GEORGIA DOT RESEARCH PROJECT 20-19

Final Report

RECOMMENDATIONS FOR FUTURE SPECIFICATIONS TO ENSURE DURABLE NEXT GENERATION CONCRETE

GDOT
Georgia Department of Transportation

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7. Author(s): Kimberly E. Kurtis (PI), Ph.D., Lauren K. Stewart (PI), Ph.D., Emily A. Grubert (PI), Ph.D., Renee T. Rios, Ph.D., Francesca Lolli, Ph.D., Tobias Kopp (Graduate Research Assistant), Tom Rigaud (Graduate Research Assistant), Devon Golden (Graduate Research Assistant), Samuel Paredes (Graduate Research Assistant)		8. Performing Organization Report No.: 20-19
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16. Abstract:
Current Georgia Department of Transportation (GDOT) specifications for concrete rely on prescribing the materials and their proportions as well as minimum strength and workability requirements to indirectly control long-term performance. An alternative method, performance-based specifications (PBS), uses direct measures of long-term durability and performance through performance metrics or tests. Research presented in this report demonstrates that performance-based specifications can be implemented in the GDOT standard specifications for concrete in a way that results in more durable concrete and reduces the financial and environmental costs associated with the state's concrete infrastructure. This report extensively considered Sections 430, 439, and 500 of the GDOT standard specifications which include concrete pavements and structural concrete, as well as preliminary consideration of PBS for special applications in Sections 452, 504, and High-Performance Concrete (Section 500 HPC). A state-of-the-art review of state and international performance-based specifications was conducted to determine how successful performance specifications had been implemented. Using the review, proposed performance tests were evaluated, and limits were developed for the chosen metrics. The additional financial cost due to added testing was contrasted with the potential for financial savings from more durable concrete and it was found that the long-term financial benefits of adopting performance-based specifications outweighed the short-term costs. An environmental life cycle analysis concluded that the adoption of the proposed performance-based specifications would result in reduced maintenance needs and consequently fewer greenhouse gas emissions. It is recommended that the proposed performance-based specifications for Sections 430, 439, 452, 500, 500 HPC and 504 be adopted to improve the durability of concrete used by GDOT.

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By
Dr. Kimberly E. Kurtis
Professor

Dr. Lauren K. Stewart
Associate Professor

Dr. Renee T. Rios
Graduate Research Assistant

Dr. Francesca Lolli
Post-doctoral Fellow

Tobias Kopp
Graduate Research Assistant

Devon Golden
Graduate Research Assistant

Samuel Paredes
Graduate Research Assistant

Georgia Institute of Technology

Dr. Emily A. Grubert
Associate Professor

Notre Dame University

Tom Rigaud

Graduate Research Assistant

Université de Toulouse

Georgia Tech Research Corporation

Contract with
Georgia Department of Transportation

In cooperation with
U.S. Department of Transportation, Federal Highway Administration

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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EXECUTIVE SUMMARY

The research conducted under this GDOT project has resulted in a set of proposed concrete specifications for pavements and structures that rely on performance metrics to guide the design of the mix in a shift from the current prescriptive-based specifications for concrete used by GDOT. The current method of concrete specifications relies on requiring specific materials and mix design proportions as well as strength and workability metrics to indirectly control the long-term properties of concrete, a process that has been recognized to result in less durable concrete and limit innovation. Performance-based specifications qualify and verify a concrete mix design by testing it against a battery of metrics with site-specific limits.

This research reviewed current performance-based concrete specifications from other states and around the globe to determine state-of-the-art specifications. Feedback sourced from surveys sent to AASHTO committees and presentations to industry stakeholders was gathered to draft performance-based specifications for adoption by GDOT that could achieve more durable concrete with industry accessible measures of performance. An evaluation of a set of suitable metrics for concrete performance to measure the long-term performance was studied including measures of permeability, resistance to freeze/thaw attack, resistance to sulfate attack, and limits on total water-soluble chlorides. Limits for permeability were adjusted to be class-specific to reduce over or under design of concrete mixtures when used in the wide range GDOT applications. Performance limits for the remaining metrics were set to provide producers with geographical and material availability flexibility while maintaining a focus on improving durability.

Life cycle analysis on the environmental impact of pavement and structures was conducted to examine the potential environmental impacts GDOT could expect from the proposed specifications. It was found that the resulting improvements in durability from the performance-

based specifications reduced greenhouse gas emissions over the 30- and 40-year study periods. Additional analysis of the net financial impact from increased testing costs and reduced maintenance costs found that for all scenarios studied, the financial benefits outweighed the costs. Both environmental and financial analysis supported the recommended specifications, showing that adopting performance-based specifications would reduce GDOT’s environmental impact and decrease long-term costs.

Based on the results of this research, this project has recommended the drafted specifications for GDOT Section 430, 439, and 500 Concrete Standard Specifications. These sections cover concrete pavements and structural concrete. The draft specifications for these sections have been included in the appendix. It is also recommended that future research study potential future performance metrics for inclusion in specifications as improvements in performance metrics occur. The performance metrics proposed in this project are based on extensive reviews of other PBS from around the US and internationally, but it is reasonably expected that future performance metrics could result in time and financial cost savings. Finally, it is recommended that performance-based specifications be written for additional GDOT standard specifications, including Sections 452, 504, and High-Performance Section 500 concrete in order to align all state concrete specifications with performance-based specifications.

CHAPTER 1. INTRODUCTION

MOTIVATION

Concrete is widely used around the world because of its desirable physical properties coupled with its ready availability and relatively low cost. When properly designed, placed, and cured, concrete is a durable material that provides long-term performance with the ability to maintain its function in aggressive environments. Concrete's ability to be flowable during placement yet harden to a solid form facilitates ease of installation before setting to its final shape. Concrete's versatility allows it to be used in many construction applications from pavements to high-performance structures. These benefits have made concrete the second most widely used material on Earth after water [1]. As a construction material, concrete has a staggering global usage with over 30 billion tons produced worldwide in 2021 with growth expected to continue [2].

The benefits of concrete as a construction material need to be compared with its impacts on the environment and society. The production of cement, the main binder in concrete, accounts for 8% of all carbon emissions in the US [3]. Production of cement for usage in concrete has grown at a steady rate for the last century and projections for the usage of concrete are set to increase from 4.2 billion tons in 2021 to nearly 6 billion tons by 2050 [1]. A ton of cement produces approximately a ton of CO_2 emissions with roughly half the emissions linked to chemical changes the raw materials undergo to become clinker and 40% of emissions associated with the fuel used during production [4].

The impacts on society are exacerbated by the increasing amount of concrete used around the world. As society increases its usage of concrete, the costs of production and maintenance for sub-par quality concrete will increase, reducing financial resources available to fund other projects. The production of less durable concrete will act as a fiscal drag on state departments of transportation (DOTs) ability to maintain services within their state. In 2022, the maintenance costs for GDOT grew twice as fast as the overall budget, indicating maintenance costs are an increasing share of the budget which may strain the allocation of resources to other areas [5]. The American Society of Civil Engineers (ASCE) expects the cost of maintenance over the next decade in the US to be $2.5 trillion with 43% of roads in the nation in mediocre or poor condition [6]. Moving towards designing concrete for long-term performance will reduce the financial cost and environmental impacts for a critical material.

Figure 1 shows that the increase in concrete consumption is outpacing the growth of population, illustrating the importance of designing concrete that can perform for its full-service life. Concrete that does not meet the designed service life will increase costs as expanded maintenance or early replacement occurs. To decrease the financial burden associated with concrete, specifications that address long-term performance will decrease the long-term financial costs through reducing maintenance needs and extending service life.

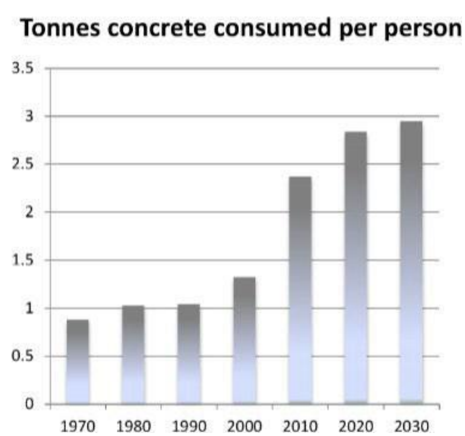


Figure 1. Graph. Global tonnes of concrete consumed per capita [7].

To regulate the production and placement of concrete that will meet the designed service life and function, state DOTs have standard specifications. Specifications around the country were created by their State Engineer's office and include the work of federal technical advisory committees as well as outside consultants [8]. The requirements in the specifications have been determined in the past to accurately predict the performance of concrete over time; however, the requirements in GDOT and other specifications have been shown to result in less durable and underperforming concrete [9].

The current GDOT concrete specifications for pavements and structures are best described as prescriptive because there are specific materials and proportioning requirements, along with minimum requirements for strength and workability, but without long-term performance measures [10]. The framework for prescriptive-based specifications relies on certain prescriptive measures like minimum cement factors and prescribed cement composition (e.g., ASTM C150 Type). These prescribed materials and proportions are intended by specifiers to be able to contribute to long-term durability by designing concrete that meets minimum strength requirements. It has been shown that these prescriptive measures alone are unable to do so, and result in concrete that may meet the designed strength requirements but is not necessarily durable enough to perform over the long-term [11]. Further, prescriptive specifications limit innovation in mix design and materials use. A newer method of designing specifications includes creating performance metrics that are predictions of long-term durability as a method to specify concrete performance. Performance-based specifications (PBS) are a fundamental shift in thinking from relying on specific material types and proportions to designing a concrete mix to meet performance limits without limitations on materials or proportions. No longer does the specification drive the mix design, instead the required concrete durability and performance determines the designer’s choices in materials and proportions. Further, as Beuhausen *et al* [10] explains in a recent review of this topic, rational performance design approaches facilitate innovation in concrete construction, contribute to effective quality control, and provide efficient means of conformity assessment of the as-built structure, since designs are based on the measurement of relevant concrete properties that can be used as input parameters in service life models to predict durability of the specific structure under consideration.

Since the first recorded use of concrete specifications by Vitruvius around 30 BC, the hardened properties of concrete have been most commonly specified through the constituents of the mix and its proportions [12]. Early prescriptive concrete specifications began by isolating which materials caused a strong cementing action along with quality controls on materials to reliably produce concrete [13]. The proportioning of materials in early concrete specifications relied on field judgements from mixtures that performed well at the time but did not use any rigorous testing for durability [14]. To design concrete mixtures that would meet the design requirements for strength and workability, early prescriptive-based specifications included high factors of safety, an example of which can be seen through the introduction of minimum cement factor as specified by the number of sacks of cement in the first ever Portland Cement Association specification from 1916 shown in Figure 2.

QUANTITIES OF MATERIALS REQUIRED FOR VARIOUS MIXTURES OF MORTAR AND CONCRETE

	MIXTURE MATERIALS FOR ONE BAG BATCH			RESULTING VOLUME IN CUBIC FEET		QUANTITIES OF CEMENT, SAND, AND PEBBLES OR STONE REQUIRED FOR ONE CUBIC YARD OF COMPACTED MORTAR OR CONCRETE				
							Sand		Stone or Pebbles	
	Cement in Sacks	Sand cu. ft.	Pebbles or Stone cu. ft.	Mortar	Con-crete	Cement in Sacks	Cu. Ft.	Cu. Yd.	Cu. Ft.	Cu. Yd.
1:1½	1	1.5		1.75		15.5	23.2	.86		
1:2	1	2.0		2.1		12.8	25.6	.95		
1:2½	1	2.5		2.5		11.0	27.5	1.02		
1:3	1	3.0		2.8		9.6	28.8	1.07		
1:2:3	1	2.0	3.0		3.9	7.0	14.0	.52	21.0	.78
1:2:4	1	2.0	4.0		4.5	6.0	12.0	.44	24.0	.89
1:2½:4	1	2.5	4.0		4.8	5.6	14.0	.52	22.4	.83
1:2½:5	1	2.5	5.0		5.4	5.0	12.5	.46	25.0	.92
1:3:6	1	3.0	6.0		6.4	4.2	12.6	.47	25.2	.94

(Based on tables in "Concrete, Plain and Reinforced," by Taylor & Thompson)

Figure 2. Illustration. Early mix proportion guidelines with minimum cement factor [15].

Modern day prescriptive-based specifications have several features that are inconsistent with a modern understanding of concrete and contribute to both limited useable materials and unnecessary overdesign of mixtures. Prescribed material standards limit the usage of new mix constituents. As innovative products come onto the market, a lack of standards can limit the selection of materials available and slow down construction. Prescribed minimum cement factors and maximum supplementary cementitious material (SCM) replacements result in the overdesign of certain concrete mixtures through requiring more cement than is needed for adequate performance as well as reduced sustainability and lower durability by limiting SCM usage [16]. A study by Buffenbarger *et al* [16] saw a 6.7% increase in cement usage across the US as a result of overdesign of mixtures to meet the current specification requirements. The impacts from specifying concrete using prescriptive-based specifications are less innovation in mix designs and increased costs to owners [17].

The construction of any structure in Georgia for the Georgia Department of Transportation (GDOT) is governed by a collection of standard specifications that inform contractors and suppliers on the allowable materials and procedures [18]. This collection of standard specifications strongly affects the costs and long-term performance of a structure through the construction materials and techniques allowed. Quality construction materials are linked with lower lifetime costs through reduced maintenance and improved lifespans [19]. Miller [19] saw a 14% reduction of greenhouse gas (GHG) emissions for more durable concrete through fewer required maintenance treatments and less frequent structure replacements. It is now increasingly expected for all new concrete structures in Georgia to have design lifespans approaching 100 years [20]. So, reducing the number and intensity of maintenance activities over that time is more necessary than ever to reduce expenses for the state. However, in order to qualify concrete mixtures using PBS to determine if the specified performance has been met requires additional testing during the initial design stages and field verification. Concrete producers will be required to make more samples and perform more tests than before which will increase the initial cost to qualify mixtures. These initial extra costs will likely be passed on to the project's owners through higher prices. Thus, it is important to quantify the additional expected costs from testing and the expected maintenance savings over the lifetime to justify GDOT adopting the proposed PBS.

A cost benefit analysis comparing the additional testing costs to the expected lifetime savings supports the proposed specifications to reduce long-term maintenance spending. Longer- serving concrete infrastructure is expected to create measurable environmental impacts resulting from the specifications. A life cycle analysis (LCA) allows for the comparison between alternatives through a set functional unit to determine how certain environmental factors change. Comparing the current prescriptive-based specifications and the proposed performance-based specifications through an LCA will allow for the change in environmental impact between the two specifications to be quantified. The environmental and social impacts calculated by the LCA support the proposed specifications as a method to reduce environmental impacts caused by state transportation infrastructure. Examples of environmental impacts are emissions resulting from the construction and maintenance of concrete pavements or structures, as well as other pollutants such as increased acidification and ozone depletion. The UN defines social impacts as “impacts on people” with a broader focus on how society is affected by a change [21]. There can be at times little distinction between environmental and social impacts, with increased in pollutants in the environment having a negative impact on people’s social wellbeing and health. However, examples of social impacts without direct ties to environmental impacts are reduced traffic from decreased amounts of required maintenance and safer roads through higher service levels [22]. The proposed specifications have been shown to reduce financial and environmental impacts from the current prescriptive specifications through improvements in durability and long-term performance. Using performance metrics in PBS will require additional testing and materials, offset by measurable increases in performance and service life. The net effect will create measurable environmental impacts from the specifications. A life cycle analysis (LCA) allows for the comparison between the current prescriptive-based specifications and the proposed performance-based specifications through a functional unit to determine how certain environmental factors change.

RESEARCH OBJECTIVES

This research concerns the potential for the adoption and usage of performance-based specifications for pavements and concrete structures for the Georgia Department of Transportation. The adoption of performance-based specifications is expected to improve the durability and long-term performance of concrete pavements and structures under GDOT's care. Redlined copies of the proposed specifications for Sections 430, 439, and 500 are included in Appendices B, C, and D, respectively.

The research objectives of this report are to:

1. Determine the current state of specifications across industry
2. Review promising performance metrics for use in performance-based specifications, quantify cost and environment-related savings associated with adoption of performance-based specifications
3. Produce draft performance-based specifications for GDOT Sections 430, 439, and 500.

CHAPTER 2. LITERATURE REVIEW

PRESCRIPTIVE-BASED SPECIFICATIONS

Introduction

Historically, concrete specifications have been prescriptive and based across state level departments of transportation (DOTs) as well as in international specifications [12]. The current concrete pavement and structural concrete specifications in the state of Georgia are best considered prescriptive-based specifications. Prescriptive-based specifications are used widely around the country both due to designers' and contractors' familiarity with and because of constraints imposed by owners. That is, contracting language often dictates reliance on prescriptive specifications. The development of prescriptive-based specifications is a process of using the past experiences of designers and constructors to create requirements for material usage and proportioning [23]. Requirements for materials have been refined over time using advances in concrete research to provide added insights on materials and their impact on concrete, but a lack of requirements geared towards long-term performance has persisted. Instead, collective industry experience and the performance desires of the project owners created a system of specifications that relied on historical results of materials to provide adequate performance.

Prescriptive-based specifications place the large burden of determining the material restrictions on the owners who are responsible for maintaining concrete elements over the long term. The GDOT Construction Standards and Details Book is published with periodic updates with the accepted standards and details [24]. While prescriptive-based specifications do not have an automatic, built-in method for accepting new materials, they are not static. GDOT issues supplemental specifications that have been altered to reflect new design requirements and industry practices. An example of this is the adoption of Type IL blended cement in accordance with ASTM C595 in 2021 as a supplementary specification. Issuing supplemental specifications allows updates to occur outside of the specification editing window for major changes that will provide GDOT with benefits, but this does not give the department the latitude to make changes to the specifications as material availability or quality change.

The development of specifications on allowable materials was first driven by the need to ensure quality materials were being used in construction and to minimize variability between batches [13]. Prescriptive specifications typically take a conservative approach; innovative ideas such as blended cements or higher SCM replacement values need to be conclusively shown to not have a detrimental impact over an element or structure's lifespan. This method does not prevent specifications from changing over time because a contractor or new research can demonstrate innovations that perform as well or better than the established method. An example of this is the recent allowance of Type IL cement in GDOT specifications after research showed similar performance with reduced environmental impacts [25]. However, prescriptive-based specifications change at a slower pace compared to performance-based specifications because the testing methods for performance are not built into the specifications. For example, a hypothetical concrete mix designed in accordance with the current GDOT standards would not be allowed to use an ASTM C595 Type IP blended pozzolan cement with the same proportion of fly ash as a mix using ASTM C150 cement with the fly ash blended at the batch plant. It has been shown as early as the 1990's during the development of blended cements that there is no meaningful difference between pre-blended cement and those combined at the batch plant [26]. Using a performance-based specification, a mix is not qualified based on the specific type of cement used, rather the satisfactory performance of the concrete in a series of tests is how a mix is qualified. As a result of this, performance-based specifications are more open to innovation because materials and their proportions can be tailored to meet the design needs without stifling innovative products.

Prescriptive-based specifications have typically relied on the compressive strength of concrete to be the leading indicator of performance [27]. In the past, this has led in some cases to specifying the strongest concrete possible for an application without regard for potential sources of degradation or environmental impacts. Because concrete is usually part of structural systems where it is expected to carry loads, the design strength is often the first and sometimes only design metric that is considered by a designer. A study by the National Ready-mix Concrete Association (NRMCA) showed that 46% of specifications currently had a minimum cement factor [28]. The intent of minimum cement factors is to guarantee minimum strengths, but it has been shown that a specified minimum cement content is not necessary to achieve required strengths and is potentially detrimental to durability with its higher paste content because of proportionally more pores [29].

Usage of prescriptive-based specifications across the country

Most state DOT standard specifications for concrete have been augmented by template specifications from the American Concrete Institute (ACI) or the Federal Highway Administration (FHWA). Figure 3 shows an example of typical prescriptive-based requirements from GDOT Section 500. Each class of concrete has a typical set of applications that the mix proportions have been designed for and a specified minimum 28-day strength. Note the minimum cement factor for each class of concrete precludes a reduction for cement per cubic yard of concrete even if the strength requirements can be met without it, potentially increasing the amount of embodied emissions associated with the mix. According to Elahi, M. *et al.* [181] minimum cement factors and the associated increase cement fraction are not responsible for increases in durability or long-term performance. Also, the current GDOT concrete standard specifications for both pavements and structures do not have performance metrics that would test for long-term performance, rather the performance of the concrete is indirectly controlled by the proportions and allowable materials.

English								
Class of Concrete	(2) Coarse Aggregate Size No.	(1 & 6) Minimum Cement Factor lb./yd³	Maximum Water/ Cement ratio lbs./lb.	(5) Slump Acceptance Limits (in) Lower - Upper		(3 & 7) Entrained Air Acceptance Limits (%) Lower - Upper		Minimum Compressive Strength at 28 days (psi)
"AAA"	67,68	675	0.44	2	4	2.5	6	5000
"AA1"	67,68	675	0.44	2	4	2.5	6	4500
"D"	57, 67	650	0.445	2	4	3.5	7	4000
"AA"	56,57,67	635	0.445	2	4	3.5	7	3500
"A"	56,57,67	611	0.49	2	4	2.5 (3)	6	3000
"B"	56,57,67	470	0.66	2	4	0	6	2200
"CS"	56,57,67 Graded Agg.*	280	1.4	-	3½	3	7	1000 (4)

Figure 3. Illustration. Section 500 Concrete Mix Requirements [30].

Figure 4 shows an example qualified mix based off of the current prescriptive-based GDOT Section 500 standards for class AAA concrete. Note that the mix design has cement proportioned exactly at the current minimum cement factor and the mix design is not site specific. This mix design has been qualified by the GDOT Office of Materials and Testing (OMAT) and would be usable by multiple concrete producers. A major benefit of a highly prescriptive concrete specification is the flexibility afforded to use a qualified mix design without going through a requalification process if material suppliers change. If the materials used within the mix meet the requirements in the concrete specifications, the mix proportion would not need to be requalified. Additionally, the class AAA concrete provided by this mix design would be expected to perform within the required strength and fresh concrete properties regardless of the concrete producer, allowing a contractor flexibility to switch producers during a project if supply constraints appear.

Class Concrete	Cement (lbs)	Fly Ash (lbs)	Slag	Sand Prim (lbs)	Sand Blend (lbs)	Stone (lbs)	Water (gals)	Design Air (%)	Accept Air LL - UL	F/A	Water Redr (oz) *	Retr (oz) *	Design Slump (ins.)	Accept Slump LL - UL	Max Water (gals)
Class AAA Concrete (1053926941)	675	0	0	1135	0	1859	33.0	4.0	2.5 - 6.0	0.38	Yes	Yes	3.0	2.0 - 4.0	35.7

Figure 4. Illustration. Section 500 Concrete Mix Proportions [31].

PERFORMANCE-BASED SPECIFICATIONS

Introduction

PBS are a fundamentally different framework for implementing specifications.

Performance specifications remove explicit allowances or disallowances of materials and proportions, instead using performance metrics as requirements that need to be met for the material to be qualified for use regardless of the exact materials in the mix. The development of the metrics that will accurately predict long-term performance of concrete is the main challenge to the successful implementation of PBS because the qualification of a mix is determined by its ability to meet the performance metrics. The hallmark of PBS is creating performance metrics that can reliably, quickly, and inexpensively measure the ability of concrete to perform in the field long-term. Performance metrics include workability, strength, and durability.

Because of the overall lack of consideration for durability in the current specifications, PBS, as seen in other states and international standards, focuses most on durability. The typical PBS uses a battery of performance metrics to test against known causes of degradation like freeze/thaw, sulfate attack, and chloride ingress. Additional considerations for PBS are the workability and strength of the mix design, elements that remain equally important along with the added focus on durability.

Workability requirements are typically unchanged for PBS, but the importance of ease of placement and constructability does not diminish with the adoption of PBS and typical measures such as slump. Workability has traditionally been measured using slump for concrete used in normal applications but with the rise of self-consolidating concrete (SCC), performance metrics for workability have been applied. For example, the ability for SCC to flow around rebar has been measured using the J-ring test and the ability to resist segregation of the aggregate from the paste has been measured using the stability indexes [32], [33]. While these measures are for specialized types of concrete, the use of performance metrics to qualify and verify a mix design provides owners with reassurance their concrete will perform as promised when delivered.

Further, workability is often improved through the complimentary adoption of other performance metrics that require higher SCM dosages to be met. For example, it was seen that usage of higher rates of fly ash to meet permeability requirements improved the workability of a standard Colorado DOT mix design [34].

The strength metrics become even more critical with the adoption of PBS because of the removal of minimum cement factors and designer's past reliance on them ensured strengths were able to be met [29]. The ACI Report on Performance-based Requirements for Concrete recommends specifying the in-place required strength as the performance metric for strength, in conjunction with the time at which that strength needs to be achieved to account for potentially slower strength gains with higher SCM dosages [35].

Most current mix design practice follows the ACI volumetric method which was developed to account for material variability and used historical inputs to inform future decisions [36]. However, relying on past performance to inform the decisions for innovations in concrete has not allowed for specifications to grow at the pace of materials innovation. For example, FHWA has begun to issue advisories that push for the adoption of specifications that can adapt to changes in industry and create flexibility for both owners and contractors [37].

A requirement for the development of PBS is for metrics that can accurately predict several determinants of long-term performance to be used in combination in specifications to give owners concrete that will perform as needed [38]. Day suggested that performance metrics be geared towards what the designers want in the concrete, whether being less susceptible to chloride ingress or showing higher sulphate resistance. The durability metrics used should measure exactly how the mixtures perform for permeability or sulfate expansion, with tests mirroring the desired properties of the concrete. Measures of concrete's fresh properties including workability and shrinkage are included within performance metrics because those have a high impact on the later performance of the concrete. For example, a concrete mix design that is susceptible to early age shrinkage may result in a less durable concrete over time as the cracks that develop at an early age allow for aggressive ions to enter. State DOTs such as Alabama have included shrinkage limits that specifically measure the ability of concrete to resist early age shrinkage with deviations from AASHTO test procedure to better account for plastic shrinkage [39].

Another way of thinking about testing was reported in a RILEM study on SCM reactivity where new testing methods were evaluated as possible future standardized methods. Each testing method was considered in terms of if the tests are rapid enough to qualify mixtures in a reasonable time, robust enough to measure how conditions may affect the concrete mix, and relevant towards how concrete is expected to degrade [40]. The so-called "R3" test method is among the approaches for evaluating SCM reactivity that could be used as guidance when developing performance metrics to ensure that the metrics have maximum impact for DOTs. Additional test methods that could be applied to PBS include acceleration of surface resistivity methods and modified R3 test method. Accelerating measures of surface resistivity has been shown to be able to detect the reactiveness of SCMs, but the process of accelerating surface resistivity measures could be broadly applied to increasing the speed of performance metrics [41]. By applying accelerated testing methods, the time needed for qualification could be reduced to be more similar to the current prescriptive specifications. The modified R3 test uses statistical analysis to reduce the amount and size of samples required to determine reactivity [42]. Applying the usage of statistics to other performance metrics would allow for easier mix qualification through a reduction in the scale needed to qualify as well as reduced testing burdens for 3rd party testers. Moving forward, it should be ensured that the performance metrics used within the PBS are state- of-the-art and apply the latest technologies to provide a seamless qualification and verification of mix designs.

Flexibility for adaptation to different environments and material sourcing

Performance-based specifications allow for flexibility in designing concrete mixtures through a reduction in prescriptive requirements; however, a potential pitfall is a lack of explicit requirements for external conditions. Examples of differing site condition considerations are freeze/thaw cycles, external sulfate concentrations, and actual service levels exceeding what was originally designed. The site conditions need to be specified within contract documents by the owner and project engineer, so the mix design is benchmarked against the performance limits for the conditions it is expected to face.

The current prescriptive specifications have no requirements to adjust mix designs for environmental conditions such as higher external chlorides in locations near the coast or higher concentrations of sulfates in soils or water. Mix designs following prescriptive-based specifications may use methods to improve performance such as different types of cements for sulfate resistance, but the specifications do not call out performance limits that must be met. PBS consider site conditions to inform the limits for the metrics to provide more durable concrete, and to ensure that the concrete being delivered will be able to perform in the given environment.

An added benefit of PBS is flexibility in qualifying and sourcing materials. Material availability has recently become more difficult to predict and limits on allowable types of cement reduce designer's and contractor’s ability to react to changing supplies. Prescriptive-based specifications include limitations on useable materials such as specifying Portland cement in accordance with ASTM C150 and only allowing certain blended cements in accordance with ASTM C595 as the current GDOT specifications do [18]. The restriction on cement decreases the supply of materials able to be used and may lead to increased costs when materials cannot be sourced [43]. PBS do not typically restrict the type of cement used and instead require performance metrics to be met using whichever materials are available. This provides flexibility to designers to qualify mixtures using materials that would not otherwise be allowed. The flexibility and increase in material supplies applies to SCMs as well because SCMs currently not allowed under most specifications such as reclaimed fly ash [44] and calcined clays [45] has been shown to match or improve current concrete performance. Usage of SCMs not currently permitted by the specifications that can meet the performance requirements in a concrete mix design would be able to be used in mixtures where they otherwise would not be allowed under the current specifications, providing additional sources of SCMs.

Potential for durability and sustainability in performance-based specifications

PBS use metrics that predict durability in addition to compressive strength to qualify concrete mixtures. Current prescriptive specification's focus on compressive strength and the indirect measure of concrete quality using strength has not been able to adequately predict the long- term performance of concrete. As shown by several studies during the early 2000's, high strength concrete did not guarantee durability would be improved [46], [47]. The term high-performance concrete was developed to reflect the need for concrete with higher strengths and resistance to aggressive environments. The focus on higher performance from concretes has culminated in ultra-high-performance concrete (UHPC) which has compressive strengths of at least 22,000 psi and typical w/cm ratios below 0.25 [48]. Additionally, deterioration has been likened to a negative feedback loop where the initial stages of deterioration cause physical changes to the concrete such as cracks that allow more aggressive damage to occur, spiraling towards unplanned early replacement of a structure [49]. Durability requirements drove the development of higher performing concrete as DOTs realized that most concrete structures and pavements were failing not due to low compressive strengths, but rather due to premature failure caused by low durability mix designs that were not able to perform over time in the environment [50]. Specifications that are written for higher performance and better response to aggressive environments slow the deterioration process for structures, decreasing the financial and environmental costs.

Current specifications generally do not have requirements that focus directly on improving the sustainability of concrete used on state projects. The issue of making concrete more sustainable has become a broader question of both environmental and financial importance, where several studies have shown more environmentally sustainable concretes made using higher SCM replacements or alternative binder compositions like LC3 have lower upfront environmental impacts and lower long-term financial costs due to decreased maintenance costs [51], [52]. An estimate of the financial costs of maintenance from Mehta, P.K. & Monteiro, P.J., shows that approximately 40% of the construction cost can be expected to be spent on maintenance and repair over the lifetime of concrete structures, costs which can be expected to increase as the design lives of structures becomes longer [49]. Improvements to the durability of concrete and the resulting reduction in maintenance will lower the lifetime cost of a concrete element.

Current national implementation of performance-based specifications

A review of the applicable sections in standard specifications from states and countries which have already seen some implementation of PBS was conducted to determine best practices and evaluate working examples of PBS. The states reviewed were Alabama, Virginia, Colorado, and Florida. The international specifications reviewed were from Japan, Australia, and Canada. Finally, proposed model specifications from federal agencies and industry groups including the FHWA and NRMCA were reviewed. A summary of each is included below highlighting key parts that distinguished each specification from other implementations and were thus critical to understand when crafting the proposed PBS for GDOT.

Alabama Department of Transportation (ALDOT)

The current standard specifications for ALDOT were adopted in 2022 with updates that included adding performance metrics for concrete pavement and structures [39].

Section 450 specifies Portland cement concrete pavements and has several innovative performance metrics and performance-based design criteria. The specifications include a limit on the total alkalis in the concrete of 4 lbs/yd^3 for mixtures without SCMs. It has been shown that limiting the total alkalis in the concrete rather than in the cement alone is more effective when using concrete with high amounts of cement [53], [54].

Table 1. Maximum Percent Mineral Admixture Replacement Section 450 [39]

Mineral Admixture	Percent Substitution (by weight)
Class C or Class F Fly Ash	30%
Ground Granulated Blast Furnace Slag (GGBFS)	50%
Microsilica	10%

Section 450 also allows higher amounts of SCM replacements compared to many other DOTs, as shown in Table 1. The amount of fly ash replacement is higher than GDOT's current limit for concrete pavements (15%), the GGBFS replacement is the same, and ALDOT allows the use of microsilica where GDOT currently does not. Microsilica, also known as silica fume, has been shown to reduce the permeability of concrete through reducing the pore size and refining the pore microstructure [55], but high replacement rates of microsilica are known to reduce the workability above 10% [56].

Section 501 specifies structural Portland cement concrete which is divided into classes of concrete with required compressive strengths and typical uses for each. The structural concrete section includes performance metrics known to improve the long-term durability of concrete such as drying shrinkage limits and permeability limits and has removed a minimum cement factor. The drying shrinkage limits are in place for cast-in-place structures that are considered critical such as box culverts and bridge superstructures, and ALDOT has provided an adjustment to the AASHTO T160 test where the initial reading is taken at 7 days to account for early-age length changes. It has been shown reducing drying shrinkage improves performance through reducing the permeability of concrete and preventing cracking [57]. The section also includes permeability as measured using Rapid Chloride Penetration Test (RCPT) for concrete placed within 10 miles of the coast. The specifications require concrete that may be exposed to external chlorides to contain some SCMs. Finally, the specifications do not specify a minimum cement factor for each class of concrete, leaving the amount of cement up to the producer. The minimum strengths for each class of concrete remain in force, and the strength test method requires the average cylinder compressive strength to meet the design criteria with no one cylinder below 95% of the standard.

Virginia Department of Transportation (VDOT)

The current standard specifications for VDOT were adopted in 2020 with updates to allowable hydraulic cement concrete [58]. Section 217 concerns hydraulic cement concrete which is used in both pavements and structures. The usage of the term "hydraulic cement concrete" shows a more expansive definition of cement which does not limit cement to only Portland cements. The specifications include permeability limits which apply to critical concrete elements like pavements and structures but not sound barriers or slope protection. This limits the qualification and testing requirements for concrete that does not have critical service levels.

Upper limits for SCM replacement rates are set based on the total alkalis in the cement, with higher levels of alkalis allowing higher replacement rates. However, Section 217 only allows blended cements via approval of the project engineer which limits the ability of producers to provide cement that has been shown to perform similarly with reduced environmental impact. Section 217 provides three methods to qualify a mix design: prescriptive-based via the ACI 211 absolute volume method, performance-based with no previous field experience, and performance-based with previous field experience. This is an innovative way to provide producers with multiple avenues to qualify a mix, even if it perpetuates a prescriptive-based design. The prescriptive-based design method qualifies a mix using compressive strength tests and a 3 yd^3 test pour for plastic properties. Following qualification, VDOT's quality control measures take over which may require permeability following qualification.

The performance-based qualification method has two options: with and without prior field performance. The major difference is that the method without prior field performance requires additional testing cylinders to establish statistical evidence that strength requirements are met. The performance-based methods waive the minimum cement factor which provides a potential cost and sustainability savings opportunity. Durability tests are not required for any of the three methods for qualification but permeability tests for specific classes of concrete are required for field verification. VDOT includes permeability along with strength in pay-for-limits. Strength is the governing qualification metric, with a reduction in pay for low strength concrete below certain limits and the potential for refusal and contractor replacement of concrete that fails strength tests. Concrete that has permeability exceeding the limits as measured by RCPT tests sees a reduction in price proportional to the exceedance of the permeability. Both strength and permeability have class specific limits. The reduction in pay is limited to 5% total regardless of how much the concrete may be over the permeability limit. VDOT's usage of a combined pay reduction is innovative and encourages the design for both strength and durability without overly penalizing concrete that fails the permeability test.

Colorado Department of Transportation (CODOT)

The current standard specifications for CODOT were adopted in 2022 with several recent revisions of interest for measures of sustainability and durability [59]. Recent revisions to the general specifications include adding EPD reporting requirements for concrete and steel placed on CODOT jobs larger than $3 million in total bid price and the addition of sulfate resistance to the structural concrete specifications [60]. Section 412 governs over concrete pavement and Section 601 over structural concrete. Concrete pavement calls for a specific class of concrete specified in Section 601, with class P or early-age strength concrete being specified. Quality control measures within the concrete pavement section are for the physical placement and construction methods used whereas the quality control program for the concrete is measured through Section 601.

Section 601 is the section that specifies hydraulic cement concrete for CDOT projects. 12 classes of concrete are divided by typical usage, and each has specific metrics such as compressive strength, air content, slump, and maximum w/cm ratio. The divisions include general concrete with different strength requirements, concrete for prestressed members, concrete for pavements and bridge deck resurfacing, and shotcrete. Requirements for each class of concrete are described in the specifications with some classes of concrete able to be substituted by project engineer discretion.

CDOT has incorporated several best practices for PBS and mix qualification. Several classes of concrete allow all blended cements in accordance with ASTM C595 standards with no added cement replacements. This practice includes SCMs in the mix which have several improvements to concrete durability while reducing the number of silos needed for a producer. Additionally, all mixtures call for permeability testing either using RCPT in accordance with ASTM C1202 or surface resistivity in accordance with AASHTO T358. The permeability limits are set at 2,500 Coulombs and 12 kOhm-cm, respectively, which is in line with moderate chloride ingression guidance from the FHWA [61]. Finally, for high strength applications, Classes S35 and S40 have shrinkage limits of 0.40% and Class S50 has a limit of 0.50% using a standard CODOT testing procedure similar to ASTM C157 [62].

Metrics for durability for concrete specified under Section 601 include sulfate resistance and permeability. Sulfate resistance is classified based on the site conditions with the contractor responsible for testing to determine the concentration of sulfates in the soil or water in accordance with ACI 318 limits. The maximum w/cm ratio is determined based on the sulfate exposure class with lower required w/cm ratios for higher sulphate exposure. The type of cement that is allowable for each exposure class depends on the expansion due to sulphate attack in accordance with ASTM C1012. Higher sulphate exposures require minimum amounts of SCMs (20% for exposure class S2 and S3) as well as Types II and V ASTM C150 cements. CODOT does not have specific requirements for which cement can be used for each exposure class, rather the expansion is limited to ensure that performance of the concrete can be met without restricting the cement that producers can use.

Permeability limits for concrete depend on the expected use of the concrete. Most classes of concrete under the specification call for charge passed and surface resistivity limits of 2,500 Coulombs and 12 kOhm-cm, respectively. The limits are more stringent for high-strength concrete classes with limits reduced to 1,500 Coulombs and 18 kOhm-cm for class S50. The charge passed values are measured at 56 days while surface resistivity is measured at 28 days. The producer need only use permeability to qualify the mixtures and the permeability values are not used as a quality control measure or pay factor.

Florida Department of Transportation (FDOT)

The current standard specifications for FDOT were adopted in 2023 with several recent revisions to the structural concrete specifications [63]. Concrete for pavements is specified under Section

350 and structural concrete is specified under Section 346. The updates of interest to the structural section include adding surface resistivity limits for concrete using highly reactive pozzolans, broadly increasing the allowable SCM replacement rate for all classes, allowing for concrete that exceeds the mixing time/rotation limits to be accepted by the project engineer if plastic properties are met, and allowing compressive strength acceptance at 56 days at the contractor's request.

Section 350 for concrete pavements calls for the use of concrete covered by Section 346 Class I concrete with a minimum compressive strength of 3,000 psi and a maximum w/cm ratio of 0.50. All pavement mix designs have a minimum cement factor of 470 lb/yd^3 which includes SCMs as a part of the cementitious materials factor. Pavements do not have performance metrics used for quality control in the field beyond compressive strength and measures of construction quality such as thickness and planeness.

Concrete used for structural purposes is governed by Section 346 with the classes of concrete divided based on the typical uses of the department. FDOT limits the allowable cement based on the exposure conditions and the component type, where component types are defined by FDOT as broad categories for bridge structures. The exposure classes are determined by the project engineer and the cements allowed can include those under ASTM C150 and ASTM C595. The replacement of cement by SCMs is required for all mixtures and the proportions for each are determined based on additional use categories with specific proportions depending on blend of SCMs used. Mixtures with highly reactive pozzolans such as silica fume, metakaolin, and ultra-fine fly ash have surface resistivity limits of 29 kOhm-m, a resistivity limit that does not exist for mixtures without those SCMs, potentially stressing the importance of durability in design for mixtures using highly reactive pozzolans. Compressive strength is the only hardened property used for quality control, but FDOT allows both 28-day and 56-day tests to be used for qualification. The use of 56 days is beneficial for qualification of mixtures with high SCM replacement rates and later, slower strength development but increases the verification time needed for a mix.

Current international implementation of performance-based specifications

International concrete standards have included performance metrics for decades with a broader focus on setting performance limits without limiting the materials used [64]. European standards have allowed Type IL blended cement since the 1970's and Canadian standards have focused on durability since the 1980's through specific guidance for durability [65]. Through understanding how international countries use PBS, the proposed specifications can benefit from their collective experience and best practices.

Japan

The current base standard specifications for concrete structural design in Japan were adopted in 2007 with several addendums, the most recent being in 2012, updating materials and design parameter changes [66]. The specifications call for the use of performance metrics for carbonation and chloride ingress in conjunction with service life modeling to determine the appropriate limits for each based on the size of members and cover. The determination of the limits is more variable compared to the specifications in the United States because of the design dependent on the element size. The amount of cover, and allowable difference in cover, changes based on the element's use and the expected structure lifetime in its respective environment.

The standards have some blanket limitations meant to improve the durability such as general limits on maximum w/cm ratios and requirements that all concrete be air entrained. The allowable cements include Portland cement with SCMs blended at the batch plant (JS R 5210) and prepackaged blended cements including SCMs and limestone (JS R 5211-5213). The standards provide commentary on which cement should be used in certain areas, with guidance suggesting the use of any cement that can meet the performance requirements for strength and durability at the lowest cost.

The specifications note mix proportions have no specific requirements beyond maximum w/cm ratios and the use of specific aggregate size and gradations depending on the structure being built. There are no limits on the amount of SCMs used for a specific mix design and no general minimum cement factors for strength. Minimum cement factors are used for mix designs that call for large aggregate sizes to ensure workability requirements can be met. The durability metrics used in the concrete mix design standards are chloride ingression and carbonation. The total chlorides in the concrete are limited to 0.30 kg/m^3 and the w/cm ratio is limited to a maximum of 0.45 for concretes where chloride ingress may be a concern. The total chloride limit is much lower than other comparable limits from around the world, which may limit the allowable cements and the total amount of cement in the mix design. The limits for carbonation are less defined and only specify that the rate of carbonation should be estimated based on the cover and the design should be adjusted accordingly. The Japanese standards do not prescribe many restrictions on the mix proportions or constituents, rather the project engineer could alter the mix depending on the expected conditions.

Interestingly, the Japanese standard specifications for concrete mix design reference specifications for maintenance which are specified methods to ensure the performance level of concrete structures is maintained regardless of exposure conditions. The standard specifications for maintenance detail typical causes of deterioration and best practices to address the decrease in service level [67]. The premise of designing for maintenance over the lifetime of the structure can be seen in Figure 5. The requirement in performance level over the structure's lifetime typically stays constant over an initial period with an increase stemming from increased demand on the system, modeled in the figure as the line labeled S. The actual performance level of the system is modeled as line R. The specific performance can be designed to be initially much higher than the required level with a later managed decrease in performance or as a set level of performance lower than in the first option that is maintained through service processes throughout the service life. A study by Tamon (2005) has shown the second option results in lower lifetime financial costs due to lower initial construction and design costs and the reliance on technological advancements over time to decrease the long-term maintenance costs.

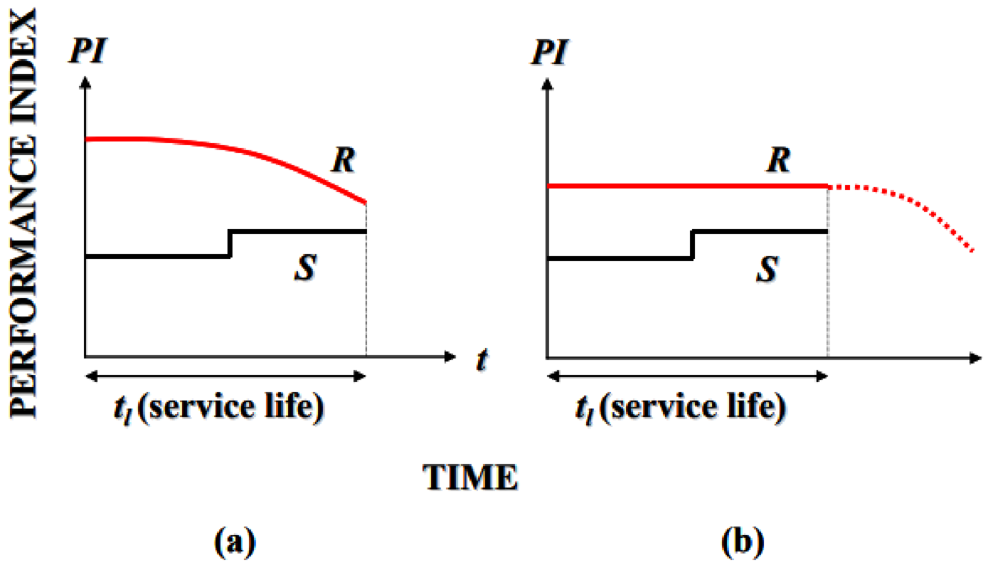


Figure 5. Illustration. (a) designing for steady decline in performance above the service limit and (b) ensuring maintenance keeps performance above limit [68].

Australia

The Australian specifications for concrete mix design were adopted most recently in 2018 under AS 3600 [69]. Concrete mix designs are split into either normal class or specialty class with the majority expected to fall under normal mixtures. Examples of specialty mixtures are high slump spread mixtures and very high early age strength mixtures. The Australian concrete specifications allow for performance-based cements that are governed by AS 3972 and have similar requirements to ASTM C1157 [70]. Both packaged blended cement and Portland cement blended with SCMs at the batch plant are allowed under the specifications for supplying concrete according to AS 1379 [71]. The AS 1379 specification does not set a required cement type but limits the amount of chloride within the concrete (set at 2.0 kg/m3), which indirectly determines which cement may be used depending on the mix proportions and chlorides in the cement.

Additionally, drying shrinkage is assessed within AS 1379 at early ages as well as 56 days with the limit for a standard sample set at 1000 microstrain. Design for durability within the Australian standards is based on the exposure class that each site experiences. This is determined based on the location of the project within the country as a baseline and with project engineer discretion based on local conditions. Figure 6 below shows how the country is divided into exposure classes. The division of the country represents the worst- case exposure classes for a combination of degradation methods including sulfate attack, chloride ingression, and acid exposure.

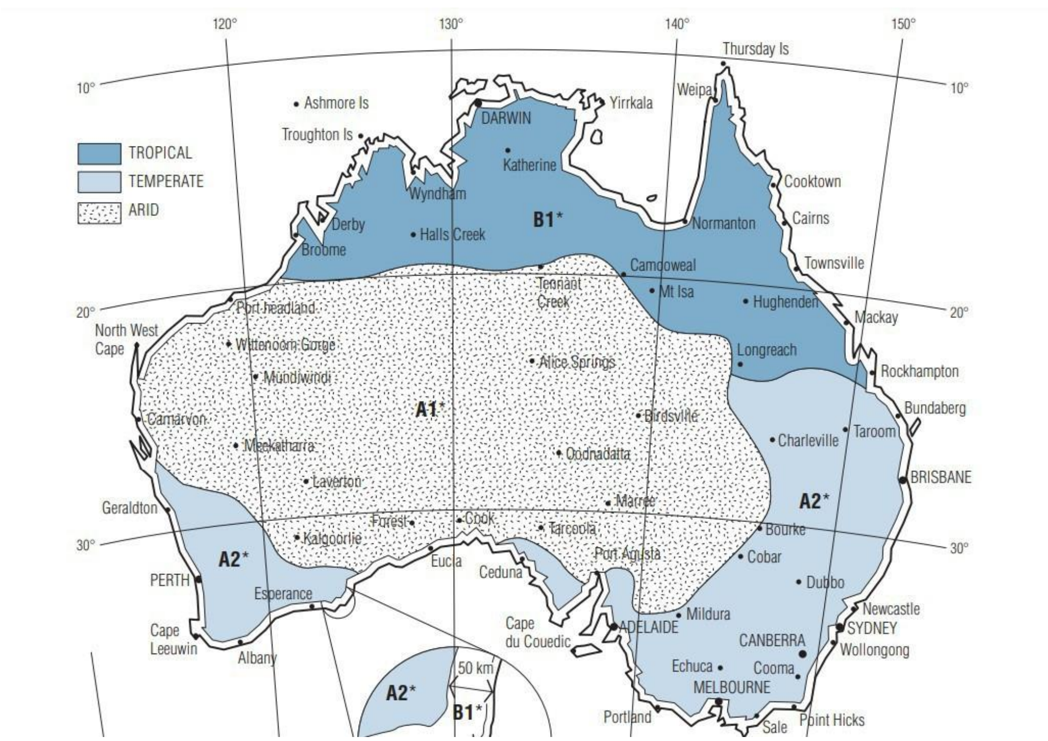


Figure 6. Illustration. Exposure class based on location [69].

Resistance to chemical attack is specified through qualification of mix designs using SCMs with differing levels of replacement and specific w/cm ratios based on the exposure class. Air entrainment is determined by the number of freeze/thaw cycles and the size of the aggregate. The minimum air content regardless of the number of cycles is 3%. For exposure to sulfates, the cement must pass expansion limits that differ based on the used cement, allowing the producer to tailor the mix design based on the available cement. The limits vary with more stringent limits for general Portland cement and lower limits with shorter testing times for sulfate-resistant cement as determined by the performance-based cement standard AS 3972. The minimum compressive strength and curing time for concrete exposed to sulfates is also determined based on exposure as determined by the country-wide exposure map. Under the Australian standards, the process of qualifying a mix includes producing trial mixtures designed to meet the performance requirements and then testing them against the performance metrics. A guide for qualifying mixtures suggests expecting 12 months to qualify mix due to long lead time for the sulfate tests and the potential need to redesign several times [72].

Canada

The Canadian concrete specifications are governed by specifications most recently updated in 2019 to include surface resistivity tests and new qualification methods [53]. Hooten, R.D. *et al.* [9] has described the Canadian standards as "among the most progressive" of concrete standards for their adoption of performance metrics. The Canadian specifications have permitted innovative materials into the specifications such as Type IL as early as 2005 and more recently UHPC in 2019 [73]. The specification of concrete in Canada is one of the most performance-based methods, relying on the performance metrics with location specific limits determined by exposure classes without major prescriptive direction to guide the design of mixtures. The CSA standards allow plain Portland cement, blended cement and performance cements if the concrete meets the performance requirements [53]. Like the Australian and Japanese specifications, Canadian standards include exposure classes for chlorides, freeze/thaw, sulphate attack, but have additional classes for acidic exposures and interior concrete. The exposure classes are determined not by location but rather by the project engineer's discretion and can be changed depending on the site conditions. Limits for chloride ingression are measured using RCPT and surface resistivity tests, and measurements are reported at 56 days but can qualify earlier if the contractor wishes to measure earlier. Freeze/thaw concerns are addressed using minimum air contents of at least 3% for all mixtures and higher air contents for smaller aggregates and more aggressive conditions. Sulfate resistance is measured using an expansion test similar to ASTM C1202 with a maximum testing time of 12 months. If the concrete expands either less than 0.10% at 12 months for S1 and S2 conditions or 0.10% at 6 months for the more aggressive S3 condition, the mix is qualified. Allowable cement types are limited based on the sulphate exposure with Type MS or moderate sulphate resistance or better required for all exposure classes. Resistance to acid exposure is specified through maximum w/cm ratios and minimum compressive strengths.

Verification of concrete mix design occurs primarily using strength tests but also includes permeability. Strength tests allow for a bonus payment to the contractor if the compressive strength of all samples is within 95% pay limits established in the design with the payment being a maximum of 5%. If the compressive strength of all samples is below the 90% pay limits, a penalty is assessed with the pay-for amount determined by the difference of the percent of samples below 90% of the pay limits. Limits for acceptable permeability are set by the design standard from the specifications but can be modified in the contract documents. Similar bonus and penalty payments are included for permeability.

Current industry group summary on performance-based specifications

National concrete trade groups and specification writers have long realized the need for PBS to be adopted to improve concrete performance. The NRMCA and AASHTO have created documents that have modeled best practices and procedures to design performance-based mix designs.

Understanding proposed PBS and modeled specifications will help guide the proposed GDOT specifications and align the proposal with national organizations.

NRMCA

NRMCA has advocated for increased adoption of PBS since 2012 through the Prescriptive to Performance (P2P) initiative and increased reporting of Environmental Product Declarations (EPDs) to increase transparency in the industry's environmental impact [74], [75]. An industry group dedicated to increasing the use of ready-mix concrete, the NRMCA understands the challenges that the industry faces with an increased focus on long-term performance and sustainability of concrete [75], [76]. NRMCA has developed checklists for developing performance mixtures and modeled changes that they believe if implemented would improve the ACI code.

The P2P initiative's focus is to begin the transition from prescriptive-based specifications to PBS using a combination of hybrid specifications in the short term and an increased adoption of full-fledged PBS over the long term. The goal is to begin laying the groundwork for performance specifications without bringing about confusion to an industry that is well-known for adapting slowly to change. Example research from the P2P initiative examines whether minimum cementitious factors are still necessary for required strength. This research has shown strengths are achievable without a minimum and improvements in durability are possible [28].

Another report from the NRMCA showed the addition of more rapid measures of durability such as resistivity and limits that adapt to the required performance can help drive adoption in state DOTs of PBS [77]. The P2P initiative has also focused on developing wider adoption of PBS through lobbying efforts directed at owners, producers, and contractors via webinars and presentations at conferences [78].

The efforts aimed at determining how to transition specifications towards performance- based and creating momentum from the organizations in a position to do so has culminated in a series of guides for selecting the exposure classes for performance metrics and commentary on model specifications in accordance with ACI. The guidance from NRMCA is to set the exposure class limits so the durability constraints are satisfied but no further to keep from overdesigning. An example of setting the limits for freeze/thaw indicate the project engineer should, by not "requiring a higher air content than that stated," see improvements in the durability and will not need to compensate for strength loss with an increase in cement [79]. The best practices for other exposures have been described with similar inputs from the project engineer and tests of the site conditions to determine which class each mix design will fall in. The model specifications the NRMCA has produced include suggested changes to ACI 318 to improve the durability response of mixtures. Examples of suggested changes are to include measures of surface resistivity in the specifications to determine chloride ion penetration resistance instead of pure w/cm restrictions and considerations on the critical nature of the element that will be formed to determine how stringent water-soluble chloride limits should be. The work done by the NRMCA has prepared DOTs and producers for increased adoption of PBS and created model specifications that include best practices for PBS.

AASHTO

AASHTO recently published a document guiding the design of performance-based concrete mixtures for pavements in 2022 based on the provisional document AASHTO TP84 [80]. The rationale behind developing this guidance was to design mixtures that met the performance metrics being developed as well as to provide producers with more flexibility to use innovative materials. The metrics proposed to measure performance include both compressive and flexural strength, shrinkage cracking, freeze/thaw resistance, and permeability as measured using formation factor. These metrics are intended to be used in conjunction with DOT specifications to reflect the local environment where the pavement would be located, but the main point of the chosen performance metrics is to measure how the mix design would be expected to perform as a pavement and to create mix designs that are able to perform at a certain service level.

The document does not provide recommendations for the types of cement used or limit the materials that can be used in the mix design, granting the producer maximum flexibility when determining what materials to use. The design process for a pavement following this guidance determines at the same time the proper cementitious materials needed to meet strength and durability requirements and the w/cm ratio that will allow the strength and durability requirements to be met. The performance metrics chosen are like typical ones seen in current state DOT specifications except for formation factor. Formation factor is the ratio between the pore solution resistance and the measured surface resistivity of the concrete, a ratio that isolates the physical surface resistivity of the concrete from the chemical affects from differing pore solution chemistries. The formation factor has been shown by Spragg, R. *et al.* (2016) to be a better measure of a concrete's ability to resist chloride ingression and provides a better comparison between concrete mix designs with less impact from potentially confounding factors such as aggregate proportion and SCM replacement rates. No instances of formation factor being included in specifications have been seen at the time of this review, but the inclusion of formation factor in an AASHTO practice would be expected to increase adoption in upcoming revisions to specifications.

Survey of current industry acceptance of performance-based specifications

To gauge the current usage of PBS and their application within state specifications, AASHTO

Subcommittee on Materials and Pavements (CoMP) distributed a survey designed by this project to state DOT officials. The survey was designed to probe the usage and limitations of PBS in current state standard specifications as well as to receive comments on the implementation of PBS from the respondents who indicated their states had done so. Figure 7 shows the results from AASHTO survey respondents. Approximately a third of respondents report no use of PBS for current applications. The remaining respondents report using PBS for concrete quality (33%), pavements (30%), and other applications (7%). From DOTs reporting usage of PBS, the plurality is using performance-metrics for quality control; however, no respondent indicated their state had used PBS at the time for project delivery. When drafting proposed PBS for GDOT, it is important to recognize how other states are currently using their performance standards. For example, because DOTs heavily rely on PBS to guide concrete quality, proposed specifications should verify concrete quality through setting limits on field verification using performance metrics. Potential proposals include pay-for limits based on the proposed resistivity performance metrics and increased use of statistical verification of compressive strength when verifying the field strength of a mix.

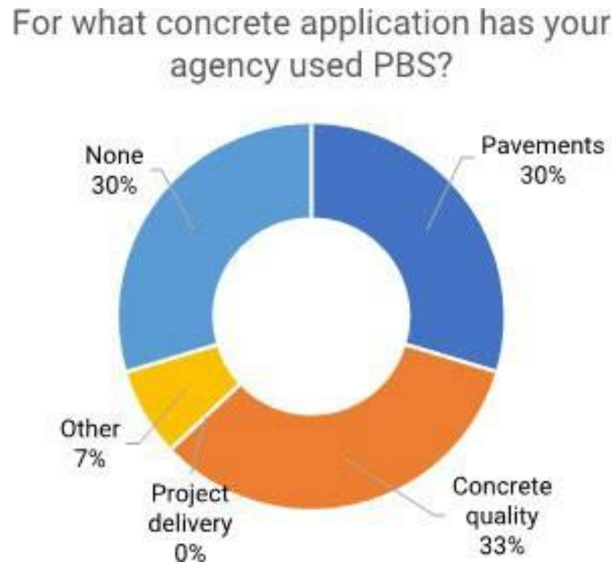


Figure 7. Graphs. Usage of PBS from AASHTO respondents.

Industry and DOT concerns with Performance-based specification adoption

Owners and producers have widely accepted PBS as the direction of specifications in the future with increased adoption by DOTs and initiatives like the P2P by the NRMCA [77]. However, there are concerns with PBS adoption due to uncertainty associated with the ability to predict field performance from tests, added time and costs required, unintended consequences seen when PBS are adopted, and difficulties with enforcement.

Concerns with the validity of lab-based performance tests have been seen in several studies with a focus on how testing conditions will be able to replicate conditions in the field [81] and how the mix design itself will perform in the field [82]. Initial studies have shown that mix designs can underperform strength and permeability when tested in the field compared to a lab setting [82]. The switch to PBS will increase the amount of testing needed to qualify a mix design compared to the current prescriptive specifications because proposed specifications involve previously untested performance metrics. One study estimated that testing time for performance-based tests can vary from hours to days [83]. A second study estimated that testing time and costs will decrease with PBS due to fewer samples being required and the use of tests such as surface resistivity which can be performed within minutes [29]. Though the degree to which performance testing will change testing time is not conclusive, the nature of requiring more tests seems to indicate that the testing regime needs to be managed by the producer in a way that limits additional testing time. By specifying performance metrics that are fast to perform and do not require much pre-conditioning of the samples, the specifications can reduce concerns over increased testing time.

It has been reported by Dihr, R.M. [183] that specifications play an important role in improving the durability of concrete and understanding the impact of changes in specifying materials, and these proportions can improve overall sustainability. However, it has been seen that specifications with better performance and durability as a goal may have unintended consequences such as reducing early age strength with increased SCM replacement rates and allowances of recycled wash water in specifications causing unpredictable set times [84]. The unintended consequences may extend beyond to reception from producers, with the proposed changes in specifications potentially reducing the ability for smaller and mid-sized producers to supply concrete as well as limitations in testing abilities compressing qualification timelines. This is a risk of changing the specification and is an unintended consequence of the proposed specifications.

As a part of the study for this report, an additional question was asked in the survey sent to AASHTO CoMP members on the limitations that their states saw in not adopting PBS. The responses are detailed in Figure 8. The major concerns from the surveyed state DOT officials reflected the general responses from conversations with the FHWA and industry practitioners.

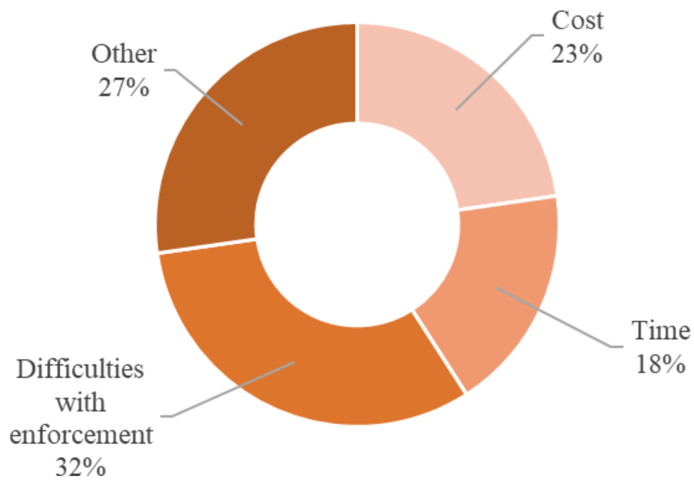


Figure 8. Graphs. Concerns with adoption of PBS from AASHTO respondents.

To provide GDOT with proposed redlined PBS, the concerns cited in the study were addressed throughout the project. Measures of cost and time were studied to compare between the current and proposed methods to determine to what extent the concerns were valid, and if so, how to improve the proposed specifications. Difficulties with enforcement were addressed in the proposed specifications through specifying standardized test methods and involving a pay factor reduction during the field verification process to signal the desire of GDOT that PBS is a focus moving forward.

Figure 9 below shows how likely DOTs were to use PBS if the concerns they had identified in Figure 8 were addressed through new specifications and what would need to occur for them to transition. Notably, none of them selected the “not use again” choice and the majority of responses indicated they would use PBS again.

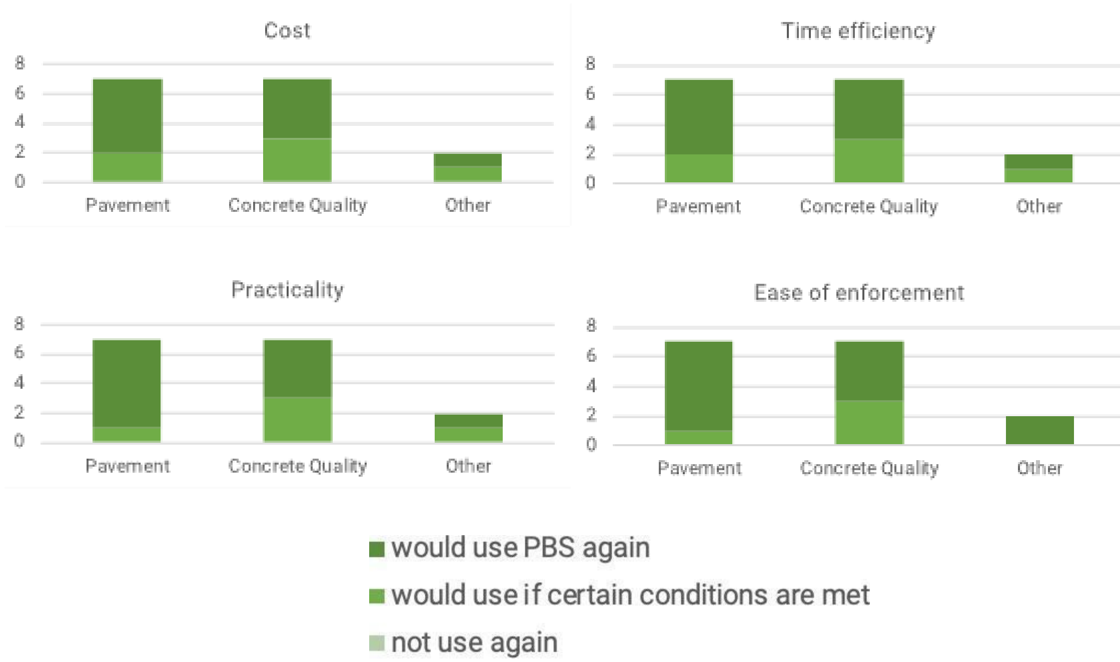


Figure 9. Graphs. Use of PBS if concerns were addressed. Y-axis is the number of responses.

The survey sent to AASHTO CoMP members indicates DOT officials generally see value in adopting PBS but there are concerns. These responses agree with results from the literature which show interest in using PBS due to the known benefits, but apprehension with moving to a new method of specification with different areas of risk [85].

Finally, DOT officials were asked how likely they would be to switch to PBS from their current method if they were able to reach the same level of performance. Figure 10 shows the results from 29 officials' responses. The plurality responded either with a level of likelihood or with "neither likely or unlikely", but only 7% were at some level unlikely to switch over. These results show officials are willing to switch to PBS if the same level of performance that structures and pavements can achieve now are able to be met using PBS. If the uncertain performance and concerns from the previous survey questions can be met, it appears state DOT officials see PBS as a viable specification type moving forward.

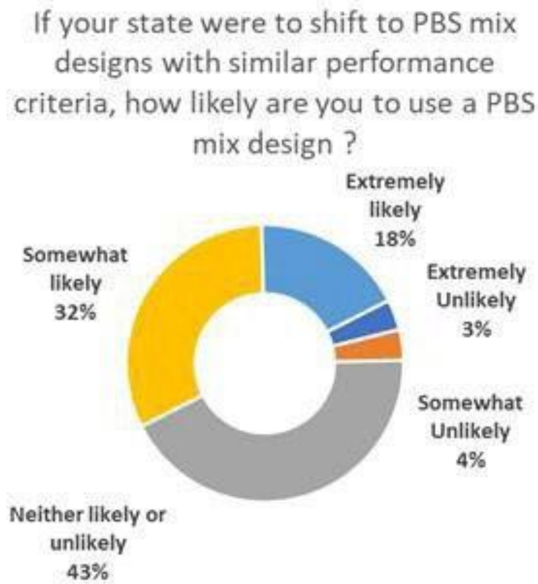


Figure 10. Graphs. Response to switching to PBS from current specification.

LIFE CYCLE ANALYSIS

Introduction

To assess the impact of proposed changes to a system as large as the specified concrete for the state of Georgia, a detailed analysis of financial and environmental impacts is necessary. LCAs are a method used to compare the environmental costs linked with alternatives [86]. The basis of an LCA is to quantify all the external impacts from the processes within a system and to tabulate total values for a set of impact categories [87]. The quantification of external impacts for a system relies on the ability to place a specific value for each process, some of which are difficult to quantify, as well as determine the long-term impact for objects that may not have historical data. LCAs began use as a tool to study energy flows in the 1970’s and create analysis on areas that could see efficiency improvements [88]. Two common misconceptions regarding LCA usage are that the results will inform the user if a product is sustainable and that an LCA will direct the user to which single process can be changed to reduce the impact of the system [89]. LCAs are effective tools to provide the user with data that shows a snapshot of the impacts but need to be coupled with an understanding of how decisions made in one process will affect another area.

An LCA occurs in several stages that have information on the system that needs to be identified before the analysis of data can begin. LCAs can broadly be divided into four main parts: the initial scope and definition, inventory analysis of impacts, an impact assessment of the processes, and the final interpretation of the analysis [90]. In the first stage, several items are clearly defined: the scope of the study, the functional unit on which all environmental impacts are calculated, and system boundaries. This guides the rest of the LCA but may see changes as the study progresses. In the second stage, the required inventory of resources for each process in the LCA is gathered. In the third stage, an impact assessment is conducted to connect the effects of each process to an appropriate environmental impact category. Finally, the results produced are used to provide conclusions and recommendations.

Environmental analysis on projects is currently relegated to impact assessments that occur during the project planning phase; however, as can be seen through Colorado DOT's adoption of mandatory reporting of material emission intensity for large projects, it is not unreasonable to expect that future PBS will include some form of environmental impacts from direct construction. The current proposal does not include mandatory reporting of EPDs for materials, but included in the appendix are sample calculations to make producers aware and assist with potential calculations. As PBS are developed and demand for more environmental impact reporting grows, the environmental analysis of construction materials will gain more importance and likely play a larger role in specifications.

The System Boundary

A system for a product made of concrete would be expected to include and track the materials from the quarrying stage of the raw materials, through production and transportation, to the batch plant and construction site, and finally through the maintenance and end-of-life stage. The life stages of the project can be seen below in Figure 11.

Product stage			Construction process stage		Use stage								End-of-life stage			
extraction and upstream production	transport to factory	manufacturing	transport to site	installation	use	maintenance	repair	replacement	refurbishment	operational energy use	operational water use	deconstruction / demolition	transport	waste processing	disposal of waste	extraction and upstream production
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	A1

Figure 11. Illustration. Typical LCA Project Timeline [75].

A cradle-to-gate approach includes the raw material and construction stages and has been generally preferred due to simpler data collection and lower uncertainty involved with production of materials [91]. However, studies show that there can be a significant impact on GHG emissions from the use phase and the end-of-life phase, showing the need to consider the entire life cycle of concrete to compare the long-term implications of different specifications [92]. Additionally, the use phase of a project is assumed to be the longest duration and typically sees the largest financial inputs for maintenance activities [93].

The long-term performance of concrete plays a significant role in the service life and the environmental impact during the service period [94]. Maintenance and repair can increase the amount of GHG emissions due to continued energy consumption over the lifetime of the structure, but higher levels of consumption during production may be offset by longer service lives which is expected to reduce the emissions when adjusted for total service life [95].

When modeling with an LCA, two main types can be studied: deterministic and probabilistic, where deterministic LCAs assign specific values to each process for every iteration and probabilistic LCAs calculate a range of options for the impact values [96]. A review of the literature showed the majority of LCAs are deterministic with reasons stemming from the lack of quantified uncertainty in industry data and the lack of statistical analysis capable of comparing process impact in a system [97]. Collecting uncertainty for impact data is difficult, with collecting data for general impacts a challenge in and of itself; however, without uncertainty being incorporated into an LCA, all that can be said of the analysis is that it is a possible measure of the impacts. Improvements to the data collection used for LCAs requires long-term collection of environmental impacts from a range of producers to establish uncertainty within the dataset. Because of the difficulties in estimating impacts from producers, most LCA databases use single values and account for the uncertainty through simulations [98].

Impact Categories and Industry Comparison though Product Categories

Impact categories are typically chosen for a specific project in order to capture the most pressing environmental concerns [99]. The choice of which impact categories to report can be determined by several methods determined by the industry using the analysis. For example, Esnouf, A. *et al* [99] has created a representativeness index that focuses on the correlation between impact categories. While the goal of reporting impact categories is to assess how a specific product influences the outside environment, comparisons between industries and even significantly different products will not allow for meaningful conclusions to be drawn. To determine the overall impacts from a product, data must be provided for each constituent in a standardized way accessible to all industry partners.

Environmental Product Declarations

Environmental Product Declarations (EPD) are provided by material producers to quantify the impacts each product has. An EPD allows for the impacts of a product to be traced through the usage of those products, allowing for the end consumers to quantify how decisions using those products affect the overall emissions of a project [100]. An EPD is like a food label that notes the constituents that make up a product and the expected environmental impacts from those materials. Figure 12 below shows an example EPD for cement. EPDs can be made to incorporate all the materials and processes involved in a product, such as concrete, and used to quantify the impacts from complex mixtures with many constituents.

Figure 12. Illustration. Example EPD for cement [101].

EPD adoption across the US has increased as owners of projects have begun to include requirements on the impact building materials and maintenance supplies have over the life of the project, as well as due to increased adoption of reporting requirements from end-users [102].

A growing number of producers and consumers of industrial goods have recognized the larger role industrial products can have on the environment which necessitates documentation for a wide variety of materials. The International Organization for Standards (ISO) has developed standards for which information needs to be reported on a product declaration in ISO 14020 and the procedures for the development of an EPD have been codified in ISO 14025 [103]. To produce an EPD for a specific industry, the parameters that are most affected by that industry need to be identified using a Product Category Rule (PCR). The development of PCRs is addressed by the ISO 14025 standard and are typically defined by industry members following a period of outreach to key industry partners [104]. An example of an approved PCR is the National Science Foundation (NSF) PCR for Concrete [105]. First developed in 2012 with the most recent update in December 2022, the PCR for concrete was a partnership between the NSF and the NRMCA. The document outlines specific requirements such as how each stage of the product’s use is reported and the required impact categories. The best practice in the concrete industry is to use the NSF-NRCMA Product Category Rules, so the same default data is reported and available for emissions impacts. The development of a PCR, and by extension EPDs that follow it, the emissions impacts of products can be tracked and reported to the end users of the product. While in the past there were concerns that the amount of data needed to report environmental impacts was not sufficient, there has been a major increase in the reporting of EPDs in the concrete industry. The NRMCA has compiled a database of nearly 3,000 EPDs from plants and mixtures around the US as well as geographical averages for the US [75].

From the collected data of many materials producers, industry average EPDs can be generated. This broad set of data, with many influences, can begin to account for minor differences in production processes to create a unified average. Averages exist for other countries as well, with the Canadian ready-mix association producing an industry EPD for Canadian producers [106]. It is important to track the differences between products to adequately compare the concrete's function. The idea of functional equivalence has been used within LCAs as a functional unit to ensure systems are being compared “apples to apples” [107]. The best practice in industry wide averages is to combine only mix designs that have equivalent properties such as designed compressive strength, air content, and SCM replacement levels. This provides equivalent analysis with even comparisons between mixtures produced for different purposes.

The NRMCA has produced industry average every two years which allows comparisons to be made across the wider industry and decisions to be informed based on industry trends. For example, the global warming potential (GWP), which normalizes global warming impacts from a variety of greenhouse gases, reported that 3,000 psi concrete without any SCM replacement has reduced from 264 kg CO2 per yd^3 in 2019 to 238 kg CO2 per yd^3 in 2021, a reduction of 10% [75]. This can be attributed to higher adoption of Type IL cements, but this analysis is possible only because the impacts of the production of concrete has been tracked using LCAs and the materials-used measured using EPDs. Finally, as seen in CODOT's requirement of EPDs reporting the impact on jobs worth over $3 million, the reporting of emissions for materials required for construction projects is not far away in the future. Reporting for construction projects may see LCAs and EPDs becoming more commonplace in specifications, with requirements for maximum environmental intensities a potential future part of specifications.

CHAPTER 3. DEVELOPMENT OF SURFACE RESISTIVITY/PERMEABILITY TESTING METRICS AND RECOMMENDATIONS

INTRODUCTION

Following the review of current US state and international PBS, several guiding principles for the recommendations for the proposed GDOT specifications recognized as “best practices” in other specifications were determined. The first principle is that performance metrics should be drafted as site-specific guidelines where limits are determined depending on the exposure environment. This guides the improvement in concrete durability through increasing the designed performance of the concrete according to external factors. The second principle is that the chosen metrics should relate to common causes of concrete degradation. This allows providers methods to measure and reflect the potential of the mix to resist deterioration. The final principle is that the testing procedures used to measure each of the performance metrics should be a standard accepted by GDOT (i.e., AASHTO methods). This is necessary for the proposed specifications to be adopted by DOTs and see the metric measured across laboratories consistently. Performance metrics were developed that addressed these three guiding principles and were updated with feedback from industry and GDOT stakeholders as summarized in Appendix A.

Over the course of the project, several rounds of testing were conducted toward developing surface resistivity and permeability limits that reflected the current mix designs and usages, statistical analysis to aid with field verification of strength tests, and time trials for resistivity as a proxy for performance metrics in qualification and verification of mix designs. Ultimately, the purpose of this testing is to determine limits for performance metrics that are representative of GDOT concrete mixtures and to develop holistic durability metrics for the specifications while ensuring the implementation of the PBS metrics will not detrimentally affect the qualification processes.

DEVELOPMENT OF RESISTIVITY AND PERMEABILITY LIMITS

Mix design used in limit development and validation

The proposed performance metrics were developed using mix designs from qualified GDOT mixtures and reviews of literature on mix designs undergoing similar tests to provide a large dataset for mixtures. Table 2 shows the mix designs tested for development of surface resistivity limits. Added mix designs from the literature were included from work done by Nadelman and Rios because the mixtures used were GDOT approved mix designs with a variety of cement types and SCM replacement rates, and surface resistivity results were reported [108], [41]. The mix designs were used when experimentally measuring surface resistivity and estimating the pore solution to develop limits for each class of concrete for Sections 430, 439, and 500.

Table 2. Mix designs used for development of surface resistivity limits

	W/cm Ratio	Mix Name	Water (lb/yd³)	Cement (lb/yd³)	Fine Aggregate (lb/yd³)	Coarse Aggregate (lb/yd³)	SCM (lb/yd³)
This project	0.465	Class A PC*	284	611	1167	1873	0
		Class A Type IL	284	611	1167	1873	0
		Class A 20% F	284	489	1167	1873	122
		Class A 30% F	284	428	1167	1873	183
		Class A 20% C	284	489	1167	1873	122
		Class A 30% C	284	428	1167	1873	183
		Class A 10% MK	284	550	1167	1873	61
		Class A 15% MK	284	519	1167	1873	92
		Class A 20% MK	284	489	1167	1873	122
		Class A 5% GBFS	284	580	1167	1873	31
		Class A 10% GBFS	284	550	1167	1873	61
		Class A 20% GBFS	284	489	1167	1873	122
		Class A 40% GBFS	284	367	1167	1873	244
	0.60	Class B PC*	284	470	1286	1873	0
		Class B Type IL	284	470	1286	1873	0
	0.445	Class AA PC*	282	635	1124	1859	0
		Class AA Type IL	282	635	1124	1859	0
Nadelman	0.445	AL	283	635	1260	1889	0
		AL 15% F	281	537	1260	1889	95
		AL 15% C	281	537	1260	1889	95
		BL	283	635	1260	1889	0
		CL	283	635	1260	1889	0
		CL 15% F	281	537	1260	1889	95
		CL 15% C	281	537	1260	1889	95
		DL	283	635	1260	1889	0
		EL	283	635	1260	1889	0
Rios	0.40	PC*	340	850	1000	1738	0
		20% F*	340	680	1000	1738	170

*mixtures based on Portland cement – all others based on Type IL cement

The collection of mix designs that were performed on this project differ based on the replacement rate of SCMs and the class of concrete. A wide range of SCMs were tested with both Class C and F fly ash, metakaolin, and slag used within the dataset. The replacement rate for both Class C and F fly ash were 20 and 30% by mass, which exceeds the current allowable rate for pavements and structures but is in line with rates allowed by comparable specifications. Metakaolin was used as a widely available natural pozzolan at dosages of 10, 15, and 20% by mass. Slag was replaced at rates of 10, 20 and 40%, the latter replacements in line with the current GDOT specifications. The samples with SCMs were tested with Type IL cements in a Class A mix. Control mixtures using Portland cement (PC) and Type IL cement without SCMs were tested to establish a baseline for plain mixtures. To establish the impact of classes of cements on surface resistivity and pore solution, plain mixtures using Portland cement and Type IL cement were tested for Classes B and AA in accordance with Section 500. For the cements experimented on in this project, there were two types: a PC cement (Type I/II) and a Type IL. The PC was sourced from Argos (Roberta, GA). The Type IL cement was also sourced from Argos (Roberta, GA). The Class C fly ash was sourced from Boral Materials (Juliette, GA), and the Class F fly ash was also sourced from Boral Materials (Cartersville, GA). The Metakaolin was sourced from BASF (Gordon, GA) and was marketed as Metamax. The coarse aggregate used was granite #57 stone with an MSA of 1” with a specific gravity of 2.65. The fine aggregate used was natural sand with a specific gravity of 2.63 and a fineness modulus of 2.4.

The mixtures from Nadelman and Rios were designed in line with GDOT standards and were used both to expand the dataset for setting surface resistivity and permeability limits and account for natural variability between different “producers” of concrete. The mixtures from Nadelman conform to Class A concrete from Section 500 and were made using Type IL cements. Different Type IL cements were used with 0 and 15% fly ash. The mixtures from Rios were also designed in accordance with Class A concrete in Section 500. These mixtures were chosen to expand the control set without any replacement to create a more robust baseline from different experimenters. The PC used by Rios was sourced from Argos (Roberta, GA), and the Class F fly ash was sourced from Boral Materials (Cartersville, GA). The cements used by Nadelman were anonymized from five different sources in the southeast. All five used were Type IL cements.

Material Characterization

Table 3 below shows the XRF data for the cements experimented on in this project and collected from the literature. Table 4 below shows the XRF data for the SCMs used in each of the respective mix designs. Gaps in analysis of values from the literature reflect minor differences in measurement techniques between papers where the sensitivity for the collection of data may have been lower.

Table 3. Phase and oxide content data for cements

	This project		Nadelman [108]					Rios [41]	
Component	Type I/II	Type IL	AL	BL	CL	DL	EL	Type I/II	Type IL
C_3S	55.13	53.3	50.8	54.3	52.7	53.5	61.9	55.13	53.3
C_2S	18.39	14.1	17.3	15.3	17.9	15.3	7.6	18.39	14.1
C_3A	6.77	3.6	3.3	2.6	1.5	5.0	3.9	6.77	3.6
C_4AF	9.56	12.1	9.3	13.5	12.1	10.8	10.3	9.56	12.1
SiO_2	20.86	17.58	17.1	18.2	18.6	18.5	18.2	19.2	17.58
Al_2O_3	4.54	3.89	4.2	4.6	4.6	4.5	4.3	4.5	3.89
Fe_2O_3	3.13	3.96	2.9	4.2	3.5	3.3	3.2	3.0	3.96
SO_3	3.1	3.27	3.3	3.2	3.2	3.2	3.0	3.1	3.27
CaO	62.86	63.66	62.1	62.9	62.4	63.3	62.2	62.8	63.66
Na_2O	0.09	0	0.4	0.3	0.4	0.4	0.5	0.5	0
MgO	3.26	6.38	3.1	1.1	1.5	1	2.8	3.6	6.38
K_2O	0.44	0.27	-	-	-	-	-	0	0.27
P_2O_5	0.07	0.05	-	-	-	-	-	0	0.05
TiO_2	0.22	0.27	0.3	0.3	0.3	0.2	0.2	0.3	0.27
SrO	0.04	0.12	-	-	-	-	-	0.4	0.12

Table 4. Phase and oxide data for SCMs

Component	This project				Nadelman [108]	
	Class F	Class C	Slag	Metakaolin	Type F	Type C
C_3S	To be updated as data is processed					
C_2S						
C_3A						
C_4AF						
Amorphous Content						
SiO_2	55.5	34.9	37.8	45.14	51.3	34.57
Al_2O_3	18.6	17.6	7.91	40.72	23.32	18.78
Fe_2O_3	11.3	5.9	0.72	0.39	13.31	5.52
SO_3	1.0	2.0	0.79	0.05	0.48	1.98
CaO	6.4	28.1	36.81	9.41	2.75	26.41
Na_2O	1.2	1.6	0.51	0.21	0.82	1.92
MgO	1.4	6.0	11.44	0.06	1.03	6.6
K_2O	2.6	0.5	0.3	0.11	2.43	0.47
P_2O_5	0.5	0.9	0.5	0.05	0.48	1.14
TiO_2	0.9	1.3	0.5	1.94	1.25	1.39
SrO	0.1	0.4	0.1	0.01	0.13	0.11

Surface Resistivity Methodology

Surface resistivity measurements were performed using a 4-probe Wenner probe following AASHTO T358 procedure which allows for quick determinations of a sample's surface resistivity [109]. The surface resistivity of concrete has been correlated with a concrete mix design's durability by Tanesi, J, and Ardani, A. as a method to quickly measure the permeability of concrete and its resistance to chloride ion penetration [110]. The test for surface resistivity measures the voltage difference between two probes in response to an applied current using a 4-probe Wenner probe [111]. The spacing between the probes influences the reading and is standardized at 1.5 inches by AASHTO T358 [109]. Figure 13 shows how the Wenner probe uses voltage difference between probes in response to an applied current.

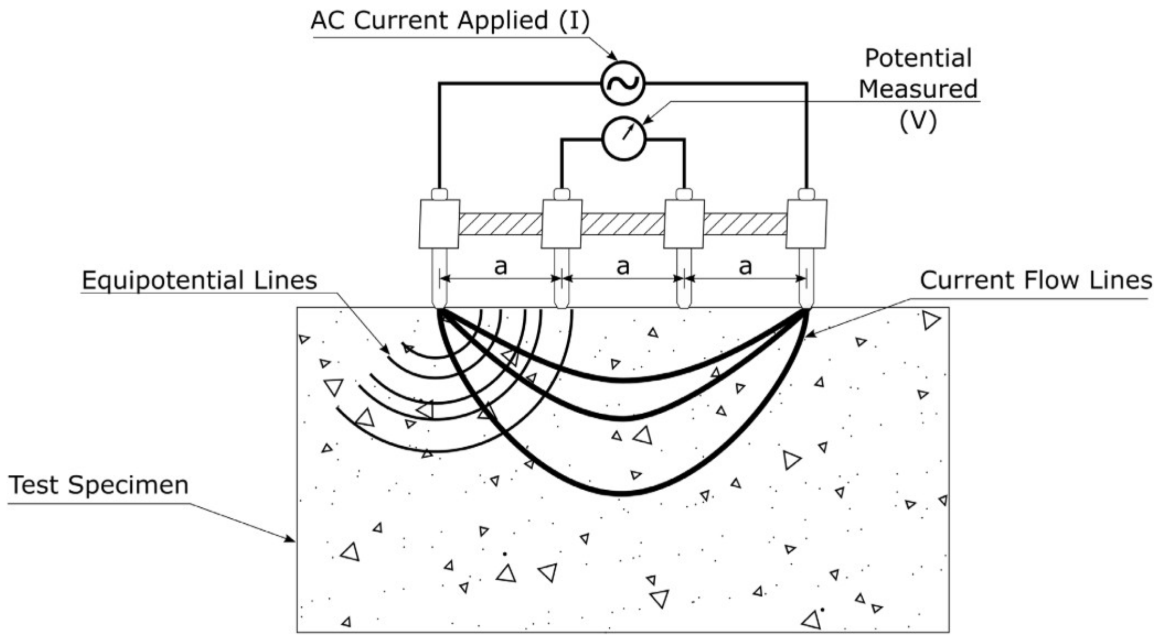


Figure 13. Illustration. 4-probe Wenner schematic [109].

Equation 1 shows Ohm's law, where with a constant voltage (V) and a known current flow (I), the resistance (R) can be determined. Using this principle, the surface resistivity can be measured using the Wenner probe with known voltages and currents.

$$\text{Equation 1:} \quad V = IR$$

The measurement is reported in kOhm-cm and the limit for moderate chloride ion penetration surface resistivity is >12 kOhm-cm per FHWA guidance [109]. The Wenner probe used was a Screening Eagle Proreq Resipod shown below in Figure 14 testing a standard sample.

Figure 14. Photo. Proreq Resipod.

Three 4” x 8” cylinders were made for each mix design following AASHTO R39 [112]. The samples were left to cure in the laboratory for 24 hours before being demolded and placed in 5-gallon buckets with a prepared saturated limewater curing solution made in accordance with AASHTO T358. The three replications of the same mix design were placed in a single 18.9-liter (5-gallon) bucket. Baseline measurements were taken initially following demolding, then daily until day 14, followed by measurements on days 17, 21, 24, and 28, before weekly measurements until day 56, similar to the approach in Nadelman and Kurtis [187]. AASHTO T358 does not provide guidance for when testing should be halted since this test is often performed at a single age, but the literature indicates most adopted specifications use day 56 results as the measure of surface resistivity. The additional measurements made before day 56 were done to investigate the time dependence of resistivity development and to determine if an earlier measurement time could be established. In conjunction with the results of the literature review, day 56 was determined to be the preferred reported measurement.

Results: Surface Resistivity

The cement-only mix designs were tested to determine the difference between measured resistivity in concrete classes. PC and Type IL cement mixtures were tested for Classes B, A and AA for a total of 6 sample sets. The results are shown below in Figures 15 and 16.

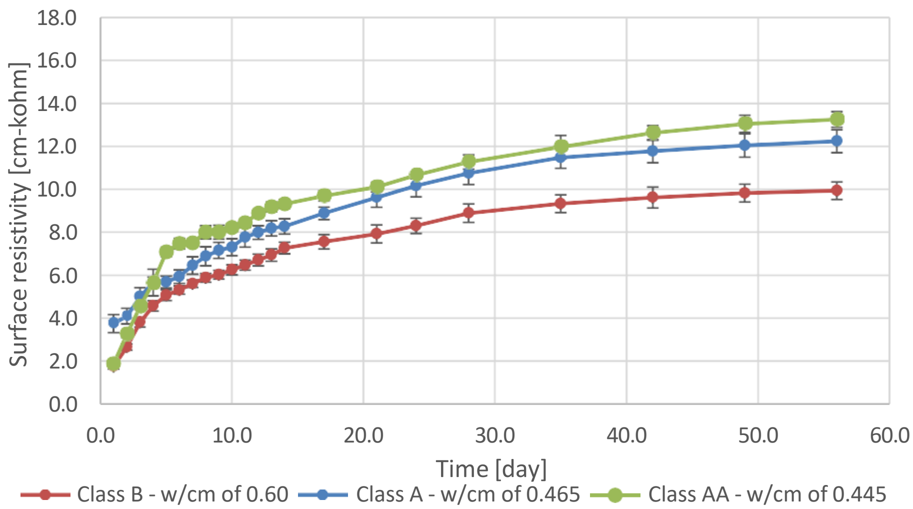


Figure 15. Graphs. Type IL limewater curing.

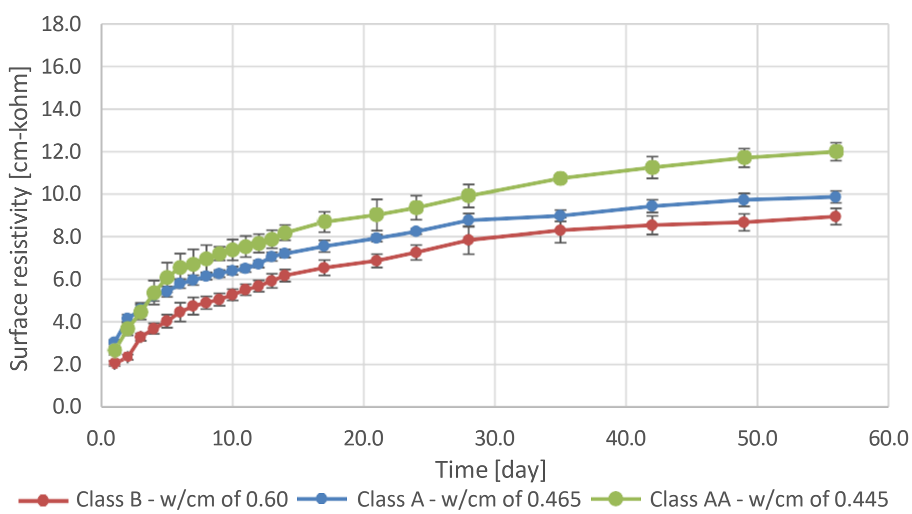


Figure 16. Graphs. PC limewater curing.

Figures 15 and 16 both show higher classes of concrete, which have higher cement factors and thus a higher paste content, exhibiting higher resistivity at all days. The difference in resistivity may be connected to the larger amount of paste, where the pore solution exists. The pore solution is the dominant factor for determining the surface resistivity of a sample because of the interconnected pores and the ionic pore solution itself, as well as the highly resistive nature of aggregate causing current to flow through the paste [108].

Figures 17 and 18 below show the impact of SCMs on the measured surface resistivity for Class A concrete using Type IL cement with SCM replacement, all with the same w/cm ratio of 0.465. Type F and C fly ashes were used at 20% and 30% replacement as well as metakaolin at 10% replacement. All mixtures using SCMs were made with Type IL cement to reflect growing usage in the state. Figure 18 excludes the results of metakaolin to show the surface resistivity development of the other SCMs with more detail.

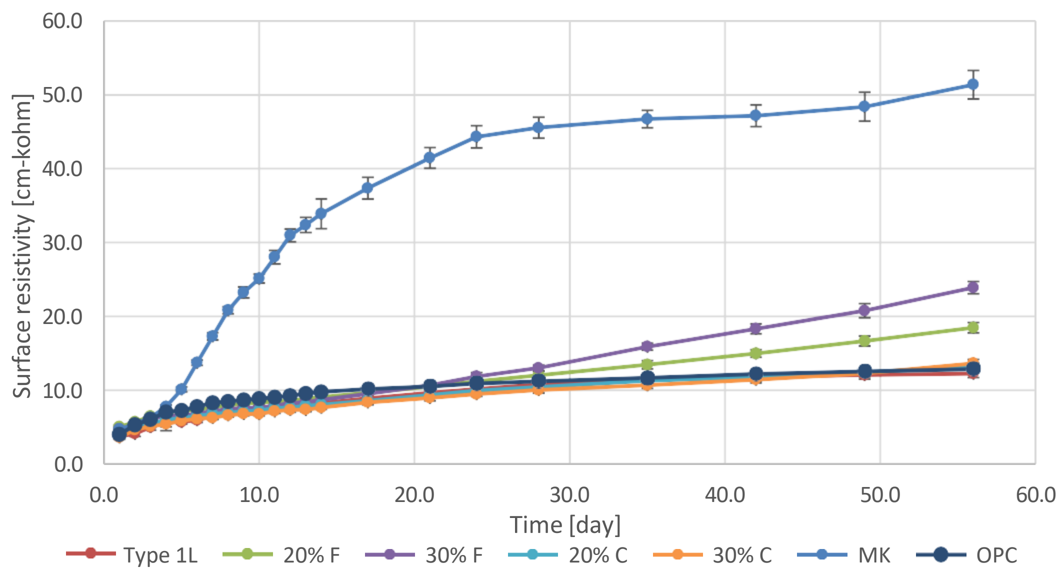


Figure 17. Graphs. Type IL limewater curing with SCMs in class A concrete, with same w/cm of 0.465.

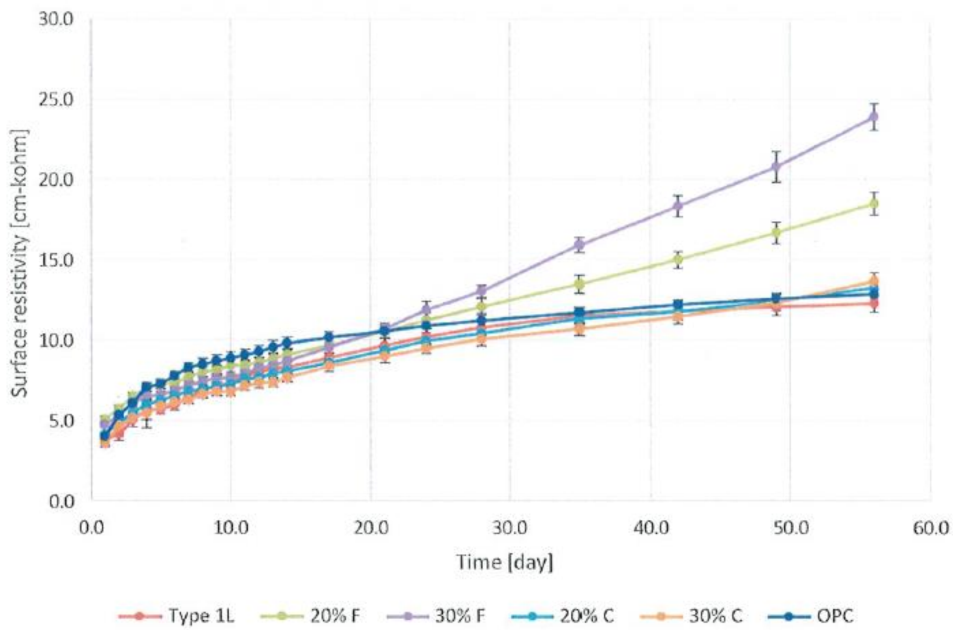


Figure 18. Graphs. Type IL limewater curing, excluding the metakaolin mixture in Figure 17, from the graph in class A concrete, all with same w/cm of 0.465.

Figure 17 and 18 above show how SCMs can increase the surface resistivity of the samples above the controls (plain PC and Type IL mixtures). The later pozzolanic reaction refines the pore structure which increases the surface resistivity of the concrete paste. The reactions would be expected to change the resistance of the pore solution and to determine how the pore solution changes with differing SCMs and dosages. Modeling of the constituents and concentrations were done using CEMGEMs software [113].

Pore solution modeling using CEMGEMs software

The composition of concrete pore solution can be either calculated experimentally or modeled using the chemical composition of the concrete constituents. Kulik, D. A. *et al.* [116] found thermodynamic models, such as CEMGEMs, can accurately predict the hydration kinetics for cementitious systems compared to experimental results obtained through pore fluid extraction under pressure. Modeling the final pore solution composition allows for the conductivity and thus resistivity of the pore solution to be calculated based on its concentration of ionic species. Alternative methods of expressing the pore solution have been researched, including high pressure extraction and more recent developments in cold water extraction [114], [115]. Pore solution composition determination by extraction methods has been shown to vary based on the methods used as well as exhibiting high variability depending on the temperature at the time of extraction [115]. Also, as water-to-cement ratios decrease, pore solution extraction becomes more difficult and, in some cases, cannot be achieved. Because of the variability and use of published data in combination with new mixtures, it was determined using CEMGEMs software to estimate the pore solution of the paste using a similar protocol for all the mixtures would result in an accurate estimated pore solution without impacts from the experimental differences. The parameters used in the model used the same degree of hydration, curing temperature of 23 C, and estimated pore solution makeup at 56 days. The pore solution composition was determined using the material characterization available for all materials in the experimental mixtures in this project and those from literature mix designs as inputs into CEMGEMs software.

The modeled designs included all experimented mixtures and the designs collected from the literature. The 27 total mixtures split among several GDOT class concretes and different SCMs usages. Additionally, Type IL mixtures from Nadelman and Rios used different cement sources, allowing for assessment of how different cements would be expected to change the pore solution resistance and thus affect the surface resistivity. Figure 19 shows the modeled pore solution resistivity for the studied concrete mixes. The black bar for each mix design shows the results for the PC control mix with cement only and all the others are either control (Type IL) or those with SCM replacement.

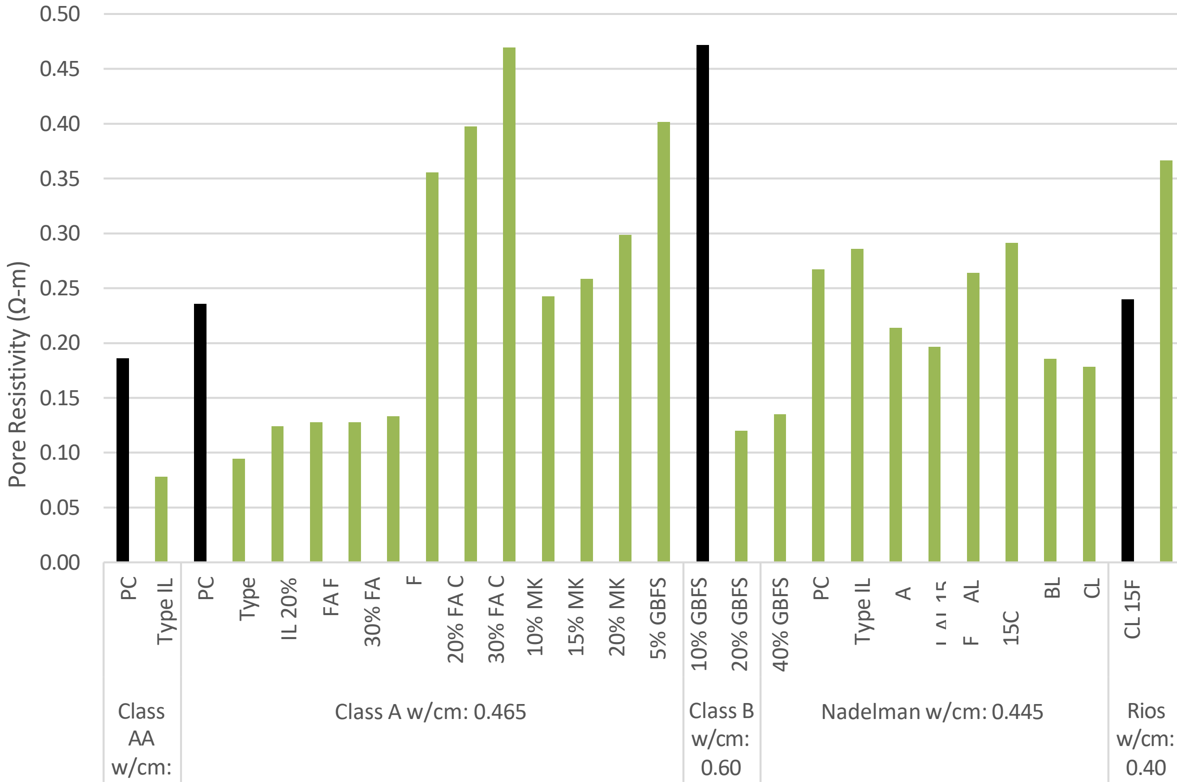


Figure 19. Graphs. Modeled pore solution resistivity (Ω-m) at 56 days.

The modeled pore solution results are similar to values for experimental and modeled pore solutions from the literature. Teymouri, M. & Shakouri, M. (2023) found a range of modeled pore solutions from .11-.18 Ω-m for mixes with a constant w/cm ratio of 0.48 with varying amounts of corn stover ash. Additionally, Chang, M. *et al.* (2019) found a range of experimental and modeled pore solution using CEMGEMs software of pore solution resistivities ranging from .055-.193 Ω-m for mixes using a Type I cement at a w/cm ratio of 0.36. Finally, AASHTO R101 suggests a value of 0.127 Ω-m as an assumed value for the pore solution when measuring formation factor, suggesting that value as a stand-in for pore solution where modeling or experimental methods are not possible [80]. The modeled values from the work conducted for this project are similar to the values from the literature, showing agreement in the order of magnitude with the differences between the classes and SCMs to be discussed further.

There are several trends that can be seen in Figure 19 with regards to the estimated pore solution resistance. The modeling of the pore solution is an estimation for hydration kinetics and may not reflect the resistivity of experimentally extracted pore solution. However, it has been shown that modelling software using Gibbs free energy minimization has correlated well with experimental data in the past [116]. While the modeling reduces the need for physical testing, it was important to ensure the assumptions made for the physical and curing conditions reflected conditions expected during experimentation. The physical properties of the material were referenced with the material data sheets where reported and material averages were used where direct producer data was not.

First, the higher amounts of cement in higher class concretes tends to increase the pore solution resistivity among both concrete with plain PC and Type IL mixes. This may be caused by the higher amount of cement and lower w/cm. To be as conservative as possible, the mix designs used the maximum w/cm ratio for each class of concrete to reflect the least permeable mix for each class. Higher amounts of cement contribute greater ionic concentrations in the pore solution which decreases the pore solution resistance. The higher-class concretes have higher strength requirements and have a higher prescribed minimum cement factor to achieve that. The average difference of PC and Type IL in the estimated pore solution for Class AA and A is 9% and between Class A and Class B is 37%. This difference shows, when coupled with differences in concrete microstructure between samples, that the pore solution resistance varies widely between the classes of concrete. The difference between the estimated pore solution resistance of plain PC and Type IL for all classes shows a slightly higher estimated pore solution for the PC, which may be caused by the finer particle size of Type IL cement which can result in greater dissolution into the pore solution [117]. The differences between the PC and Type IL cement pore solution resistance when compared across classes of concrete is very small relative to the changes between classes, implying that the chemical affects are dominated by changes in the mix design proportions.

Second, considering the estimated pore solution differences between SCMs and different dosages when the proportions were held constant in a Class A mix design, several trends appear for mixes with those SCMs. The first is that a larger dosage or replacement rate seems to increase the estimated resistivity of the pore solution across the SCMs studied. This may be due to the delayed pozzolanic reactions reacting with the initial products to form additional CSH which reduces the concentration of ions in the pore solution.

Finally, comparing the results from the literature with the mix designs experimented on in this project, the range of estimated pore solution compositions for Type IL cements from Nadelman are close to the Type IL cement used for this project. There is also a wide range of variability between the five cements tested within the Nadelman study, which also relied on calculations rather than direct pore solution analysis. The five Type IL cements tested by Nadelman came from different producers in the Southeast and were part of an effort of that study to determine how different producer's Type IL cement affected the early age properties [108].

The variability may indicate that a single set of limits based on the type of cement used may not be possible due to intrinsic material differences between producers. However, it appears that the variability is less between classes of concrete relative to that between materials, which suggests that limits based on the class of concrete may result in a set of limits that offer the ability to specify concrete using surface resistivity values that account for differences between the chemical and microstructure of different mix designs.

Surface resistivity and permeability limit development by concrete class

The pore solution resistivity differs between different classes of concrete and within the same class when SCMs are used. As shown in Figure 19, differences exist between the classes of concrete and concrete with different replacement rates of SCMs. Concrete conforming to class AA has a lower pore solution resistivity compared to class B due in part to the larger amount of cement paste fraction which produces a higher concentration of ions in the pore solution. Figure 20 below shows the difference between a more porous microstructure where aggressive ions would be expected to degrade the concrete quicker versus a more refined pore structure where the aggressive ions would take longer to reach the reinforcement. The lack of interconnected pores reduces the routes for electrons to pass through the sample and increases the surface resistivity.

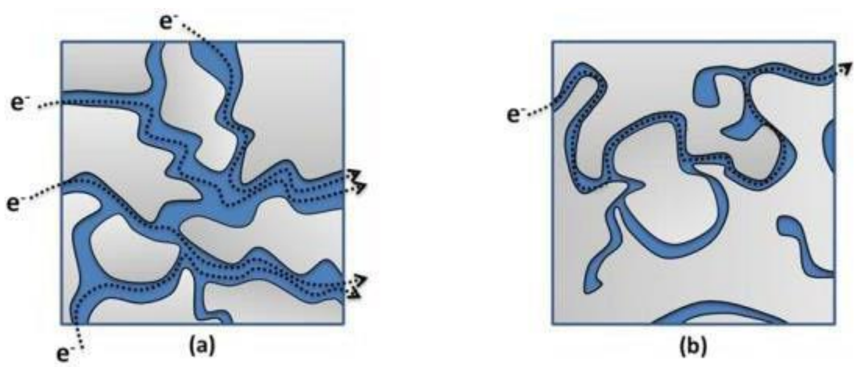


Figure 20. Illustration. Flow of electricity through (a) highly porous and interconnected microstructure versus (b) a less porous and interconnected microstructure [108].

Electricity flows more easily through solutions with higher concentrations of ions which results in a lower resistivity when using methods such as surface resistivity [118]. Additionally, aggregate typically has an electrical resistance on the order 10-100 Ohm-m which is 1-2 orders of magnitude larger than the pore solution [119]. The differences in resistance between the pore solution and aggregate cause the system to behave like a parallel circuit with the current flowing through the material proportional to the inverse of the material's resistance. Equation 2 shows the relationship in a parallel circuit with different resistivities on the overall resistivity. Combined with Equation 1, it can be seen that the current (flow of ions) is related to the inverse of the resistivity and thus flows most through the pore solution.

Equation 2: $$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots \frac{1}{R_n}$$

The current chloride ion penetration limits in AASHTO T358 were originally laid out in AASHTO TP95 as a proposed testing method and specification [120]. The original chloride ion penetration limits for the provisional standard were calculated using the relationship between RCPT and surface resistivity outlined by Chini, A.R. *et al.* [61]. The research focused on a collection of mixes that was split between several strength classes of concrete before being combined into a single set of limits for all concrete.

The classes of concrete within GDOT's specification have required strength limits which are similar to the ones used during the development of the original AASHTO surface resistivity limits. Additional research by Vivas, E. *et al.* [177] produced surface resistivity limits using confidence intervals to confirm different limits that would be appropriate for concrete mixes between classes. Following the trends seen in the modeled pore solution and the history of the development of the AASHTO limits, it is proposed that the limits for each class of concrete be adjusted from the AASHTO limits in proportion with the differences in pore solution resistance.

To identify limits that can be more fairly applied to the different concrete classes in the current GDOT specifications, the relative difference between pore solution resistivity is proposed as a method to scale the current resistivity limits from the AASHTO T358 standard. Table 5 shows the differences between classes for both Type I/II PC and Type IL cement pastes. Note the similar relative differences between the different cement compositions. An average value between the differences for PC and Type IL mixes was used to create the proposed limits.

Table 5. Differences in pore solution between classes

	Cement	Percent Difference
Class B to Class A	Type I/II PC	-36%
	Type IL	-37%
Class A to Class AA	Type I/II PC	9%
	Type IL	9%

The difference in pore solution between the classes was used to determine the proposed resistivity limits for each class of concrete. Higher classes of concrete which showed higher pore solution resistance had their limits adjusted upwards to reflect the impact of the more resistant pore solution. Similarly, for lower classes of concrete, the surface resistivity limits were adjusted downwards to reflect the less resistant pore solution. These changes account for the impact pore solution resistance has on the measured surface resistivity.

Figures 21 through 23 below show the results from the surface resistivity tests used to test and confirm the proposed limits. The samples were made using the mix designs from Table 5 above. Note: these mixes were made per Section 500 but represent worst case mix designs. The w/cm was the highest allowed under the specification and, as has previously been shown, a high w/cm plays a large factor in decreasing the measured surface resistivity. All tested samples met the moderate or above chloride penetration potential as noted on each figure. The moderate surface resistivity is the limit shown in other state specifications and in related FHWA documentation.

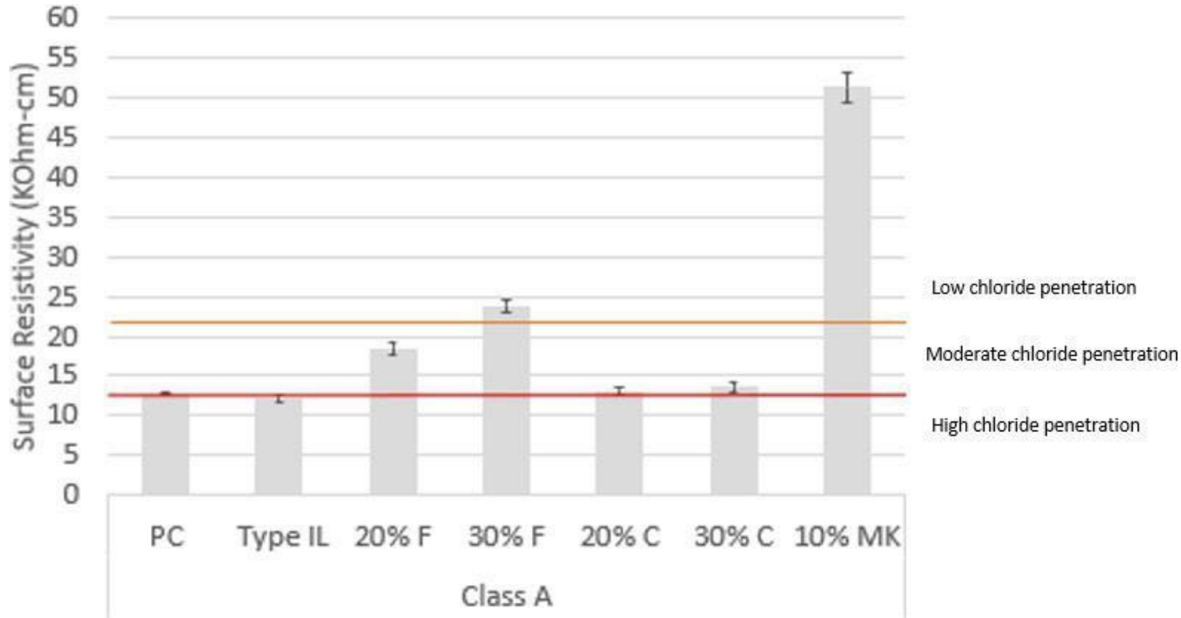


Figure 21. Graphs. Proposed adjusted surface resistivity limits for Class A concrete mixes, showing experimented concrete mix designs.

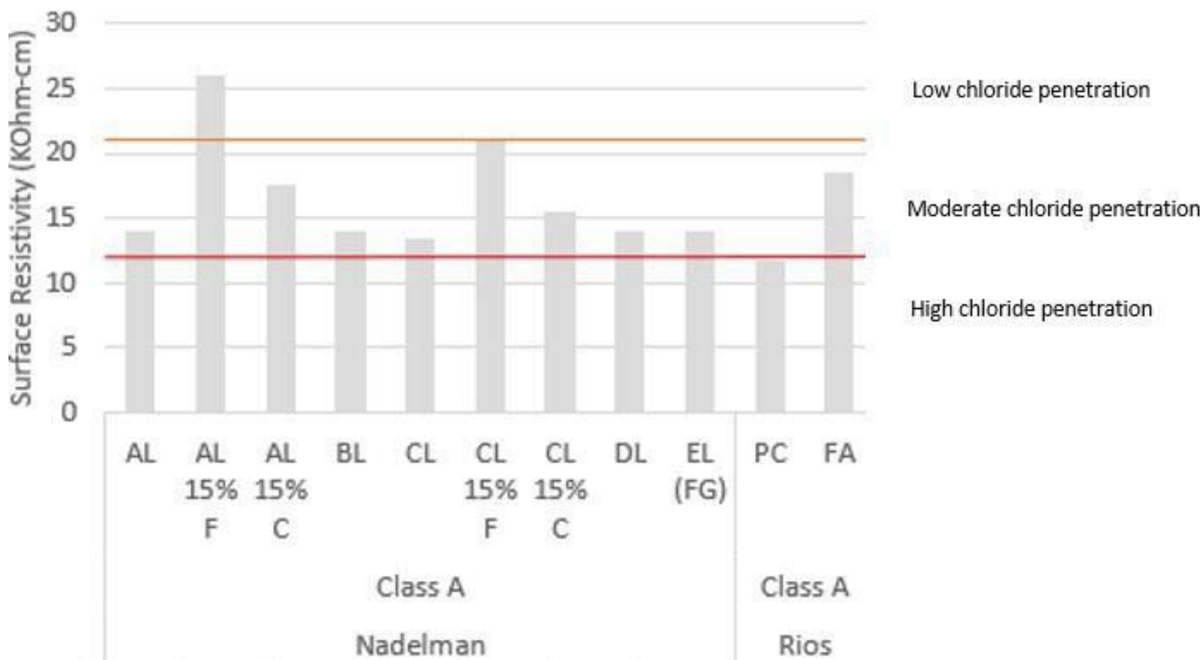


Figure 22. Graphs. Proposed adjusted surface resistivity limits for Class A concrete mixes, showing literature concrete mix designs.

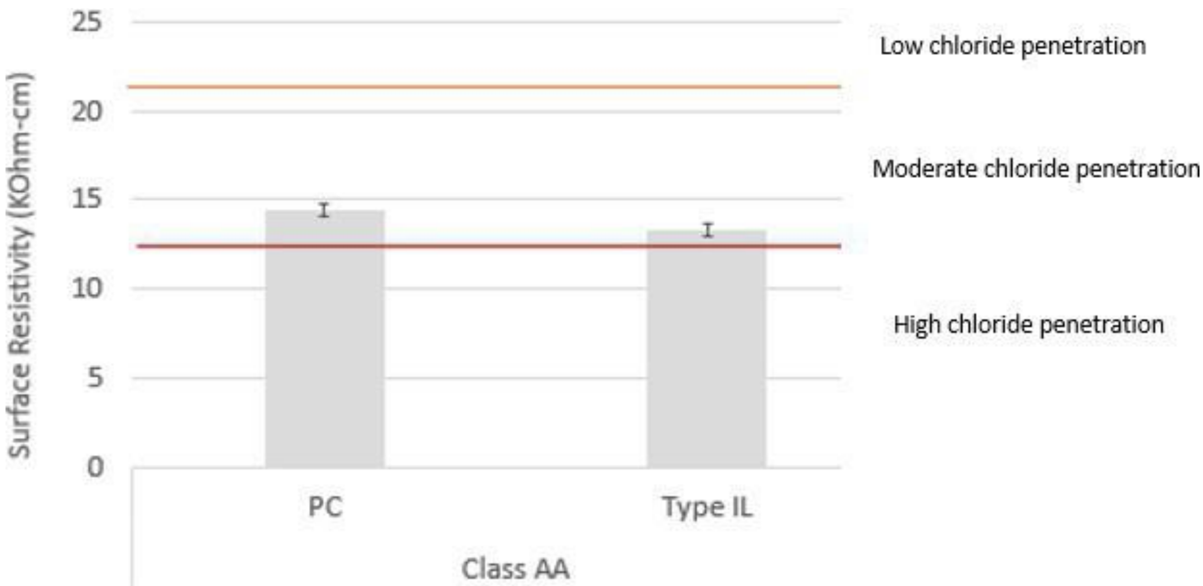


Figure 23. Graphs. Proposed adjusted limits for surface resistivity of Class AA concrete mixes.

The proposed adjusted limits are detailed in Tables 18 and 19 in Section 6.3 for each class of concrete along with the adjusted limits for all chloride penetration potentials in case a project required more stringent limits. Figure 21 shows that adding SCMs at all dosages increases the surface resistivity, allowing for a higher resistance to chloride ion penetration. In particular, 20% and 30% Class F fly ash as well as 10% metakaolin improved the surface resistivity, with 30% Class F and 10% metakaolin mix designs able to provide low surface resistivity and high resistance to chloride ion penetration. In cases where projects require additional resistance to chloride ion penetration, SCMs – including metakaolin at 10% or above and Class F fly ash at 30% or above - are useful as measured using surface resistivity. Rapid Chloride Penetration Test as an additional method. The limits proposed in the section above are for surface resistivity, a method that has gained adoption due to its speed, its ease of use, and its non-destructive nature [110]. However, following the literature review of other state DOTs, it was determined that specifying a single test method may limit the ability of producers to qualify mix designs and contractors to verify in the field. Specifications that allow several methods of qualification give producers flexibility in qualifying a mix and will make the transition to PBS more fluid. With improvements in testing methods and in the methods allowed, adoption of PBS is expected to increase, as shown by the responses to the CoMP member survey in Figure 10 where 70% of respondents would consider using or definitely use PBS if the practicality of the tests improved and 75% would if the ease of testing was improved. Because of this, it is proposed that a secondary method for qualifying a mix on the ability to resist chloride penetration be included in the specifications.

The proposed second method is the rapid chloride permeability test (RCPT) procedure, in accordance with AASHTO T277. This method has been noted in several other state specifications including Virginia's and Alabama's DOTs with limits based on FHWA guidance for chloride ion penetration. The test allows for both prepared samples and cores from a hardened mix. The test provides a measure of the total charge passed through a sample with ends saturated in a sodium chloride solution with a constant voltage flowing through the sample's cross section. A less permeable, and thus more durable sample, would have a lower value for the charge passed with <4,000 Coulombs indicating a moderate chloride ion penetration [121]. The RCPT method has been adopted because of its widespread use and is continued to be included in specifications due to DOT familiarity with it. However, there are some well-documented concerns with the method that make it at best a temporary method for initial adoption in PBS to allow for producer flexibility. Some of the concerns that exist with the RCPT method stem from the conditions required to perform the test, namely the aggressive solution needed with both a 3% NaCl solution and a 0.3 M NaOH solution, and the high voltage required over the length of 6 hours. The concerns with the test are that the aggressive solution and temperature generated by the high voltage pose both safety and reliability problems [122]. However, the test has continued to be used within certain state specifications because of the relatively short time of 6 hours and the results that give a quantified value for a mix's ability to resist chloride ingression. The simple nature of the results does not require advanced knowledge to interpret, and for this reason, the test is still in use today. Because of the prevalence, it is being proposed that the relationship between permeability and surface resistivity be used to provide adjusted limits for both surface resistivity and permeability for GDOT to provide to producers to qualify their mixes within order to provide maximum flexibility in testing method to providers. In the future, as other measures of permeability become feasible, it may be possible to phase the RCPT as a method out of the specifications.

The original AASHTO provisional standard for surface resistivity, AASHTO TP 95, references research on establishing validity for surface resistivity through finding a relationship between the RCPT results and the surface resistivity results. The relationship used in the original standard was developed by Chini, A.R. *et al* [61] on a large number of tests collected from the state of Florida on DOT projects as shown in Figure 24. To establish limits for the proposed specifications that matched with the adjusted surface resistivity results from above, the relationship between the two methods was used to ensure measurements using either test would come to the same conclusion for chloride ion penetration resistance. A similar relationship has been found by Tanesi, J. and Ardani, A. using concrete mixes with a range of SCM replacement rates and Type IL cements as shown in Figure 25 [110]. Note a higher surface resistivity is related to a lower charge passed because of the fundamental (Ohm's Law) relationship between resistance and current under constant voltage.

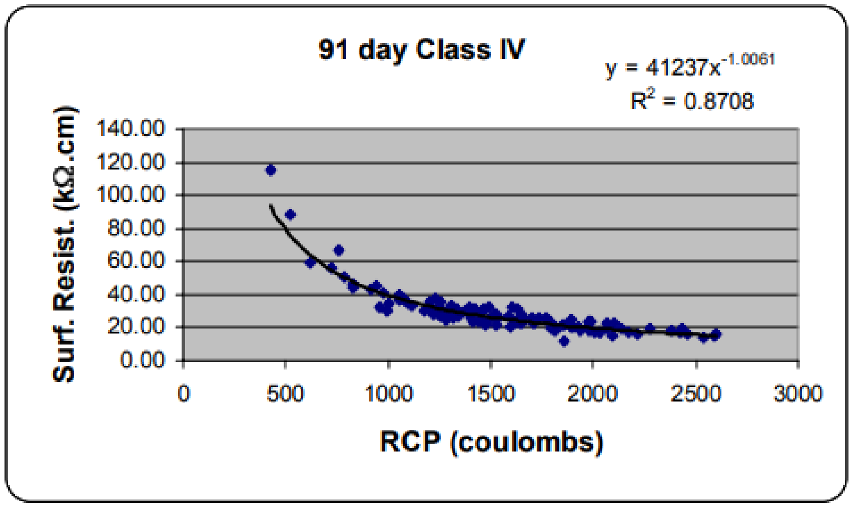


Figure 24. Graphs. Relationship derived by Chini, A.R. *et al* to develop permeability and surface resistivity limits [61].

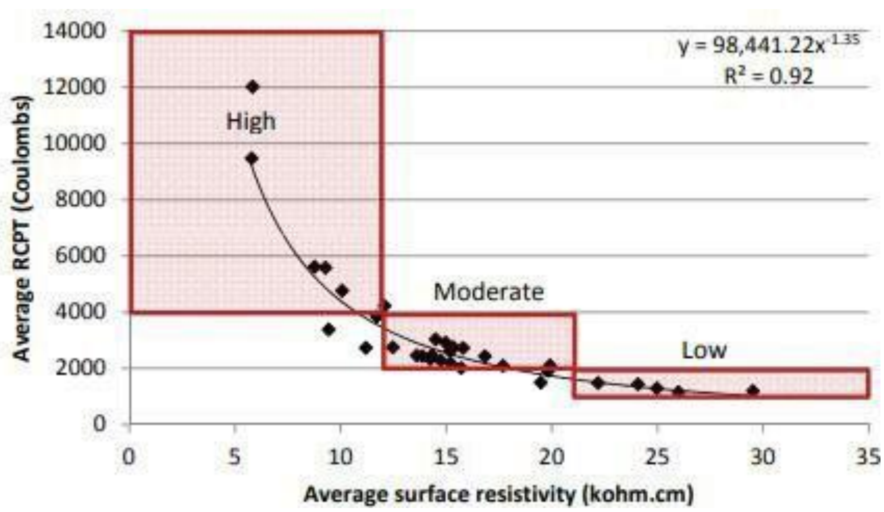


Figure 25. Graphs. Relationship derived by Tanesi, J. and Ardani, A. to develop permeability and surface resistivity limits [110].

The two relationships shown above are one of several that have been developed linking the two tests, with differences in fits depending on the mixes tested. These two studies included a wide range of SCMs at different dosages and had many samples from different labs. With this varied data set, the two studies created fits that generally agreed with each other seen in Table 6.

Table 6. Comparison of relationship between Chini, A R. *et al.* and Tanesi, J. and Ardani, A.

Chloride Ion Penetration	Adjusted Surface Resistivity	Chini, A R. *et al*	Tanesi, J. and Ardani, A.
High	< 12	>3440	>3380
Moderate	12.0 - 21.0	1920-3440	1930-3380
Low	21.1 -40.0	680-1920	1010-1930
Very Low	40.1 - 254.0	60-680	160-1010
Negligible	>254	<60	<160

Because the development of the AASHTO standard was based on the relationship developed by Chini, A.R. *et al.* [61], the proposed RCPT limits were adjusted using the relationship shown in Figure 24. The proposed RCPT limits can be found in Table 20 in Section 6.4.

Sensitivity of measured resistivity to curing conditions

The literature shows that the curing condition of the samples has an impact on the surface resistivity of the samples [123]. Curing conditions analyzed as a part of this project are the curing time and the solution samples are cured in. The temperature was kept constant throughout the experiments at 23 C. The samples were moist-cured in solutions and were considered to be saturated. The differences in the measured resistivity reflect the differences in resistance in the internal pore solution following equilibrium being reached between the external curing solution and the internal pore solution. Alkalis are known to leach from the pore solution when cured in limewater which increases the measured resistivity of the sample [124]. The "bucket test" has been proposed as an alternative curing to saturated limewater to reduce the leaching of alkalis seen when surface resistivity measurements are made in accordance with AASHTO T358 [109]. The bucket test involves curing samples in a simulated pore solution designed to mimic the concentration and makeup of the internal pore solution to reduce leaching of alkalis.

Leaching of alkalis from the sample artificially increases the measured resistivity of the concrete due to alkalis within the concrete pore solution driving the conduction of electricity. Leaching occurs when the concentration of alkalis within the concrete moves towards an equilibrium with the curing solution, reducing the total amount of alkalis within the concrete pore solution. As a result of fewer alkalis within the sample's pore solution, leaching causes higher surface resistivity values to be measured, overestimating the durability of the concrete [125]. The impact of leaching of alkalis has been shown to increase the resistivity of concrete by 30% to 40% [124]. To test the difference the two curing conditions may have on the surface resistivity measurements, samples using the same mix design were cured in both saturated limewater and a simulated pore solution. Surface resistivity measurements were performed using a 4-probe Wenner probe following AASHTO T358 procedure.

The mix designs used to compare the curing method are shown below in Table 7. All mixes were based on the proportions for GDOT Section 500 Class A concrete [30]. The cement only PC and Type IL mixes were control mix designs to measure the impact leaching had without the effect of SCM replacement. The other 5 mixes did not conform to the current specification due to higher levels of cement replacement (20% for fly ash versus 15% currently allowable and 10% of metakaolin versus 0% currently allowable). The nonconforming mixes were used to determine if the specifications could be updated to allow for blended cements and higher levels of cement replacement.

Table 7. Mix design for comparing impact of curing conditions

Mix Name	W/cm ratio	Water (lb/yd^3)	Cement (lb/yd^3)	Fine Aggregate (lb/yd^3)	Coarse Aggregate (lb/yd^3)	SCM (lb/yd^3)
PC	0.465	284	611	1167	1873	0
Type IL		284	611	1167	1873	0
20% F		284	489	1167	1873	122
30% F		284	428	1167	1873	183
20% C		284	489	1167	1873	122
30% C		284	428	1167	1873	183
MK		284	550	1167	1873	61

Six cylinders for each mix were made according to ASTM C192 for a total of 42 samples [126]. The samples were demolded after 24 hours, and three samples of each mix design were placed in either the saturated limewater solution or the simulated pore solution. The simulated pore solution is described in AASHTO TP119 and was developed based on simulation of typical pore solution concentrations [127]. The simulated pore solution had a concentration of 7.6g/L NaOH, 10.64 g/L KOH, and 2 g/L $CA(OH)_2$. The saturated limewater solution had a concentration of 2 g/L $CA(OH)_2$. Each set of samples were cured in 18.9 L (5 gallon) buckets with 12.7 liters of solution. The amount of solution was chosen to ensure a minimum depth above the top of the samples in each bucket of 38 mm [109]. Measurements were initially taken daily for 1 week beginning 7 days after placing the samples in the solution, then alternating between 3 and 4 days for 2 weeks, followed by 5 weekly measurements for a total testing length of 56 days including the initial saturation period. The results of the two curing conditions are shown in Figure 26. Two different cement types were used to investigate the impact limestone would have on the difference between measure resistivity values. All mix designs had the same w/cm ratio of 0.465.

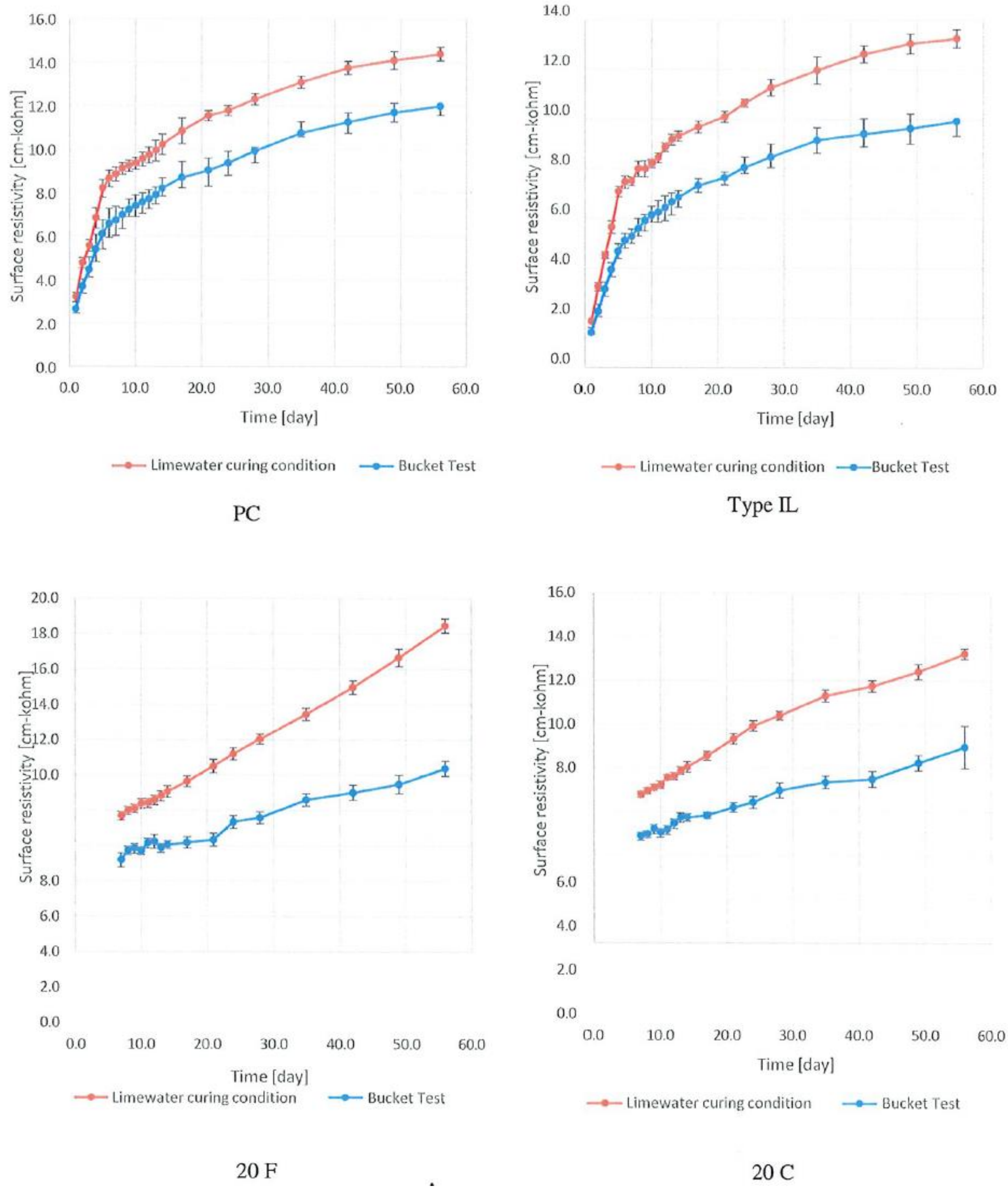
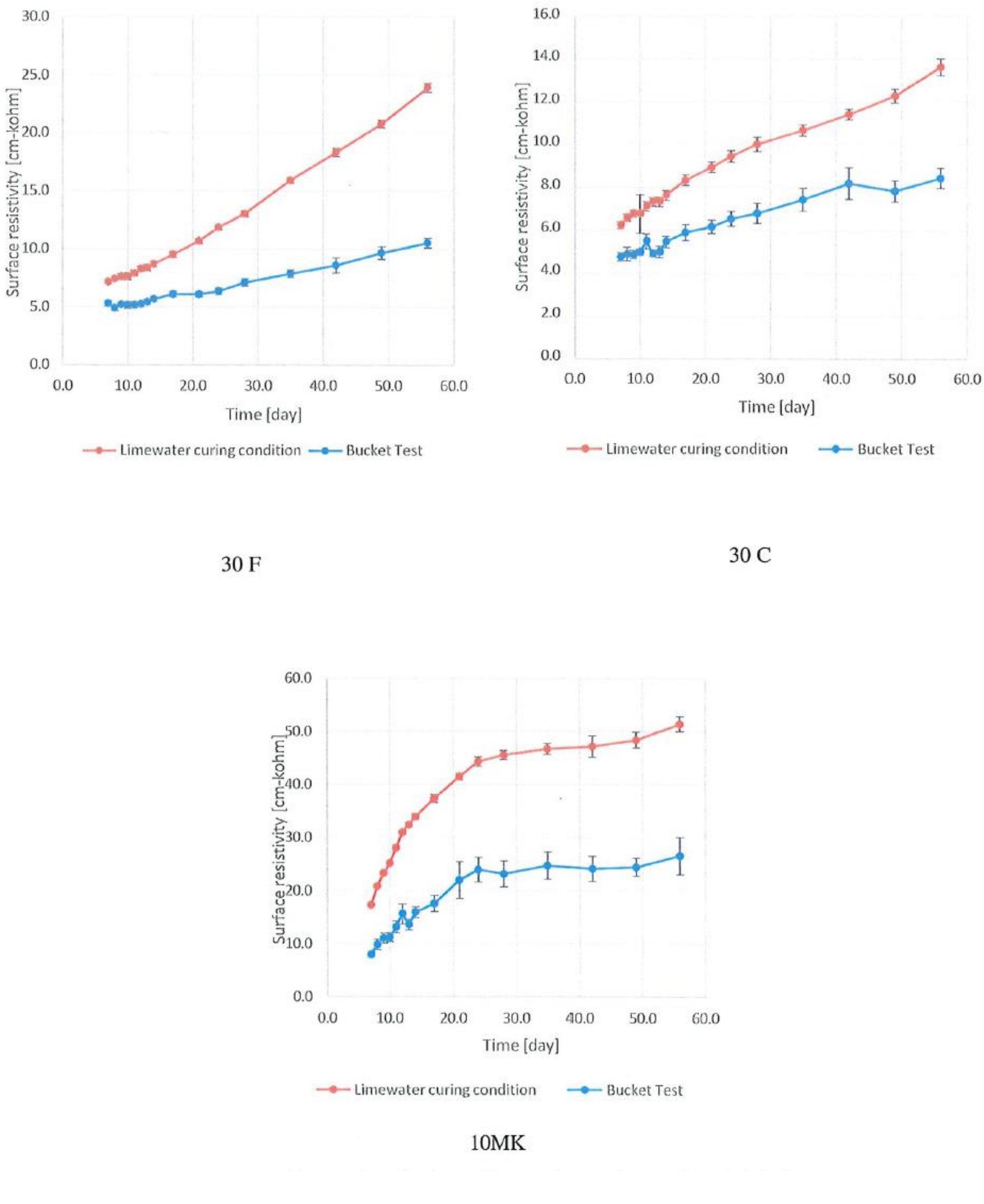


Figure 26 A. Graphs. Comparison between limewater curing and bucket test curing for measured surface resistivity.



30 F

30 C

10MK

Figure 26 B. Graphs. Comparison between limewater curing and bucket test curing for measured surface resistivity.

The difference in surface resistivity resulting between curing conditions is significant, with limewater showing higher values compared to the bucket test results, with a roughly 20% increase for plain mixes and larger increases for mixes with SCMs. The limewater curing method is the method specified in AASHTO T358 and the bucket test has not yet been accepted for this method [109]. The difference in surface resistivity shows the importance of specifying the curing conditions to standardize the methods used to measure resistivity and the need to specify a curing method in the specifications.

Several concerns have been raised regarding the bucket test method compared to limewater curing. The chemicals involved with the simulated pore solution carry safety risks both when producing the pore solution and require special care when measuring the samples. Secondly, the bucket test requires an adequate amount of surrounding solution for the samples to be immersed in which needs a large amount of solution and materials to conduct experiments.

Finally, conversations with the Turner-Fairbank Research Center indicated the FHWA is considering moving away from suggesting the bucket test as a test procedure except for specialized cement research. Because of these factors, it is recommended that the bucket test not be included in the updated specifications for general concrete for GDOT projects. The proposed curing method for this project's specifications is saturated limewater curing in accordance with AASHTO T358 and that the curing method should be explicitly specified for all projects.

CHAPTER 4. STATISTICAL ANALYSIS OF COMPRESSIVE STRENGTH AND ADDITIONAL FUTURE PERFORMANCE METRICS

STRENGTH RESULTS OF PERFORMANCE-BASED SPECIFICATIONS USING STATISTICAL ANALYSIS

Testing for compressive strength was a focus of this project due to the proposed removal of the minimum cement factor. Other performance metrics like formation factor and sorptivity were considered as additional performance metrics but are not currently acceptable for inclusion in the proposed specifications. Fresh properties like shrinkage and workability are important early-indicators of the future performance of concrete, but this project reviewed the current methods and deemed them acceptable as-is for inclusion without an in-depth consideration of class-specific changes for surface resistivity and permeability. Future work may focus on development of additional performance metrics to broaden the testing of concrete mixes as future testing methods are developed.

Introduction

The proposed performance metrics do not have the benefit of historical data for each mix design compared to the current metrics which have had years of results to compare to. A method for a statistical analysis to reduce both risk and iterative testing for use in PBS has been proposed. To test the ability of the methods, a series of compressive strength tests were carried out on mixes that both conformed and did not conform to Class A requirements. The purpose was to illustrate how the use of statistical techniques may be applied in the specifications to reduce risk for new methods.

With the proposed specifications removing the minimum cement factor, several stakeholders have brought forth concerns that strength tests may not meet the requirements. The minimum cement factor has historically been included in specifications so compressive strength requirements were likely to be met regardless of external factors such as poor mixing quality or materials [28]. It has been shown that minimum cement factor increases the amount of embodied emissions associated with a unit of concrete and likely results in an overdesign of the mix [29]. Because of the focus on optimizing mix designs and a wider emphasis on reducing emission, removing minimum cement factor has been proposed alongside the addition of a proposed statistical method that reduces the risk of low compressive strength concrete.

Strength mix designs and results

The mix design used for these compressive tests is shown below in Table 8. The mix designs are based on Class A concrete from Section 500. The Portland cement (PC) mix has no SCM replacement and the Type IL mix used Type IL cement with no replacement. Two types of fly ash, Type F and Type C were used at both 20% and 30% replacements by mass. The clay mix used an impure, uncalcined clay at 10% replacement, and the MK mix used a metakaolin at 10% replacement. All mix designs were tested at a constant 0.46 w/cm ratio. The reduced Portland cement (RPC) mix used 5% less cement than the called for minimum cement factor. The fly ash, clay, MK, and RPC mixes do not comply with current Section 500 Class A concrete due to the higher SCM replacement rates for the FA, Clay, and MK mixes and the reduced Portland cement in the RPC mixes. These mix designs were chosen to illustrate the usefulness of the statistical method when qualifying a mix that has no historical data, as well as the potential for similar mixes to be used under the proposed specifications.

Table 8. Mix designs for statistical analysis

Mixture	Water (kg/m^3)	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	FA or Clay (kg/m^3)
PC	168	363	705	1115	0
Type IL	168	363	705	1115	0
20% Class F	168	290	705	1115	73
30% Class F	168	254	705	1115	109
20% Class C	168	290	705	1115	73
30% Class C	168	254	705	1115	109
Clay	168	326	705	1115	36
MK	168	326	705	1115	36
RPC	160	344	941	993	0

Thirty samples were cast for each mix design using 4" x 8" cylinders cured in a fog room for 28 days. Figure 27 shows the compressive strength measure for the nine mix designs. The tests were conducted in accordance with AASHTO T22 at 28 days. The dashed line is the minimum strength required under Class A concrete from Section 500. Note that all mixes averaged above the limit and no single test for any of the samples were tested below the limit.

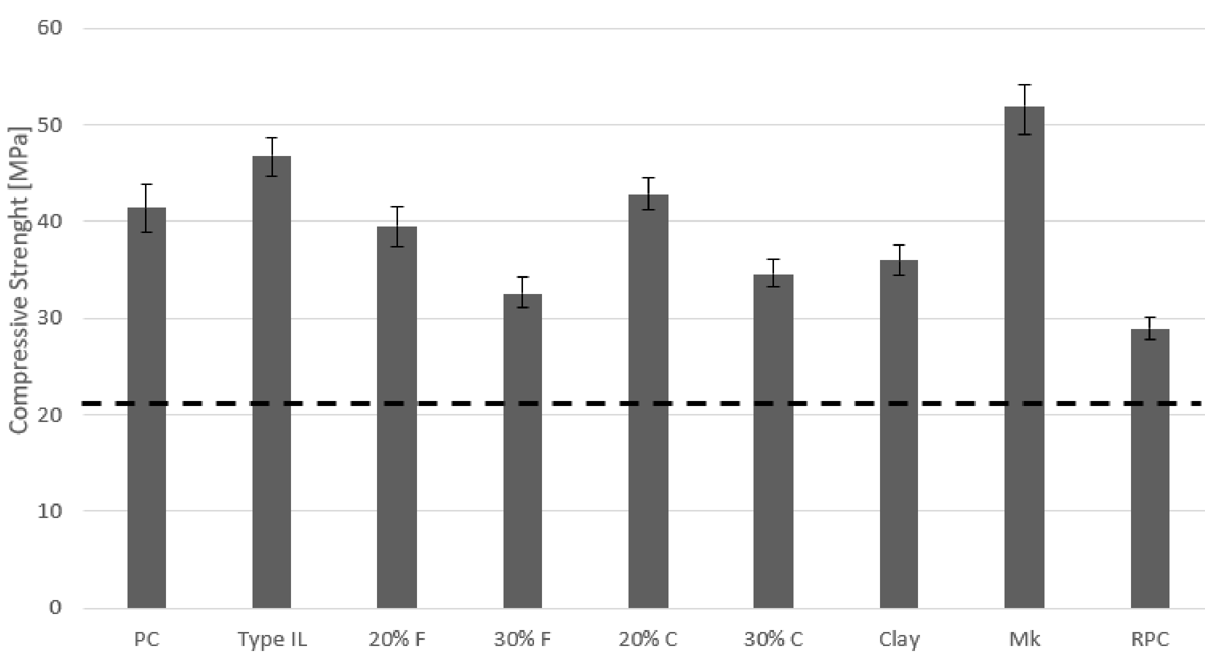


Figure 27. Graphs. Compressive strength results for the 7 mixes analyzed.

The MK mix had the highest compressive strength at 51.99 MPa (7.5 ksi), more than double the requirement for Class A concrete's minimum 20.6 MPa (3.0 ksi) compressive strength requirement and 25% higher than the compressive strength of the GDOT compliant PC mixture (41.41 MPa, 6.0 ksi). The compressive strengths of the 20% Class F fly ash mix (39.54 MPa) and 20% Class C fly ash mix (42.88 MPa) are both higher than their respective 30% replacement mixes. This can be explained by the testing occurring at 28-days, showing the need for potentially longer test times for higher rates of SCM replacements in order to more accurately measure the final compressive strength. The clay mixture's compressive strength (35.96 MPa, 5.2 ksi) has a 10.7% decrease compared to PC's compressive strength. While the impure, uncalcined kaolin clay possesses little to no reactivity, it can be used as a partial replacement for Portland cement in mixes according to current performance requirements. Since it is known that this material would not contribute to the durability of a concrete that includes it, this highlights the importance of including a durability metric in specifications in conjunction with a strength requirement. Finally, the 30% reduction in strength of RPC (28.96 MPa, 4.2 ksi) compared to PC is not surprising due to the decreased cement content compared to the reference mixture. This reduces the amount of the primary strength-giving phase in concrete, CSH. However, RPC's compressive strength is still above the minimum allowable compressive strength, and no sample tested below the 3,000 psi limit.

Statistical Methodology and Analysis

To reduce the amount of iterative testing needed and to minimize risk of incorrectly qualifying a mix design with limited data, qualifications of mix designs can be done with high certainty using statistical analysis. Additionally, with sufficient data points, this method of statistical analysis could be applied to the field verification method. To accomplish this, one-sided, one-sample mean t-tests can be conducted on the compressive strength results to determine the certainty that they pass

GDOT's minimum compressive strength requirement for each class. To perform a t-test on a dataset, one of two pre-requisites must be satisfied: (1) the sample size n must be greater than or equal to 30 or (2) the distribution of the data must be normally distributed. In this experiment, the number of samples for each mix design was 30 which satisfies the first requirement. Additional statistical tests were done to determine if the tests were normally distributed, but it was determined they were not.

If the compressive strength results are not normally distributed, the sample size must be greater than or equal to 30. Therefore, right-tailed t-tests were performed in the following manner for potential concrete mixtures [128]. First, the mean of the mixtures' compressive strengths was hypothesized to be greater than the Class A minimum compressive strength requirement of 3 ksi (μ0). Note that since these 30 compressive strength tests are only samples from a population, the mean (x bar) and standard deviation (s) of a mix's compressive strength results will henceforth be reported as the sample mean and the sample standard deviation. The t-test uses the sample mean and the sample standard deviation to determine if the population mean (μ) is greater than μ0. The number of samples for this analysis is n = 30.

As a result, the null hypothesis (H_0) becomes μ=μ0 and the alternate hypothesis (Ha) becomes μ>μ0. The t-test statistic (presented in Equation 3) and a quantity known as degrees of freedom (d.f.) (presented in Equation 4) are calculated for each mixture.

Equation 3 $$\mathrm{t} = \frac{x\ bar - \mu_0}{\frac{s}{\sqrt{n}}}$$

Equation 4 $$d.f. = \mathrm{n} - 1$$

Table 9 shows the results of the statistical analysis from the compressive strength tests. The value of α = 0.01 is the significance level for a p-value of 0.05. This is the common value set in the scientific community. For a result to be significant, the p-value should be less than the significance level. If this is true, it can be concluded that the null hypothesis is statistically likely to not be correct.

Table 9. T-test results at α = 0.01

Mix	Average (MPa)	Standard Deviation (MPa)	t-test statistic	d.f.	p-value	Conclusion
Type IL	41.41	2.14	42.1	29	<0.00001	Reject H_0
20% Class F	46.83	1.53	30.1	29	<0.00001	Reject H_0
30% Class F	39.54	1.54	24.0	29	<0.00001	Reject H_0
20% Class C	32.61	1.65	42.5	29	<0.00001	Reject H_0
30% Class C	42.88	1.34	31.0	29	<0.00001	Reject H_0
Clay	34.6	1.57	53.3	29	<0.00001	Reject H_0
MK	35.96	2.18	39.0	29	<0.00001	Reject H_0
RPC	51.99	1.16	39.2	29	<0.00001	Reject H_0

As can be seen in the above Table 9, the null hypothesis that each sample's mean compressive strength is less than the minimum required by the current specification is rejected and the alternative hypothesis of the sample mean being higher than the minimum strength is accepted. It can also be concluded instead that the average values being higher than the compressive strength requirement is statistically significant. This is an example calculation for a set of mix designs using compressive strength as the performance metric. A different metric could be sampled from a trial batch and, using the proposed limits, it could be determined whether the trial batch meeting the specified performance limits is statistically significant or not. This method provides a reduction in risk associated with the new metrics and is a more rigorous method of qualifying a mix using the performance metrics.

PERFORMANCE METRIC TESTING TIMES

Introduction

To address the concerns shown in the AASHTO CoMP survey responses, a time trial study of a proposed performance metric was carried out. The purpose was to compare the time needed to prepare and test the required samples under a prescriptive testing metric and a performance metric to determine to what extent the concern of increased time was represented by the data. The chosen tests were compressive and flexural strength tests for the prescriptive metric, and surface resistivity for the performance metric. The tests were performed by an experienced operator in a testing lab environment under similar circumstances. The total times for an operator to complete each testing regime were measured and compared. Additionally, a comparison between the preparation and testing time for each metric was made to investigate the relative importance each step had for both specification types.

Testing time trial method

The time trial included the preparation needed for each test: weighing and mixing materials for both prescriptive and performance, along with creating the necessary samples. The prescriptive method included both cylinders for compressive strengths and beams for flexural strength. The performance method utilized the same cylinders for the surface resistivity and compressive strength tests. The active time needed to test the samples was included as the sample testing time and reflected the time needed to prepare and test them. The time trials were performed multiple times to determine an average time needed for each part of the sample testing, then that value was multiplied by the total number of samples required in the standards for each respective test method to calculate the total amount of active time.

Note that the same samples used for the surface resistivity tests in the performance testing method will be used for the compressive strength testing too, reducing the number of samples needed overall. The usage of surface resistivity also provides a measure of resistance to chloride ingression that is otherwise not known. Table 10 shows the results from the time trials and the total amount of time needed for the prescriptive and performance methods.

Table 10. Comparison of test times for sample prescriptive and performance tests [29]

Prescriptive-based testing	Process Description	Time (minutes)	Number of tests	Total amount of active time (minutes)
Sample preparation	Weighing Materials	60	N/A	60
	Using Tilting Drum Machine	10	N/A	10
	Creating Concrete Cylinder Samples	2	N/A	2
	Creating Concrete Beams	2	N/A	2
Sample testing	Crushing Concrete Cylinder Samples	6	8	48
	Crushing Concrete Beams	10	4	40
			Sum	**162**
Performance-based testing	Process Description	Time (minutes)	Number of tests	Total amount of active time (minutes)
Sample preparation	Weighing Materials	60	N/A	60
	Using Tilting Drum Machine	10	N/A	10
	Creating Concrete Cylinder Samples	2	N/A	2
Sample testing	Measuring surface resistivity	5	5	25
	Crushing Concrete Cylinder Samples	6	5	30
			Sum	**127**

Figure 28 graphs the results and shows the relative time needed for sample preparation and sample testing. The sample preparation for both specification times is similar, with performance only 2 minutes less because no flexural strength tests were required for the performance method. The testing time was 38% lower for the performance method because of the lack of flexural strength testing. The sequencing of testing is important because surface resistivity is a non-destructive testing method that does not affect the measured compressive strength of the sample. This reduces the amount of material and storage space needed for samples when using this example performance-based metric.

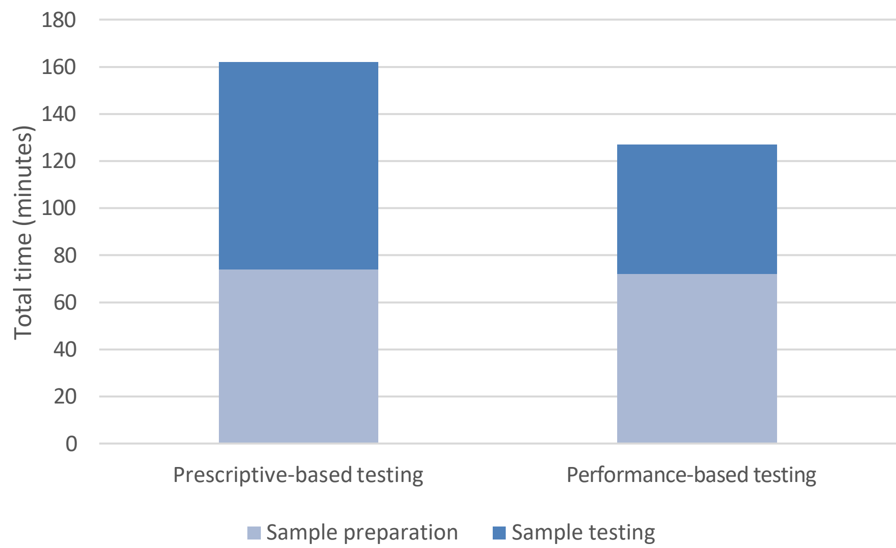


Figure 28. Graphs. Time trial results for sample preparation and testing [29].

This analysis refers specifically to the type of testing metric used because this affects the amount of material needed for the test and the time to conduct it. However, it is interesting that for this case study, time would not be considered a barrier to implement PBS, and there are some synergistic overlaps with the chosen testing methods that allow for sample reuse between metrics.

Limitations on mixing time and rotations

Proposed updates to the number of allowable revolutions were based off literature of comparable specifications from state DOTs and the results of a survey sent to AASHTO members. Other state DOTs such as Tennessee [129] and Missouri [130] have adopted specifications that eliminate the maximum number of allowable revolutions or time constraints. In some specifications, a test pour under project engineer supervision is required to ensure the delivered concrete meets the necessary performance standards [131]. A survey question to the AASHTO

CoMP member group about the current state of limitations on the number of rotations was sent as part of the earlier PBS usage survey and the results are shown below in Figure 29. Note that the majority of DOT officials report a current limit of 300 revolutions.

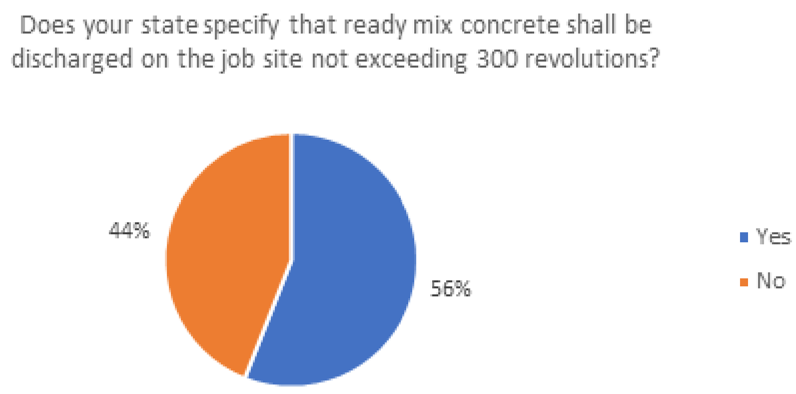


Figure 29. Graphs. Mixing requirement among stage DOT officials.

A second question was posed to the same group of transportation officials regarding the perceived willingness to switch to a performance-based specification. Specific examples provided in the question regarded adding in trial pours for mixtures requiring more than the 300 rotations or 90 minutes under current specifications and allowing for performance metrics to replace prescribed material limits. The results show that most state officials report a positive or neutral opinion on adopting performance-based specifications while 8% are unlikely to adopt.

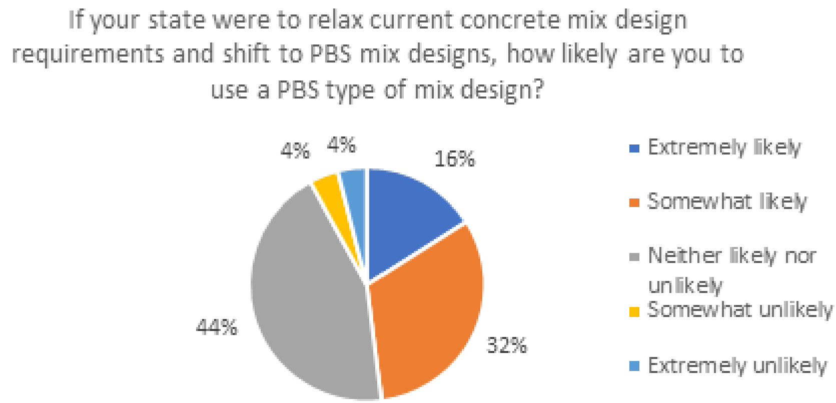


Figure 30. Graphs. Willingness to adopt PBS among stage DOT officials.

Based on the feedback received from the survey conducted among state DOT officials as well as examples across other state concrete specifications for eliminating the limit on rotations, the proposed specifications allow a trial pour to be overseen by the project engineer in cases where the 300 revolution or 90-minute mix time limits cannot be achieved and a waiver has been sought from the Engineer. The concrete's fresh properties will be verified by the project engineer to ensure that the extra mixing does not negatively affect it. However, the proposed specifications will continue to list 300 rotations or 90-minute mix times as the required limits in line with current DOTs.

ALTERNATIVE PERFORMANCE METRICS

Several other tests for permeability and resistance to aggressive ions were also considered during the development of these proposed specifications. For completeness, the other tests are discussed below along with potential performance limits and a discussion of reasons why the tests were not proposed. The potential tests were graded against relative speed and ease of use and could be adopted into future specifications. Each test measured the ability of a mix design to resist the ingression of aggressive ions.

Sorptivity

Sorptivity is the measure of the rate of water ingress into a concrete sample, which is related to the ability of concrete to resist ingression of ions that may be present in the water [132]. The standard method of testing for sorptivity is ASTM C1585. The test does not require specialized equipment, with only the sample, a stopwatch, and a scale needed to perform the test [133]. The test measures the short-term gain of water through the capillary pores of the concrete by measuring the weight gain of the sample at specific time periods. The frequency of the sampling is more during the initial stages of the test (testing after the first minute of immersion, after 5 minutes, after 10 minutes, et cetera), followed by a series of less and less frequent tests before typically ending after 6 hours. The reasoning for more frequent early measurements is that sorptivity is a time dependent process that is best estimated by the early measurements as the concrete sample becomes effectively saturated over time and other forces become dominant [134].

Using the measurements collected, a sorptivity constant can be derived from the slope of a graph showing mass gain versus the square root of time. Figure 31 below shows how the slope changes over time which contributes to the difficulty in establishing a single value for a mix's sorptivity.

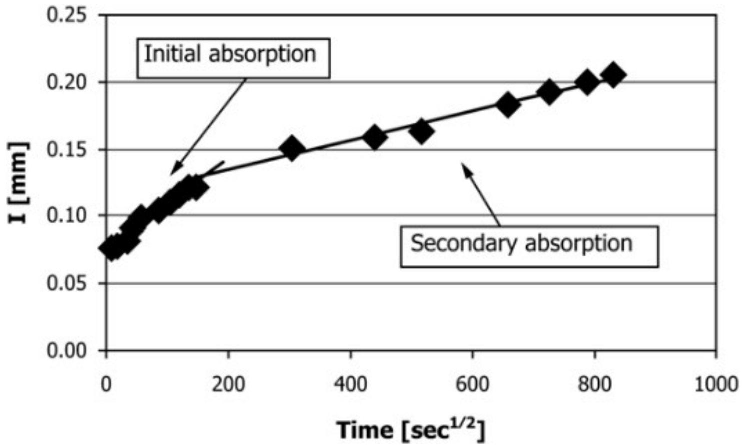


Figure 31. Illustration. Sample data to determine sorptivity constant [133].

Other problems with the sorptivity test as a performance metric include differences between a mix design's sorptivity coefficient depending on finishing conditions, differences when measuring in the field and the laboratory, and dependence of coefficient on early age curing conditions. It has been seen by several studies that the finishing conditions have a significant impact on the measured sorptivity coefficient [132], [135]. Finishing techniques that overwork the surface may result in lower sorptivity coefficients that are not reflective of the concrete's general ability to resist the ingress of water, and areas without similar finishing may show a higher than expected rate of ingress. A difference between field and laboratory measurements has been seen where differences in relative humidity impacts results, with lower relative humidity increasing the measured coefficient [136]. Finally, the curing conditions that the samples experience at an early age affect the measured values significantly with Castro, J. reporting a nearly 12 times increase in initial sorptivity for samples with a 0.40 w/cm ratio that were initially cured at 50% relative humidity compared to saturated conditions [136].

Additionally, the so-called "moisture history" of a sample continues to affect the results of a sample regardless of how the concrete is later conditioned [136].

Sorptivity has been used in the PBS of New South Wales, with maximum allowable coefficients as the performance limit; however, mandated curing conditions are needed, and additional metrics are used to qualify a mix [137]. Due to the heavy impact curing and conditioning has on samples, as well as the tendency for sorptivity to differ due to field finishing, it was determined that sorptivity was not a preferred performance metric. The ease of the test is a favorable aspect, but the test is not being proposed as a current performance metric.

Formation Factor

The formation factor has been proposed as a durability metric that considers the sample's pore connectivity and pore solution resistivity [125]. The formation factor is the ratio of the resistivity of the concrete sample to the resistivity of the pore solution as shown in Equation 5.

$$\text{Equation 5:} \quad \text{Formation factor} = \frac{\rho_{concrete}}{\rho_{pore\ solution}}$$

Formation factor is a measure of a concrete's resistivity that has been normalized to the specific pore solution for each cementitious system [138]. The normalization of the concrete's surface resistivity with the sample's pore solution is beneficial because outside impacts that affect comparisons of surface resistivity across concrete mixtures, such as aggregate fraction and cement replacement, can be mitigated. An added benefit of using the formation factor is the relationship between the formation factor and the rate of ingression of chlorides in concrete.

Chloride ingression is the primary method of corrosion in reinforced concrete and the time required for corrosion to begin has been related to formation factor [139]. The equation comes from the Nernst-Einstein relationship and is shown below in Equation 6.

$$\text{Equation 6:} \quad \frac{Cx - C0}{C_s - C_0} = 1 - erf\left[\frac{x}{2\sqrt{\frac{D0}{F} * t}}\right]$$

—

The variable C_x is the chloride concentration at a specific depth x at time t, C_0 is the original chloride concentration, C_s is the chloride concentration at the surface, D_0 is the species diffusion coefficient ($2.03*10^{-9}$ m^2/s for chloride), and F is the formation factor. Using the calculated formation factor, the expected chloride concentration can be calculated for any depth of the concrete given the external chloride concentrations. This is helpful when determining the estimated service life of a structure and designing the amount of cover.

However, the formation factor has several characteristics that make it a difficult value to specify due to the properties needed to define it and the standard testing methods needed. Work done by Spragg, R. *et al.* (2016) has shown the need for formation factor to be corrected for several outside influences (such as saturation of the sample, temperature of the measurement, and leaching of alkalis from the curing solution) to compare formation factors from samples following different curing regimens. These correction factors would need to be applied to each sample to account for the curing conditions and to produce a formation factor that could be compared to the benchmark limits.

The saturation correction is a function of the degree of saturation and a fitting coefficient. To determine the specific degree of saturation, many samples were tested for both air content and resistivity when they are fully saturated, and then compared to the measured values at the field or laboratory conditions [123]. The temperature correction adjusts for measurements taken of samples cured at temperatures different from 23 C and the correction for measurements at standard temperature is 1. Finally, a leaching correction is applied to samples cured in limestone solution to account for the leaching of alkalis from the cement system. Spragg, R. *et al.* (2016) used a correction coefficient of 0.36 representing 36% of alkalis have leached from the pore solution into the curing solution for standard limewater curing and 0% leaching for a simulated pore solution.

Using Equation 4, an estimate can be calculated for when corrosion is expected to begin and when repairs are required. Figure 32 shows the impact the cover depth and formation factor has on the expected time until corrosion is a concern. Several conditions need to be known before these calculations can be completed, but the field measurement of these variables is not difficult or reasonable values can be estimated. For this example, the chloride concentration parameters have been set to an initial concentration of 0% chlorides, concentration of chlorides at the depth of rebar at 0.05% to initialize corrosion, and a chloride surface concentration of 0.7%. The cover for the rebar has been set to 2 inches (50.8 mm) and the diffusion coefficient for chlorides at standard conditions is $2.03 * 10^{-9}\ m^2/s$. Corrosion occurs once the passive layer around the rebar caused by the alkalinity of the concrete has been broken down by the ingress of ions, a process that has been estimated to take 6 years [140]. To begin to develop an approximation of the service life for a structure, the results of the estimated service life can be added to the expected time until the passive layer has been broken down to estimate the total time until corrosion is expected. Several examples of time needed before corrosion begins are shown in Figure 32.

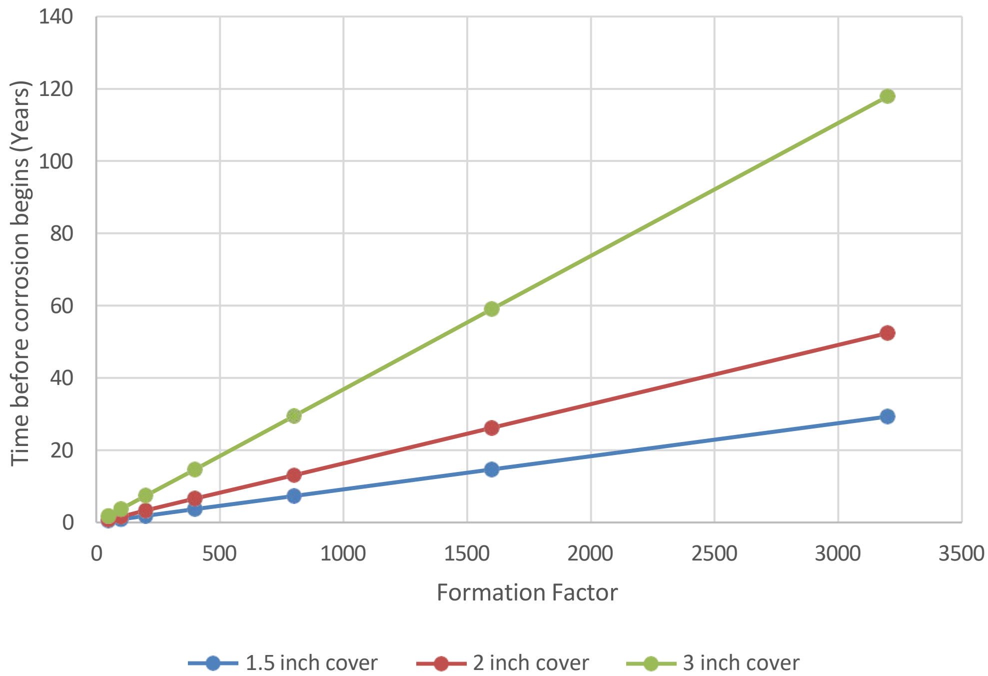


Figure 32. Graphs. Estimated time before corrosion may occur.

As seen in Figure 32, the time until corrosion is expected to occur depends on the depth of cover and the formation factor. The depth of cover can be designed for in the structural and construction design, while the formation factor is a property of the material that can be designed for during the mix qualification stage.

The predictive properties of formation factor, along with its quantification of surface resistivity with a normalization of the pore solution resistivity, makes it a powerful tool for both design professionals and specifiers. However, the major drawback of the ratio is the need to be able to measure the pore solution resistivity to use it. To measure the pore solution, specialized equipment is needed and currently no ASTM or AASHTO guidance has been written to standardize a method to do so. Because of this, without the proper equipment, the pore solution can currently only be estimated using a similar software procedure as described in the report above or estimated using a generic value for pore solution such as in AASTHO R101 [80]. The value used in AASHTO R101 is .127 Ohm-m, which when compared to Figure 19 and values seen in the literature, does not fully capture the values estimated between the different classes of concrete and with SCM replacement rates [141]. Using the generic pore solution resistance value from the AASHTO guide when the true pore solution resistance is higher will result in an overestimate of the formation factor which could lead to low quality concrete being accepted.

Alternatively, when the true value of the pore solution resistance is lower than the generic value, the quality of the concrete could be underestimated, leading to the incorrect denial of a concrete mix design. To measure the pore solution experimentally, several methods exist: the high-pressure extraction method which uses a prepared sample of cement paste pressurized to extract the pore solution and a newer method which runs a solution of known pH and resistance. The high- pressure method was developed in 1973 by Longuet, *et al.* and requires pressures up to 145 ksi to express the solution into an anvil where it can be extracted and the resistivity measured [142].

The more recent cold-water extraction method avoids the need for high pressures but does not measure the resistance of the pore solution directly. Instead, a crushed sample of cement paste is allowed to leach into an extraction solution that has a known alkalinity and, following a period of time, the final alkalinity of the solution at equilibrium is measured to indirectly determine which ionic species and in what concentration are present [115]. The two processes require training to be carried out before the formation factor can be determined.

Additionally, as Ranger, M. *et al.* [115] noted, there are currently no ASTM or AASHTO standards for this method which reduces the ability to include pore solution extraction in a set of standard DOT specifications. A potential workaround to experimentally determine the pore solution resistivity would be to model the pore solution in a similar way as done in this report; however, this approximates the true pore solution resistivity. Because formation factor requires the pore solution resistivity to calculate, expressing the pore solution is currently not covered by specifications and modeling, and the pore solution using CEMGEMs software is not a complete solution, it was decided that the formation factor should not be proposed to be currently included the specifications. With that said, formation factor is a measurement that considers both the microstructure and pore solution when determining the quality of a concrete and represents a potential performance metric for the future as the field develops easier methods to directly measure the pore solution resistivity.

ADDITIONAL PERFORMANCE METRICS FOR FUTURE WORK

Additional properties that are important for long-term performance are workability and shrinkage, with each occurring during placement or soon after, but affecting the durability and manifesting problems over time. However, with the current specifications addressing workability directly and shrinkage controlled through the curing processes, this report focused on developing a statistical tool that would address concerns with compressive changes following the proposed removal of minimum cement factors.

Workability is an important characteristic when placing the concrete and can be critical to a project being able to be constructed as designed. With less than workable concrete, additional water may be added on site to improve the ease of placement, examples of which have been noted by ACI and are strongly recommended to be avoided in the field [143]. Additional water changes the mix design from the one qualified and also directly increases the w/cm ratio which has been shown to decrease strength and durability [144]. This project did not conduct experiments on workability, with the current measure using slump being sufficient to measure the workability of concrete and widely understood by industry members. As a result, no recommendations are proposed from this project for additional performance metrics for workability.

Early-age shrinkage as a performance metric is used by some other state DOTs to measure the ability of mix design to resist shrinkage as the concrete cures. Shrinkage can be split into two types:

drying and autogenous. Drying shrinkage is associated with water within the concrete being lost to the environment, for example, through evaporation driven by high temperatures or wind. Drying shrinkage can be mitigated through quality curing and often is reduced through following the standard specifications for concrete curing [145]. Autogenous shrinkage is associated with the chemical hydration process of cement and the fundamental reduction in volume driven by capillary pore stress. Autogenous shrinkage can be reduced by maintaining additional reservoirs of water to the hydrating concrete or through internal curing [146]. While both types of shrinkage can be mitigated through the curing process, the impact of the mix design is important to the performance as well. SCMs such as calcined clays increase the water demand and thus the change in shrinkage, while other materials like fly ash reduce water demand.

It has been shown that shrinkage is a measure of an early-age property of the concrete mix that can determine long-term performance through increasing an element’s susceptibility to aggressive agents [147]. By decreasing the amount and extent of cracks due to shrinkage, the permeability of an element is reduced, which plays a large role in reducing further ingress of aggressive ions to the concrete. State DOTs typically measure drying shrinkage for classes of concrete with high strength roles and leave filler concrete materials out, e.g., Class B and CS in GDOT section 500. These lower-class concretes are used in applications without critical durability needs. The project did not study a specific performance metric for concrete, but instead has included a modified version of AASHTO T160 in line with other state DOTs to qualify mixtures on shrinkage.

CHAPTER 5. LIFE CYCLE ANALYSIS OF PROPOSED SPECIFICATIONS

INTRODUCTION TO LIFE CYCLE ANALYSIS

To determine the impact of the proposed specifications on the state, an LCA was conducted comparing two scenarios that accounted for the different specifications studied under this proposal. The life cycle analysis measured the amount of GHGs for each scenario to analyze the environmental impact of the proposed specifications over the long term. The GHG analysis used the global warming potential (GWP) weights from AR5. The LCA provided several insights into the overall use phase of concrete pavements and columns. The study was conducted for two functional units to reflect the main concrete specifications studied: pavements with one lane-mile of concrete for Sections 430 and 439 and concrete columns for Section 500. An acceptable performance level was defined for each functional unit so that the serviceability was constant during the entire lifetime. The service lives analyzed for the mixtures were 30 and 40 years to account for differences in the mix design.

The LCA for this report considered the production of materials, construction process, and use phase with maintenance tasks for a pavement section and a column. The demolition phase of the two functional units were excluded from the LCA because the demolition phase is expected to incur a reconstruction of the element as well as the demolition process is not expected to reflect meaningful differences between concrete specifications. The demolition phase typically includes heavy equipment usage, transportation of materials, and final disposal, all of which would not be expected to be altered based on the type of concrete specification used to design the mix.

The LCA process was performed using the OpenLCA software which allows material databases and individual processes to be input into a model that calculates the impacts for the functional unit [148]. The emissions associated with the production stage of the LCA have been determined from the materials used within each mix. The TRACI impact assessment method was used in the analysis for impact characterization values for environmental pollutants and emissions. A database collection was used with a robust data set for material production and construction activity emissions. The embedded ELCD database in OpenLCA was supplemented with the Federal LCA Commons Database [149], [150]. For the use phase of the two functional units, a maintenance plan was developed using concrete structure and concrete pavement guides from the FHWA [151] as well as the standardized procedures for concrete repairs from GDOT's standard specifications for concrete structure and pavement repairs [18]. An important general note about an LCA is that the results depend heavily on the assumptions made for the system boundary and on the processes involved within. Those assumptions have been detailed in Sections 5.2 and 5.4.2. Major changes to the collection may result in different results and conclusions, while minor changes are not expected to change the conclusions. Overall, based on data input selection and the scale of the differences between the prescriptive-based specifications and the PBS, the data shows the prescriptive-based specifications are more environmentally intensive over the long term.

LIFE CYCLE ANALYSIS BOUNDARY

Setting the boundary of an LCA is the first step in the process and is critical to being able to bound the analysis. The system boundary typically depends on the desired range of the study, either extending to the end of production or to the disposal of a good [90]. For this project, two separate boundaries were studied. The first was a cradle-to-gate production of the two functional units. The second was a cradle-to-grave study up to the demolition phase for the two functional units. Cradle-to-gate sets the system boundary to include the processing of raw materials with the processes used to finish the product up to the "gate" of the factory or production facility while cradle-to grave LCA expands the system boundary past the final production stage to also assess the transportation and use phase of the system as well as the final disposal at the end of its life. The processes used for production of concrete at a batch plant plus necessary transportation to the site and construction equipment to place the concrete were considered within the production and transport phase of the LCA and was considered the “cradle-to-gate” analysis. This is because in this study, the final product being delivered to the owner was either pavement or columns, both requiring installation to be considered complete. The construction processes associated with each functional unit were determined using the GDOT standard specification method sections for the respective functional unit. The environmental impacts of small hand- tools like shovels or hammers were neglected because the impacts were assumed to be much smaller compared to the material or larger equipment. The use phase extended the boundary past the construction of the functional units and included the maintenance program. The analysis that included the production, transportation, and use phase was considered the “cradle-to-grave” analysis for this report. Figure 33 shows the initial boundary from the LCA that includes material production through the maintenance period and Figure 34 shows the use phase boundary for the pavement functional unit.

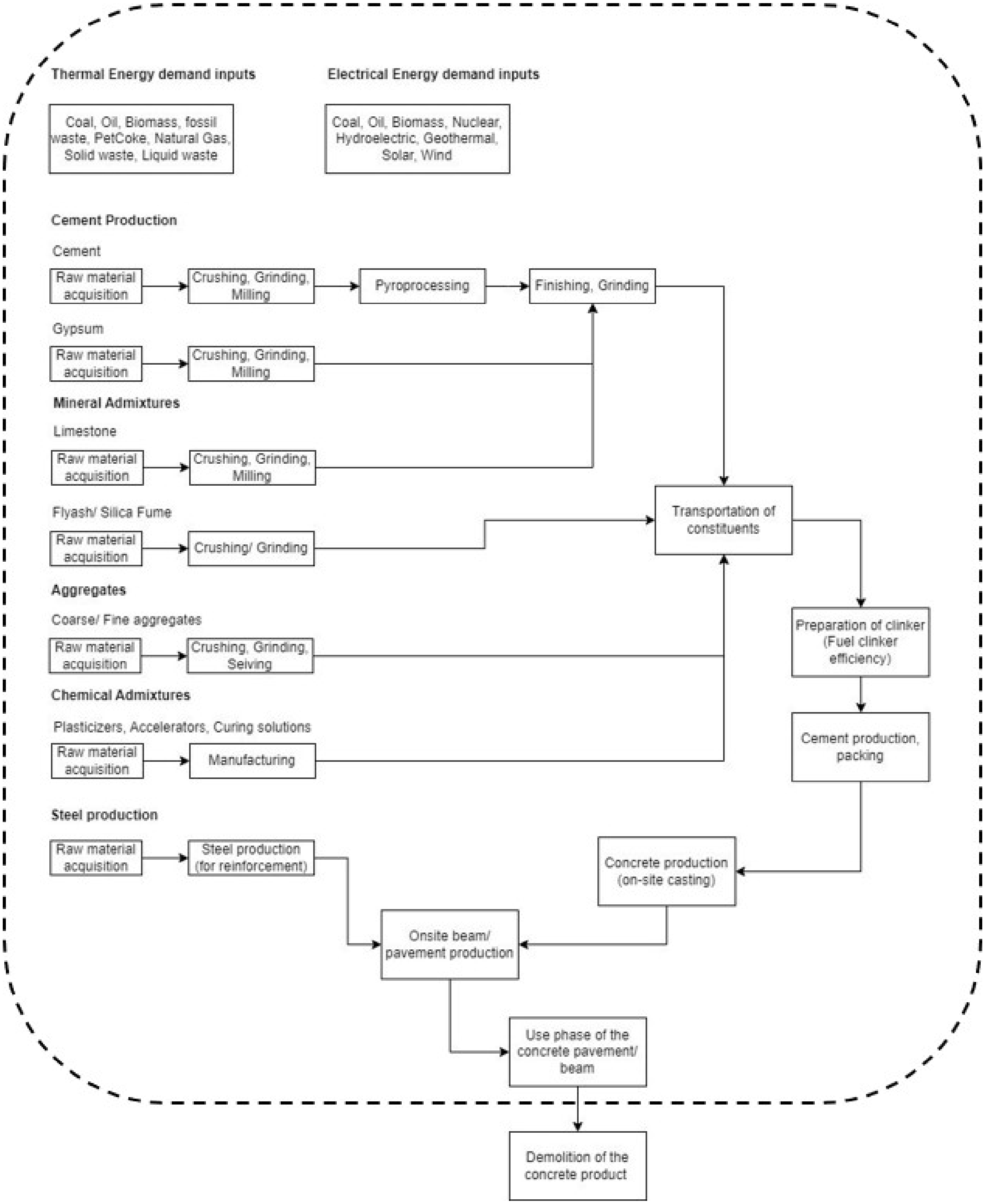


Figure 33. Illustration. Boundary with use phases placeholders for pavements with exclusion of demolition shown.

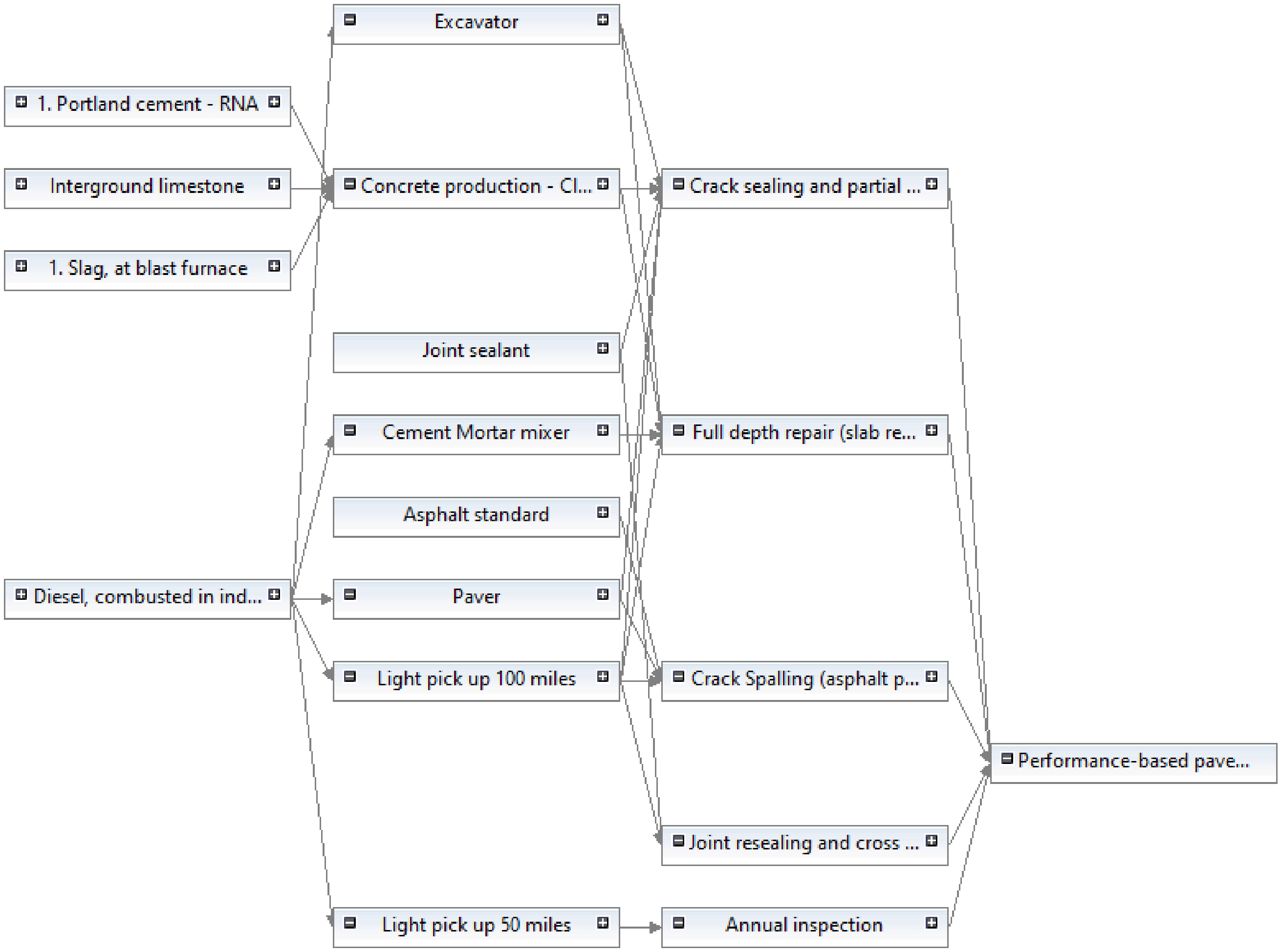


Figure 34. Illustration. Use phase boundary for 30-year performance pavements.

The two project boundaries shown in the figures above list the processes for illustration purposes only and do not encompass all the evaluated subprocesses within each one. The LCA process tracks many subprocesses that produce impacts that need to be accounted for but would be unviewable if all were shown: for example, Figure 35 shows the subprocesses listed for crack sealing, with further subprocesses connected upstream.

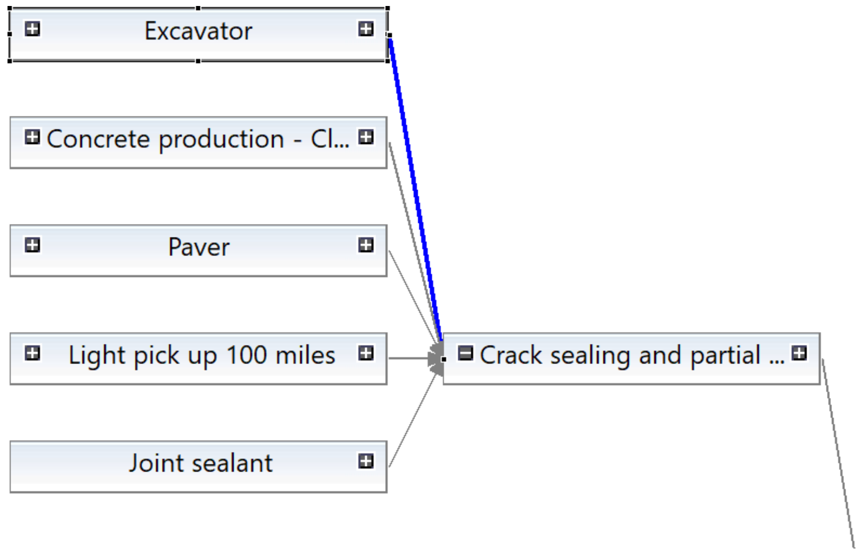


Figure 35. Illustration. Example of subprocesses for maintenance treatment for crack sealing.

Major processes are shown to illustrate how the cradle-to-gate production measures the impacts from the raw material being mined, followed by processing, transportation, and finally construction. The cradle-to-grave boundary includes similar processes, with additional maintenance processes, which have their own supply chain associated with them.

IMPORTANCE OF MAINTENANCE AS USE PHASE OF LIFE CYCLE ANALYSIS

To develop the use phase of the LCA, an assumed maintenance program was constructed using maintenance manuals from FHWA and GDOT [151], [24]. The maintenance phase of a concrete pavement or structure may seem outside of the scope of the construction specifications; however, the downstream environmental impacts associated with concrete can be traced back to decisions made during the production of concrete [152]. By specifying more durable concrete, emissions associated with the maintenance phase may be reduced through a combination of fewer required treatments and an extended lifespan that spreads the impacts over a longer period. However, using PBS to specify more durable concrete may result in higher GHG intensity during the construction phase that is not offset during the maintenance phase. Thus, it is crucial to use an LCA, with a specific focus on the cradle-to-grave emissions, to determine if any burden shifting between the phases has occurred.

Figure 36 shows how maintenance is expected to rehabilitate the service life of the structures. Note the gradual drops in overall serviceability shown in Figure 36 before the element has been remediated and the increase in the reliability of the structure being returned to higher levels. Importantly, serviceability in the model was not assumed to return to the original state showing a definite service life. The modeled service lives for this analysis were 30 and 40 years with the values coming from the estimated initial period of corrosion for Class A concrete mixes with and without SCMs according to the relationship with formation factor described in Equation 4.

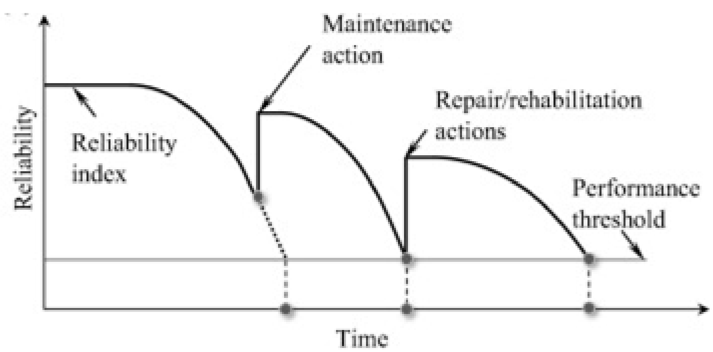


Figure 36. Illustration. Timeline of serviceability of with repairs [153].

The maintenance required to meet each performance threshold or minimum service level for each element is expected to be set by the GDOT, but for the purposes of this study the assumption was made that the maintenance treatments suggested in the manuals would bring the functional units to the expected service level. For example, a lower service level may be feasible for a low use roadway while an interstate lane may have a higher required level of service.

Because corrosion has a delayed period of initiation and propagation which can lead to failure and reduction in the service life, it serves as a useful measure for when maintenance treatments would be needed and when a structure's replacement would be expected [49]. The maintenance schedules for each service life used in this analysis are listed below in Tables 11 and 12. The time between treatments was taken at the lower value for provided ranges to be as conservative as possible in the analysis.

Using the formation factor for each mix design studied allowed for an approximation of the effective service life and provided a guide for the sequencing of treatments. It should be noted that this method uses formation factor to estimate the service life but does not have field data for verification. Formation factor has been shown to accurately estimate the onset of corrosion but the service life in this study was not experimentally determined [140]. An estimate of the use phase of a concrete structure allows for specifiers to determine the impact the concrete produced using the concrete specifications will be expected to have over its lifetime. Producing concrete that has a longer service life and reduces the need for maintenance is expected to reduce the amount of GHG over the lifespan of the structure [154].

LIFE CYCLE ANALYSIS DATABASE COLLECTION AND METHODOLOGY

Sources for data collection

The data required for an environmental LCA involves inventories of emissions and other environmental flows (in categories called "impact categories," such as climate impact, eutrophication potential, and others) associated with physical products and processes that use fuel and equipment. The data from producers typically is reported by producers using a similar format to an EPD that measures the impacts for a unit of product. The emissions associated with fuel are more straightforward because the impacts are generally stoichiometric in nature, requiring a simple calculation of the environmental impacts from combustion of a unit of fuel. The emissions associated with the production of equipment used for construction and maintenance are more challenging because the impacts from the inputs and allocations of equipment are not as easily tracked at the unit process level. Regardless, it has been shown that the emissions associated with the equipment's production account for ~6% of the total emissions from use of equipment, with the rest associated with fuel use [155]. While the equipment production is small compared to fuel usage, data was collected to provide a holistic accounting of environmental impacts.

With the development of the necessary construction and maintenance equipment and the required materials, the inputs for each process were developed to inform what data was needed. A custom database for the LCA was created for the products and equipment using the Federal LCA Commons and data from the National Renewable Energy Lab (NREL). The Federal LCA Commons provided data for the raw materials needed for construction and maintenance materials through databases maintained by the EPA and NIST [156], [157]. The NREL data was used for the environmental impact from fuel usage and equipment production. These sources were combined into a unified database that contained data for the production and maintenance of concrete pavement and structures.

The impact assessment method used was the TRACI 2.1 method. TRACI is a well-known impact assessment tool that includes the most typical pollutants analyzed. Environmental impacts are broad categories of so-called "harmful stressors" or quantifiable measures that research has shown to have negative downstream effects [158]. Example measures of environmental impacts are global warming potential, acidification, and eutrophication. To measure these effects, an impact assessment method needs to be specified to account for different pathways the negative effects develop in the environment. For example, global warming potential (GWP), measures the relative warming of different GHGs to carbon dioxide to simplify measurements and provide a single quantified value of the potential for the greenhouse gas to contribute to global warming. This analysis used the TRACI method developed by the EPA to account for GWP for each of the processes within the boundary.

Design of maintenance strategies

When creating a maintenance plan to measure the impacts of the use phase, standard application types and frequency were determined from several maintenance manuals [24], [159]. These manuals described the necessary materials and equipment for each treatment and the expected timeline. The FHWA guide offered different treatment intensities that varied based on the condition of the concrete in question. These required maintenance needs ranged from low to medium to high. It was determined that a high level of maintenance would serve as the best study case due to it representing the highest cost to GDOT in terms of financial and environmental inputs. With the high level of maintenance chosen for the comparison, it would be expected that concrete which likely required fewer treatments compared to the current methods would compare less favorably, i.e., more durable concrete would be expected to require fewer maintenance treatments to keep the same relative service level compared to the current concrete. Because of this, the comparison using the high levels of maintenance is a conservative choice.

The amount of materials required for each treatment as well as the scope of maintenance was based off best practices for application of the materials and a study on current concrete maintenance strategies [160]. Tables 11 and 12 show the treatments and number of treatments used for the use phase of each functional unit for 30 and 40 years, respectively. The 30 and 40 years were chosen to represent the current expected design lives of concrete structures and to reduce the uncertainty associated with longer-term predictions of service lives and maintenance treatments.

Table 11. Total number of treatments for study boundary time for the 30-year study period

Pavement		
	Prescriptive Number of activities	Performance Number of Activities
Annual Inspection	30	30
Crack sealing	10	8
Joint Sealing	6	5
Concrete Patching	6	5
Partial Depth Replacement	5	4
Full slab replacement	3	2
Columns		
	Prescriptive Number of activities	Performance Number of Activities
Annual Inspection	30	30
Crack sealing	6	5
Spall repair	6	5

Table 12. Total number of treatments for study boundary time for the 40-year study period

Pavement		
	Prescriptive Number of activities	Performance Number of Activities
Annual Inspection	40	40
Crack sealing	13	11
Joint Sealing	8	6
Concrete Patching	8	6
Partial Depth Replacement	7	5
Full slab replacement	4	3
Columns		
	Prescriptive Number of activities	Performance Number of Activities
Annual Inspection	40	40
Crack sealing	8	**7**
Spall repair	8	**7**

Software utilization

The OpenLCA software was used to conduct the LCA. OpenLCA is an opensource software produced by Green Delta [148]. Like other commercially available products, the software allows material databases and individual processes to be input into a model that calculates the impacts for the functional units. OpenLCA was chosen because the open-source software allowed the user to adjust the parameters for the impact categories more easily than alternative software, and it had no cost associated with the use of the software. Additionally, the software has been used in several other case studies for construction, specifically building life cycles and concrete pavements [161], [162]. Finally, conducting an LCA of any scale larger than for a single product requires some form of software because of the large amounts of data being accounted for, as well as the different processes that are used as shown in Figure 33. OpenLCA was an effective choice of software for a project of this scope and was able to provide quality analysis for the LCA of pavements and columns.

LIFE CYCLE ANALYSIS RESULTS

Life cycle analysis mix designs and functional unit details

To compare the cradle-to-gate impacts associated with the two functional units, 6 concrete mixtures were designed with Class A concrete specifications in mind as shown in Table 13. The PC and Type IL mixtures have no SCM replacement, and the goal was to compare the impact of using a blended cement. The additional mixtures used Type IL cement with a variety of SCMs at varying dosages. In terms of nomenclature, the 10MK mix uses metakaolin as a calcined clay for 10% by cement replacement, and the 15F mix has the maximum current replacement rate for fly ash of 15% and the 30F mix has 30% fly ash replacement, with both being Type F fly ashes. The current prescriptive specifications would allow all the mix designs provided the strength minimums were met except for the 30F and 10MK due to higher than currently acceptable dosages of SCMs. The proposed performance specification would allow all the mixtures provided they were able to meet the required performance metrics. The actual mix designs are to illustrate the differences in environmental impact directly associated with the construction and use phase with mix designs allowable under different specification regimes. The mixtures with SCM replacements were designed to mimic Class A mixtures with a higher dosage of SCMs. SCMs are known to reduce the GHG emissions associated with concrete production and improve durability. In order to focus on reductions in maintenance through general PBS, analysis has not been done on mixtures with different levels of SCMs within the functional units.

Using the database created, the emissions associated with each material's production were determined and the mix proportions were accounted for. The construction techniques used were not expected to change based on the mix design used, thus the construction process emissions were constant for all mix designs.

Table 13. Mix designs used for the LCA

Mix Name	Water (lb/yd^3)	Cement (lb/yd^3)	Fine Aggregate (lb/yd^3)	Coarse Aggregate (lb/yd^3)	SCM (lb/yd^3)
PC	284	611	1167	1873	0
Type IL	284	611	1167	1873	0
10MK	284	550	1167	1873	61
15F	284	520	1167	1873	91
30F	284	428	1167	1873	183

The pavement design for this analysis was detailed from the GDOT Pavement Design Manual for the software required, the GDOT Design Policy Manual for guidance on typical design decisions, and GDOT standard detail 5046H for the amount of reinforcing and dowels [163], [164], [165]. The pavement was a jointed Portland cement concrete with a depth of 8" and a width of 12'. The design depth was kept constant for all the mix designs regardless of the strength of the concrete mix for simplicity. The depth is expected to be increased in the case where the concrete strength of a mix design is lower than typical. The design for the columns used in this analysis was determined from the Bridge and Structures Design Manual [166]. A square column, 3' wide with a height of 30' was used as the base design. A cover of 2" was assumed for all concrete mixtures. However, it is reasonable to assume that different rates of carbonation and chloride ingress would occur for different concrete mixtures, requiring larger amounts of cover. For simplicity in this analysis, the cover was kept the same for all mixtures.

Cradle-to-gate of pavement

Figure 37 shows the GHGs associated with one lane-mile of construction. The dimensions and amount of reinforcing material were designed from the GDOT standard construction details [24]. Note the PC mix had the largest emissions associated with construction, followed by Type IL. The mixtures with SCMs decrease in emissions associated with construction with increasing levels of cement replacement. Interestingly, Type IL cement results in an ~8% reduction in emissions compared to the PC mix, which is slightly below the estimated reduction of 10-15% in GHG emissions associated with using a Type IL cement compared to Portland cement [167]. This is likely caused by the assumed uniform construction techniques for all mix designs resulting in similar emissions. The resulting variability stems solely from the reduction in concrete production emissions. Because a portion of the overall construction emissions do not change, the variability associated with the differences in emissions due to the concrete has less of an impact in reducing the overall construction emissions. However, using both Type IL cement and additional SCM replacement can reduce emission associated with construction, up to 30% in the case of 30% fly ash replacement compared to the plain PC mix. This illustrates the benefits of reducing the clinker fraction within concrete mixtures through use of blended cements and SCMs.

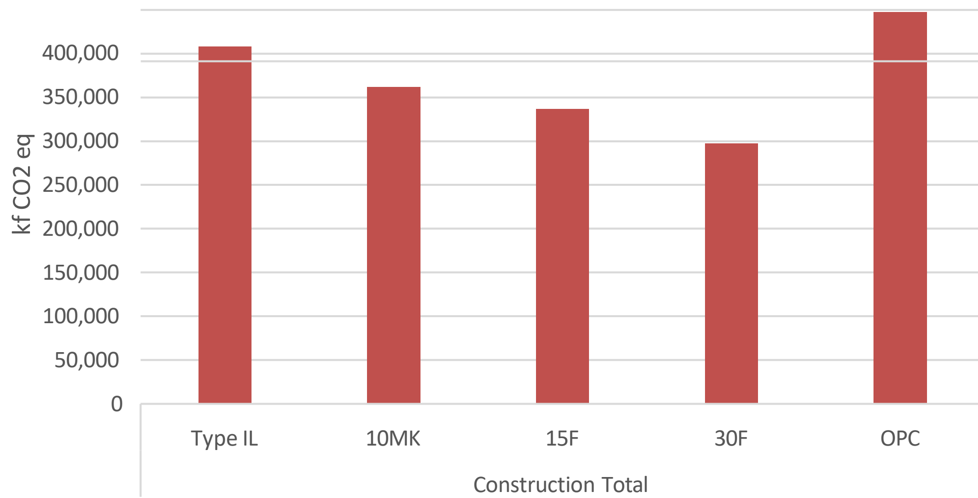


Figure 37. Graphs. Construction GHG emissions for one lane-mile of concrete.

Cradle-to-gate of column

Figure 38 shows the construction GHG associated with one concrete column. The dimensions and amount of reinforcing material were designed from the GDOT standard construction details for a 3-foot diameter column [24]. Note the PC mix had the largest emissions associated with construction, followed by Type IL; however, the differences were not as great for the columns as for the other functional unit of pavement. This is due to a smaller volume of concrete needed for this functional unit, and the source of variability for the emissions in this analysis is caused by the concrete alone. Additionally, the proportion of emissions associated with equipment and fuel use is larger for the columns compared to the pavements because it was assumed the column was the only constructed item. Similar to the pavements, mixtures with SCMs decrease in emissions associated with construction with increasing levels of cement replacement and the highest replacement rate; 30% class F fly ash has the lowest construction emissions.

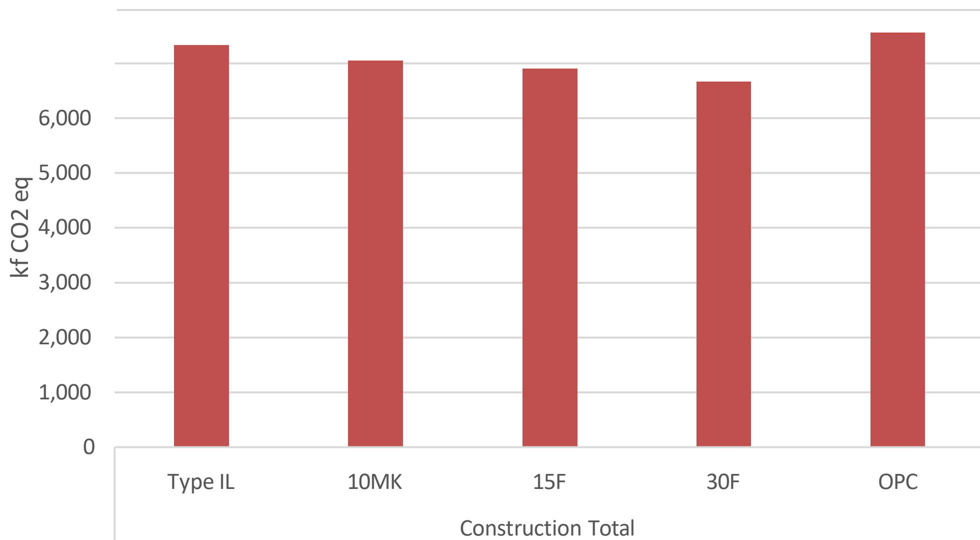


Figure 38. Graphs. Construction GHG emissions for one concrete column.

Cradle-to-grave of pavement

To calculate the cradle-to-grave emissions, the emissions associated with the maintenance phase were determined and added to the emissions calculated previously for the construction phase. The sum of emissions for construction and maintenance are the total cradle- to-grave emissions up to demolition. As discussed above, the emissions associated with the construction phase do not change based on the specifications used except that the proposed specifications would allow all the mix designs and the current prescriptive specifications would not allow the 30F and 10MK mixtures. The maintenance phase does depend on whether the current prescriptive specifications or the proposed performance specifications are used because of the difference in maintenance treatments. By designing for long-term performance in the PBS, the maintenance treatments can be applied less often and later in the project life span. This reduces the total number of treatments needed for the same service level over the same amount of time, which accounts for the reduction in emissions. Figure 39 shows the combined GHG emissions for one lane-mile of pavement for Type IL cement for a 30-year service life and Figure 40 shows the combined emissions for the same functional unit using Type IL cement for a 40-year service life.

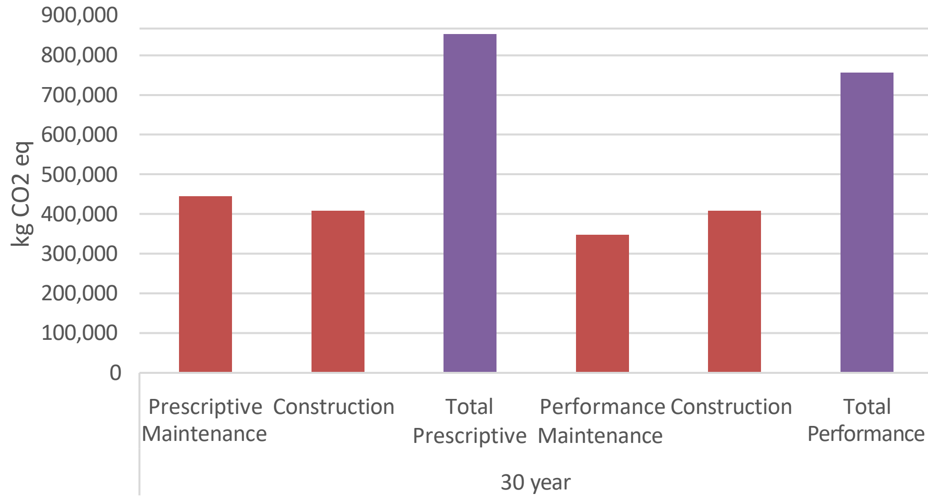


Figure 39. Graphs. Cradle-to-grave GHG emissions for one lane mile of Type IL pavement for 30-year time period.

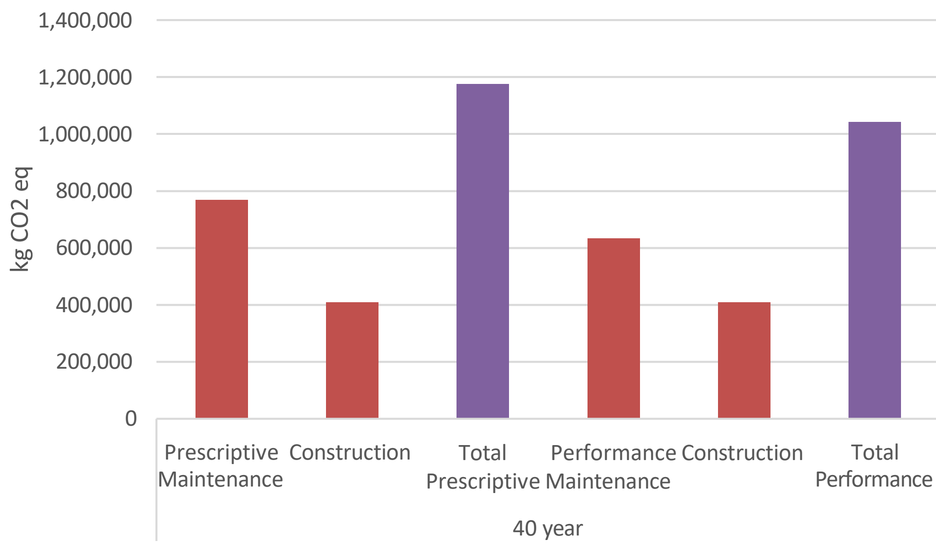


Figure 40. Graphs. Cradle-to-grave GHG emissions for one concrete column for 40-year time period.

Several trends stand out from the two above figures. In the figures, only a comparison between the use phase differences of the two types of specifications was made with a constant concrete mix design of Type IL cement. The trends when analyzing mix designs with SCM replacements were similar. The first is that the performance-based specifications have a clear reduction in use phase emissions which lowers the overall environmental impact of the functional unit by nearly 13% for the 30-year life span and nearly 11% for the 40-year life span. As discussed above, construction emissions are constant so the improvement is entirely due to the higher durability concrete produced under the PBS allowing for fewer maintenance treatments. An additional point of interest is that there are proportionally higher emissions associated with the 40-year service life compared to the 30-year life. Table 14 shows a comparison over a 120-year theoretical study period where the equivalent performance for both service lives has been achieved for the same cement type with both specification type. To calculate this, the least common denominator of time between the 30 and 40 years was determined, with 4 cycles of construction and maintenance required for the 30-year service period and 3 cycles for the 40-year service period. No improvements in technology were assumed to occur, but the higher use phase emissions for the 40-year service life increase the overall emissions compared to an equivalent time period. The results suggest that there is an optimal time between 30 and 40 years within this model where the incremental year of service life begins to add additional maintenance treatments and may be a candidate time for a larger overhaul to reduce the overall use phase emissions. However, the shorter service life and increased number of reconstructions required to reach the same total lifetime would be expected to increase costs through an additional construction cycle. A balance between the financial and environmental impacts needs to be struck and an optimal timing for scheduling reconstruction of performance-based concrete could be the subject for future work.

Table 14. Comparison over equivalent 120-year lifetimes of emissions for 30- and 40-year service life of 1 lane mile of pavement

	Prescriptive-based		Performance-based	
LCA Phase	Service Lives			
	30 years	40 years	30 years	40 years
Construction	408,000	408,000	408,000	408,000
Use	445,000	768,000	348,000	633,000
[redacted]				
120-year total	**3,412,000**	**3,528,000**	**3,024,000**	**3,123,000**

Finally, the trends between the different concrete mix designs with varying SCMs show similar results. The lowest total emission mix for any time period of maintenance is 30F with the next lowest emission mix designs following the same order as the emissions from construction processes. Higher amounts of SCM replacement remove Portland cement with its higher energy intensity and replace it with a less energy intensive material with the added benefit of an increased lifespan through more durable concrete. These findings add support to the push to replace the clinker fraction in cement with alternatives, whether that be limestone in a Type IL cement or with SCMs.

Cradle-to-grave of column

To calculate the cradle-to-grave for the concrete columns, the emissions associated with the use and demolition phase were determined and added to the emissions calculated previously for the construction phase. As discussed for the pavement functional unit, the emissions associated with the construction phase do not change based on the specifications used except that the proposed specifications would allow all the mix designs and the current prescriptive specifications would not allow the 30F and 10MK mixtures. Additionally, like the pavement functional unit, the use phase of the columns does depend on whether the current prescriptive specifications or the proposed performance specifications are used because of the difference in maintenance treatments. The amount of maintenance treatments for the columns were also reduced for the performance-based specifications because the concrete mix design would be designed to be more durable and thus require less upkeep over time. Figure 41 shows the combined GHG emissions for one lane-mile of pavement for Type IL cement for a 30-year service life, and Figure 42 shows the combined emissions for the same functional unit for a 40- year service life.

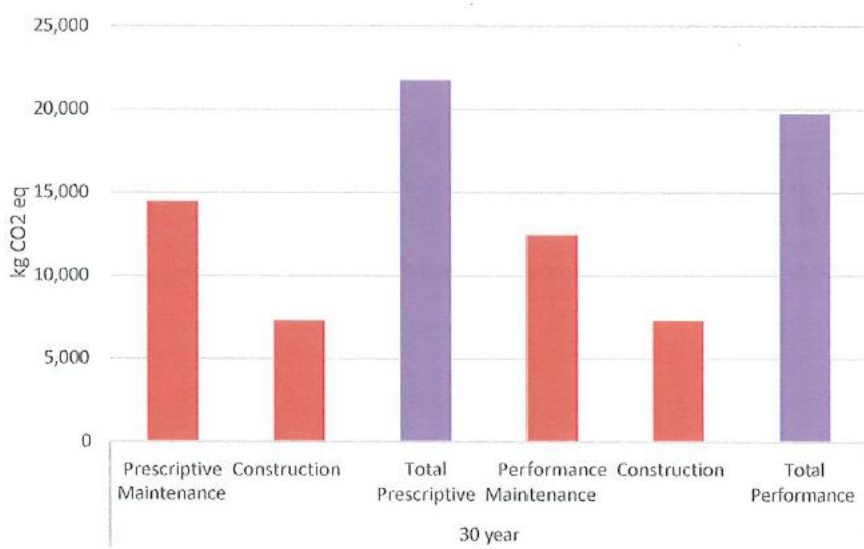


Figure 41. Graphs. Cradle-to-grave GHG emissions for one lane mile of Type IL concrete column for 30- year time period.

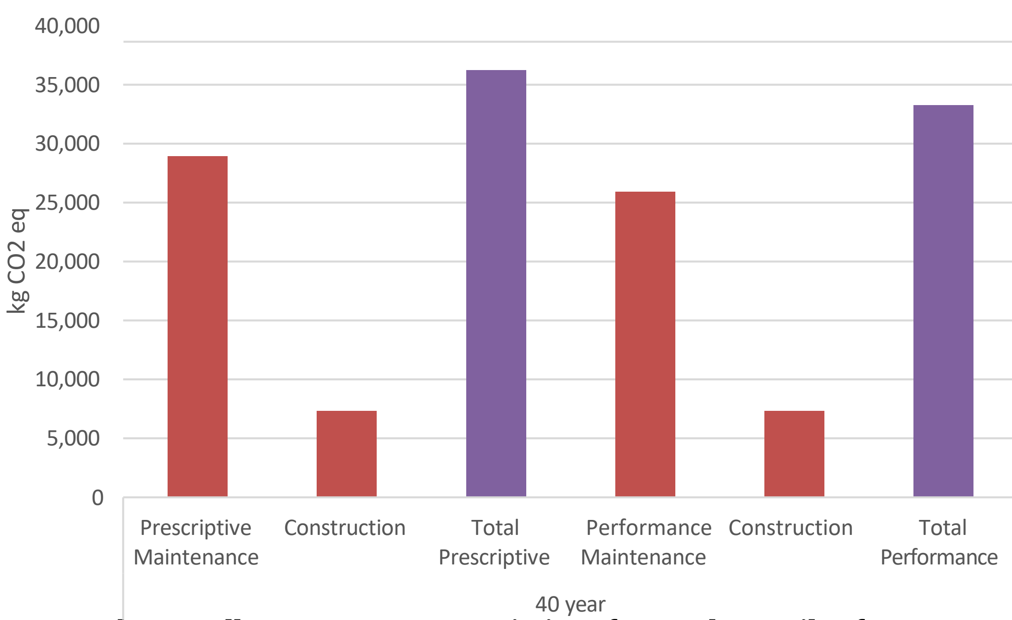


Figure 42. Graphs. Cradle-to-grave GHG emissions for one lane mile of Type IL concrete column for 30- year time period.

Like the pavement functional unit, there are interesting trends that can be seen in the figures above. The first is that the performance-based specifications have a clear reduction in use phase emissions in the column function unit which reduces total emissions by nearly 10% for the 30-year life span and nearly 9% for the 40-year life span. Construction emissions are constant as discussed above so the improvement is entirely due to the higher durability concrete produced under the PBS allowing for fewer maintenance treatments. An additional point of interest is that there are proportionally higher emissions associated with the 40-year service life compared to the 30-year life. This suggests that there is an optimal time between 30 and 40 years within this model where the incremental year of service life begins to add additional maintenance treatments and may be a candidate time for a larger overhaul to reduce the overall use phase emissions.

Table 15 shows the results of the equivalent lifespan analysis for the concrete column, conducted similarly to the comparison of the concrete pavements above. The trend is more pronounced for the columns compared to the pavement functional unit; additionally, the relative difference between the two equivalent lifetimes is larger for the columns compared to the pavement. Potential reasons for this may be that the smaller quantity of emissions for construction are dominated by the reduction in maintenance emissions or the typical service life for a structural element is longer and the maintenance plan is overconservative in the applied treatments.

The initial period before applying maintenance treatments does not contribute to the use phase emissions, and the extra 10 years after the initial 30 years for the 40-year service life may be having a disproportionate impact. Note that the use phase emissions are due to the applied maintenance treatments, and as shown in Figure 5, to meet the same level of performance in an element. Additional treatments are required over time which helps to explain the increased use phase emissions for a longer designed service life. As a result of this, concrete that is designed to be more durable may have an increased reduction in emissions because the number of reconstructions necessary is reduced as well as the amount of maintenance required to keep the service level within the required values.

Table 15. Comparison over equivalent 120-year lifetimes of emissions for 30- and 40-year service life of 1 column

	Prescriptive-based		Performance-based	
LCA Phase	Service Lives			
	30 years	40 years	30 years	40 years
Construction	7,300	7,300	7,300	7,300
Use	14,500	28,900	12,500	25,900
[redacted]				
120-year total	**87,200**	**108,600**	**79,200**	**99,600**

Finally, the trends between the concrete mix designs show similar results to the pavements regarding higher values of SCM replacements with lower total emissions. The lowest total emission mix for any period of maintenance is 30F with the next lowest emission mix designs following the same order as the emissions from construction processes. Again, reducing the amount of clinker fraction in the concrete mix design is responsible for a major reduction in emissions and when associated with concrete designed to be more durable through the use of SCMs and minimum performance standards, reductions in environmental impact are achieved both during the construction and use phases.

CHAPTER 6. POTENTIAL IMPACTS ON STATE OF GEORGIA

INTRODUCTION TO POTENTIAL IMPACTS

The potential economic impact, including any financial savings, to the state from the adoption of the proposed specifications will be quantified. With the adoption of the proposed specifications, testing costs to qualify a mix are expected to increase from the current prescriptive methods due to an increased number of tests needed. However, the qualified concrete is expected to be more durable, potentially resulting in lower long-term maintenance costs. The added testing costs were quoted from 3rd party testing agencies to estimate the additional costs. These were compared to a financial cost estimate of the long-term maintenance costs. The same maintenance strategies performed in accordance with GDOT and FHWA were used as part of a financial cost estimate using RS Means data to calculate the reduction in maintenance costs. These two values were compared to determine a cost-benefit ratio between the additional testing needed and the expected savings from reduced maintenance. Dong, Y. [153] reviewed the potential for a reduction in maintenance needs in higher performance concrete mixtures over time when used in bridge structures. It was found that the increase in costs associated with more durable mixtures and additional testing is more than offset during the use of the structure through reduced maintenance. Finally, the environmental and social benefits were estimated for the proposed specifications. Reducing the amount of maintenance through creating more durable concrete is expected to reduce environmental impact by decreasing impacts such as the total acidification and carcinogen potentials associated with concrete specified for GDOT. The societal improvement can be quantified by combining the reduced environmental and financial burdens for the agency which allows for more spending on other areas of GDOT's mission.

FINANCIAL IMPACTS OF TESTING

To quantify the additional testing costs associated with the proposed PBS, an estimate from one

3rd party company in Georgia and RS Means data were calculated for each proposed test. The quote from the 3rd party testing center was provided as a range dependent on variable material costs. The RS Means cost estimate was determined using the costs for the testing materials and technician labor. The estimated value included the cost of the materials required for each test and would be expected to be less if the material were provided by the producer at a testing location on site. Additionally, the testing company noted that the costs for some tests were tied to the prices for materials to run the test. For example, sulfate resistance tests require a large amount of sodium sulfate and the price paid by the testing company varies based on market conditions. As shown in Figure 43, a range of costs were produced from the estimates to create a low and high range which ranged from $3920 to $4905 per mix qualification.

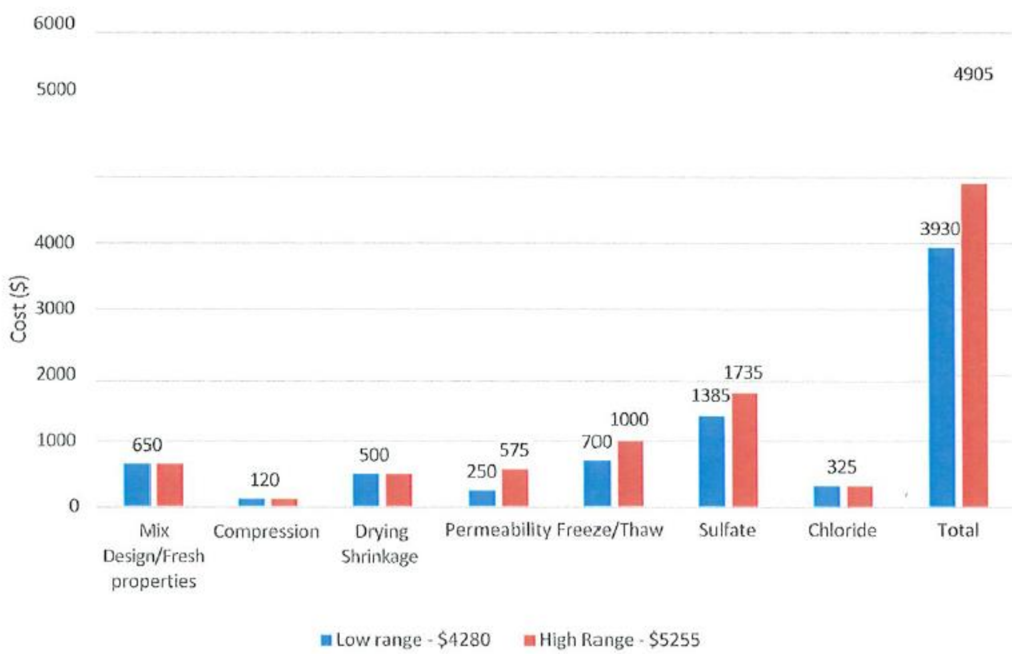


Figure 43. Graphs. Estimated range of additional costs associated with qualifying one mix.

The additional cost is associated with tests that have additional labor, material, and testing space requirements compared to the current prescriptive requirements. Following conversations with several large producers, the general thought was that the additional testing costs would be passed onto the owners by the producers, but the more durable concrete mixtures that resulted from the mix design process would offer a benefit over time. The increase in cost is above the typical quoted price of $650 to design a mix under the current specifications.

In addition to the testing costs required for the qualification of mixtures, field verification using surface resistivity or RCPT is being proposed in addition to the typical compressive strength tests. The reasoning for this is to verify the strength and the durability of the concrete being delivered to the site. This is now being designed for under the proposed specifications. Field tests require different numbers of testing samples depending on the volume of concrete being placed. The proposed specifications call for either surface resistivity or permeability tests to be done at the same frequency as the strength tests, allowing for the same samples to be used for both tests. Including the surface resistivity or permeability for field verification will be expected to increase the cost for verifying the mix compared to the current specifications.

However, as shown above, performance metrics often can be tested faster than prescriptive ones and have the benefit of being non-destructive. Finally, it has been shown that using performance metrics can result in savings to a state DOT by verifying concrete quality using performance metrics like surface resistivity in conjunction with instead solely the typical compressive strength tests. Testing done by Kansas DOT showed an estimated testing savings of more than $68,000 per year of using surface resistivity to verify mixtures compared to alternatives where the total current testing cost per year was estimated to be ~$71,000 [168]. KDOT estimates the DOT testing lab qualifies nearly 600 mixtures per year with additional testing done by 3rd party testers.

The KDOT study saw that savings were initially offset by the cost to purchase the equipment for an estimated $106,000; however, over a three-year period, estimated cost-benefit ratio was 1.9 which shows the cost savings are larger than the cost of the equipment overtime. A study performed for the Louisiana DOT estimated savings to the department of $100,000 and contractor savings of more than $1,500,000 because of using a performance metric such as surface resistivity compared to a typical testing cost of ~$110,000 for the DOT and $1.6 million for contractors [169]. The findings were the result of fewer labor hours required to perform a test using surface resistivity and the lack of additional testing preparation compared to the ASTM C1202 method. The larger savings for a contractor were the result of spreading the cost of the equipment over a larger number of samples. The report notes that with a competitive bidding process, the savings from the contractor testing for quality control could reasonably be expected to be passed on to the state.

IMPACTS ON COSTS FOR CONSTRUCTION AND MAINTENANCE

The financial impact of the proposed specifications was estimated through construction and maintenance costs associated with each specification. Construction cost and maintenance treatments were estimated using RS Means and adjusted for the Atlanta city index, a measure of the relative construction costs from major cities in the US which allows for costs to be normalized to the local construction market. The construction costs were assumed to take place in year 0 with each of the maintenance activities taking place at the end of the year they were scheduled for. The scheduling of the maintenance activities was made using the same sequencing as for the LCA analysis for environmental impacts. Using the principle of the time value of money, the net present value for all the construction and maintenance of a lane-mile and a column could be calculated for the two time periods. Then, the annual cost of the outlays could be calculated to determine the difference in cost to construct and maintain the two functional units. This allows for a comparison between the testing costs and the estimated benefits to the state when switching to the proposed PBS. The minimum acceptable rate of return (MARR) was set to 5%, the average of the 30-year treasury bond over the last 30 years. Adjustments to the MARR impacts the calculations with an increase in the rate reducing the present value of the construction and decreasing the annual cost. Alternatively, decreasing the MARR would increase the present worth and annual costs for construction and maintenance.

Figures 44 and 45 show the annual costs for the two functional units. Trends to note are that the proposed performance specifications have lower estimated annual costs compared to the prescriptive for all time periods and both functional units. This can be attributed to more durable concrete resulting in lower maintenance costs due to less frequent treatments. The construction costs were estimated to be the same regardless of the specification type so the decrease in annual worth is entirely attributable to improvements in durability.

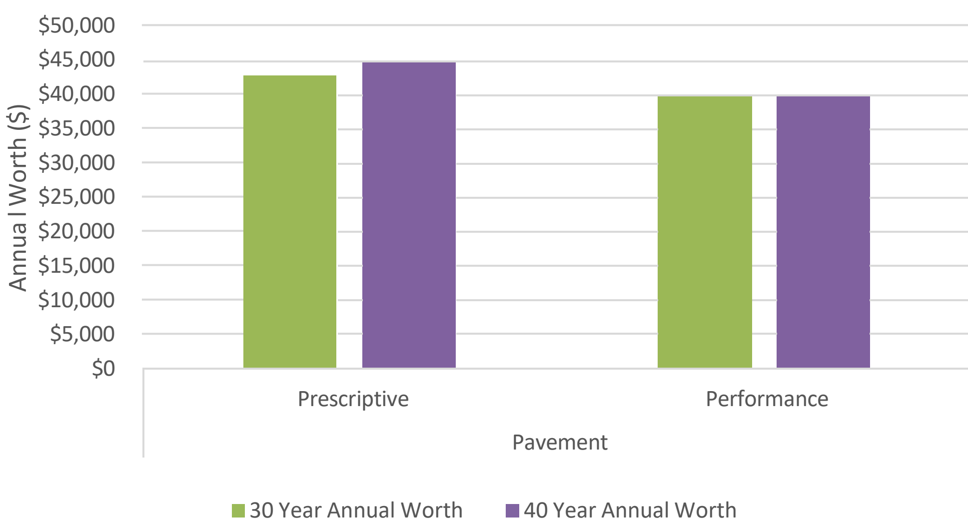


Figure 44. Graphs. Estimated annual cost for one lane-mile of pavement over 30 and 40 years.

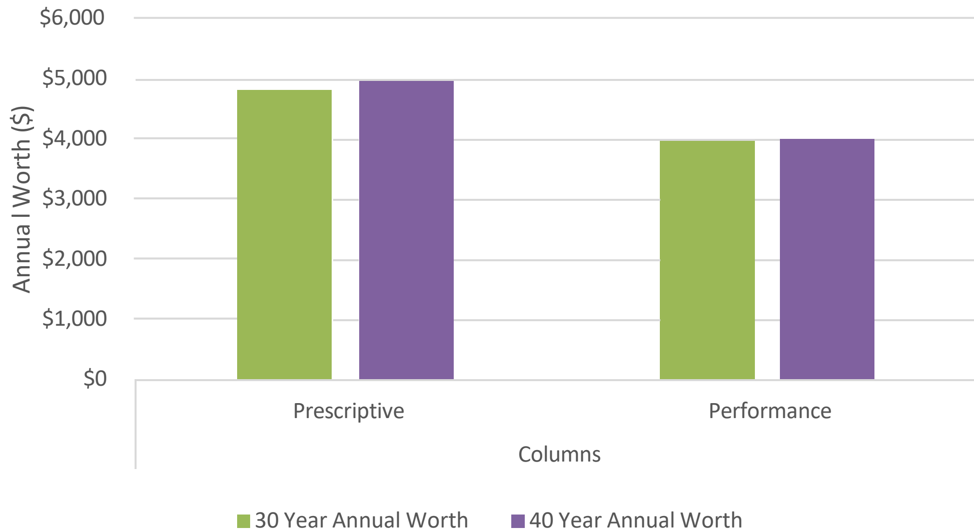


Figure 45. Graphs. Estimated annual cost of a column over 30 and 40 years.

Using the decrease in annual cost compared to the quoted average additional testing cost for each mix, a cost-benefit ratio can be calculated to determine if the decrease in annual costs makes up for the increase in testing costs. Because the annual costs are measured for the specific functional units which are one lane-mile of pavement and a single concrete column, and the costs with qualifying a mix design are incurred only once at the beginning of a project, it was determined to use the GDOT item mean summary to find the average size of a project using pavement and columns. This gives a comparison for the decrease in maintenance cost for all the pavement and columns typically included in a project versus the costs incurred to qualify a mix for that project. The average pavement project from January until April has been 0.85 lane-miles of concrete pavement and the typical bridge project has required 26.3 columns [170]. These values are reported from the GDOT item mean summary and were rounded up to one lane-mile of concrete pavement and 27 columns. From the section above, note the testing costs in addition to the typical quoted mix design costs were $3270 to $4255. Table 16 shows the difference in annual costs between the prescriptive- and performance-based specifications. Table 17 shows the range of cost-benefit ratios between the expected benefit from reduced annual costs and the increased testing costs. A ratio greater than 1 shows the benefits outweigh the costs.

Table 16. Difference in annual worth

	Difference in annual worth	
	Pavements	Columns
30 Year	$5,300	$1,000
40 Year	$5,500	$900

Table 17. Cost-benefit ratios

	Cost Benefit Ratio	
	Pavements	Columns
30 Year	1.25-1.62	6.35-8.26
40 Year	1.29-1.68	5.71-7.43

As can be seen by the cost-benefit ratio being above 1 for both the pavements and columns for both time periods, the expected increase in testing costs associated with the qualification of performance-based mix designs can be expected to be more than offset by a savings in the annual cost of the maintenance. A final note is that once a mix design has been qualified, it is not expected to require additional testing unless material changes from the original design occur. Thus, the costs associated with testing could be spread out over larger amounts of concrete from a producer, reducing the average costs to qualify a mix.

ENVIRONMENTAL POLICY AND SOCIAL IMPACTS

The environmental and social impacts from the proposed specifications result from a reduction in harmful pollution associated with the upkeep of concrete pavements and structures, as well as improvements to the public's interactions with the built environment through reduced scheduled maintenance. Additionally, while not being a part of the proposed specifications, the measure of embodied carbon is a growing part of the concrete industry.

New Jersey recently passed a law that provides a tax credit for concrete that can be shown to be low-emission concrete, a policy framework that will encourage the adoption of more sustainable practices within the industry to win bids [171]. The New Jersey law will go into effect January 1, 2024 and provide for tax credits for quantified reductions in emissions associated with concrete for projects above a minimum size. For emphasis, the proposed specifications do not require embodied GHGs as a performance metric, but reporting is encouraged, since this practice is increasingly common in the industry. An appendix to the proposed specifications includes a sample calculation on how to calculate embodied emissions for concrete from the mix constituent EPDs. The NRMCA has produced an industry standard set of EPDs for various strength concrete mix designs that can be used as a benchmark when comparing the emissions associated with a concrete to an industry average [76]. The National Institute of Standards and Technology (NIST) has developed several reporting tools for modeling the service life of concrete without requiring extensive experiments and has worked on developing standards that allow for innovative and less carbon intensive materials [172].

Finally, the social aspects of reducing the maintenance needs of concrete through improved durability help with decreasing the number of treatments that need to be scheduled, which limits disruptions to the traveling public and reliability of the overall transportation network. Pollutants from infrastructure include more than the GHGs emitted to produce and process materials. The processes also create harmful substances that lead to increases in acidification in state waters and depletion of the ozone layer. Using the LCA, these pollutants can be determined for the total production and use phase. Figures 46 and 47 show the additional impact in acidification and ozone depletion resulting from using the current prescriptive specifications compared to the proposed specifications.

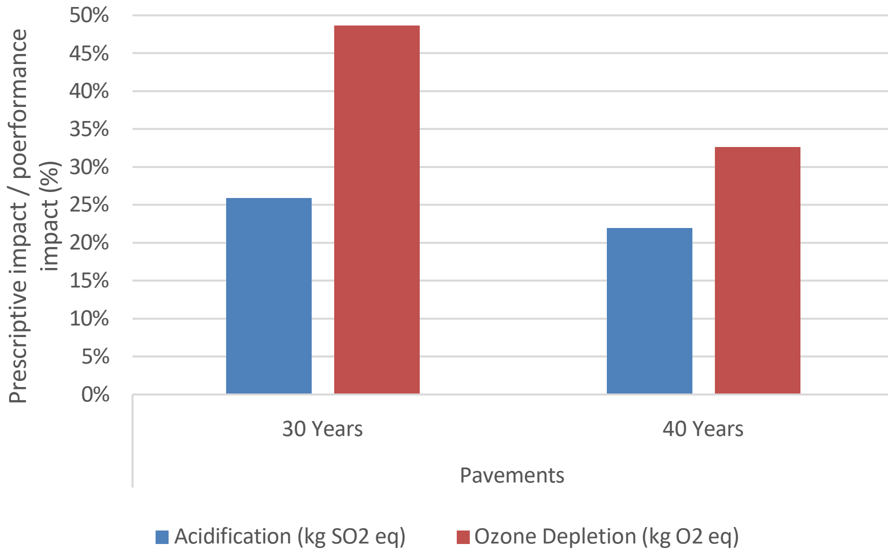


Figure 46. Graphs. Increase in impact over prescriptive-based specifications for lane-mile of pavement.

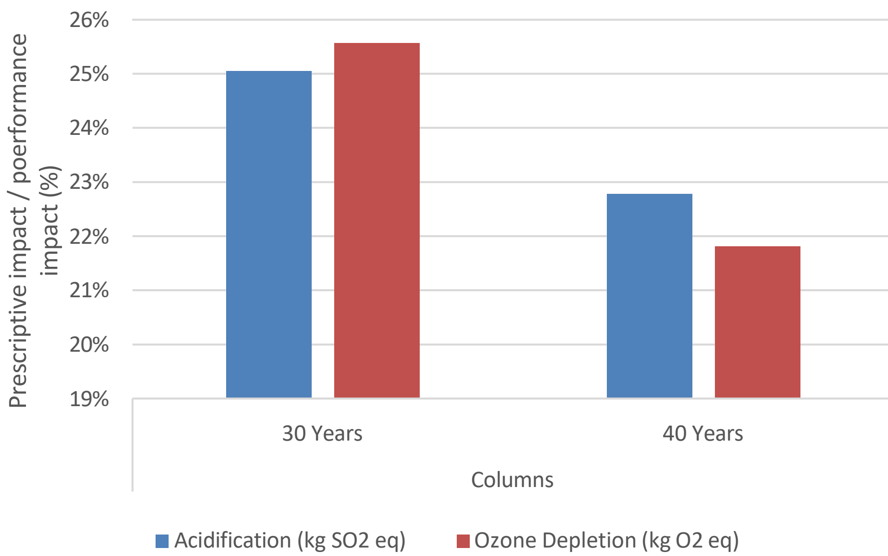


Figure 47. Graphs. Increase in impact over prescriptive-based specifications for lane-mile of pavement.

The growing environmental focus of private owners has begun to affect how public infrastructure owners are looking at their impact on the environment. With the passage of tax credits for reduced emissions and a "greenium" private owners are willing to pay for seemingly more environmentally friendly materials, the trend towards reducing the built environment's impact on the larger environment is becoming clearer. While the proposed specifications do not include GHG limits by class of concrete as a performance metric required to be met to qualify a mix, several federal agencies have released rules implementing those requirements [176]. These maximum limits on GHGs would encourage the use of blended cements and increase the typical SCM replacement rates beyond the maximum currently allowed, potentially towards no maximum limit on replacement rates. Those steps are the ones most likely to be undertaken to improve the durability of concrete, which begs the question that if by specifying for durability over the long-term, will concrete become less detrimental to the environment due to the emissions associated with its production? If so, producers may be inclined to report the reduced emissions of their mix designs. Because of this movement, the proposed specifications include sample calculations to aid with determining the embodied GHGs from the production of concrete.

Social impacts of improving the durability of concrete include less delays due to maintenance on the roadways and improved reliability. The FHWA estimated that roadway delays cost the US nearly $19 billion in 2014, a value that is certain to have increased [174]. Additionally, the need for maintenance increases the risks associated with poor road conditions, with the Transportation Research Board (TRB) reporting poor roadway conditions resulting in nearly 1/3 of highway fatalities [175]. Improving the durability of concrete will lead to reductions for required maintenance which will have positive social impacts for the Georgia public.

CHAPTER 7. PROPOSED UPDATES TO CONCRETE SPECIFICATIONS

INTRODUCTION TO PROPOSED SPECIFICATIONS AND STAKEHOLDER FEEDBACK

The proposed draft specification language was developed to create a set of documents support state specification of more durable concrete. With PBS, prescribed limits on materials and mixture proportions for a mix design are avoided, focusing instead on the final performance of a mixture in response to a collection of metrics chosen to support the long-term performance of concrete in a specific application. In this study, performance tests were evaluated, and limits were developed for surface resistivity and permeability to suit the current GDOT concrete specifications for different classes of concrete. Additionally, a set of durability metrics were adopted to suit local conditions; these are adapted from an ACI-funded study to unify durability limits in their design codes. That effort, which has resulted in a paper, informed the simplified guidance recommended to represent the geographical realities and uses of GDOT concrete [176].

After drafting proposed changes to the existing Sections 430, 439, and 500 specifications, the project team solicited feedback from stakeholders to support successful implementation. A discussion of the major proposed changes is included below. Redlined copies of the proposed specifications for Sections 430, 439, and 500 are included in Appendices B, C, and D, respectively. Subsequently, additional effort was taken on to address concrete with high and early strength requirements, resulting in proposed changes to specifications for Sections 500 HPC, 504 and 452, provided in Appendix E, to support incorporation of PBS into those documents.

CONCRETE MIX PROPORTIONS TABLE UPDATE

Design requirements in Table 18 include strength requirements, maximum w/cm ratios, minimum and maximum slump, acceptable air content ranges, and drying shrinkage limits for each concrete class. The existing specification for minimum cement factor has been removed to focus on performance.

Additionally, it is recommended that there are no longer limits the maximum amount of SCMs that are allowed within a specific mix, only requiring that the mix design be able to meet the performance metrics. The testing time for mixtures is proposed to be extended from 28 days to a maximum of 56 days to account for the slower rate of strength development from higher SCM usage. The intent is that *a mixture can be qualified at any point up until 56 days*, with the ability to qualify a mix under the strength performance metric as soon as it can be determined it has met the requirements. For example, if a mixture meets the strength or resistivity requirements by 7 or 28 days, the concrete can be qualified at that time. The inclusion of drying shrinkage is meant to provide a measure of the early-age shrinkage of concrete to qualify mixtures that have a lower likelihood to develop cracks due to shrinkage. Removing the limits on the specified proportions of the mix design is not expected to reduce the overall quality of the concrete being provided to the state because producers will still be required to meet the same strength performance as before with additional durability requirements. The result is expected that the overall quality and performance of delivered concrete will improve because of the proposed specifications.

Table 18. Concrete Strength and Early-age Performance Table

Imperial								
Class of Concrete	Minimum Compressive Strength at 28 days (psi)	Coarse Aggregate Size No.	Maximum w/cm ratio lbs/lbs	Slump acceptance Limits (in) Lower-Upper		Entrained Air Acceptance Limits (%) Lower-Upper		Maximum Drying Shrinkage at 28 days (%)
AAA	5000	67,68	0.440	2	4	2.5	6.0	0.04
AA1	4500	67,68	0.440	2	4	2.5	6.0	0.04
D	4000	57,67	0.445	2	4	3.5	7.0	0.04
AA	3500	56,57,67	0.445	2	4	3.5	7.0	0.04
A	3000	56,57,67	0.490	2	4	2.5	6.0	0.04
B	2200	56,57,67	0.660	2	4	0.0	6.0	N/A
CS	1400	56,57,67	1.400	-	3½	3.0	7.0	N/A
Metric								
Class of Concrete	Minimum Compressive Strength at 28 days (MPa)	Coarse Aggregate Size No.	Maximum w/cm ratio kgs/kgs	Slump acceptance Limits (mm) Lower - Upper		Entrained Air Acceptance Limits (%) Lower-Upper		Maximum Drying Shrinkage at 28 days (%)
AAA	35	67,68	0.440	50	100	2.5	6.0	0.04
AA1	30	67,68	0.440	50	100	2.5	6.0	0.04
D	28	57,67	0.445	50	100	3.5	7.0	0.04
AA	25	57,67	0.445	50	100	3.5	7.0	0.04
A	20	56,57,67	0.490	50	100	2.5	6.0	0.04
B	15	56,57,67	0.660	50	100	0.0	6.0	N/A
CS	7	56,57,67	1.400	-	90	3.0	7.0	N/A

Notes:

1. Hydraulic cement used for any class or application shall conform to the specifications in any of the following: AASHTO M85/ASTM C150 or ASSHTO M240/ASTM C595.

2. Compressive strength will be determined based upon result of six cylinders prepared and tested in accordance with AASHTO T 22. If minimum compressive strength is not reached by 28 days (or earlier), samples from the same batch shall be tested at 56 days using the same compressive strength limits from 28 days. Pay reduction based on meeting 56-day strength (but when the 28-day strength requirement was not met) may apply at the

discretion of the Engineer.

3. Cementitious materials include hydraulic cement and all supplementary cementitious materials (SCMs). Inert fillers such as interground limestone shall not be considered an SCM for the purposes of this specification. Water/cementitious ratio (w/cm) refers to the ratio of water to total cementitious material including hydraulic cement and all SCMs.

4. Designed slump may be altered by the Office of Materials and Research when Type "F" water reducers are used. If higher slumps are determined to be necessary, the Engineer shall be consulted. Approval of higher slumps shall be approved by the Engineer as needed on the project.

5. If contractor determined self-consolidating concrete (SCC) is desirable for precast or prestressed concrete applications, approval from the Engineer is required and workability acceptance requirements in Table 7 supersede slump requirements in Table 1.

6. Specific size of coarse aggregate may be specified by the Engineer.

7. Lower entrained air limit shall be waived when air entrained concrete is not required.

8. When Class A is specified for bridge deck concrete, the entrained air acceptance limits shall be 3.5% to 7.0%.

9. Air content shall be measured in accordance with AASHTO T152 utilizing a Type B meter.

10. 28 day drying shrinkage shall be measured in accordance with AASHTO T160 using concrete prisms exposed to drying at a concrete age of 7 days. The initial reading for drying shrinkage calculations shall be the reading taken at the start of drying at a concrete age of 7 days ± .5 hours. Classes B and CS have no maximum drying shrinkage requirements.

SURFACE RESISTIVITY AND CHARGE PASSED LIMITS BY CONCRETE CLASS

Tables 19 and 20 show both surface resistivity and charge passed limits corresponding to AASHTO T358 and ASSHTO T277, respectively. The minimum acceptable surface resistivity limits were correlated to RCPT maximum allowable limits using the relationship established by Chini, A. *et al* [61] and used in the AASTHO T358 standard. The proposed curing conditions for the samples are for the cylinders to be submerged so they achieve a saturated state in a limewater solution. The limewater solution used for curing is prescribed in AASHTO T358. Surface resistivity tests are to be conducted at 56 days, per the standard, and reported as the average of three samples in accordance with AASHTO T358. Charge passed tests are to be conducted following 56-day curing, per the standard, and reported as the average of three samples in accordance with AASHTO T277. No surface resistivity or permeability limits are proposed for Classes B or CS.

Table 19. Proposed Surface Resistivity Limits by Class for Sections 500 Concrete

Chloride Ion Penetration	Surface Resistivity Limits	Minimum Allowable Surface Resistivity by Concrete Class (KOhm-cm)				
		AAA	AA1	D	AA	A
High	≤ 12.0					
Moderate	12.1-13.0					✓
	13.1-16.0			✓	✓	✓
	16.1-21.0		✓	✓	✓	✓
Low	21.1-40.0	✓	✓	✓	✓	✓
Very Low	40.1-254.0	✓	✓	✓	✓	✓
Negligible	≥ 254.1	✓	✓	✓	✓	✓

Table 20. Proposed Permeability Limits by Class for Section 500 Concrete

Chloride Ion Penetration	Charge Passed Limits	Minimum Allowable Charge Passed by Concrete Class (Coulombs)				
		AAA	AA1	D	AA	A
High	≥4001					
Moderate	4000-3501					✓
	3500-2801			✓	✓	✓
	2800-2001		✓	✓	✓	✓
Low	2000-901	✓	✓	✓	✓	✓
Very Low	900-101	✓	✓	✓	✓	✓
Negligible	≤100	✓	✓	✓	✓	✓

UNIFIED DURABILITY MEASURES FOR FREEZE/THAW, SULFATE, AND CHLORIDE EXPOSURE

The proposed durability performance metrics were inspired by the work of an ACI Technical Committee to unify durability requirements between ACI 201, 219, and 318 [176]. The implementation of performance metrics to improve the quality of concrete was inspired by the implementation of metrics by other DOTs, as shown above, and improved through workshops with industry stakeholders. Following the feedback, some of the suggested unified guidance was adjusted to best reflect conditions in the state.

Freeze/Thaw Performance Metrics

Freeze/thaw requirements hold for any location above the Fall Line, and the Engineer has the flexibility to add freeze/thaw concerns for any mix or location below the Fall Line at their discretion. Table 21 shows the two freeze/thaw classes.

Table 21. Freeze/Thaw Exposure Classes

FT Exposure Class	No FT Exposure	FT Exposure
Exposure Condition	Not exposed to FT cycles	Exposed to FT cycles with frequent exposure to water
Maximum f'_c, psi (MPa)	None	4500 (32)
Maximum w/cm	None	0.45

The freeze/thaw durability tests allow for just one of the three to be measured and met for the concrete mix to qualify for freeze/thaw resistance, as shown in Table 22. This was proposed to allow producers as much flexibility as possible when using on-site or 3rd party testers.

Table 22. Freeze/Thaw Durability Metrics

FT Exposure Class	No FT Exposure	FT Exposure
Minimum specific surface, in.^{2}/in.^{3} (mm^2/mm^3)	None	600 (21)
Maximum spacing factor, in. (mm)	None	0.009 (0.23)
Minimum durability factor	None	90

Sulfate Performance Metrics

No changes are proposed to the ACI unified sulfate exposure classes, as shown in Table 23. The testing on the soil or water sulfate concentration will be done by GDOT to provide the producer with guidance on which exposure class the location experiences.

Table 23. Sulfate Exposure Classes

Sulfate Exposure Class	Water soluble sulfate in soil, % by mass	Dissolved sulfate in water, ppm
S0	$SO_4 < 0.10$	$SO_4 < 150$
S1	$0.10 \leq SO_4 \leq 0.20$	$150 \leq SO_4 \leq 1{,}500$
S2	$0.20 \leq SO_4 \leq 2.00$	$1{,}500 \leq SO_4 \leq 10{,}000$
S3	$SO_4 > 2.00$	$SO_4 > 10{,}000$

The proposed addition to the specifications for sulfate resistance is to specify expansion limits of the concrete based on the exposure class and the type of cement. Table 24 shows the various expansion limits possible at certain times for different cement types in sulfate exposure classes.

This method was chosen to acknowledge that the availability of cement may not be consistent, but to also provide assurance the concrete will be able to resist sulfate attack regardless of the cement used. The mix may be qualified after the first period where expansion is lower than the required limit.

Table 24. Sulfate Attack Durability Metrics

Sulfate Exposure Class	Cement Designation	Maximum w/cm	Minimum f_p' psi (Mpa)	Performance requirements expansion in ASTM C1012 (maximum %)		
				6 months	12 months	18 months
S0	No Requirements					
S1	Performance Requirement Only	0.55	3500 (25)	0.05	0.10	-
	Type II or Type MS-designated blended cements	0.50	4000 (25)	0.10	-	-
	No restriction	0.45	4500 (32)	-	-	-
S2	Performance Requirement Only	0.50	4000 (25)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.45	4500 (32)	0.05	0.10	-
	Type II or Type MS	0.40	5000 (35)	0.10	-	-
S3	Performance Requirement Only	0.45	4500 (32)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.40	5000 (35)	0.05	0.10	-

Water-soluble Chloride Performance Metrics

No changes are proposed to the ACI unified structural importance, as shown in Table 25. The type will be determined by GDOT to provide the producer with guidance for chloride limits.

Table 25. Structure Importance and Type

Structural Importance	Definition
T1	Minor risk of reinforcement corrosion can be tolerated
T2	Reinforcement corrosion cannot be tolerated; non-environmental structures
T3	Reinforcement corrosion cannot be tolerated; environmental structures

The proposed water-soluble chloride limits are for chlorides within all cementitious materials which includes Portland cement and all SCMs. The limits are lower for prestressed concrete to address concerns of prestressed strands being critical to prestressed concrete from GDOT. Table 26 shows the water-soluble chloride limits for each exposure class.

Table 26. Water Soluble Chloride Limits

Chloride Exposure Class	Structural Importance	Chloride limits for new construction (% by mass of cementitious material)	
		Water-soluble (ASTM C1218/C1218M)	
		Reinforced Concrete	Prestressed concrete
C0 - Concrete in dry environment	T1	1.00	0.06
	T2	0.25	0.06
C1- Concrete exposed to moisture but not to external sources of chlorides in service	T1	0.30	0.06
	T2	0.15	0.06
C2 -Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salts, brackish water, seawater, or spray from these sources in service	T1, T2	0.15	0.06
C3 - Concrete exposed to severe exposure conditions, including concentrated chemicals, wetting-and-drying cycles, FT cycles	T2, T3	0.10	0.06

OPTIONAL EMISSIONS REPORTING

The emissions associated with concrete includes the production of the constituents from raw materials and the processing required, the construction processes involved in installing the concrete, maintenance treatments during the usage phase, and demolition of the final structure. To track the total lifetime emissions of concrete, data needs to be collected from the beginning of the material supply chain to the disposal stage of the project. Based on the feedback from GDOT, the GHG emissions associated with a unit of concrete will not be used as a performance requirement, rather the quantity of emissions linked to concrete production may be reported as requested. Sample calculations to determine the embodied emissions from a unit of concrete are included in appendixes for all proposed PBS to help producers calculate the environmental impact of their mix designs. The calculations require EPDs for the materials used in the mix design along with the proportions of the mix. The tools needed for this calculation are required at the material producer scale, where a life cycle assessment is performed to track the emissions associated with materials such as cement, SCMs, and aggregates. These EPDs are expected to become more readily available and prevalent within the building construction space as owners and ready-mix producers have a greater demand for tracking embodied emissions. The EPDs from the mix constituents are expected to become similar to material safety data sheets, available and provided by supplies for all materials.

CHAPTER 8. CONCLUSIONS AND FUTURE WORK

CONCLUSIONS

The proposed performance-based specifications represent a fundamentally different method of specifying concrete for the state of Georgia. Rather than relying on prescribed limits for the mix proportions and a restricted set of materials to produce concrete for the many different uses required in the state, the proposed specifications remove some prescriptive-based requirements and replace them with performance metrics. These performance metrics are designed to predict, using simple and fast tests, the future performance of concrete and allow for mix designs to more reliability respond to different site conditions. To measure the impacts of the proposed specifications, a life cycle analysis was conducted that measured the cradle-to-gate and cradle-to-grave impacts of both pavements and concrete structures under the new specifying regime. Results showed that the performance-based specifications have lower lifetime emissions due to reduced amounts of cement and reduced maintenance needs. Additionally, the financial impact of switching to performance-based tests was compared to the savings expected from more durable concrete. It was shown that the savings created by more durable concrete outweigh the potential costs of performance-based tests for the average project while financial benefits are expected to be far greater for large-scale projects. Finally, a discussion of the social impacts of reduced maintenance needs demonstrated improved safety and reliability for the traveling public.

The proposed performance specifications remove prescriptive limits on proportions and allowable materials. This is expected to decrease costs for producers when designing mixtures through allowing optimal mixtures to be designed to meet strength and durability requirements as well as increasing flexibility in using materials. The proposed performance metrics include measurements of surface resistivity and permeability to determine the mix's resistance to chloride ion penetration. Either method may be used with limits set based on the class of concrete to avoid over or under designing mixtures with blanket limits for all GDOT concrete classes. A suggested unification of ACI durability guidance was used as a baseline to create additional durability metrics. These include measures of freeze/thaw resistance, sulfate attack resistance, and water-soluble chlorides. Feedback from industry members and GDOT technical teams were incorporated as the ACI unified guidance was adjusted for GDOT's usage. The durability metrics use specific exposure classes determined by the project Engineer to set different limits based on the conditions the concrete will be required to perform in. This provides a more holistic approach to specifying concrete by tailoring the mix design to the field conditions. The design is being proposed to be driven by the performance needs of the concrete rather than the historic, prescriptive limits currently in practice.

To quantify the environmental impacts of the proposed specifications, an LCA was undertaken to evaluate the total impact from the production of raw materials through disposal of two functional units produced using the current prescriptive- and proposed performance-based specification. The results show the performance-based specifications allow for both lower construction phase and use phase emissions. This is due to higher cement replacement limits reducing the amount of clinker used in concrete during the construction phase and more durable concrete requiring fewer maintenance treatments during the use phase. By using an LCA, the total life impacts can be compared using a large dataset that accounts for all the inputs required to produce, construct, and maintain concrete pavements and structures.

The additional testing under the proposed performance-based specifications is expected to increase the costs associated with qualifying a mix; however, the reduced maintenance costs are expected to more than offset the increased costs, resulting in lower lifetime costs for the state. Testing costs were estimated from 3rd party labs to determine the expected testing costs. A financial study of the expected maintenance costs was conducted and the annual worth for each functional unit under each specification regime was calculated. Using these two measures, the cost-benefit ratio was determined, and the results showed significant savings for the average agency project.

Finally, the social impact of improved durability and reduced maintenance were discussed. Pollutants associated with production and maintenance were calculated to be lower under the performance-based specifications. More durable concrete will require less maintenance, thus improving the reliability of the state transportation network.

RECOMMENDATIONS FOR FUTURE WORK

It is recommended that future research investigate the potential for draft PBS for additional concrete standard specifications and potential additional performance metrics for inclusion in specifications. The framework used in this project for analyzing the financial and environmental impacts of proposed specifications can be used to model the potential impacts for other standard specifications, such as high early-age strength concrete and repair/patch concrete. Recommendations for specific sections to focus on are Sections 452 and 504 with a review of the remaining concrete specifications to gauge the potential alignment with the proposed PBS from this report.

Improvements in performance metrics and tests are expected in the future as PBS gain even wider adoption from DOTs and industry members begin to qualify and verify mix designs. New tests may reduce both the time required to perform testing, the financial costs, and become more accurate predictors of long-term performance. Based on the framework in this project, it is recommended that improved metrics be targeted towards specific causes of degradation in order to measure the potential long-term performance. Recommendations of specific performance metrics that could be researched are tests that can quantify the susceptibility of concrete in terms of carbonation and sorptivity. Carbonation of concrete is expected to become a larger issue in the future as clinker fraction continues to be reduced in search of more sustainable concrete, but that leaves structures vulnerable to carbonation-induced corrosion. Adding a test that quantifies the potential for concrete to carbonate and the rate at which it occurs is recommended to address this future problem. An improved sorptivity test could be used to replace RPCT as a measure of permeability and improve the proposed PBS. Finally, with increased dosages of SCMs likely, salt scaling is expected to become more prevalent in locations where deicing salts are applied, particularly on bridge decks. It has been shown by Thomas, M. *et al.* [64] that higher replacement of both Type I/II cement and Type IL with SCMs resulted in higher amounts of scaling, but it was noted that the testing methods used were aggressive. This suggests a need for the tests to be studied further to determine how higher amounts of SCMs can be incorporated in mix designs to achieve better performance while also meeting scaling challenges. Potential solutions include specifying bridge deck mixtures with limits on SCM usage and delays to applying an initial deicer to the decking.

APPENDIX A: SUMMARY OF STAKEHOLDER FEEDBACK

<u>GDOT Draft Specification Initial Technical Review - 2/8/23</u>

- GWP functions best for now as a report value only and not a requirement
  - Create an Appendix that shows how GWP per unit of concrete can be calculated and the necessary documentation needed
- AASHTO documents are preferred but ASTM is okay if no AASHTO standard
- Formation factor is a better measure for quantifying the physical and chemical effects for permeability
  - There is no AASHTO standard currently for pore solution extraction and modeled pore solution show there is a wider variance than the TP119 assumed value of .1 Ohm-m
  - Not proposing formation factor as a performance metric but will be discussed in report
- Clarify that the SCM replacement limit and minimum cement factor have been removed in examples

<u>Producer #1 - 2/13/23</u>

- Include both ASTM and AASHTO standards where equivalent
- ASTM C94 removed mixing time/revolutions maximums in recent edition and could be considered to removed current limitations in specifications
  - The updated ASTM C94 provides no guidance beyond the owner's specifications for max mix time/revolutions but without stated maximums, defers to a delivered batching being able to meet fresh properties required elsewhere (slump, segregation, etc.)
- Concerns about responsibility for added cost of qualification and time to shifting to new

specifications

  - Smaller and mid-sized producers may not have all testing equipment to do onsite
  - GT is producing a cost estimate to qualify and field verify a mix to quantify and compare to potential benefits to the state

- Ensure EPDs for report only GWP are for batch plant specific and not an industry average
  - Type I and III EPDs

Contractor #1 – 2/20/23

- Current prescriptive-based specifications have very similar mixtures where a producer's design can be swapped on site if immediate supply is an issue. From a contractor's standing, additional site requirements could make the procurement process harder.
  - Batch plants should be able to use multiple prequalified mixtures that would not have differences between classes but that will be able to individually meet theoretical site
- Mix time limits on a concrete truck would need to be reactive to site conditions and a test pour may not be able to predict delays accurately enough to be of value
  - Best is either to keep limits as is now so requirements are hard or to remove requirements altogether
- Availability of construction materials should not impact the proposed PBS

- Warranty on contractor for performance will be difficult to track because producer typically has shown the materials meet the requirements but once on site, it is almost impossible to track specific batches to later issues

<u>Producer #2 – 2/21/23</u>

- Proposed specifications need to be clarified on if the performance metrics are mix qualification or field verification
    - Performance metrics are mix qualification for the site condition. The only proposed field verification is strength and permeability (SR or RCPT). The wording will be updated.
- FT requirements may be too detailed for the expected conditions in Georgia
    - Split the FT requirements to be based on geography with no FT requirements below Fall Line and FT requirements representative of F2 from ACI above the Fall Line
- Concern with qualification of mixtures in lab environment being unable to be see performance benefit in field
- Shrinkage requirements could be tailored to specific usages of classes
    - Remove shrinkage requirements for B on down
- Permeability requirements could be tailored to specific usages of classes
    - Remove permeability requirements for B on down
- Sulfate tests could be loosed for S1 exposure class
    - Speaking with GDOT
- When sulfate and chloride site conditions exist at the same time, the chloride limits should be the limiting factor because it will dominate degradation.
    - The current specifications require all performance metrics to be met based on site

conditions and a mixture of aggressive site conditions would not affect individual limits

- Permeability requirements should allow for limits to be met at least by 56 days
    - If it can be shown that the limits have been met before 56 days, the mix will be qualified. If the limits cannot be met before 56 days, the mix will not be qualified.
- Lab tests at producers may not be in labs currently certified or accredited to GDOT standards
    - Will tests be allowed at producer labs or will tests need to be done at third-party if producers aren't accredited?

Third-party concrete lab #1 2/21/23

- Testing costs are generally stable but the proposed specifications will require additional qualification costs
    - Producers generally send lab samples to be tested if required in contract or if demand/equipment requirements are too much at producer

Admixture Company #1 2/22/23

- Slump as a fresh property may not a good measure of workability based on advances in admixture technology, but producers/owners are very familiar with slump
    - Benefit of using slump is that placement can be better estimated and has standards associated with the test

Producer Company #3 3/7/2023

- Pre-cast/-stressed members typically exceed AAA strengths and may need a new strength class

- High performance concrete combines high strength with high durability but may need to be differentiated by location
    - Could add in different requirements based on proximity to the coast that creates carveouts for pre-cast/-stressed members
- Pre-cast/-stressed members may need carveouts for finishes that allow SOP-3

APPENDIX B: REDLINED SECTION 430

Section 430—PortlandHydraulic Cement Concrete Pavement

430.1 General Description

This work includes constructing pavement composed of ~~Portland~~hydraulic cement concrete, with or without reinforcement as specified, on a prepared subgrade or subbase course.

Follow the requirements of these Specifications and conform to the lines, grades, thicknesses, and cross sections shown on the Plans or by the Engineer.

430.1.01 Definitions

General Provisions 101 through 150.

430.1.02 Related References

A. Standard Specifications

Section 106—Control of Materials

Section 152—Field Laboratory Building

Section 431—Grind Concrete Pavement

Section 461—Sealing Roadway and Bridge Joints and Cracks Section

500—Concrete Structures

Section 800—Coarse Aggregate

Section 801—Fine Aggregate

Section 830—Portland Cement

Section 831—Admixtures

Section 832—Curing Agents

Section 833—Joint Fillers and Sealers

Section 853—Reinforcement and Tensioning Steel

Section 880—Water

Section 886—Epoxy Resin Adhesives

B. Referenced Documents

AASHTO T 126 AASHTO

T 97 AASHTO T 22

AASHTO T 23

AASHTO T27

AASHTO T152

AASHTO T160

AASHTO T161

AASHTO T277

AASHTO T290

AASHTO T358

AASHTO M31

AASHTO M85

AASHTO M240

ACI 214

ASTM C 94, Requirements for Uniformity

ASTM C 684, Method A

ASTM C452

ASTM C457

ASTM C666

ASTM 1012

ASTM C1218

ASTM D516

GDT 26

GDT 27

GDT 28

GDT 31

GDT 32

GDT 72

GDT 78

SOP 34

Report form, furnished by the

Engineer Requests for certification

430.1.03 Submittals

A. Profilograph Equipment and Operator Certification

Include in the Contract Unit Bid Price the cost to furnish and operate a Rainhart (Model 860) Profilograph to measure pavement profile deviations.

Before paving, ensure that the operator and the profilograph are certified by the Office of Materials and Research in accordance with Standard Operating Procedure No. 34, Certification of Contractor Personnel and Equipment for Smoothness Testing of ~~Portland~~hydraulic Cement Concrete Pavement with the Rainhart Profilograph. Certification includes a mechanical check of the profilograph functions and a written examination by the operator.

Request certification in writing to the Office of Materials and Research at least two weeks before it is needed.

B. Concrete Design

Submit for approval a concrete design that is prepared by a testing laboratory approved by the Office of Materials and Research. The Contractor ~~will~~shall transmit the design to the Engineer for approval at least 35 days before use.

C. Approval of Mix Design Proportions

Obtain approval from the Office of Materials and Research for proposed concrete mix designs. Class 1 and 2 concrete mix designs ~~will~~ shall be verified for early compressive strength according to ASTM C~~-~~684, Method A. Class HES concrete mix designs ~~will~~ shall be verified for compressive strength development at 72 hours according to AASHTO T 126 and AASHTO T 22. Design concrete mixes to meet the requirements in Table 1 – Concrete Mix Design by class of concrete and to meet the performance metrics in Tables 2A through Table 6 when applicable. The Engineer shall determine the applicable site conditions and requirements for concrete placed for each project. Mix designs that meet the requirements shall be qualified and shall meet the remaining quality assurance standards as described in subsection 439.03.06 for field verification of batches. A mix that has previously qualified for a specific collection of exposure classes shall remain qualified. Mixes shall require requalification if a material or proportion changes. A waiver for requalification for a mix design from GDOT may be requested. Concrete mix designs shall only be utilized for sites and applications as approved by the Engineer.

430.2 Materials

Ensure that materials meet the requirements of the following Specifications:

Material	Section
Portland cement	830.2.01
Portland Pozzolan cement	830.2.03
Water	880.2.01
Fine Aggregate, Size No. 10	801.2.02
Coarse Aggregate, Class A or B Crushed Stone or Gravel, Sizes as Specified	800.2.01
Steel Bars for Reinforcement	853.2.01
Steel Wire for Concrete Reinforcement	853.2.06
Welded Steel Wire Fabric for Concrete Reinforcement	853.2.07
Dowel Bars and Bar Coatings	853.2.08
Curing Agents	832
Air Entraining Admixtures	831.2.01
Fly Ash, Raw and Natural Calcined Pozzolan, Slag, and Microsoilica ~~and Slag~~	831.2.03
Joint Fillers and Sealers	833
Low Modulus Silicone Sealant for Roadway Construction Joints	833.2.06
Epoxy Adhesive for Repairing Cracks	886.2.01
Chemical Admixtures	831.2.02

~~**A. Fly Ash**~~

~~Use fly ash, if appropriate, as a concrete additive to promote workability and plasticity. It may be used as a partial replacement for Portland cement in concrete, but follow these limits:~~

~~1. Do not replace the cement quantity more than 15 percent by weight.~~

~~2. Replace cement with fly ash at the rate of 1.25 to 2.0 lbs (1.25 to 2.0 kg) of fly ash to 1 lb (1.0 kg) of cement.~~

~~3. Ensure that the fly ash mix conforms to Subsection 430.3.06, "Quality Acceptance."~~

~~4. Do not use Type IP cement in fly ash mixes.~~

~~**B. Granulated Iron Blast-Furnace Slag**~~

~~If high early strengths are not desired, use granulated slag as a partial replacement for Portland cement in concrete. Follow these limits:~~

~~1. Replace the quantity of cement 50 percent or less by weight if the 5-day forecast of the National Weather~~

Service expects temperatures higher than 60 °F (15 °C).

a. If the 5-day expected low temperature is less than 60 °F (15 °C) but not less than 40 °F (4 °C), replace the quantity of cement 30 percent or less by weight.

b. If the 5-day expected low temperature is less than 40 °F (4 °C), do not use granulated slag.

2. Replace cement with slag at the rate of 1 lb (1 kg) of slag to 1 lb (1 kg) of cement.

3. Ensure that the granulated slag mix conforms to Subsection 430.3.06, "Quality Acceptance."

4. Do not use Type IP cement or fly ash in slag mixes.

A. Supplementary Cementitious Materials

The Contractor may use supplementary cementitious materials (SCMs) to achieve the performance requirements in Subsection 430.3.06. SCMs have been shown to have synergistic properties when used in combination and mix designs are not limited to a single SCM.

Notes:

1. Ensure SCMs meet the requirements in subsection 831.
2. Calculate the water-cementitious material (w/cm) ratio based on the total cementitious material in the mix including hydraulic cement and all SCMs

A.B. Composition of Concrete

Design the concrete mix to conform to the following requirements:

Coarse Aggregate

a. Use coarse aggregate size No. 467, 67, or 57 for plain Portlandhydraulic cement concrete pavement. Use size No. 67 or 57 coarse aggregate for continuous reinforced concrete pavement.

b. Separate size No. 467 or 456 in individual stockpiles of size No. 4 and size No. 67. Blend according to approved mix proportions.

Fine Aggregate

c. Use fine aggregate that meets the requirements for size No. 10.

d. When using two sizes or sources of fine aggregate to produce the proper gradation, blend according to the approved design proportions.

B. C. Protective Materials

Provide materials to protect the concrete edges and surface from rain, including:

- Standard metal forms or wood planks to protect the pavement edges
- Covering material such as burlap or cotton mats, curing paper, or plastic sheeting material to protect the pavement surface

430.2.01 Delivery, Storage, and Handling

Store aggregate from different sources in separate stockpiles.

430.3 Construction Requirements

430.3.01 Personnel

A. Certified Operator

Before paving, have the Office of Materials and Research, certify a profilograph equipment operator. Certification includes a written examination by the operator.

430.3.02 Equipment

A. Equipment Requirements

Provide equipment and tools to perform the work. Provide equipment that allows the paver to operate at a constant production rate and rarely start and stop. The Engineer may limit the production rate or batch size if equipment does not keep pace with the other operations or causes poor workmanship.

B. Scales

Before use, the Engineer ~~will~~shall inspect and approve the scales to weigh concrete materials and the devices to measure water. Tolerances are ± 1.0 percent throughout the operating range. Measure admixtures to ± 3.0 percent.

C. Paving Equipment

Ensure that equipment operating on the pavement has rubber-tired wheels or flat steel wheels. Wait to operate concrete or shoulder paving equipment on the pavement until the concrete slab is 14 days old or has 2,500 psi (15 MPa) compressive strength.

Paving equipment may be either slip-form or fixed form.

D. Surface Finish Equipment

Use mechanical equipment to produce the surface finish of the mainline and transverse plastic concrete grooving. Ensure that the equipment uses rectangular-shaped steel tines of the same size and uniform length. Use tines with a width between 0.08 in (2 mm) and 0.130 in (3.5 mm). Space the tines approximately 1/2 in (13 mm) apart.

E. Field Laboratory

Provide a field laboratory according to Section 152.

F. Mechanical Sprayers

Provide fully atomizing spraying equipment with a tank agitator to place curing compounds.

403.3.03 Preparation

A. Prepare the Road Bed

Prepare the roadbed as required by the Plans and Specifications before placing concrete pavement.

B. Observe Condition of Subgrade and Subbase

Check the subgrade and subbase as follows:

1. Prepare the full width of the subgrade and subbase according to the Plans and Specifications.
2. Ensure that the surface immediately under the concrete pavement allows proper pavement thickness and yield.
3. Trim high areas to the proper elevation.
4. Ensure that the subbase can support paving equipment without rutting or bogging.

430.3.04 Fabrication

General Provisions 101 through 150.

430.3.05 Construction

A. Mix the Concrete

Produce ~~Portland~~hydraulic cement concrete by combining authorized proportions of materials in batches according to the construction methods in this Specification.

Mix the concrete produced in a stationary central mix plant for at least 60 seconds after all materials have entered the drum. Reduce the mix time if representative tests show that the concrete meets requirements of ASTM C 94, Requirements For Uniformity. Never reduce the mix time to less than 50 seconds.

B. Set Forms

Set the forms as follows:

1. Compact the foundation under the forms true to grade. Set the form so that it firmly contacts the foundation for the entire length at the specified grade.
2. Prevent the forms from settling or springing under the finishing machine.
3. Clean and oil the forms before placing the concrete.

C. Dowel Bars

Provide dowel bars at transverse joints unless otherwise noted in the Contract Plans.

D. Place Concrete

After depositing the concrete on the grade, avoid rehandling. Unload and place it as follows:

1. Unload the concrete into an approved spreading device and mechanically spread it on the grade.
2. Place the concrete continuously between transverse joints without using intermediate bulkheads.
3. Hand spread the concrete with shovels, not rakes.

NOTE: Do not allow personnel to walk in freshly mixed concrete with shoes coated with dirt or other materials.

4. Thoroughly consolidate the concrete against the faces of forms and along the full length and sides of joint assemblies.
5. Ensure that vibration does not cause puddling or grout accumulation on the surface.

   For construction or expansion joints, do not use grout that accumulates ahead of the paver.
6. Deposit concrete near the formed joints. Dump or discharge concrete only in the center of a joint assembly.
7. Take slab depth measurements as follows:
   a. Probe the plastic concrete behind the paver.
   b. Record the station number and depth measurements at least every 500 ft (150 m) at 3 random increments across the slab.
   c. Provide these measurements to the Engineer when requested.
8. Take air and slump determination tests at a rate of at least three of each test evenly distributed during the workday. Provide the results to the Engineer when requested.
9. Keep reinforcing steel free of dirt, oil, paint, grease, mill scale, and loose or thick rust that could impair the bond of the steel to the concrete.
10. Arrange operations to prevent "leave-outs" in continuous reinforced concrete pavement. The Engineer may approve "leave-outs" in emergencies if a Plan is approved to increase the reinforcement. The Department ~~will~~shall not pay for extra leave-outs.

E. Place Reinforcement

Place reinforcement according to the Plans and as follows:

1. Do not insert lane tie bars in unsupported sides of fresh concrete.
2. Ensure that the steel placement method does not damage or disrupt concrete.
3. Use bent lane tie bars if needed in longitudinal formed joints construction. However, replace broken or damaged bars at no additional cost to the Department.

F. Construct the Ramps

Prevent pavement slab stress by constructing a ramp of compacted earth or other material for movement on and off the pavement. Do not allow equipment that exceeds legal load limits on the pavement.

G. Consolidate and Finish

Ensure that the sequence of operations is continuous from placement to final finish.

1. Consolidation

   Perform vibration for the full width and depth of the pavement as follows:

   a. Do not allow the vibrators to misalign load transfer devices, or to contact forms or base.

   b. Ensure that the vibrator amplitude is within the range recommended by the manufacturer.

      - Use spud vibrators with an adjustable operating frequency between 8,000 and 12,000 vibrations per minute.
      - Use surface pan vibrators with an adjustable operating frequency between 3,000 and 6,000 vibrations per minute.

   c. If appropriate, use surface vibrators and internal vibrators on concrete greater than 8 in (200 mm) thick.

   d. If appropriate, use surface vibrators exclusively on pavements less than 8 in (200 mm) thick.

   e. Stop vibration when the machine cannot go forward.

   f. Obtain uniform consolidation and density throughout the pavement.

      If it is not uniform, stop the operation and provide methods or equipment that will produce pavement that conforms to the Specifications.

2. Finishing

   After striking off and consolidating the concrete, follow these steps:

   a. Smooth and true the concrete using a float or finishing machine to minimize or eliminate hand finishing. Perform hand finishing only under the following conditions:

      - Irregular dimension areas where operating mechanical equipment is impractical
      - Mechanical equipment breakdown (only finish the concrete already deposited when the breakdown occurred)
      - Abnormal circumstances approved by the Engineer

   b. Ensure that the pavement surface final finish is true to grade, uniform in appearance, and free of irregular, rough, or porous areas.

   c. Prevent the surface within 6 in (150 mm) of the pavement edge to deviate more than 0.25 in (6 mm) in 10 ft (3 m) when tested with a 10 ft (3 m) straightedge in both transverse and longitudinal directions.

   d. Use mechanical equipment to produce a surface finish of transverse plastic concrete grooving for the mainline and ramps.

   e. Have the Engineer determine the texture depth by conducting pavement surface tests such as GDT 72 at selected locations.

   f. Transversely saw-groove mainline and ramp areas with a surface texture depth less than 0.018 in (0.5 mm). Meet the depth requirement of 0.035 in (0.9 mm) or greater.

      Perform saw-grooving to meet the following dimensions:

Width	1/8 in (3 mm)
Depth	3/16 in (5 mm)

Spacing	3/4 in (19 mm) center-to-center

g. If required, use hand tools to texture ramps, acceleration lanes, and deceleration lanes to surface texture mainline requirements. Finish irregular sections to a surface texture of at least 0.025 in (0.64 mm) as shown in GDT 72.

3. Numbering Stations

   Cast station numbers with a die in the pavement every 500 ft (200 m) and 1 ft (300 mm) from the right edge of the travel lane.

4. Protection From Rain

   Protect the unhardened concrete from rain. See Subsection 430.2.D, "Protective Materials."

   When rain is imminent, stop paving operations and place forms against the sides of the pavement. Cover the surface of the unhardened concrete with the protective covering.

H. Remove Forms

Do not remove forms from freshly placed concrete until it has set for at least 12 hours, unless otherwise provided.

1. Remove forms carefully to avoid damaging the pavement.
2. After removing the forms, immediately cure the sides of the slab using the same method used to cure the pavement surface.
3. Remove and replace major honeycombed areas.

I. Work at Night

Provide adequate lighting for work performed at night. If lighting will not be provided at night, stop the concreting operation in time to finish and saw during daylight hours.

J. Provide Joints

Ensure that joints are designed, configured, and located as shown on the Plans or required by the Specifications.

1. Provide dowel bars at transverse joints unless otherwise noted.
2. Remove and replace plain concrete pavement that cracks during construction with no additional cost to the Department, at the Engineer's discretion.
3. When chipping out random cracks for sealing, use nonrigid epoxy on cracks that are not under expansion- contraction influence and that meet Subsection 886.2.01.
4. Seal continuous cracks that are under movement with sealant that meets Subsection 833.2.06.
5. When removing and replacing a pavement section, remove an area at least 6 ft (1.8 m) long and the full width of the lane.
   a. Saw to vertical face the sections to be removed and replace the concrete as a construction joint with dowels.
   b. Use deformed bars as dowels in the saw-cut construction joint. Use the size specified for contraction joints in the Plans.
6. Thoroughly clean the drilled holes of contaminants and set the dowels into the hardened concrete face of the existing pavement with a Type VIII epoxy bonding compound. See Section 886 for epoxy bonding requirements.
7. For contraction joints, use undamaged and properly positioned dowels in existing construction or slab replacement areas. Coat the protruding dowel portions with a thin film of heavy grease.
8. When both sides of an existing construction or contraction joint require slab replacements, replace slabs continuously from saw-cut construction joint to saw-cut construction joint. Use dowels specified for contraction joints.
9. Before placing concrete, uniformly apply a thin coat of heavy grease to epoxy-coated dowels.

10. When placing slabs continuously across transverse contraction joint locations, use saw-cuts to provide planes of weakness according to the requirements of this Specification and the standard drawing for contraction joints.

K. Types of Joints

1. Longitudinal Joints

   For longitudinal joints, use unpainted and uncoated deformed steel bars that are the size and length specified on the Plans.

   Place the bars perpendicular to the joint using a mechanical device, or rigidly secure the bars in place with supports.

2. Longitudinal Formed Joints

   Construct longitudinal formed joints while the concrete is in a plastic state.

   Use methods and equipment that locate the joint reinforcement properly without disrupting it during construction.

3. Longitudinal Sawed Joints

   Cut longitudinal sawed joints with a mechanical saw within three days after the concrete is placed and before traffic or equipment enters the pavement.

4. Transverse Joints

   Transverse joints consist of construction joints, contraction joints, or expansion joints constructed at required locations.

   a. Construct transverse joints in partial width or adjoining lanes to abut the same joint of adjacent lanes unless otherwise specified on the Plans.
   b. Ensure that transverse joints in plain ~~Portland~~ Hydraulic cement concrete requiring load transfer devices contain either plastic-coated or epoxy-coated dowels.
   c. Before placing concrete, secure dowel bars in place with supporting assemblies.
   d. Secure the assemblies in position on the subbase to keep the dowels from moving during concrete placement.
   e. Place dowel bars to a vertical and horizontal tolerance of plus or minus 1 in (25 mm) of the Plan position. Do not misalign the dowel bar more than 3/8 in per 1 ft (10 mm per 300 mm) in the horizontal or the vertical plane.
   f. Remove and replace dowel assemblies displaced from the Plan position more than the tolerances in Subsection 430.3.05.J.
   g. When using epoxy-coated dowels, coat the entire surface with a thin film of heavy waterproof grease.
   h. Ensure accurate positioning of transverse sawed joints by marking the position of dowel bar assembly locations.

5. Construction Joints

   Construct transverse construction joints when interrupting concreting operations for more than one hour.

   NOTE: Do not construct transverse construction joints within 10 ft (3 m) of an expansion joint, contraction joint, or transverse plane of weakness.

   a. Move an unanticipated construction joint back to the last Plan joint, if necessary. Remove and dispose of excess concrete.
   b. Form construction joints by securing in place a removable bulkhead or header board.
      1) Place the board so that it conforms to the full cross section of the pavement. Secure it flush with the subbase and parallel to the normal transverse joints.
      2) Slot or drill the board to allow placement of reinforcement as required by the Plans.

NOTE: Do not use the roll of laitance and grout that forms in front of the paver adjacent to transverse construction joints.

c. Consolidate to full width and depth concrete adjacent to transverse construction joints with mechanical hand- type spud vibrators. Keep one auxiliary vibrator available in case of mechanical malfunctions.

d. Before applying the final finish to the concrete, stringline and correct variations of the concrete surface within 30 ft (9 m) on either side of the transverse construction joints. Provide equipment and tools such as:

- Work bridges
- Personnel
- String lines
- Straightedges
- Lighting

e. While the concrete is in a plastic condition, stringline the surface longitudinally and correct surface deviations greater than 1/8 in per 15 ft (3 mm per 4.6 m) in any direction.

f. When using plain ~~Portland~~hydraulic cement concrete pavement, place dowel bars in construction joints. Cast half the length of each dowel bar in the concrete during each phase of joint construction.

g. When using epoxy coated dowels, coat the protruding half of each dowel bar with a thin film of heavy waterproof grease before resuming joint construction. Grease coating is not required on plastic coated dowels.

h. After the concrete has hardened, dismantle the bulkhead supporting the dowels. Do not disturb the dowels.

6. Contraction Joints

Create planes of weakness in plain ~~Portland~~hydraulic cement concrete pavement by cutting joints in the pavement surface. Create the planes according to the Plans as follows:

a. Saw transverse contraction joints before the pavement cracks. Begin sawing when the concrete has hardened enough to prevent surface raveling, usually 4 hours after placement, but no more than 24 hours.

b. Continue sawing day and night regardless of weather conditions.

7. Expansion Joints

Transverse expansion joints are required at locations shown on the Plans.

a. Form expansion joints by securing a removable bulkhead that conforms to the full cross section of the pavement. Use bulkheads that can construct a vertical expansion wall without offsets, indentations, or burrs.

b. Use expansion joint filler required by the Plans.

c. Furnish and install preformed joint filler in lengths equal to the pavement width or the width of one lane. Do not use damaged or repaired joint fillers.

d. Position the expansion joint filler vertically in the joint and at the proper grade. Use an installing bar or other device to secure the expansion joint filler at the proper grade and alignment.

L. Cure the Concrete

Immediately after finishing the concrete, cure the entire surface when the concrete will not mar. Use one or more of these methods:

1. Impervious Membrane

Method To use this method:

a. Spray the entire surface of the pavement with white pigmented curing compound immediately after finishing the surface and before the concrete has set.

If the pavement is cured initially with cotton mats, burlap, or cotton fabric, apply the compound after removing the mats.

NOTE: Do not apply curing compound during rain.

b. Use mechanical sprayers to apply curing compound under pressure at a minimum rate of 1 gal per 150 ft^2 (1 L per 3.5 m^2).

c. Thoroughly mix the compound with uniformly dispersed white pigments.

d. During application, use a mechanical device to stir the compound continuously.

e. Use a hand sprayer (if required) to spray odd widths, odd shapes, and concrete surfaces exposed by removing forms.

f. Do not apply curing compound to the inside faces of joints to be sealed.

g. If the membrane film becomes damaged within the curing period, repair the damaged portions immediately with additional compound.

2. White Polyethylene Sheeting

To use this method:

a. Cover the top surface and sides of the pavement with polyethylene sheeting. Lap the units at least 18 in (450 mm).

b. Place the sheeting and weigh it down so that it contacts the surface.

c. Extend the sheeting beyond the edges of the slab at least twice the thickness of the pavement.

d. Unless otherwise specified, maintain the covering in place for 72 hours after placing the concrete.

3. Burlap, Cotton Fabric, or Other Methods

Contractors may cure the pavement with burlap, cotton fabrics, or other materials if the section remains wet for the duration specified by the Engineer.

4. Cold Weather Curing

To use this method:

a. Remove and replace concrete that freezes before the initial set time at no cost to the Department.

b. Use polyethylene or canvas to protect concrete that has set but is exposed to freezing temperatures within 24 hours of placement. Ensure that the internal concrete temperature is above freezing for at least 24 hours after placing the concrete.

c. Obtain approval from the Engineer to use other protection methods such as hay, straw, or grass, or to change the duration of the protection.

M. Seal the Joints

Clean and seal the joints according to Section 461 and the Plans.

Immediately after completing the curing period, fill in the joints with joint sealing material before opening the pavement to traffic.

During sealing, do not spill the material on the concrete surface. Immediately remove excess material on the concrete surface and clean the surface.

Do not use sand or similar material as a cover for the seal. Seal joints according to the Plans.

N. Open Pavement to Traffic

Wait to open the pavement slab to traffic, except for joint sawing vehicles, until the concrete is 14 days old unless representative compressive tests show that the slab has a compressive strength of 2,500 psi (15 MPa). Cure compressive test specimens used for traffic opening as near as possible to the roadway.

Protect the pavement against traffic from the public, employees, and agents.

1. Erect and maintain barricades. Employ watchmen to block traffic from the newly constructed pavement for the period required in this Specification.
2. Arrange the barriers away from public traffic on lanes remaining open.
3. Maintain signs that clearly indicate the lanes open to public traffic.
4. If traffic must go across the pavement, construct crossings satisfactory to the Engineer to bridge over the concrete. Construct the crossing without additional compensation.
5. Repair or replace pavement damaged by traffic or other causes before Final Acceptance without additional compensation. Make repairs to the Engineer's satisfaction.

430.3.06 Quality Acceptance

The typical section sheet in the Plans gives specific uses for each concrete classification. Refer to this Specification for the minimum requirements of the concrete classifications for concrete design approval, concrete mix design proportions, batching control responsibilities, and acceptance of hardened concrete based upon compressive strength development.

A. Transit Mixed Concrete

Ensure that transit mixed concrete meets the requirements of Subsection 500.2, "Materials."

B. Mix Design Criteria

Proportion concrete mix designs using the following requirements:

	Minimum Cement Content per Cubic Yard Concrete (CWT)	Max. Water-Cement Ratio (lbs/lb)	Design Air Content Range (%)
Class 1	5.41	0.53	4.0 to 5.5
Class 2	5.64	0.50	4.0 to 5.5
Class HES	6.58	0.47	4.0 to 5.5

	Minimum Cement Content per Cubic Meter Concrete (kg)	Maximum Water-Cement Ratio (kg/kg)	Design Air Content Range (%)
Class 1	320	0.53	4.0 to 5.5
Class 2	335	0.50	4.0 to 5.5
Class HES	390	0.47	4.0 to 5.5

Table 1— Concrete Strength and Early-age Performance Table

English				
	Minimum Compressive Strength at 28 days (psi)	Maximum w/cm Ratio (lbs/lbs)	Air Content Range (%)	Maximum Drying Shrinkage at 28 days (%)
Class 1	3000	0.53	4.0 to 5.5	.04

Class 2	3500	0.50	4.0 to 5.5	.04
Class HES	3000	0.47	4.0 to 5.5	.04

Metric				
	Minimum Compressive Strength at 28 days (MPa)	**Maximum w/cm Ratio (kgs/kgs)**	**Air Content Range (%)**	**Maximum Drying Shrinkage at 28 days (%)**
Class 1	20	0.53	4.0 to 5.5	.04
Class 2	25	0.50	4.0 to 5.5	.04
Class HES	20	0.47	4.0 to 5.5	.04

Notes:

1. Hydraulic cement used for any class or application shall conform to the specifications in any of the following: AASHTO M85/ASTM C150 or ASSHTO M240/ASTM C595.
2. Compressive strength will be determined based upon result of six cylinders prepared and tested in accordance with AASHTO T 22 and T 126. Produce evidence Class HES concrete has strength development potential for 72 hours and at 28 days as specified in Subsection 430.3.06.C, "Approval of Mix Design". If minimum compressive strength is not reached at 28 days for any class, samples from the same batch shall be tested at 56 days using the same compressive strength limits from 28 days. Pay reduction based on meeting 56-day strength (but when the 28-day strength requirement was not met) may apply at the discretion of the Engineer.
3. Cementitious materials include hydraulic cement and all supplementary cementitious materials (SCMs). Inert fillers such as interground limestone shall not be considered an SCM for the purposes of this specification. Water/cementitious material ratio (w/cm) refers to the ratio of water to total cementitious material including hydraulic cement and all SCMs.
4. Air content shall be measured in accordance with AASHTO T152 utilizing a Type B meter.

   28 day drying shrinkage shall be measured in accordance with AASHTO T160 using concrete prisms exposed to drying at a concrete age of 7 days. The initial reading for drying shrinkage calculations shall be the reading taken at the start of drying at a concrete age of 7 days ± .5 hours.

Table 2A—Concrete Surface Resistivity

Chloride Ion Penetration	**Surface Resistivity Limits**	**Minimum Allowable Surface Resistivity by Concrete Class (KOhm-cm)**	
		Class 1 and HES	**Class 2**
High	≤ 13.0		
Moderate	13.1-21.0	✓	✓
Low	21.1-40.0	✓	✓
Very Low	40.1-254.0	✓	✓
Negligible	≥ 254.1	✓	✓

Table 2B—Concrete Charge Passed

Chloride Ion Penetration	Charge Passed Limits	Minimum Allowable Charge Passed by Concrete Class (Coulombs)	
		Class 1 and HES	Class 2
High	≥ 3501		
Moderate	3500-2001	✓	✓
Low	2000-901	✓	✓
Very Low	900-101	✓	✓
Negligible	≤ 100	✓	✓

Notes:

1. All reinforced concrete shall show moderate or better chloride ion penetration using either surface resistivity requirements (Table 2A) or charge passed utilizing the Rapid Chloride Penetration Test (RCPT) requirements (Table 2B). The Engineer shall determine if site conditions warrant more stringent surface resistivity or chloride ion penetration limits.
2. Requirements for surface resistivity in Table 2A refer to results from an 4in. x 8 in. cylinder in accordance with AASHTO T358. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch. Samples shall be cured in limewater solution. A mix will be qualified once the average of the samples exceeds the required surface resistivity limits at any time before the 56-day maximum curing time.
3. Requirements for RCPT in Table 2B refer to results from a 4 in. diameter sample in accordance with AASHTO T277. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch. Samples shall be cured in limewater solution. A mix will be qualified once the average of the samples exceeds the required charge passed limits at any time before the 56-day maximum curing time.

Table 3A—Freezing-Thawing Exposure Classes

FT Exposure Class	No FT exposure	FT exposure
Exposure Condition	Not exposed to FT cycles	Exposed to FT cycles with frequent exposure to water
Minimum f'_c, psi (MPa)	None	4500 (32)
Maximum w/cm	None	0.45

Notes:

1. Freezing-thawing (FT) refers to conditions where cycles of freezing and thawing may result in cracking and crumbling of the placed concrete. FT exposure class shall be determined by the Engineer. Both minimum f'_c, and maximum w/cm limits are required for specified FT exposure classes.
2. FT concerns are heightened above the Fall Line, and may exist below the Fall Line. The Engineer shall determine if FT concerns are expected.

Table 3B—Freezing-Thawing Durability Metrics

FT Exposure Class	No FT concerns	FT Concerns
Minimum specific surface, in.^{2}/in.^{3} (mm^2/mm^3)	None	600 (21)
Maximum spacing factor, in. (mm)	None	0.009 (0.23)
Minimum durability factor	None	90

Notes:

1. At least one FT durability test metric shall be passed according to the requirements by FT exposure class set forth in Table 3B. FT exposure class shall be determined by the Engineer.
2. Specific surface shall be calculated using results from tests conducted in accordance with ASTM C457/ASTMC457M.
3. Spacing factor shall be calculated in accordance with ASTM C457/ASTM C457M as average of three assessments from single mixture during construction, where no assessment for spacing factor is greater than 0.012 in. (0.30 mm) for FT concerns. Note that with values for air content, paste fraction, and specific surface, spacing factor may be calculated.

~~1.~~4. Durability factor measured shall be calculated in accordance with ASTM C666/C666M, by either Procedure A or B, as an average of three separate specimens that are representative of same concrete mix.

Table 4A—Sulfate Exposure Class

Sulfate Exposure Class	Water soluble sulfate in soil, % by mass	Dissolved sulfate in water, ppm
S0	$SO_4 < 0.10$	$SO_4 < 150$
S1	$0.10 \leq SO_4 \leq 0.20$	$150 \leq SO_4 \leq 1{,}500$
S2	$0.20 \leq SO_4 \leq 2.00$	$1{,}500 \leq SO_4 \leq 10{,}000$
S3	$SO_4 > 2.00$	$SO_4 > 10{,}000$

Notes:

1. Water soluble sulfate in soil shall be determined in accordance with AASHTO T290.
2. Dissolved sulfate in water shall be determined in accordance with ASTM D516.

Table 4B—Sulfate Attack Durability

Sulfate Exposure Class	Cement Designation	Maximum w/cm	Minimum f'_c psi (Mpa)	Performance requirements expansion in ASTM C1012 (maximum %)		
				6 month	12 month	18 month
S0	No Requirements					
S1	Performance Requirement Only	0.55	3500 (25)	0.05	0.10	-
	Type II or Type MS-designated blended cements	0.50	4000 (25)	0.10	-	-
	No restriction	0.45	4500 (32)	-	-	-
S2	Performance Requirement Only	0.50	4000 (25)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.45	4500 (32)	0.05	0.10	-
	Type II or Type MS	0.40	5000 (35)	0.10	-	-
S3	Performance Requirement Only	0.45	4500 (32)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.40	5000 (35)	0.05	0.10	-

Notes:

1. Sulfate attack refers to conditions where sulfate-rich environments causes chemical reactions with hardened cement paste forming expansive products which cause cracking and premature failure. Sulfate exposure class shall be determined by the Engineer.
2. Mix designs under the same sulfate exposure class shall conform either to performance limits determined by cement usage or performance requirements. Utilizing designated cements reduces the performance requirements.
3. Cement Types II and V refer to cements that meet requirements in AASHTO M85/ASTM C150.

4. Type MS refers to blended cements that meet the requirements for MS designation in AASHTO M240/ASTM C595. Type HS refers to blended cements that meet the requirements for HS designation in AASHTO M240/ASTM C595.
5. Where hydraulic cement and SCMs are combined at the concrete mixer, it shall be demonstrated that the blend meets the performance requirements listed in ASTM C1012.
6. If Type V cement is used as the sole cementitious material for a S3 exposure class, an optional sulfate resistance requirement of 0.04% maximum expansion (when tested in accordance with ASTM C452) shall be in force.

Table 5—Structure Importance/Type

Structural Importance	Definition
T1	Minor risk of reinforcement corrosion can be tolerated
T2	Reinforcement corrosion cannot be tolerated; non-environmental structures
T3	Reinforcement corrosion cannot be tolerated; environmental structures

Note:
1. Definitions for structural importance not inclusive or representative of all circumstances potentially encounterable. The Engineer shall determine most applicable category by project requirements.

Table 6—Water Soluble Chloride Matrix

Chloride Exposure Class	Structural Importance	Chloride limits for new construction (% by mass of cementitious material)	
		Water-soluble (ASTM C1218/C1218M)	
		Reinforced Concrete	Prestressed concrete
C0 - Concrete in dry environment	T1	1.00	0.06
	T2	0.25	0.06
C1- Concrete exposed to moisture but not to external sources of chlorides in service	T1	0.30	0.06
	T2	0.15	0.06
C2 -Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salts, brackish water, seawater, or spray from these sources in service	T1, T2	0.15	0.06
C3 - Concrete exposed to severe exposure conditions, including concentrated chemicals, wetting-and-drying cycles, FT cycles	T2, T3	0.10	0.06

Notes:
1. Water soluble chloride refers to chlorides in concrete that are not bound and have the ability to accelerate corrosion within reinforced or prestressed concrete. Chloride exposure class shall be determined by the Engineer.
2. Total cementitious material includes both hydraulic cement and all SCMs.
3. Dry environment corresponds to maximum relative humidity of 60%, normally, found in interior of buildings.

C. Approval of Mix Design ~~Proportions~~

The Department ~~will~~ shall approve each proposed combination of materials and mix designs based on the use of approved materials, compliance with Subsection 430.3.06.B, "Mix Design Criteria," and the following:

1. Flexural Strength

   Prepare at least 9 normally cured flexural specimens and test according to AASHTO T 126 and T 97 to ensure that the demonstrated laboratory flexural design strength at 28 days meets the following minimum Design Acceptance Requirement (DAR).

NOTE: Take the 9 flexural specimens from 3 separate trial batches. Make 3 specimens from each batch.

Class No. 2	Concrete DAR = 700 psi + .50 s Concrete DAR = 4.8 MPa + .50 s
Class HES	Concrete DAR = 700 psi + .50 s Concrete DAR = 4.8 MPa + .50 s
s = a standard deviation of all 28-day flexural specimens for a given combination of materials and mix proportions prepared together. Do not use a value of "s" greater than 37 psi (255 kPa) to calculate DAR.	

2. Compressive Strength

   Prepare and test at least 6 cylinders according to AASHTO T 126 and T 22 to ensure that the demonstrated laboratory compressive strength at 28 days for Class 1 and 2 concrete exceeds the minimum Job Performance Value (JPV).

   Produce similar evidence that demonstrates strength development at 72 hours for Class HES concrete.

Class 1	Concrete JPV Minimum = 3,000 psi + .18 R Concrete JPV Minimum = 20 MPa + .18 R
Class 2	Concrete JPV Minimum = 3,500 psi + .21 R Concrete JPV Minimum = 25 MPa + .21 R
Class HES	Concrete JPV Minimum = 3,000 psi + .05 R Concrete JPV Minimum = 20 MPa + .05 R
R = the difference between the largest observed value and the smallest observed value for all compressive strength specimens at 28 days for a combination of materials and mix proportions prepared together.	

   a. Class 1 and 2 Concrete

      1) Submit early compressive strength test results made at 24 hours plus or minus 30 minutes for at least 12 cylinders. Prepare and test according to ASTM C 684, Method A.

      2) Prepare cylinders from three separate trial batches, and make four specimens from each batch.

      3) Determine the average strength, standard deviation, and coefficient of variation for the design according to ACI 214. Do not use designs that produce a coefficient variation greater than 10 percent.

   b. Class HES Concrete

      Submit evidence that designs proposed for use as Class HES concrete have compressive strength development potential at 72 hours of 3,000 psi (20 MPa) plus .05 R.

3. Durability Metrics

Table 2A specifies surface resistivity limits and Table 2B specifies charge passed limits for concrete when required by the Engineer. Additional durability requirements, as required by the Engineer, shall be satisfied according to the requirements in Tables 3A through 6. A concrete mix shall only be qualified if it can be shown the mix meets the performance requirements from Tables 3A through 6 based on the Engineer's assessment of exposure class. A mix that has previously qualified for a specific collection of exposure classes shall remain qualified. Mixes shall require requalification if a material or proportion changes. A waiver for requalification for a mix design from GDOT may be requested. Concrete mix designs shall only be utilized for sites and applications as approved by the Engineer.

D. Field Adjustments on Concrete Mixes

Determine the aggregate surface moisture and apply free moisture corrections to the approved mix design. The Engineer ~~will~~shall verify that the corrections are made properly.

Class No. 1	Concrete DAR = 600 psi + .67 s Concrete DAR = 4.1 MPa + .67 s

Adjust the approved proportions of the fine and coarse aggregate and water as desired, provided:

1. The ~~cement~~ cementitious material factor is not decreased.
2. The water-~~cement~~ cementitious material ratio is not increased.
3. Adjustments produce concrete proportions according to this Specification.
4. The Engineer is notified before use.

E. Concrete Mix Tolerances

Keep concrete consistency and air content to vary within the following limits:

1. Consistency

   Immediately before placement, use GDT 27 to determine concrete slump. Do not use concrete for ~~Portland~~hydraulic cement concrete pavement with a slump value greater than 2.5 in (65 mm).

2. Air Content

   Immediately before placement, use GDT 26, GDT 28, or GDT 32 to determine the air content of the concrete. Concrete will not be accepted that has an air content outside of these limits:

Lower acceptance limit	3.0%
Upper acceptance limit	6.5%

F. Concrete Strength Acceptance

The concrete strength of ~~Portland~~hydraulic cement concrete pavement is accepted based upon the compressive strength development at a specific time.

Strength development is determined by a lot acceptance plan. The pavement is subdivided into separate concrete lots of approximately 5,334 yd^2 (4400 m^2) placed continuously, except for required work stoppages.

1. Ramps

   Ramps may be set apart as individual lots. Include acceleration or deceleration lanes, wedges, or other varied width sections in other lots if the total paving quantity is not greater than 7,500 yd^2 (6300 m^2). The Engineer ~~will~~shall randomly select three production units from each lot for strength determination tests.

2. Class 1 and 2 Concrete

   a. Cast at least two cylinder sets for each production unit selected for acceptance testing. A set is two 6 by 12 in (150 by 300 mm) cylinders. Cure one set according to ASTM C-684, Method A. Cure the other set according to AASHTO T 23.

   b. After curing, test each concrete cylinder according to AASHTO T 22. The test result is the average strength of the two cylinders.

3. Acceptance Based on 24-Hour Strength

Concrete may be accepted by early strength determinations. However, concrete will not be accepted based on early strength development when the difference between the largest observed strength value and the smallest observed strength value exceeds 35 percent of the average.

a. Compute the average (X) and the range (R) from the three acceptance tests results.

b. Have the Engineer establish the minimum early strength (S) to be used for concrete acceptance.

   The minimum early acceptance strength is the average strength at 24 hours plus or minus 30 minutes of the laboratory design less 1.5 times the standard deviation of the laboratory design.

c. If the average (X) of the three lot acceptance tests equal or exceed the value (S), the lot will be accepted at the full contract price, and 28 day cylinders for this lot can be discarded.

d. If the average of the three lot acceptance tests fails to meet the acceptance limit, the Engineer ~~will~~ shall contact the Contractor immediately. The Contractor may immediately remove the concrete in the lot or leave it in place pending acceptance or rejection from the 28-day strength test results.

4. Acceptance Based on 28-Day Strength Tests

   When a lot is potentially defective based on the early strength determinations and the Contractor leaves the lot in place to be judged by the 28-day strength tests results, retain and cure all 3 sets of 28-day cylinders.

   a. If the average 28-day strength of the lot does not meet the lower acceptance limit for a 0.70 pay factor, the Engineer may either:

      - Order removal of the concrete in the
      - lot Apply a pay factor of 0.50 for the

        lot

   b. The Unit Price of concrete pavement will be reduced for areas represented by each lot that does not meet the specified compressive strength at 28 days according to the following schedule:

Pay Factor Schedule for Strength Determinations at 28 Days			
Acceptance Limits for Pay Factor Levels			
	1.00 LAL*	**0.95 LAL**	**0.70 LAL**
Concrete Class 1	3,000 psi (20 MPa) + 0.18 R	3,000 psi (20 MPa) - 0.07 R	3,000 psi(20 MPa)- 0.30 R
Concrete Class 2	3,500 psi (25 MPa)+ 0.21 R	3,500 psi (25 MPa)- 0.07 R	3,500 psi (25 MPa)-0.30 R
* Lower acceptance limit (LAL)			

5. Classification HES Concrete

   Cast at least two sets of cylinders for each production unit selected for acceptance testing.

   a. Cure one set for 72 hours under conditions similar to those under which the pavement is cured. Cure the other set of cylinders for 28 days according to AASHTO T 23.

   b. Test each cylinder according to AASHTO T 22 when the specified curing is complete. The test results are the average strength of the two cylinders.

   c. The Engineer may accept the concrete at full contract price if the average of the three 72-hour test results exceeds the JPV established in Subsection 430.3.06.C.

   d. When the 72-hour strength tests determine that a lot is potentially defective, the Engineer ~~will~~shall immediately notify the Contractor. At this time, the Engineer may require the immediate removal of the pavement in question.

      If the Engineer does not require immediate removal of the pavement, select removal or acceptance on the basis of the 28-day strength development.

e. When the 72-hour strength tests determine that a lot is potentially defective and the concrete is retained for subsequent judgment, conduct acceptance tests at 28 days on selected cylinders cured according to AASHTO T 23.

   Questionable lots will be accepted based on the 28-day strength and provisions for testing, computations, and payment for Classification No. 2 concrete in Subsection 430.3.06.F.2, "Class 1 and 2 Concrete."

G. Smoothness

Pavement smoothness will be accepted only after the Engineer determines that the work was performed according to this and other Specifications. The completed pavement, including corrective work, must meet the applicable profile index value requirements.

Perform smoothness testing as follows:

1. Ensure that the mainline riding surface produces a profile index value no greater than 7 in/mile (100 mm/ km) on each travel lane. Conduct tests according to GDT 78.
2. Determine a profile index value for each tracing for each 0.25 mile (0.5 km) segment. Correct individual bumps or depressions that exceed the blanking band by more than 0.2 in (5 mm) at no additional expense to the Department.
3. If a paving operation exceeds a profile index value of 7 in/mile (100 mm/km) per lane for any segment, suspend the paving operation and take corrective action approved by the Engineer.
4. Use GDT 78 to test ramps and acceleration and deceleration lanes to attain an average profile index value no greater than 12 in/mile (200 mm/km) by Rainhart Profilograph for the entire section length. Correct individual bumps or depressions that exceed 0.2 in (5 mm) from the blanking band at no additional expense to the Department.
5. Take pavement profiles that are 4 ft (1.2 m) away from and parallel to the new pavement edges on pavements greater than 16 ft(4.8 m) wide and up to 24 ft (7.2 m) wide.

   Test pavement 6 to 16 ft (1.8 to 4.8 m) wide parallel to and at the center line of the pavement section.
6. Begin the 0.25 mile (0.5 km) record segments at the first day's placement and continue until Project completion, except as noted in this Specification.
7. Combine pavement sections less than 700 ft (200 m) long that approach a bridge. Use the previous 0.25 mile (0.5 km) segment to determine the profile index.

   Calculate as a separate record segment 700 ft (200 m) sections or greater that approach a bridge. This exception applies also to sections at Project limits.
8. Determine a separate profile index value using GDT 78 for the 100 ft (30 m) of roadway approaching each end of a bridge up to and including the joint with the approach slab.

   Average the profile index from the right and left wheelpaths for each 100 ft (30 m) segment for each lane for each approach. The average profile index value shall not exceed 30 in/mile (500 mm/km).
9. Before paving farther, perform and evaluate profiles from the first day's placement.
   a. After completing and evaluating this test run, adjust equipment as required by the Engineer to improve smoothness before paving continues.
   b. Complete the report form furnished by the Engineer and attach to the profilograph tracings of each day. Include the following information in each trace:
      - Project number
      - Beginning and ending station
      - numbers 500 ft (150 m) paving

        stations

- Traffic direction
- Lane number
- Date paved and tested
- Construction joint locations

Have the certified profilograph operator obtain and evaluate the traces and submit the evaluation to the Engineer. Provide results no later than the end of the second work day following placement.

10. For mainline pavement, correct 0.25 mile (0.5 km) segments not meeting the profile index requirement using one of these methods:

    a. Grind the entire lane surface of the 0.25 mile (0.5 km) segment to a profile index value less than 7 in/mile (100 mm/km). Use equipment that meets requirements in Section 431.

    b. Grind roughness in small segment areas no more than 50 ft (15 m) of full lane width to produce a profile index value no greater than 7 in/mile (100 mm/km).
    If more than 50 ft (15 m) of grinding is required, grind the complete 0.25 mile (0.5 km) segment according to Method a, above.

11. Correct ramps and acceleration and deceleration lanes that do not meet the profile index requirement to a profile index no greater than 12 in/mile (200 mm/km). Prevent individual bumps from exceeding 0.2 in (5 mm) from the blanking band. Use equipment specified in Section 431.

12. Correct 100 ft (30 m) bridge approach sections that do not meet the profile index requirement.

    a. Grind according to Section 431.

    b. If appropriate, use a bump grinder to correct bumps with a baseline of 5 ft (1.5 m) or less.

    c. Grind the full lane width even when grinding including individual bumps.

    d. Retest pavement segments containing corrective slab replacements for Final Acceptance.

13. Correct segments that do not meet the profile index criteria of this Specification at no additional expense to the Department. Retest segments after correction with the Rainhart Profilograph.

14. Notify the Engineer before profile testing. The Engineer ~~will~~shall verify the results by randomly selecting a minimum of 1 out of every 10 consecutive record segment profiles to compute the profile index and to compare with Contractor results.

    The Engineer may conduct profilograph tests at any time to verify Contractor results. The Department may test record segments if the Engineer determines that the Contractor test results are inaccurate. See Subsection 430.5.01, "Adjustments."

H. Thickness

The Engineer shall determine the pavement thickness using average core measurements tested according to GDT 31. The following table contains units for paving widths:

Paving Widths – Feet (meters)	Length of Unit (Bridges Excluded)—Feet (meters)
0 – 24.0 (0 – 7.2)	1000 (300)
24.1 – 36.0 (7.2 – 10.8)	750 (225)
36.1 – 48.0 (10.8 – 14.4)	500 (150)

Areas of equal depth in intersections, entrances, crossovers, ramps, etc. are considered one unit, and the thickness of each unit is determined separately. If appropriate, include small irregular areas as part of another unit.

1. Take one core for each 2,000 yd² (1675 m²) of pavement, or fraction of pavement, in each unit where the

Engineer selects.

The Department ~~will~~shall take one core at random in each unit.

a. When the core measurement is deficient 0.2 in (5 mm) or less from the Plan thickness, full payment is made.

b. When the measurement is deficient more than 0.2 in (5 mm) and not more than 1 in (25 mm) from the plan thickness, two additional cores are secured from the unit and used to determine the average thickness.

c. A random selection process determines where to secure additional cores. However, do not secure cores within 50 ft (15 m) of other thickness measurement cores. The adjusted Unit Price in Subsection 430.5.01.A, "Concrete Pavement Thickness Deficiency" is used to determine payment for the unit.

2. Consider pavement more than 0.2 in (5 mm) thicker than the specified thickness to be the specified thickness plus 0.2 in (5 mm). Measurements more than 1 in (25 mm) less than the specified thickness are not included in the average.

3. When the core measurement is at least 1 in (25 mm) less than the specified thickness:

   a. Determine the pavement thickness in the affected location by taking additional cores at no less than 10 ft (3 m) intervals parallel to the center line in each direction.

   b. Continue until a core is found that is not deficient by more than 1 in (25 mm).

   c. Have the Engineer evaluate areas more than 1 in (25 mm) deficient in thickness. Remove deficient areas and replace with concrete pavement of the thickness shown on the Plans, if the Engineer requires.

   Exploratory cores for deficient thickness are not used in averages for adjusted Unit Price.

430.3.07 Contractor Warranty and Maintenance

General Provisions 101 through 150.

430.4 Measurement

The area that will be paid for under this Item is the number of square yards (meters) of concrete pavement accepted as measured complete in place. The pavement width measured is shown on the typical cross section of the Plans, including additional widening as required or widening directed in writing by the Engineer.

The length is measured along the pavement surface.

Work is accepted lot-to-lot according to Section 106 and this Specification.

430.4.01 Limits

General Provisions 101 through 150.

430.5 Payment

Concrete pavement completed and accepted that meets the Specification requirements will be paid for at the full Contract Unit Price per square yard (meter).

Payment for other accepted concrete pavement will be based on an adjusted Unit Price per square yard (meter). This price will be adjusted for payment for concrete pavement accepted but deficient in depth or compressive strength at 28 days. Price adjustments are specified in Subsection 430.5.01, "Adjustments."

No additional payment over the Contract Unit Price will be made for pavement units with an average thickness greater than on the Plans. No additional payment over the Contract Unit Price will be made for a lot of concrete that develops more strength at 28 days than the compressive strength established in Subsection 430.3.06.F, "Concrete Strength Acceptance."

Payment is full compensation for furnishing and placing materials, reinforcements, dowel and joint materials, supplies, and incidentals to complete the work.

Payment will be made under:

Item No. 430	Plain ~~Portland~~hydraulic cement concrete pavement, class no. 1 concrete______in (mm) thick	Per square yard (meter)
Item No. 430	Plain ~~Portland~~hydraulic cement concrete pavement class no. 2 concrete____in (mm) thick	Per square yard (meter)
Item No. 430	Plain ~~Portland~~hydraulic cement concrete pavement, class HES concrete______in	Per square yard (meter)
	(mm) thick	
Item No. 430	Continuously reinforced concrete pavement, class no. 1 concrete______________in (mm) thick	Per square yard (meter)
Item No. 430	Continuously reinforced concrete pavement, class no. 2 concrete______________in (mm) thick	Per square yard (meter)
Item No. 430	Continuously reinforced concrete pavement, class HES concrete______________in (mm) thick	Per square yard (meter)

430.5.01 Adjustments

The Contract Unit Price per square yard (meter) of concrete pavement will be adjusted for concrete pavement accepted but deficient in thickness or compressive strength at 28 days. Adjusted Unit Prices per square yard (meter) of concrete pavement are based on one or both of the following conditions:

A. Concrete Pavement Thickness Deficiency

1. If the core is deficient 0.2 in (5 mm) or less from the Plan thickness, full payment will be made. If the core is deficient in thickness more than 0.2 in (5 mm), but not more than 1 in (25 mm) from the Plan thickness, 2 additional cores will be taken from the area.
   a. If the average measurement of these 3 cores is deficient 0.2 in (5 mm) or less from the Plan thickness, full payment will be made.
   b. Where the average pavement thickness is deficient by more than 0.2 in (5 mm), but not more than 1 in (25 mm), payment will be made at a portion of the Unit Price per square yard (meter) of concrete pavement as shown in the following table:

Concrete Pavement Deficiency	
Deficiency in Thickness Determined by Cores– in (mm)	**Proportional Part of Contract Price Allowed**
0.0 through 0.20 (0.0 through 5.0)	100 percent
0.21 through 0.25 (5.1 through 6.4)	95 percent
0.26 through 0.30 (6.5 through 7.6)	91 percent
0.31-0.40 (7.7 through 10.0)	86 percent
0.41-0.50 (10.1 through 12.8)	80 percent
0.51-0.75 (12.9 through 19.2)	70 percent
0.76-1.00 (19.3 through 25.0)	60 percent

   c. When the thickness of pavement is deficient by more than 1 in (25 mm) and the Engineer determines that the deficient area should not be removed or replaced, 50 percent of the Contract Unit Price will be paid.
2. No payment or compensation for cost will be made for removing concrete according to this provision.

B. Compressive Strength Deficiency

When the compressive strength at 28 days, expressed as an average strength (X) for a lot of concrete pavement is less than the values established by the Pay Factor Table, payment will be made at a reduced Unit Price per square yard (meter) as shown in the Pay Factor Table.

C. Combined Deficiencies

When a pavement section is deficient in thickness and compressive strength, the Contract Unit Price will be adjusted by the total reduction from applying the percentages in Subsections 430.5.01.A and Subsection 430.5.01.B, above.

For combined deficiencies of 50 percent or more, the Engineer may leave the pavement in place at the combined payment reduction or order the deficient areas removed and replaced at no additional cost to the Department.

If the Engineer orders removal of the pavement, payment will not be made for the original pavement or removal. Pavement replaced will be paid for at the appropriate Unit Price.

D. Profilograph Testing

If, based on the Department's profilograph tests, the Engineer determines that the Contractor profilograph test results are inaccurate, the Contractor ~~will~~shall be charged for profilograph testing at $500 for each trace mile ($250 for each trace kilometer), with a minimum charge of $500.

430.6 Appendix A: Embodied GHG Emissions (Report Only - Optional)

Notes:

1. Embodied greenhouse gases (GHGs) may be reported only; this is optional. GHGs shall not be used as a primary means to specify concrete but the example calculations provided in Appendix A may be used for project specific emission limits.
2. GHGs may be attested to by the concrete producer using either Type I or Type III Environmental Product Declarations (EPDs) conforming to ISO 14025. Embodied GHGs refers only to cradle-to-gate emissions associated with the production and transportation for a unit volume of concrete. Use product EPDs to determine the carbon equivalent intensity for each mix constituent.
3. Table A.1 includes embodied emission guidelines from the General Services Administration. The limits are industry wide averages from 2022. The emissions are to be interpreted as guidelines only.

Table A.1—Embodied Emission Guidelines

Class of Concrete	**Maximum Embodied Greenhouse Gases (kg CO_2 eq./yd^3)**
Class 1	235
Class 2	266
Class HES	235
Class of Concrete	**Maximum Embodied Greenhouse Gases (kg CO_2 eq./m^3)**
Class 1	306
Class 2	346
Class HES	306

Embodied Emissions Calculation

$$\text{Mix Embodied Emissions (kg } CO_2 \text{ eq./yd}^3) = \sum_{i=1}^{n} AA_{i} \text{ (kg } CO_2 \text{ eq/lb)} * \text{Material Proportion}_{i} \text{ (lb / yd}^3)$$

Where AA_i is the emission intensity of the ith mix constituent and the ith material proportion is the mass of each mix constituent per unit of concrete for a mix with n different constituents.

The units for emission intensity should be in kg CO2 eq / yd^3. Adjustments for reported units from a material EPD shall be made to ensure units match throughout the calculation. Typical reported EPD units are kg CO2 eq / ton and kg CO2 eq / metric ton.

Note:

1. 1 ton = 2000 lb
2. 1 metric tonne = 2200 lb

Sample Calculation

Table A.2—Sample Calculation

Raw Material	Material Embodied GWP (**kg CO_2** eq/ton)	Class AAA Mix Proportions (lbs/yd^3)	Constituent Embodied GHG **kgs CO_2** eq
Type II	942	575	270
Fly Ash	198	101	10
Fine Aggregate	3	1135	1
Coarse Aggregate	4	1859	4
		Total	286

Mix Embodied Emissions (kg CO_2 eq./yd^3) = $\left(942\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 575\frac{lb}{yd^3}\right) + \left(198\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 101\frac{lb}{yd^3}\right) + \left(3\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 1135\frac{lb}{yd^3}\right) + \left(4\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 1859\frac{lb}{yd^3}\right) = 286\ \frac{kg\ CO2\ eq}{yd^3}$

The embodied GHG emissions for the sample mix is 286 $\frac{kg\ CO2\ eq}{yd^3}$. This represents the embodied GHG emissions associated with production and transportation to the batch plant. Additional emissions associated with construction and long-term maintenance are not accounted for in this calculation and should be determined separately if required.

APPENDIX C: REDLINED SECTION 439

Section 439—~~Portland~~ Hydraulic Cement Concrete Pavement (Special)

439.1 General Description

This work includes constructing pavement composed of ~~Portland~~ Hydraulic cement concrete, with or without reinforcement as specified, on a prepared subgrade or subbase course.

Follow the requirements of these Specifications and conform with the lines, grades, thicknesses, and typical cross-sections shown on the Plans or established by the Engineer.

439.1.01 Definitions

General Provisions 101 through 150.

439.1.02 Related References

A. Standard Specifications

Section 152—Field Laboratory Building
Section 430—~~Portland~~Hydraulic Cement Concrete Pavement

Section 431—Grind Concrete Pavement

Section 461—Sealing Roadway and Bridge Joints and Cracks

Section 500—Concrete Structures

Section 800—Coarse Aggregate

Section 801—Fine Aggregate

Section 830—Portland Cement

Section 831—Admixtures

Section 832—Curing Agents

Section 833—Joint Fillers and Sealers

Section 853—Reinforcement and Tensioning Steel

Section 880—Water

Section 886—Epoxy Resin Adhesives

B. Referenced Documents

AASHTO M31
AASHTO M85
AASHTO M240
AASHTO T 126
AASHTO T22
AASHTO T23
AASHTO T27
AASHTO T152
AASHTO T160
AASHTO T161
AASHTO T290
AASHTO T277
AASHTO T358
ASTM C 94, Requirements for Uniformity
ASTM C452
ASTM C457

ASTM C666
ASTM C1012
ASTM C1218
ASTM D516
GDT 26
GDT 27
GDT 28
GDT 32
GDT 72
GDT 78
SOP 34

439.1.03 Submittals

A. Profilograph Certification

Before paving, ensure that the profilograph and operator are certified by the Office of Materials and Research in accordance with Standard Operating Procedure No. 34, Certification of Contractor Personnel and Equipment for Smoothness Testing of ~~Portland~~hydraulic Cement Concrete Pavement with the Rainhart Profilograph. Certification includes a mechanical check of the profilograph functions and a written examination by the operator.

Request certification in writing to the Office of Materials and Research at least two weeks before it is needed.

B. Report Form

Refer to Subsection 439.3.06.L, *Smoothness Testing* for report form and submittal requirements.

C. Concrete Design

Submit for approval a concrete design prepared by a testing laboratory approved by the Office of Materials and Research. The Contractor will transmit the design to the Engineer for approval at least 35 days before use.

Or, submit for approval concrete mix proportions with commonly used materials without preparation by a laboratory. The Office of Materials and Research may approve proportions based upon the past performance of the material combination.

439.2 Materials

Ensure that materials meet the requirements of the following Specifications:

Material	Section
Portland cement	830.2.01
Portland Pozzolan cement	830.2.03
Water	880.2.01
Fine Aggregate, Size No. 10	801.2.02
Coarse Aggregate, Class A or B Crushed Stone or Gravel, Sizes as Specified	800.2.01
Steel Bars for Reinforcement	853.2.01
Steel Wire for Concrete Reinforcement	853.2.06
Welded Steel Wire Fabric for Concrete Reinforcement	853.2.07
Dowel Bars and Bar Coatings	853.2.08
Curing Agents	832
Air Entraining Admixtures	831.2.01
Fly Ash, ~~and Slag~~ Raw or Natural Calcined Pozzolan, Slag, and Microsilica	831.2.03

Joint Fillers and Sealers	833
Low Modulus Silicone Sealant for Roadway Construction Joints	833.2.06
Epoxy Adhesive for Repairing Cracks	886.2.01
Chemical Admixtures	831.2.02

A. Fly Ash

Fly ash may be used as a concrete additive to promote workability and plasticity. Use it as a partial replacement for Portland cement in concrete, but follow these limits:

1. Do not replace the cement quantity more than 15 percent by weight.
2. Replace cement with fly ash at the rate of 1.25 to 2.0 lbs. (1.25 to 2.0 kg) of fly ash to 1 lb. (1.0 kg) of cement.
3. Ensure that the fly ash mix conforms to Subsection 430.3.06, *Quality Acceptance.*
4. Do not use Type IP cement in fly ash mixes.

B. Granulated Iron-Blast-Furnace Slag

If high early strengths are not desired, use granulated slag as a partial replacement for Portland cement in concrete. Follow these limits:

1. Replace the quantity of cement 50 percent or less by weight if the 5-day forecast of the National Weather Service expects temperatures higher than 60 °F (15 °C).
   a. If the 5-day expected low temperature is less than 60 °F (15 °C) but not less than 40 °F (4 °C), replace the quantity of cement 30 percent or less by weight.
   b. If the 5-day expected low temperature is less than 40 °F (4 °C); do not use granulated slag.
2. Replace cement with slag at the rate of 1 lb. (1.0 kg) of slag to 1 lb. (1.0 kg) of cement.
3. Ensure that the granulated slag mix conforms to Subsection 430.3.06, *Quality Acceptance.*
4. Do not use Type IP cement or fly ash in slag mixes.

A. Supplementary Cementitious Materials

The Contractor may use supplementary cementitious materials (SCMs) to achieve the performance requirements in Subsection 430.3.06. SCMs have been shown to have synergistic properties when used in combination and mix designs are not limited to a single SCM.

Notes:

1. Ensure SCMs meet the requirements in subsection 831.
2. Calculate the water-cementitious material (w/cm) ratio based on the total cementitious material in the mix including hydraulic cement and all SCMs.

C. B. Composition of Concrete

Design the concrete mix to conform to the following requirements:

1. Obtain approval from the Office of Materials and Research for proposed concrete mix designs. Design concrete mixes to meet the requirements in Table 1 – Concrete Mix Design by class of concrete and to meet the performance metrics in Tables 2A through Table 6 when applicable. The Engineer shall determine the applicable site conditions and requirements for concrete placed for each project. Mix designs that meet the requirements shall be qualified and shall meet the remaining quality assurance standards as described in subsection 439.03.06 for field verification of batches. A mix that has previously qualified for a specific collection of exposure classes shall remain qualified. Mixes shall require requalification if a material or proportion changes. A waiver for requalification for a mix design from GDOT may be requested. Concrete mix designs shall only be utilized for sites and applications as approved by the Engineer.

1. 2. Coarse Aggregate

   Use coarse aggregate size No. 467, 67, or 57 for plain Portlandhydraulic Cement concrete pavement.

Use size No. 67 or 57 coarse aggregate for continuous reinforced concrete pavement.

Separate size No. 467 or 456 in individual stockpiles of size No. 4 and size No. 67. Blend according to approved mix proportions.

~~2.~~3. Fine Aggregate

Use fine aggregate that meets the requirements for size No. 10.

When using two sizes or sources of fine aggregate to produce the proper gradation, blend according to the approved design proportions.

439.1.04 Delivery, Storage, and Handling

Store fine aggregate from different sources in different stockpiles.

439.3 Construction Requirements

439.3.01 Personnel

A. Certified Operator

Before paving, have the Office of Materials and Research certify a profilograph equipment operator. Certification includes a written examination by the operator.

439.3.02 Equipment

A. Equipment Requirements

Provide equipment and tools to perform the work. Provide equipment that allows the paver to operate at a constant production rate and minimizes starting and stopping. The Engineer may limit the production rate or batch size if equipment does not keep pace with the other operations or causes poor workmanship.

B. Ramp Screeds and Hand FinishingTools

Ramp screeds and hand finishing tools may be used instead of conventional mainline paving equipment.

C. Scales

Before use, the Engineer will inspect and approve the scales to weigh concrete materials and the devices to measure water. Tolerances are ± 1.0 percent throughout the operating range. Measure admixtures to ±
3.0 percent.

D. Protective Equipment

Provide materials to protect the concrete edges and surface against rain, including:

- Standard metal forms or wood planks to protect the pavement edges
- Covering material such as burlap or cotton mats, curing paper, or plastic sheeting material to protect the pavement surface

E. Auxiliary Vibrator

Keep one auxiliary vibrator available in case of mechanical malfunctions.

F. Texturing Equipment

Ensure that the tines on the equipment:

- Are the same size and length and are rectangular shaped
- Have approximately 0.5 in (13 mm) of space between them
- Are between 1/16 in and 1/8 in (2 mm and 3 mm) wide

439.3.03 Preparation

A. Prepare the Roadbed

Prepare the roadbed as required by the Plans and Specifications before placing concrete pavement.

B. Observe Condition of Subgrade and Subbase

Check the subgrade and subbase as follows:

1. Prepare the full width of the subgrade and subbase according to the Plans and Specifications.
2. Ensure that the surface immediately under the concrete pavement allows proper pavement thickness and yield.
3. Trim high areas to the proper elevation.
4. Ensure that the subbase can support paving equipment without rutting or bogging.

439.3.04 Fabrication

General Provisions 101 through 150.

439.3.05 Construction

A. Set Forms

Set the forms as follows:

1. Compact the foundation under the forms true to grade. Set the form so that it firmly contacts the foundation for the entire length at the specified grade.
2. Prevent the forms from settling or springing under the finishing machine.
3. Clean and oil the forms before placing the concrete.

B. Place Concrete

After depositing the concrete on the grade, avoid rehandling it. Unload and place it as follows:

1. Unload the concrete into an approved spreading device and mechanically spread it on the grade.
2. Place the concrete continuously between transverse joints without using intermediate bulkheads.
3. Perform any necessary hand spreading of concrete with shovels, not rakes.

> **NOTE: Do not allow personnel to walk in freshly mixed concrete with shoes coated with dirt or other materials.**

4. Thoroughly consolidate the concrete on both sides of joint assemblies.
5. Ensure that vibration does not cause puddling or grout accumulation on the surface.

   For construction or expansion joints, do not use grout that accumulates ahead of the paver.
6. Deposit concrete near the formed joints. Do not dump or discharge concrete on a joint assembly unless the concrete is centered on the joint assembly.
7. Keep reinforcing steel free of dirt, oil, paint, mill scale, and loose or thick rust that could impair the bond of the steel to the concrete.

C. Consolidate and Finish

Ensure that the sequence of operations is continuous from placement to final finish.

1. Consolidation

   Perform vibration for the full width and depth of the pavement as follows:

   a. Do not allow the vibrators to misalign load transfer devices or contact forms or the foundation.

   b. Ensure that the operating frequency is within these ranges.

      Use spud vibrators with an operating frequency of at least 7,000 vibrations per minute. Use tube vibrators with an operating frequency of at least 5,000 vibrations per minute.

      Use surface pan vibrators with an operating frequency of at least 3,500 vibrations per minute.

   c. Use hand-held vibrators if needed.

Ensure that the operating frequency is at least 4,500 vibrations per minute. The intensity shall be sufficient to affect the mass of concrete having a 1 in. (25 mm) slump through a radius of at least 18 in. (450 mm).

d. Obtain uniform consolidation and density throughout the pavement.

If the pavement is not uniform, stop the operation and provide methods or equipment that will produce pavement that conforms to the Specifications.

e. Keep a standby vibratory unit available in case a primary unit malfunctions.

2. Finishing

After striking off and consolidating the concrete, follow these steps:

a. The concrete may be smoothed and trued using a hand float.

b. Ensure that the surface within 6 in. (150 mm) of the pavement edge shows no more than a ¼ in. (6 mm) deviation in 10 ft. (3 m) when tested with a 10 ft. (3 m) straightedge in both transverse and longitudinal directions.

c. Ensure that mainline riding surface produces a profile index value of less than 7 in./ mile (100 mm/km) on each travel lane.

D. Protection from Rain

Protect the unhardened concrete from rain. See Subsection 439.3.02.D, *Protective Equipment.*

When rain is imminent, stop paving operations and place forms against the sides of the pavement. Cover the surface of the unhardened concrete with the protective covering.

E. Remove Forms

Remove forms from in-place concrete after it has set for at least 12 hours, unless otherwise provided.

1. Remove forms carefully to avoid damaging the pavement.
2. After removing the forms, immediately cure the sides of the slab using the same method used to cure the pavement surface.
3. Remove and replace major honeycombed areas.

F. Work at Night

Provide adequate lighting for work performed at night. If lighting will not be provided at night, stop the concreting operation in time to finish and saw during daylight hours.

G. Provide Joints

Ensure that joints are designed, configured, and located as shown on the Plans or required by the Specifications.

1. At the Engineer’s discretion, remove and replace plain concrete pavement that cracks during construction with no additional cost to the Department.
2. When chipping out random cracks for sealing, use nonrigid epoxy that meets Subsection 886.2.01 on cracks that are not under expansion-contraction influence.
3. Seal continuous cracks under movement with sealant that meets Subsection 833.2.06.
4. When removing and replacing a pavement section, replace an area at least 6 ft. (1.8 m) long and the full width of the lane.
   a. Saw to vertical face the sections to be removed and replace the concrete as a construction joint with dowels.
   b. Use deformed bars as dowels in the saw-cut construction joint. Use the size specified for contraction joints in the Plans.
5. Thoroughly clean the drilled holes of contaminants and set the dowels into the hardened concrete face of the existing pavement with a Type VIII epoxy bonding compound. See Section 886 for epoxy bonding compound requirements.
6. For contraction joints, undamaged and properly positioned dowels may be used in existing construction or slab

replacement areas. Coat the protruding dowel portions with a thin film of heavy grease.

7. When both sides of an existing construction or contraction joint require slab replacements, slabs may be replaced continuously from saw-cut construction joint to saw-cut construction joint. Use dowels specified for contraction joints.
8. Before placing concrete, uniformly apply a thin coat of heavy grease to epoxy-coated dowels.
9. When placing slabs continuously across transverse contraction joint locations, use saw-cuts to provide planes of weakness according to the requirements of this Specification and the GDOT construction standard for contraction joints.
10. Seal the joints according to the Plans.

H. Determine Types of Joints

1. Longitudinal Joints

   Longitudinal joints shall contain unpainted and uncoated deformed steel bars that are the size and length specified on the Plans.

   Place the bars perpendicular to the joint using a mechanical device, or rigidly secure the bars in place with supports.

2. Longitudinal Formed Joints

   Construct longitudinal formed joints while the concrete is in a plastic state.

   Use methods and equipment that locates the joint reinforcement properly without disrupting it during construction.

3. Longitudinal Sawed Joints

   Cut longitudinal sawed joints with a mechanical saw within three days after the concrete is placed and before traffic or equipment enters the pavement.

4. Transverse Joints

   Transverse joints consist of construction joints, contraction joints, or expansion joints constructed at required locations.

   a. Construct transverse joints in partial width or adjoining lanes to abut the same joint of adjacent lanes unless otherwise specified on the Plans.

   b. Ensure that transverse joints in plain ~~Portland~~hydraulic Cement concrete requiring load transfer devices contain either plastic-coated or epoxy-coated dowels.

   c. Before placing concrete, secure dowel bars in place with supporting assemblies.

   d. Secure the assemblies in position on the subbase to keep the dowels from moving during concrete placement.

   e. Place dowel bars to a vertical and horizontal tolerance of ± 1 in. (± 25 mm) of the Plan position. Do not misalign the dowel bar more than 3/8 in. per foot (10 mm per 300 mm) in the horizontal or vertical plane.

   f. Remove and replace dowel assemblies displaced from the Plan position more than the tolerances in Subsection 430.3.05.J, *Provide Joints.*

   g. When using epoxy-coated dowels, coat the entire surface with a thin film of heavy waterproof grease.

   h. Ensure accurate positioning of transverse sawed joints by marking the position of dowel bar assembly locations.

5. Construction Joints

   Construct transverse construction joints when interrupting concreting operations for more than one hour.

NOTE: Do not construct transverse construction joints within 10 ft. (3 m) of an expansion joint, contraction joint, or transverse plane of weakness.

   a. Move an unanticipated construction joint back to the last Plan joint and remove and dispose of excess concrete.

   b. Form construction joints by securing in place a removable bulkhead or header board.

      1) Place the board so that it conforms to the full cross section of the pavement. Secure it flush with the subbase and parallel to the normal transverse joints.

2) Slot or drill the board to allow placement of reinforcement as required by the Plans.

> **NOTE: Do not use the roll of laitance and grout that forms in front of the paver adjacent to transverse construction joints.**

c. Consolidate to full width and depth concrete adjacent to transverse construction joints with mechanical hand-type spud vibrators. Keep one auxiliary vibrator available in case of mechanical malfunctions.

d. Before applying the final finish to the concrete, stringline and correct variations of the concrete surface within 30 ft. (9 m) on either side of the transverse construction joints. Provide equipment and tools such as:

Work bridges

Personnel

String lines

Straightedges

Lighting

e. While the concrete is in a plastic condition, stringline the surface longitudinally and correct surface deviations greater than 1/8 in. in 15 ft. (3 mm in 4.6 m) in any direction.

f. When using Plain ~~Portland~~hydraulic cement concrete pavement, place dowel bars in construction joints. Cast half the length of each dowel bar in the concrete during each phase of joint construction.

g. After the concrete has hardened, dismantle the bulkhead supporting the dowels. Do not disturb the dowels.

h. When using epoxy coated dowels, coat the protruding half of each dowel bar with a thin film of heavy waterproof grease before resuming joint construction. Grease coating is not required on plastic coated dowels.

6. Contraction Joints

Create planes of weakness in plain ~~Portland~~hydraulic cement concrete pavement by cutting joints in the pavement surface. Create the planes according to the Plans and as follows:

a. Saw transverse contraction joints before the pavement cracks. Begin sawing when the concrete has hardened enough to prevent surface raveling, usually 4 hours after placement but no more than 24 hours.

b. Continue sawing day and night regardless of weather conditions.

7. Expansion Joints

Transverse expansion joints are required at locations shown on the Plans.

a. Form expansion joints by securing a removable bulkhead that conforms to the full cross section of the pavement. Use bulkheads that can construct a vertical expansion wall without offsets, indentations, or burrs.

b. Use expansion joint filler required by the Plans.

c. Furnish and install preformed joint filler in lengths equal to the pavement width or the width of one lane. Do not use damaged or repaired joint fillers.

d. Position the expansion joint filler vertically in the joint and at the proper grade. Use an installing bar or other device to secure the expansion joint filler at the proper grade and alignment.

I. Seal the Joints

Clean and seal the joints according to Section 461 and the Plans.

Immediately after completing the curing period, fill in the joints with joint sealing material before opening the pavement to traffic.

J. Cure the Concrete

Immediately after finishing the concrete, cure the entire surface when the concrete will not mar. Use one or more of these methods:

1. Impervious Membrane Method

To use this method:

a. Spray the entire surface of the pavement with white pigmented curing compound immediately after finishing the surface and before the concrete has set.

If the pavement is cured initially with cotton mats, burlap, or cotton fabric, apply the compound after removing the mats.

NOTE: Do not apply curing compound during rain.

b. Use mechanical sprayers to apply curing compound under pressure at a minimum rate of 1 gal per 150 ft.^{2} (1 L per 3.5 m^2).

Use fully atomizing spraying equipment that is equipped with a tank agitator.

c. Thoroughly mix the curing compound immediately before use.

d. During application, use a mechanical device to stir the compound continuously.

e. If required, use a hand sprayer to spray odd widths, odd shapes, and concrete surfaces exposed by removing forms.

f. Do not apply curing compound to the inside faces of joints to be sealed.

g. If the membrane film becomes damaged within the curing period, repair the damaged portions immediately with additional compound.

2. White Polyethylene Sheeting

To use this method:

a. Cover the top surface and sides of the pavement with polyethylene sheeting. Lap the units at least 18 in (450 mm).

b. Place the sheeting and weigh it down so that it contacts the surface.

c. Extend the sheeting beyond the edges of the slab at least twice the thickness of the pavement.

d. Unless otherwise specified, maintain the covering in place for 72 hours after placing the concrete.

3. Burlap, Cotton Fabric, or Other Methods

Contractors may cure the pavement surface with burlap, cotton fabrics, or other materials if the section remains wet for the duration specified by the Engineer.

4. Cold Weather Curing

To use this method:

a. Remove and replace concrete that freezes before the initial set time at no additional cost to the Department.

b. Use polyethylene or canvas to protect concrete that has set but is exposed to freezing temperatures within 24 hours of placement. Ensure that the internal concrete temperature is above freezing for at least 24 hours after placing the concrete.

c. Obtain approval from the Engineer to use other protection methods such as hay, straw, or grass, or to change the duration of the protection.

K. Open Pavement to Traffic

Wait to open the pavement slab to traffic, except for joint sawing vehicles, until the concrete is 14 days old unless representative compressive tests show that the slab has a compressive strength of 2,500 psi (15 MPa).

Prevent pavement slab stress by constructing a ramp of compacted earth or other material to move on and off the pavement. Do not allow equipment that exceeds legal load limits on the pavement.

Protect the pavement against traffic from the public, employees, and agents.

1. Erect and maintain barricades. Employ watchmen to block traffic from the newly constructed pavement for the period required in this Specification.

2. Arrange the barriers away from public traffic on lanes remaining open.
3. Maintain signs that clearly indicate the lanes open to public traffic.
4. If traffic must go across the pavement, construct crossings satisfactory to the Engineer to bridge over the concrete. Construct the crossing without additional compensation.
5. Repair or replace pavement damaged by traffic or other causes before Final Acceptance without additional compensation. Make repairs to the Engineer's satisfaction.

439.3.06 Quality Acceptance

The typical section sheet in the Plans specifies concrete classifications for specific uses.

This Specification establishes minimum requirements for these concrete classifications for concrete design approval, concrete mix design proportions, batching control responsibilities, and acceptance of hardened concrete based upon compressive strength development.

Produce ~~Portland~~hydraulic cement concrete by combining proportions of approved materials in batches according to the construction methods specified in this Specification.

Mix concrete produced in a stationary central mix plant for at least 60 seconds after the materials enter the drum. Mix time may be reduced if the representative tests show that the concrete meets requirements of ASTM C 94, Requirements for Uniformity. Never mix less than 50 seconds.

A. Transit Mixed Concrete

Ensure that transit mixed concrete meets the requirements of Subsection 500.3.04.E.3, *Transit-Mixed Concrete.*

B. Mix Design Criteria

~~Proportion concrete mix designs using the following requirements:~~

	~~Minimum Cement per Cubic Yard Concrete (CWT)~~	~~Maximum Water–Cement Ratio (lbs./lb.)~~	~~Design Air-Content Range (%)~~	~~Minimum Compressive Strength at 28 Days (psi)~~
~~Class 3~~	~~5.64~~	~~0.53~~	~~4.0 to 5.5~~	~~3,000~~
~~Class HES~~	~~6.58~~	~~0.47~~	~~4.0 to 5.5~~	~~3,500~~

	~~Minimum Cement per Cubic Meter Concrete (kg)~~	~~Maximum Water–Cement Ratio (kg/kg)~~	~~Design Air-Content Range (%)~~	~~Minimum Compressive Strength at 28 Days (MPa)~~
~~Class 3~~	~~335~~	~~0.53~~	~~4.0 to 5.5~~	~~20~~
~~Class HES~~	~~390~~	~~0.47~~	~~4.0 to 5.5~~	~~25~~

Table 1 – Concrete Mix Table

English				
	Minimum Compressive Strength at 28 days (psi)	Maximum w/cm Ratio (lbs/lbs)	Air Content Range (%)	Maximum Drying Shrinkage at 28 days (%)
Class 3	4000	0.53	4.0 to 5.5	.04
Class HES	3000	0.47	4.0 to 5.5	.04

Metric				
	Minimum Compressive Strength at 28 days (MPa)	Maximum w/cm Ratio (kgs/kgs)	Air Content Range (%)	Maximum Drying Shrinkage at 28 days (%)
Class 3	30	0.53	4.0 to 5.5	.04
Class HES	20	0.47	4.0 to 5.5	.04

Notes:

1. Hydraulic cement used for any class or application shall conform or meet the specifications in any of the following: AASHTO M85/ASTM C150 or ASSHTO M240/ASTM C595.
2. Compressive strength will be determined based upon result of six cylinders prepared and tested in accordance with AASHTO T 22 and T 126. Produce evidence that the mix design proportions for Class HES concrete has strength development potential for 72 hours and at 28 days as specified in Subsection 439.3.06.C, "Approval of Mix Design". If minimum compressive strength is not reached at 28 days for any class, samples from the same batch shall be tested at 56 days using the same compressive strength limits from 28 days. Pay reduction based on meeting 56-day strength (but when the 28-day strength requirement was not met) may apply at the discretion of the Engineer.
3. Cementitious materials include hydraulic cement and all supplementary cementitious materials (SCMs). Inert fillers such as interground limestone shall not be considered an SCM for the purposes of this specification. Water/cementitious material ratio (w/cm) refers to the ratio of water to total cementitious material including hydraulic cement and all SCMs.
4. Air content shall be measured in accordance with AASHTO T152 utilizing a Type B meter.
5. 28 day drying shrinkage shall be measured in accordance with AASHTO T160 using concrete prisms exposed to drying at a concrete age of 7 days. The initial reading for drying shrinkage calculations shall be the reading taken at the start of drying at a concrete age of 7 days ± .5 hours.

Table 2A—Concrete Surface Resistivity

Chloride Ion Penetration	Surface Resistivity Limits	Minimum Allowable Surface Resistivity by Concrete Class (KOhm-cm)	
		Class 3	Class HES
High	≤ 13.0		
Moderate	13.1-21.0	✓	✓
Low	21.1-40.0	✓	✓
Very Low	40.1-254.0	✓	✓
Negligible	≥ 254.1	✓	✓

Table 2B—Concrete Charge Passed

Chloride Ion Penetration	Charge Passed Limits	Minimum Allowable Charge Passed by Concrete Class (Coulombs)	
		Class 3	Class HES
High	≥ 3501		
Moderate	3500-2001	✓	✓
Low	2001-901	✓	✓
Very Low	900-101	✓	✓
Negligible	≤ 100	✓	✓

Notes:

1. All reinforced concrete shall show moderate or better chloride ion penetration using either surface resistivity requirements (Table 2A) or charge passed utilizing the Rapid Chloride Penetration Test (RCPT) requirements (Table 2B). The Engineer shall determine if site conditions warrant more stringent surface resistivity or chloride ion penetration limits.
2. Requirements for surface resistivity in Table 2A refer to results from an 4in. x 8 in. cylinder in accordance with AASHTO T358. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch. Samples shall be cured in limewater solution. A mix will be qualified once the average of the samples exceeds the required surface resistivity limits at any time before the 56-day maximum curing time.

~~2.~~3. Requirements for RCPT in Table 2B refer to results from a 4 in. diameter sample in accordance with AASHTO T277. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch. Samples shall be cured in limewater solution. A mix will be qualified once the average of the samples exceeds the required surface resistivity limits at any time before the 56-day maximum curing time.

Table 3A—Freezing-Thawing Exposure Classes

FT Exposure Class	No FT exposure	FT exposure
Exposure Condition	Not exposed to FT cycles	Exposed to FT cycles with frequent exposure to water
Minimum f'_c, psi (MPa)	None	4500 (32)
Maximum w/cm	None	0.45

Notes:

1. Freezing-thawing (FT) refers to conditions where cycles of freezing and thawing may result in cracking and crumbling of the placed concrete. FT exposure class shall be determined by the Engineer. Both minimum f'_c, and maximum w/cm limits are required for specified FT exposure classes.
2. FT concerns are heightened above the Fall Line. The Engineer shall determine if FT concerns are expected to exist below the Fall Line.

Table 3B—Freezing-Thawing Durability Metrics

FT Exposure Class	No FT concerns	FT Concerns
Minimum specific surface, $in.^2/in.^3$ (mm^2/mm^3)	None	600 (21)
Maximum spacing factor, in. (mm)	None	0.009 (0.23)
Minimum durability factor	None	90

Notes:

1. At least one FT durability test metric shall be passed according to the requirements by FT exposure class set forth in Table 3B. FT exposure class shall be determined by the Engineer.
2. Specific surface shall be calculated using results from tests conducted in accordance with ASTM C457/ASTMC457M.
3. Spacing factor shall be calculated in accordance with ASTM C457/ASTM C457M as average of three assessments from single mixture during construction, where no assessment for spacing factor is greater than 0.012 in. (0.30 mm) FT concerns. Note that with values for air content, paste fraction, and specific surface, spacing factor may be calculated.
4. Durability factor measured shall be calculated in accordance with ASTM C666/C666M, by either Procedure

A or B, as an average of three separate specimens that are representative of same concrete mix.

Table 4A—Sulfate Exposure Class

Sulfate Exposure Class	Water soluble sulfate in soil, % by mass	Dissolved sulfate in water, ppm
S0	$SO_4 < 0.10$	$SO_4 < 150$
S1	$0.10 \leq SO_4 \leq 0.20$	$150 \leq SO_4 \leq 1{,}500$
S2	$0.20 \leq SO_4 \leq 2.00$	$1{,}500 \leq SO_4 \leq 10{,}000$
S3	$SO_4 > 2.00$	$SO_4 > 10{,}000$

Notes:

1. Water soluble sulfate in soil shall be determined in accordance with AASHTO T290.
2. Dissolved sulfate in water shall be determined in accordance with ASTM D516.

Table 4B—Sulfate Attack Durability

Sulfate Exposure Class	Cement Designation	Maximum w/cm	Minimum f'_c psi (Mpa)	Performance requirements expansion in ASTM C1012 (maximum %)		
				6 month	12 month	18 month
S0	No Requirements					
S1	Performance Requirement Only	0.55	3500 (25)	0.05	0.10	-
	Type II or Type MS-designated blended cements	0.50	4000 (25)	0.10	-	-
	No restriction	0.45	4500 (32)	-	-	-
S2	Performance Requirement Only	0.50	4000 (25)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.45	4500 (32)	0.05	0.10	-
	Type II or Type MS	0.40	5000 (35)	0.10	-	-
S3	Performance Requirement Only	0.45	4500 (32)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.40	5000 (35)	0.05	0.10	-

Notes:

1. Sulfate attack refers to conditions where sulfate-rich environments causes chemical reactions with hardened cement paste forming expansive products which cause cracking and premature failure. Sulfate exposure class shall be determined by the engineer.
2. Mix designs under the same sulfate exposure class shall conform either to performance limits determined by cement usage or performance requirements. Utilizing designated cements reduces the performance requirements.
3. Cement Types II and V refer to cements that meet requirements in AASHTO M85/ASTM C150.
4. Type MS refers to blended cements that meet the requirements for MS designation in AASHTO M240/ASTM C595. Type HS refers to blended cements that meet the requirements for HS designation in AASHTO M240/ASTM C595.
5. Where hydraulic cement and SCMs are combined at the concrete mixer, it shall be demonstrated that the blend meets the performance requirements listed in ASTM C1012.
6. If Type V cement is used as the sole cementitious material for a S3 exposure class, an optional sulfate resistance requirement of 0.04% maximum expansion (when tested in accordance with ASTM C452) shall be in force.

Table 5—Structure Importance/Type

Structural Importance	Definition
T1	Minor risk of reinforcement corrosion can be tolerated
T2	Reinforcement corrosion cannot be tolerated; non-environmental structures
T3	Reinforcement corrosion cannot be tolerated; environmental structures

Note:

1. Definitions for structural importance not inclusive or representative of all circumstances potentially encounterable. The Engineer shall determine most applicable category by project requirements.

Table 6—Water Soluble Chloride Matrix

Chloride Exposure Class	Structural Importance	Chloride limits for new construction (% by mass of cementitious material)	
		Water-soluble (ASTM C1218/C1218M)	
		Reinforced Concrete	Prestressed concrete
C0 - Concrete in dry environment	T1	1.00	0.06
	T2	0.25	0.06
C1- Concrete exposed to moisture but not to external sources of chlorides in service	T1	0.30	0.06
	T2	0.15	0.06
C2 -Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salts, brackish water, seawater, or spray from these sources in service	T1, T2	0.15	0.06
C3 - Concrete exposed to severe exposure conditions, including concentrated chemicals, wetting-and-drying cycles, FT cycles	T2, T3	0.10	0.06

Notes:

1. Water soluble chloride refers to chlorides in concrete that are not bound and have the ability to accelerate corrosion within reinforced or prestressed concrete.
2. Total cementitious material includes both hydraulic cement and all SCMs.
3. Dry environment corresponds to maximum relative humidity of 60%, normally, found in interior of buildings.

C. Compressive Strength

Prepare and test at least 6 cylinders according to AASHTO T 126 and T 22 to ensure that the demonstrated laboratory compressive strength at 28 days for Class 3 concrete is at least 4,000 psi (30 MPa), and the minimum laboratory compressive strength for Class HES concrete is 3,000 psi (20 MPa) at 72 hours.

D. Field Adjustments on Concrete Mixes

Determine the aggregate surface moisture and apply free moisture corrections to the approved mix design. The Engineer will verify that the corrections are made properly.

Adjustment may be made to the approved proportions of the fine and coarse aggregate and water provided:

- The ~~cement~~ cementitious material factor is not decreased.
- The water-~~cement~~ cementitious material ratio is not increased.
- Adjustments produce concrete proportions according to thisSpecification.
- The Engineer is notified before use.

Concrete Mix Tolerances

Ensure that concrete consistency and air content is maintained within the following limits:

1. Consistency

   Immediately before placement, use GDT 27 to determine concrete slump. Do not use concrete for ~~Portland~~hydraulic cement concrete pavement with a slump value greater than 3.5 in. (90 mm).

2. Air Content

   Immediately before placement, use GDT 26, GDT 28, or GDT 32 to determine the air content of the concrete. Concrete will not be accepted that has an air content outside of the following limits:

Lower acceptance limit	3.0%
Upper acceptance limit	6.5%

E. Concrete Strength Acceptance

1. Class 3

   ~~Portland~~Hydraulic cement concrete pavement strength will be accepted based on compressive strength development at 28 days. The compressive strength value shall be at least 4~~3~~,000 psi (3~~2~~0 MPa).

   a. Fabricate and cure specimens for field acceptance according to AASHTO T 23.

   b. After curing, the OMR will test the cylinders according to AASHTO T 22. The test frequency is outlined in the Department's Sampling and Testing information.

2. Class HES

   High early concrete strength pavement may be accepted based on compressive strength development at 72 hours. The compressive strength value shall be at least 3,000 psi (20 MPa).

   When concrete is defective based on the 72-hour strength test and the concrete is retained for acceptability judgment, acceptance will be based on test results conducted at 28 days. The acceptance strength value shall be at least 3,500 psi (25 MPa).

   a. Cure specimens fabricated for 72-hour strength for 72 hours under conditions that are similar to those under which the pavement will be cured.

   b. Cure specimens fabricated for 28-day evaluation per AASHTO T 23.

   c. Test all specimens per AASHTO T 22.

F. Depth Measurement

The Engineer will designate pavement areas to be examined for depth measurement compliance with the Plan and Specifications.

Remove and replace areas deficient more than 1/4 in. (6 mm). The Engineer may require a reduction in payment. Correct deficiencies in slab depth as directed by the Engineer.

G. Final Finish

Ensure that the final finish produces a pavement surface that is true to grade, uniform, and free of irregular, rough, or porous areas.

Produce the final surface finish using mechanical or hand-operated equipment to groove the plastic concrete. Use texturing equipment with rectangular-shaped spring steel tines.

H. Texture Depth Testing

Test the pavement surface to determine the texture depth by using GDT 72 at locations selected by the Engineer.

Transversely saw-groove areas that have a surface texture depth less than 0.02 in. (0.5 mm). Ensure that the areas meet the average depth requirement of 0.04 in. (0.9 mm) or greater. Saw-groove the areas to meet these dimensions:

- Width—1/8 in. (3 mm)
- Depth—3/16 in. (5 mm)
- Spacing—3/4 in. center-to-center (19 mm)

I. Smoothness Profile

Include in the Contract Unit Bid Price the cost to furnish and operate a Rainhart (Model 860) Profilograph to measure pavement profile deviations.

Measure and correct pavement profile deviations as follows:

1. Ensure that the mainline riding surface produces a profile index value no greater than 7 in./mile (100 mm/ km) on each travel lane. Conduct tests according to GDT 78.

   Determine a profile index value for each tracing in each ¼ mile (0.5 km) segment.
2. Correct individual bumps or depressions that exceed the blanking band by more than 0.2 in. (5 mm) at no additional expense to the Department.
3. Suspend paving operations if a profile index value exceeds 7 in./mile (100 mm/km) per lane for any segment. Take corrective action approved by the Engineer.
4. Test ramps, acceleration lanes, and deceleration lanes using GDT 78 to ensure that the average profile index value does not exceed 12 in./mile (200 mm/km) for the entire section length.
5. Correct individual bumps or depressions that exceed 0.2 in (5 mm) from the blanking band at no additional expense to the Department.
6. Take pavement profiles 4 ft. (1.2 m) from and parallel to the new pavement edges for pavements greater than 16 ft. (4.8 m) wide and up to 24 ft. (7.2 m) wide. Test pavement 6 to 16 ft. (1.8 to 4.8 m) wide parallel to and at the center line of the pavement section.
7. Begin the 0.25 mile (0.5 km) record segments at the first day's placement and continue until project completion, except as noted in this Specification.

   Combine pavement sections less than 650 ft. (200 m) approaching a bridge with the previous 0.25 mile (0.5 km) segment to determine the profile index.
8. Calculate as separate record segment sections 650 ft. (200 m) or greater approaching a bridge and sections at Project limits.
9. Determine a separate profile index value according to GDT 78 for the 100 ft. (30 m) of roadway approaching each end of a bridge, up to and including the joint with the approach slab.

   Average the profile index from the right and left wheelpaths for each 100 ft. (30 m) segment for each lane for each approach. Ensure that the average profile index value is no greater than 30 in./mile (500 mm/ km).
10. Notify the Engineer before profile testing. The Engineer will verify the results by randomly selecting at least 1 out of every 10 consecutive record segment profiles to compute the profile index and to compare with Contractor results.

J. Pavement Tolerances

For Projects that include weigh-in-motion truck scales, follow these pavement tolerances:

1. Ensure that the Rainhart Profilograph readings do not exceed 5 in/mile (80 mm/km) in the 600 ft. (180 m) approach to the scales and the 200 ft. (60 m) beyond the scales.
2. Ensure that the rolling straightedge measurements show no deviation greater than 1/16 in. (2 mm) within 10 ft. (3 m).

K. Smoothness Testing

Perform smoothness testing as follows:

1. Perform and evaluate profiles from the first day of placement before continuing paving.

   When the test run is complete and evaluated, the Engineer may require equipment adjustments to improve smoothness before paving continues.
2. Complete the report form furnished by the Engineer, and attach it to each day's profilograph tracings. Include the following information in each trace:
   - Project number
   - Beginning and ending station numbers
   - 500 ft. (150 m) paving stations
   - Traffic direction
   - Lane number
   - Date paved and tested
   - Construction joint locations
3. Have the certified profilograph operator obtain and evaluate traces to be submitted to the Engineer. Provide results no later than the end of the second work day following placement.
4. For mainline pavement, correct 0.25 mile (0.5 km) segments that do not meet the profile index requirement by using one of these methods:
   a. Grind the entire lane surface of the 0.25 mile (0.5 km) segment to a profile index value no greater than 7 in./mile (100 mm/km). Use equipment that meets the requirements in Section 431.
   b. Grind roughness in small segment areas no more than 50 ft. (15 m) of full lane width to produce a profile index value no greater than 7 in./mile (100 mm/km).

      If more than 50 ft. (15 m) of grinding is required, grind the complete 0.25 mile (0.5 km) segment according to Method a, above.
5. Correct ramps and acceleration and deceleration lanes that do not meet the profile index requirement to a profile index no greater than 12 in./mile (200 mm/km). Prevent individual bumps from exceeding 0.2 in. (5 mm) from the blanking band. Use equipment specified in Section 431.
6. Correct 100 ft. (30 m) bridge approach sections that do not meet the profile index requirement.
   a. Grind according to Section 431.
   b. Use a bump grinder to correct bumps with a baseline of 5 ft. (1.5 m) or less.
   c. Grind the full lane width even when grinding individual bumps.
   d. Retest pavement segments containing corrective slab replacements for Final Acceptance.
7. Correct segments that do not meet the profile index criteria of this Specification at no additional expense to the Department. Retest segments after correction with the Rainhart Profilograph as specified.
8. The Engineer may conduct profilograph tests at any time to verify Contractor results. The Department may test record segments if the Engineer determines that the Contractor test results are inaccurate. If this occurs, see Subsection 439.5.01, *Adjustments.*

L. Acceptance

Pavement smoothness will accepted when:

- The Engineer determines that the work was satisfactorily performed according to the Specifications.
- The completed pavement, including corrective Work, meets the applicable profile index value requirements.

439.3.07 Contractor Warranty and Maintenance

General Provisions 101 through 150.

439.4 Measurement

~~Portland~~Hydraulic cement concrete pavement (special) complete, in-place and accepted, is measured by the square yard (meter).

439.3.08 Limits

General Provisions 101 through 150.

439.4 Payment

Concrete pavement completed and accepted will be paid for at the full Contract Unit Price per square yard (meter).

Payment is full compensation for furnishing and placing materials, reinforcements, dowels, joint materials, supplies, and incidentals to complete the work.

Payment will be made under:

Item No. 439	Plain ~~Portland~~hydraulic cement concrete pavement, Class 3	Concrete_______in. (mm) thick	Per square yard (meter)
Item No. 439	Plain ~~Portland~~hydraulic cement concrete pavement, Class HES	Concrete_______in. (mm) thick	Per square yard (meter)
Item No. 439	Continuously reinforced concrete pavement, Class 3	Concrete_______in. (mm) thick	Per square yard (meter)
Item No. 439	Continuously reinforced concrete pavement, Class HES	Concrete_______in. (mm) thick	Per square yard (meter)

439.4.01 Adjustments

A. Profilograph Tests

If based on the Department's profilograph tests, the Engineer determines that the Contractor profilograph test results are inaccurate, the Contractor will be charged for profilograph testing at $500 for each trace mile ($250 for each trace kilometer) with a minimum charge of $500.

439.5 Appendix A: Embodied GHG Emissions (Report Only- Optional)

Notes:

1. Embodied greenhouse gases (GHGs) may be reported only; this is optional. GHGs shall not be used as a primary means to specify concrete but the example calculations provided in Appendix A may be used for project specific emission limits.
2. GHGs may be attested to by the concrete producer using either Type I or Type III Environmental Product Declarations (EPDs) conforming to ISO 14025. Embodied GHGs refers only to cradle-to-gate emissions associated with the production and transportation for a unit volume of concrete. Use product EPDs to determine the carbon equivalent intensity for each mix constituent.
3. Table A.1 includes embodied emission guidelines from the General Services Administration. The limits are industry wide averages from 2022. The emissions are to be interpreted as guidelines only.

Table A.1—Embodied Emission Guidelines

Class of Concrete	**Maximum Embodied Greenhouse Gases (kg CO_2 eq./yd^3)**
Class 3	235
Class HES	235
Class of Concrete	**Maximum Embodied Greenhouse Gases (kg CO_2 eq./m^3)**
Class 3	306
Class HES	306

Embodied Emissions Calculation

Mix Embodied Emissions (kg CO_2 eq./yd^3) = $\sum_{i=1}^{nn} AA_{ii}$ (kg CO_2 eq/lb) $*$ Material Proportion$_{ii}$ (lb / yd^3)

Where AA_{ii} is the emission intensity of the ith mix constituent and the ith material proportion is the mass of each mix constituent per unit of concrete for a mix with n different constituents.

The units for emission intensity should be in kg CO2 eq / yd^3. Adjustments for reported units from a material EPD shall be made to ensure units match throughout the calculation. Typical reported EPD units are kg CO2 eq / ton and kg CO2 eq / metric tonne.

Note:

1. 1 ton = 2000 lb
2. 1 metric tonne = 2200 lb

Sample Calculation

Table A.2—Sample Calculation

Raw Material	Material Embodied GWP (**kg CO_2** eq/ton)	Class AAA Mix Proportions (lbs/yd^3)	Constituent Embodied GHG **kgs CO_2** eq
Type II	942	575	270
Fly Ash	198	101	10
Fine Aggregate	3	1135	1
Coarse Aggregate	4	1859	4
		Total	286

Mix Embodied Emissions (kg CO_2 eq./yd^3) = $\left(942\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 575\frac{lb}{yd^3}\right) + \left(198\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 101\frac{lb}{yd^3}\right) + \left(3\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 1135\frac{lb}{yd^3}\right) + \left(4\ \frac{kg\ CO2\ eq}{ton} * \frac{1\ ton}{2000\ lb} * 1859\frac{lb}{yd^3}\right) = 286\ \frac{kg\ CO2\ eq}{yd^3}$

The embodied GHG emissions for the sample mix is 286 $\frac{kg\ CO2\ eq}{yd^3}$. This represents the embodied GHG emissions associated with production and transportation to the batch plant. Additional emissions associated with construction and long-term maintenance are not accounted for in this calculation and should be determined separately if required.

DEPARTMENT OF TRANSPORTATION STATE OF GEORGIA

SUPPLEMENTAL SPECIFICATION

Section 500—Concrete Structures

500.1 General Description

This Work consists of manufacturing and using ~~Portland~~hydraulic cement concrete to construct structures. See the Contract Plans for the specified color and locations for placing integrally colored concrete.

500.1.01 Definitions

General Provisions 101 through 150.

500.1.02 Related References

A. Standard Specifications

Section 104—Scope of Work

Section 211—Bridge Excavation and Backfill

Section 431—Grind Concrete Pavement

Section 507—Prestressed Concrete Bridge Members

Section 511—Reinforcement Steel

Section 530—Waterproofing Fabrics

Section 531—Damp proofing

Section 621—Concrete Barrier

Section 800—Coarse Aggregate

Section 801—Fine Aggregate

Section 830—Portland Cement
Section 831 - Admixtures

Section 836—Special Surface Coating for Concrete

Section 838—Graffiti-Proof Coating for Concrete

Section 853—Reinforcement and Tensioning Steel

Section 865—Manufacture of Prestressed Concrete Bridge Members

B. Referenced Documents

ASTM A 653/653M

ASTM A 924/924/M
ASTM C 595

ASTM C 666
ASTM C 685
ASTM C 979
ASTM C 1610
ASTM C 1611
ASTM C 1712
ASTM D 516

ASTM D 260, Type I or Type II

AASHTO C 309

AASHTO C 171

AASHTO M 85

AASHTO M 240

AASHTO M 194M/M 194

AASHTO R 39

AASHTO T 23
AASHTO R 81
AASHTO T 277
AASHTO T 290
AASHTO T 345
AASHTO T 347
AASHTO T 358

AWS D 1.5

SOP 10

SOP 17

SOP 46

American Iron and Steel Institute Specification for the Design of Cold Formed Steel Structural Members

Federal Specification TT-P-641d, Type II

Georgia Standards 4941B and 4949 Series

QPL 3

QPL 10

QPL 17
QPL 30

QPL 100

GDT 134

DOT 525

500.1.03 Submittals

A. Concrete Mix Designs

The Contractor is responsible for all concrete mix designs. Ensure that concrete mixes ~~contain enough cement to produce workability within the water-ratio~~ meet the requirements specified in Table 1—Concrete Mix Table. ~~, below.~~

~~Design concrete mixes that meet the requirements of the Table 1—Concrete Mix Table, below.~~ Design concrete mixes to meet the requirements in Tables 2A through Table 7 when applicable. The Engineer shall determine the applicable site conditions and requirements for concrete placed for each project. In the case the contractor determines self-consolidating concrete (SCC) is a viable and effective means of construction for precast/prestressed concrete production, the Contractor or Producer shall seek Engineer approval for all locations and applications of SCC. Use of SCC shall meet the requirements in Table 7 as approved by the Engineer. Mix designs that meet the requirements shall be qualified and shall meet the remaining quality assurance standards as described in subsection500.03.06 for field verification of batches. The Office of Materials and Testing ~~will~~ shall determine the concrete properties using the applicable method in Section 500 of the Sampling, Testing, and Inspection Manual.

TABLE 1—CONCRETE MIX TABLE

English								
Class of Concrete	(2) Coarse Aggregate Size No.	(1&6) Minimum Cement Factor lb./yd³	Maximum Water/ Cement ratio lbs./lb.	(5) Slump Acceptance Limits (in) Lower -	Upper	(3&7) Entrained Air Acceptance Limits (%) Lower -		Minimum Compressive Strength at 28 days
“AAA”	67,68	675	0.44	2	4	2.5	6	5000
“AA1”	67,68	675	0.44	2	4	2.5	6	4500
“D”	57, 67	650	0.445	2	4	3.5	7	4000
“AA”	56,57,67	635	0.445	2	4	3.5	7	3500
A	56,57,67	611	0.49	2	4	2.5 (3)	6	3000
B	56,57,67	470	0.66	2	4	0	6	2000
CS	56,57,67 Grade d	280	1.4	--	3½	3	7	1000 (4)

Metric								
Class of Concrete	(2) Coarse m Aggregate Size No.	(1&6) Minimu Cement	Maximum Water/ Cement ratio kg/kg	(5) Slump Acceptance Limits (mm) Lower – Upper		(3 & 7) Entrained Air Acceptance Limits (%) Lower-Upper		Minimum Compressive Strength
“AAA”	67,68	400	0.44	50	100	2.5	6	35
“AA1”	67,68	400	0.44	50	100	2.5	6	30
“D”	57,67	385	0.445	50	100	3.5	7	28
“AA”	56,57,67	375	0.445	50	100	3.5	7	25
“A”	56,57,67	360	0.49	50	100	2.5 (3)	6	20
“B”	56,57,67	280	0.66	50	100	0	6	15
“CS”	56,57,67	165	1.4	-	90	3	7	7 (4)
	Graded Agg.*							

NOTES:

1. **Portland cement or Blended Hydraulic Cement (Portland-limestone cement Type IL) may be partially replaced with fly ash as provided in Subsection 500.3.04.D.4 or with granulated iron blast furnace slag as provide for in Subsection 500.3.04.D.5.**
2. **Specific size of coarse aggregate may be specified.**
3. **Lower limit is waived when air entrained concrete is not required.**
4. **The mixture will be capable of demonstrating a laboratory compressive strength at 28 days of 1000 psi (7 MPa) + 0.18 R*. Compressive strength will be determined based upon result of six cylinders prepared and tested in accordance with AASHTO T 22 and R 39.**

   *** Where R = Difference between the largest observed value and the smallest observed value for all compressive strength specimens at 28 days for a given combination of materials and mix proportions prepared together.**
5. **Designed slump may be altered by the Office of Materials and Testing when Type “F” water reducers are used.**
6. **Minimum cement factor shall be increased by 50 lbs/yd³ (30 kg/m³) when size No. 7 coarse aggregate is used.**
7. **When Class A is specified for bridge deck concrete, the entrained air acceptance limits shall be 3.5% to 7.0%.**

Table 1—Concrete Mix Table

Class of Concrete	Minimum Compressive Strength at 28 days (psi)	Coarse Aggregate Size No.	Maximum w/cm ratio lbs/lbs	Slump acceptance Limits (in) Lower-Upper		Entrained Air Acceptance Limits (%) Lower-Upper		Maximum Drying Shrinkage at 28 days (%)
AAA	5000	67,68	0.440	2	4	2.5	6.0	0.04
AA1	4500	67,68	0.440	2	4	2.5	6.0	0.04
D	4000	57,67	0.445	2	4	3.5	7.0	0.04
AA	3500	56,57,67	0.445	2	4	3.5	7.0	0.04
A	3000	56,57,67	0.490	2	4	2.5	6.0	0.04
B	2200	56,57,67	0.660	2	4	0.0	6.0	N/A
CS	1400	56,57,67	1.400	-	3½	3.0	7.0	N/A
Class of Concrete	**Minimum Compressive Strength at 28 days (MPa)**	**Coarse Aggregate Size No.**	**Maximum w/cm ratio kgs/kgs**	**Slump acceptance Limits (mm) Lower - Upper**		**Entrained Air Acceptance Limits (%) Lower-Upper**		**Maximum Drying Shrinkage at 28 days (%)**
AAA	35	67,68	0.440	50	100	2.5	6.0	0.04
AA1	30	67,68	0.440	50	100	2.5	6.0	0.04
D	28	57,67	0.445	50	100	3.5	7.0	0.04
AA	25	57,67	0.445	50	100	3.5	7.0	0.04
A	20	56,57,67	0.490	50	100	2.5	6.0	0.04
B	15	56,57,67	0.660	50	100	0.0	6.0	N/A
CS	7	56,57,67	1.400		90	3.0	7.0	N/A

Notes:

1. Hydraulic cement used for any class or application shall conform to the specifications in any of the following: AASHTO M85/ASTM C150 or ASSHTO M240/ASTM C595.
2. Compressive strength will be determined based upon result of six cylinders prepared and tested in accordance with AASHTO T 22. If minimum compressive strength is not reached at 28 days, samples from the same batch shall be tested at 56 days using the same compressive strength limits from 28 days. Pay reduction based on meeting 56-day strength (but when the 28-day strength requirement was not met) may apply at the discretion of the Engineer.
3. Cementitious materials include hydraulic cement and all supplementary cementitious materials (SCMs). Inert fillers such as interground limestone shall not be considered an SCM for the purposes of this specification. Water/cementitious ratio (w/cm) refers to the ratio of water to total cementitious material including hydraulic cement and all SCMs.
4. Designed slump may be altered by the Office of Materials and Research when Type "F" water reducers are used. If higher slumps are determined to be necessary, the Engineer shall be consulted. Approval of higher slumps shall be approved by the Engineer as needed on the project.
5. If contractor determined self-consolidating concrete (SCC) is desirable for precast/prestressed concrete production, approvable from the Engineer is required and workability acceptance requirements in Table 7 supersede slump requirements in Table 1.
6. Specific size of coarse aggregate may be specified by the Engineer.
7. Lower entrained air limit shall be waived when air entrained concrete is not required.
8. When Class A is specified for bridge deck concrete, the entrained air acceptance limits shall be 3.5% to 7.0%.
9. Air content shall be measured in accordance with AASHTO T152 utilizing a Type B meter.
10. 28 day drying shrinkage shall be measured in accordance with AASHTO T160 using concrete prisms exposed to drying at a concrete age of 7 days. The initial reading for drying shrinkage calculations shall be the reading taken at the start of drying at a concrete age of 7 days ± .5 hours. Classes B and CS have no maximum drying shrinkage requirements.

Table 2A—Concrete Surface Resistivity

Chloride Ion Penetration	Surface Resistivity Limits	Minimum Allowable Surface Resistivity by Concrete Class (KOhm-cm)				
		AAA	**AA1**	**D**	**AA**	**A**
High	≤ 12.0					
Moderate	12.1-13.0					✓
	13.1-16.0			✓	✓	✓
	16.1-21.0		✓	✓	✓	✓
Low	21.1-40.0	✓	✓	✓	✓	✓
Very Low	40.1-254.0	✓	✓	✓	✓	✓
Negligible	≥ 254.1	✓	✓	✓	✓	✓

Table 2B—Concrete Charge Passed

Chloride Ion Penetration	Charge Passed Limits	Minimum Allowable Charge Passed by Concrete Class (Coulombs)				
		AAA	**AA1**	**D**	**AA**	**A**
High	≥4001					
Moderate	4000-3501					✓
	3500-2801			✓	✓	✓
	2800-2001		✓	✓	✓	✓
Low	2000-901	✓	✓	✓	✓	✓
Very Low	900-101	✓	✓	✓	✓	✓
Negligible	≤100	✓	✓	✓	✓	✓

Notes:

1. All reinforced concrete shall show moderate or better chloride ion penetration using either surface resistivity requirements (Table 2A) or charge passed utilizing the Rapid Chloride Penetration Test (RCPT) requirements (Table 2B). The Engineer shall determine if site conditions warrant more stringent surface resistivity or chloride ion penetration limits. Classes B and CS have no surface resistivity or charge passed requirements.
2. Requirements for surface resistivity in Table 2A refer to results from a 4 in. x 8 in. cylinder in accordance with AASHTO T358. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch. Samples shall be cured in limewater solution. A mix will be qualified once the average of the samples exceeds the required surface resistivity limits at any time before the 56-day maximum curing time.
3. Requirements for RCPT in Table 2B refer to results from a 4 in. diameter sample in accordance with AASHTO T277. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch. Samples shall be cured in limewater solution. A mix will be qualified once the average of the samples exceeds the required charge passed limits at any time before the 56-day maximum curing time.

Table 3A—Freezing-Thawing Exposure Classes

FT Exposure Class	No FT concerns	FT Concerns
Exposure Condition	Not exposed to FT cycles	Exposed to FT cycles with frequent exposure to water
Minimum f'_c, psi (MPa)	None	4500 (32)
Maximum w/cm	None	0.45

Notes:

1. Freezing-thawing (FT) refers to conditions where cycles of freezing and thawing may result in cracking and crumbling of the placed concrete. FT exposure class shall be determined by the Engineer. Both minimum f'_c and maximum w/cm limits are required for specified FT exposure classes.
2. FT concerns are heightened above the Fall Line. The Engineer shall determine if FT concerns are expected to exist below the Fall Line.

~~2.~~2. Concrete placed on a bridge deck shall be designed for FT concerns regardless of location.

Table 3B—Freezing-Thawing Durability Metrics

FT Exposure Class	No FT exposure	FT exposure
Minimum specific surface, in.^{2}/in.^{3} (mm^2/mm^3)	None	600 (21)
Maximum spacing factor, in. (mm)	None	0.009 (0.23)
Minimum durability factor	None	90

Notes:

1. At least one FT durability test metric shall be passed according to the requirements by FT exposure class set forth in Table 3B. FT exposure class shall be determined by the Engineer.
2. Specific surface shall be calculated using results from tests conducted in accordance with ASTM C457/ASTMC457M.
3. Spacing factor shall be calculated in accordance with ASTM C457/ASTM C457M as average of three assessments from single mixture during construction, where no assessment for spacing factor is greater than 0.012 in. (0.30 mm) for FT concerns. Note that with values for air content, paste fraction, and specific surface, spacing factor may be calculated.
4. Durability factor measured shall be calculated in accordance with ASTM C666/C666M, by either Procedure A or B, as an average of three separate specimens that are representative of same concrete mix.

5. **Table 4A—Sulfate Exposure Class**

Sulfate Exposure Class	Water soluble sulfate in soil, % by mass	Dissolved sulfate in water, ppm
S0	$SO_4 < 0.10$	$SO_4 < 150$
S1	$0.10 \leq SO_4 \leq 0.20$	$150 \leq SO_4 \leq 1,500$
S2	$0.20 \leq SO_4 \leq 2.00$	$1,500 \leq SO_4 \leq 10,000$
S3	$SO_4 > 2.00$	$SO_4 > 10,000$

Notes:

1. Water soluble sulfate in soil shall be determined in accordance with AASHTO T290.
2. Dissolved sulfate in water shall be determined in accordance with ASTM D516.

Table 4B—Sulfate Attack Durability

Sulfate Exposure Class	Cement Designation	Maximum w/cm	Minimum f'_c psi (Mpa)	Performance requirements expansion in ASTM C1012 (maximum %)		
				6 month	12 month	18 month
S0	No Requirements					
S1	Performance Requirement Only	0.55	3500 (25)	0.05	0.10	-
	Type II or Type MS-designated blended cements	0.50	4000 (25)	0.10	-	-
	No restriction	0.45	4500 (32)	-	-	-
S2	Performance Requirement Only	0.50	4000 (25)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.45	4500 (32)	0.05	0.10	-
	Type II or Type MS	0.40	5000 (35)	0.10	-	-
S3	Performance Requirement Only	0.45	4500 (32)	-	0.05	0.10
	Type V or Type HS-designated blended cements	0.40	5000 (35)	0.05	0.10	-

Notes:

1. Sulfate attack refers to conditions where sulfate-rich environments causes chemical reactions with hardened cement paste forming expansive products which cause cracking and premature failure. Sulfate exposure class shall be determined by the Engineer.
2. Mix designs under the same sulfate exposure class shall conform either to performance limits determined by cement usage or performance requirements. Utilizing designated cements reduces the performance requirements.
3. Cement Types II and V refer to cements that meet requirements in AASHTO M85/ASTM C150.
4. Type MS refers to hydraulic cements that meet the requirements for MS designation in AASHTO M240/ASTM C595. Type HS refers to blended cements that meet the requirements for HS designation in AASHTO M240/ASTM C595.
5. Where hydraulic cement and SCMs are combined at the concrete mixer, it shall be demonstrated that the blend meets the performance requirements listed in ASTM C1012.
6. If Type V cement is used as the sole cementitious material for a S3 exposure class, an optional sulfate resistance requirement of 0.04% maximum expansion (when tested in accordance with ASTM C452) shall be

in force.

Table 5—Structure Importance/Type

Structural Importance	Definition
T1	Minor risk of reinforcement corrosion can be tolerated
T2	Reinforcement corrosion cannot be tolerated; non-environmental structures
T3	Reinforcement corrosion cannot be tolerated; environmental structures

Note:

1. Definitions for structural importance not inclusive or representative of all circumstances potentially encounterable. The Engineer shall determine most applicable category by project requirements.

Table 6—Water Soluble Chloride Matrix

Chloride Exposure Class	Structural Importance	Chloride limits for new construction (% by mass of cementitious material)	
		Water-soluble (ASTM C1218/C1218M)	
		Reinforced Concrete	Prestressed concrete
C0 - Concrete in dry environment	T1	1.00	0.06
	T2	0.25	0.06
C1- Concrete exposed to moisture but not to external sources of chlorides in service	T1	0.30	0.06
	T2	0.15	0.06
C2 -Concrete exposed to moisture and an external source of chlorides from deicing chemicals, salts, brackish water, seawater, or spray from these sources in service	T1, T2	0.15	0.06
C3 - Concrete exposed to severe exposure conditions, including concentrated chemicals, wetting-and-drying cycles, FT cycles	T2, T3	0.10	0.06

Notes:

1. Water soluble chloride refers to chlorides in concrete that are not bound and have the ability to accelerate corrosion within reinforced or prestressed concrete.
2. Total cementitious material includes both hydraulic cement and all SCMs.
3. Dry environment corresponds to maximum relative humidity of 60%, normally found in interior of buildings.

Special Consideration for Self-Consolidating Concrete

Self-consolidating concrete (SCC) has applications in precast/prestressed concrete production. SCC may be used in Class AAA concrete for a precast application or in other applications with approval of Engineer. The Engineer, Contactor, and Producer shall note the additional requirements presented in Table 7. SCC shall be regulated under the durability requirements from Tables 2A through 6 with the exception of slump requirements. The requirements for SCC in Table 7 shall be in addition to those in Tables 2A through 6. Submit a mix design for approval to the Office of Materials and Testing. Include the sources, actual quantity of each ingredient, fine and coarse aggregate gradations, including gradation curves, design slump flow, design air and laboratory results that demonstrate the ability of the design to attain both the required compressive strength and chloride permeability. A SCC mix design shall be qualified if the requirements in Tables 2A through 6 are meet (except for slump) and Table 7.

Table 7—Self-Consolidating Concrete Requirements

SCC Properties	Test	Standard Testing Method	Acceptance Criteria
Filling Ability	Slump Flow	AASHTO T347	Minimum = 20 in Maximum = 29 in
Passing Ability	J-Ring	AASHTO T345	Difference between slump flow and J-ring Flow ≤ 2.0 in
Static Segregation	Column Segregation	ASTM C1610	S ≤ 15%
	Rapid Assessment of Static Segregation	ASTM C1712	Pd ≤ 15 mm
	Visual Stability Index	ASTM C1611	VSI ≤ 1
	Hardened Visual Stability Index	AASHTO R81	HVSI≤1

Notes:

1. Filling ability shall supplant slump requirements for SCC.
2. SCC shall meet the acceptance criteria for at least one of the tests for each of the three SCC properties: filling ability, passing ability, and static segregation. The Contract shall note which test was utilized for each SCC property.
3. The Contractor may use Type F or G high range water-reducing admixtures in combination with water-reducing admixtures or mid range water-reducing admixtures in the production of SCC/HPC-SCC for

prestress/precast products at the discretion of OMAT Concrete Branch.

4. Ensure that the SCC mix meets the requirements of Subsection 500.1.03.A.4 and that water-reducing admixtures meet the requirements of Subsection 831.2.02, "Chemical Admixtures for Concrete".

Submit all concrete mix designs to the Office of Materials and Testing (OMAT) for review. The Department will approve mixes that contain materials from approved sources and produce concrete that meets these Specifications.

Submit concrete mix design proportions for approval by one of the following methods:

1. Request Approval of Specific Proportions

   When requesting approval of specific concrete mix design proportions for classes of concrete, include the following information:

   - Source of each material
   - Apparent specific gravity of the cement and ~~the fly ash~~SCMs, if used
   - Bulk specific gravity (saturated surface dry) of each aggregate
   - Percent absorption of each aggregate
   - Amount of each material required to produce a cubic yard (meter) of concrete
   - Proportions of admixtures per cubic yard (meter) of concrete and any use limitations
   - Proposed slump and air content of the design
   - Evidence that the proposed mixture complies with Subsection 500.1.03, .

   Concrete mix designs that do not have a proven performance record and have not been used by the Department must meet minimum laboratory strength requirements~~.~~ A mix that has previously qualified for a specific collection of exposure classes shall remain qualified. Mixes shall require requalification if a material or proportion changes. A waiver for requalification for a mix design from GDOT may be requested. Concrete mix designs shall only be utilized for sites and applications as approved by the Engineer. Laboratory tests for mix qualification shall be performed by a lab accredited by the CCRL.

2. Obtain Ready-Mix Design Proportions for commonly used materials

   Get approved concrete mix designs from authorized ready-mix concrete plants.

   Ready-mix concrete plants approved according to Laboratory Standard Operating Procedure "Quality Assurance for Ready Mix Concrete Plants in Georgia" (SOP 10) are authorized to submit concrete mix designs for approval. See QPL 10 for a list of approved plants.

3. ~~Use Laboratory-Designed Proportions for commonly used materials~~

   ~~Use laboratory-designed concrete mix proportions from either of the following sources:~~

   ~~a. Laboratory-designed proportions are available for commonly used combinations of materials. Request these mixes in writing from the Engineer. Request specific classes of concrete and specify the source of ingredients.~~

   ~~b. Select a combination of materials from approved sources and request that the laboratory determine a mix that meets requirements in the Table 1—Concrete Mix Table above. The laboratory will establish proportions for strength and workability under laboratory conditions~~

B. Delivery Tickets

Have the concrete plant transmit delivery tickets (DOT Form 525) with each load of concrete delivered to the work site. Give the Engineer one of these delivery tickets.

Ensure that the following information is on the delivery ticket:

- Project designation
- Date
- Time
- Class and quantity of concrete
- Actual batch proportions
- Free moisture content of aggregates
- Quantity of water withheld

C. Formwork Plans

- Concrete mixing revolutions

If available forms do not provide the required information, ask the Engineer to provide one.

The Engineer may require detailed formwork plans for review. If so prepare the formwork plans and submit them to the Engineer. In no case will the Contractor be relieved of responsibility for the formwork plans.

When constructing permanent steel bridge deck forms, submit bar support details and types to the Department for approval before placing the deck form reinforcement.

D. Falsework Plans

Submit, for review by the Engineer, detailed falsework plans for spans under which traffic flows.

The Engineer may require plans for spans that do not accommodate traffic.

E. Shop and Erection Drawings

Submit fabricators' shop and erection drawings to the Engineer for review and approval. Indicate the following in the drawings:

- Grade of steel
- Physical and section properties for permanent steel bridge deck form sheets

- Locations where the forms are supported by steel beam flanges subject to tensile stresses

F. Hauling Vehicle Information

Before hauling starts on new bridges, submit the following information for each vehicle:

- Weight on each axle, empty
- Weight on each axle, fully loaded
- Center-to-center distances of axles
- Center-to-center distances of wheels measured parallel to each axle

G. Cold Weather Concrete Curing and Protection Plan

Secure the Engineer's approval of a "Cold Weather Concrete Curing and Protection Plan" for bridges and structures. Emphasize protection for the underside of bridge decks when using metal forms and include the protection procedures to be used.

Protection procedures shall keep the concrete above 50 °F (10 °C) for 72 hours after placement and above freezing for 6 days after placement. Choose the protection method from Table 28 based on the expected temperature within 48 hours after concrete placement. The contractor shall provide a suitable curing box for structural concrete to protect the cylinders. The box may be constructed of plywood and lined with insulation or a commercially made device.

TABLE 28—COLD WEATHER PROTECTION

Protection Procedure	Expected Temperatures Within 48 Hours
Heated enclosures	Below 25 °F (-4 °C)
Commercial blankets	Below 25 °F (-4 °C)
Batt insulation	Below 25 °F (-4 °C)
Heavy-duty polyethylene	25 °F (-4°C) or above

H. Color Additives

Submit to the Engineer the following:

1. Product Data: Manufacturer's specifications and instructions for color additives.

Samples for Concrete Color Selection: Submit sample chip of specified color indicating color additive number and required dosage rate. Submittals are for general verification of color.

500.2 Materials

Ensure that materials meet the Specification requirements of Table ~~3~~9:

TABLE 9~~3~~—MATERIALS SPECIFICATIONS

Material	Section
Coarse Aggregate (1)	800.2.01
Fine Aggregate Size No. 10	801.2.02
Damp proofing or Waterproofing Material (Bituminous)	826.2.01
Portland Cement and Blended h~~H~~ydraulic Cement (Type IL Portland-limestone cement) (2)	830.2.01
Portland-Pozzolan Cement (2)	830.2.03
Admixtures:	
Air-Entraining Admixtures	831.2.01
Retarding Admixtures	831.2.02
Water Reducing Admixtures	831.2.02
Granulated Iron Blast-Furnace Slag	831.2.03.A.3
Fly Ash, Raw and Natural Calcined Pozzolan, Slag, and Microsoilica	831.2.03~~.A.1~~
Curing Agents	832
Joint Fillers and Sealers	833
Special Surface Coating	836
Linseed Oil	870.2.06.A.1&2
Mineral Spirits	870.2.06.A.4
Water	880.2.01
Graded Aggregate (3)	815.2.01
Graffiti Proof Coating	838.2.01
Concrete used in Bridge Construction	500.3.04.F

1. Use either Class A or Class B coarse aggregate of the designated size, except when using limestone or dolomite in bridge structures. When using limestone or dolomite, use Class A coarse aggregate.

2. ~~Use Type I or Type II Portland cement, Blended Hydraulic Cement (Type IL Portland-limestone cement or Type IP Portland-Pozzolan cement) unless otherwise specified.~~ Hydraulic cement that complies under AASHTO M85/ASTM C150 or ASSHTO M240/ASTM C595. ~~Do~~Do not use air-entraining cement.

3. The gradation requirements of graded aggregate are modified to require 30% to 45% by weight passing the No. 10 (2.00 mm) sieve.

Construct bridge sections containing duct enclosures for stressing tendons using concrete with a maximum stone size of No. 7.

Use concrete manufactured at plants that qualify as approved sources according to the Standard Operating Procedure for Ready Mix Concrete (SOP 17). See QPL 10 for a list of approved plants.

Use colored concrete additive made with pure, concentrated mineral pigments especially processed for mixing into concrete and complying with ASTM C 979.

If adding color additives to the mix at the jobsite, furnish color additives in pre-measured Mix-Ready disintegrating bags to minimize jobsite waste.

Do not use accelerator admixtures containing calcium chloride in colored concrete mix.

500.2.01 Delivery, Storage, and Handling

A. Aggregate Stockpile

Stockpile aggregate as follows:

1. Keep stockpile areas firm, reasonably level, well-drained, clean, and free of sod or foreign matter.
2. Stockpile aggregate separately by type and source.
3. Form stockpiles using methods and equipment that do not cause the aggregate to segregate, become contaminated, or degrade. The Engineer may reject improperly formed stockpiles.
4. Stockpile aggregate long enough for the moisture content to stabilize.
5. Do not use aggregates stored in pits or silos that contain water.

B. Aggregate Handling

Operate aggregate handling equipment carefully to minimize segregation, breaks, spills, contamination, and mixing of the sizes and types of aggregates.

C. Cement Storage

Store cement as specified below. Reject all caked, lumpy, or contaminated cement.

1. Bulk Cement

   Use bulk cement unless the Engineer allows bag cement to be used.

   Store bulk cement in bins or silos designed for this purpose. Provide moisture-proof storage containers with a mechanism that allows cement to flow freely from the discharge opening.

2. Different Brands

   Store and use cement of different brands and types, or from different mills separately.

D. Admixture Storage and Handling

Carefully store and dispense admixtures as recommended by the manufacturer to prevent contamination.

E. Concrete Handling and Placing

Handle and place concrete according to the following:

1. Haul Time Limitations

   Ensure that concrete reaches its final position in the forms within one hour after adding the cement to the aggregates.

   If retarders or water reducers are used, the allowable time limit increases to 1-1/2 hours. Test concrete immediately for acceptance tolerances before placing in forms using limits established in Table 1—Concrete Mix Table.

2. Placement Limitations

   After delivering the concrete to the job site or the staging area at the site or after mixing the concrete at the site, transport it carefully to the placement point to prevent excessive slump loss or segregation. Use any of the following equipment:

   - Buckets
   - Buggies
   - Pumps
   - Other approved means Store forms off the ground

F. Form Storage

Except as noted below, the applicable portions of Subsections 507.2.01,*"Delivery, Storage, and Handling,"* 507.3.05.A, *Prepare Bearing Areas*, 507.3.05.B, *Erecting PSC Bridge Member* and 507.3.05.D, "*Concrete Finish*, shall govern.

G. Precast Unit Handling

Handle precast, non-prestressed units as follows:

1. Do not lift the units from the casting bed until the concrete reaches a strength of at least 1,500 psi (10 MPa).
2. Do not transport or erect the units until they reach a strength of at least 3,000 psi (20 MPa).
3. Restrict live loads (including erection equipment) on the units until they reach a minimum strength of 4,500 psi (30 MPa).

H. Color Additives

Comply with manufacturer's instructions. Deliver to site or batch plant in original, unopened packaging. Store color additives in dry conditions.

500.3 Construction Requirements

500.3.01 Personnel

A. Supervision, Personnel, and Skilled Workers

Provide enough supervision, personnel, and skilled workers to do the following:

1. Properly produce, place, and finish concrete in each pour unit according to Subsection 500.3.05.P, Table ~~5~~11— Minimum Placement Rates or as required by the Plans.
2. Check screed clearances and tolerances before beginning deck pours.
3. Place concrete without delays.

B. Plant Operator Certification

Volumetric proportioning requires that the operator be certified by the Office of Materials and Testing. The volumetric truck may be approved on a per project basis or listed on the Qualified Products List (QPL-100).

500.3.02 Equipment

A. Equipment Restrictions

Do not use delivery, conveyance, or vibratory units that leak grout, water, oil, or gas.

Provide enough equipment, tools, and materials to properly produce, place, and finish concrete in each pour unit according to the Subsection 500.3.05.P, Table 511–Minimum Placement Rates or as required by the Plans.

The Engineer may prohibit equipment that delays concrete placement.

B. Volumetric Proportioning Equipment

When concrete ingredients are proportioned volumetrically, equipment needs to be listed on QPL-100 or obtain the Engineer's approval for the equipment and its calibration and operation.

Ensure the following:

- The equipment meets the specifications in ASTM C 685.
- The concrete producer conducts calibration tests at least every 6 months.
- The equipment is calibrated for each new concrete mix before production.

C. Batching Plant Equipment

Ensure that batching plants have the following equipment and that the equipment meets the standards listed.

1. Bins

   Ensure that bins and bin compartments meet the following standards:

   - Adequate capacity for the required concrete production
   - Supported on a rigid framework on a stable foundation capable of holding the bins securely
   - Designed to discharge efficiently and freely into the weigh hopper
   - Positive means of control that slows down and shuts off the material flow when the weigh hopper has the correct quantity.

- Discharging mechanisms that prevent material leaks when closed
- Leak-free aggregate storage bins
- Divided aggregate storage bins for fine aggregate and each size of coarse aggregate
- Partitioned aggregate storage bin compartment that prevents the materials from mixing
- Leak-proof, moisture-proof cement bins with a vibrator or other mechanism to discharge cement

2. Weigh Hoppers

Ensure that weigh hoppers meet the following standards:

- Have suitable containers freely suspended from scales
- Have adequate capacity to maintain the Subsection 500.3.05.P, Table ~~5~~11—Minimum Placement Rates
- Have a discharge mechanism that prevents material leaks when closed
- Have vents to permit air to escape
- Have vibrators or other equipment that ensures complete and efficient discharge of materials
- Have a dust seal and a port or valve for sampling cement

3. Scales

Scales used for weighing concrete materials shall have accuracy within plus or minus one percent under operating conditions.

Ensure the following:

- When directed by the Engineer, the owner demonstrates the accuracy of the scales.
- Scales are kept clean and in good operating condition.
- The scale operator can clearly see indicating devices.
- The scale operator can easily access controls.

D. Mixers and Agitators

Ensure that mixers and agitators meet the following requirements:

1. General Requirements for Mixers and Agitators

Provide mixers and agitators that meet these requirements:

a. Capacity Plates

Ensure that the mixer or agitator has a legible metal plate or plates attached in an easily visible location. The plates shall indicate the rated capacity in cubic yards (meters) for mixing and agitating.

b. Concrete Production

The mixer shall produce concrete that meets the requirements in the Table 1—Concrete Mix Table.

c. Mixer Performance Test

The mixer or agitator may be required to pass a mixer performance test. Mixer performance will be evaluated at the discretion of the Engineer.

Mixer performance tests will include the following by the OMAT:

1) Taking samples of concrete at the one-quarter and three-quarter points of the batch discharge
2) Measuring the slumps of each concrete sample

If the two slump values differ by more than 2 in. (50 mm), do not use the mixer or agitator until it meets the requirements of the test.

The Engineer may permit the equipment to be used if the 2 in. (50 mm) tolerance can be met by using a longer mixing time or a smaller batch.

2. Mixing Speed

Follow these guidelines for mixing speed: when utilizing ready-mix concrete trucks with capacities of 8-12 yd3. For concrete trucks outside the 8-12 yd3 capacity range, consult with the Engineer: for additional requirements.

- Do not exceed 150 revolutions at mixing speed.
- Discharge all concrete from truck mixers before drum or blades reach 300 revolutions, including revolutions at agitating speed or minutes have passed since first wetting. If more than 300 revolutions or 90 minutes are required, a test pour simulating the expected delays is required. A test pour shall replicate the expected conditions for the pour including the total mixing time, travel time from the batch plant, and expected additional time prior to final placing of concrete. The results of the test pour shall be approved by the Engineer. Results should confirm concrete

properties are not detrimentally affected by increasing mixing time.

- Use the mixing speed defined by the manufacturer for the mixing equipment.
- If the manufacturer's definition of mixing speed is not available, use a mixing speed of 6 to 18 revolutions per minute.

3. Mixer and Agitator Maintenance

Maintain mixers and agitators as follows:

- **a.** When mixers and agitators are discharged, remove the entire contents before adding materials for the next batch.
- **b.** Clean mixers and agitators often to prevent concrete and grout accumulation.
- **c.** Do not discharge cleaning water into any pipe, catch basin, or structure.
- **d.** If cement or aggregates accumulate in mixers and agitators when cleaning water is discharged, remove them immediately at no expense to the Department.

4. Mixer Types

Use stationary mixers or truck mixers.

- **a.** Stationary Mixers
  - **1)** Combine the concrete ingredients into a homogeneous, uniform mass within the specified time and when loaded to capacity.
  - **2)** Efficiently and uniformly discharge the concrete within the tolerances allowed in Subsection 500.3.02.D.1.c, *Mixer Performance Test*.
  - **3)** Permit discharge only after the specified mixing time has elapsed using a locking device.
- **b.** Truck Mixers
  - Meets the requirements listed in Subsection 500.3.02.D.4.a, *Stationary Mixers*
  - Has an approved revolution counting device in good operating condition
  - Does not haul more than the rated capacity in cubic yards (meters) as shown on the attached capacity plates

5. Agitator Types

Use truck agitators or truck mixers operating at agitating speed.

Ensure that agitators meet the following requirements:

- **a.** Keeps the mixed concrete in a homogeneous, uniform mass
- **b.** Efficiently and uniformly discharges the concrete within the tolerances allowed in Subsection 500.3.02.D.1.c, *Mixer Performance Test*

E. Concrete Buckets

Keep concrete buckets clean and in good working condition.

F. Concrete Buggies

Keep concrete buggies clean and in good working condition.

G. Concrete Pumps

Concrete pumping equipment is subject to the Engineer's approval. Use pumping equipment that has adequate capacity and is suitable for the proposed work.

H. Chutes and Troughs

Do not use chutes longer than 50 ft. (15 m) without the Engineer's permission.

Flush chutes and troughs with water after each run. Do not discharge this water into freshly placed concrete or into conveyance unit.

Promptly remove hardened concrete from chutes and troughs.

Ensure that chutes and troughs meet the following requirements:

1. Metal or metal lined

2. Slope not exceeding one vertical to three horizontal

3. Baffles or a series of short lengths placed to reverse the direction of the concrete flow, when used on

I. Pipes or Tubes

steep slopes

Use pipes or tubes to place concrete when the operation requires dropping the concrete more than 5 ft. (1.5 m). Thoroughly clean the pipes or tubes after each pour.

Use pipes made of metal or other approved material and long enough to deposit the concrete as close to its final position as possible.

Provide enough vibratory units, including at least one additional stand-by unit in good working condition, to compact concrete immediately after it is placed. Have a stand-by unit at the site before each pour is started.

On Projects consisting entirely of small pours (10 yd^3 [8 m^3] or less), the Engineer may waive the stand-by requirement.

Ensure that vibrators meet the following conditions:

- Approved internal rotation-type design
- A power supply that constantly vibrates the concrete at frequencies of not less than 4500 impulses per minute
- A vibration intensity that visibly affects a mass of concrete with a 1 in. (25 mm) slump through at least a 18 in. (460 mm) radius

K. Screeds

Do not use vibratory screeds (screeds that use a transverse strike-off motion) without the Engineer's approval.

Use screeds that are:

- Mechanically operated
- Designed and constructed to screed with the strike-off parallel to the center line
- Readily adjustable
- Capable of maintaining proper adjustment throughout the screeding operation

The two screed types are:

1. Longitudinal Screeds

   Unless otherwise noted on the Plans, use longitudinal screeds only on pour lengths of 70 ft. (20 m) or less.

2. Transverse Screeds

   Use transverse screeds on any pour, unless otherwise noted on the Plans. However, transverse screeds are required on pour lengths above 70 ft. (20 m).

Support screeds outside the pour area that will receive a surface finish. Do not use intermediate supports or guides.

Adjust screeds to the camber specified on the Plans. Check the camber as often as necessary.

Have the Engineer approve the following for screeds and their supports:

- Weight
- Durability
- Adjustability
- Accuracy
- Mechanical condition
- Operational results

Furnish the equipment necessary to check screed clearances and tolerances before pouring decks.

L. Underwater Placement Equipment

Place concrete under water using the following underwater placement equipment:

1. Tremie

   Use a tremie when depositing concrete in water above 10 ft. (3 m) deep. Ensure that tremie is:

   - At least 8 in. in (200 mm) diameter
   - Constructed in sections with watertight couplings

2. Bottom Dump Bucket

Where the Engineer permits, use a bottom dump bucket in water up to 10 ft. (3 m) deep.

Ensure that the bottom of the bucket opens only when it touches the surface that receives the charge and that the top of the bucket has a lid or cover.

To supply additional moisture to the concrete, use fogging equipment with the following characteristics:

- A heavy-duty pump capable of delivering 2-gal (7.6 L) of water per minute to a 0.062 in. (1.6 mm) diameter tip at an air pressure of 100 psi (700 kPa).

  An example of a suitable pump is the Alemite Pump 7878-A.
- The ability to consume approximately 22 ft³/min. (0.6 m³/min) of compressed air
- A 3/8 in. (10 mm) inside diameter hose long enough to reach all areas of the deck
- An adjustable spray gun and tip to provide various patterns of atomized spray or fog for changing finishing conditions

  An example of a suitable spray gun is the Gun Jet No. 43 with a 120-2 Multi Jet Nozzle.

If necessary, substitute other equipment that is capable of equal performance.

500.3.03 Preparation

A. Pre-Pour Conference

Before beginning deck placement operations on each Project, and for individual deck pours of an unusual nature, the Engineer will schedule a pre-pour conference with Project supervisory personnel, and a representative of the concrete supplier, if applicable. Project supervisory personnel will coordinate with a representative from the Concrete Branch of OMAT.

Conference topics of discussion include the following:

- Reinforcing steel support method
- Final screed setting check
- Anticipated placement rate
- Personnel number
- Equipment type
- Curing methods
- Adverse weather placement procedures
- Emergency procedures
- Other Work-related details

500.3.04 Fabrication

A. Measure Materials

Measure materials as follows:

1. **Cement.** Weigh bulk cement on scales to plus or minus one percent of the designated weight. If the Engineer allows bag cement, proportion the batch to use only whole bags.
2. **Aggregates.** Weigh all aggregates on scales to plus or minus two percent of the designated weight. Apply the proper corrections for aggregate surface moisture.
3. **Water.** Measure water by volume or weight to within plus or minus one percent.
   a. Construct the measuring system to be independent of water pressure fluctuation.
   b. Ensure that measuring systems have outside taps and valves to facilitate plant calibrations.
   c. You may use recycled wash water provided that it meets the requirements of Subsection 880.2.02.
4. **Admixtures.** Measure admixtures by weight or volume within plus or minus three percent of the required amount.

B. Control Concrete Batching

Control batching as follows:

1. Mix batches of concrete according to the proportions of an approved mix design.

C. Prestressed Concrete Deck Panel Requirements

2. Ensure that concrete materials are from the designated sources.
3. Correct the batch weights to account for surface moisture in aggregates.
4. Conduct batching control tests according to the procedures in the Sampling, Testing, and Inspection Manual.

Do not use prestressed concrete deck panels unless approved by the Engineer.

D. Add Admixtures to Concrete

Additives are required when specified herein or as directed by the Engineer.

1. Air-Entraining Admixtures

   a. All bridge structure concrete uses air-entraining additives, except for seal concrete and non-exposed footings.
   b. The Contractor may use air-entraining additives in other concrete to improve workability when job or material conditions dictate.

   When using air-entraining additives as an option to improve workability or when required, do not exceed the upper limit of the entrained air content requirement in the Table 1—Concrete Mix Table.

2. Retarding Admixtures

   Use concrete-retarding additives in bridge concrete when the average temperature is above 65 °F (18 °C) (the average of the expected high and the predicted low).

   a. Retarders shall meet requirements for AASHTO M194 (ASTM C494) D admixtures.
   b. Normally, concrete-retarding additives are not required for bridge curbs, handrails, crosswalks, or other appurtenances constructed separately from the decks.
   c. The Engineer may waive the use of retarders in substructure concrete when concrete can be placed within one hour after batching.

3. Water-Reducing Admixtures

   The Contractor may use water-reducing admixtures in Class AA or Class D concrete for bridge decks when conditions do not require a retarder. The Contractor may use water-reducing admixtures in other concrete when job or material conditions dictate a reduction in water requirements or when minimal set retardation is desired.

   The laboratory may allow Type F water-reducing admixtures when the Contractor requests it. The Contractor may construct bridge sections containing duct enclosures for stressing tendons with concrete using Type F (AASHTO M 194/ M 194M) water reducer as approved by the laboratory.

4. Viscosity Modifying Admixtures

   The Contractor may use viscosity modifying admixtures (VMA) to attain the desired SCC performance.

   When using a VMA, ensure that the SCC mix meets the requirements of Subsection 500.1.03.A.4 and that the VMA causes no harmful effects in the hardened concrete.

   Chemical admixtures may be used to increase the slump of the concrete if this is shown on the approved mixture design. Chemical admixtures may be used to alter the slump flow and stability of self-consolidating concrete if these admixtures are shown on the approved mix design sheet.

~~4. Fly Ash~~

~~The Contractor may use fly ash as an additive in concrete to promote workability and plasticity. The Contractor may use fly ash as a partial replacement for Portland cement in concrete if the following limits are met:~~

~~a. Replace no more than 15 percent of the cement by weight.~~
~~b. Replace cement with fly ash at the rate of 1.0 to 1.5 lbs. (1.0 to 1.5 kg) of fly ash to 1.0 lb. (1.0 kg) of cement.~~
~~c. Ensure that the fly ash mix meets the requirements of Subsection 500.1.03.A, Subsection 830.2.03, *Portland Pozzolan Cement* and Subsection 831.2.03.A, *Fly Ash*.~~
~~d. Calculate water-cement ratio based on the total cementitious material in the mix including fly ash.~~
~~e. Do not use Type IP cement in mixes containing fly ash.~~

~~5. Granulated Iron Blast-Furnace Slag~~

~~If high-early strengths are unnecessary, the Contractor may use granulated iron blast-furnace slag as a partial replacement for Portland cement in concrete if the following limits are met:~~

~~a. Replace no more than 50 percent of the cement by weight.~~

~~b. Replace the cement with slag at the rate of 1.0 lb. (1.0 kg) of slag to 1.0 lb. (1.0 kg) of cement.~~

~~c. Ensure that the slag mix meets the requirements of Subsection 500.1.03.A.3, Subsection 830.2.02, *Portland Blast-Furnace Cement* and Subsection 831.2.03.A.3, *Granulated Iron Blast-Furnace Slag*~~

~~d. Calculate the water-cement ratio based on the total cementitious material in the mix including granulated iron-blast furnace slag.~~

~~e.~~ a. ~~Do not use Type IP cement or fly ash in slag mixes.~~

~~6.~~ **Supplementary Cementitious Materials (SCMs)**

a. Ensure SCMs meet the requirements in section 831.

b. Ensure a concrete mix design utilizing SCMs meets the requirements in subsection 500.01.03.

c. Replace cement by weight with SCMS as needed to meet requirements for durability and workability.

d. Calculate the water-cementitious (w/cm) ratio based on the total cementitious material in the mix including hydraulic cement and all other SCMs. SCMs may be blended in any combination to replace hydraulic cement with mix designs not limited to a single SCM.

E. Mix Concrete

~~6.~~5. Central-Mixed Concrete

Mix central-mixed concrete as follows:

a. Establish the mixing time.

The Engineer will determine the mixing time for central mixed concrete, but the minimum mixing time will be one minute for stationary mixers of up to 1 yd³ (1 m³) capacity. Mixing time may be adjusted in the following situations:

- The Engineer will increase the minimum time by 15 seconds for each additional cubic yard (meter) or fraction thereof.
- For mixers with a capacity above 3 yd³ (2 m³), the minimum mixing time may be 90 seconds if the resulting mixture is homogeneous and meets the requirements of Subsection 500.3.02.D.1.c, *Mixer Performance Test*.
- The Engineer may waive mixing time requirements for stationary mixers of improved types or new designs that produce homogeneous concrete in less time than that established for a particular capacity by the foregoing. For these types of mixers, the Engineer may establish a minimum mixing time of one minute.

b. Start the mixing time when all cement and aggregates have been placed in the mixer.

c. Add some water to the mixer before adding the cement and aggregates, but ensure all water is in the mixer by the end of the first 1/4 of the specified mixing time.

7. Shrink-Mixed Concrete

Mix shrink-mixed concrete as follows:

a. Mix the batches as specified in Subsection 500.3.02.D.2. *Mixers and Agitators*.

b. Do the initial mixing in a stationary mixer for at least 30 seconds to thoroughly mix the ingredients. Do the final mixing in truck mixers.

c. Discharge all concrete before the drum or blades exceed 300 revolutions.

d. Do not allow truck mixing at mixing speed to exceed 100 drum or blade revolutions except as allowed when adding water according to Subsection 500.3.05.M, *Add Water to Concrete*.

8. Transit-Mixed Concrete

Mix transit-mixed concrete as follows:

a. For concrete mixed completely in a truck mixer, place all concrete ingredients into the mixer at the concrete plant except the quantity of water that may be withheld according to Subsection 500.3.05.M, *Add Water to Concrete*.

b. After loading the truck, begin operating at either agitating or mixing speed; however, start the mixing speed within 30 minutes after loading the truck mixer.

c. Mix the concrete for 70 to 150 revolutions at mixing speed.

For revolutions above those specified for mixing speed, use agitating speed.

d. Discharge all concrete before exceeding 300 drum or blade revolutions. If additional rotations are required for jobsite conditions, perform a trial batch and pour under supervision of Engineer to ensure concrete properties are not affected.

9. Colored-Mixed Concrete

- **a.** Proportion, batch and mix color additives in accordance with manufacturer's instructions. Mix until color additives are uniformly dispersed throughout mixture and disintegrating bags, if used, have disintegrated.
- **b.** If mixed at batch plant, schedule delivery of concrete to provide consistent mix times from batching until discharge.

1. Requirements

~~Use Type I or Type II Portland cement, Type IL Portland-limestone Cement or Type IP Portland-Pozzolan cement for bridge construction, unless otherwise specified.~~ Use hydraulic cement conforming to AASHTO M85/ASTM C150 or AASHTO M240/ASTM C595. Admixtures or SCMs that conform to section 831 may be included for bridge construction. Ensure hydraulic cement concrete meets requirements in subsection 500.01.03.

NOTES:

1. **Do not use air-entraining cement.**
2. **Do not use accelerators (24-hour accelerated strength concrete) that contain chlorides in any bridges where the concrete containing the additive will contact the reinforcing steel.**
3. **Type IL ~~Portland~~hydraulic-limestone Cement may be used anywhere that Type I or Type II ~~Portland~~hydraulic cement is specified.**

Concrete Types: Use the tabulated results from the Table 1—Concrete Mix Table for the classes and specific requirements for each class of concrete. Use the appropriate class of concrete shown in the Plans or specifications for each component of a structure, of the type as follows:

- **a.** Class AAA–Prestressed concrete and precast concrete as called for on the plans.
- **b.** Class AA1–Precast concrete as called for on the plans

  If approved by the Engineer, you may use this class as high early-strength concrete and may use any of the following: Type III (ASTM C150), or Type HE (AASHTO M240/ASTM C595) cement in concrete used for this purpose.

  The Engineer may also specify the rate of compressive strength development when this concrete is used

NOTE: The Department will not add compensation to the Contractor for Class AA1 concrete when it is used at the request of the Contractor.

- **c.** Class D – Bridge superstructure concrete as called for on the plans.
- **d.** Class AA–Bridge concrete, cast in place concrete, or precast concrete as called for on the plans
- **e.** Class A–General purposes

NOTE: Do not air-entrain Class A concrete deposited in water (seal concrete). Ensure that the concrete has 10 percent additional cement and sufficient water to provide a 6- to 8-in. (150- to 200-mm) slump.

- **f.** Class B–Massive sections or lightly reinforced sections or miscellaneous non-structural concrete
- **g.** Class CS– (~~Portland~~Hydraulic cement concrete subbase). Use this class as a subbase where required by the Plans. Concrete subbase may be composed of a mixture of ~~Portland~~hydraulic cement and graded aggregate or ~~Portland~~hydraulic cement, aggregate, and sand.

2. Acceptance of Design

Determine laboratory acceptance strength by at least 8 compressive test specimens prepared and cured according to AASHTO R 39.

- **a.** Make the specimens from two or more separate trial batches.
- **b.** Make an equal number of specimens from each batch.
- **c.** Calculate the minimum average strength or acceptance strength (X) as follows:

$X = f'c + 2.0s$

Where:

f 'c = required minimum compressive strength for each class of concrete from the Table 1—Concrete Mix Table s = average standard deviation of all 28-day specimens made in the field representing concrete of a given class from all ready-mix plants

Use the standard deviations shown in Table 104:

Table 104—Standard Deviations for Calculating Acceptance Strength

Class of Concrete	Standard Deviation (s)	
	Psi	(MPa)
B	370	(2.5)
A	650	(4.5)
AA	620	(4.3)
O	590	(4.0)
AA1	540	(3.7)
AAA	500	(3.4)

500.3.05 Construction

A. Meet General Responsibilities

General construction responsibilities include:

1. Batch, mix, deliver, and place concrete according to the Specifications.
2. Have enough production and placement capacity to continuously mix, place, and finish the concrete in each pour unit during daylight hours.

   If necessary, place concrete at night when adequate lighting facilities exist, and the Engineer approves of the operations and facilities.
3. If a pour cannot be completed, do the following:
   a. Form an approved construction joint.
   b. Remove the partial pour.
   c. Take other remedial measures directed by the Engineer at no additional expense to the Department.
4. Schedule placement to minimize exposure of freshly poured concrete to potentially harmful drying elements such as wind and sun before curing materials are applied and protect freshly poured concrete from exposure to excess moisture and freezing for a minimum of 24 hours when such weather conditions exist.

B. Construct Falsework

Accept responsibility for the design, construction, protection, and performance of falsework. Repair or remove and replace (as the Engineer directs) concrete, other material, or portions of the structure that are damaged or destroyed due to falsework failure.

Construct falsework for prestressed post-tensioned concrete structures according to the Contract Special Provisions.

Construct falsework for structures other than post-tensioned box girders as follows:

1. Meet Design Criteria

   Ensure that falsework structural components that have similar functions in an individual permanent span have the same geometric properties and are made of the same materials.

   When designing and centering formwork, treat concrete as a liquid, and use the following weights:

   - 150 lbs./ft.^{3} (23.6 kN/m^3) for vertical loading
   - 85 lbs./ft.^{3} (13.4 kN/m^3) for horizontal loading
   - 75 lbs./ft.^{2} (3.6 kN/m^2) live load for deck placement operations

   Use the following falsework design criteria:

   - Design and construct falsework logically so the Bridge Design Office can analyze it using a commonly accepted structural design theory.
   - Avoid exceeding safe working values for material stresses.
   - Provide support for the imposed loads, without settling or deforming and a way to compensate for settlement, if it occurs.

2. Support Falsework

Support falsework using one of these methods:

- Support on piling driven and removed as directed
- Found on a footing approved by the Engineer

3. Construct Falsework

Construct and set falsework to provide the finished structure the specified camber and finished grade.

Place “telltales” at locations directed by the Engineer to observe how much the falsework settles.

C. Meet Form Design Criteria

Ensure that forms meet the following design criteria:

- Provide wet concrete and other loads and forces of construction support without bulging between the supports or bracing and without deviating from the lines and contours shown on the plans.
- Meet the design criteria for falsework in Subsection 500.3.05.B.1, *Meet Design Criteria*.
- Account for the use of retarded concrete.

Ensure that bracing, ties, and supports are placed accurately.

If the formwork appears to be inadequately supported, tied, or braced (before or during concrete placement), the Engineer may require that the Work stop until the defects are corrected.

D. Use Acceptable Form Materials

Except as noted, fabricate forms from the following materials:

- Lumber
- Plywood
- Metal
- Plastic
- Combinations of these

Use material free of defects that materially affect form strength or materially impair the accuracy or appearance of the concrete surface.

Use the form materials as follows:

1. Lumber Forms

Construct wood forms as follows:

a. Size and dress the lumber.
b. Use lumber at least 1 in. (25 mm) thick.
c. Use lumber for header forms used as screed supports and for curb face forms at least 2 in. (50 mm) thick.
d. Avoid using scrap material or doing patchwork.
e. Stagger all joints but those between abutting panels.
f. Line the lumber used to form outside vertical surfaces of exterior beams or girders with an approved form liner.
g. Use chamfer strips mill-produced from high-quality lumber, free of defects.
h. Dress and finish chamfer strips on all three sides.
i. Size chamfer strips to the proper dimensions.

2. Plywood Forms

Construct plywood forms as follows:

a. If plywood is the type made for general concrete forms and is at least 5/8 in. (16 mm) thick, use it in place of 1 in. (25 mm) thick lumber to construct forms, if necessary.
b. Ensure that plywood used to form open joints and to line forms is at least 1/4 in. (6 mm) thick.
c. When nailing plywood directly to form studs, do not space the studs more than 16 in. (400 mm) apart.
d. Use plywood in full sheets wherever practical. Do not do patchwork with small, irregular pieces.
e. Have the Engineer inspect and approve plywood sheet layout.

3. Metal or Plastic Forms

a. Construct metal or plastic forms as follows:

b. Use metal or plastic to form concrete only if the Engineer approves the forms and if the forms produce satisfactory results.

c. Use metal forms that produce finished concrete equal to or superior to concrete made from comparable wooden forms.

d. Countersink bolts and rivets in the surfaces of metal forms that touch concrete.

e. Grind welds smooth in the surfaces of metal forms to provide a smooth plane surface.

4. Other Material Uses

Use tempered fiberboard for form liners when necessary if it is at least 1/4 in. (6 mm) thick. Use tempered fiberboard 1/8 in. (3 mm) thick only to form open joints. Support the fiberboard with suitable spacers arranged properly.

Use approved synthetic materials for forming open joints and for other special uses, if necessary.

E. Construct Form Supports

Construct form supports using metal ties, anchors, and hangers as follows:

1. Construct supports that will remain in the finished concrete so they can be removed from the concrete face to a depth of at least 1 in. (25 mm) without damaging the concrete.
2. Weld form supports to girder or beam flanges in continuous or cantilever spans only in the flange areas which are in compression.
3. When ordinary wire ties or snap ties are permitted, cut them back at least 3/8 in. (10 mm) from the face of the concrete.
4. Design metal tie fittings that minimize the cavities made when they are removed. Fill all cavities after removing metal tie fittings.

F. Construct Temporary Forms

Construct temporary forms as follows:

1. Construct and maintain forms in a mortar-tight condition.
2. Construct forms so that they can be removed easily without damaging the concrete, unless using forms that will remain in place.
3. Build, line, and brace forms so that the formed concrete surface conforms with the dimensions, lines, and grades shown on the plans.
4. Build headwall forms for skewed pipe parallel to the roadway centerline or at right angles to the radius on curves. Construct headwall forms as follows:

   a. Lay enough pipe to extend through the headwall form.

   b. After the concrete is poured and hardened, carefully cut and dress the protruding pipe ends so no ragged edges remain.

   The Contractor may choose, as an alternate to the above method, to build a circular form that exactly fits the pipe circumference and face of the headwall form.

5. Construct form liner using plywood or other approved form liner as follows:

   a. Use form liner in large sheets. Do not do patchwork.

   b. Avoid irregular joint location in form liners.

   c. Have the Engineer inspect and approve the proposed liner layout.

6. Bevel forms at beam copings, girders, and other projections to ease removal.
7. Place chamfer strips to chamfer exposed edges of the concrete by the required amount. Use ¾ in. (19 mm) chamfers unless otherwise shown on the plans.
8. Patch with tin or other metal only in those areas of the superstructure lying between and including the inside faces of the exterior beams.
9. When shown on the plans, splice water stops to form continuous water-tight joints. Hold stops in position while placing concrete.
10. Immediately before erecting forms or just before placing bar reinforcement steel, coat forms with a clear oil or other bond breaker to keep concrete from sticking to the forms.

    a. Do not allow the substance to stain or soften the concrete surface.

    b. Do not apply by reaching or pouring through previously placed reinforcement steel.

11. Wait to place concrete in any form until the Department inspects and approves the form.

Inspection and approval does not diminish the responsibility to produce concrete surfaces free of warping, bulging, or other defects.

12. When removing forms, remove chamfer strips, blocks, and bracing.
13. Do not leave any part of a wooden form in the concrete.
14. If concrete surfaces do not meet finish specifications, correct the problems with the following steps, as directed by the Engineer:
    - Repair the defects using approved methods.
    - Remove and replace the affected portion of the work.

G. Reuse Forms

Reuse forms and form material in good condition and satisfactory as determined by the Engineer. Do not use forms or form materials that are warped, cracked, split, bulging, have separated plies, or have unsatisfactory form liner.

Ensure that used forms are mortar tight and produce a finished concrete equivalent to that produced by new forms.

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H. Construct Permanent Steel Bridge Deck Forms for Concrete Deck Slabs

Unless otherwise designated on the Plans, construct and use permanent steel bridge deck forms for concrete bridge deck slabs according to these Specifications. Do not use permanent steel bridge deck forms in panels where longitudinal deck construction joints are located between stringers.

Provide a structurally satisfactory slab when using permanent steel bridge deck forms.

1. Fabricate permanent steel bridge deck forms and supports from steel that conforms to ASTM A 653/653M Designation SS, Grade 80/550, Coating Designation G-165/Z-500 and ASTM A 924/924M.
2. Design permanent steel bridge deck forms as follows:
    a. Account for the dead load of the following:
        - Form
        - Reinforcement steel
        - Plastic concrete
    b. Add 50 lbs./ft^2 (2.4 kN/m^2) for construction loads.
    c. Ensure that the unit working stress in the steel sheet does not exceed 0.725 of the specified minimum yield strength for the material furnished. However, do not allow the unit working stress to exceed 36,000 psi (250 MPa).
    d. Account for deflection under the weight of the forms, the plastic concrete, and the reinforcement as follows:
        1) If deflection exceeds 1/180 of the design span or 1/2 in. (13 mm), whichever is less, use intermediate supports.
        2) Do not base deflection on a total load of less than 120 lbs./ft^2 (5.7 kN/m^2).
    e. Base the permissible form camber on the actual dead load condition.
    f. Do not use camber to compensate for deflection that exceeds the above limits.
    g. Compute the form sheets design span using the clear span of the form, plus 2 in. (50 mm), measured parallel to the form flutes.
    h. Compute physical design properties according to the requirements of the latest published edition of the American Iron and Steel Institute Specification for the Design of Cold Formed Steel Structural Members.
    i. Ensure that all bottom reinforcement has a minimum concrete cover of 1 in. (25 mm) as shown in Figure 1. (Figure 1 metric).

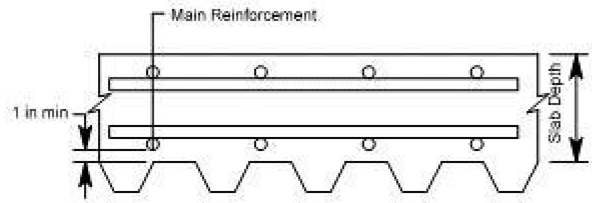

FIGURE 1

- **j.** Maintain the Plan dimensions of both layers of primary deck reinforcement from the top surface of the concrete deck.
- **k.** Do not use precast mortar blocks to support the deck reinforcement.
- **l.** Do not treat permanent steel bridge deck forms as lateral bracing for the compression flanges of supporting structural members.

3. Do not weld to flanges in tension or to structural steel bridge elements fabricated from non-weldable steel grades.

Have welders certified by the Department weld metal deck forms or supports for metal deck forms.

I. Install Forms

Install and maintain forms in a mortar-tight condition and according to approved fabrication and erection Plans.

Place transverse construction joints at the bottom of a flute. Field drill 1/4 in. (6mm) weep holes no less than 12 in. (300 mm) on center along the line of the joint.

1. Highway Bridge Forms

Install highway bridge forms with a 1 in. (25 mm) minimum clearance between the top of the form and the bottom of the main deck reinforcement. See Figure 1.

2. Railroad Bridge Forms

Install railroad bridge forms as follows:

- **a.** Place the forms so the tops of the form ribs adjacent to the beam flange are at the bottom of the deck slab specified by the plans.
- **b.** Maintain the full slab depth detailed on the plans.
- **c.** Do not allow form ribs to project above the plan bottom of the deck slab.
- **d.** Do not place form sheets directly on top of the stringer or floor beam flanges.
- **e.** Securely fasten form sheets to form supports using self-drilling screw fasteners, not by welding. If the Engineer approves, use fastener pins driven into place by a power tool.
- **f.** Ensure that form sheets have a minimum bearing length of 1 in. (25 mm) at each end.
- **g.** Do not leave loose sheets or accessories on the deck at the end of a day's work.
- **h.** Place form supports so that they contact the flange of the stringer or floor beam.
- **i.** Attach form supports using welds, bolts, clips, or other approved means.
- **j.** Do not weld form supports to the flanges of non-weldable steel or to portions of the flange subject to tensile stresses.
- **k.** Ensure that welding and welds comply with AWS D 1.5 for fillet welds. However, 1/8 in. (3 mm) fillet welds are permitted.

J. Repair Damaged Forms

Repair permanently exposed form metal to the Engineer's satisfaction if the galvanized coating is damaged.

1. Clean the damaged area.
2. Go over the damaged area with a wire brush.
3. Paint the area with two coats of zinc oxide-zinc dust primer that meet Federal Specification TT-P-641d, Type II and has no color added.
4. Do not touch up minor heat discoloration in weld areas.

K. Construct Runways

Provide runways into a deck pour area for moving buggies. If the Engineer approves, use runways to bridge a previous pour that has not reached the minimum strength or age requirements in Subsection 500.3.05.AF.4, *Live Loads—Pouring Equipment*.

Construct and support runways to protect the forms and the reinforcement steel position.

L. Construct Work Bridges

Provide a work bridge on deck pours. Support the bridge outside the area of the pour receiving a surface finish. If two or more spans will be poured on the same day, the Engineer may require two work bridges.

Design and construct work bridges to meet the following:

- Do not allow the bridge to sag into the fresh concrete.
- Construct the bridge so that transverse finish and curing material can be applied easily regardless of the screed type.

M. Add Water to Concrete

Add water to the concrete at the concrete plant. Do not add indiscriminate amounts of water at the job site.

If placement conditions require concrete of a more workable consistency, add small amounts of water at the job site if approved by the Engineer.

Add water at the job site as follows:

1. Determine the quantity of water required to provide the necessary consistency.

   The Engineer will not approve additions of water that cause the total amount of water to exceed the maximum water/cement ratio established in the Table 1—Concrete Mix Table.

   The Engineer will reject concrete with water added to it that produces a higher slump than specified in the Table 1—Concrete Mix Table.
2. Do not add water to concrete that has begun to set because of excessive mixing or to concrete that has exceeded mixing or haul time limitations.
3. When adding the water, carefully control the conditions.
4. Position the delivery so the measuring operation is not affected.
5. Measure the water carefully.
6. Inject the water into the mixer forcefully to facilitate uniform mixing.
7. Add water before discharging an appreciable amount of concrete.
8. Do not add more water after concrete discharge begins.
9. After adding the water, mix the concrete an additional 30 revolutions.
10. Finish mixing the concrete before the total revolutions at mixing speed exceed 150.

N. Volumetrically Proportion Concrete

Concrete ingredients may be proportioned volumetrically when non-air entrained concrete is used in miscellaneous concrete, non-exposed footings, culverts smaller than bridge culvert size, or when approved by the Engineer.

O. Prepare for Concrete Placement

Prepare for concrete placement as follows:

1. Ensure that an adequate supply of concrete will be furnished and placed to meet the requirements specified in Subsection 500.3.05.P, Table 5—Minimum Placement Rates for Bridges, Culverts and Retaining Walls.
2. To ensure a full bond between prestressed concrete deck panels and the cast-in-place concrete, clean the panel before placing the slab concrete.
3. Immediately before placing cast-in-place slab concrete, saturate the prestressed concrete deck panels with water.
4. Immediately before placing concrete in the forms, the concrete will be measured for acceptance tolerances. Acceptance tolerances for each class of concrete are listed in the Table 1—Concrete Mix Table. .

   Conduct the applicable tests according to the procedures in the Sampling, Testing, and Inspection information.

P. Meet the Minimum Placement Rates

If concrete is not produced, placed, and finished according to the minimum placement rates, the Engineer may reject the pour. Concrete pours of a similar nature and size will not be allowed until the problem is corrected and the placement rate met.

The minimum placement rates are listed in Table ~~5~~11:

TABLE ~~5~~11—MINIMUM PLACEMENT RATES FOR BRIDGES, CULVERTS AND RETAINING WALLS

5. Bridge Substructure

Pour Size in Cubic Yards (Meters)	Minimum Placement Rate in Cubic Yards (Meters) per Hour
0-25 (0-19)	10 (8)
26-50 (20-39)	15 (12)
51-75 (40-59)	20 (15)
76-100 (60-75)	25 (20)
101 and over (76 and over)	30 (25) or as designated on the Plans or in the Special Provisions

The minimum placement rate for columns shall be the same as for culvert sidewalls and wingwalls.

Pour Size in Cubic Yards (Meters)	Minimum Placement Rate in Cubic Yards (Meters)per Hour
0–25 (0-19)	15 (12)
26–50 (20–39)	20 (15)
51–75 (40–59)	25 (20)
76 and over (60 and over)	30 (25) or as designated on the Plans or in the Special Provisions

6. Bridge Superstructure

Pour handrail, parapet, curb, and barriers at a rate satisfactory to the Engineer

7. Culverts

Structure	Minimum Placement Rate in Cubic Yards (Meters)per Hour
Footings and slabs	Same as for bridge substructures
Sidewalls and wingwalls	Use placement rates so that fresh concrete is not placed on concrete that has attained its initial set. Cover all concrete with fresh concrete within 45 minutes.

8. Retaining Walls

Structure	Minimum Placement Rate in Cubic Yards (Meters)per Hour
Footings	Same as for bridge substructures
Walls	Same as for culvert sidewalls and wingwalls

Q. Place Concrete

Place concrete as follows:

1. Do not allow aluminum to touch the concrete while mixing, transporting, handling, or placing it.
2. Transport, handle, and place concrete quickly so that it reaches its final position in the forms within the haul time limitations in Subsection 500.2.01.E.1, *Haul Time Limitations*.
3. Manipulate the delivery or conveyance unit to avoid vibration damaging to partially set concrete.
4. Immediately before placing the concrete, thoroughly clean and wet the forms.
5. Place concrete as close as possible to its final position in the forms.
6. Use chutes, troughs, or tubes to pour the concrete in the forms, without displacing reinforcement steel.
7. Modify or stop using the equipment if chutes, troughs, or tubes cause honeycombed or otherwise inferior concrete.
8. When placing concrete by pumping, operate the pumping equipment so that the concrete is produced in a continuous stream without air pockets.

NOTE: Convey and place concrete by pumping only when specified in the Contract or when authorized by the Engineer.

9. When concrete placement requires dropping the concrete more than 5 ft (1.5 m), use pipes or tubes to place the concrete.

   Do not allow concrete to free-fall more than 5 ft. (1.5 m) from the pipe or tube.
10. Place concrete in horizontal layers no more than 18 in. (0.5 m) thick.
11. Place and compact succeeding batches in each layer before the preceding batch takes its initial set.
12. Place each succeeding layer before the underlying layer sets.
13. Consolidate the concrete to avoid cold joints between layers.
14. If the forms sag or bulge while concrete is being placed, remove the concrete causing the distortion and the concrete in adjoining areas if the Engineer requires. Removal prevents cold joints and displaced or damaged reinforcement.
15. Work the concrete around reinforcement bars without displacing them.
16. Compact concrete using suitable tools and vibration.
17. Vibrate concrete where it is deposited and vibrate other concrete while it is fresh. Vibrate as follows:
    a. Insert and withdraw vibrators slowly.
    b. Manipulate vibrators to work the concrete around reinforcement and embedded fixtures and into corners of forms.
    c. Vibrate sufficiently to compact the concrete but avoid causing the concrete to segregate.
    d. Stop vibrating before local areas of grout are formed.
    e. Apply vibrators no farther apart than twice the radius through which the vibration is visibly effective.
    f. Do not use vibrators or any other means that could cause segregation to move masses of concrete in

the forms.

g. Do not apply vibrators to sections of concrete that are no longer plastic.

h. Vibrate concrete-filled steel grid floors by applying the vibrators to the steel.

i. Vibrate concrete for precast or prestressed units as specified above in steps **a through g**, unless the Engineer approves alternate methods.

j. Stop vibration when a mortar line appears on the face of the form and when the coarse aggregate particles are submerged in the concrete mortar.

18. Supplement vibration with spading to ensure smooth surfaces and dense concrete along form faces and in locations difficult to reach with vibrators.

19. After concrete sets initially, do not disturb the forms or the projecting reinforcing bars.

R. Create Construction Joints

Place construction joints according to the Plans or as directed by the Engineer.

If an emergency affects continuous placement, the Engineer will decide if a construction joint is allowed. If allowed, the Engineer will provide instructions about where and how to make the joint.

The Engineer may eliminate certain construction joints if placement, finishing and forming methods can produce satisfactory results.

Create construction joints as follows:

1. Remove mortar splashed on form surfaces and projecting reinforcement steel before concrete reaches its initial set.
   a. Do not puddle dried mortar chips and dust into the plastic concrete.
   b. If excess mortar is not removed from reinforcement steel before the concrete reaches its initial set, delay cleaning until the concrete is thoroughly hardened.
2. If joining fresh concrete and hardened concrete, clean the hardened surface of laitance and incompletely bonded, loose, or foreign material.

   Ensure that laitance is completely removed from the following:
   - Joints between decks and curbs
   - Tops of seal courses
   - Construction joints in concrete exposed to sea water
3. Ensure that the surface of the concrete is dry before pouring the concrete against it.
4. Immediately before placing fresh concrete, tighten the forms against the existing concrete.
5. Use tremies or pumps to coat areas where fresh concrete will be poured with mortar or cement grout.
6. Begin placing concrete immediately after placing the mortar or grout.
7. Apply enough vibration to blend the material with the concrete at the construction joint.

S. Protect Fresh Concrete

Do not drive pile, blast, or perform other operations that vibrate the formwork or the concrete noticeably before the concrete reaches a strength of 2,000 psi (15 MPa) and is 3 days old.
Protect fresh concrete from rainfall with waterproof material such as tarpaulins or plastic film. Ensure that the waterproof material is ready before pouring and is sufficient to cover the area of the pour.

T. Place Bridge Deck Concrete

Do not use calcium chloride or any other admixture containing chloride salts in concrete placed on permanent steel bridge deck forms.

Ensure that the tolerances are accurate for bar reinforcement placement in cast-in-place concrete so the top clearance to the bar reinforcement complies with Subsection 511.3.05.G.6, *Bridge Deck Slab Tolerances*.

Place bridge deck concrete according to the Contract Specifications and as follows:

1. Before pouring decks, set substantial bulkheads or headers and shape them to the required deck surface cross-section.
2. Ensure that pouring sequences, procedures, and mixes comply with the plans and specifications.

3. Pour the deck according to the numbered sequence as follows:
   a. Unless otherwise shown on the Plans, pour each deck in one continuous operation.
   b. When dividing deck pours within any one complete unit (a simple span or a continuous or cantilever unit), pour and finish the concrete in the numbered sequence shown on the plans, beginning with the lowest number.
   c. Make pours with the same number before pours with higher numbers. Make pours with the same number in any sequence.
   d. The numbered sequence shown on the plans also applies to sidewalk pours, but it need not apply to curb, parapet, and handrail pours.
   e. Pour diaphragms between steel or prestressed concrete roadway beams at least 24 hours before pouring the deck slab.
   f. Unless otherwise authorized by the Engineer, pour all diaphragms within a complete unit before pouring decks.
   g. When constructing concrete T-Beams, place girder stems in uniform layers before placing slabs.
   h. If T-Beam spans are supported without intermediate false bents, begin deck placement as soon as the first four stems are placed. After the first four stems, avoid getting more than three stems ahead of the advancing line of the deck pour and lagging by more than the space between stems.
   i. If T-Beam spans are supported by intermediate false bents, place decks and stems the same as for T-Beam spans supported without intermediate false bents. However, ensure that the slab is placed before a cold joint develops between the stem and slab.

4. Do not make the deck pour until any previously poured concrete in the complete unit has set for 24 hours. This requirement may be waived under certain conditions if the succeeding pour can be completed (except for final finishing) within four hours of the initial placement of the day. The Engineer must give written approval for this requirement to be waived.

   Unless otherwise shown on the plans, do not place handrail, sidewalks, parapets, and curbs in a complete unit until all the deck slabs in the unit have been poured.
5. Ensure that the pour is the same as the overlap direction (as shown in the shop drawings).
6. Use the following deck pour method:
   a. If there is super-elevation, begin deck pours on either the high or the low side.
   b. Dump each batch against previously placed concrete.
   c. Pour at a rate that ensures fresh concrete along the advancing line of the pour.
   d. Vibrate or tamp concrete dumped on fresh concrete to make the grout flow as follows:
      - Forward with or slightly ahead of the concrete
      - Along the bottoms and sides of the forms
      - Around the reinforcement steel

7. Once the concrete is poured, vibrate it enough to avoid honeycomb and voids, especially at the following locations:
   - Construction joints
   - Expansion joints
   - Valleys and ends of form sheets Screed the concrete as follows:
   a. Use finishing devices operating parallel to the center line. As pouring proceeds, keep the concrete surface screeded to the required grade.
   b. Fill depressions ahead of the screed, and keep a small roll of grout on the leading edge of the screed. Perform further screeding with minimum disturbance to the surface already brought to the grade.
   c. Take care during the placement and screeding to obtain sound concrete at the construction joint located where the slab joins the curb, parapet, or sidewalk.
   d. Do not place excess grout on the leading edge of the screed and do not allow it to remain in this area.
   e. Use either a longitudinal screed or a transverse screed.
      - Longitudinal Screed

        Before doing the final screeding, place enough concrete in front of the screeding position to deflect the dead load.

- Transverse Screed

  On beam or girder-supported spans with skew angles of 65° or less, place and operate the truss or beam supporting the strike-off parallel to the skew and make the advancing pour line parallel to the skew.

  On beam or girder-supported spans with skew angles between 65° and 90°, position the screed either on the skew or at right angles to the bridge center line.

  On superstructures supported by non-deflecting falsework and on beam- or girder-supported spans with a total dead load deflection no more than 1/2 in. (13 mm), position the screed at right angles to the bridge center line and make the advancing line of pour at right angles to the bridge center line.

f. As the pouring proceeds, keep the concrete surface screeded to the required grade.

g. Fill depressions ahead of the screed. Keep a small roll of grout on the leading edge of the screed.

h. Continue to screed without disturbing the surface already brought to the required grade.

i. Avoid producing unsound concrete where the slab joins the curb, parapet, or sidewalk. Remove excess grout from the leading edge of the screed at these construction joints.

8. Edge joints to be sealed, including dummy joints, as follows:

a. Edge before the initial set or after the final set.

b. If edging before the initial set, use edging tools of the proper radius as shown on the plans.

c. Carefully remove concrete from pouring operations on adjacent pours to achieve the required rounded edge.

d. If edging after the final set, allow the joints to harden. After at least 12 hours, grind joints to approximate the plan radius either by hand or by mechanically operated grinding stones.

e. To achieve full and uniform bearing, finish areas that are recessed for receiving joint members.

9. Finish bridge decks as follows:

a. As soon as the concrete is hard enough and standing water and moisture sheen disappear, give the concrete a final finish by belting, brooming, or dragging.

- Belt longitudinally using a wet canvas belt. Limit belting to spans no longer than 40 ft. (12 m).
- Drag transversely or longitudinally with a wet burlap drag.
- Broom transversely using a stiff-bristled broom.

b. Finish the following areas carefully:

- Gutter lines
- Joints
- Drains

c. After belting, dragging, or brooming and when shown on the plans, groove the bridge deck and approach slabs perpendicular to the center line as follows:

1) Do not begin grooving until the bridge deck is cured according to Subsection 500.3.05.Z, *Cure Concrete*.

2) If necessary, groove in conjunction with planing required to make the surface corrections specified in Subsection 500.3.06.D, *Bridge Deck Surface Check*. Wait until the concrete is hard enough to support the equipment without distorting.

3) Cut grooves into the hardened concrete using a mechanical saw device capable of producing grooves 0.125 in. (3 mm) wide, 0.125 in. (3 mm) deep, and 0.50 in. (13 mm) apart, center-to-center.

4) Extend the grooves across the slab to within 1ft. (300 mm) of the gutter lines.

5) Do not groove within 3 in. (75 mm) of bridge joints, including “dummy” joints detailed in the plans.

U. Place Concrete Parapet on Bridge Decks

Place concrete barrier or parapets on bridge decks. The slip form method with an approved self-propelled extrusion machine as specified in Section 621 is optional.

V. Place Seal Concrete

Deposit concrete in water only when required by the Plans or when considered necessary by the Engineer.

When depositing the seal concrete, follow these guidelines:

- Keep the water as motionless as possible.
- Place the concrete continuously from beginning to end.
- Ensure that the concrete surface remains as horizontal as possible.

Place seal concrete as follows:

1. Place seal concrete carefully in a compacted mass as near to its final position as possible using a tremie, a bottom dump bucket, or other approved means.
    a. Use tremies to place seal concrete as follows:
        1) Support tremies so that the discharge end can move freely over the entire top surface of the work.
        2) Support tremies so that they can lower rapidly to stop or retard the flow of concrete.
        3) At the beginning of the work, close the discharge end to keep water out of the tube.
        4) Keep the tube sealed.
        5) Keep the tremie tube full to the bottom of the hopper.
        6) When dumping a batch into the hopper, induce concrete flow by slightly raising the discharge end and keeping it within the previously deposited concrete. This maintains a seal and forces the concrete to flow into position by hydraulic head.
    b. Use bottom-dump buckets to place seal concrete as follows:
        1) Ensure that the bottom-dump bucket is level full.
        2) Open the bucket only when it rests on the surface that will receive the charge.
        3) In lowering and raising the bucket, do not move the water unnecessarily.
    c. When approved by the Engineer, place seal concrete by pumping.
2. Wait at least 24 hours after placement to begin dewatering seal concrete, unless the Engineer determines a longer waiting period is necessary.
3. Remove laitance from the seal concrete before placing the footing.
4. Bore seals under spread footings the entire depth of the seal as specified for foundations in Subsection 211.3.05.C, *Boring of Foundations and Seals*.
5. If laitance buildup on seals under spread footings exceeds 1/4 in./ft. (20 mm/m) of seal depth, the Engineer may decide to core the seal to determine acceptability.
6. When placing concrete exposed to sea water, control the water content to produce concrete of maximum density and create construction joints and prepare their surfaces according to the requirements of Subsection 500.3.05.R, *Create Construction Joints*.

W. Pour CS Concrete

Pour CS concrete as follows:

1. Meet CS concrete depth and surface finish requirements.
    - Ensure that the minimum depth is the same as shown on the plans.
    - Do not vary the depth variation more than 1 in. (25 mm).
    - Ensure that the surface finish is generally smooth and uniform.
    - Smooth or fill float marks, voids, and other deformities exceeding 1/2 in. (13 mm) before placing approach slabs.
2. To prevent bonding:
    a. Lay clean polyethylene sheeting uniformly over the CS concrete in the approach slab area before placing the slabs.
    b. Use new, unused polyethylene sheeting free of holes, rips, and tears.
    c. Use polyethylene bond-breaking material at least 8 mils (0.2 mm) thick with an overlap of at least 6 in. (150 mm).
3. Maintain polyethylene sheeting in good condition throughout the construction process.

Repair or replace sheeting deemed unsatisfactory as directed by the Engineer.

4. Cure CS concrete with the polyethylene sheeting used for bond breaking.

X. Pour Concrete in Cold Weather

When pouring concrete in cold weather, keep the concrete temperature at the point of delivery at least 50 °F (10 °C). Do not use accelerator-containing chlorides.

Mix and pour concrete in cold weather as follows:

1. Keep concrete materials at the right temperatures.
    - Do not use materials in concrete mix that contain frozen lumps.
    - Do not incorporate water and aggregates into the mix with temperatures more than 150 °F (65 °C).
    - If aggregates or water temperatures are above 100 °F (40 °C), discharge the aggregates and water into the mixer and allow the temperatures to equalize before adding the cement.
    - Heat aggregate with steam, hot water coils, or other methods that do not damage the aggregates. Do not heat aggregates with direct flame.
2. Protect the poured concrete.
    - Keep concrete above 50 °F (10 °C) for at least 72 hours after placement.
    - Protect concrete from freezing for 6 days after placement.

Y. Pour Concrete in Hot Weather

Reduce hazards and difficulties related to placing and finishing concrete in hot weather before pouring. The Engineer may require measures to prevent concrete workability reduction, losses from cement hydration, evaporation, drying, or elevated concrete temperatures.

1. Place Concrete

    Cool forms and reinforcement with water immediately before placing concrete. Meet the minimum placement rates specified in Subsection 500.3.05.P, Table 5—Minimum Placement Rates for Bridges, Culverts, and Retaining Walls.

2. Keep Concrete Cool

    Keep concrete cool as follows:

    a. Keep the concrete used for construction at no more than 95 °F (35 °C) when measured at the point of discharge from the delivery unit.

    b. If the concrete temperature might exceed 95 °F (35°C) during concrete placement, begin placement when the air temperature cools if the Engineer requires.

    c. Cool the aggregates by fogging or other means that do not affect moisture content.

    d. Use chipped or crushed ice in the mix as a portion of the mixing water on a pound (kilogram) basis. If using ice, ensure that the ice melts before the batch is discharged from the mixing unit.

    e. If necessary, cool water by refrigeration to provide a lower concrete temperature.

3. Finish Concrete

    Do not "splash on" water to aid screeding or finishing operations.

    For bridge decks, fog the surface when required, according to Subsection 500.3.05.Z.3, *Bridge Deck Curing*. If needed, use wind screens to prevent thermal or shrinkage cracks caused by rapid concrete surface drying.

Z. Cure Concrete

Concrete curing is an integral part of the concrete placement operation. Improperly cured concrete will be considered defective.

If the Engineer determines that curing procedures do not comply with these Specifications, stop placing concrete. Resume concrete placement after taking remedial measures to ensure proper curing.

Begin curing unformed surfaces when the water sheen disappears from the surface or immediately after applying the surface finish. Continue curing for 5 days.

Cure the formed surfaces after removing the forms. Remove them within 5 days after placing concrete. Continue curing until the concrete is 5 days old (from the time it is poured).

Cure concrete surfaces exposed to air using methods that prevent premature drying or moisture loss. Ensure that curing conditions are the same throughout separate curing areas.

Use either or a combination of the two methods specified for curing concrete except bridge decks. Cure bridge decks as described in Subsection 500.3.05.Z.3, *Bridge Deck Curing*.

Cure colored concrete in accordance with manufacturer's instructions.

1. General Curing—Supplying Additional Moisture

Do not use a method that causes the concrete to be alternately wet and dry.

Cure concrete properly by supplying additional moisture through ponding, sprinkling, or fogging and then retaining the moisture as follows:

a. Use cotton mats, burlap, sand, hay, or straw coverings.

Cover with at least 2 in. (50 mm) of sand. Cover with at least 3 in. (75 mm) of hay or straw.

b. Do not use sawdust or coverings that cause unsightly discoloration of concrete.

c. Place coverings after completing the finishing operations when there is no danger of surface damage.

d. Keep coverings moist continuously.

2. General Curing—Preventing Moisture Loss

Keep concrete moist before and during the rubbing from the Type III—Rubbed Finish.

Start curing immediately after the rub using approved waterproof paper, plastic sheets, or membrane-forming curing compounds, except when curing compounds are prohibited.

a. Waterproof Paper or Plastic Sheets

Ensure that the sheets and paper meet the requirements of AASHTO C 171 and use them as follows:

- Use the widest possible widths.
- Lap adjacent sheets at least 6 in. (150 mm).
- Seal the laps with tape, mastic, glue, or other approved methods to form a waterproof cover of the entire area.
- Keep the curing material from being displaced by wind.
- Immediately replace or repair sheets or paper that tear, break, or become damaged during the curing period.

b. Membrane-Forming Curing Compounds

Use as the curing agent AASHTO C 309, membrane-forming curing compounds, Type 1-D, Class A or B, or Type 2, Class A or B, white pigmented. Use the curing agent as follows:

- Do not use membrane-forming curing compounds on bridge decks or prestressed concrete bridge members, or in construction joint areas.
- When the water sheen disappears from the concrete surface, apply the curing compound uniformly to unformed areas.
- Apply the compound to formed surfaces if the forms are removed during the 5-day curing period.
- Cure the areas to be rubbed with liquid membrane-forming compounds for curing concrete, Type1-D, Class A or B (non-acrylic).
- Apply curing compound with fine-spraying equipment.
- Thoroughly agitate the compounds just before using them.
- Spray the surface again immediately after the first application at right angles to the first application.

  Apply at least 1 gal (1 L) for each 150 ft.^{2} (3.7 m^2) of surface.
- Do not apply curing compound to the following:
  - Joints where a concrete bond is required
  - Reinforcement steel
  - Joints where joint sealer will be placed
- Close the surface to pedestrian or vehicular traffic for 7 days unless the surface is protected by planks, plywood, or a layer of sand at least 1 in. (25 mm) thick.

  Do not place this protection until at least 12 hours after applying the curing compound.

3. Bridge Deck Curing

Cure bridge deck concrete as follows:

a. Immediately after the water sheen disappears and the surface finish is applied, fog the surface to keep a film of water on the surface.

b. If surface damage occurs, delay fogging.

c. Keep the surface wet until after applying the sheet curing covers.

d. Thoroughly soak curing covers on the fabric side.

e. As soon as the concrete sets enough to prevent damage, apply the covers with the white-poly side up.

f. Use two-layer sheet curing material for bridge concrete according to AASHTO C 171.

   For the bottom layer, use a polyethylene film. For the top layer, use a white, burlap polyethylene sheet or a white, co-polymer-coated, absorbent, non-woven synthetic fabric.

g. Ensure that sheet curing material for bridge concrete meets Specification requirements for reflection and moisture retention and has no holes or tears.

h. Use enough sheet curing material to cover the deck surface.

i. Place the curing covers so that adjoining sheets overlap at least 18 in. (450 mm).

j. Weight all laps and side edges to prevent cover displacement before curing is completed.

k. Weight and overlap covers so the curing sheets maintain intimate contact with the concrete surface.

l. If there is no moisture under the curing covers during the 5-day curing period, apply additional moisture.

4. Parapet, Sidewalk, End Post, and Curb Face Curing

   The surface of parapets, sidewalk, end post, and horizontal and vertical faces of curbs are not considered part of the bridge deck. Cure these structures using the general curing methods in Subsections 500.3.05.Z.1, *General Curing—Supplying Additional Moisture*, and 500.3.05.Z.2, *General Curing—Preventing Moisture Loss*, unless the surfaces will receive a special surface coating (Subsection 500.3.05.AB.4, *Type III—Special Surface Coating Finish*).

   Do not cure surfaces receiving a special surface coating with membrane-forming curing compounds.

   Do not cure surfaces receiving protection surface treatment (75 percent boiled linseed oil and 25 percent mineral spirits solution) with membrane-forming curing compounds that contain acrylics.

AA. Prevent Plastic Shrinkage Cracking

Take precautions to prevent plastic shrinkage cracking of concrete by doing the following:

- Provide wind screens
- Provide fogging equipment
- Apply temporary wet coverings before moisture loss begins

The Engineer will evaluate the effects of plastic shrinkage cracks and will require repair of cracks that create structural defects and corrode reinforcement steel.

AB. Finish Concrete

Concrete surface finishes are classified according to whether the surfaces are formed or unformed. Refer to Table ~~6~~12.

When other Sections of the Specifications for concrete work state that the requirements of Section 500 apply, finish the concrete according to the other sections.

TABLE 12~~6~~—CONCRETE FINISH TYPES

Surface	Finish Type
Formed	Type I—Ordinary Formed Surface Finish
	Type II—Special Formed Surface Finish
	Type III—Rubbed Finish
	Type III—Special Surface Coating Finish
Unformed	Type IV–Floated Surface Finish
	Type V–Sidewalk Finish
	Type VI–Stair Tread Finish

Except for bridge deck finishes, which are covered in Subsection 500.3.05.T, *Place Bridge Deck Concrete*, step 9, finish all structural concrete surfaces with one or more of the finishes described here, unless otherwise shown on the plans.

1. Type I—Ordinary Formed Surface Finish

   Complete formed concrete surfaces with this finish. However, leave concrete exposed directly to sea water undisturbed unless the Engineer requires additional work. See Subsection 500.3.05.V, *Place Seal Concrete*, step 6.

   Achieve a Type I finish as follows:

   a. Immediately after removing the forms, remove fins and surface irregularities.
   b. Fill or point up the following:
      - Cavities produced by forms or ties
      - Holes
      - Broken corners or edges
      - Defects
      - Honeycombed edges
   c. Remove and patch honeycombed areas to sound concrete.
   d. Use patch mortar that consists of the same sand and cement as the concrete. Use the sand and cement in the same ratio as in the concrete.

   Use epoxy mortars in areas where heat generation and moisture will not decrease patch performance.

   e. Cure the patches using one of the general curing methods specified in Subsection 500.3.05.Z.1, *General Curing—Supplying Additional Moisture* and 500.3.05.Z.2, *General Curing—Preventing Moisture Loss*.
   f. Produce a sound and uniform finish.
   g. If the Type I finish is not satisfactory, give the surfaces a Type III—Rubbed Finish where the Engineer considers it necessary to achieve a uniform and pleasing appearance.

2. Type II—Special Formed Surface Finish

   Give a Type II finish to the following:

   - Exposed portions of pipe headwalls and culverts
   - Parapets and wingwalls
   - Ends of culvert slabs and walls

   Achieve a Type II finish as follows:

a. Use a form liner unless the forms are made of plywood or steel.

b. Rub only when necessary if the surface has a pleasing, uniform appearance after completing the Type I finish and blending all pointed and patched areas.

c. If the surface finish is not satisfactory, give surfaces the Type III—Rubbed Finish where the Engineer considers it necessary to achieve a uniform and pleasing appearance.

3. Type III—Rubbed Finish

Apply a Type III finish to bridge areas checked in the table of Bridge areas Requiring a Type III Finish, below and to exposed areas of retaining walls, unless the Plans specify otherwise.

Achieve a rubbed finish as follows:

a. Begin the first rub immediately after removing forms, completing the Type I finish, and ensuring that all patches are thoroughly set, but before applying the required curing compound.

If finishing is postponed or there is not enough labor to keep it up-to-date, the Engineer will order a stop to any other work until the finishing is satisfactory.

b. Rub chamfered surfaces only once, but not during the first rubbing. Rub chamfered surfaces during either the second or the final rubbing.

c. To rub, wet the moist concrete on the curing surface with a brush and rub with a medium-coarse carborundum stone or equal abrasive until a paste comes to the surface.

Keep the entire concrete surface moist during rubbing to assure adequate curing.

d. Continue rubbing until all form marks and projections disappear, leaving a smooth, dense surface with no pits or irregularities.

e. Spread the paste material carefully and uniformly over the entire surface and leave it.

f. No earlier than 24 hours after the first rub, do the final rub with a fine carborundum stone or equal abrasive, leaving a smoothly textured surface that is uniform in color.

g. Finish the final rub before applying protective surface treatment required by the plans.

h. Do not “whitewash” finished areas by using separately mixed grout or paste on the rubbing stone or by spreading it on the surface to be rubbed.

i. Thoroughly clean and blend into the surrounding surfaces any areas that are disfigured by drips from concrete placement or rubbing.

Bridge Areas Requiring a Type III Finish (X)

	Single Bridge Over Stream	Multiple Bridges Over Stream	Single Bridge Over Railroad	Multiple Bridges over Railroad	Single Bridge over Traffic Artery	Multiple Bridges Over Traffic Artery	Railroad Bridge Over Traffic Artery	Pedestrian Bridge Over Traffic Artery
All exposed substructure areas, except tops and bottoms of caps. (5)					X	X	X	X
Outside surface of any exterior concrete beam, Lt. or Rt. (1), (2)		X		X				
Outside surface of any exterior concrete beam, LT. and Rt. (1), (3)					X	X	X	X
Vertical surfaces of overhangs, curb, or sidewalk	X	X	X	X	X	X	X	X
All vertical surfaces outside exterior beam, Lt. or Rt. (2)		X		X				
All vertical surfaces outside exterior					X	X	X	X

beam, Lt. and Rt. (3)								
End bent cap beyond outside beam or girder	X	X	X	X				
End bent end walls beyond outside beam or girder	X	X	X	X	X	X	X	X
End bent posts and end bent wingwalls all exposed surfaces	X	X	X	X	X	X	X	X
Traffic face of curbs	X	X	X	X	X	X		X
Entire handrails and posts, handrail parapets, and barriers (4), (5)	X	X	X	X	X	X	X	X
All other locations specified on Special Provisions	X	X	X	X	X	X	X	X

Notes:

(1) - Including Prestressed Concrete Bridge Members

(2) - "Lt. or Rt." - Rub the applicable surface when it can be seen from any adjoining/adjacent bridges.

(3) - "Lt. and Rt." - Rub the applicable surfaces on both sides of centerline of each bridge.

(4) - Rubbing of bottom surface of rail not required.

(5) - Bottoms of Caps and handrails shall be given a Type II finish.

For bridges using PSC Beams or PSC Deck Units, a Type III Special Surface Coating Finish shall be used where a Type III finish is required for exterior beams. For bridges using PSC Beams or PSC Deck Units, a Type III Special Surface Coating Finish shall be used where a Type III finish is required for exposed substructure areas. The Type III Special Surface Coating Finish shall also be used on the exterior vertical faces of the parapet, barrier, and overhangs where PSE Beams or PSC Deck Units are used.

4. Type III—Special Surface Coating Finish

A Type III—Special Surface Coating Finish may be substituted for a Type III—Rubbed Finish.

The special surface coating finish consists of either a Class A or a Class B coating system, applied to produce a masonry-like textured finish on concrete surfaces.

For contiguous structures, whether in the same Contract or in separate Contracts, use the same brand of special surface coating.

If contiguous structures are in separate contracts, coordinate the Work with the other Contractor so that coating is applied as near as possible to the same time.

If contractors cannot coordinate Work, the one who finishes the work last shall use the same brand or shall recoat all contiguous areas to provide a uniform appearance.

Achieve a special surface coating finish as follows:

a. Ensure that surface coating material meets the requirements of Section 836.
Select coating material from the QPL 17.

b. Do not use form oils that affect the bonding of surface coatings.

c. Do not use wax-based or other curing compounds incompatible with surface coatings.
Have the coating manufacturer or the laboratory determine compatibility.

d. Use the coating color required in Section 836.

e. On surfaces that will receive a coating finish, do not cure with membrane-curing compound or remove forms with bond-breaking agents or excessive oil.

f. Apply coatings as follows:

- Class A coatings at a rate that develops a 1/16 in. (1.5 mm) thick coating.
- Apply Class B coatings at a maximum rate of 60 $ft.^2$ per gallon (1.5 m^2 per liter).
- Ensure that the temperatures of the air, concrete, and compound are above 50 °F (10 °C).
- Apply a test section as directed by the Engineer to determine the acceptance of a coating under field conditions.
- Apply the coatings using a method that produces an acceptable finish, such as spraying, rolling, or a combination of these.

g. Protect coated surfaces from rain or freezing temperatures for 24 hours after application.

h. Ensure that the final coating produces a smoothly textured surface that is uniform in color, thickness, and appearance.

i. Remove and reapply coatings that chip, crack, blister, peel, or present an unsatisfactory appearance.

j. If the final appearance is unsatisfactory, apply a rubbed finish to slip-formed and formed walls and barriers.

5. Type IV—Floated Surface Finish

Use a Type IV finish only on the horizontal surfaces of the following:

- Curbs and sidewalks
- Tops of caps and footings
- Surface of slope paving
- Other similar structures

Apply the Type IV finish as follows:

a. After compacting the surface and screeding to the correct cross sections, float the surface with a wood float.

b. While floating the surface, bring enough mortar to the surface to achieve the desired finish, but do not reduce the wearing quality of the surface.

c. Make the final finish with a wood float or stiff-bristle broom.

d. If brooming, make the marks transverse to the traffic.

6. Type V—Sidewalk Finish

Apply a Type V finish as follows:

a. After placing and compacting the concrete, strike it off and give it a Type IV finish.

b. Use an edging tool on all edges and along expansion joints unless the Plans require chamfers.

c. Mark off sidewalk surfaces in blocks with suitable grooving tools when required by the plans or the Engineer.

d. Extend the rubbed finish on the traffic face of the curb to include the horizontal area of sidewalk between the curb corner and the longitudinal sidewalk groove.

7. Type VI—Stair Tread Finish

Achieve a Type IV finish using a stiff-bristled broom.

AC. Remove Forms

Do not remove forms and their supports, including falsework, until the Engineer approves. Use a removal method approved by the Engineer. Approval does not relieve responsibility for the safety of the Work.

1. Form Removal Time

Use a removal time shown on the Plans or specified by the Engineer.

Use Table ~~7~~13 to help establish when forms can be removed safely. However, do not count days where the temperature at any time during the day is at or below 40 °F (4 °C), unless the cold weather concrete protective measures described in Subsection 500.1.03.G, *Cold Weather Concrete Curing and Protection Plan* were used.

TABLE ~~7~~13—ESTIMATE OF FORM REMOVAL TIME

Form	Time Required
Bottom of beams	10 days
Bottom of caps, trestle pile bents	4 days
Bottom of all other caps	7 days
Overhangs and slabs, including culverts	7 days
Columns and retaining walls	18 to 48 hours
Sides of beams, psots, rails, caps, footings, wingwalls, and parapets	12 to 24 hours
Bottoms of cast-in-place rails and diaphragms	48 hours
Front face of curbs	3 hours

If using high-early strength concrete, the Engineer may reduce the time limitations if the concrete develops satisfactory strengths.

2. Form Removal Method

Remove forms and falsework without injuring the concrete surface or overstressing the concrete members.

Ensure that the stress from the weight of the removal process is transferred gradually and uniformly to the concrete.

At the Contractor's request, time of removal may be controlled by field tests on cylinders, subject to the following conditions:

- **a.** No tests will be performed until concrete is a least 3 days old.
- **b.** Required strengths will be shown on the Plans, as noted elsewhere in these Specifications, or as determined by the Engineer.
- **c.** The Engineer may specify a minimum time in conjunction with minimum strength requirements.
- **d.** Falsework and forms for culverts may be removed at such time as 75% of the concrete design strength is achieved.

AD. Apply Protective Surface Treatment

When the Plans specify a protective surface treatment, apply a boiled linseed oil mixture of 75 percent boiled linseed oil and 25 percent mineral spirits by volume to the concrete surfaces.

Use linseed oil that meets the requirements of ASTM D 260, Type I or Type II. Use a quality commercial mineral spirit that passes infrared spectroscopic analysis to the satisfaction of the laboratory.

Unless otherwise noted on the Plans or the manufacturer's recommendations, apply the mixture as a preservative seal coat to the top surfaces of bridge decks, curbs, and sidewalks and to the inside vertical faces of curbs, parapets, and end posts. Protect metal handrailing and metal handrail posts from treatment.

Apply the protective surface treatment as follows:

CAUTION: Because the linseed oil-petroleum spirits mixture has a low flash point and is readily flammable, protect the mixture from fire, especially cigarettes and sparks. Prohibit traffic from the treated area until the Engineer determines the concrete has regained its dry appearance.

1. Do not place the protective surface treatment until concrete work, including final rubbing, is completed and expansion joint sealing compound is placed.
2. Do not apply the treatment until the concrete is at least 14 days old.
3. Unless otherwise permitted by the Engineer, apply the treatment when the temperature of the concrete and air is at least 50 °F (10 °C).
4. Apply in time to allow the treatment to dry thoroughly before allowing traffic, including haul traffic, on the structure.

   If the structure meets the following exceptions, apply the treatment after using the structure for hauling.

   - Temperature limitations prohibit application.

     The Engineer will send a written notification to the Contractor (or Bridge Contractor) if temperature requirements prohibit application.

   - The structure is absolutely required for hauling to complete a Contract.

     Request a written approval from the Engineer if hauling across a structure before the treatment is placed.
5. If applying the treatment after using the structure for hauling, thoroughly clean the surfaces to be treated to allow the treatment to penetrate completely.
6. If there are separate bridge and roadway Contracts, have the roadway Contractor clean the surfaces immediately upon request by the Engineer.
7. Prepare the surface for the treatment as follows:
   a. Clean off oil, grime, and loose particles that prevent the mixture from penetrating.
   b. Ensure that the concrete surfaces have at least 48 hours to dry after rainfall or wet cleaning operations.
   c. Immediately before applying the treatment, direct an air blast over the surfaces to remove dust.
   d. Mask the exposed plates of joints.
8. Apply the mixture by hand or by spraying in one application at the rate of 1 gal (1 L) of mixture per 37.5 yd^2 (8.5 m^2).
   a. Thoroughly clean the inside of spraying equipment before putting the surface treatment in.
   b. Keep spray nozzles within 18 in. (600 mm) of the concrete unless otherwise directed by the Engineer, plans, or manufacturer.

AE. Apply Graffiti-Proof Coating

When the Plans specify a graffiti-proof coating, apply the coating system to concrete surfaces or over special surface coatings. Use material that complies with Section 838.

Apply the coating as follows:

1. Clean loose particles, dirt, grease, oil, and other foreign particles off the surface.
2. Apply the coating according to the manufacturer's recommendations for:
   - Weather conditions

- Material preparation
- Coating application
- Number of coats

AF. Expose New Concrete to Loads

Prohibit dead or live loads during or after construction except as described in this section. If using high early strength concrete, the Engineer may reduce time limitations if the concrete develops adequate strength.

1. Dead Loads on the Substructure

   After pouring footings, do not begin work on columns or piers for at least 12 hours.
   After pouring columns, do not begin cap construction for at least 24 hours.

   Do not place beams on caps or place falsework and forming for concrete T-Beam construction before the cap concrete reaches a minimum strength of 2,500 psi (17 MPa).

2. Dead Loads on the Superstructure

   If necessary, stockpile construction materials on decks within a complete unit (a simple span or continuous or cantilever unit) if the following conditions exist:

   - The deck concrete of the complete unit reaches its 28-day cylinder strength.
   - The deck concrete is at least 10 days old.
   - The curbs are at least 5 days old.

   The Engineer must approve the location, height, and spread of the loads.

   On composite-design bridges (those that have prestressed concrete beams or steel beams with shear connectors), do not pour curbs, parapets, or sidewalks until the deck concrete reaches a minimum strength of 1,500 psi (10 MPa) or is at least 3 days old.

3. Dead Loads on Concrete Box Culverts

   Do not backfill any section of a concrete box culvert until the last concrete placed in that section is at least 14 days old, unless early cylinder breaks indicate otherwise.

   If early cylinder breaks indicate that design strength has been achieved, backfill sections of culverts when the concrete placed last is at least 7 days old.

4. Live Loads—Pouring Equipment

   Do not allow power-operated concrete buggies to cross a deck until the concrete reaches a minimum strength of 1,500 psi (10 MPa) or is at least 3 days old.

   Allow hand-operated buggies to cross after the concrete is 24 hours old.

5. Live Loads—Mixing and Lifting Equipment

   Do not place mixers on a deck in a complete unit (a simple span or continuous or cantilever unit) until the deck concrete of the complete unit reaches its 28-day cylinder strength and is at least 10 days old.

   When deck concrete reaches its 28-day cylinder strength and is at least 10 days old, allow mixer trucks on the unit during the curb concrete pour only if the pour is completed within 45 minutes of being started.

   Do not allow any equipment on the unit for 5 days after curb pours.

   The Engineer may allow concrete placement procedures that use heavy lifting equipment on the decks if the following conditions exist:

   - The deck concrete reaches its 28-day cylinder strength.
   - The deck concrete is at least 14 days old.
   - The curbs on the deck are at least 10 days old.

6. Live Loads—Hauling over Bridges

   Use a new bridge for hauling only if no other practical haul routes are available and only if the Engineer permits it.

   a. Govern hauling by the restrictions and requirements listed in Table ~~8~~14. If any of the restrictions and requirements are violated, the Engineer will limit loads to the following:

      - Single 32,000 lb. (14 515 kg) axle when the bridge design loading is HL-93 or HS 20-44 Single 24,000 lb. (10 886 kg) axle when the bridge design loading is HS 15-44 or H 15-44

TABLE ~~8~~14—WEIGHT LIMITS FOR HAULING ON NEW BRIDGES

Axle Criteria	Bridge Design Loading	
	HL-93 or HS 20-44 Loading	HS 15-44 or H 15-44
Maximum Axle Load Per Axle	60,000 lbs. (27 216 kg)	44,000 lbs. (19 958 kg)
Maximum Axle Load on Dual Axles Per Axle	45,000 lbs. (20 412 kg)	33,000 lbs. (14 969 kg)
Maximum Total Load	100,000 lbs. (45 360 kg)	73,000 lbs. (33 113 kg)

- **b.** Ensure that bridge concrete, including curbs, parapets, barriers and sidewalks, is at least 14 days old and has a minimum compressive strength of 3,000 psi (20 MPa).
- **c.** Apply the linseed oil special protective treatment, if required see (Subsection 500.3.05.AD, *Apply Protective Surface Treatment*).
- **d.** After applying the protective treatment (if required), apply water-repellent silicone materials to the handrail, handrail posts, end posts, and curb faces before hauling begins.
- **e.** Do not allow more than one vehicle at a time on a simple or multiple-span unit.
- **f.** Ensure that vehicle speeds, loaded or unloaded, do not exceed 5 miles/hr. (8 km/hr.) when the following loads occur:
  - Bridges designed for HL-93 or HS 20-44 Loading:
    - — Loads on single axles exceed 32,000 lbs. (14 515 kg)
    - — Loads on each dual axle exceed 24,000 lbs. (10 886 kg)
  - Bridges designed for HS 15-44 or H 15-44 loading:
    - — Loads on single axles exceed 24,000 lbs. (10 886 kg)
    - — Loads on each dual axle exceed 16,000 lbs. (7257 kg)

  When axle loads do not exceed these loads, ensure that vehicle speeds are 15 mph (24 kph) or less.
- **g.** Place temporary guides on beams so wheels will track directly.
- **h.** Keep earth approaches smooth and level with the bridge floor or approach slab to minimize impact. Stabilize sandy and other unstable soils (at no expense to the Department) with crushed stone or other suitable material for at least 10 ft. (3 m) from the end of the bridge or approach slab.
- **i.** Protect the ends of bridges or approach slabs with a timber strip at least 4 in. (100 mm) wide, cut to rest on either the paving rest of the bridge end or the pavement subgrade at the end of the approach slab. Keep the strip in place for protection during incidental hauling. Remove it before constructing the adjacent pavement.

  Keep the top of each timber strip flush with the top of the concrete surface. Fit the strip tightly against the end of the bridge or approach slab. If the timber strip is displaced, stop hauling until the strip is reset or replaced.
- **j.** Clean spills off the bridge floor.

AG. Complete Corrective Work

After the Department gives the deck surface a Ride Quality Test described in Subsection 500.3.06.E, “Ride Quality Test,” complete corrective work at no cost to the Department and before doing the final surface texturing.

Complete corrective work as follows:

1. Plane the deck according to Section 431.
2. Limit concrete removal by planing so that the final bar cover is not less than the Plan cover minus 1/2 in. (13 mm).
3. If the final bar cover limits cannot be met, perform the corrective work as directed by the Engineer.
4. Ensure that the final riding surface complies with this Specification and the requirements for a grooved finish.
5. If necessary, use a bump grinder to correct bumps with a profile base line of 5 ft. (1.5 m) or less.
6. Have planed decks retested as described in Subsection 500.3.06.E, *Ride Quality Test*, to ensure that the ride quality meets the requirements of this Specification.

AH. Plane the Deck

The Contractor shall schedule the ride quality test at least 7 days before needed by contacting the Office of Materials and Testing, Concrete Branch. Ensure that the area to be tested is clean and clear of obstructions.

When possible, delay expansion joint installation and temporarily bridge the joint to operate Lightweight Profiler and planing equipment across the joint.

Planing responsibilities are shown in Table ~~9~~15:

TABLE ~~9~~15—PLANING RESPONSIBILITIES

Area Planed	Person Responsible
Bridge decks	Bridge Contractor
Approach slabs constructed under the bridge Contract	Bridge Contractor
Approach slabs constructed under the roadway Contract	Roadway Contractor

AI. Perform Retaining Wall Incidentals

Retaining wall incidentals are as follows:

1. Drainage

   Unless otherwise shown on the Plans or in the Special Provisions, ensure that drainage for retaining walls is either Alternate A or Alternate B on Georgia Standards 4941B and 4949 Series.

   Ensure that the Number 10 concrete sand complies with Subsection 801.2.02, *Fine Aggregate for Portland cement Concrete of All Types and for Mortar* and has a permeability coefficient of at least 100 ft. (30 m) per day.

   The Engineer may waive the grading requirement for Number 10 concrete sand if the permeability coefficient of the material does not exceed 500 ft. (150 m) per day.

   Omit the drainage blanket and stone for retaining walls only when the height does not exceed 6 ft. (1.8 m).

   When the Plans specify different drainage details, furnish, place, or build the various items according to the plan requirements.

2. Waterproofing and Damp proofing

   When waterproofing and damp proofing are specified in the Plans, comply with the requirements of Sections 530 and 531.

AJ. Place Utility Installation Hardware

When the Plans require placing utility installation hardware, the utility company involved will furnish the items.

Place the items as directed on the plans or Shop Drawings. All other work, including painting as required, is the utility company's responsibility.

AK. Widen Bases and Pavement

When using narrow sections of ~~Portland~~hydraulic cement concrete to widen existing bases or bases and pavements, use Class B concrete as shown on the Plans or as directed by the Engineer.

AL. Open the Structure to Traffic

Open a structure to traffic other than haul traffic after all concrete in the decks, parapets, or curbs (sidewalks) reaches its 28-day cylinder strength and is at least 14 days old.

500.3.06 Quality Acceptance

A. Strength and Resistivity Requirement Tests

1. At the Contractor's request, the Department will determine the removal time for forms by conducting field tests on cylinders.

   Tests are subject to the following:

   a. ~~T~~Strength tests will be performed when the concrete is at least three days old. Resistivity tests will be performed when the concrete is at least seven days old.

   b. The Plans will show the required strengths and resistance~~s.~~

   c. At the Contractor's request, the Engineer may specify a minimum time with minimum strength requirements.

   ~~c.~~d. Resistivity test results shall report the 56-day average resistance of the samples. The contractor may test the samples at an earlier date in order to achieve the required quality acceptance; however, 56-day results will be required to be reported in addition.

2. A pay factor of 1.00 shall be applied if the average 28-day strength of the cylinder set meets the strength requirements and the average 56-day resistance of the cylinder set meets the resistance requirements. The strength tests shall be the average of 2 cylinders with additional cylinders cast in case of failure at 28 days at the Contractor's discretion with no charge to the department. The resistance tests shall be the average of 3 cylinders. Measurements may be taken at any time to verify the mix, but 56-day average resistance values shall be reported.

~~2.~~3. When job site test specimens fail to meet the 28-day strength requirements in the Table 1 – Concrete Mix Table~~.~~, determine the Final Acceptance at a reduced price with a minimum of $1000 reduction (% of the contract price, if available, or the latest Item Mean Summary as unit cost) or rejection/removal of concrete in place by coring for structural concrete materials or by conducting non-destructive testing for non-structural concrete materials, as specified by the Engineer:

a. 1.00 pay factor will be applied if the average 28-day strength of the cylinder set meets strength and resistivity requirements in the Table 1 – Concrete Mix Table and Table 2A – Concrete Surface Resistivity, or if cylinder strength does not meet 28-day cylinder strength requirements and the contractor elects, within 7 days upon notification of failure, to obtain cores (on structural concrete) or perform non-destructive testing (on non-structural concrete) and passes 28-day strength requirements.

b. If average strength of the cylinders set does not meet 28-day strength requirements in the Table 1, but meets these requirements at 56 days strength requirements, then ~~the following~~ pay factors for the amount the 28-day compressive strength is less than specified strength ~~,~~ will be applied. Additional reductions in pay factors shall applied if the 56-day average resistance is below the specified requirements in Table 2A.~~:~~

Reduction in strength below specified 28-day compressive strength (psi)	Pay factor for mix below 28-day specified strength AND meeting 56-day resistance requirements	Pay factor for mix below 28-day specified strength AND <2 kOhm-cm below 56-day resistance requirements	Pay factor for mix below 28-day specified strength AND ≥2 kOhm-cm below 56-day resistance requirements	Pay factor for mix meeting 28-day specified strength AND <2 kOhm-cm below 56-day resistance requirements	Pay factor for mix meeting 28-day specified strength AND ≥2 kOhm-cm below 56-day resistance requirements
1-499	0.90 (90%)	0.88 (88%)	0.85 (85%)	0.98 (98%)	0.95 (95%)
500-549	0.80 (80%)	0.78 (78%)	0.75 (75%)		
550-599	0.70 (70%)	0.68 (68%)	0.65 (65%)		
600 or above	Remove & Replace	Remove & Replace	Remove & Replace		

c. If average strength of the cylinders set does not meet 28-day strength requirements in Table 1 (the cylinders original cylinders ~~marked with "A" and "B"~~) and also does not meet them at 56 days (the additional cylinders if cast ~~marked with "C" and "D"~~), then core samples (for structural concrete), or non-destructive test (for non-structural concrete) should be obtained within 7 calendar days – three at a time, for each strength test/non-destructive test. If the core or non-destructive test meets the strength requirements in the Table 1, then reduce price concrete with the pay factor in Section 500.3.06.A.3~~2~~.b above may be accepted.

(1) Coring for Determination of Structural Adequacy: Notify the Engineer 48 hours prior to taking core samples. The Engineer will select the size and location of the drilled cores so that the structure is not impaired and does not sustain permanent damage after repairing the core holes. Sample three undamaged cores taken from the same approximate location where the questionable concrete is represented by the low strength concrete test cylinders. Repair core holes after samples are taken.

(2) Core Testing: Test the cores in accordance with ASTM C 42. Test the cores after obtaining the samples within three calendar days.

d. If average strength of the cores does not meet a minimum pay factor of 0.65~~70~~ (or 65~~70~~%), then concrete will be rejected, and will be removed and replaced at no additional cost to the Department. For all concrete materials including both structural concrete and non-structural concrete, core samples have to be obtained for testing and for the decision of rejection. Non-destructive test results will not be used for the decision of rejection of the concrete in-place.

B. Honeycombed Area Check

If there are honeycombed areas that extend beyond the reinforcement steel, the Engineer may reject the entire pour with the honeycombed area.

C. Bridge Deck Slab Concrete Inspection

The Engineer will carefully observe the construction methods used during all phases of the bridge deck slab construction. These phases include the following:

- Metal form installation
- Reinforcement location and fastening
- Concrete item composition
- Mixing procedures
- Concrete placement and vibration
- Bridge deck finishing

Provide the needed facilities for the Engineer to safely and conveniently inspect the concrete.

The concrete inspection procedure is as follows:

1. After the deck concrete has been in place for at least two days, the Engineer will sound a hammer on at least two areas of the deck for each slab pour. This test checks for concrete soundness and form bonding.

   The two areas will encompass at least 10 percent of the total area of the deck pour.
2. The Engineer will sound other areas of the deck randomly.
3. If the Engineer doubts the soundness of an area, or if the Engineer decides that the concrete placement procedures used call for an inspection of the underside of the deck, remove at least one section of the forms for each span in the Contract.
4. Remove the form section after the pour is strong enough and when the Engineer desires to provide visual evidence that the concrete mix and the placement procedures are acceptable.
5. Remove another form section if the Engineer decides changes in the concrete mix or in the placement procedures warrant additional inspection.
6. Where form sections are removed, do not necessarily replace the forms, but repair the adjacent metal forms and supports neatly and securely.
7. When the form is removed, the Engineer will examine the concrete surfaces for cavities, honeycombing, and other defects.
8. If the Engineer finds irregularities but determines that the irregularities do not justify rejection of the Work, repair the concrete as the Engineer directs and give it an ordinary surface finish according to the Contract Specifications.
9. If the concrete where the form is removed is not acceptable, remove additional forms as necessary to inspect and repair the slab.
10. Modify the construction methods as required by the Engineer to create satisfactory slab concrete.
11. Remove or repair all unsatisfactory concrete as the Engineer directs.

    If the construction methods used and the inspection results indicate that the slabs have sound concrete, the Engineer may moderate the amount of random sounding and form removal after a substantial amount of slab has been constructed and inspected.

D. Bridge Deck Surface Check

After the final strike-off of the concrete and as close behind the final strike-off as possible, the Engineer will check the surface with a 10 ft. (3 m) straightedge.

Attach the straightedge to a broom-type handle for easy control and use.

Bridges and approach slabs must meet a 1/8 in. in 10 ft. (3 mm in 3 m) straightedge check made longitudinally and transversely.

E. Ride Quality Test

After the bridge decks and approach slabs are completed, the Contractor will contact the Department's Office of Materials and Testing, Concrete Branch to schedule to have a Ride Quality Test performed using the Lightweight Profiler and a profile index value determined according to GDT 134.

The Department will conduct the test as follows:

1. Obtain Profile Index Values for all bridge decks and approach slabs not detailed to include an overlay.
2. Bridges and approach slabs must meet the straightedge check limits described in Subsection 500.3.06.D, *Bridge Deck Surface Check*.
3. Obtain profiles in the wheel paths and in safety areas to within 6 ft. (1.8 m) of barrier or curb lines.
4. Average the profile index values for bridge decks including the approach slabs for the left and right wheel path for each lane.

   The average value must not exceed 15 in./mile (235 mm/km) for each lane.

After the test is complete, correct individual bumps or depressions that exceed 2/10 in. (5 mm) from the blanking band on the profiler trace.

The deck surface must then meet a 1/8 in. in 10 ft. (3 mm in 3 m) straightedge check made transversely.

Correct bridge decks and approach slabs that do not pass the Ride Quality Test as described in Subsection 500.3.05.AG, *Complete Corrective Work*.

500.3.07 Contractor Warranty and Maintenance

General Provisions 101 through 150.

500.4 Measurement

This work is measured for payment either per cubic yard (meter), per Lump Sum, or per linear foot (meter), whichever is shown on the plans.

- **Seal Concrete.** The quantity of seal concrete to be measured for payment is calculated using the horizontal seal dimensions specified on the Plans.
- **Grooving.** Grooving on bridge decks and approach slabs, completed acceptably according to Subsection 500.3.05.T, *Place Bridge Deck Concrete*, step 9.c, will be measured and paid for by the square yard (meter). Payment is full compensation for furnishing the necessary equipment and performing the Work.
- **Class B Concrete.** Class B concrete used for base and pavement widening will be measured and paid for by the cubic yard (meter) complete in place and accepted.

500.4.01 Limits

A. Measurement for Separate Payment

There will be no separate measurement and payment for the following:

1. On permanent steel bridge deck forms for concrete deck slabs:
   - Extra reinforcing
   - Extra concrete
   - Other costs incurred because of the requirements of this specification

   All costs are included in the Lump Sum prices bid for superstructure concrete and superstructure reinforcement.

B. Payment per Cubic Yard (Meter)

Measurement limits on payment per cubic yard (meter) are:

1. Bridges, Concrete Culverts, Headwalls, and Retaining Walls

   The quantity of concrete measured for payment is the algebraic summation of the Base Pay Quantity and authorized quantity changes.

   If additional quantities are necessary because of any of the following, these quantities are measured separately for payment:

   - Rocks were removed carefully but additional quantities are needed because footing depth and keyway dimension are irregular from unanticipated rock removal.
   - Voids or crevices exist within the spread footing area.
   - The Engineer authorized filling trenches cut in rock outside footing areas to ease dewatering.

   These additional quantities will be paid as filler concrete per cubic yard (meter).

2. Seals

   When the Plans do not require a seal but a seal becomes necessary, or when the Plans do not show seal dimensions, the maximum pay dimensions in each direction will be the Plan dimension of the structural footing plus 3 ft. (1 m), with 18 in. (460 mm) on each side.

   If the Contractor uses lesser dimensions, measurement is based on the lesser dimensions. Concrete placed beyond the maximum pay limits are not measured.

C. Payment per Lump Sum

For Lump Sum payment, determine the quantities required before submitting the bid.

The concrete quantity must conform to the Plan dimensions. Measurement is made as a unit, complete in place, and includes the following:

- Diaphragms
- Sidewalks
- Concrete parapets

Measurement does not include concrete in the following items that will be paid for separately:

- Concrete handrailing
- Barriers
- Prestressed bridge members.

Payments for parapets placed by slip-form method is included in the Lump Sum price bid for superstructure concrete.

Unless otherwise shown on the Plans, the cost of steel joints and metal bearing assemblies used in structures where there is no structural steel Pay Item are included in the Contract Price for superstructure concrete.

D. Retaining Wall Incidentals

Retaining wall incidentals will be measured for payment as follows:

1. Drainage Systems

   Drainage items required by Special Plans are measured for payment by the unit specified on the plans only when they are set up as specific Pay Items and are paid for separately. Otherwise, their costs are included in the Contract Price for concrete.

   Payment is full compensation for the costs of excavation and backfill necessary to place the drainage items required by Special Plans.

   The following are not measured for separate payment. Costs are included in the Contract Price for concrete.

   - Sand blankets
   - Crushed or broken stone
   - Weep holes

2. Miscellaneous

   The following are not measured for separate payment. Costs are included in the Contract Price for concrete.

   - Expansion material
   - Rubber or polyvinyl plastic water stops

E. Utility Installation Hardware

The cost of placing utility hardware items is included in the Contract Price for the class of concrete the items are placed in.

500.5 Payment

This Work will be paid for at the Contract Price per cubic yard (meter), per Lump Sum, or per linear foot (meter), each complete in place and accepted.

Payment is full compensation for all things, including incidentals, and direct and indirect costs, to complete the Work.

Payment will be made under:

Item No.	Item	Payment
500	Superstructure concrete class_____, Bridge no.______	Per lump sum
500	Concrete handrailing (designation)	Per linear foot (meter)
500	Class_____concrete	Per cubic yard (meter)
500	Class_____concrete, high-early strength	Per cubic yard (meter)
500	Seal concrete	Per cubic yard (meter)
500	Class B concrete base or pavement widening	Per cubic yard (meter)
500	Class_____concrete including reinforcement steel	Per cubic yard (meter)
500	Class A concrete—filler	Per cubic yard (meter)
500	Class_____concrete—retaining wall	Per cubic yard (meter)
500	Grooved concrete	Per square yard (meter)
500	Concrete barrier	Per linear foot (meter)

500.5.01 Adjustments

A. Contractor Costs

Assume the following costs:

1. Costs related to rejected concrete and removing rejected concrete
2. Costs of forming an approved construction joint, removing a partial pour, or completing other remedial measures requested by the Engineer unless the fault lies solely with the Department
3. Costs of repairing, removing, and replacing falsework as directed by the Engineer
4. Costs of repairing, removing, or replacing forms
5. Costs of air-blown mortar to repair honeycombed areas, if required by the Engineer
6. Costs of using a higher class of concrete to widen existing bases or bases and pavements
7. Costs related to obtaining an approved specialty mix design.

B. Ride Quality Testing

The Department will conduct ride quality testing of bridge decks and approach slabs only twice per bridge at no cost to the Contractor.

The Department will conduct additional ride quality testing at the cost of $2000 per test.

The Department may issue a pay reduction based on the square yards (meters) of the span not passing the required 15 in./mi (235mm/km), and not having any bumps or depressions greater than 2/10 in. (5mm) required in Subsection 500.3.06.E. This pay reduction will be calculated based on SOP 48 for Bridge and Approach Penalties. A minimum of $1500.00 per bridge will be assessed for any pay reductions.

C. Plastic Shrinkage Crack Repair

The Engineer will determine how to repair cracks caused by plastic shrinking. Repair cracks at no cost to the Department.

D. Plan Quantities

For all bridges (except seal concrete), concrete culverts, headwalls, and retaining walls, the quantities shown on the Contract Plans, including Standard Plans, will be considered the Base Pay Quantity.

For seal concrete, the Plan quantities are approximate and are for estimating purposes only. The quantities will not be considered as Base Pay Quantities.

Calculated additions or deductions will be applied to the Base Pay Quantity when the Engineer makes authorized changes. Changes include, but are not limited to, authorized changes in the following:

- Footing dimensions
- Lengthening or shortening of concrete culverts
- Correcting Plan Quantities
- Dimension errors
- Multi-barrel culvert wall thicknesses
- Lengthening or shortening bridge columns
- Raising or lowering foundations

Calculations of the Base Pay Quantity and any changes will be made as follows:

1. No deductions will be made for the volume of concrete used by scorings, panels, and chamfers if the individual areas are less than 1 in.^{2} (645 mm^2).

   The volume of concrete in fillets of the same area will be neglected.
2. The volume of structural steel and of steel and concrete piling encased in concrete will be deducted.
3. The volume of timber piling encased in concrete will be deducted on the basis of 0.8 ft.^{3}/linear foot (0.07 m^3/linear meter) of pile.
4. No deduction will be made for the volume of concrete displaced by the following:
   - Steel reinforcement
   - Shear connectors
   - Floor drains (unless they are paid for as separate Pay Items)
   - Incidentals such as expansion material
   - Joint sealing compound
   - Utility thimbles and hangers

E. Filler Concrete

Filler concrete, measured as described in Subsection 500.4.01.B.1, *Bridges, Concrete Culverts, Headwalls, and Retaining Walls*, will be paid at 40 percent of the Contract Price per cubic meter for Class A Concrete or Class AA Concrete.

F. Seal Concrete

If there is no Contract Price for seal concrete, payment will be per cubic yard (meter), measured as described in Subsection 500.4.01.B.2, *Seals*, and will be paid at 60 percent of the Contract Price per cubic yard (meter) for Class A concrete.

G. Lump Sum Payment Adjustments

Adjust the payment as follows:

1. Authorized Change Adjustments

   When authorized changes are made as described in Subsection 500.5.01.D, *Plan Quantities,* the lump sum payment may be adjusted on a pro rata basis or according to Section 104 and as determined by the Engineer.

   The Plans show tabulated quantities as a service. This does not relieve any responsibility to conform to plan details.
2. Optional Plan Feature Adjustments

   If exercising an optional Plan feature, the Base Pay Quantity will not be changed if it is the only quantity change involved.

However, if other changes are necessary, the quantity change resulting from the optional feature will be considered in the necessary quantity adjustments.

3. Falsework for Post-Tensioned Box Girder Bridge Adjustments

   When the falsework is completed for post-tensioned box girder bridges, 20 percent of the Lump Sum superstructure concrete price will be paid.

   Additional payments made as the concrete is placed must be adjusted for the payment for falsework. In other words, payment for concrete placed will be based on 80 percent of the superstructure bid price.

4. When Metal Deck Forms are used and have been placed, payment in the amount of 5% of the Lump Sum Superstructure Concrete price will be made. For Post-Tensioned Box Girder Bridges, this percentage (5%) will apply to that part of the superstructure

500.6 Appendix A: Embodied GHG Emissions (Report Only - Optional)

Notes:

1. Embodied greenhouse gases (GHGs) are to be reported only; this is optional. GHGs shall not be used as a primary means to specify concrete but the example calculations provided in Appendix A may be used for project specific emission limits.
2. GHGs may be attested to by the concrete producer using either Type I and Type III Environmental Product Declarations (EPDs) conforming to ISO 14025. Embodied GHGs refers only to cradle-to-gate emissions associated with the production and transportation for a unit volume of concrete. Use product EPDs to determine the carbon equivalent intensity for each mix constituent.
3. Table A.1 includes embodied emission guidelines from the General Services Administration. The limits are industry wide averages from 2022. The emissions are to be interpreted as guidelines only.

Table A.1—Embodied Emission Guidelines

English	
Class of Concrete	**Maximum Embodied Greenhouse Gases (kg CO_2 eq./yd^3)**
AAA	296
AA1	296
D	281
AA	266
A	235
B	186
CS	186
Metric	
Class of Concrete	**Maximum Embodied Greenhouse Gases (kg CO_2 eq./m^3)**
AAA	385
AA1	385
AA	346
A	306
B	242
CS	242

Embodied Emissions Calculation

Mix Embodied Emissions (kg CO_2 eq./yd^3) = $\sum_{i=1}^{n} A_i\,(\text{kg } CO_2 \text{ eq/lb}) * \text{Material Proportion}_i\,(\text{lb/yd}^3)$

Where A_i is the emission intensity of the ith mix constituent and the ith material proportion is the mass of each mix constituent per unit of concrete for a mix with n different constituents.

The units for emission intensity should be in kg CO2 eq / yd^3. Adjustments for reported units from a material EPD shall be made to ensure units match throughout the calculation. Typical reported EPD units are kg CO2 eq / ton and kg CO2 eq / metric ton.

Note:

1. 1 ton = 2000 lb
2. 1 metric ton = 2200 lb

Sample Calculation

Table A.2—Sample Calculation

Raw Material	Material Embodied GWP (**kg CO_2** eq/ton)	Class AAA Mix Proportions (lbs/yd^3)	Constituent Embodied GHG **kgs CO_2** eq
Type II	942	575	270
Fly Ash	198	101	10
Fine Aggregate	3	1135	1
Coarse Aggregate	4	1859	4
		Total	286

Mix Embodied Emissions (kg CO_2 eq./yd^3) = $\left(942\,\frac{kg\ CO2\ eq}{ton}*\frac{1\ ton}{2000\ lb}*575\frac{lb}{yd^3}\right)+\left(198\,\frac{kg\ CO2\ eq}{ton}*\frac{1\ ton}{2000\ lb}*101\frac{lb}{yd^3}\right)+\left(3\,\frac{kg\ CO2\ eq}{ton}*\frac{1\ ton}{2000\ lb}*1135\frac{lb}{yd^3}\right)+\left(4\,\frac{kg\ CO2\ eq}{ton}*\frac{1\ ton}{2000\ lb}*1859\frac{lb}{yd^3}\right)=286\,\frac{kg\ CO2\ eq}{yd^3}$

The embodied GHG emissions for the sample mix is 286 $\frac{kg\ CO2\ eq}{yd^3}$. This represents the embodied GHG emissions associated with production and transportation to the batch plant. Additional emissions associated with construction and long-term maintenance are not accounted for in this calculation and should be determined separately if required.

APPENDIX E: SECTIONS 500 HPC, 504 AND 452

INTRODUCTION

This appendix addresses performance-based specification for concrete with high early strength, as detailed in GDOT sections 500 HPC, 504 24-hour accelerated strength concrete, and 452 full slab depth replacement. Section 500 HPC is relevant to high performance concrete used for precast bridge elements like beams and piling. Section 504 is for high early strength concrete, achieved in 24 hours or 3 days. Section 452 covers full depth slab replacement for partial or full pavement repair. Tables 27-28 show the current specifications for Section 500 HPC and 504 24- hour accelerated strength. Section 452 relies on Section 504 for the mix design and curing. Each contains both prescriptive (e.g., minimum cement factor, maximum w/c) and performance (e.g., minimum compressive strength) elements.

Table 27. Section 500 HPC mixture requirements

English									
Class of Concrete	Coarse Aggregate Size No.	(1) Minimum Cement Factor (lbs/yd^3)	Maximum Water/ Cement ratio (lbs/lbs)	(2) Slump Acceptance Limits (in) Lower-Upper		Entrained Air Acceptance Limits (%) Lower-Upper		(3) Minimum Compressive Strength at 56 days (psi)	Maximum Chloride Permeability at 56 days (Coulombs)
"AAA HPC"	67	650	.330	2	7	3.5	6.5	Beams – As shown on the Plans Piling – 5000	Beams – 3,000 Piling – 2,000
Metric									
Class of Concrete	Coarse Aggregate Size No.	(1) Minimum Cement Factor (kg/m^3)	Maximum Water/ Cement ratio (kg/kg)	(2) Slump acceptance Limits (mm) Lower-Upper		Entrained Air Acceptance Limits (%) Lower-Upper		(3) Minimum Compressive Strength at 56 days (MPa)	Maximum Chloride Permeability At 56 days (Coulombs)
"AAA HPC"	67	386	.330	50	180	3.5	6.5	Beams – As shown on the Plans Piling – 35	Beams – 3,000 Piling – 2,000

Table 28. Section 504 twenty-four hour accelerated strength concrete mixture requirements

Minimum Cement cwt/cu yd. (kg/m^3)	Maximum Water Cement Ratio lbs./ lbs. (kg/kg)	Minimum Compressive Strength at 24 Hours psi (MPa)	Air Content (%)	Slump Range inch (mm)
7.52 (446)	0.45	2500 (17)	3 to 6	2 to 5(50 to 125)

In this effort, strength development is examined in a series of concrete mixtures meant to explore the expansion of the mixture characteristics to include higher SCM replacement levels and to include Type IL cements, which are increasingly available in Georgia. Both SCMs and IL cements can produce concrete with lower early strength. So, for Section 504 and 452, the use of non-chloride accelerator is also examined, in combination with the Type IL cement and SCM.

MATERIALS AND METHODOLOGY FOR GDOT 504 AND 500 SECTIONS

Both Type IL and a more finely ground, high early strength Type IL (HE) were obtained (Argos, Roberta). Table 29 provides the properties of the cements. Class C fly ash (Ecomaterials) replacement was examined at 15%, which is the current GDOT limit, and 30% by mass of cement. A super plasticizing admixture (Master Glenium 7920, Master Builders) and a non- chloride accelerating admixture (X-seed 44, Master Builders) were used. All concretes were produced with a No. 67 crushed granitic gneiss coarse aggregate and a natural sand (Lambert).

Mixing was performed according to ASTM C192, mixing coarse aggregate and some water for at least a minute and then 3 minutes mixing with remaining materials, followed by with 3 minutes of rest and 2 minutes of final mixing. Concrete cylinders, 4x8in, were cast and cured in a fog room until testing. Compression testing was performed at 1, 3, 7, 28 and 56 days according to ASTM C39, testing five samples for each mixture at each age.

Table 29. Cement properties (provided by manufacturer)

	Type IL	Type IL (HE)
Specific Gravity	3.12	3.12
Limestone (%)	11.0	9.4
Blane Fineness (m^2/kg)	413	602

ADDITIONAL PERFORMANCE METRICS FOR GDOT 504 AND 500 SECTIONS

Tables 30 and 31 provide details on the concrete mixtures examined, toward understanding the role of materials selection and mixture proportioning in early strength development for concrete specified under GDOT Sections 500 HPC and 504. As shown in Table 30, for HPC, the effects of Type IL and IL(HE) will be explored, as are lower cement contents and higher fly ash replacement values. As shown in Table 31, the effect of decreasing cement content on early age strength was examined, where SCM content was varied and the use of a non-chloride accelerator was included with the 30% fly ash mixtures. In this way, these series of mixes include compositions that extend outside the current prescriptive ranges. Because of the limited time available to conduct these additional tests, the number of mixtures tested were limited; further testing is recommended.

Table 30. Mix designs for GDOT Section 504

Mixture	Water (lb/yd^3)	Cement (lb/yd^3)	Fine Aggregate (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Master Glenium 7920 (lb/yd^3)	Fly Ash (lb/yd^3)	Slump (in)
Type IL	313	756	1117	1819	4	0	8.5
Type IL (HE)	313	756	1108	1819	4	0	7.5
Type IL15% Class C fly ash	314	642	1098	1819	2.5	113	7.5
Type IL 30% Class C fly ash	315	529	1080	1819	2	227	7.25

Table 31. Mix designs for GDOT Section 500 HPC

Mixture	Water (lb/yd^3)	Cement (lb/yd^3)	Fine Aggregate (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Master Glenium 7920 (fl oz./cwt)	Accelerator (fl oz./cwt)	Fly Ash (lb/yd^3)	Slump (in)
Type IL	288	849	1202	1819	3.5	0	0	2.25
Type IL 15% Class C fly ash	289	721	1181	1819	3.5	0	127	5.50
Type IL 30% Class C fly ash w/ Accelerator	289	594	1160	1819	3.5	22	255	8.00

RESULTS

Overall, the majority of the mixtures with compositions beyond the current largely prescriptive specifications met the required compressive strength. As shows in Figure 48, the minimum strength criteria in Section 500 HPC was met for all mixes at all ages. This demonstrates that the current specification's 56-day strength requirement for piling and the requirement of strength of 1500 psi to lift from precasting bed (as specified in 500.2.01G) typically at 1-day relevant for precast concrete can be met with Type IL cements and with lower cement contents. For the 30% fly ash mixture, the addition of the accelerator produced 1-day strength matching that of the 15% fly ash mixture. This suggests that even lower cement contents could be explored for HPC.

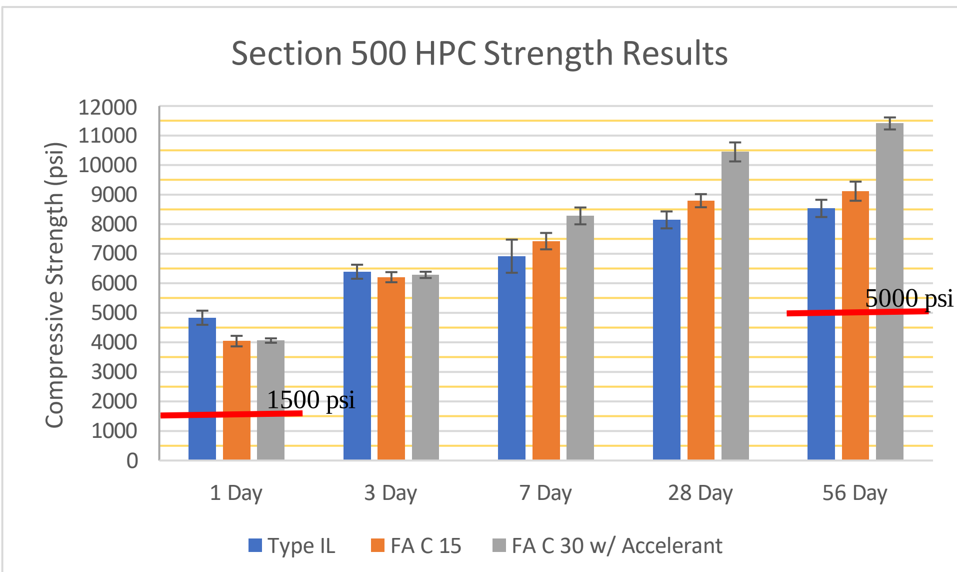

Figure 48. Graphs. Average compressive strength for Section 500 HPC mixtures.

Similarly, Figure 49 shows that the minimum 1-day and 3-day compressive strength of requirements of Section 504 have been met by the Type IL, IL (HE) and 15% fly ash mixtures. The 30% fly ash mixture met the 3-day strength requirement, but not the 1-day requirement; this could be an additional application for a non-chloride accelerator. Another notable point is the higher strength of the Type IL (HE) at all ages. Shrinkage, however, was not measured in this work, but prior effort [Shalan, 2016] has shown that more finely ground Type IL cements can experience excessive shrinkage [191].

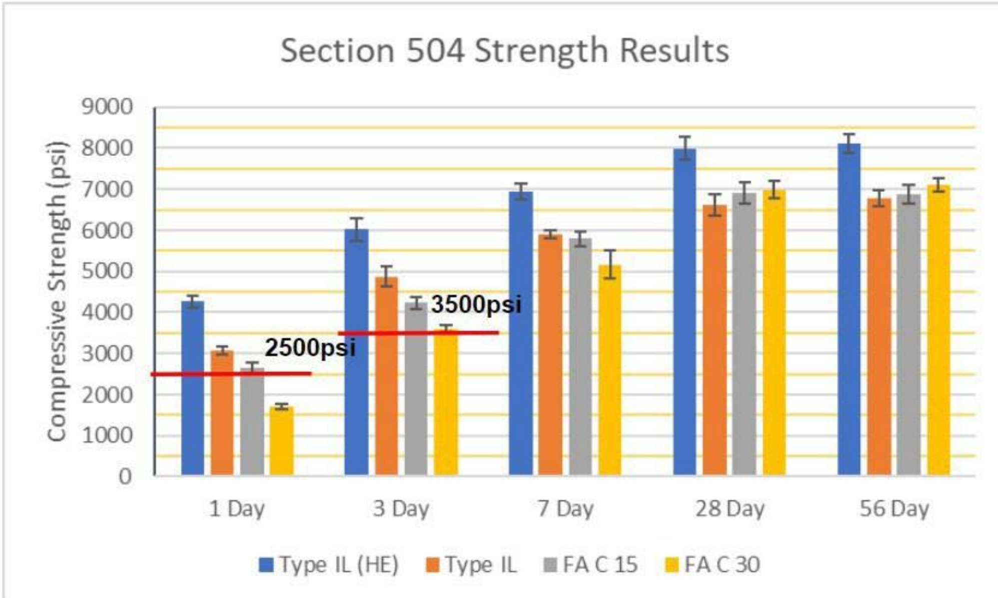

Figure 49. Graphs. Average compressive strength for Section 504 mixtures.

PROPOSED UPDATES TO CONCRETE SPECIFICATIONS

In this study, based on the strength measurements for a limited series of concrete mixes, it is apparent that expanded mix compositions can meet the necessary strength for these applications. Specifically, it is recommended that the the minimum cement factor, present among the current state specifications, be removed. Additionally, current limits on the maximum amount of SCMs, including fly ash, allowed is also recommended to be removed. Furthermore, for Section 452, it is proposed to consider a minimum strength by opening time using relationships established by Delatte [2023] to allow more flexibility for opening to traffic. Lastly, inclusion of Type IL Portland cement is recommended [190]. Specific recommended changes, shown as redlines to existing Sections 452, 500 HPC, and 504 specifications, are included at the end of this appendix.

CONCLUSIONS AND FUTURE WORK

The proposed performance specifications remove prescriptive limits of proportions in concrete mixes and allowable materials. This is expected to increase flexibility for producers when designing mixes through allowing greater material replacements when designing for the strength and durability requirements. The proposed performance metrics include removing the minimum cement factor across sections 500 HPC and 504 and adding Type IL into high performance concrete and allowing Type IL, IL(HE) cements in these high strength applications. Additionally, to give greater flexibility, the option of specifying strength at an opening time, rather than a specific age, is suggested.

However, because this study was limited in time and scope, additional testing is needed to better understand the implications of these proposed changes. This includes examination of a broader range of SCMs (e.g., calcined clays or Metakaolin), silica fume, Class F fly ash, ground glass) and a broader range of replacement levels, for early strength mixes. This would further increase the flexibility for producers when designing mixes to cater to more optimal or easily accessible materials. Further, examination of higher cement replacement values will allow for the quantification of environmental and economic impact at the time of construction and through savings due to increased durability. It is recommended to examine the use of a broader range of Type IL cements in early strength mixes. Recommendations for further admixture usage that could be tested would include calcium chloride accelerators and a greater range of non-chloride- based accelerators. Recommendations of additional performance metrics, such as non-destructive strength evaluation (e.g., maturity) and shrinkage testing. Shrinkage testing is vital to minimize the potential for cracking in early strength mixes and for preserving prestress in precast HPC elements.

APPENDIX F: REDLINED SECTION 500 HPC

Georgia Department of Transportation

State of Georgia

Special Provision

Section 500-Concrete Structures

Delete Subsection 500.1 and substitute the following:

This work consists of manufacturing and using High Performance hydraulic cement concrete to construct precast-prestressed concrete bridge members as shown in the plans and using normal weight hydraulic cement concrete to construct structures as shown in the Plans.

Add the following to Subsection 500.1.02.A:

Section 831 -Admixtures

Add the following to Subsection 500.1.02.B:

AASHTO T277

Add the following to Subsection 500.1.03.A:

High Performance Concrete Mix Designs

The Fabricator is responsible for all concrete mix designs. Ensure that concrete mixes contain enough cement to produce workability within the water-cement ratio specified in Table lA-High Performance Concrete Mix Table, below.

Submit a mix design for approval to the Office of Materials and Research. Include the sources and actual quantity of each ingredient and laboratory results that demonstrate the ability of the design to attain both the required compressive strength and chloride permeability by 56 days.

Include laboratory compressive strength test results of at least eight test cylinders prepared and cured according to AASHTO T 126. Ensure these test cylinders are made from two or more separate batches with an equal number of cylinders made from each batch.

Also include laboratory chloride permeability test results of at least two test specimens prepared and tested according to AASHTO T277. Ensure these test specimens are made from two or more separate batches with an equal number of specimens made from each batch.

Table 1A—High Performance Concrete Mix Table

English									
Class of Concrete	Coarse Aggregate Size No.	~~(1) Minimum Cement Factor (lbs/yd³)~~	Maximum Water/ Cement ratio (lbs/lbs)	(2) Slump Acceptance Limits (in) Lower-Upper		Entrained Air Acceptance Limits (%) Lower-Upper		(3) Minimum Compressive Strength at 56 days (psi)	Maximum Chloride Permeability at 56 days (Coulombs)
"AAA HPC"	67	~~650~~	.330	2	7	3.5	6.5	Beams – As shown on the Plans Piling – 5000	Beams – 3,000 Piling – 2,000

Metric									
Class of Concrete	Coarse Aggregate Size No.	~~(1) Minimum Cement Factor (kg/m³)~~	Maximum Water/ Cement ratio (kg/kg)	(2) Slump acceptance Limits (mm) Lower-Upper		Entrained Air Acceptance Limits (%) Lower-Upper		(3)Minimum Compressive Strength at 56 days (MPa)	Maximum Chloride Permeability At 56 days (Coulombs)
"AAA HPC"	67	~~386~~	.330	50	180	3.5	6.5	Beams – As shown on the Plans Piling – 35	Beams – 3,000 Piling – 2,000

Section 500: Concrete structures

1. Determine the slump acceptance after the addition of high-range water reducer.

2. Determine the minimum compressive strength at 56 days using 4 in. diameter x 8 in. high (100 mm x 200 mm) cylinders.

Add the following to Subsection 500.2 Table 3:

Fly Ash 831.2.03.A.1

Silica Fume 831.2.03.A.4

Add the following note to Subsection 500.2 Table 3:

4. Use Type I, III, or IL Portland cement in High Performance concrete. Do not use air-entraining cement.

Add the following to Subsection 500.3.04.D.4:

~~a.~~ For High Performance concrete, fly ash may be used as an additive at an addition rate not to exceed 15% of the cement by weight. Fly ash may be used as an additive at an addition that may exceed 15% of the cement by weight if used in conjunction with a non-chloride accelerator.

Add the following to Subsection 500.3.04.D:

6. Silica Fume

Silica Fume may be used as an additive at an addition rate not to exceed 10% of the cement by weight.

Section 504 ~~Twenty-FourHour~~ Accelerated Strength Concrete

504.1 General Description

This work consists of manufacturing and placing accelerated strength concrete designed to produce a compressive strength of 2,500 psi (17 MPa) within 24 hours.

Except as modified in this Specification, the provisions of Section 500 shall apply to concrete produced and placed under this Specification.

504.1.01 Definitions

General Provisions 101 through 150.

504.1.02 Related References

A. Standard Specifications

Section 109-Measurement and Payment

Section 500-Concrete Structures

B. Referenced Documents

AASHTO M 194, Type E, Table I

504.1.03 Submittals

A. Approve Chemical Admixture for Concrete

Ensure that the manufacturer submits an affidavit that the chemical admixture for concrete meets the requirements of AASHTO M 194, Type E, Table I.

B. Establish Concrete Mix Proportions

Choose one of the following two procedures for establishing concrete mix proportions for concrete placed under this Specification.

Notify the Engineer of the chosen procedure at least 45 days before placing the concrete.

1. Concrete Mix Proportions Established by the Contractor

   The Contractor may propose specific concrete mix design proportions for concrete placed under this Specification. In this case, the Contractor shall meet these requirements:

   a. Ensure that all materials are from approved sources or from materials stored or stockpiled at the site.

   b. Have all materials tested before they are used.

   c. Have the laboratory verify that the proposed proportions will produce concrete that develops 2,500 psi (17 MPa) within 24 hours.

      Proposed mixes may be approved without laboratory design study when they include commonly used material combinations.

2. Concrete Mix Proportions Established by the Department

   The Contractor may choose to have the Department establish concrete mix proportions. However, the Department's approval of the design mix does not relieve the Contractor of the responsibility to produce concrete with the specified compressive strength of 2,500 psi (17 MPa).

   The Department will establish the proportions as follows:

   a. The Contractor shall notify the Office of Materials and Research of the proposed sources of all materials.

   b. The Department will establish the job mix proportions from materials representative of the materials proposed for use, provided all materials conform to their respective Specifications.

c. The Office of Materials and Research will determine the following based upon materials intended for use:

Minimum cement content

- Required water content
- Quantities of aggregate
- Addition rates of admixtures

d. The Department will make the proportions available as public information within one month after the Contractor proposes the material sources.

e. The Department will not allow materials to be substituted after releasing an approved design unless the Office of Materials and Research approves of the substitution.

The Department will base job mix design proportions upon the following table:

~~Minimum Cement cwt/cu yd (kg/ m³)~~	Maximum Water Cement Ratio lbs/ lbs (kg/kg)	Minimum Compressive Strength at 24 Hours psi (MPa)	Air Content (%)	Slump Range inch (mm)
~~7.52 (446)~~	0.45	2500 (17)	3 to 6	2 to 5(50 to 125)

The Department will accept initial design admixture meeting the requirements of materials established in this Specification. However, the Department will not approve any combination of admixture and cement that produces undesirable characteristics of set time or strength development.

504.2 Materials

All materials shall meet the requirements of the following Specifications:

Material	Section
Portland Cement (~~Type I or Type III~~) (Type IL, IL (HE), or Type I, I/II, III)	830.2.01
Fly Ash, Raw or Calcined Natural Pozzolan, Slag, and Microsilica	831.2.03
Air-Entraining Admixtures	831.2.01
Coarse Aggregate, Class A or B, Gravel or Stone	800.2.01
Fine Aggregate, Size No. 10	801.2.02
Chemical Admixtures	831.2.02
Calcium Chloride	884.2.01
Water	880.2.01

For Accelerated Strength concrete, fly ash maybe used as an additive at an addition that mayexceed 15% of the cement by weight if used in conjunction with an accelerator. If reinforced, a non-chloride accelerator shall be used..

The concrete acceleration admixtures maybe either of the following:

- Calcium chloride
- Non-Chloride Accelerator (ASTM C-494)
- A chemical admixture

The Engineer must authorize chemical admixtures before they are used for concrete. Admixtures will be approved only if an acceptable concrete design is established in the laboratory with materials representative of those proposed for use.

Do not use accelerators containing chlorides in prestressed concrete; or, in bridges or box culverts when the concrete containing the additive will contact the reinforcement steel

504.2.01 Delivery, Storage, and Handling

General Provisions 101 through 150.

504.3 Construction Requirements

General Provisions 101 through 150.

504.3.01 Personnel

A. Quantity of Personnel

Provide enough labor to place, consolidate, and screed each batch of concrete within one hour after introducing the cement and first mixing water into the mix.

Do not place concrete when there are not enough personnel to meet this requirement.

504.3.02 Equipment

A. Quantity of Equipment

Provide enough equipment to place, consolidate, and screed each batch of concrete within one hour after introducing the cement and first mixing water into the mix.

Do not place concrete when there is not enough equipment to meet this requirement.

B. Portable Mixers

The Engineer may approve portable mixers when placement quantities at a given location are less than one cubic yard (meter).

504.3.03 Preparation

General Provisions 101 through 150.

504.3.04 Fabrication

General Provisions 101 through 150.

504.3.05 Construction

A. Batch and Mix Materials

1. Transit-Mixed Concrete

   When transit-mixed concrete is used for concrete containing an acceleration admixture, do the following:

   a. At the plant, mix the concrete ingredients, excluding the acceleration admixtures and 3 gal (15 L) of withheld water per cubic yard (meter) of concrete, at mixing speed for 35 revolutions of the drum.
   b. Mix the concrete enroute to the job site at an agitating speed of no more than three revolutions per minute.
   c. At the job site, add the acceleration admixture and withheld mixing water to the concrete according to these requirements:
      1) The Engineer will approve the method of adding the acceleration admixture and withheld mixing water.
      2) The Contractor shall measure the admixture into the concrete with an accuracy of plus or minus three percent.
      3) The Contractor shall not add accelerating admixture to concrete that has attained the age of 45 minutes as measured from the beginning of the initial mixing at the plant.
   d. Mix the concrete for 40 additional revolutions at mixing speed.

2. Central-Mixed Concrete

   When central-mixed concrete is used for concrete containing an acceleration admixture, do the following:

a. Shrink-mix all concrete ingredients, excluding acceleration admixture and 2 gal (10 L) of withheld water per cubic yard (cubic meter), in the central mixer.

~~b.~~ Mix the above ingredients enroute to the job site at agitating speed.

Section 504---Twenty-Four Hour Accelerated Strength Concrete

All other provisions of Subsection 504.3.05.A.1, "Transit-Mixed Concrete," shall apply for adding the acceleration admixture and mixing the concrete at the job site.

B. Cure Concrete

Cure the concrete according to Subsection 500.3.05.Z, "Cure Concrete," except that the Engineer may waive the concrete curing period when test results indicate the compressive strength exceeds 2500 psi (17 MPa).

All provisions of Subsection 500.3.05.X, "Pour Concrete in Cold Weather," shall apply except that the protection requirements in step 2 of Subsection 500.3.05.X may be suspended when test results indicate the compressive strength exceeds 2500 psi (17 MPa).

504.3.06 Quality Acceptance

A. Compressive Strength Testing

Compressive strength testing are conducted as follows:

1. Georgia DOT personnel will cast four test cylinders for each day of concrete placement.
2. Georgia DOT personnel will store the cylinders on or adjacent to the pour in a moist condition.
3. Minimum compressive strength shall be according to either of the following for an average of two specimens

Strength development at 24 hours	2,500 psi (17 MPa)
Strength development at 3 days	3,500 psi (24 MPa)

504.3.07 Contractor Warranty and Maintenance

General Provisions 101 through 150.

504.4 Measurement

~~Twenty-Four Hour~~ Accelerated strength concrete will be measured for payment by the square yard (meter) or cubic yard (meter) as indicated on the Plans and in the Proposal.

- Square yard (meter) measurements shall be as defined in Section 109.
- For structure concrete, cubic yard (meter) measurements will be the algebraic summation of the Plan quantity and any authorized quantity changes.

504.4.01 Limits

General Provisions 101 through 150.

504.5 Payment

~~Twenty-Four Hour~~ Accelerated strength concrete will be paid for at the Contract Unit Price bid either by the cubic yard (meter) or square yard (meter) as shown on the Plans or in the Proposal.

Payment will be made under:

Item No. 504	~~Twenty-Four-Hour~~ Accelerated Strength Concrete	Per cubic yard (meter)
Item No. 504	~~Twenty-Four-Hour~~ Accelerated Strength Concrete	Per square yard (meter)

504.4.02 Adjustments

General Provisions 101 through 150.

APPENDIX H: REDLINED SECTION 452 FULL DEPTH SLAB REPLACEMENT

Section 452-Full Depth Slab Replacement

452.1 General Description

This work includes replacing Portland cement concrete pavement slabs, full or partial length. Remove the slabs according to the Plans or as directed by the Engineer. See Section 609.

452.1.01 Definitions

General Provisions 101 through 150.

452.1.02 Related References

A. Standard Specifications

Section 431-Grind Concrete Pavement

Section 461-Sealing Roadway and Bridge Joints and Cracks

Section 504 ~~Twenty-Four Hour~~ Accelerated Strength Concrete

Section 609-Removal of Portland Cement Concrete Roadway Slabs

Section 833-Joint Fillers and Sealers

Section 853-Reinforcement and Tensioning Steel

Section 886-Epoxy Resin Adhesives

B. Referenced Documents

GDT72

452.1.03 Submittals

Obtain approval of the mix design from the Office of Materials and Research before using the mix.

452.2 Materials

Ensure that materials used in full depth slab replacement conform to the following Specifications:

Material	Section
Accelerated Strength Concrete	~~Section 504~~
Dowel Bars and Bar Coatings	~~Subsection 853.2.08~~
Epoxy	~~Section 886~~
Silicone Sealant	~~Subsection 833.2.06~~

452.2.01 Delivery, Storage, and Handling

General Provisions 101 through 150.

452.3 Construction Requirements

452.3.01 Personnel

Furnish traffic control while the Department conducts slab movement testing descnbed in Subsection 452.3.06.B. "Quality of Work" at no additional cost to the Department.

452.3.02 Equipment

Use sufficient equipment to perform work such as drilling dowel holes, setting dowels, spreading, striking off, consolidating, screening concrete, and sawing and sealing joints. Obtain the Engineer's approval of the equipment before starting the work.

Place the dowels at the locations specified on the Plans by using pneumatic or hydraulic drills and bits that will drill a 1-3/8 in (35 mm) diameter hole in the existing concrete faces.

452.3.03 Preparation

A. Clean the Exposed Faces

Before placing the concrete, thoroughly clean the vertical exposed faces of the existing slabs to remove contaminates.

1. Use wire brushing or other methods approved by the Engineer.
2. Remove existing silicone or other joint sealant from the exposed concrete faces.

B. Preparing Base

Remove debris and standing water from the base. Thoroughly compact loose base material by hand tamping before placing concrete.

452.3.04 Fabrication

General Provisions 101 through 150.

452.3.05 Construction

A. Installing the Dowels

Complete these steps to install the dowels:

1. Use a pneumatic or hydraulic drill to drill a 1-3/8 in (35 mm) diameter hole in the existing concrete faces. Place the dowels at locations specified on the Plans.
2. If the Engineer allows, drill a hole no greater than 1.5 in (38 mm) diameter to insert the dowel bars. Follow these guidelines:
   a. Operate the equipment so as to prevent damage to the pavement being drilled.
   b. Obtain the Engineer's approval for the drilling procedure.
   c. Thoroughly clean the drilled holes of contaminants.
3. Set the type and size of dowels specified in the Plans into the hardened concrete face of the existing pavement with Type VIII epoxy bonding compound that meets the requirements in Section 886.
   a. Place the dowels at locations noted on the Plans with one-half of the dowel protruding out of the pavement.
   b. Place the dowels at the correct horizontal and vertical alignment. Do not misalign them more than 3/8 in (10 mm) within the vertical or oblique plane.
   c. Place enough epoxy in the back of the hole to completely fill the entire cavity around the dowel upon insertion of the dowel bar. Remove excess epoxy.
   d. Use epoxy adhesive packaged in a cartridge with a mixing nozzle that thoroughly mixes the two components as they are dispensed. Use a mixing nozzle at least 8 in (200 mm) long.

      Or, use a machine that mixes the two components thoroughly to the proper ratio as the material is being placed.
   e. Allow the epoxy to harden before placing the concrete to prevent the dowels from moving during the concrete placement.
4. At the free joints shown on the Plans, use epoxy-coated, plain, round, steel dowel bars that meet the requirements of Subsection 853.2.08.

   Coat the protruding portion of the epoxy coated dowels with a thin film of grease or other approved material to ensure proper bond-breaking characteristics.
5. Cleanly saw the edges of the epoxy-coated smooth dowels bars. Do not shear them.

NOTE 1: Never drive dowels into a dowel hole with a sledge hammer or other device.

NOTE 2: Coated dowels will be rejected if they cannot be freely inserted into a dowel hole.

B. Setting Forms

Forms are not required for this work. The vertical faces of the existing pavement and shoulder bordering the replaced slab or joint area serve as the forms.

However, if the shoulder is irregular or unstable:

1. Place a form the full depth of the replaced slab or joint area to maintain a true, straight shoulder joint and to prevent the concrete from intruding into the shoulder area.
2. Compact the foundation under the form true to grade so that the form, when set, will firmly contact the base at the correct grade.
3. Clean and oil the forms before placing the concrete.
4. Wait four hours to remove the forms from the freshly placed concrete, unless otherwise specified. Carefully remove the forms to avoid damaging the pavement.
5. Repair the shoulder to the Engineer's satisfaction at no additional cost to the Department.

C. Placing and Finishing Concrete

The required concrete for the work will be accelerated strength concrete that meets the requirements of Section 504. Obtain mix design approval from the Laboratory before use.

Place the concrete only when the ambient temperature is 40 °F (4 °C) and rising. Do not place concrete when the underlying base material is muddy or frozen.

1. Deposit the concrete within the slab replacement area in a way that requires as little rehandling as possible and prevents mix segregation.
2. Minimize hand spreading as much as possible. But where necessary, use shovels not rakes.

NOTE: Do not allow workmen to walk in fresh concrete with shoes coated with earth or other foreign substances.

3. Fill the replaced slab area with concrete and thoroughly consolidate by rodding, spading, and using sufficient vibration to form a dense homogeneous mass throughout the area.
4. Ensure the final surface area has a uniform appearance and is free of irregularities and porous areas.

   The finished surface, including joints, shall meet a surface tolerance of 1/8 in. in 10 ft (3 mm in 3 m) in any direction.

   For slab replacements done in preparation for resurfacing of the pavement, the finished surface, including joints, shall meet a surface tolerance of 3/16 in. in 10 ft (5 mm in 3 m) in any direction.

Perform necessary corrections by grinding according to Section 431. The Engineer may order replacement if any replaced slab is low in relation to adjacent slabs. The Engineer will require replacement if it is determined that excessive pavement grinding is necessary to match the profile of the full depth slab replacement or if grinding the adjacent pavement would create a drainage problem.

Do the following at no additional cost to the Department:

- Perform all necessary corrections
- Furnish all necessary traffic control personnel, materials, and equipment to detect deviations.
- Grind or replace slabs to correct surface tolerance deviations

If the Project involves resurfacing or grinding the pavement surface, a fht finish will be satisfactory. Otherwise, a broom or hand-tine finish will be required that will produce a surface texture depth of 0.20 in. (5mm)or greater as measured by GDT 72. The Engineer shall approve the finishing method and any deficient areas corrected to his or her satisfaction and performed at your expense.

D. Curing Concrete

Use the applicable portions of Section 504 regarding concrete mix and curing in this work.

E. Sawing and Sealing Joints

Establish transverse and longitudinal joints within the slab replacement area by doing the following:

1. Saw and seal the joints with silicone sealant that meets the requirements of Subsection 833.2.06. Seal according to Plan details and Section 461.
2. Ensure that the width of the sawed joints is 3/8 in (10 mm), unless otherwise directed.
3. Saw and seal the joints as soon as possible, but not more than 60 days after placing the slab, unless the Plans specify otherwise.

   Sawing and sealing of the reestablished joints is included in the bid cost for slab replacement.

F. Protecting from Rain

Properly protect the concrete from rain before the concrete hardens by following these guidelines:

1. Keep the materials to protect the concrete surface available at all times.

   Protective materials include burlap or cotton mats, curing paper, or plastic sheeting material.
2. When rain is imminent, stop the paving operations and begin covering the surface of the unhardened concrete with the protective covering.

G. Working at Night

If night work is authorized on the Project, provide lighting for work performed at night for safety, traffic control, and work control and completion.

Correct unsatisfactory work to the Engineer's satisfaction at no additional cost to the Department.

H. Opening to Traffic

Schedule slab replacements so that the concrete will have a curing time of at least four hours. Complete the work and open the lanes to traffic before sunset the day it is placed, unless authorized otherwise.

Consider a minimum opening strength, as determined in contract for compressive strength:

1. **Must be within limits of 1600-3500 psi for 6-8 hour opening time.**
2. **Must be within limits of 2500-3500 psi for 20-24 hour opening time.**

The Engineer may require a longer curing period, mix design adjustments, or other corrective action to ensure sufficient concrete strength development before opening to traffic.

452.3.06 Quality Acceptance

A. Surface Tolerance

Ensure that the finished surface tolerance, including joints, is 1/8 in per 10 ft (3 mm in 3 m)in any direction. Make corrections by grinding according to applicable items in Section 431.

B. Quality of Work

Complete work that meets the requirements in the Specifications and Plans.

Until Final Acceptance of this work, replace damaged or broken slabs due to the following:

- Improper or unsatisfactory methods, equipment, or materials
- Construction or public traffic

Replace the slabs at no additional cost to the Department. The Department may also require removal and replacement of repaired slabs with a differential movement at the transverse joints greater than 0.01 in (0.25 mm) at no cost to the Department. The Department will measure the movement using an 18,000 lb (8165 kg) , single-axle load with dual tires and with the axial load centered 1 ft (300 mm) from the edge of the shoulders as close to the transverse joints as possible. Testing will be done between 3:00 AM and 9:00 AM when slab movement is the greatest. The movement will be measured using dial gauges that can detect movement to the nearest 0.00lin (0.025 mm)..

The Engineer will determine whether the slab movement test is required.

452.3.07 Contractor Warranty and Maintenance

General Provisions 101 through 150.

452.4 Measurement

Full depth replacement slabs are measured for payment by the cubic yard (meter) using the average squared dimensions times the average depth.

Dowels and dowel placement are not measured for separate payment but are included in the Unit Price bid for full depth slab replacement.

452.4.01 Limits

General Provisions 101 through 150.

452.5 Payment

Full depth replacement slabs will be paid for at the Contract Unit Price per cubic yard (meter). Payment is full compensation for:

- Furnishing materials including dowels, epoxy, and ~~24 hour~~ accelerated strength concrete
- Performing work such as repairing shoulders if required, removing unsatisfactory materials sawing and sealing new joints, and performing other work specified in this Specification

Payment will be made under:

Item No.452	Full depth slab replacement	Per cubic yard (meter)

452.5.01 Adjustments

General Provisions 101 through 150.

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