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DEVELOPING CRITERIA FOR PERFORMANCE-BASED CONCRETE SPECIFICATIONS

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COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

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16. Abstract

For more than 50 years now, concrete technology has advanced, but CDOT specifications for durability have remained mostly unchanged. The minimum cement content for a given strength is derived from mix design guidelines that were developed before water reducing admixtures were widely used and accepted. The minimum cement content generally controls the mix design process, with many mix designs exceeding the minimum strength requirements by 500 to 1,000 psi. Ready mix suppliers that supply to non-CDOT projects have developed mix designs that use less cement and more fly ash than CDOT mix designs and exceeded their strengths. They are able to accomplish this improvement through gradation optimization and admixture combinations. The proposed study tested current CDOT standard mix designs to determine minimum required performance criteria that will be used to develop performance-based concrete mix design criteria.

Implementation

The product of this research will provide the CDOT Materials and Geotechnical Branch with criteria that can be used in the development of performance-based concrete mix design specifications. The use of performance-based specifications would allow ready mixed concrete suppliers to optimize the materials used in creating mix designs. This materials optimization can lower cement content and increase fly ash content that would lead to reduction of costs and concrete carbon footprints in CDOT construction projects.

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EXECUTIVE SUMMARY

Many of CDOT's concrete mixture requirements are based on durability studies performed in the 1940's and 1950's. In the past 50 years concrete technology has advanced and the majority of CDOT's specifications have remained unchanged. The concrete mixture requirements are generally governed by minimum cement content for a given class of concrete. These minimum values generally yield concrete strengths in excess of design compressive strengths on the order of 500 to 1,000 pounds per square inch (psi). Local ready mix suppliers who supply concrete to non-CDOT projects have developed mixtures that exceed CDOT strength specifications with less cement and more fly ash. Typically this is accomplished through the use of gradation optimization and admixture combinations.

Prescriptive specifications set boundaries on specific items in the concrete mixture. For example, a water-to-cementitious materials ratio (w/cm) range of 0.38 to 0.42. This specification is prescriptive based because the concrete mixture designer cannot go outside of these limits. Generally these limits are specified to give the engineer of record the confidence that the concrete mixture will have adequate strength and durability, for instance. However, if the concrete mixture can be shown to have the same level of strength and durability while being outside the specified w/cm ratio, the concrete mixture should still be acceptable.

A comprehensive literature review started the research with finding and evaluating the previous work that had been performed on performance-based concrete. Then various CDOT Classes D and P concrete mixtures were selected from the CDOT concrete mixture database. Fifteen concrete mixtures were selected based on location around the state and various materials, ingredients, and proportions. These mixtures were then batched and tested within the concrete laboratory at the University of Colorado at Denver. Each of the mixtures was then evaluated and analyzed for data trends.

Actual results found exhibit variations, but did not leave linear trends between two variables as expected. Results can be found in the appropriate sections. These variations in test result data made the development of recommendations for performance-based criteria difficult.

The information herein will aid the CDOT in the development of performance-based criteria for their concrete specifications. These specifications should first be implemented using pilot projects and monitored very closely prior to full implementation or adoption as CDOT project special provision and hopefully as a standard specification.

Further research should be performed in the areas of developing performance-based criteria for alkali-silica reaction and sulfate resistance. Once these items can be determined, performance specifications can be determined for other classes of concrete. Performance-based specifications will hopefully allow concrete designers the ability to reduce the overall cost of the concrete mixture, thereby reducing the bid cost for CDOT projects. With lower construction costs, more CDOT projects could be constructed each year. Better quality concrete produced through performance-based specifications can potentially reduce maintenance and repair costs as well.

Implementation Plan

CDOT should use the information contained within this report to develop preliminary performance-based specifications for Classes D and P Concrete mixtures. These preliminary specifications should be used as an alternative to traditional specifications for pilot projects around the state. The contractor should be able to bid on the project under the new specifications and should be given adequate time to address the new specifications. More time allowed for the development of the concrete mixtures for the project will ultimately provide for more complete data and a more successful project. Concrete suppliers will be required to provide the CDOT with adequate information verifying their concrete mixtures meet the prescriptive requirements for alkali-silica reaction and sulfate resistance.

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1. INTRODUCTION

1.1. Background

The CDOT *Standard for Road and Bridge Construction* specification guide section 601 – Structural Concrete lists the current requirements to be met by various concrete classes. Each class is set for different uses of concrete, the general requirements for two types of concrete are listed in Table 1. CDOT Classes D and P concrete mixtures that were chosen for their relatively low risk applications among these classes of concrete are used. Concrete mixtures used in the research study were selected by CDOT.

Table 1.1. CDOT Table 601-1 CONCRETE TABLE

Concrete Class	Required Field Compressive Strength (psi)	Cementitious Content: Minimum or Range (lbs./cy)	Air Content: % Range (Total)	Water to Cementitious Content Ratio: Maximum
D	4500 at 28 Days	615 to 660	5 – 8	0.45
P	4200 at 28 Days	660	4 – 8	0.44

CDOT Class D concrete is a medium dense structural concrete. Typical uses include: bridge decks, median barriers, box culverts, and other minor structures at various locations where needed. Maximum aggregate size is ¾-inch, and usually contains 55 percent coarse aggregate when placed in a bridge deck.

CDOT Class P concrete is used in pavements. Concrete within this class are typically designed at low slumps for use in slip-form paving machines or curb and gutter machines. Alternatively, higher slumps can be used when concrete will be placed by hand-set. Maximum aggregate sizes range from 1 ½ to ¾-inch depending on placement types. Flexural strengths of the pavement concretes are specified as 650 psi in the laboratory. Flexural strength of 650 psi comes from pavement design calculations used to withstand the repeated loading and unloading of vehicles as they pass over the pavement surface. Experience, pavement durability, and life span of the structures have kept the design value at 650 psi.

Additional information regarding specific details of Class D or Class P concrete mixtures can be found in the CDOT concrete specifications section of the Roadway Design Manual.

Concrete mixtures are required by CDOT to be designed for a sulfate Class 2 exposure unless other testing can show a less severe exposure limit is applicable. Sulfate Class 2 exposure is defined as soils containing 2.00 percent water-soluble sulfate (SO_4) or less. Concrete mixture requirements include a maximum w/cm ratio of 0.45 and the cementitious material must conform to one of the following:

(1) ASTM C 150 Type V with a minimum of a 20 percent substitution of Class F fly ash by weight.
(2) ASTM C 150 Type II or II with a minimum of a 20 percent substitution of Class F fly ash by weight. The Type II or III cement shall have no more than 0.040 percent expansion at 14 days when tested according to ASTM C 452.
(3) ASTM C 1157 Type HS; Class C fly ash shall not be substituted for cement.
(4) ASTM C 1157 Type MS plus Class F fly ash where the blend has less than 0.05 percent expansion at 6 months or 0.10 percent expansion at 12 months when tested according to ASTM C 1012.
(5) A blend of portland cement meeting ASTM C 150 Type II or III with a minimum of 20 percent Class F fly ash by weight, where the blend has less than 0.05 percent expansion at 6 months or 0.10 percent expansion at 12 months when tested according to ASTM C 1012.
(6) ASTM C 595 Type IP(HS); Class C fly ash shall not be substituted for cement.

Current CDOT minimum specifications for cementitious content and fly ash levels currently exceed required design strengths. These minimum cementitious contents, w/cm ratio, and fly ash contents were based on durability studies performed 50 to 60 years ago. These studies were performed before the widespread usage of chemical admixtures and improved cement manufacturing. The current concrete industry trend has been towards concrete mixture optimization with the usage of special chemical and mineral admixtures. These “optimized” concrete mixtures have been used on other non-DOT projects with reduced cementitious contents performing satisfactorily under service conditions.

1.2. Study Objectives

Develop testing criteria that will be implemented to ensure concrete conformance to project specifications. A set of test methods will be recommended for implementation along with test result criteria. These test methods and performance requirements will replace the current prescriptive concrete mixture requirements for Classes D and P concretes in Colorado, allowing concrete producers the ability to optimize concrete mixtures without strict adherence to prescriptive methods.

Current prescriptive methods give the designer reasonable assurance the concrete mixture will perform as intended under service conditions. These prescriptive limits are based on research performed before modern concrete mix specification and construction practice. If concrete mixtures are accepted based on results from standard test methods, this provides data applicable to pavement durability and performance. Ultimately, performance-based specifications will provide better assurance of durable in-place concrete.

1.3. Scope of Study

Numerous CDOT pre-approved concrete mixtures were batched and tested under laboratory conditions. The plastic and hardened concrete properties were performed on each of these mixtures in an effort to identify controlling test methods and results. Data gathered from the test results was analyzed and recommendations are generated on the appropriate test methods and acceptance criteria to use.

2. LITERATURE REVIEW

A literature review was performed on applicable research performed by others that may be useful in developing performance-based concrete mixture specifications.

Unlike a prescriptive specification that defines a concrete mixture in terms of its constituents and their proportions, a performance specification defines a concrete mixture in terms of measurable plastic and hardened properties that show the mixture will satisfy certain performance criteria (Bickley, et al 2006). An example of this can be seen from specifying compressive strength. A certain level of compressive strength can be specified without requiring specific material constituents or proportions to obtain that compressive strength level. Compressive strengths are widely used as performance specifications by state and local agencies, to larger governing bodies like the American Concrete Institute and Federal agencies.

An increasingly popular concrete mixture optimization technique has been to use aggregates that create a "well-graded" material. This idea is not a new concept, where the origins date back to William Fuller and Sanford Thompson's text regarding proportioning concrete written in 1907. These ideas seem to fall slightly by the wayside as time went on, until James Shilstone's work in the 1990's. Since Shilstone's work there have typically been three methods for optimizing concrete aggregates to obtain a well-graded blend.

2.1. Well-Graded Aggregate Blend

A well-graded aggregate blend is a mixture that contains little to no void spaces. This concept is best visualized as a clear jar full of spherical balls, and between each of the balls is a void space. These void spaces are then filled with smaller spherical particles, and the void spaces between them is filled with even smaller particles. This process will continue so that the void spaces from the larger particles are successively filled with smaller particles. A visualization of "well-graded", uniform graded and gap-graded aggregate blends are shown below in Figure 2.1.

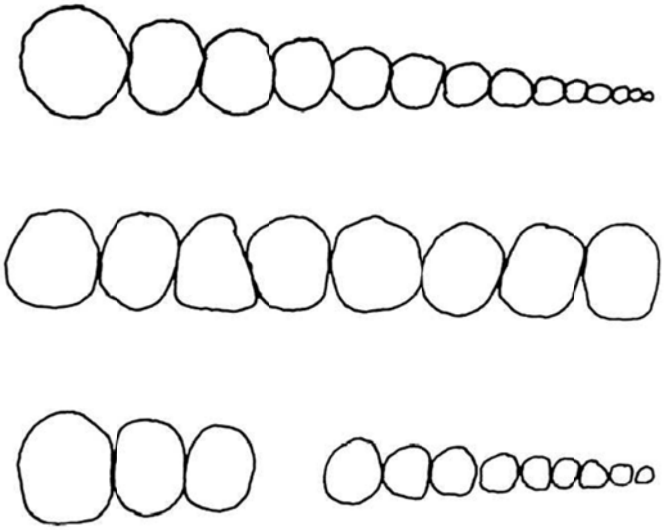


Figure 2.1. Well-Graded, Uniform Graded, and Gap Graded Aggregates.

There are several methods of determining if an aggregate blend is well-graded, or gap-graded. Traditional concrete is typically made with 1-inch or ¾-inch nominal maximum coarse aggregate and concrete sand. The combination of these two materials results in large aggregate particles and small particles with no material in between, creating a gap-graded aggregate blend. If concrete is made with aggregates that bridge the gap between the coarse and fine aggregate fractions, it would create a well-graded aggregate blend. Gradation testing can be performed on the combined aggregates used in the concrete mixture and the test results are plotted on various types of graphs to analyze whether the material is well-graded, or gap-graded. The most commonly used methods for analyzing the combined aggregate blends used in concrete have been the 0.45 power curve, coarseness and workability factor charts, and the “8-18” chart.

2.1.1. 0.45 Power Curve

The 0.45 power curve is a graphical representation of the individual sieve sizes raised to the 0.45 power. This allows a straight line to be drawn from the 100% passing of the largest nominal aggregate size down to 0% passing at the #200 sieve. The various other individual size percentages passing each sieve is plotted and analyzed to see how the graph follows along the straight line drawn. This can be shown below in Figure 2.2.

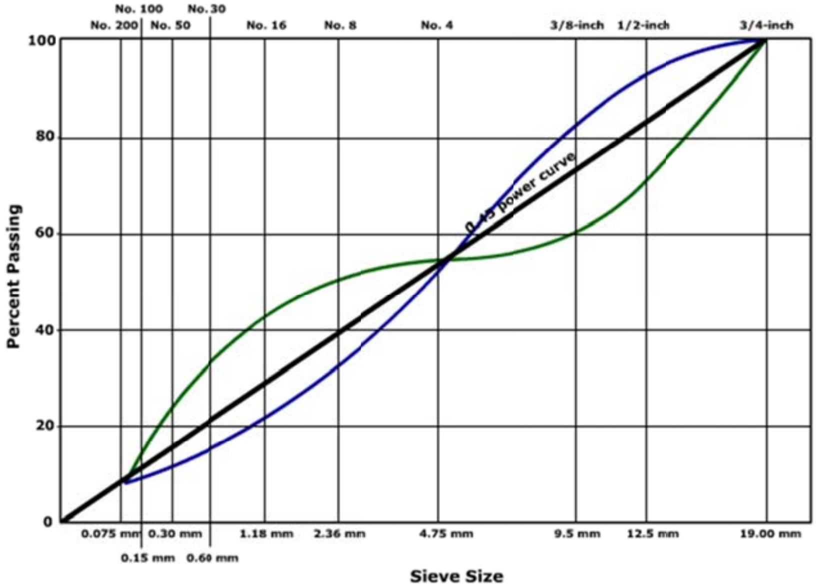


Figure 2.2. 0.45 Power Curve (FHWA, Pavement Interactive).

The straight line labeled as 0.45 power curve on the graph above represents the maximum density line. If a ¾-inch nominal maximum aggregate material were to have a gradation that followed along the black line it would have no space available in the matrix to allow for additional material, it would be as dense as it could possibly be. The green line represents a typical gap-graded aggregate blend when plotted on the graph, while the blue line indicates a well-graded aggregate blend.

2.1.2. Coarseness and Workability Factors

The coarseness factor and workability factor chart is a development from the work done by James Shilstone. The material sizes in the gradation were split into quality, intermediate and workable sizes. The quality size fractions are all the material that is larger than 3/8-inch, the intermediate size fractions is the material passing the 3/8-inch sieve and retained on the #8 sieve size, and the workable size fractions is the material that passes the #8 sieve. Quality size materials are inert filler sizes where generally more is better. These material sizes reduce the need for mortar that shrinks and cracks (Shilstone, 1990). The intermediate particle sizes fill major voids and aid in mix mobility, if these particles are elongated and sharp, they become interference particles and contribute to mixture harshness (Shilstone, 1990). The minus #8 sieve fraction provides the mixture with workability. These particles act as ball bearings by providing reductions in “friction” just as machinery uses them.

Using the quality, intermediate, and workable fractions of aggregate materials it is important to have them proportioned in a way that provides the optimum gradation. The coarseness and workability factors were created to mathematically and graphically illustrate the degree of coarseness and workability a given aggregate gradation would give a concrete mixture. The coarseness factor is represented by the amount of +3/8-inch material over all the material greater than the #8 sieve size. This calculation is shown below.

$$CF = [Q / (Q + I)]$$

Calculation of the workability factor is the percentage of material passing the #8 sieve size. The relationship between the coarseness factor and the workability factor is plotted graphically with the coarseness factor on the X-axis while the workability factor is plotted on the Y-axis. An example of this chart is shown below in Figure 2.3.

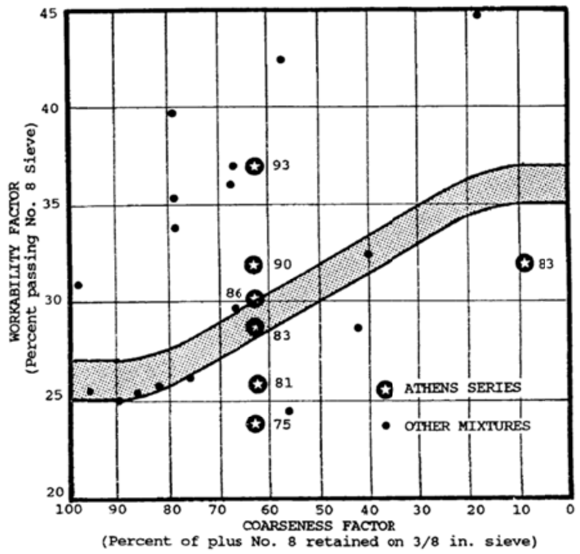


Figure 2.3. Coarseness and Workability Factor Chart (Shilstone, 1990).

A balance must be achieved between the amount of fine and coarse aggregates in a concrete mixture, which is illustrated by the gray trend bar shown above in Figure 2.3. Due to the nature of the calculation for the coarseness and workability factors it is possible to have individual material constituents that have adequate coarseness and workability factors but lack adequate size distribution. An example of this is best explained where a sand has 100% passing the 3/8-inch sieve size, but 100% retained on the #16 sieve size. This material may have calculated coarseness and workability factors that are acceptable, where the material itself will not be due to the one or possible two sieve sizes that contain material and will not fill void spaces. Due to this fact it is important to analyze the material on an individual sieve size basis and determine if there is adequate material of each size fraction.

The coarseness and workability factor chart used above has seen some modifications where differentiation has been made for different nominal maximum aggregate sizes as well as sandy and rocky zones. The new chart is separated into five zones, listed below:

- Zone I – This zone represents a coarse gap-graded aggregate with a deficiency in intermediate particles (passing the 3/8-inch) sieve and nominally retained on the No. 8

sieve). The aggregate with a gradation in this zone has a high potential for segregation during concrete placement.

- Zone II – This is the optimum zone for concrete mixtures with nominal maximum size from 1.5 inches through ¾-inch.
- Zone III – This is an extension of the Zone II mix for finer mixtures with nominal maximum size less than ¾-inch.
- Zone IV – Concrete mixtures in this zone generally contain excessive fines, with high potential for segregation during consolidation and finishing.
- Zone V – This is a mixture with too much coarse aggregate, which makes the concrete unworkable.

These zones are represented on the modified coarseness and workability factor chart shown below in Figure 2.4. Most concrete mixture applications will fall into zone II.

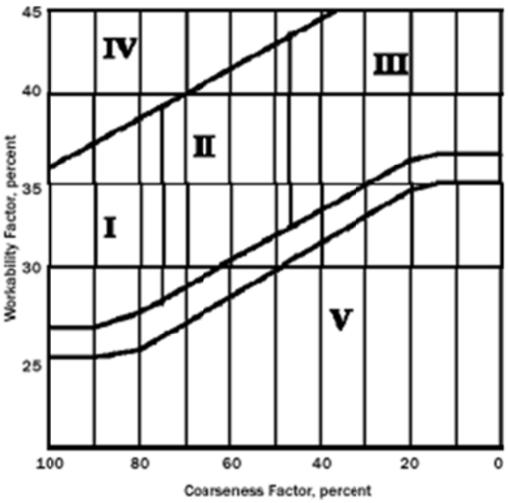


Figure 2.4. Modified Coarseness and Workability Factor Chart.

This chart has been employed in some state DOT's and the Army Corp of Engineers for acceptance testing of concrete mixtures. Examples of these can be found below in section 2.3.

2.1.3. Individual Percent Retained

To evaluate each individual sieve size fraction it is possible to calculate the individual percent retained and plotted graphically to analyze. According to Shilstone, an optimum gradation would have a "haystack" configuration. This optimum gradation would have the approximate shape shown in Figure 2.5 below.

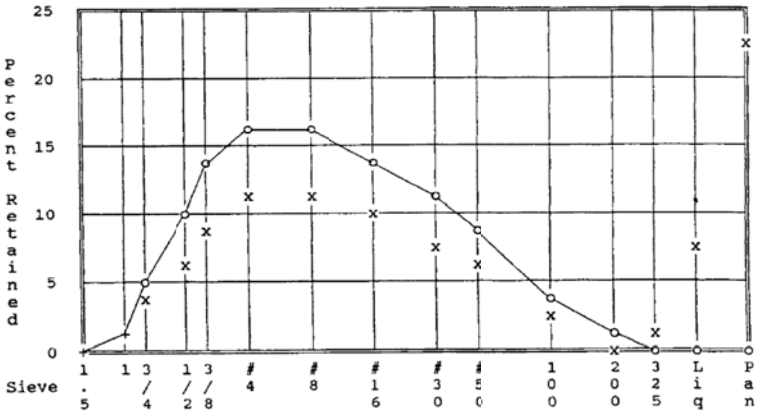


Figure 2.5. Optimum Graded Mixture (Shilstone, 1990).

Concrete made with practically any sound aggregate can be combined to produce a given strength (Shilstone, 1990). However, poor particle distribution can cause problems in concrete mixtures. Some deficient sieve sizes can necessitate the use of more mortar, placing and finishing problems, etc (Shilstone, 1990). Figure 2.6 below illustrates a near gap graded mixture on the individual sieve size graph.

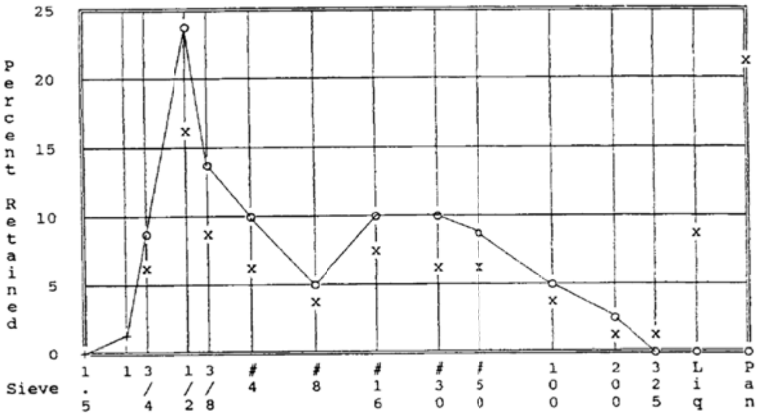


Figure 2.6. Gap Graded Mixture (Shilstone, 1990).

The above graph clearly indicates the deficiency of material on the #8 sieve size, and the surplus of material on the ½-inch sieve size. To obtain a well-graded mixture using the above materials, the addition of an intermediate aggregate size such as a pea gravel or similar. Using the above materials with the addition of a pea gravel the material particle distribution is now shown below in Figure 2.7.

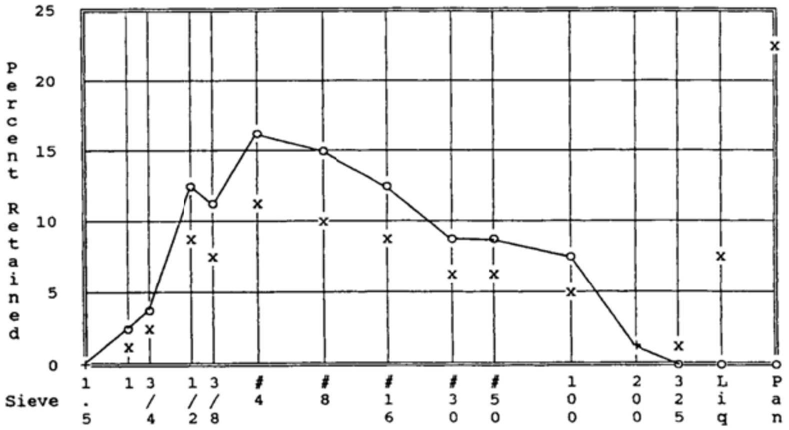


Figure 2.7. New Combined Gradation (Shilstone, 1990).

The gradation shown above is considered acceptable for the optimum combined aggregate gradation. It is also critical to realize that there may be some "peaks and valleys" in the haystack gradation where there may be a slight deficiency on a sieve or abundance on a sieve size. These are considered acceptable and deficiencies can be compensated by abundances, and vice versa. A deficiency on one sieve size fraction can be compensated by an abundance on an adjacent sieve size, and two deficient sieve size fractions can be compensated by two abundant sieve size fractions on two adjacent sieve sizes.

Shilstone concluded from his work on the coarseness and workability factors:

- That for every combination of aggregates mixed with a given amount of cementitious materials and cast at a constant consistency, there is an optimum combination which can be cast at the lowest water-cement ratio and produce the highest strength.
- The optimum mixture has the least particle interference and responds best to a high frequency, high amplitude vibrator.

- The optimum mixture cannot be used for all construction due to variations in placing and finishing needs.

The individual percent retained chart has also seen some modifications where upper and lower limits have been placed on the range of amounts of material retained on each individual sieve size. Typically the limits placed on each sieve size is greater than eight percent and less than 18 percent, hence the commonly use name “8-18” band. This is shown below in Figure 2.8.

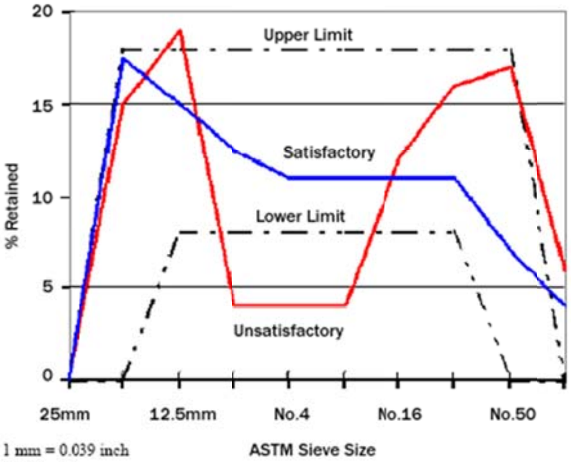


Figure 2.8. “8-18” Band.

From the graph above it can be seen where the upper and lower limits, satisfactory and unsatisfactory gradation plots. The red line indicates an unsatisfactory gap graded gradation, and the blue line indicates a satisfactory gradation. Each governing agency that uses this chart can use these limits, or specify other limits or modifications. This information can be found below in other sections.

2.1.4. Combined Fineness Modulus

When aggregates are tested for gradation limits, the fineness of the material can be calculated. This fineness modulus mathematically illustrates the relative coarseness or fineness for a given gradation, where higher numerical answers are aggregates that are more “coarse” and vice versa.

According to the Kansas University concrete mixture optimization program (KU beta mix) the following limits on the combined aggregate gradation yield the following results:

- Fineness modulus >4.75 yields an over-sanded concrete mixture
- Fineness modulus between 4.75 and 5.5 is appropriate for most applications
- Fineness modulus >5.5 yields a harsh mixture that can lack proper consolidation

The KU beta mix is based on the principles set forth in Shilstone's methods above, while applying optimization methodology in a software program.

2.2. Current CDOT Performance Specifications

The CDOT currently uses some performance tests and criteria when evaluating concrete mixtures for acceptance both in the initial laboratory phase and for project acceptance. Concrete compressive strength is widely used and accepted method for concrete mixture acceptance. Currently all CDOT concrete mixtures have minimum required field compressive strengths. These field compressive strengths are required to have a 15% overdesign when developed in the laboratory. These field compressive strengths range from 4,200 pounds per square inch (psi) to upwards of 7,250 psi. Direct flexural strength is also evaluated for concrete mixture acceptance by the ASTM test method C 78 Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). This test method is used in concrete paving mixtures that are created in the laboratory and used for acceptance on projects that have elected to use concrete mixtures with a reduced total cementitious content.

CDOT's concrete classification of “H” and “HT” are concrete mixtures typically used for concrete bridge decks that will not receive a waterproofing membrane and specify performance criteria (CDOT, 2005). These concrete mixtures must be tested in accordance with ASTM test method C 1202 Electrical Indication of Concretes Ability to Resist Chloride Ion Penetration and also the ASTM test method C 1581 or AASHTO T 334 Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete under Restrained Shrinkage. The rapid chloride ion penetration (RCP) test ASTM C 1202 has a specified limit of 2000 Coulombs passed during the test. The restrained shrinkage test has a specified test result where the concrete does not exhibit a crack before 14 days of age. These test methods allow for different variations to achieve the same basic outcome and are considered end-result tests.

The above specified performance test methods give CDOT confidence that the bridge deck concrete will have the required durability characteristics needed for adequate life-cycle in the weather conditions the concrete will experience. The chloride ion penetration test is an indicator of permeability (NRMCA 2007). Because the test gives an indication of the concrete's permeability, it is specified for bridge deck mixtures so that the concrete will have reasonable assurance it will resist intrusion of chlorides or other harmful materials. The restrained shrinkage test examines the concrete's shrinkage characteristics while under restraint from rebar, earthen subgrade, or other similar item. Concrete bridge decks encounter restraint from the reinforcement as well as the bridge superstructure (Cavaliero, 2010, pg. 10). Specification of the restrained shrinkage test provides information on the concrete mixtures ability to resist cracking in restrained environments. If cracking can be reduced or reasonably eliminated, it provides limited pathways for deleterious materials to permeate into the concrete, thereby increasing durability and life-cycle.

These are only examples of the currently used performance-based specifications by the CDOT. Currently all concrete mixtures for the CDOT are based on prescriptive specifications or limits.

2.3. Other DOT Performance Specifications

The Colorado DOT is not the only state department that is using performance-based concrete specifications. Florida, Iowa, Kansas, Missouri, Oklahoma, and Texas have all used some kind of performance specification. Performance specifications in these states typically focus on creating a well-graded aggregate mixture for use in concrete. Other performance criteria used can be found below in Table 2.1.

Table 2.1. State DOT Performance Criteria.

State DOT	Compressive Strength	Flexural Strength	Permeability	Shrinkage	Aggregate Gradations
Colorado	X	X	X	X	
Florida	X		X		
Indiana	X				X
Illinois	X				X
Iowa	X		X		
Kansas	X	X			X
Minnesota	X				X
Missouri	X				X
Oklahoma	X	X			X
Tennessee	X				X
Texas	X				X
Virginia	X		X*		
Washington	X				X
Wisconsin	X				X

*****Employed in pilot project only

2.3.1. Florida

The Florida DOT also has prescriptive concrete mixture requirements and specifications according to the class of concrete. These classes of concrete range from Class I to Class VI, with varying uses and compressive strength levels for each one. Performance specifications included in the Florida DOT concrete specifications include a test entitled “Concrete Resistivity as an Electrical Indicator of its Permeability (Test method FM 5-578)”, in the higher compressive strength concrete classes. The FM 5-578 is specified to ensure low permeability in those concrete classes. This test method is similar to the rapid chloride ion penetration test, except that the test apparatus is placed on the outside of the concrete cylinder and readings are taken on the surface. This test method provides faster results and comparable to the rapid chloride ion penetration test.

In 2002, a report was released to the Florida Department of Transportation regarding the use of concrete mixture optimization to enhance the durability and life-cycle cost optimization. The coastal region of Florida has very severe conditions for concrete to withstand, coupled with a minimum 75 year design life-cycle, poses a tall order for concrete bridge structures. Cores taken from the structures that see daily chloride exposure, just above the splash-zone of the saltwater spray, were analyzed for chloride ion ingress. Results from the cores showed the only chloride ions were contained within the paste of the concrete matrix. This lead to the hypothesis that a well-graded aggregate blend would minimize the paste content reducing the deleterious effects of the chloride ions.

The research program involved designing a well-graded aggregate concrete mixture and a typical gap-graded aggregate mixture, and testing them for chloride ion ingress as per a wet chemistry method. Results from the research indicate the coarse aggregate pore structure is not a significant factor where concrete durability and service life are controlled by chloride induced reinforcement corrosion. This finding suggests that the Iowa Pore Index and mercury porosimetry results are not useful for qualifying or characterizing coarse aggregates for such service (Hart et al, 2002). Conclusions also drawn from the research were that coarse aggregates did act as an impediment to the ingress of chloride ions into the concrete matrix, and a dense aggregate blend would limit these destructive effects.

Another research study performed in Florida analyzed the effects of well graded aggregate blends on the drying shrinkage, water demand and compressive strength. The aggregates were blended according to the “8-18” band, and evaluated for the above properties. The results of the research indicated that the well graded aggregate concrete mixture did not exhibit lower water demand, lower shrinkage or higher compressive strength. Additionally, the researchers suggest that the design professional should state the desired concrete properties and allow the concrete producer to achieve this result using locally available materials (McCall et al, 2005).

2.3.2. Iowa

Iowa DOT has various concrete mixture classes, and within each class various absolute volumes are specified. The specifications are very prescriptive based, with very few exceptions as of the 2009 revision of the construction specifications. Developmental specifications have been put forward for specific projects where workability, compressive strength, and permeability are specified. These specifications are individual project specific, and still call out specific absolute volumes of concrete mixture proportions. The desired “workability” specification is somewhat arbitrary and is based on ease of place-ability.

Concrete paving in Iowa is governed by the coarseness and workability factor chart. Zone II of the chart is split into smaller sections, and based on where the gradation falls for the day’s production dictates the pay rate for that section of pavement. Iowa DOT bases the pay factors on what gradation range they believe will provide the best potential for constructing a smooth pavement. The coarseness and workability factor chart is considered the primary method to be used for developing the combined gradation (Richardson, 2005). The “8-18” and the power 0.45 charts are considered to be used for identifying areas that deviate from a well-graded aggregate.

2.3.3. Kansas

Kansas employs various classifications for concrete mixtures that are broken out by specific usage. Each of the concrete mixtures has varying compressive strength levels for performance specifications. These compressive strengths typically range from 3,000 psi and up, with flexural strengths at 600 psi in seven days. In addition to the compressive and flexural strength performance specifications, Kansas DOT allows aggregates to be graded for optimization according to ACI 302 or similar. With the optimized aggregate grading, the Kansas DOT also specifies the range of percent passing for certain sieve sizes depending on the usage of the concrete mixture.

2.3.4. Missouri

The state of Missouri uses varying compressive strengths for different concrete uses. These compressive strengths range from 3,000 psi to 6,000 psi, with typical concrete strengths in the range of 3,000 psi to 4,000 psi. Missouri does allow for aggregate optimization by the Shilstone method, or other recognized aggregate optimization method. No other performance specifications were located in the current construction specification manual at the time of publication.

2.3.5. Oklahoma

Concrete classifications follow specific usage categories as determined in contract documents or according to general use found in Oklahoma DOT material specifications. These classes are broken down also by compressive strength levels, where typical compressive strength ranges from 3,000 psi to 4,000 psi. Flexural strength performance specification is required in addition to compressive strengths for pavement mixtures where these mixtures must attain 650 psi flexural strength in 28 days, or 700 psi in 56 days. Specifications updated for the 2009 year did not include any other performance specifications. A standard test method (OHD L-52) from the Oklahoma DOT did include an *Aggregate Proportioning Guide For Optimized Gradation Concrete Mix Designs.* This document is not a specification, but covers a procedure for developing well-graded aggregate combinations for use in concrete paving. Within the document it states that well graded aggregate blends reduce the water demand, provide and maintain adequate workability, require minimal finishing and consolidate without segregation (OklaDOT, 2006). This document also places the responsibility on the mix designer of designing a proper concrete mixture with the appropriate properties for the intended application and placement method. The guide employs the coarseness and workability factors chart as the main way of determining the overall mixture, and secondarily the 0.45 power curve and the “8-

18” band to analyze individual material sizes for proper conformance to being well-graded. The mixture must plot in Zone II of the coarseness and workability factors chart for concrete paving. If the mixture falls outside of this zone, it will be rejected.

2.3.6. Texas

Texas DOT uses concrete mixture classifications broken out by usage and compressive strength. The compressive strength levels typically range from 3,000 psi to 4,500 psi, and other strength levels can be specified by contract documents. As of the 2004 specification book, compressive strength is the only performance criteria. In 2006 the Texas DOT did have a test procedure for *Optimized Aggregate Gradation for Hydraulic Cement Concrete Mix Designs* (Tex-470-A). This test method covers using individual aggregates combined to create an optimized blend. The test method requires individual gradations to be submitted for each material, mathematically combined gradation, coarseness and workability factors chart, 0.45 power curve, and an individual sieve size percentage retained chart. Additionally, the test method covers how to calculate each of these items.

2.3.7. Utah

The Utah Department of Transportation has had several bridge projects where performance concrete mixtures were used. The specifications were developed by a report from the University of Utah, Department of Civil Engineering. Within the report, it is made necessary to have a “decision tree” where based on certain questions, the exposure levels applicable to the concrete are determined. “Decision trees” presented from the University of Utah are shown below in Table 2.2. The “decision tree” works from left to right using a series of questions, and is somewhat similar to the various exposure levels presented in ACI documents 301, 318, and 201.

Table 2.2. Example of "Decision Tree" for Performance Grade Levels

SH Shrinkage	Is the concrete exposed to moisture, chloride salts or soluble sulfates environments?	YES	Is the member constructed without joints?	YES	Member designed to be watertight / crack free?	YES. Use SH- Grade 3
						No. Use SH- Grade 2
				No. Use SH- Grade 1		
		No. SH grade should not be specified.				
SU Sulfate Resistance	Is the concrete exposed to more than 0.10 percent soluble sulfates?	YES	Member exposed to more than 0.20% soluble sulfates?	YES	Member exposed to wet-dry cycles?	YES. Use SU- Grade 3
						No. Use SU- Grade 2
				No. Use SU- Grade 1		
		No. SU grade should not be specified.				
CP Chloride Penetration	Is the concrete exposed to chloride salts or soluble salts?	YES	Is the member exposed in a potentially moist environment?	YES	Member subjected to wet / dry cycling?	YES. Use CP- Grade 3
						No. Use CP- Grade 2
				No. Use CP- Grade 1		
		No. CP grade should not be specified.				
CS Compressive Strength	Is the concrete structural or a pavement?	YES	Member a slender column or prestressed beam?	YES	Member optimized for high strength?	YES. Use CS- Grade 3
						No. Use CS- Grade 2
				No. Use CS- Grade 1		
		No. CS according to drawings.				
FT Freeze Thaw Durability	Is the concrete exposed to freezing and thawing environments?	YES	Is the member exposed to deicing salts?	YES	Member saturated during freezing?	YES. Use FT- Grade 3
						No. Use FT- Grade 2
				No. Use FT- Grade 1		
		No. FT grade should not be specified.				
AS Alkali Silica Reaction Durability	Does the concrete contain reactive aggregates?	YES	Is the concrete exposed to moisture?	YES	Member saturated during freezing?	YES. Use AS- Grade 3
						No. Use AS- Grade 2
				No. Use AS- Grade 1		
		No. AS grade should not be specified.				
SD Strength Ratio	Concrete to go into service after a minimum of 7 days after being cast?	YES	Member benefit from long-term strength gain?	YES	Member greater than 3 feet in thickness?	YES. Use SD- Grade 3
						No. Use SD- Grade 2
				No. Use SD- Grade 1		
		No. SD grade should not be specified.				

Once the exposure level, or grade, is determined, a set of performance criteria applicable to that exposure condition is applied. These levels vary depending on how extreme the exposure levels are, and are presented below in Table 2.3:

Table 2.3 Grade Levels from Decision Tree.

Performance Property	Test Method	Grade 1	Grade 2	Grade 3
Chloride Penetration	AASHTO T 277	4000≥X>2500 Coulombs	2500≥X>1500 Coulombs	1500≥X Coulombs
Compressive Strength	AASHTO T 22	3500≥X>4600 psi	4600≥X>8000 Psi	8000≥X psi
Shrinkage	ASTM C 157	800≥X>500 microstrain	500≥X>200 Microstrain	200≥X microstrain
Freeze Thaw	AASHTO T 277	60%≤X≤80%	80%≤X≤90%	90%≤X
ASR Mitigation	ASTM C 1567	<0.20% @ 14 days	<0.10% @ 14 days	<0.10% @ 28 days
Strength Ratio	ASSHTO T 22	1.15 28/7 Day f_c	1.33 28/7 Day f_c	1.45 28/7 Day f_c
Sulfate Resistance	ASTM C 1012	X<0.10% @ 6 months	X<0.10% @ 10 months	X<0.10% @ 18 months

2.3.8. Virginia

The Virginia Department of Transportation has had some pilot projects where end-result specifications (ERS) were employed. ERS projects included bridge deck and substructure concrete, as well as concrete pavements. Responsibility was shared between the contractor/producer and the acceptance agency. The contractor/producer has the authority to prepare concrete mixtures and is expected to take responsibility for performance. Acceptance, rejection, or applying a pay adjustment depending on varying degrees of compliance is up to the acceptance agency.

ERS considers the concrete in both the plastic and hardened state. Plastic properties tested were the slump, air content, unit weight and temperature. Hardened properties considered were the compressive strength and permeability. Within the ERS special provision, it includes process control measures (QC plan by the contractor applicable to preconstruction and during construction), concrete mixture design approval, and acceptance. The process control measures should include:

- personnel, equipment, supplies and facilities
- Ingredients
- Concrete mixture designs
- Sampling, type of test and frequency
- Certified technicians
- Complete record of tests

Concrete mixtures are then submitted for review and project acceptance. Documentation shows the requirements are met, using past experience and trial batches. Acceptance of concrete mixtures involves screening tests on the plastic concrete by the contractor, pay factor tests are based on hardened concrete, and is accepted on a lot-by-lot basis. Lots are limited to 500 cubic yards and consist of sub-lots with a maximum of 100 cubic yards in each sub-lot (minimum one sub-lot for each days placement). Acceptance is a compressive strength of 4000 psi and a rapid chloride permeability (ASTM C 1202) maximum value of 2500 coulombs using the accelerated cure method. In order to evaluate the compliance of the concrete supplied, the test results are plotted on control charts showing each individual test result, and the moving average of three results. Plastic property test results are plotted individually on control charts for tracking of the concrete mixture. Combined aggregate gradation concrete paving mixtures were used on one project where the aggregate did not meet the gradation requirements set forth in ASTM C 33. The aggregate did meet applicable durability requirements and was combined with other aggregates to meet a well graded blend. This paving concrete mixture did not have gradation tests run during production, instead the permeability was used as the indicator for checking gradation changes.

The pay factors for the projects were not changed, but the new percent within limits (PWL) method was presented to the contractors to indicate the advantages of the new method. Existing pay factors were based on test results being above a certain lower limit. The new PWL method is based on the number of tests that fall within upper and lower acceptance values. 100% pay is obtained for 90% PWL, and the total pay is the average pay factor times the unit bid price plus the additional price adjustment for deficient thickness (pavement) and incentive or disincentive payment for the ride quality.

2.3.9. Wisconsin

Laboratory and field concrete mixtures were examined in a pilot paving project conducted in Wisconsin. Several mixtures were analyzed including gap-graded and optimized aggregate blends. The optimized aggregate blend concrete mixtures, when compared to the gap-graded concrete mixtures, exhibited 15% less water demand to achieve similar slumps, 20-30 percent less air entraining agent was needed to entrain the same amount of air, and less segregation after extended vibration (1-3 min), and the strength increased 10 to 20 percent in the laboratory and 14 percent in the field.

Another Wisconsin DOT study focused on durability with optimized aggregate blend concrete mixtures. The near gap-graded concrete mixtures exhibited compressive strengths 2-14 lower than the control/optimized mixtures, drying shrinkage was 8 percent greater the control/optimized, permeability was 25 percent greater, and showed lower freeze/thaw durabilities (Richardson, 2005).

Wisconsin allows the optimization of the coarse aggregate fraction of the concrete mixture for concrete bridge decks at the discretion of the contractor.

2.4. New York / New Jersey Port Authority

New York / New Jersey Port Authority have been employing performance-based concrete specifications for approximately 20 years. The end result specifications have focused on the concrete mixture meeting certain percentages within specified limits depending on the desired qualities. These qualities typically include strength (compressive or flexural), entrained air content, water content, and permeability. Pay factors for the contractor involve most of the performance tests, except that to receive incentive pay certain test results must fall 100% within limits. Specification limits for the permeability are 1,500 Coulombs (when no calcium nitrite is used) or 2,000 Coulombs (when calcium nitrite is used). Compressive or flexural end result specifications vary depending on the project.

Performance tests used to evaluate concrete pavements include:

- Water in plastic concrete (AASHTO T-318)
- Entrained air in plastic concrete (ASTM C 231)
- Permeability – rapid chloride permeability test (ASTM C 1202)
- Shrinkage (ASTM C 157)
- Bond strength – ACI 503R

These performance criteria are not evaluated with the typical minimum specification limits. Instead, they are evaluated using the “Percent Within Limits” method. Where each test must have so many results within upper and lower boundary limits. The PWL values typically used are summarized below in Table 2.4.

Table 2.4 Performance Test Minimum PWL Values.

Performance Parameters	**Minimum PWL**
Flexural Strength	95
Compressive Strength	95
Permeability	90
Bond Strength	80
Water to Cement Ratio	80
Air Content	70
Pavement Thickness	90
Chloride Content	100

2.5. U.S. Air Force / ACPA

The United States Air Force adopted the coarseness factor concept for its specifications to try and eliminate the joint spalling and surface delamination or raveling of concrete pavements. Specifications require the use of the "8-18" band, the 0.45 power curve, and the coarseness and workability factor chart to analyze the aggregate blend in the concrete mixture.

American Concrete Paving Association (ACPA) has included the importance of having an intermediate size aggregate within the overall aggregate blend. This was discussed in the ACPA Fast Track paving publication (ACPA, 1989).

2.6. NRMCA Prescriptive to Performance Initiative

The National Ready Mixed Concrete Association (NRMCA) has developed the Prescription to Performance (P2P) Initiative. This initiative has several guides for transitioning from the prescriptive concrete specifications that are currently being used in place of a new performance-based system. One of the developed guides offers performance specifications that comply with the basic requirements set forth in ACI documents 318 and 301, with additional specifications that may be of optional consideration depending on job requirements.

Currently used plastic concrete mixture tests are still used in the P2P documents, but instead of specifying minimum cementitious contents, fly ash replacement levels or maximum w/cm ratios, this document places much emphasis on the rapid chloride ion penetration (RCIP) test for evaluation of hardened concrete properties. To address the need to limit the amount of gas or liquid allowed to penetrate into the concrete matrix, ACI 318 limits the maximum allowable w/cm ratio. This specification could be addressed through a specified permeability limit for the RCIP test. The specifying agency would need to list the applicable exposure classes the concrete structure would be subjected while in service, along with the applicable RCIP test limit. Using this test method would be in lieu of the currently used minimum compressive strength levels and maximum w/cm ratio used by ACI currently. A history of test results would be required on the concrete mixture and evaluated for standard deviations in the same way that compressive strength historical data is used when determining the minimum f'_{cr}.

P2P guide also covers the details for ensuring adequate protection against sulfate attack on the concrete, providing adequate corrosion protection for reinforcing steel. To qualify concrete mixtures for sulfate resistance, the RCIP test is used, and where corrosion protection of reinforcing steel is required, the ASTM test method C 1218 *Water-Soluble Chloride in Mortar and Concrete* would be required and have specific limits based on specific exposure classifications.

The guide on the P2P Initiative also includes a section on optional specification provisions. These optional provisions include the bulk density of the fresh concrete, drying shrinkage, modulus of elasticity, creep of concrete, alkali silica reactivity, and abrasion resistance. These specifications can be used when specific job requirements may benefit from the particular test data. This guide also includes performance and prescriptive specifications based on each of the exposure conditions.

2.7. Canadian Standards

Since 2004, the Canadian Concrete Standard A23.1 has required that concrete either be specified with performance or prescriptive specifications. The trend has been to specify concrete performance so that the designer/specifier does not have to be responsible for the performance of the concrete that is prescribed. Performance requirements apply “when the owner requires the concrete supplier to assume the responsibility for the performance of the concrete delivered and the contractor to assume responsibility for the concrete in place” (Hooten, 2011).

According to CSA A23.1, a performance concrete specification is a method of specifying a construction product in which a final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods. The processes, materials, or activities used by the contractors, manufacturers, and materials suppliers are then left to their discretion. For durability, CSA uses a table of exposure classifications to set the level of performance needed. These exposure classes are summarized below in Table 2.5.

Table 2.5 Canadian CSA A23.1 Exposure Classes.

Exposure Class	**Relates to**	**Sub-classes**
C	Chlorides	C-XL, C-1, C-2, C-4, C-5
F	Freeze-thaw	F-1, F-2
N	Not exposed to external influences	No sub-classes
A	Chemical Effluents (Agricultural)	A-1, A-2, A-3, A-4
S	Sulphates	S-1, S-2, S-3

Typical specification limits for each of these exposure classes are presented below in Table 2.6.

Table 2.6 CSA 23.1A Performance Requirements Depending on Exposure Class.

Exposure Class	Max w/cm	Specified Strength (psi) at age (days)	Air Content (%)	Curing Type	Cement Restriction	ASTM C 1202 Chloride Resistance (Coulombs)
C-XL	0.40	7,250 @ 56 days	4-7 or 5-8% if frost exp.	Extended	--	<1000 @ 56 d
C-1, A-1	0.40	5,000 @ 38 days	4-7 or 5-8% if frost exp.	Additional	--	<1500 @ 56 d
C-2, A-2	0.45	4,600 @ 28 days	5-8%	Additional	--	--
C-3, A-3	0.50	4,400 @ 28 days	4-7%	Basic	--	--
C-4, A-4	0.55	3,600 @ 28 days	4-7%	Basic	--	--
F-1	0.50	4,400 @ 28 days	5-8%	Additional	--	--
F-2	0.55	3,600 @ 28 days	4-7%***	Basic	--	--
N***	For structural design	For structural design	None	Basic	--	--
S-1	0.40	5,000 @ 56 days	4-5%	Additional	HS or HSb	--
S-2	0.45	4,600 @ 56 days	4-7%	Basic	HS or HSb	--
S-3	0.50	4,400 @ 56 days	4-7%	Basic	MS or MSb+	--

Basic curing requires maintaining curing conditions for 3 days (>10^0 C) or until 40% of specified strength, while additional curing requirements must last for 7 days (>10^0 C) and 70% of specified strength. The extended curing requires wet curing for 7 days. Curing types allowed are ponding, continuous sprinkling, absorptive mat or fabric kept continuously wet. The w/cm requirements are not tested, the concrete producer must certify that the concrete is within the standard. For concrete that must meet minimum rapid chloride permeability results (Class A-1, exposed to freezing and thawing, for instance) must have the average of all test results below 1500 Coulombs, with no individual test result above 1750 Coulombs. Sulfate and alkali silica reaction resistance can be demonstrated with performance tests in lieu of current prescriptive methods for risk minimization.

The Canadian standards address the need for varying levels of acceptance based on prequalification, specification values, and in-place values. Certain values are specified for prequalification and during construction, to give a reasonable estimation that the hardened concrete properties are of an acceptable level to achieve adequate service life and longevity. Each specified value should vary based on evaluation point. These values are listed below in Table 2.7.

Table 2.7 CSA Standard Target, Specified, and In-place Concrete Specifications.

Test Parameter	**Target Value**	**Specified Value**	**In-Place Value**
Compressive Strength	1.15 x f'_c	Varies	0.85 x f'_c
Air Content	~6.5%	5-8%	~3.0%
Air Void Spacing Factor	~170 um	230 um	Average < 230 um, with no value > 260 um
Permeability	~1150 Coulombs	1500 Coulombs	Average < 1500 Coulombs, No value > 1750 Coulombs

New developments for Canadian Standards include more simple tests for evaluating concrete durability, including using the bulk diffusion test that Florida, and some other DOTs are already using. Ideally, CSA standard committees would like a test that could evaluate the durability of concrete while still in the plastic state, before being placed.

2.8. American Concrete Institute

The American Concrete Institute Strategic Development Council identified the need for performance-based concrete specifications and approved Innovation Task Group 8. This group was charged with the task of creating a document for the development of performance-based specifications for concrete. Within the document, it covers the differences between prescriptive and performance-based specifications, definitions and acronyms, identifies principal elements of performance-based specifications, acceptance criteria and implementation into new projects, and reviews the performance opportunities already presented in ACI documents 301 and 318. The specification limits in the document are duplicated from those found in the NRMCA reports mentioned earlier.

3. EXPERIMENTAL DESIGN

In order to evaluate the potential performance-based criteria for CDOT Class D and P mixtures, previously submitted and approved CDOT concrete mixtures were batched and tested. Fifteen concrete mixtures were selected from the CDOT database to be batched and tested in the laboratory and then two concrete mixtures that were non-standard CDOT mixtures were also tested. The non-standard concrete mixtures were two mixtures that were used on CDOT pilot projects. Local ready mix companies were contacted to provide concrete mixtures, where the research team would not necessarily know the mixture proportions, except that the ready mix supplier felt these mixtures could be used in applications where a traditional CDOT Class D or P mixture could be used. Despite the research team efforts, no local supplier expressed any interest to participate in the study.

Selection of the 15 concrete mixtures from the CDOT database was based on various attributes to gain a wide range of concrete mixtures. Criteria used in the selection were based on:

- Evaluating both CDOT Classes D and P mixtures,
- Low to high replacements of fly ash,
- Varying amounts of total cementitious contents,
- Varying water to cementitious materials ratios,
- Varying coarse aggregate contents,
- Multiple material types, sources, brands, etc.,
- Location from throughout the State of Colorado.

Concrete mixtures selected with the above criteria are summarized below in Table 3.1.

Table 3.1. Mixture Proportions of Selected CDOT Approved Concrete Mixtures

Mix Number	CDOT Record #	CDOT Mix #	Region	Concrete Class	Cement (lb/cy)	Fly ash (lb/cy)	Coarse Agg (lb/cy)	Intermediate Agg (lb/cy)	Fine Agg (lb/cy)	Air Entrainment (oz/cy)	Water Reducer (oz/cy)	Water Reducer (oz/cy)	Water (lb/cy)	Mix Design w/cm
1	1897	2011008	6	D	559	99	1650		1266	2.6	26.3		261	0.40
2	1894	2011006	6	P	462	198	1790		1100	4.6	33		262	0.40
3	1887	2011001	6	D	528	132	1564		1280	3.6	47.3		290	0.44
4	1883	2010183	APL	D	526	132	1745		1240	none listed	20		250	0.38
5	1882	2010182	APL	D	495	165	1707		1087	5.9	46.2		271	0.41
6	1881	2010181	APL	P	550	155	1204	520	1147	5.6	63		275	0.39
7	1878	2010178	1	D	528	132	1665		1270	3.8	46.2		265	0.40
8	1875	2010175	2	D	528	132	1680		1282	5.2	13.2	39.6	260	0.39
9	1861	2010165	4	P	528	132	1650		1310	5	23.1		240	0.36
10	1858	2010164	4	D	515	145	1440	700	725	2	53		275	0.42
11	1856	2010163	4	D	528	132	1800		1305	1	33		228	0.35
12	1855	2010162	1	D	528	132	1660		1310	none listed	26.4		233	0.35
13	1852	2010159	APL	D/P	528	132	1880		1150	1	52.8		247	0.37
14	1828	2010141	APL	P	528	132	1710		1235	4.9	19.8	19.8	254	0.38
15	1822	2010137	2	D	585	65	1720		1250	3.6	13	32.5	270	0.42

In the above table, not all mixtures required the additional column for intermediate size aggregates, or the second water reducer column. These additional columns were added for the mixtures that utilized more than two aggregates, or more than two water reducers.

The two non-standard concrete mixtures that CDOT wanted to have batched and tested were selected because they use four different aggregate sizes to achieve a well-graded blend. To obtain the well-graded aggregate blend, aggregate sizes that were not typically included in the CDOT specifications were used. The aggregate size used that was not typically in the CDOT specifications was the ASTM C 33 size #9 aggregate. Using this aggregate size to fill the gradation gap between the larger coarse aggregate and the smaller fine aggregate allowed for an optimized gradation. These concrete mixtures would have the aggregates adjusted during production to account for variances in the gradation. This was done to maintain the optimized gradation. Basic concrete mixture proportions for the optimized gradation concrete are summarized in Table 3.2.

Table 3.2. Concrete Mixture Proportions for Non-standard CDOT Mixtures.

Mix Number	CDOT Mix #	Region	Concrete Class	Cement (lb/cy)	Fly ash (lb/cy)	Coarse Agg Size #4 (lb/cy)	Intermediate Agg Size #67 (lb/cy)	Intermediate Agg Size #9 (lb/cy)	Fine Agg (lb/cy)	Air Entrainment (oz/cy)	Water Reducer (oz/cy)	Water (lb/cy)	Mix Design w/cm
16	2010047	4	P	720	80	409	954	273	1090	10	40	280	0.35
17	2011121	6	P	422	108	670	880	620	1055	3.2	23.7	220	0.42

Local ready mix concrete suppliers were attempted to be contacted by various means with no success. The research team was not able to procure any performance samples of concrete to be tested and compared from local ready mix concrete suppliers. We have attributed this to the new nature of the specifications and unknown realm for the suppliers. This is not a detriment to the research. Each of the suppliers will have time to evaluate its own materials and test them in accordance with the new specifications and then customize the mixtures to meet these specifications.

3.1. Laboratory Concrete Mixture Batching

Each of the concrete mixtures was batched in general accordance with applicable ASTM, AASHTO, and CDOT specifications. Batch sizes were selected that would allow all of the required specimens to be fabricated from one laboratory sample, eliminating the need for multiple batches and increased potential for variability.

Concrete mixture proportions were duplicated from the submitted mixtures to CDOT, including air entrainment and water reducer dosage rates. This was performed such that each of the concrete mixtures could be tested as they would have been supplied to CDOT projects. No attempt was made by the research team to control the entrained air content and slump of each concrete mixture within the data set, so long as the values were within CDOT specification limits. Concrete mixtures #1, 4, 8, 9, 11, 12, 13, 14, and 16 required additional water to achieve a similar slump to the originally submitted concrete mixtures, while concrete mixtures #2 and 10 required less water than the submitted mixture proportions to achieve a similar slump. Water to cementitious materials ratios were not allowed to exceed CDOT specification limits in cases where additional water was required.

Plastic concrete physical property tests conducted were concrete unit weight, entrained air content (pressure method), hydraulic slump, and temperature.

3.1.1. Plastic Unit Weight of Concrete

Plastic unit weight of the concrete was performed in general accordance with ASTM C 138. Concrete was placed in a 0.25 cubic foot measure in three separate lifts, rodded with a 5/8 inch hemispherical rod 25 times per lift, and then tapped on the outside of the measure 10 to 15 times per lift. Excess concrete was then struck off with a plastic plate and the lip cleaned of excess concrete. Measure and concrete were weighed, and unit weight was calculated.

3.1.2. Entrained Air Content

Upon the completion of plastic unit weight testing, the same measuring apparatus is used for the entrained air content test. A lid with separate pressure vessel and gauge is clamped to the top of the measure, and the entrained air content is then found in general conformance of ASTM C 231. Water is added in one petcock to remove any space from the top of the concrete surface and the bottom of the lid. Air is then added to the pressure vessel to a pre-determined initial pressure, petcocks are closed to prevent escape of water or air, and the pressure is allowed to escape the pressure vessel while the side of the measure is tapped with a mallet to insure there are no trapped air voids in the concrete. Once the gauge reading has stabilized, the entrained air content is read from the gauge.

3.1.3. Hydraulic Slump of Plastic Concrete

Hydraulic slump of plastic concrete is a good measure of the consistency of concrete from batch to batch. Measured slumps from laboratory trial mixes when compared to those found in this research study were discussed in section 3.1. Laboratory Concrete Mixture Batching. Slump of the plastic concrete was performed in general accordance with ASTM C 138. Slump cone was placed on a flat, level surface and filled in three layers based on equal volume of the slump cone. Each layer was rodded 25 times, and the top layer was filled to overflowing before rodding the top layer. Cone was then struck off, raised at a rate of 5 ± 2 seconds and the concrete subsidence was measured from the top of the cone.

3.1.4. Temperature of Freshly Mixed Concrete

After mixing of the concrete in the laboratory, the temperature was taken. Temperature recordings were taken in general conformance with ASTM C 1064. A location was chosen on the corner of the wheelbarrow where the thermometer would not be disturbed, thermometer inserted in that location, voids were closed by hand around the thermometer to prevent outside ambient air from affecting readings, and the thermometer was allowed to stabilize. Temperature readings were then recorded after the thermometer stabilized.

3.2. Laboratory Hardened Concrete Testing

Each concrete mixture batched in the laboratory was subjected to the following tests:

- Compressive Strength
- Modulus of Rupture (Flexural Strength)
- Rapid Chloride Permeability
- Freezing and Thawing Resistance

- Salt Scaling Resistance
- Unrestrained Shrinkage

Restrained shrinkage testing was also performed on two concrete mixtures.

3.2.1. Compressive Strength

Specimens were cast from each mixture for testing at 1, 7, 28, and 56 days. Compressive strength was tested in general accordance with ASTM C 39. Four-inch diameter by eight-inch height replaceable compressive strength specimen molds were cast by filling with concrete in two equal layers, rodded 25 times with a 3/8 inch diameter rod, and then tapped on the outside 10 to 15 times. Top layer of the specimen was struck off and finished with a steel trowel. After the initial curing period of 24 hours in the laboratory, the specimens were stripped from the molds and placed in lime-saturated water tanks until test date.

3.2.2. Modulus of Rupture (Flexural Strength)

Concrete mixtures classified as Class P pavement mixtures were also subjected to flexural strength testing. Specimens were tested in general accordance with ASTM C 78 by third point loading. Testing on the specimens was performed at 7 and 28 days. Prior to testing, the specimens were cured in lime saturated water. Figure 3.1 indicates the test apparatus for third point loading.

Figure 3.1. Flexural Strength Testing.

3.2.3. Rapid Chloride Permeability

Cylindrical specimens were cast from plastic concrete for testing at 28 and 56 days. Testing was performed in general accordance with ASTM C 1202. Preparation for rapid chloride permeability starts with saw cutting the cylindrical specimen to a thickness of 2 inches, placing in a vacuum, and then soaking in water before testing. Each specimen is placed in the chamber with sodium hydroxide solution and sodium chloride solution on alternate sides, where each is then connected to a voltage source which is spread across the specimen. Test apparatus is shown in Figure 3.2. Current is measured across the specimen and measured in Coulombs passed.

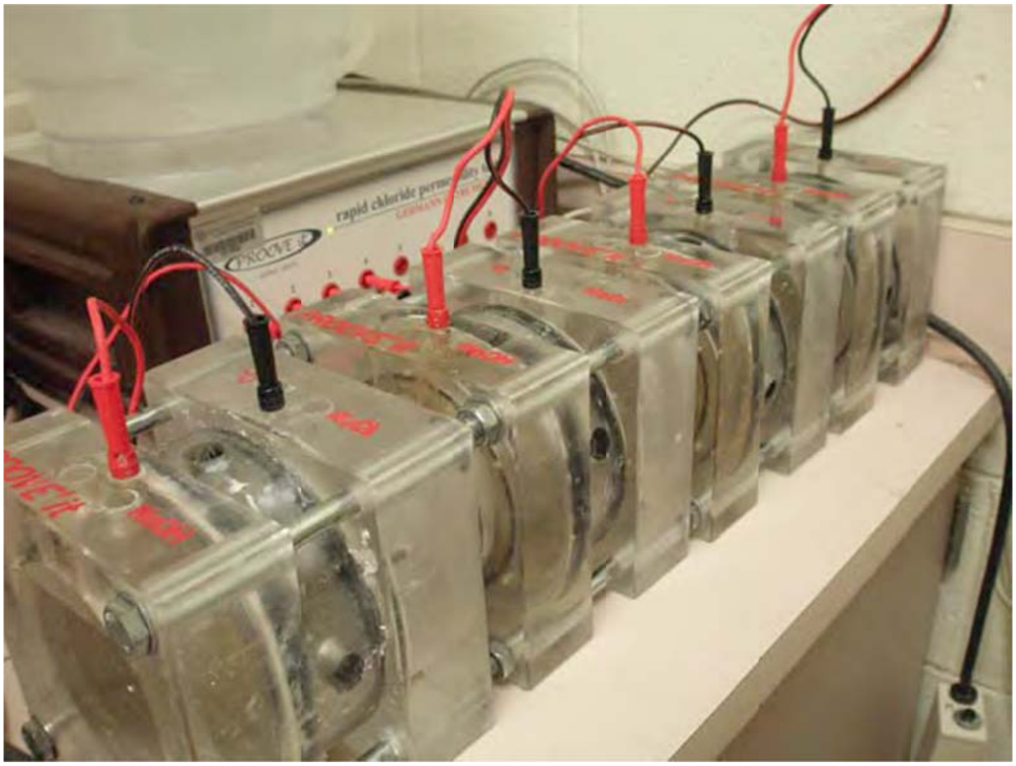


Figure 3.2 Rapid Chloride Permeability Test Setup.

3.2.4. Freezing and Thawing Resistance

Testing for freezing and thawing resistance was performed in general accordance with ASTM C 666. Specimens were cast in beam prism samples and cured in lime saturated water for 28 days before the first freezing cycle. Increasing the curing time to 28 days is a deviation from the ASTM test method that allows for the secondary cementitious reaction to occur from the fly ash in concrete mixtures. After the initial curing time in the lime saturated water, the specimens were placed in the freezing and thawing chamber to be cycled automatically between freezing and thawing and back again. Figure 3.3 shows the freezing and thawing chamber that automatically cycles the temperatures for the specimens. In addition to the freezing and thawing cycles, the dynamic modulus of elasticity is measured for calculation of the durability factor. Placing the concrete beam prism on rubber supports, placing a probe on one end of the specimen and striking the opposite end with a hammer measure dynamic modulus of elasticity. The probe then registers the frequency of that passes through the specimen.

Figure 3.3 Freezing and Thawing Chamber.

3.2.5. Salt Scaling Resistance

Concrete specimens were fabricated from 12-inch square molds that were 3.5 inches deep. These molds were made from wood and tested in accordance with ASTM C 672. Specimens were allowed to cure in lime saturated water for 28 days before being subjected to the salt brine solution and subsequent freezing and thawing cycles. Specimens had a berm that was created around the perimeter to pond the salt brine solution. Salt brine solution was made in the laboratory by dissolving salts in water to the required concentration in the test method. Solution was then poured on specimens and cycled between freezing and thawing. Specimens were then visually classified. Specimens including solution and berm are shown in Figure 3.4.

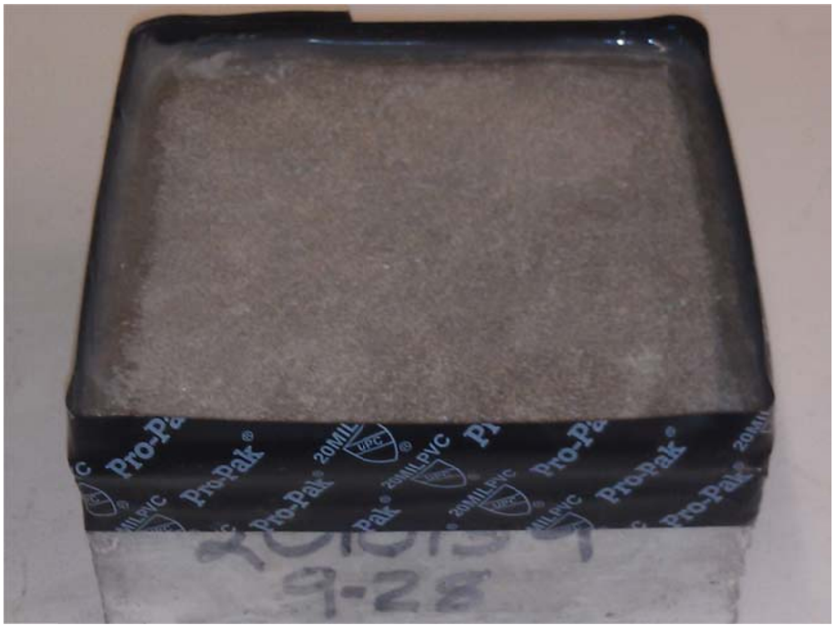


Figure 3.4 Salt Scaling Specimen.

3.2.6. Unrestrained Shrinkage

Unrestrained shrinkage followed a modified ASTM C 157 test method. Instead of the longer moist curing period laid out in C 157, the specimens within the research study were allowed to cure for 7 days in lime saturated water and then to air dry in 50 percent humidity for 28 days. Shrinkage was measured at the end of the 28-day air curing period. Specimens were fabricated in beam prisms with steel studs in the end so the shrinkage measurements can be recorded. Figure 3.5 shows a beam specimen within the measuring device.

Figure 3.5. Unrestrained Shrinkage Specimen in Measuring Device.

3.2.7. Restrained Shrinkage

Restrained shrinkage testing was performed on two concrete mixtures after unrestrained shrinkage values were obtained from all of the laboratory concrete mixtures. Testing generally followed AASHTO T 334. Ring specimens were cast in the annular space between the steel ring on the inside and the cardboard mold on the outside. Immediately after casting the specimens, strain gages that were attached to the inside of the steel ring were connected to a data logger that would record strain measurements every 30 minutes for the duration of the test. After the initial curing of the ring specimens, the top edge around the specimen was de-burred to remove any potential stress concentrations. Specimens were allowed to shrink for 3 weeks or until cracking occurred. Figure 3.6 indicates the restrained shrinkage specimen and strain gage attachments.

Figure 3.6. Restrained Shrinkage Specimen.

4. ANALYSIS OF EXPERIMENTAL RESULTS AND CONCLUSIONS

4.1. Concrete Physical Property Test Results

Results from the plastic concrete physical property tests are summarized below in Table 4.1.

Table 4.1. Concrete Plastic Physical Property Test Results.

Mix #	CDOT Record #	CDOT Mix #	Region	Concrete Class	Unit Weight (pcf)	Air Content (%)	Slump (in.)
1	1897	2011008	6	D	139.8	6.9	3.5
2	1894	2011006	6	P	138.7	7.4	4.5
3	1887	2011001	6	D	139.6	7.9	3
4	1883	2010183	APL	D	143.4	6	2.25
5	1882	2010182	APL	D	138.8	6.7	3.5
6	1881	2010181	APL	P	141.8	5.8	4.25
7	1878	2010178	1	D	142.9	5.6	3.5
8	1875	2010175	2	D	141.2	5	3
9	1861	2010165	4	P	139.8	7.2	3.25
10	1858	2010164	4	D	143.4	5	4.75
11	1856	2010163	4	D	143.1	5.9	3
12	1855	2010162	1	D	139.8	5.8	4.25
13	1852	2010159	APL	D/P	144.2	5.2	1.25
14	1828	2010141	APL	P	141.2	5.1	1.25
15	1822	2010137	2	D	141.2	6.5	3
16		2010047	4	P	139.0	7.2	2.25
17		2011121	6	P	144.3	7.6	1.75

CDOT record numbers were not available for concrete mixtures 16 and 17.

Individual results for air content all fell within the specification limits set by CDOT, and all of the slump results were close to the as submitted slumps from the submittals in the CDOT database.

4.1.1. Entrained Air Content

Current CDOT air entrainment ranges can be viewed as both prescriptive and performance. They are considered prescriptive because specifications require a certain percentage air entrainment and not the performance element air entrainment provides, which is freeze thaw resistance. A critical element to freeze thaw resistance is the air void structure within the hardened concrete matrix. Rather than specifying a certain percentage of air entrainment in concrete mixtures, the air void spacing factor could be measured instead. This would allow the actual hardened concrete to be specified via performance, rather than a prescriptively set air content range.

Current air content ranges can also be considered performance-based when specifications allow for mixture adjustments without the need to resubmit the proportions for approval. Specifications do not call for a required amount of air entrainment per cubic yard of concrete, instead the desired plastic property is specified for the concrete.

Concrete mixtures exhibiting adequate freeze-thaw durability should not be required to perform air entrainment testing. However, freeze-thaw durability testing is time consuming, expensive, and does not provide immediate results. Because of these factors, the concrete supplier should be prepared to either perform freeze-thaw testing at adequate intervals during the job, or stick with the current air entrainment ranges. Future research should be performed on air void spacing and air entrainment if the current air content specification range is to be removed from CDOT specifications.

4.1.2. Hydraulic Slump of Concrete Mixtures

Slump for concrete mixtures should be allowed to adequately flow for the intended placement method, and should be based on laboratory trial mixtures. It should be the responsibility of the concrete supplier to communicate with the contractor placing the concrete, what slump is desired for each application. It should be the responsibility of the contractor placing the concrete to minimize any segregation, honeycombing, or other placement issues with the slump range the concrete supplier has delivered. Current range of ± 1 ½ inches for Classes D and P concrete mixtures should still be specified.

4.1.3. Plastic Unit Weight

Unit weight is dependent on proper mixture proportions, material specific gravities, entrained air content and other factors. Unit weight should only be used for the calculation of yield, to insure the owner is getting the proper amount of concrete, and the concrete mixture is staying consistent during production.

4.2. Hardened Physical Properties of Concrete Mixtures

Hardened concrete properties were tested at various ages through various test regimens. Each of the concrete mixtures batched in the laboratory were subjected to rapid chloride permeability, freezing and thawing, 28-day modified shrinkage, and scaling resistance testing. Results of the testing are summarized in Table 4.2.

Table 4.2. Hardened Properties of Concrete Mixtures.

Mix #	CDOT Record #	CDOT Mix #	Region	Concrete Class	28 Day Mod. Shrinkage	28 Day RCIP (coulombs)	56 Day RCIP (coulombs)	Scaling	Durability Factor
1	1897	2011008	6	D	0.043	3203	1918	1	89
2	1894	2011006	6	P	0.039	2990	1755	3	91
3	1887	2011001	6	D	0.038	3344	1988	2	89
4	1883	2010183	APL	D	0.0095	3896	2510	3	90
5	1882	2010182	APL	D	0.035	3190	1850	2	92
6	1881	2010181	APL	P	0.055	3350	1610	1	87
7	1878	2010178	1	D	0.04	3150	1598	2	95
8	1875	2010175	2	D	0.041	3435	1746	3	94
9	1861	2010165	4	P	0.054	2950	1745	1	93
10	1858	2010164	4	D	0.033	3304	1650	3	92
11	1856	2010163	4	D	0.045	3010	1790	1	91
12	1855	2010162	1	D	0.04	3510	2053	2	88
13	1852	2010159	APL	D/P	0.022	2370	1490	1	95
14	1828	2010141	APL	P	0.058	2878	1907	1	90
15	1822	2010137	2	D	0.041	3067	2210	3	89
16		2010047	2	P	0.045	2189	1865	1	91
17		2011121	2	P	0.028	2200	1902	1	92

In addition to the testing listed above, two restrained shrinkage tests were performed on mixtures 4 and 14. These mixtures were selected because of the shrinkage measured for the unrestrained 28-day modified tests. Restrained shrinkage testing on the two additional mixtures was terminated at three weeks since no cracking was exhibited during that time. CDOT currently uses the criteria where no cracking should be observed within 14 days of age on concrete mixtures where shrinkage could be detrimental to the life span of the structure.

4.2.1. Concrete Compressive Strength

Compressive strength is the most widely used performance specification that engineers use to monitor in-place concrete. All of the compressive strength test results have been tabulated below in Table 4.3.

Table 4.3. Concrete Compressive Strength.

Mix #	CDOT Record #	CDOT Mix #	Region	Concrete Class	1 Day f'c (psi)	7 Day f'c (psi)	28 Day f'c (psi)	56 Day f'c (psi)
1	1897	2011008	6	D	1750	4780	5510	6110
2	1894	2011006	6	P	1580	3750	5270	5850
3	1887	2011001	6	D	1600	3685	4715	5200
4	1883	2010183	APL	D	149	6070	7510	8440
5	1882	2010182	APL	D	1860	4535	5410	6250
6	1881	2010181	APL	P	1920	5010	6230	6870
7	1878	2010178	1	D	1870	4640	5930	6410
8	1875	2010175	2	D	2050	4910	6070	6230
9	1861	2010165	4	P	1710	4320	5010	5540
10	1858	2010164	4	D	1990	4945	5905	7080
11	1856	2010163	4	D	1800	4750	6010	6850
12	1855	2010162	1	D	1810	4820	6380	7280
13	1852	2010159	APL	D/P	2550	5340	6750	7550
14	1828	2010141	APL	P	1940	4510	6090	6670
15	1822	2010137	2	D	1890	4380	5890	6360
16		2010047	2	P	2540	4950	5690	5960
17		2011121	2	P	1210	3210	4850	5230

Compressive strength criteria for CDOT Class D concrete mixtures is 4,500 psi in the field, with a 15% over-design for the laboratory which equates to 5,175 psi at 28 days. CDOT Class P concrete field compressive strength is 4,200 psi, and when subjected to the same 15% over-design the laboratory compressive strength becomes 4,850 psi. Concrete mixture #3, was the only concrete mixture that did not meet the current CDOT specification for the compressive strength criteria. However, mixture #3 did reach the required compressive strength by 56 days of age.

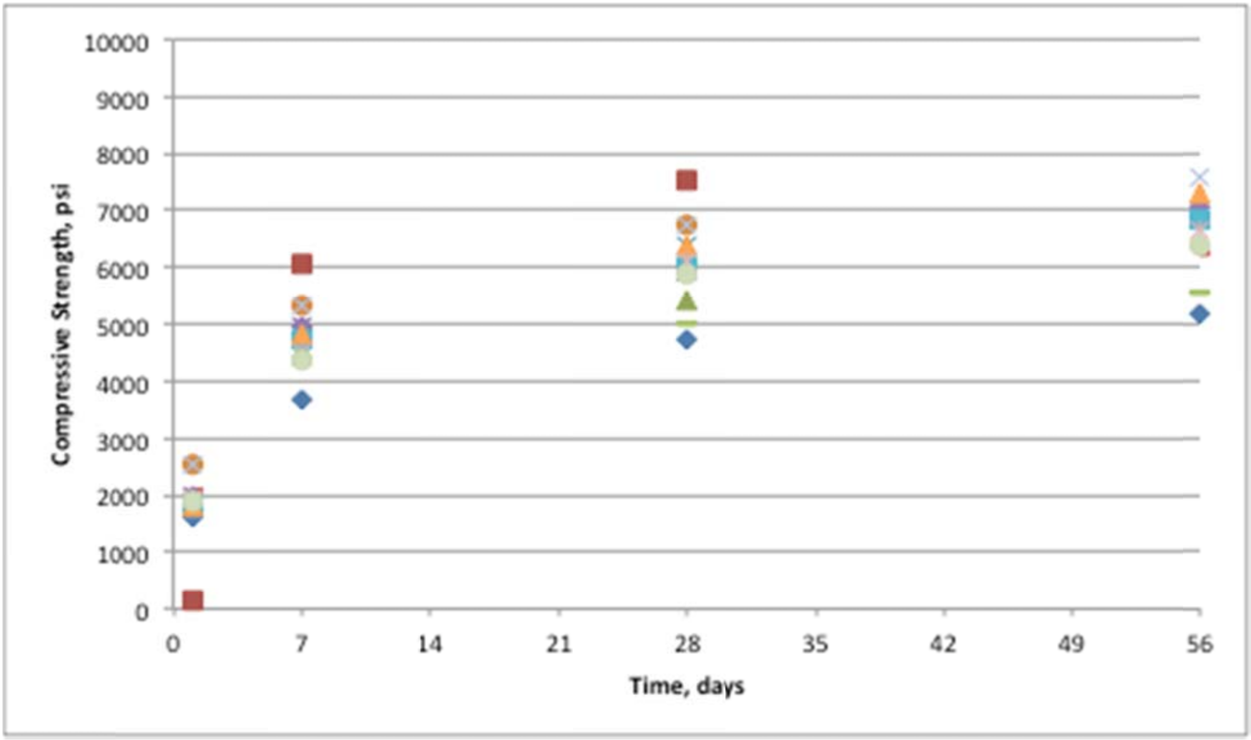


Figure 4.1. Compressive Strength of Concrete Mixtures.

The individual results indicated that concrete mixture #3 was the only mixture that did not meet the required over design set forth in the CDOT specifications. It is believed the strength did not meet the required over design due to a slightly higher entrained air content. The laboratory mix design submitted to CDOT had a similar strength development curve, while the experimental compressive strengths the research team found was only slightly less.

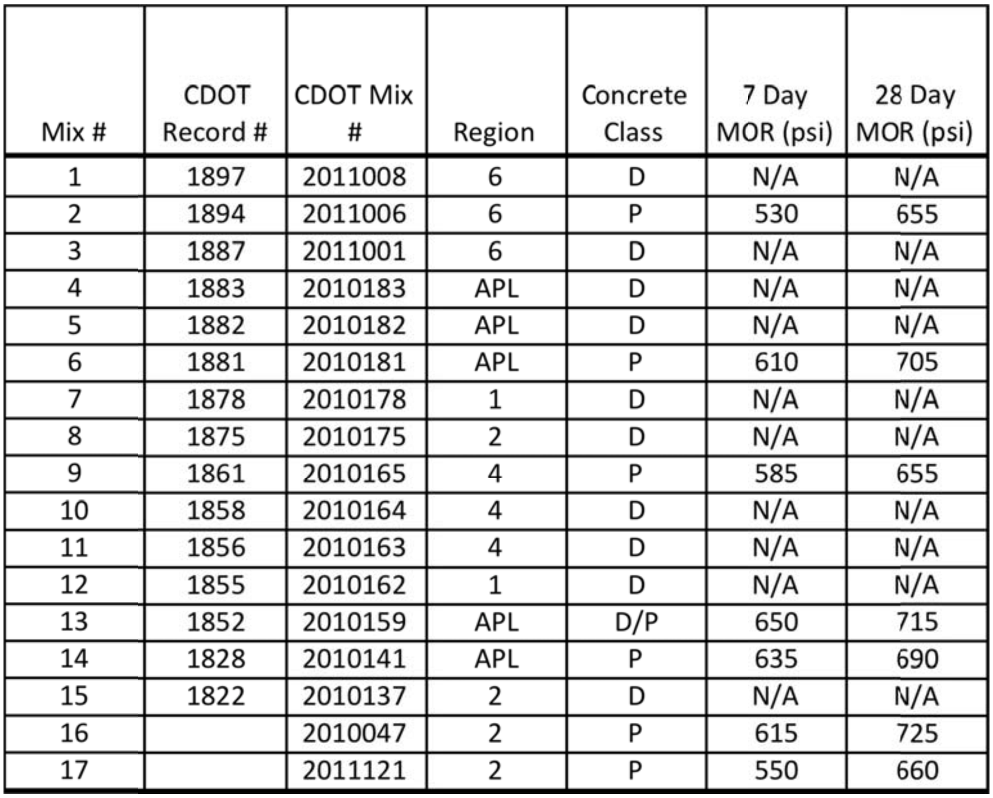
Figure 4.1 above not only indicates the compressive strength, and the strength development of each of the concrete mixtures but shows that each of the concrete mixtures (except #3) meet design strength in approximately 14 days. This is attributed to the current cement manufacturing process and increased efficiency of the cement from the use of chemical admixtures. Cement is currently ground to have a higher Blaine fineness for increased strength development at earlier ages to facilitate fast construction schedules. Technological advancements in chemical admixtures have also increased the strength of concrete mixtures through dispersion of the cement particles and efficiency of the hydration reaction.

CDOT concrete specifications currently use prescriptive specifications for durability requirements. Compressive strength minimums are based on durability studies that are before the time of modern cements and chemical admixtures. Specifying performance tests that directly measure durability can reduce the need for concrete that is over designed in terms of compressive strength. Compressive strengths in other DOTs can be as low as 3,000 psi, and when measuring durability the compressive strength requirements do not need to be as high as 4,500 psi. Compressive strength for Classes D and P concrete mixtures have had good service records at the current specification levels and there is a comfort level with DOT design engineers. Where structural design governs, the compressive strength should be specified by the design engineer of record and when structural considerations do not govern, the compressive strength should be 4,500 psi. Specification level of 4,500 psi should be the laboratory design level and the field acceptance level should be 4,000 psi at 28 days. If construction schedule allows, the 28-day specification for compressive strength should be extended to 56 days. By extending the date at which compressive specimens were tested, allows for the secondary cementitious reaction to occur and allows the concrete to become more durable.

4.2.2. Concrete Flexural Strength

Flexural strength determination is very important to monitor, since the pavement design is based on the value of 650 psi. Modulus of rupture was measured on concrete mixtures meant for concrete paving applications. This criterion is required since the rigid pavement design of roadways is based on a specific flexural strength of the concrete. Modulus of rupture on all the concrete mixtures met the required laboratory design strengths. Measured flexural strengths of the CDOT Class P concrete mixtures are tabulated in Table 4.4.

Table 4.4. Modulus of Rupture for Concrete Mixtures.



Mix #	CDOT Record #	CDOT Mix #	Region	Concrete Class	7 Day MOR (psi)	28 Day MOR (psi)
1	1897	2011008	6	D	N/A	N/A
2	1894	2011006	6	P	530	655
3	1887	2011001	6	D	N/A	N/A
4	1883	2010183	APL	D	N/A	N/A
5	1882	2010182	APL	D	N/A	N/A
6	1881	2010181	APL	P	610	705
7	1878	2010178	1	D	N/A	N/A
8	1875	2010175	2	D	N/A	N/A
9	1861	2010165	4	P	585	655
10	1858	2010164	4	D	N/A	N/A
11	1856	2010163	4	D	N/A	N/A
12	1855	2010162	1	D	N/A	N/A
13	1852	2010159	APL	D/P	650	715
14	1828	2010141	APL	P	635	690
15	1822	2010137	2	D	N/A	N/A
16		2010047	2	P	615	725
17		2011121	2	P	550	660

Each of the Class P concrete mixtures had the flexural strengths presented graphical below in Figure 4.2. From the graph, it can be seen that the flexural strength does not have the same rate of increase from 7 to 28 days like the strength gain in compressive strengths.

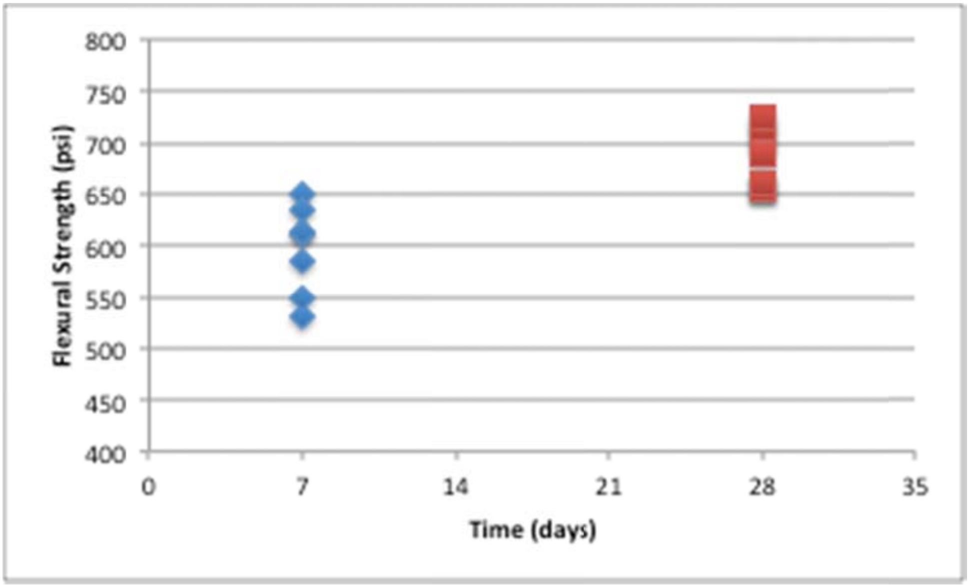


Figure 4.2. Flexural Strength vs. Time.

CDOT specifications currently do not require any overdesign on flexural strength specimens in laboratory mixtures. An optimized mixture task force is currently looking at the possibility of adjusting the flexural strength levels to add in some laboratory overdesign criteria. CDOT should keep the current 650 psi at 28 days flexural design criteria since roadway design is based on this value. No specific literature was found saying that pavements must have a design value of 650 psi, but there is a comfort factor with this value and CDOT roadway design engineers are familiar with this value.

4.2.3. Rapid Chloride Permeability

ASTM C 1202 test is a measure of the electrical conductivity through a concrete specimen. This electrical conductivity is a general measure of the pore space, inter-connectivity of the pore spaces, and saturation levels within the pore space. Specific test procedures try to limit the variations from the saturation levels of the specimens, and should only compare the pore spaces and connectivity of the pores between specimens. Intrusion of deleterious materials into the concrete matrix is generally the cause of poor durability performance in the field. Therefore, lower values of electrical conductivity generally indicate higher levels of durability. Concrete will continue to gain strength and reduce the connectivity of the pore spaces over time; this is also true of concrete with supplementary cementitious materials that react more slowly over time. Due to the slow reaction of supplementary cementitious materials, the rapid chloride permeability should be measured at 28 days and 56 days of age. With supplementary cementitious materials and lower w/cm ratios the pore spaces become smaller and less connected. Maximum w/cm ratios are generally imposed for durability reasons. Based on these theories, the w/cm ratio has been plotted against the permeability values obtained during the testing.

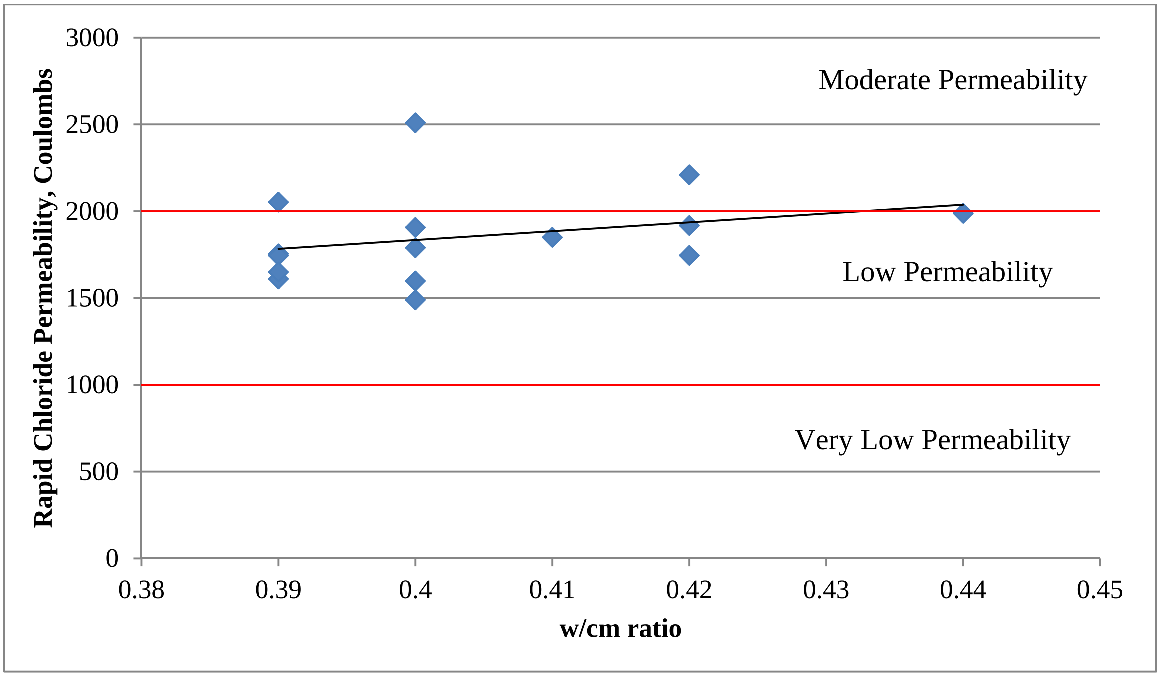


Figure 4.3. w/cm Ratio vs. Permeability at 56 days.

The black line in Figure 4.3 represents the trend line for the data series. From this line we can tell there is a relationship between rapid chloride permeability and w/cm ratio. As the w/cm ratio decreases, the rapid chloride permeability decreases. There is much scatter in the data that is due to material variances and types of microstructure formed with different admixtures, cement types, fly ash types, and air entrainment. Each concrete mixture’s individual Coulombs passed in the rapid chloride permeability test at 56 days as shown in Figure 4.4.

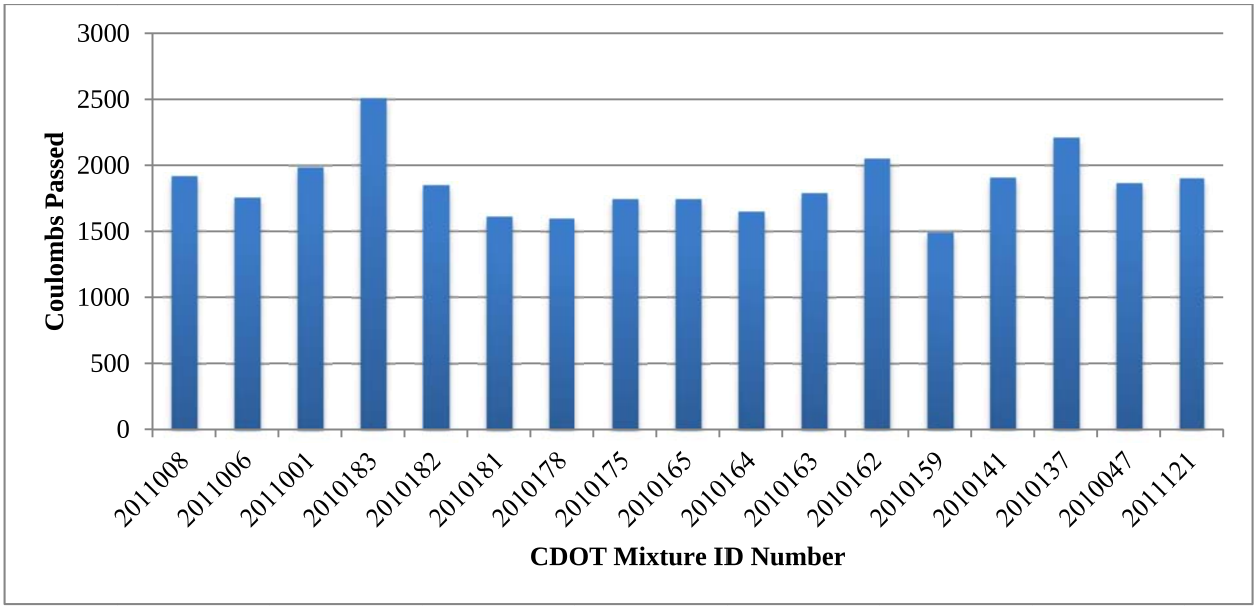


Figure 4.4. Concrete Mixture vs. RCP.

Rapid chloride permeability testing evaluates the overall microstructure of the concrete matrix. Pore structure, interconnectivity, and the w/cm ratio are critical items that are evaluated with this test. Each of the items is a direct indication of the overall durability of the concrete specimen. One of the largest contributors to the durability of concrete is the w/cm ratio. Maximum w/cm ratios are mandated by the CDOT to insure an adequate level of durability against various forms of deleterious attack. Current specifications require either a 0.44 or a 0.45 maximum w/cm ratio depending on the concrete classification. The recommendation based on the study findings is that the current prescriptive maximum w/cm ratio be eliminated and a maximum chloride ion permeability value of < 2,500 Coulombs passed at 56 days. This value was chosen based on recommendations from the NRMCA publications, and the values found in the mixtures for this research study were all below the value of 2,500 Coulombs.

There may also be the need for faster test results, and accelerated curing methods could be used to get 56-day results before the actual 56-day date arrives.

4.2.4. Concrete Unrestrained Shrinkage

Concrete shrinkage was measured to provide information on the paste properties on each of the concrete mixtures as well as coarse aggregate content. Shrinkage is inherently a paste property, and the aggregate filler is generally considered a restraining element that reduces the overall shrinkage potential. Current CDOT specifications generally require a minimum of 55 percent coarse aggregate for this reason. Research performed by Shilstone (section 2.1.3) has indicated that a well-graded aggregate blend may also reduce the shrinkage potential. Well-graded aggregate blends may not necessarily meet a 55 percent coarse aggregate requirement due to local material variations. Figure 4.5 shows a graphical representation of the coarse aggregate content vs. the measured shrinkage in the laboratory concrete mixtures. Shrinkage was measured out to 28 days after the initial 7-day moist curing period.

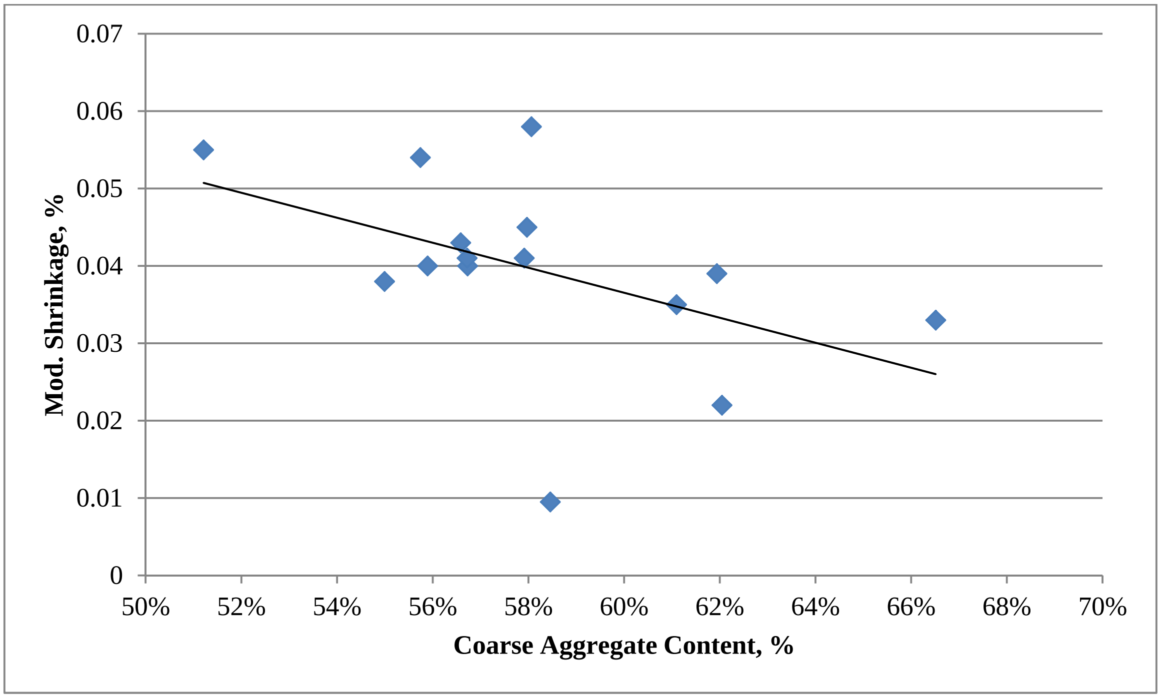


Figure 4.5. Aggregate Content vs. Shrinkage.

Shrinkage specimens were modified from the standard ASTM C 157 test method to allow for a quicker test result. Specimens were cured in lime-saturated water for 7 days, measured for initial length, and then stored in a 50 percent humidity room. Measurements were taken every 7 days for the next 28 days. Total shrinkage is determined as the change in length when compared to the original length. If concrete suppliers keep a running record of the ASTM C 157 test method results, this would be preferable to the modified method, but the modified method should also be considered applicable.

Unrestrained shrinkage is not a test method that is typically used, and has minimal guidelines for what is considered acceptable and not. Based on the black trendline in Figure 4.5, there is a relationship between shrinkage and the coarse aggregate content of a mixture, and has also been seen in optimal aggregate gradations for concrete by Shilstone.

Current CDOT specifications require 55 percent coarse aggregate in certain concrete mixtures where low shrinkage is determined to be an important design factor. Shrinkage within concrete specimens is generally attributed to the paste properties and the coarse aggregate resists that shrinkage. Unrestrained shrinkage is an important property to measure to insure the shrinkage is relatively low, and adequate coarse aggregate content is present. Data trendline from the coarse aggregate content vs. shrinkage figure shows the close convergence of the 0.050% shrinkage and the 55 percent coarse aggregate junction. Based on the data trend and the design intent of the CDOT concrete mixtures, the unrestrained shrinkage of the concrete should be measured and the 55 percent coarse aggregate content prescriptive specification should be revised. Unrestrained shrinkage values should be below 0.050% when measured after the initial moist cure and 28 days in the 50% humidity environment.

4.2.5. Salt Scaling Resistance

Salt scaling is much more prevalent on pavement surfaces than it is for structural concrete members. Any area exposed to deicing salts is susceptible to scaling. Concrete typically resists scaling with adequate compressive strength, and low w/cm ratios. With rapid chloride permeability measurements and compressive strengths being measured with other performance specifications, there is little need for the salt scaling test.

Salt scaling test results are found in Table 4.5.

Table 4.5. Salt Scaling Deterioration.

CDOT Concrete Mixture ID	Scaling Deterioration Value
2011008	1
2011006	3
2011001	2
2010183	3
2010182	2
2010181	1
2010178	2
2010175	3
2010165	1
2010164	3
2010163	1
2010162	2
2010159	1
2010141	1
2010137	3
2010047	1
2011121	1

All concrete mixtures tested in the laboratory had visual classifications above level 3. Visual classification is based on the severity of damage from 1 to 5, where 1 would be the least amount of damage and 5 being the worst amount of damage.

The test method is based mostly on visual assessments of the concrete surface, where results can vary from individual to individual and could cause a high standard deviation between testing laboratories. However, in the beginning stages of implementing performance specifications, salt scaling resistance testing should be performed to better evaluate mixture proportions and salt scaling resistance. After a given number of tests, the salt scaling resistance test should be reevaluated for its validity and contribution to the information necessary to evaluate the concrete based on its performance. Initial salt scaling values should be < 3.

4.2.6. Freezing and Thawing Resistance

Concrete placed in weathering regions where freezing temperatures are expected need to have adequate air entrainment so that the expanding ice will have somewhere to go. ASTM C 666 is a test method that tests the concrete’s ability to resist the forces caused by the expansion of water when forming ice. Strength of the hardened concrete will also play a factor in the freezing and thawing durability along with having sound aggregates. Concrete prisms were cast from the plastic concrete and were allowed to cure in lime saturated water for 28 days before being subjected to 300 cycles of freezing and thawing. The 28 day cure time is 14 days longer than the standard C 666 calls for. Specimens should be allowed to cure for 28 days prior to subjecting them to freezing and thawing to allow for the secondary cementitious reaction to start. Durability factors are calculated from the loss of dynamic modulus of elasticity when compared to the original dynamic modulus of elasticity. Test results have been tabulated above in Table 4.2.

Concrete placed in Colorado is almost always subjected to periods of freezing and thawing over the course of its design lifetime. Freezing water expands within the concrete and can cause cracking and subsequent expansion. To mitigate this problem, air entrainment is added for tiny spaces where the water can expand into and relieve the expansion pressure. By subjecting concrete specimens to cycles of freezing and thawing tests the pore structure and spacing of those pores. Freezing and thawing durability is currently accounted for by requiring a range of entrained air content, compressive strength, and maximum w/cm ratios, each would be tested in the performance tests. The required equipment to run the test is quite specialized, and laboratory personnel would need to be properly trained to perform the testing. Based on these items, and that this test is aggressive in nature, it suggests the test is only necessary for determining the integrity of the concrete mixture while in the laboratory. Correlation between freeze thaw durability and entrained air content should be developed so that a field process control can monitor the freeze thaw durability. Routinely measuring the air entrainment would be accurate for this, as long as there is a correlation between acceptable entrained air contents, strength, and durability factors. Durability factor of the concrete specimens should be > 60.

4.2.7. Restrained Shrinkage

Restrained shrinkage testing was performed on two laboratory mixtures where the unrestrained shrinkage values seemed very high and very low. To further evaluate the shrinkage in these mixtures, restrained shrinkage testing was performed on them.

Concrete mixtures shrink over time as the hydration reaction of cement progresses. Resulting reaction causes the paste to shrink around the steel ring in the restrained shrinkage test. It is the restraint from the steel ring that causes the concrete specimen to crack if the shrinkage of the mixture is too high. Actual shrinkage is not measured, but rather the force imparted on the ring from the shrinkage is determined.

Two concrete mixtures tested here did not have any cracking exhibited on the specimens, resulting in mixtures that had inherently low shrinkage. Restrained shrinkage testing was performed on these two concrete mixtures to evaluate whether the unrestrained shrinkage values were reasonable. Restrained shrinkage testing is a very delicate test with the electronics and specialty equipment involved. Many testing labs do not have the capability to run this specialized test. Restrained shrinkage testing should only be used if unrestrained shrinkage testing reveals results that are above specification limits or below 0.020% after 28 days.

5. FINAL RECOMMENDATIONS

CDOT should allow pilot projects within the state that have performance-based concrete specifications. These specifications would replace the current prescriptive specifications set forth in CDOT section 601 for Classes D and P concrete. Current alkali-silica reaction prescriptive specifications and/or sulfate resistance specifications should be retained and incorporated into the new performance-based specifications. ASR and sulfate resistance are areas that could use more research to develop performance-based criteria. Recommended parameters for consideration in specifying performance-based criteria are summarized below.

- Compressive strength should remain as currently specified
- Modulus of rupture should remain as currently specified
- Unrestrained shrinkage < 0.050 percent
- Rapid chloride permeability values < 2,500 Coulombs passed
- Salt scaling resistance < 3 by visual determination
- Freezing and thawing > 60 durability factor

Comparisons between existing prescriptive specifications and the new performance specifications can be found in Table 5.1.

Table 5.1. Existing Specifications Compared to New Performance-Based Specifications.

Criteria	Existing CDOT Prescriptive Specification	Proposed Performance-Based Specification
Class D Compressive Strength	4,500 psi at 28 days	4,500 psi* at 28 days
Class P Compressive Strength	4,200 psi at 28 days	4,200 psi* at 28 days
Class P Modulus of Rupture	650 psi at 28 days	650 psi* at 28 days
Coarse Aggregate Content	55 percent minimum	Unrestrained shrinkage <0.050 percent
Water to Cementitious Materials Ratio	0.44 Class P, 0.45 Class D	Coulombs Passed <2500 at 56 days
Salt Scaling Test	None	Visual Determination <3**
Freezing and Thawing Resistance	None	Durability Factor >60***

*See section 4.2.1. and 4.2.2. for more information

**See section 4.2.5. for more information

***See section 4.2.6. for more information

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