0	58	6,210	52	64
2363368	6.3	8.0	143.1	79	6,210	71	84
2246955	6.0	3.3	142.1	60	6,220	52	64
2250716	5.0	3.0	144.1	77	6,230	44	54
2266881	6.2	3.0	144.1	61	6,230	52	64
2282009	6.6	2.8	143.1	73	6,250	44	54
2286764	5.7	3.5	143.6	63	6,270	44	54
2309743	6.6	3.5	139.6	63	6,270	37	41
2363066	5.0	8.0	143.6	77	6,270	80	98
2286353	5.0	2.5	144.6	69	6,280	37	41
No Data	5.2	2.0	145.1	58	6,370	39	51
2338899	6.2	7.0	142.1	74	6,380	77	91
No Data	6.5	3.8	140.6	60	6,390	37	41
No Data	5.5	1.3	142.1	75	6,390	59	79
2348548	7.1	8.8	140.5	90	6,400	56	71
2271810	6.0	3.5	144.1	82	6,410	77	95
2356341	6.6	7.3	141.5	82	6,410	80	99
2267463	5.5	2.5	142.6	69	6,420	37	41
2346129	5.7	3.8	144.1	76	6,420	58	69
2342786	5.3	3.5	145.1	73	6,430	70	88
2283444	5.5	3.3	143.1	54	6,450	28	37

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
No Data	5.8	3.3	142.6	70	6,450	53	62
No Data	5.5	3.5	141.6	76	6,450	66	77
2338802	6.0	7.3	143.6	62	6,460	80	99
2306650	5.3	4.0	142.6	60	6,490	35	44
2334177	5.5	3.0	144.1	65	6,490	28	37
2266895	5.0	2.5	146.2	62	6,490	28	37
2366686	5.2	8.5	144.1	71	6,490	56	71
No Data	6.2	4.0	143.6	67	6,500	44	48
No Data	6.6	3.3	143.6	63	6,520	39	51
No Data	5.2	2.8	143.6	61	6,550	50	56
No Data	6.0	2.8	142.1	81	6,560	44	54
2339022	6.0	7.5	142.6	70	6,560	69	80
2334174	6.9	4.0	141.5	50	6,630	68	82
2367179	5.5	8.0	143.1	73	6,710	61	72
2367189	7.3	8.8	144.6	71	6,710	65	75
2366690	7.5	8.8	140.5	79	6,720	67	81
2379197	6.2	4.0	145.7	82	6,720	67	81
2359203	6.2	4.3	143.6	70	6,810	60	75
No Data	5.2	3.0	143.1	62	6,830	52	65
2348551	6.8	8.5	141.0	86	6,910	71	82
2377149	5.4	8.5	146.7	86	6,910	65	77
2310070	6.2	3.5	140.6	62	6,920	26	37
2365855	7.0	8.8	143.1	74	7,020	65	73
No Data	5.6	2.8	143.6	78	7,070	70	81
2374192	7.0	8.3	142.6	87	7,070	65	73
2308849	5.5	3.0	143.6	65	7,080	36	45
2310063	5.5	3.0	141.6	62	7,080	20	29
2341395	5.3	7.0	143.1	79	7,080	78	97
2368759	6.0	9.0	143.6	70	7,080	82	93
2375577	6.5	8.8	144.6	81	7,080	82	96
2377147	6.8	9.0	145.7	81	7,080	82	96
2315040	5.0	21.0	143.6	68	7,080	57	59
2366017	6.3	8.0	143.6	68	7,080	65	77
2310061	6.0	3.0	141.6	57	7,090	34	46
2310065	5.2	2.8	143.1	71	7,090	30	41
2364894	7.0	8.8	137.5	63	7,090	72	81
2368761	6.8	8.0	147.2	76	7,090	78	99
2370369	6.0	9.0	146.7	81	7,090	78	91
2370437	6.5	8.3	145.7	81	7,090	78	89
2372007	6.0	8.8	146.7	77	7,090	81	99
2372023	5.7	8.5	146.2	73	7,090	81	99
2374183	6.4	8.8	145.1	87	7,090	71	91
2375587	5.5	9.0	146.7	86	7,090	71	91
2356671	5.5	6.8	144.1	73	7,090	57	74

Sample ID	% Air	Slump (in)	Cyl unit Weight (lbs/ft³)	Concrete Temp	Com. Strength (psi)	Average Daily Temp (F)	Daily High Temp (F)
2359866	6.0	6.5	143.1	72	7,090	54	61
2341423	5.0	8.0	145.7	69	7,100	65	81
2364869	5.8	9.0	139.5	74	7,100	59	77
2365852	6.5	8.8	143.1	64	7,100	76	94
2323457	5.8	1.3	144.6	79	7,100	67	71

Table 91: Summary of the data from Figure 20

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	72.63	76.93	81.72	91.11
0.25	72.95	77.25	79.68	77.90
0.5	73.81	77.67	79.11	78.15
0.75	78.48	78.15	79.59	78.55
1	80.91	78.78	80.17	80.01
1.25	82.38	79.20	80.49	80.10
1.5	84.78	79.59	81.14	80.01
1.75	84.52	80.10	81.72	80.49
2	87.53	80.65	82.45	81.14
2.25	87.71	80.98	82.62	81.72
2.5	89.15	82.04	82.96	82.45
2.75	90.09	82.29	83.61	83.19
3	89.74	82.45	84.18	83.86
3.25	90.70	83.53	84.69	84.43
3.5	92.52	83.70	85.44	84.85
3.75	91.90	84.69	85.35	85.35
4	92.25	84.94	85.60	85.93
4.25	89.49	85.35	85.77	86.68
4.5	91.29	85.77	86.52	87.53
4.75	94.35	86.11	86.52	88.38
5	92.52	86.61	86.61	89.40
5.25	94.10	86.77	87.53	90.61
5.5	90.09	87.44	87.96	91.72
5.75	94.35	87.78	87.71	93.13
6	93.04	88.03	88.21	94.44
6.25	93.74	88.47	88.90	95.86
6.5	92.86	88.63	88.72	97.32
6.75	93.22	89.15	89.40	98.69
7	90.00	89.56	90.00	100.17
7.25	88.63	89.65	90.09	101.75
7.5	88.72	90.18	90.70	103.57
7.75	87.03	90.86	91.72	105.40
8	85.26	91.11	92.16	107.38
8.25	85.77	91.56	92.68	109.09

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
8.5	83.77	92.08	93.38	110.12
8.75	81.23	92.86	94.35	110.75
9	80.26	93.38	95.07	111.06
9.25	79.11	94.17	95.52	111.25
9.5	78.31	93.65	95.16	111.25
9.75	76.78	93.65	94.89	111.06
10	76.30	92.77	94.17	110.75
10.25	75.81	92.08	93.31	110.34
10.5	75.58	91.63	93.04	109.71
10.75	75.58	91.04	92.43	109.20
11	74.37	91.20	92.16	108.59
11.25	74.30	90.77	91.81	107.78
11.5	72.86	90.27	91.72	107.29
11.75	72.00	90.34	91.29	106.68
12	72.14	89.49	90.18	106.00
12.25	70.88	88.72	89.40	105.12
12.5	70.32	88.12	88.63	104.34
12.75	69.76	87.12	87.78	103.37
13	69.30	85.77	86.94	102.51
13.25	69.37	85.26	86.36	101.57
13.5	69.06	84.94	85.60	100.72
13.75	69.37	84.11	84.69	99.88
14	68.90	83.44	84.11	99.05
14.25	69.30	82.96	83.28	98.13
14.5	69.13	82.13	83.12	97.23
14.75	68.74	81.07	81.97	96.40
15	68.50	79.75	80.58	95.52
15.25	68.20	79.11	80.26	94.62
15.5	68.04	78.55	79.84	93.83
15.75	67.32	78.55	80.01	93.04
16	66.78	78.78	80.10	92.34
16.25	66.38	79.11	79.75	91.72
16.5	65.26	79.11	79.59	91.20
16.75	64.80	78.55	78.87	90.77
17	64.63	78.55	78.94	90.09
17.25	64.47	78.15	78.39	89.65
17.5	64.00	77.50	77.90	89.06
17.75	63.84	77.18	77.50	88.56
18	63.45	76.62	77.02	87.96
18.25	63.30	76.30	77.02	87.44
18.5	63.21	76.14	76.69	86.94
18.75	62.91	75.58	76.05	86.52
19	63.05	75.49	75.81	86.02
19.25	63.37	75.02	75.25	85.51

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
19.5	63.21	74.62	75.09	85.01
19.75	62.82	74.21	74.62	84.52
20	62.74	73.58	74.62	84.02
20.25	62.91	72.79	73.58	83.53
20.5	63.68	72.86	73.51	83.12
20.75	63.77	73.09	73.26	82.71
21	63.54	73.02	73.26	82.29
21.25	63.37	72.95	73.42	81.88
21.5	63.45	72.46	73.02	81.64
21.75	63.61	72.00	72.46	81.30
22	63.93	71.44	72.00	80.98
22.25	63.77	69.46	68.34	80.58

Table 92: Summary of the data from Figure 21

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	75.97	70.41	70.02	68.83
0.25	74.77	74.14	74.37	76.86
0.5	75.33	74.77	75.74	76.86
0.75	75.74	76.05	77.34	76.93
1	76.93	77.25	79.03	77.09
1.25	78.15	77.90	79.92	77.34
1.5	79.92	77.74	79.75	77.67
1.75	78.62	78.15	79.92	77.99
2	78.71	78.55	80.49	78.22
2.25	80.26	78.48	80.74	78.62
2.5	79.84	78.87	80.65	79.03
2.75	80.01	77.99	80.26	79.43
3	78.55	78.39	80.17	79.84
3.25	78.31	79.36	80.74	80.42
3.5	79.59	79.03	81.46	81.07
3.75	80.82	78.22	81.14	81.88
4	80.17	78.22	80.98	82.71
4.25	75.90	79.36	80.98	83.61
4.5	73.98	80.58	81.72	84.69
4.75	75.25	80.91	82.29	85.77
5	73.74	81.39	82.54	87.03
5.25	72.70	82.20	83.03	88.29
5.5	69.69	83.03	83.70	89.65
5.75	70.16	84.02	84.60	91.04
6	70.65	84.85	85.44	92.43
6.25	70.32	85.44	86.27	93.83
6.5	68.90	86.11	86.94	95.25
6.75	67.08	86.77	87.78	96.58
7	67.32	87.53	88.47	97.95

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
7.25	65.75	88.29	89.56	99.43
7.5	67.17	89.22	90.61	101.01
7.75	67.48	90.27	91.81	102.7
8	67.64	91.29	93.04	104.54
8.25	67.24	92.25	94.10	106.00
8.5	67.24	93.22	95.07	107.19
8.75	66.61	94.01	95.86	108.09
9	66.52	94.53	96.58	108.79
9.25	66.38	95.16	97.23	109.40
9.5	65.26	95.70	97.86	109.71
9.75	65.19	96.22	98.49	110.01
10	66.06	96.49	98.87	110.23
10.25	66.38	96.85	99.14	110.23
10.5	66.22	96.85	99.23	110.23
10.75	65.89	96.85	99.14	110.23
11	64.80	96.58	98.96	110.01
11.25	62.74	96.31	98.69	109.92
11.5	61.95	96.13	98.49	109.62
11.75	61.32	95.77	98.31	109.31
12	60.51	95.43	98.60	109.00
12.25	59.49	95.25	98.49	108.59
12.5	59.02	94.89	98.31	108.19
12.75	58.69	94.62	97.86	107.78
13	57.74	94.26	97.14	107.38
13.25	57.88	94.01	97.32	106.88
13.5	57.58	93.65	96.85	106.48
13.75	57.02	93.31	96.40	106.00
14	56.53	92.86	95.77	105.51
14.25	56.30	92.43	95.61	105.03
14.5	55.89	91.99	95.07	104.43
14.75	55.65	91.56	94.44	103.95
15	55.00	91.11	94.01	103.57
15.25	54.84	90.77	93.47	102.99
15.5	54.68	90.34	93.04	102.42
15.75	54.45	89.92	92.61	101.95
16	54.19	89.40	92.16	101.37
16.25	53.96	88.97	91.72	100.81
16.5	53.71	88.63	91.38	100.35
16.75	53.87	88.21	90.86	99.79
17	53.31	87.78	90.18	99.23
17.25	52.83	87.37	89.83	98.69
17.5	53.06	86.94	89.31	98.13
17.75	52.16	86.61	88.97	97.59
18	52.16	86.18	88.47	97.14

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
18.25	52.83	85.93	88.03	96.58
18.5	52.48	85.60	87.71	96.04
18.75	53.87	85.26	87.37	95.52
19	56.05	85.01	87.03	94.98
19.25	56.77	84.78	86.61	94.53
19.5	57.09	84.60	86.27	94.01
19.75	59.56	84.52	86.11	93.56
20	60.12	84.43	86.02	93.22
20.25	61.56	84.43	86.02	92.77
20.5	63.21	84.52	86.11	92.52
20.75	64.96	84.60	86.27	92.16
21	66.85	84.69	86.43	91.81
21.25	67.87	84.94	86.68	91.56
21.5	69.53	85.10	86.94	91.47
21.75	70.88	85.26	87.19	91.20
22	72.14	85.35	87.44	90.95
22.25	71.83	85.51	87.62	90.77
22.5	72.39	85.69	87.87	90.70
22.75	73.35	85.86	88.03	90.61
23	73.42	86.02	88.21	90.52
23.25	75.49	80.58	85.60	90.34

Table 93: Summary of the data from Figure 39

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	56.14	57.33	56.61	54.61
0.25	57.42	54.52	53.22	53.38
0.5	54.93	57.42	57.02	63.84
0.75	53.64	58.69	58.46	63.30
1	54.03	59.49	59.32	63.14
1.25	55.40	59.97	59.81	62.98
1.5	57.25	60.37	60.37	62.91
1.75	58.69	60.84	61.00	62.82
2	59.97	61.32	61.56	62.82
2.25	60.44	61.56	61.86	62.82
2.5	60.76	61.72	62.11	62.91
2.75	62.58	62.11	63.14	62.98
3	62.98	62.51	64.17	63.05
3.25	69.22	62.82	64.87	63.21
3.5	68.04	63.14	65.19	63.37
3.75	69.93	63.37	65.19	63.61
4	66.85	63.77	65.98	63.77
4.25	68.74	64.08	66.29	64.08
4.5	68.20	64.47	66.69	64.40
4.75	67.41	64.80	67.17	64.80

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
5	68.59	65.19	67.64	65.10
5.25	69.53	65.75	68.83	65.50
5.5	71.44	66.45	70.25	65.98
5.75	71.04	67.08	71.51	66.52
6	73.18	67.80	72.55	67.17
6.25	73.58	68.50	73.51	67.87
6.5	73.74	69.22	74.53	68.59
6.75	74.30	70.09	75.58	69.46
7	77.99	70.88	76.53	70.32
7.25	77.25	71.74	77.41	71.28
7.5	76.93	72.63	78.31	72.30
7.75	77.34	73.42	78.06	73.35
8	78.87	74.30	77.34	74.53
8.25	80.01	74.21	77.34	75.65
8.5	76.21	75.18	78.48	76.86
8.75	76.46	75.81	79.75	77.99
9	76.53	76.46	80.49	79.20
9.25	76.21	77.25	81.55	80.33
9.5	77.99	78.06	82.38	81.55
9.75	76.86	78.94	83.03	82.87
10	78.55	79.11	83.44	84.27
10.25	75.65	79.92	84.11	85.69
10.5	75.25	80.49	84.85	87.19
10.75	76.21	81.39	85.77	88.72
11	76.53	82.87	86.61	90.34
11.25	73.98	84.11	87.53	91.99
11.5	73.51	84.69	88.03	93.38
11.75	73.35	85.19	88.47	94.44
12	73.26	86.36	89.06	95.16
12.25	71.67	85.77	88.90	95.61
12.5	71.74	85.69	88.63	95.86
12.75	70.48	85.69	88.72	96.04
13	69.37	86.18	88.81	96.13
13.25	68.50	85.51	88.47	96.04
13.5	67.24	85.93	88.47	96.04
13.75	67.08	85.44	88.29	95.95
14	65.98	85.60	88.21	95.77
14.25	65.35	86.11	88.29	95.61
14.5	64.72	85.93	88.21	95.43
14.75	64.24	85.26	87.78	95.34
15	63.77	85.35	87.53	95.07
15.25	63.30	85.10	87.44	94.80
15.5	62.74	84.85	87.37	94.62
15.75	62.19	84.60	86.94	94.35

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
16	61.86	84.85	86.94	94.10
16.25	61.63	84.43	86.68	93.83
16.5	61.63	84.36	86.43	93.56
16.75	61.16	83.95	86.11	93.31
17	60.76	83.44	85.86	92.95
17.25	60.28	83.44	85.51	92.68
17.5	59.32	83.53	85.44	92.34
17.75	59.09	83.19	85.19	92.08
18	58.93	82.96	85.01	91.81
18.25	58.86	82.87	84.85	91.47
18.5	58.60	82.29	84.60	91.20
18.75	58.77	82.13	84.43	90.86
19	58.46	82.13	84.27	90.61
19.25	58.46	81.72	83.95	90.27
19.5	58.05	81.30	83.70	90.00
19.75	57.97	81.07	83.35	89.65
20	56.86	80.82	83.03	89.31
20.25	56.30	80.49	82.78	88.97
20.5	56.44	80.17	82.45	88.63
20.75	55.65	79.75	82.04	88.29
21	55.00	79.59	81.81	88.03
21.25	54.93	79.27	81.30	87.71
21.5	54.61	78.71	80.98	87.37
21.75	54.03	78.48	80.74	86.94
22	54.12	78.31	80.49	86.61
22.25	54.28	77.58	80.17	86.27
22.5	54.12	77.34	79.84	85.86
22.75	53.8	77.25	79.52	85.51
23	53.71	76.93	79.27	85.10
23.25	53.87	76.46	78.87	84.78
23.5	53.47	75.97	78.48	84.43
23.75	53.15	75.97	78.22	84.02
24	52.74	75.65	77.99	83.70
24.25	52.74	75.09	77.58	83.35
24.5	52.41	52.57	51.26	82.87

Table 94: Summary of the data from Figure 40

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	65.19	64.00	63.68	69.46
0.25	62.74	64.72	65.19	69.85
0.5	63.84	65.66	66.06	67.32
0.75	64.17	66.38	66.61	67.41
1	65.82	67.17	67.24	67.41
1.25	67.71	67.41	67.71	67.55

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
1.5	66.22	67.87	68.20	67.64
1.75	67.95	68.59	68.83	67.80
2	74.07	69.46	70.09	67.95
2.25	71.60	69.46	70.56	68.20
2.5	70.25	69.46	70.56	68.50
2.75	71.74	69.76	71.04	68.74
3	74.53	70.32	71.83	68.97
3.25	76.14	70.72	72.46	69.30
3.5	74.77	70.95	73.02	69.69
3.75	72.63	70.95	72.86	70.09
4	71.51	71.04	72.70	70.56
4.25	76.78	71.04	72.70	70.95
4.5	70.09	71.11	72.39	71.44
4.75	71.35	71.35	72.39	71.83
5	72.70	71.83	72.70	72.46
5.25	75.18	72.23	73.26	73.02
5.5	74.14	72.55	73.65	73.58
5.75	73.42	73.18	74.21	74.37
6	73.74	73.81	74.86	75.25
6.25	74.14	74.46	75.42	76.21
6.5	74.14	75.09	76.30	77.18
6.75	79.59	75.74	77.41	78.31
7	79.68	76.21	78.06	79.36
7.25	74.07	76.37	78.22	80.58
7.5	73.35	77.18	78.87	81.72
7.75	75.81	78.06	79.84	82.78
8	74.21	78.62	80.42	83.95
8.25	74.86	79.59	81.30	85.19
8.5	73.02	80.42	81.88	86.27
8.75	72.95	80.82	82.45	87.44
9	72.07	81.30	83.03	88.56
9.25	71.51	82.04	83.53	89.65
9.5	71.91	82.54	84.36	90.70
9.75	70.95	83.19	85.01	91.72
10	69.76	83.61	85.60	92.95
10.25	68.74	84.27	86.43	94.17
10.5	68.11	85.01	87.19	95.43
10.75	67.48	85.60	88.03	96.58
11	67.01	86.36	88.81	97.68
11.25	66.45	86.94	89.49	98.49
11.5	65.89	87.37	90.09	99.23
11.75	65.19	87.87	90.70	99.79
12	64.63	88.03	91.04	100.26
12.25	64.17	88.29	91.29	100.63

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
12.5	63.68	88.47	91.47	100.81
12.75	63.14	88.38	91.56	101.01
13	62.74	88.97	91.72	101.01
13.25	62.26	89.49	91.81	101.01
13.5	61.95	90.00	92.08	100.90
13.75	61.72	89.92	92.08	100.81
14	61.23	89.65	91.90	100.72
14.25	60.67	89.56	91.81	100.54
14.5	60.51	89.74	91.72	100.35
14.75	60.12	89.65	91.56	100.08
15	59.72	89.56	91.38	99.79
15.25	59.49	89.49	91.20	99.52
15.5	59.16	88.97	90.95	99.23
15.75	59.02	88.47	90.61	98.87
16	58.86	88.38	90.34	98.49
16.25	58.69	87.87	90.09	98.13
16.5	58.46	87.78	89.74	97.77
16.75	58.53	87.78	89.56	97.41
17	59.16	87.28	89.22	96.94
17.25	58.05	86.86	88.90	96.58
17.5	57.74	85.93	88.38	96.13
17.75	57.88	85.44	87.87	95.70
18	57.81	85.77	87.62	95.25
18.25	57.97	85.35	87.44	94.80
18.5	57.88	83.95	86.68	94.35
18.75	57.09	84.36	86.43	94.01
19	56.86	84.02	86.18	93.56
19.25	56.93	83.53	85.69	93.04
19.5	56.86	83.44	85.35	92.61
19.75	56.86	83.35	85.10	92.16
20	56.70	82.29	84.52	91.72
20.25	56.14	82.20	84.18	91.20
20.5	55.89	82.45	84.02	90.77
20.75	56.30	82.04	83.70	90.34
21	55.81	81.14	83.19	89.92
21.25	55.72	80.58	82.71	89.49
21.5	55.72	80.91	82.45	89.06
21.75	55.81	80.65	82.13	88.63
22	55.65	80.10	81.81	88.21
22.25	55.24	79.52	81.30	87.71
22.5	55.40	79.43	81.07	87.37
22.75	56.37	79.84	80.98	86.86
23	58.21	80.33	80.91	86.61
23.25	61.00	80.17	80.82	86.18

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
23.5	60.67	80.17	80.65	85.86
23.75	62.02	80.98	80.82	85.51
24	64.80	81.64	80.82	85.19
24.25	66.15	82.13	81.07	85.01
24.5	66.61	82.13	81.14	84.85
24.75	68.83	82.13	81.30	84.69
25	69.30	82.29	81.55	84.52
25.25	71.04	82.62	81.88	84.36
25.5	73.09	82.87	82.13	84.36
25.75	73.26	82.62	82.20	84.27
26	75.49	82.78	82.45	84.18
26.25	76.30	82.96	82.78	84.18
26.5	76.30	83.28	83.12	84.18
26.75	76.86	83.19	83.19	84.27
27	78.22	83.28	83.35	84.36
27.25	78.94	83.28	83.61	84.36
27.5	78.48	83.44	83.86	84.43
27.75	81.39	83.35	84.02	84.43
28	80.49	83.35	84.18	84.52
28.25	82.04	83.53	84.43	84.52
28.5	82.54	83.44	84.43	84.60
28.75	80.82	83.61	84.69	84.78
29	82.13	83.77	84.94	84.85
29.25	83.70	83.86	85.10	84.85
29.5	82.04	84.02	85.01	84.94
29.75	84.43	84.27	85.10	85.01
30	83.77	84.43	85.44	85.10
30.25	85.60	82.20	86.11	85.26

Table 95: Summary of the data from Figure 41

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	65.82	68.20	71.83	71.51
0.25	72.79	69.37	71.51	71.83
0.5	76.14	69.69	71.74	71.83
0.75	75.74	69.62	71.44	71.83
1	76.93	69.69	71.60	71.83
1.25	78.62	70.56	72.79	71.83
1.5	77.25	71.20	74.14	71.91
1.75	88.72	71.83	75.02	72.07
2	89.56	72.14	76.30	72.30
2.25	90.00	72.79	76.86	72.46
2.5	89.83	72.86	75.97	72.79
2.75	87.87	72.95	76.30	73.02
3	80.26	73.58	76.46	73.42

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
3.25	81.14	73.98	77.34	73.74
3.5	81.30	74.14	78.06	74.21
3.75	82.96	75.18	78.78	74.62
4	84.78	75.49	78.94	75.18
4.25	83.86	75.90	80.42	75.81
4.5	84.11	76.37	81.55	76.53
4.75	85.35	77.18	82.29	77.34
5	85.86	77.99	83.03	78.22
5.25	88.90	78.62	83.35	79.27
5.5	88.29	79.75	84.02	80.42
5.75	87.71	80.49	85.19	81.64
6	89.83	81.46	86.02	83.03
6.25	89.31	83.03	86.02	84.52
6.5	89.65	83.86	86.77	86.11
6.75	87.96	84.60	87.19	87.71
7	89.06	85.69	87.87	89.31
7.25	87.78	86.43	88.63	90.95
7.5	87.87	87.28	89.65	92.61
7.75	88.12	88.03	90.34	94.26
8	89.65	89.06	91.47	95.86
8.25	88.21	90.09	92.61	97.68
8.5	89.22	90.77	92.43	99.70
8.75	88.21	91.72	93.13	101.95
9	85.35	92.61	93.83	104.05
9.25	85.01	93.38	94.35	105.60
9.5	84.43	94.01	95.25	106.68
9.75	83.44	94.44	95.86	107.49
10	82.38	94.62	96.04	108.09
10.25	81.14	94.62	96.67	108.48
10.5	80.17	94.53	96.76	108.70
10.75	79.36	94.71	96.85	108.70
11	78.31	94.17	96.40	108.70
11.25	77.74	94.17	96.31	108.48
11.5	76.93	94.01	96.31	108.19
11.75	76.14	93.83	96.13	107.78
12	75.42	93.47	95.70	107.38
12.25	74.77	93.38	95.77	106.99
12.5	74.77	93.04	95.52	106.59
12.75	73.81	92.61	95.16	106.20
13	73.65	92.25	94.89	105.71
13.25	73.02	93.56	95.25	105.31
13.5	73.09	94.35	95.07	104.83
13.75	72.23	93.65	95.07	104.54
14	72.07	93.31	94.80	104.14

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
14.25	70.81	92.95	94.44	103.77
14.5	70.25	91.29	93.56	103.37
14.75	69.22	90.86	93.31	102.99
15	69.69	89.74	92.61	102.42
15.25	69.69	88.63	91.72	101.86
15.5	69.13	89.15	91.56	101.19
15.75	68.74	89.83	91.63	100.54
16	68.20	90.52	91.72	100.08
16.25	67.80	89.83	91.38	99.61
16.5	67.80	89.40	91.11	99.23
16.75	68.20	88.03	90.61	98.78
17	67.24	87.53	90.09	98.49
17.25	67.64	86.02	89.06	98.04
17.5	66.61	86.11	88.63	97.41
17.75	66.06	85.35	88.29	96.76
18	64.56	85.01	87.78	96.22
18.25	64.96	85.86	87.53	95.61
18.5	64.47	86.11	87.44	95.16
18.75	64.80	85.10	87.03	94.71
19	64.33	84.60	86.61	94.26
19.25	63.68	84.94	86.43	93.83
19.5	64.47	84.60	86.18	93.38
19.75	64.80	84.11	85.93	93.04
20	65.10	83.95	85.35	92.61
20.25	65.43	82.96	85.10	92.25
20.5	65.10	83.70	84.85	91.72
20.75	63.84	81.88	84.36	91.20
21	64.00	81.72	83.86	90.95
21.25	64.56	81.23	83.44	90.52
21.5	65.82	80.98	83.28	90.09

Table 96: Summary of the data from Figure 42

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	60.44	64.40	63.37	59.02
0.25	60.93	64.80	64.33	67.48
0.5	60.37	65.10	64.72	67.01
0.75	63.14	66.22	65.19	66.85
1	62.91	67.32	65.82	66.78
1.25	65.59	68.11	66.52	66.78
1.5	66.85	68.50	67.08	66.85
1.75	68.11	68.04	67.17	66.92
2	64.72	68.67	67.41	67.08
2.25	65.59	69.53	68.27	67.24
2.5	72.23	70.16	69.22	67.41

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
2.75	75.58	70.48	70.16	67.64
3	77.09	70.81	71.04	67.95
3.25	77.83	71.04	71.91	68.34
3.5	79.27	72.00	72.23	68.74
3.75	80.98	72.63	73.09	69.30
4	81.39	73.35	74.21	69.93
4.25	82.54	74.21	75.02	70.65
4.5	82.62	78.22	83.12	71.51
4.75	84.18	79.84	84.52	72.86
5	84.27	80.74	83.86	75.90
5.25	85.26	82.62	86.52	79.03
5.5	85.35	84.94	84.11	81.88
5.75	87.03	87.53	87.03	84.69
6	83.95	87.78	86.61	87.19
6.25	88.38	84.02	83.19	89.56
6.5	86.43	88.38	88.21	91.72
6.75	84.18	86.52	87.12	93.92
7	89.40	85.60	86.02	96.13
7.25	87.28	85.69	85.35	98.04
7.5	87.19	86.68	84.94	99.99
7.75	86.68	86.52	85.01	101.75
8	87.37	86.11	84.69	103.77
8.25	86.52	85.10	82.20	105.60
8.5	85.19	86.27	84.43	106.29
8.75	82.29	85.44	83.86	106.39
9	84.36	85.26	83.61	105.89
9.25	83.77	84.52	82.96	105.21
9.5	82.38	84.18	82.13	104.05
9.75	83.03	83.61	81.88	102.90
10	82.71	83.12	81.72	101.75
10.25	82.04	83.03	81.30	100.63
10.5	81.14	82.04	79.03	99.32
10.75	81.64	81.39	78.62	97.95
11	80.01	81.39	78.31	96.58
11.25	79.52	80.98	77.83	95.25
11.5	79.20	75.42	72.70	94.10
11.75	78.62	73.35	70.48	92.68
12	73.26	70.48	67.95	90.34
12.25	71.60	68.43	65.89	88.12
12.5	69.37	65.35	63.37	86.02
12.75	68.34	64.63	62.91	83.95
13	65.75	65.03	62.82	81.55
13.25	64.47	65.75	62.82	79.27
13.5	63.77	64.87	63.84	77.25

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
13.75	63.93	64.63	63.61	75.65
14	64.40	64.17	63.14	74.30
14.25	64.33	63.93	63.05	72.86
14.5	63.77	64.00	63.37	71.60
14.75	64.00	63.84	63.21	70.81
15	64.17	63.77	63.05	70.02
15.25	64.00	63.68	62.91	69.46
15.5	63.93	63.77	63.30	68.97
15.75	63.93	63.68	63.30	68.50
16	64.17	63.61	63.21	68.11
16.25	64.24	63.61	63.37	67.80
16.5	64.08	63.45	63.14	67.55
16.75	64.24	63.54	63.21	67.24
17	64.08	63.54	63.21	67.01
17.25	64.17	63.45	62.91	66.85
17.5	64.17	63.37	63.30	66.69
17.75	64.00	63.45	62.91	66.52
18	64.17	63.30	62.82	66.45
18.25	64.00	63.30	62.98	66.29
18.5	63.77	63.37	62.91	66.22
18.75	63.93	63.14	63.05	66.06
19	63.84	63.14	62.98	65.98
19.25	64.00	63.05	62.82	65.89
19.5	63.93	63.05	62.82	65.66
19.75	63.77	63.05	62.91	65.59
20	63.68	62.98	62.91	65.50
20.25	63.68	62.91	62.82	65.43
20.5	63.54	62.82	62.58	65.26
20.75	63.37	62.65	62.42	65.10
21	63.14	62.65	62.26	65.03
21.25	62.98	62.51	62.35	64.87
21.5	62.98	62.42	62.26	64.72
21.75	62.74	62.42	62.26	64.56
22	62.74	62.35	62.11	64.40
22.25	62.74	62.26	62.02	64.33
22.5	62.65	62.19	61.86	64.17
22.75	62.58	62.19	62.02	64.08
23	62.58	62.11	61.86	63.93
23.25	62.58	62.02	61.86	63.93
23.5	62.35	62.11	61.86	63.77
23.75	62.26	61.95	61.63	63.68
24	62.35	61.72	61.47	63.54
24.25	62.19	61.63	61.39	63.45
24.5	62.02	61.72	61.63	63.30

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
24.75	62.11	61.86	61.95	63.21
25	62.19	61.95	62.02	63.21
25.25	62.35	62.26	62.74	63.21
25.5	62.65	62.82	62.91	63.30

Table 97: Summary of the data from Figure 43

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
0	72.63	78.06	77.18	72.14
0.25	75.90	76.21	76.46	73.58
0.5	75.25	75.65	75.74	74.14
0.75	76.37	75.81	76.14	74.53
1	76.30	76.37	77.25	74.86
1.25	78.48	76.93	78.06	75.09
1.5	79.36	77.18	77.99	80.74
1.75	78.87	77.25	78.06	92.86
2	77.67	78.15	79.20	92.08
2.25	79.27	78.94	80.42	92.08
2.5	81.30	79.84	81.64	92.16
2.75	83.28	80.33	82.13	92.43
3	83.61	81.14	82.71	92.68
3.25	83.86	81.55	83.12	93.13
3.5	84.43	81.88	83.44	93.65
3.75	84.94	82.38	83.77	94.10
4	84.78	83.19	84.78	94.62
4.25	85.51	83.70	85.01	95.25
4.5	86.27	84.18	85.51	95.86
4.75	86.61	84.94	86.27	96.58
5	86.86	85.44	86.36	97.95
5.25	87.12	85.44	85.86	100.63
5.5	86.52	85.93	86.27	102.24
5.75	86.02	86.52	86.77	101.86
6	86.18	86.86	87.12	101.75
6.25	86.02	87.28	87.28	101.48
6.5	86.02	87.96	87.96	99.43
6.75	85.86	88.97	88.90	99.70
7	85.44	89.22	89.31	100.63
7.25	85.69	89.65	89.74	101.86
7.5	85.26	90.09	90.27	103.37
7.75	84.94	90.34	90.70	104.43
8	84.43	90.18	90.34	105.60
8.25	84.18	89.74	89.74	106.79
8.5	82.87	89.83	89.92	107.89
8.75	81.39	90.18	90.52	108.90
9	80.65	90.52	91.11	109.62

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
9.25	79.68	90.86	91.63	110.12
9.5	78.78	90.95	91.63	110.34
9.75	78.06	90.86	91.81	110.43
10	77.74	89.92	90.77	110.23
10.25	76.78	89.74	90.61	109.92
10.5	76.46	89.22	90.18	109.40
10.75	75.42	88.97	90.09	108.90
11	74.86	88.47	89.40	108.19
11.25	74.21	87.78	88.72	107.58
11.5	73.65	86.68	87.71	106.88
11.75	73.02	85.77	86.68	106.00
12	72.63	85.35	86.18	105.03
12.25	72.14	84.78	85.60	104.05
12.5	71.28	84.27	84.94	103.08
12.75	70.72	83.53	84.18	102.33
13	70.32	83.61	84.02	101.28
13.25	69.85	83.12	83.70	100.44
13.5	69.46	82.96	83.70	99.61
13.75	69.37	82.20	82.87	98.87
14	69.22	81.46	81.97	98.13
14.25	69.06	80.49	80.98	97.32
14.5	68.11	79.75	80.33	96.49
14.75	68.04	79.59	80.10	95.61
15	67.55	79.11	79.52	94.80
15.25	67.64	78.06	78.55	93.92
15.5	67.32	78.22	78.55	93.04
15.75	67.17	77.02	77.25	92.25
16	66.85	77.25	77.41	91.47
16.25	66.45	76.93	77.09	90.77
16.5	66.22	76.78	77.02	90.00
16.75	66.15	76.30	76.53	89.49
17	66.15	76.53	76.78	88.90
17.25	65.89	75.90	76.14	88.29
17.5	65.66	75.33	75.58	87.78
17.75	64.96	74.46	74.86	87.19
18	64.72	73.42	73.65	86.68
18.25	64.40	73.02	73.26	86.02
18.5	64.08	73.26	73.51	85.44
18.75	63.93	72.86	72.86	84.85
19	63.61	72.30	72.39	84.36
19.25	63.30	71.74	71.91	83.86
19.5	62.82	71.35	71.51	83.28
19.75	62.65	71.04	71.04	82.78
20	62.82	70.88	70.72	82.20

Hour	Outside Temp	Cooler Floor Temp	Cooler Lid Temp	Cylinder Temp
20.25	62.51	70.72	70.65	81.72
20.5	62.42	70.88	70.81	81.23
20.75	62.42	70.95	70.88	80.82
21	61.72	70.32	69.22	80.42
21.25	61.39	68.67	67.95	80.10
21.5	62.58	68.50	68.59	79.52
21.75	61.72	68.27	68.59	79.11
22	61.86	67.95	68.43	78.78
22.25	61.95	67.80	68.34	78.39
22.5	62.11	67.55	67.80	78.06
22.75	62.51	67.01	67.24	77.74
23	64.80	66.85	66.78	77.41