DEVELOPMENT OF EARLY-AGE STRENGTH AND SHRINKAGE SPECIFICATIONS FOR DURABLE CONCRETE

by

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ABSTRACT

MEMOREE SHAMONE McENTYRE. Development of early-age strength and shrinkage specifications for durable concrete. (Under the direction of DR. TARA L. CAVALLINE)

Historically, concrete strength has been one of the primary properties specified to ensure concrete quality. As the construction industry advances, owners and major stakeholders are increasingly desiring longer lasting, durable concrete pavements and structures. Durable, sustainable concrete is considered to be long-lasting and low maintenance over its service life. For many years, concrete specifications have focused on mechanical properties such as slump, air content, and strength, but there is a need for performance specifications that are geared towards concrete durability. Performance Engineered Mixtures (PEMs) have sparked interest amongst owners due to the fact that these mixtures tend to outperform mixtures specified using conventional, prescriptive, strength-focused means. Often PEMs contain Supplementary Cementitious Materials (SCMs) such as fly ash. SCMs tend to provide several benefits to concrete mixtures including increased workability and reduced permeability but also tend to slow early strength gain. To prevent cracking, properties such as shrinkage resistance have been targeted as a durable characteristic of concrete, and PEM guidance recommends shrinkage specifications for appropriate applications. However, very few State Highway Agencies (SHAs) currently utilize specifications for shrinkage limits.

The goals of this research were to evaluate the impact of fly ash on compressive strength, flexural strength, and unrestrained shrinkage resistance using North Carolina pavement and structural concrete mixtures. Utilizing current and historical test data, along with a review of federal recommendations and current SHA specifications for strength and shrinkage, this research identifies early-age strength and shrinkage resistance targets and suggests specifications for use by the North Carolina Department of Transportation (NCDOT). These specification provisions are specifically developed to ensure PEMs containing SCMs and other sustainable materials such as portland limestone cement (PLC) are not unintentionally precluded from use.

Twenty-four concrete mixtures were developed using typical materials specified by NCDOT for concrete bridges and pavements. Various water/cement ratios (w/cm), cementitious material contents, fly ash replacement rates, and PLC substitutions were used. In addition, the mixture matrix was designed to include mixtures with proportions providing a range of higher than typical, typical, and less than typical mixture characteristics. Fresh and hardened concrete properties were tested to support the identification of performance targets for early-age strength and shrinkage, as well as specifications recommendations.

It was found that NCDOT's recent decision to increase the allowable replacement rate of fly ash from 20% to 30% should not adversely impact long-term strength, but should provide durability and sustainability benefits. Test results for PLC mixtures were comparable to those for ordinary portland cement mixtures, indicating that different performance specification provisions for these types of mixtures are likely not necessary.

The findings of this research supported suggested modifications of existing NCDOT targets and specifications for early-age strength for opening concrete structures and pavements to traffic. Additionally, this research supported development of a suggested shrinkage specification that includes potential performance targets for use by NCDOT. An analysis of results indicated that the specification targets identified should be readily achievable for contractors producing quality concrete and could be readily implemented. Implementation of these performance targets and specification provisions could allow NCDOT to move towards increased use of PEMs for more durable, sustainable infrastructure.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AEA	Air-Entraining Admixture
ASTM	American Society for Testing and Materials
BASF	Badische Anilin- und Soda Fabrik
CP	concrete pavement
CF	cubic feet
CY	cubic yard
FLDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GGBFS	ground granulated blast-furnace slag
HES	high-early strength
HPC	high-Performance concrete
IDOT	Illinois Department of Transportation
IowaDOT	Iowa Department of Transportation
LDOTD	Louisiana Department of Transportation and Development
MAP	Moving Advancements into Practice
$\mu\varepsilon$	micro-strain
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MnDOT	Minnesota Department of Transportation
NCC	National Concrete Consortium
NCDOT	North Carolina Department of Transportation
NYSDOT	State of New York Department of Transportation
OPC	original portland cement
RCPT	Rapid Chloride Permeability Testing
PASB	Permeable asphalt stabilized base
PASSRC	Permeable asphalt stabilized stress relief course
PEM	Performance Engineered Mixtures
PCA	Portland Cement Association

PLC	portland limestone cement
Pcy	pounds per cubic yards
Psi	pounds per square inch
SAM	Super Air Meter
SCMs	Supplementary Cementitious Materials
SHAs	State Highway Agencies
TRB	Transportation Research Board
VDOT	Virginia Department of Transportation
w/cm	water/cement ratio
WVDOH	West Virginia Division of Highways
WRA	Water-reducing Admixture

CHAPTER 1: INTRODUCTION

1.1 Background and Significance

Sustainability has become a major consideration in the design and construction industry due to depleting resources, owners' desire to optimize dollars, and the need to limit the negative environmental footprint associated with construction. The energy-intensive process to produce portland cement (one of the primary materials in concrete), along with the transportation of aggregates is associated with significant emissions of carbon dioxide and other pollutants, disruption of ecosystems, and other negative effects on the environment and communities (Shoubi et al., 2013).

State Highway Agencies (SHAs) around the country have been developing and implementing innovative measures to ensure sustainability by increasing the durability and longevity of concrete roads and bridges. Following the lead of the Federal Highway Administration (FHWA), North Carolina Department of Transportation (NCDOT) and other SHAs are exerting effort to support the design, specification, and construction of sustainable, durable concrete infrastructure. In order to lessen the negative impacts of portland cement, there has been an increase use of supplementary cementitious materials (SCM), which improve concrete durability, reduce the environmental footprint of concrete (since less cement is used), and save money (Taylor et al., 2013, Kosmatka and Wilson, 2016).

SCMs include fly ash, ground granulated blast-furnace slag (GGBFS), silica fume, and natural pozzolans, which are normally combined with portland cement to enhance desirable concrete properties (Kosmatka and Wilson, 2016). Pozzolanic materials can be added to cement or substituted for cement depending on the use requirements, and often increase concrete performance. For example, fly ash is a by-product of coal production. Research has shown that concrete made with fly ash generally tends to be more workable, exhibits reduced segregation, and has a lower heat of hydration than a conventional cement-only mixture, reducing heat build-up in concrete structures (Kosmatka and Wilson, 2016).

Although concretes produced using higher SCM contents tend to last longer, and perform better than portland cement concrete in similar conditions, strength is gained considerably slower than normal concrete (Taylor et al., 2013). Current NCDOT specifications regarding opening pavements and other infrastructure loads (construction and/or traffic) do not specifically consider the slower rate of strength gain of concrete mixtures containing SCMs. NCDOT desires to have specifications that will allow contractors to use more concrete mixtures made with SCMs (including higher SCM content mixtures), and specification provisions to support strength requirements that consider SCM-containing mixtures would help ensure early age strength requirements are adequate while not precluding or discouraging the use of SCM mixtures.

Several performance indicators for concrete made have historically been utilized in specifications for concrete made with and without SCMs - strength, slump, and total air content. These tests, although serving as useful tools for decades, have not historically correlated well with durability performance (Cackler et al., 2017). In recent years, test results more indicative of durability performance, as shrinkage, freeze-thaw durability, and chloride penetration resistance have become of interest to stakeholders (Cackler et al., 2017). To lower the risk of cracking of concrete mixtures, some SHAs are specifying shrinkage targets in their specifications. As NCDOT aims to improve the durability and sustainability of their concrete infrastructure, and expands its allowable mixtures to include higher SCM contents and materials such as portland limestone cement (PLC) preliminary specification recommendations regarding shrinkage performance are desired.

1.2 Introduction to Performance Engineered Concrete Mixtures

As roads become increasingly congested and resources become scarcer, the transportation industry is searching for concrete systems that can be built quickly, last longer, and of course are less expensive to construct and maintain (Cackler et al., 2017). Performance Engineered Mixtures (PEM) are concrete mixtures that are designed specifically to optimize concrete performance (both early and later age), promote longevity, and provide best odds that the structure will require low maintenance. The improved performance of these mixtures are increasingly desired by government agencies due to ease of constructability and long-term reliability, the need for updated specifications and quality control provisions for PEMs increases as well (Cackler et al., 2017). As the need for guidance for SHAs to specify and use PEMs became increasingly great, the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), the Portland Cement Association (PCA), and the National Concrete Consortium (NCC) collaborated to develop the AASHTO PP 84-17, "Standard Practice for Developing Performance Engineered Concrete Pavement Mixtures," which describes several performance variables to consider with PEMs and provides guidance for specification of these variables (Cackler et al., 2017).

Use of PEM specifications shifts risk away from the agency towards the contractor. However, they promote innovation and optimization of concrete mixtures, supporting contractor rewards for their production and use (AASHTO 2018) (Cackler et al., July 2017). Like many other SHAs, NCDOT has expressed interest in developing specifications that promote the use of PEMs, along with improving other traditional tests and specification targets that predict concrete performance. While current specifications have historically focused on slump, air content, and strength as performance measures, these are not the only important measurements of performance (Cackler et al., 2017). PEMs are specialized to perform based on given conditions in order to perform with minimum maintenance for decades. Specifications for PEMs need to be performance based-instead of prescriptive-based (e.g. focusing on specifications for specific structures/environments) enabling designers to create mixtures that will be durable and perform based on targets in place prior to contractor placement (Obla and Lobo, 2017). Performance indicators of PEMs include freeze thaw resistance, sulfate resistance, permeability, shrinkage resistance and strength (AASHTO 2018). Shrinkage resistance and strength, which are the focus of this thesis, will be discussed thoroughly in the next Chapter (Obla and Lobo, 2017).

1.3 Objectives and Scope

NCDOT desires to improve their specifications to include certain PEM provisions and increase the use of SCMs, since these mixtures are proven to support longer-lasting infrastructure, requiring less maintenance than regular concrete mixtures. This effort is being undertaken in stages, with certain initiatives of high interest being explored early in laboratory and shadow project applications.

Research presented in this thesis is a part of a larger NCDOT project aiming to provide more sustainable roads and bridges by improving specifications. An early part of this project aimed at utilizing historical NCDOT databases and linking the data to performance to identify correlations between approved concrete mixes, early age test results, and performance data (Lukavsky, 2019). Another part of the project aimed to develop preliminary surface resistivity targets to promote use of low permeability concrete mixtures for pavements and bridges (Biggers, 2019). The portion of the work presented in this thesis aims to assist NCDOT in developing PEM specification recommendations and performance targets for early age strength and shrinkage. Collectively, this research will provide NCDOT with preliminary performance-based standards that should promote production and use of PEM that provide durable pavements and bridges.

CHAPTER 2: LITERATURE REVIEW

This chapter presents a review of the current published literature, as well as standards and specifications, for Performance Engineered Mixtures (PEM). In addition, a review of literature on concrete durability standards and performance measurements utilized by selected SHAs is provided, with a focus placed on use of SCMs in PEMs, specifications for early age strength, and drying shrinkage. Lastly, the needs associated with specification provisions supporting concrete made with SCMs is discussed.

2.1 Concrete Durability

Concrete performance is measured by several characteristics including slump, strength, and total air content. However, these characteristics alone are not enough to determine true concrete durability. For example, concrete with the same slump, composition (materials and proportions), and strength could last for a hundred years in one environment, while lasting only for a couple of years in a different environment (Taylor et al., 2013). A more efficient way to determine concrete durability as stated in the Transportation Research Board (TRB) Concrete Durability Committee Circular report (2013), is to establish lasting properties and performance test results in a given service life condition/environment (Taylor et al., 2013). This approach grants a more accurate assessment of concrete longevity since it is specific to exposure conditions. Although compressive strength is utilized across the industry as a performance indicator, other durability tests provide beneficial predictions as well.

For example, length measurements assessing shrinkage potential aid in determining volume loss or gain due to water movement in concrete caused by external humidity (Nawy, 2008). When concrete exhibits volume loss due to water evaporation it is called drying shrinkage, and when the concrete exhibits an increase in volume it is called swelling which be discussed more thoroughly later in this chapter (Nawy, 2008). Mixtures that limit volumetric changes due to shrinkage and/or swelling last longer since the designed volume is achieved. In addition to shrinkage, freeze and thaw stress, deleterious reactions such as ASR, and sulfate attack are all direct causes of concrete failure that need to be accounted for when considering concrete durability (Taylor et al., 2013). ASR occurs when the alkali metals in aggregates react to the silica in cementitious materials, which results in a gel-like consistency material that eventually leaks out from the concrete, creating cracks and damage to the concrete structure (Kosmatka and Wilson, 2016). Other than the direct causes of failure there are indirect causes of failure to be considered as well. For instance, curing, consolidation, and finishing are construction practices that impact concrete durability (Taylor et al., 2013). These failures and contributing factors are more fully discussed later in this chapter. As stated in the same report by the TRB, higher quality concrete tends to be more durable no matter what direct and/or indirect causes of failure are present (Taylor et al., 2013). Essentially this is the goal of the PEM initiative, to focus on optimizing durability and quality of concrete in design, which is discussed further in the next section of this chapter.

2.1.1 Performance Requirements for Durable Concrete

As demand for construction increases, some resources necessary for construction are becoming scarcer and more costly, causing researchers and industry leaders to investigate and develop sustainable options for construction materials and practices. Sustainability demands and resource scarcity are the root cause of the development of the PEM initiative, in which mixtures are designed to control and optimize the resources used in the process of making concrete (Ahlstrom and Richter, 2018). By engaging engineering approaches during initial mixture development and qualification to determine the most efficient proportions of each material in concrete, PEMs are designed to last longer, have lower life cycle costs, and lower environmental impact amongst several other benefits. In addition, designers are able to enhance the quality of concrete by matching the properties of concrete to performance (Ahlstrom and Richter, 2018). For example, the article "Performance Engineered Mixtures (PEM) for Concrete Pavements." from the

April 2017 CP Roadmap Brief identified aggregate stability, fluid transport properties, cold weather, shrinkage, strength, and workability as six properties that determine concrete mixture performance (Cackler et al., 2017). Along with these properties, research has shown that concretes with lower water/cementitious material (w/cm) ratios tend to last longer due to lower permeability (e.g. reduced tendency to allow deleterious substances such as chlorides to ingress into the structure) and many transportation departments have utilized water/cementitious ratio limits as a specification provision to support durable concrete (Taylor et al., 2013; Mastin et al., 2018). The performance requirements for durable concrete are dependent on materials used, proportions, and concrete construction as discussed in the next section of this chapter.

2.1.1.1 Materials

It has been shown in previous research that selecting appropriate and efficient materials for concrete is essential in having durable, sustainable concrete. The primary materials that impact concrete durability include aggregates, admixtures, and (the most expensive and highest environmental impactor) portland cement. Other cementitious materials, particularly SCMs are often essential to ensuring concrete that is durable is batched and placed.

Primarily, aggregate size and shape impact concrete longevity in multiple ways. For example, research has shown concretes that have well-graded aggregates last longer due to water reduction and improved dimensional stability that is a result of having aggregates of multiple sizes (Kosmatka and Wilson, 2016). Improved dimensional stability correlates to improved shrinkage resistance, less need for cement paste, and fewer deleterious reactions that can lead to sulfate attack and alkali-silica reactions amongst other destructive reactions (Taylor et al., 2013).

Cementitious materials mixed with water acts as the binder paste for concrete, and is responsible for most of the concrete’s overall strength (Kosmatka and Wilson, 2016). Research has shown that concrete durability can be directly tied to the chemical and physical properties of cement along with the microstructure (Taylor et al., 2013). For example, finer cementitious material will hydrate faster and reacts with water rapidly since the surface area is larger.

2.1.1.2 Proportions

In addition to material selection, it is essential to determine material proportions, and understand how different material proportions will impact the concrete during placement and its performance many years after it has set. In order to optimize concrete performance, concrete mixtures must be designed with proportions in mind that 1) are economical and 2) tend to be more workable and easier to place in the field (Kosmatka and Wilson, 2016). Research has shown that mixture characteristics should be selected based upon the environment of concrete placement and service, size and shape of concrete members, desired physical and chemical concrete properties, and exposure conditions (Taylor et al., 2013). Also, concrete properties such as resistance to sulfate attack and resistance to chloride penetration, should be verified and tested appropriately to ensure the concrete will optimally perform (Cackler, 2017). ACI 211.1, “Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete” is the most commonly used proportioning guide and is often used as preliminary estimate of optimum proportions (ACI, 2002).

Research has demonstrated that the w/cm ratio has a major impact on hardened concrete properties, and over 100 years since its initial study, w/cm ratio is one of the main properties driving proportioning decisions (Cackler et al., 2017). When the concrete has workability to support proper consolidation and includes sound, durable aggregates, the w/cm ratio is the next factor that concrete strength is dependent on and relate to (Taylor et al., 2013). For instance, concrete needing corrosion protection for steel reinforcement should not have a w/cm ratio over 0.40 with a minimum strength of 35 MPa (approximately 5,100 psi), while concrete in an area where frost resistance is desired should have a w/cm ratio of 0.45 with a minimum strength of 31 MPa (approximately 4,500 psi) based on consensus of the authors of the Durable Concrete Circular (TRB, 2013).

Along with w/cm ratio selection, aggregate type and material proportions play a major role in fresh concrete workability and hardened concrete to an extent (Taylor et al., 2013). As mentioned in the material selection section of this report, use of poorly graded aggregates in concrete will require more cement paste, water, and money (Kosmatka and Wilson, 2016). Research has shown mixing water needed for a desired slump is dependent on the nominal maximum coarse aggregate size and shape, determining the right amount and type of aggregate is key in ensuring concrete slump, which is a standard for durability/concrete performance in NC and many other states (Taylor et al., 2013). Also, large, midsize, and fine aggregate of necessary proportions (depending on concrete use and environment) are essential in making durable concrete (Kosmatka and Wilson, 2016). For instance, lack of midsized aggregates will likely result in concrete with poor workability, high water content, and high shrinkage properties (Kosmatka and Wilson, 2016). In order to compensate for lack of midsized aggregates, blending is suggested to ensure the aggregates are well-graded (Taylor et al., 2013). In addition, desired grading for fine aggregates depends on the type of work, leaner mixtures a finer grade is desired to ensure the concrete is workable, while richer mixtures coarse grading is more economical (Taylor et al., 2013).

Cementitious content is essential in proportioning for several reasons. Since it is the most expensive component of concrete, it is most generally most economical to limit cementitious content without impacting quality; however, the proportion of cementitious content should be based on performance requirements instead of solely economic benefits (Taylor et al., 2013). Research has shown that using the stiffest mixture that will work practically, the largest practical nominal maximum size aggregate, an optimum ration of fine-to-coarse aggregate, and a uniform aggregate distribution will all aid in minimizing water and cementitious material content (ACI, 2002). In a research project sponsored by the Ready-Mixed Concrete (RMC) Research and Education Foundation entitled, “Optimizing Concrete Mixtures for Performance and Sustainability” concrete mixtures were made with a fixed aggregate ratio, but varied in slag and fly ash content, along with varied cement contents (Obla et al., 2015). Slump, setting time, compressive strength, chloride penetration, and other tests were performed to evaluate mixture performance and how different cementitious contents impacted each test (Obla et al., 2015). Research from this project proved that with a given w/cm ratio, increasing cement content with result in compressive strengths similar to normal cement content but will increase permeability (Obla et al., 2015). This increase in permeability results in poor concrete performance, so increasing cement content in not the best way to improve concrete durability (Obla et al., 2015).

Along with cement, pozzolanic materials impact fresh and hardened properties of concrete and must be proportioned efficiently in order to exhibit durable properties. For instance, fly ash generally reduces water demand and increases workability, but can slow early strength development (Taylor et al., 2013). Also the research project for the RMC Research and Education Foundation previously mentioned states that in comparison to concrete made with portland cement, the concrete mixtures containing fly ash resulted in lower initial strength and have longer thermal final set times (Obla et al., 2015).

NCDOT's specifications for portland cement concrete have evolved over the last decades and have supported development of the nations' second largest roadway network. For portland cement concrete, NCDOT specifications state that accelerating admixtures, calcium chloride or admixtures containing calcium chloride cannot be used as per Standard Section 1078-4A (NCDOT, 2018). High range water reducer (HRWR) can be used with Engineer approval but not at a rate exceeding manufacturer's recommendations (NCDOT, 2018). For portland cement concrete, fine aggregate must be free from dirt, wood, or any other foreign material as stated in Standard section 1014-1 as must be in accordance with the department's list of approved fine aggregates (NCDOT, 2018). Coarse aggregate must be free from dirt and impurities as well, and must be resistant to abrasion as per Standard section 1014-2 (NCDOT, 2018). For concrete pavement use, coarse aggregate size No. 57, No. 57M, No. 67, or No. 78M are required unless noted otherwise by project

Engineer (NCDOT, 2018). For pre-stressed concrete coarse aggregate must pass a 1 inch sieve, and for all concrete a cement content of at least 564 pounds per cubic yard (pcy) and no more than 752 pcy as stated in the same section (NCDOT, 2018). NCDOT allows use of fly ash or GGBFS to reduce cement content as long as it is in accordance with Article 1024-1, and for concrete exhibiting compressive strength over 6,000 psi micro-silica in conformance with Article 1024-1 can be used as a substitute for cement (NCDOT, 2018). The maximum w/cm ratio, slump with and without HRWR, and air content for concrete based on its strength is shown in Table 2.1.

Table 2.1: NCDOT Portland Cement Property Requirements (NCDOT, 2018)

Property	**28 Day Design Compressive Strength 6,000psi or less**	**28 Day Design Compressive Strength greater than 6,000psi**
Maximum Water/Cementitious Material Ratio	0.45	0.40
Maximum Slump Without HRWR	3.5"	3.5"
Maximum Slump with HRWR	8"	8"
Air Content (upon discharge into forms)	5±2%	5±2%

2.1.1.3 Construction

Selecting the most efficient materials and proportions are important, but if the concrete is not batched, placed, and cured properly during construction material and proportion selection does not matter. Incorrect placement and/or curing methods can compromise the concrete's mechanical properties. From the material storing, batching, transporting, and consolidating methods to curing methods all impact the quality of fresh and hardened concrete (Lamond and Pielert, 2013).

Primarily, materials must be stored, batched, mixed, and transported without excessive damage. For example, for aggregate consistency, specifically uniform gradation, and moisture content, the aggregate chosen for a mixture should be piled, transported, and stored properly (Taylor et al., 2013). All methods of batching, mixing and transporting concrete should adhere to ASTM C94, "Standard Specification for Ready-Mix Concrete" (ASTM, 2019). During concrete batching, each individual materials must be added within tolerances provided by specifications (Kosmatka and Wilson, 2016). Concrete should be mixed thoroughly until all materials are uniformly distributed, and re-mixed within limits if mixture stiffens during transport. For hot and cold weather concrete placements there are provisions that must be followed to guarantee expected properties after concrete has set (Taylor et al., 2013).

As the industry moves to performance requirements and away from prescriptive requirements, contractors are expected to ensure mixture production and quality control (Cackler et al., July 2017). Current PEM specifications (per AASHTO PP 84-19) change the narrative of quality control for contractors allowing quality control during mixing and placement of concrete instead of strength testing after 28-days (Cackler et al., 2017). Research has shown that no matter how efficient field testing procedures are, specimens cast for testing are not exactly the same as the concrete in place, presenting the need for specifications that allow quality control during concrete placement (Lamond and Pielert, 2013). For instance, in Iowa maturity method testing was used for determining when concrete structures and pavements have reached strength to accommodate loading (Hanson, 2019). This method has become more popular since it is a non-destructive in field measurement of the strength of the concrete in-place (Hanson, 2019). Other testing methods included in the PEM initiative are super air meter (SAM), surface resistivity, formation factor, box test, and unit weight (Cackler et al., 2017).

2.2 Use of SCMs for Concrete

As concrete demand increases, the use of SCMs as an economic alternative to portland cement has increased as well. SCMs can replace or be used in combination with portland cement to save money and increase durability of concrete over time (Taylor et al. 2013). There are several benefits to using SCMs that are discussed more thoroughly in the next section of this chapter.

2.2.1 Overview of benefits of SCMs

Concrete mixtures that include SCMs tend to be less permeable, making the concrete more durable since water, chemicals and other materials are less likely to penetrate the concrete (Kosmatka and Wilson, 2016). Using SCMs can improve hydration of the paste by bonding ions to hydration which would normally be free to become deleterious and detrimental to concrete performance (Taylor et al., 2013). Also SCMs tend to decrease porosity, which is essential in combating corrosion of steel reinforcement (Taylor et al., 2013). Certain SCMs such as silica fume, Class F fly ash, and calcined clay aid with mitigation or prevention of alkali-silica reactions (ASR) (Kosmatka and Wilson, 2016). This is due to the fact that SCMs help bind chlorides with aluminate hydrates, and SCM use is one of the most common remedies for avoiding ASR (Taylor et al., 2013).

For concrete mixtures placed in cold environments and/or places that use chemical deicers, SCMs are also beneficial. Calcium chloride from deicers can cause reactions that will expand and crack hardened concrete due to calcium oxychloride formations (Yaghoob et al., 2015). SCMs will reduce the calcium chloride content due to dilution and the tendency of some SCMs to absorb the calcium chloride (Cackler et al., 2017). SCMs also lower heat of hydration in concrete, which is beneficial when placing concrete in hot weather or in mass concrete structures (Cackler et al., 2017). In addition, SCMs reduce bleeding and segregation of fresh concrete (Taylor et al., 2013). Another advantage to using SCMs, is the fact that less water is needed to increase workability (Cackler et al., 2017). Research has shown that the appropriate proportion of fly ash, slag, and/or silica fume mixed with cement can increase resistance to sulfate attack. On the other hand, too much fly ash will make the concrete susceptible to sulfate attack, so proportioning is a key factor in controlling how SCMs affect concrete (Kosmatka and Wilson, 2016).

2.2.2 Fly ash in concrete

Fly ash is the byproduct of coal combustion in coal-fired electrical power plants, and is the most widely used supplementary cementitious material in concrete due to cost savings, and behavior in concrete (Kosmatka and Wilson, 2016). During the combustion process, impurities are burned off and transferred through exhaust gases to collect in electrostatic precipitators or bag filters and cooled. Once cooled, the fused material forms spherical particles known as fly ash. Class F and Class C fly ash in accordance with ASTM C618, “Standard Specification for Coal Fly Ash and Raw or Calcinated Natural Pozzolan for Use in Concrete,” are defined by calcium content as Class F generally is low-calcium (less than 10% CaO) while Class C generally is high-calcium (10-30% CaO) (ASTM, 2019 and Kosmatka and Wilson, 2016). In NC, Class F ash is commonly used, so for the rest of this discussion, Class F fly ash is implied, as it is the fly ash used in the testing program. Since fly ash is a byproduct of coal production, it is readily available and reduces the overall cost of concrete per cubic yard (CY) since it is a recycled product (Shannon et al., 2017).

Fly ash is the most commonly used SCM because of the benefits to concrete properties as a result of using fly ash as a replacement or substitute for cement. The characteristics of fly ash change depending on coal type, boiler type, operating conditions, and processing, which affects the overall efficiency of fly ash in concrete (Xu and Shi, 2017). Fly ash in concrete tends to impact fresh and hardened concrete properties in several ways. For instance, the spherical shape of fly ash generally increases the workability of fresh concrete (Kosmatka and Wilson, 2016). Fly ash generally reduces the mixtures water demand, reduces bleeding and segregation, and the heat of hydration released while batching and placing fresh concrete (Kosmatka and Wilson, 2016).

Along with improving fresh concrete properties, fly ash used in concrete can enhance hardened properties as well. For instance, the spherical shape of fly ash particles improves the particles’ ability to fill voids in order to decrease permeability (Kosmatka and Wilson, 2016). The less permeable concrete is, the longer it lasts in structural and pavement applications. Also, studies have shown that over longer periods of time (beyond 28-day strength), concrete mixtures including fly ash have higher shear strength, and despite slower reaction times using fly ash can improve durability and longevity of concrete (Xu and Shi, 2017). Fly ash used in low to moderate amounts tends to have little impact on drying shrinkage; however, with standards allowing higher percentages of fly ash, this should be examined (Kosmatka and Wilson, 2016). The impact of fly ash on strength and shrinkage will be discussed more thoroughly in the next sections of this chapter.

2.2.2.1 Impact of fly ash on strength

As mentioned previously, as a pozzolanic material, fly ash tends to impact the overall strength of concrete. Compressive strength measures the concrete ability to resist axial-loading after curing for 28 days (normally) in pounds per square inch (psi) (Kosmatka and Wilson, 2016). Although, most specifications require a minimum 28- day compressive strength, 7-day strength of concrete is generally 75% of the strength at 28-days and can often be used to estimate strength at 28-days (Kosmatka and Wilson, 2016). Research has shown that concrete with fly ash tends to gain strength slowly initially, but the ultimate strength is higher than concrete made with just portland cement (Kosmatka and Wilson, 2016). For example, concrete made with Class C fly ashes tends to gain strength earlier than mixtures produced with Class F fly ash, but concrete made with either Class C or Class F ash tends to surpass specified 28-day strength in 28-90 days (Kosmatka and Wilson, 2016). However, research has shown that fly ash replacement levels over 35% tend to decrease overall compressive strength which is why most specifications limit substitution to 30 % (Kurad et al., 2017).

Compressive strength is primarily used as a specification provision for concrete structures such as bridges and buildings, while flexural strength is specified primarily for concrete pavements. Flexural strength can be correlated to compressive strength based on the materials used and the size of the concrete element and fly ash tends to impact flexural strength in a similar manner to compressive strength (Kosmatka and Wilson, 2016).

2.2.2.2 Impact of fly ash on shrinkage

Generally, fly ash in low doses does not impact drying shrinkage directly; however the slow setting time of concrete made with fly ash can increase drying shrinkage and prolong finishing operations (Kosmatka and Wilson, 2016). Controlling the w/cm ratio of concrete is the best way to mitigate drying shrinkage, as more water leads to increased likelihood of cracking or shrinking (Cackler et al., 2017). To combat slow setting times, an accelerating admixture could also be used (Kosmatka and Wilson, 2016). Proper placement and curing and of concrete with fly ash (and any other SCM) is essential in avoiding plastic shrinkage since bleeding is reduced (Taylor et al., 2013). Shrinkage can be mitigated with immediate and constant (over the specified duration), curing of the concrete to ensure it continues to hydrate, since the reactions are delayed due to the fly ash (Taylor et al., 2013). Since SCMs like fly ash can replace a portion of cement, the w/cm ratios can be lowered as well (while achieving the same workability) resulting in a more durable mixture (Cackler et al., 2017).

2.2.2.3 Other benefits and challenges

There are a few challenges to using fly ash in concrete. One of the main issues that directly impacts constructability and contractors is the slow early strength gain. As mentioned previously, concrete with fly ash tends to gain strength more slowly than concrete with portland cement, which could cause delays in finishing and passing inspections ultimately delaying the construction schedule (Taylor et al., 2013). Since NCDOT standard specifications state 28-day strength requirements, the slower rate of strength gain of concrete made with SCMs is not specifically considered. Also, the addition of fly ash tends to require more air-entraining admixture due to fine fly ash particles, and the tendency of unburnt carbon remaining in the fly ash to interfere with the admixture's ability to retain bubbles in the mixture, which could increase the overall cost of concrete per CY (Kosmatka and Wilson, 2016). Another challenge is the current scarcity of fly ash in some regions, as well as potentially running out of fly ash in the next coming years. As the demand for fly ash increases locally and globally, there is a potential danger of eventually running out due to power companies turning to alternate power methods, such as natural gas (NPCA, 2017).

2.3 Specifications Addressing Impact of SCMs on Concrete Performance

As specifications for roads and bridges were developed around the United States (U.S.), most were originally based on other states specifications and agency experiences instead of engineering analysis. This practice was generally true until around the mid-1990s, when specifications for opening roads to traffic began to be based on engineering properties (Cole and Okamoto, 1995). Although, agency experience heavily guided specification development for many years, recently many states across the U.S. utilize improved specification provisions, and some address the impact of SCMs on concrete performance by including provisions for slower strength gain and improved performance targets. However, the standard specifications from NCDOT for roads and bridges only includes substitutional requirements, as the NCDOT manual states that up thirty percent of cement can be substituted with SCMs at a one to one ratio (NCDOT, 2018).

2.3.1 Concrete Strength

The primary specification requirement that could potentially impact a contractor's ability to move forward with a project after concrete placement is the minimum required concrete strength that must be achieved in order to open roads and bridges to traffic along with handling construction traffic and equipment. Early age strength requirements are essential to consider when improving specifications because PEM mixtures should allow adequate strength gain to provide the required strength while also allowing contractors to progress at a reasonable rate. Ultimately, contractors need to feel comfortable utilizing PEM concrete mixtures, which will often utilize SCMs to meet performance test targets.

To aid with quality control and quality assurance, improved methods for evaluating concrete placement are essential to ensure specified compressive strength is reached for opening pavements to traffic. Maturity concepts include non-destructive testing to estimate in-place concrete performance (Hanson, 2019). For example, in the most recent meeting of the NCC conducted in the fall of 2019, improved ways to monitor and implement maturity evaluations of pavements and bridges were discussed providing construction specifications for monitoring temperatures during placement along with maturity systems after the concrete has been placed (Garber, 2019). Specifications from states that conduct mostly cold weather, and mass concrete placement were highlighted, and each put emphasis on monitoring the temperature during these types of conditions to ensure the concrete will perform (reaching specified compressive strength) as expected (Garber, 2019). Advantages to improving maturity evaluation systems include increased safety, improved construction methods, efficiency, and consistency (Garber, 2019). Maturity systems should include field early strength predictions, schedule of sawing and curing activities (as these directly affect concrete strength gain once it is set), and a plan if cracking occurs (Garber, 2019). Maturity concepts involve a maturity-strength curve produced by contractors to use to estimate in place strength and compare with actual strength using laboratory testing (Hanson, 2019). Contractors utilizing this system will be able to monitor how well the mixture that was delivered and placed compares to the mixture design using sensors, ensuring the concrete placed is performing properly (Garber, 2019). Several technologies were discussed in this presentation to aid contractors with maturity evaluations including embedded and non-embedded Bluetooth sensors, thermocouple systems, and combination systems, all of which improve the quality of concrete placement and methodology (Garber, 2019).

Specifically, Iowa Department of Transportation (IowaDOT) has implemented a maturity system as discussed for in a NCC presentation entitled, “Maturity for Opening PCC Pavements: Iowa Experience” by Todd Hanson (Hanson, 2019). This involved creating maturity curves for flexural and compressive strength in order to use for strength and temperature validation (Hanson, 2019). Although, getting contractors to cast test specimens and pay for more expensive field maturity devices, Iowa allowed contractors to use curve validations instead of developing new curves along with allowing minor changes to mixtures giving contractors some flexibility. This method has reduced construction times and costs (benefitting the owner, contractor, and the public), along with accelerating staged construction since roads can be opened earlier (Hanson, 2019).

North Carolina Department of Transportation

NCDOT has specified overall standard requirements for concrete that include slump, air content, compressive, and flexural strength at 28 days as shown in Table 2.1 (NCDOT, 2018). These standards do not provide performance targets for concrete mixtures, or modified targets for mixtures containing SCMs. As far as standards specific to SCMs, NCDOT limits the use of fly ash as a substitution for cement up to 30 percent at a one pound of fly ash to one pound of cement as stated in Section 1000-3 (NCDOT, 2018). This is a recent change to specifications, which formerly limited fly ash replacement rates to 20% at a substitution of 1.2 pounds of fly ash to each 1.0 pound of cement replaced (NCDOT, 2012). In the same section, NCDOT specifies the use of blast furnace slag as a substitute for cement can be used up to 50 percent pound for pound (NCDOT, 2018). Also, it is stated in Section 1024-5 that fly ash must meet ASTM C618 for Class F or Class C, and loss on ignition cannot exceed four percent (NCDOT, 2018). In addition, Class C fly ash cannot be used in portland cement concrete that has alkali content of 0.4 percent (NCDOT, 2018).

Table 2.2: NCDOT Requirements for Concrete Mixtures (NCDOT, 2018)

Class of Concrete	Min. Comp. Strength at 28 days	Maximum Water-Cement Ratio				Consistency Max. Slump		Cement Content			
		Air-Entrained Concrete		Non Air-Entrained Concrete		Vibrated	Non-Vibrated	Vibrated		Non-Vibrated	
		Rounded Aggre-gate	Angular Aggre-gate	Rounded Aggre-gate	Angular Aggre-gate			Min.	Max	Min	Max.
Units	*psi*					*inch*	*inch*	*lb/cy*	*lb/cy*	*lb/cy*	*lb/cy*
AA	4,500	0.381	0.426	-	-	3.5	-	639	715	-	-
AA Slip Form	4,500	0.381	0.426	-	-	1.5	-	639	715	-	-
Drilled Pier	4,500	-	-	0.450	0.450	-	5-7 dry 7-9 wet	-	-	640	800
A	3,000	0.488	0.532	0.550	0.594	3.5	4	564	-	602	-
B	2,500	0.488	0.567	0.559	0.630	1.5 ma-chine placed 2.5 hand place	4	508	-	545	
Sand Light-weight	4,500	-	0.420	-	-	4	-	715	-	-	-
Latex Modified	3,000 7 day	0.400	0.400	-	-	6	-	658	-	-	-
Flowable Fill excavatable	150 max. at 56 days	as needed	as needed	as needed	as needed	-	Flow -able	-	-	40	100
Flowable Fill non-excavatable	125	as needed	as needed	as needed	as needed	-	Flow -able	-	-	100	as need-ed
Pavement	4,500 design, field 650 flexural, design only	0.559	0.559	-	-	1.5 slip form 3.0 hand place	-	526	-	-	-
Precast	See Table 1077-1	as needed	as needed	-	-	6	as need-ed	as need-ed	as need-ed	as need-ed	as need-ed
Prestress	per contract	See Table 1078-1	See Table 1078-1	-	-	8	-	564	as need-ed	-	-

Historically, NCDOT has allowed a 20% substitution of fly ash for portland cement on a 1:1.2 by weight basis (NCDOT, 2012). However, in recent years, NCDOT has modified specifications to the current standard mentioned earlier in this section. This change to allow an increased SCM content will likely impact early age performance. Class A and pavement mixtures are the primary focuses of the NCDOT due to the higher strength requirements of each class ensuring road and bridge safety as roads and bridges are expected to reach 4,500 psi by 28-days and at least 3,000 psi prior to opening roads to traffic which will be further discussed later in this chapter (NCDOT, 2018).

Although NCDOT has acceptable values for performance of concrete at a given age, contractors are interested in requirements for opening pavements to construction and regular traffic. For existing structures traffic must be maintained and the posted load limits must be observed (NCDOT, 2018). The NCDOT standard specification 420-20 “Placing Load on Structure Members” states that structures must cure for at least 7 days prior to loading (NCDOT, 2018). In addition to curing, construction equipment and vehicles cannot load structures until 28- day strength is reached or a compressive strength of 3,000 psi is obtained (NCDOT, 2018). To remove formwork for bridge decks, beams, and girders a compressive strength of 3,000 psi is required (NCDOT, 2018). For regular traffic, structural pavements must have a minimum flexural strength of 650 psi and a minimum compressive strength of 4,500 psi within 28 days (NCDOT 2018).

These requirements do not include cold weather concrete placement. If concrete is placed in weather below 35 degrees Fahrenheit, and contains fly ash or GGBFS, the concrete must be insulated and protected for seven days prior to loading (NCDOT, 2018). Placing mixtures in cold weather, mixtures containing fly ash require a mixture of 572 pcy of cement and at least 172 pcy fly ash for insulation. Concrete mixtures including GGFBS require a mix of 465 pcy of cement and 250 pcy of GGFBS for insulation as stated in Section 420-7 (C) of the NCDOT standard specifications for roads and bridges (NCDOT, 2018).

In section 105-5, NCDOT presents equipment load restrictions for bridges as shown in Table 2.2 (NCDOT, 2018). Equipment should not exceed these maximum limits along with listed maximums for existing structures.

Table 2.3: NCDOT Equipment Load Restrictions for Bridges (NCDOT, 2018)

Property	Maximum Load in Pounds
Axle load	36,000
Axle load on tandem axles	30,000
Gross load	90,000

A number of other states have standard specifications provisions for mixtures containing SCMs, including mixtures containing relatively high SCM contents. These are discussed subsequently in order to compare with NCDOT specification provisions, and identify specification approaches that could be used to help modify NCDOT specifications to better address PEMs.

Louisiana Department of Transportation and Development (LaDOTD)

LaDOTD Standard Specifications for Roads and Bridges states in Section 901.08 "Composition of Concrete" for all concrete mixes use of fly ash is limited to a maximum of 25 percent weight of cement for concrete pipe, 20 percent weight of cement for minor structures and pavements, and 15 percent weight of cement for structural concrete depending on the class of concrete (LaDOTD, 2016). These standards state that records of any concrete material (fly ash, cement, micro-silica, granulated blast furnace slag, etc.) deliveries must be tracked by the contractor, and require trial mixes to determine performance and compatibility of the concrete materials (LaDOTD, 2016).

Along with trial mixtures, the contractor is expected to test and send results for slump, unit weight, air content, set times, compressive strength and flexural strength for pavements at 3, 7, and 28 days for state verification (LaDOTD, 2016). In addition, all structural concrete with the exception of minor structures, must use surface resistivity to determine permeability per DOTD TR 233 standard (LaDOTD, 2016). Also, LaDOTD set standards specifically for fly ash in structural concrete in Section 901.08.2 "Cementitious Material Substitution." For instance, for structural binary mixtures (combination of portland cement and one additional cementitious replacement, such as fly ash or GGBFS, the maximum permissible substitution rate for fly ash is 30 percent and 50 percent for GGBFS (LaDOTD, 2016). For ternary concrete mixtures (combination of portland cement and two additional cementitious replacements including fly ash class C and/or F, and GGBFS), the maximum permissible substitution rate is different depending on the Type of cement used (LaDOTD, 2016). LaDOTD states, "…for ternary mixtures containing Type I, II, III, 1L portland cement, the maximum substitution rate is 70 percent of cement" and "using Type IP or IS portland cement, the maximum substitution rate is 40 percent." (LaDOTD 2016).

Compressive strength required for construction loads are explained in Section 601.03.13 of the LaDOTD Standard Specifications for Roads and Bridges Manual. For instance, heavy equipment is not permitted on pavements until a minimum compressive strength of 3,000 psi is reached (LaDOTD, 2016). Also, traffic is not permitted on concrete pavements until 14 days after setting or test specimens made in accordance with standard 601.03.7 have reached a compressive strength of 3,000 psi "tested in accordance with DOTD TR 230" or a flexural strength of 550 psi "tested in accordance with AASHTO T 97" (LaDOTD, 2016). Any concrete that is supporting formwork must reach 3,000 psi compressive strength prior to placing concrete as per Section 805.05.3 (LaDOTD, 2016) On the other hand, bridge deck concrete must reach a minimum of 4,000 psi before reinforcement, forms, concrete, or metal railings can be installed as per Section 810.03 (LaDOTD, 2016).

Minnesota Department of Transportation (MnDOT)

MnDOT is unique because of newly advanced standards to improve overall concrete durability and longevity utilizing SCMs and PEMs. In 2018, the state released a new maximum water cement ratio of 0.40 and maximum cementitious value of six hundred pounds per cubic yard for concrete (MnDOT, 2018). In addition, the standard was amended to include maximum substitution of fly ash for portland cement to 25 percent, which was not included prior to 2018 (MnDOT, 2018). After these changes were made, research showed that pavements under this standard were smoother at a given year of pavement life, and the road condition deteriorated slower in comparison to pavements constructed prior to this water cement ratio standard (Masten et al., 2018). Also, core samples from pavements under the new standard were tested using ASTM C457/C457M S*tandard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete*, and results indicated "on average, an increase of air content and improved air void system" allowing the concrete to have increased "resistance to freeze/thaw deterioration" (Masten et al., 2018).

Table 2.3 shows minimum curing periods, strength requirements, and methods for testing in-place concrete strength prior to loading structures with construction vehicles and equipment (with the exclusion of mass concrete structures) (MnDOT, 2018). Construction equipment on pavements, loaded or empty hauling equipment is only permitted on the Permeable Asphalt Stabilized Stress Relief Course (PASSRC) and only the paver, roller, and bituminous haul are permitted on the Permeable Asphalt Stabilized Base (PASB) (MnDOT, 2018). Only Minnesota permitted trucks are permitted to drive up to the PASB, drop off material, and must immediately move after dumping per Standard Section 2363.3 (MnDOT, 2018). Prior to opening a pavement slab to regular traffic, the concrete must cure for 7 days, or reach a minimum compressive strength of 3,000 psi, or flexural strength based on thickness as shown in Table 2.4, whichever happens first as stated in Standard Section 2301.3 (MnDOT, 2018).

Table 2.4: MnDOT Curing Requirements for Concrete Bridge Elements (MnDOT, 2018)

Bridge Element	Minimum Curing Period	Minimum Period For Form Cure	Minimum Strength Required to Pull Forms, psi	Minimum Strength to Apply Loads, % of Required †	Method Allowed to determine in-place concrete strength
Bridge superstructures, unless otherwise specified	96 hrs	24 hrs	2000 ǂ	65	Maturity or Control Cylinders
Slab Span Superstructure	7 days	8 days	See special provisions	See special provisions	Maturity or Control Cylinders
Diaphragms and end webs not a part of box girders and cast before the bridge slab	72 hrs	24 hrs	2000 ǂ	45	Maturity or Control Cylinders
Pier Caps	72 hrs	72 hrs	2000 ǂ	65	Maturity or Control Cylinders
Retaining Walls	72 hrs	12 hrs *	Self-supporting	100	Maturity or Control Cylinders
Barriers and Parapets	72 hrs	-	Self-supporting	45 ‖	Maturity or Control Cylinders
Sections not included in superstructures, unless otherwise specified	72 hrs	24 hrs	2000 ǂ	45	Maturity or Control Cylinders
Bridge Decks	7 days	-	-	100	-
Bridge Deck Underside	7 days	8 days	2000	100	-

* When weather conditions require cold weather protection in accordance with 2401.3.G.5, "Protection Against Cold Weather," increase form curing to a minimum of 24 hours.
‖ Achieve 4000 psi prior to use as a traffic barrier.
† Applied loads include but are not limited to equipment, beams, backfilling, or successive concrete placements.
ǂ The Engineer will require verification of the minimum strength when air temperatures drop below 40° F during the curing period or when the mix design includes greater than 15% cement substitution. The minimum strength requirement does not apply to bulkheads and edge of deck forms.

Table 2.5: MnDOT Minimum Requirements for Opening Pavements to General Traffic (MnDOT, 2018)

Slab Thickness, in	Flexural Strength, psi
≤7.0	500
7.5	480
8.0	460
8.5	440
9.0	390
≥ 9.5	350

Additionally, MnDOT specifications contain mixture design requirements for concrete that include maximum allowable SCMs percentages based on the use of the concrete, maximum w/c ratios, maximum cementitious material content, along with other requirements as shown in Table

2.5 (MnDOT, 2018). Table 2.6 provides MnDOT's design requirements specifically for high early strength concrete, with strength requirements for opening roads to traffic (MnDOT, 2018).

Table 2.6: Minnesota Concrete Mix Design Requirements (MnDOT, 2018)

Concrete Grade	Mix Number	Intended Use *	Maximum w/c ratio †	Maximum Cementitious Content (lbs/yd^3)	Maximum %SCM (Fly Ash/ Slag/Ternary)	Slump Range	Minimum 28-day Compressive Strength, f'c	3137 Spec.
B Bridge Substructure	3B52 ‡	Abutment, stems, wingwalls, paving brackets, pier columns and caps, pier struts	0.45	750	30/35/40	2 - 5"	4000 psi	2.D.1
F Flatwork	3F32 ‡	Slipform curb and gutter	0.42	750	30/35/0	½ - 3" #	4500 psi	2.D.1
	3F52 ‡ 3F52EX 3F53EX 3F52CO ‖	Walks, curb and gutter, slope paving, median walks, driveway entrances, ADA pedestrian walks	0.45	750	25/30/0	2 - 5"	4500 psi	2.D.1
G General Concrete	1G52 ‡	Footings and pilecap	0.55	750	30/35/40	2 - 5"	4500 psi	2.D.1
	3G52 ‡	Footings, pilecap, walls, cast-in-place manholes and catch basins, fence posts, signal bases, light pole foundations, erosion control structures, cast-in-place box culverts, culvert headwalls, open flumes, cast-in-place wall stems	0.45	750	30/35/40	2 - 5"	4500 psi	2.D.1
M Median Barrier	3M12	Slipform barrier, median barrier, non-bridge	0.42	750	30/35/40	½ - 1" #	4500 psi	2.D.1
	3M52	Barrier, median barrier, non-bridge	0.45	750	30/35/40	2 - 5"	4500 psi	2.D.1
P Piling	1P62 ‡	Piling, spread footing leveling pad	0.68	750	30/35/40	3 - 6"	3000 psi	2.D.1
R Pavement Rehabilitation	3R52 ‡	CPR - Full depth concrete repairs, concrete base	0.45	750	30/35/40	2 - 5"	4000 psi	2.D.3
S Bridge Superstructure	3S12	Slipform bridge barrier, parapets, end post	0.42	750	30/35/40	½ - 1" #	4000 psi	2.D.2
	3S52	Bridge median barrier, raised median, pilaster, curb, sidewalk, approach panel, formed bridge barrier, parapet, end post, collar	0.45	750	30/35/40	2 - 5"	4000 psi	2.D.2
X Miscellaneous Bridge	1X62	Cofferdam seals, rock sockets, drilled shafts	0.45	750	30/35/40	3 - 6"	5000 psi	2.D.1
	3X62	Drilled shafts above frost line	0.45	750	30/35/40	3 - 6"	5000 psi	2.D.1
Y Bridge Deck §	3Y42-M 3Y42-S	Bridge decks, integral abutment diaphragms, pier continuity diaphragms, expansion joint replacement mix	0.45	750	30/35/40	2 - 4"	4000 psi	2.D.2
	3Y47 **	Deck patching mix	0.45	750	30/35/40	2 - 4"	4000 psi	2.D.2

* If the intended use is not included elsewhere in the Specification or Special Provisions, use mix 3G52, unless otherwise directed by the Engineer.
‖ Identify specific color used on the certificate of compliance. Colored concrete is only allowed when specified in the plans or the Contract.
† The minimum water/cement (w/c) ratio is 0.30.
‡ The Contractor may choose to use the Coarse Aggregate Designation "1" for the 4th digit in accordance with Table 2461-3.
\# Adjust slump in accordance with 2461.3.G.7.a for slipform concrete placement.
§ The "-S" indicates a bridge deck with a structural slab and "-M" indicates a monolithic bridge deck.
** Mix 3Y47 requires the use of Coarse Aggregate Designation "7" or "3" for the 4th digit in accordance with Table 2461-3.

Table 2.7: Minnesota High Early Strength Design Requirements (MnDOT, 2018)

Mix Number	Concrete Grades Allowed	Minimum Time to Opening	Maximum w/c ratio	Maximum Cementitious Content (lbs/ yd^3) *	Slump Range	Minimum Strength to Opening	Minimum 28-day Compressive Strength, f'c	3137 Spec.
3HE32	F	48 hrs	0.42	750	1 – 3" ‖	3000 psi	4500 psi	2.D.1
3HE52	B, F, G	48 hrs	0.42	750	2 – 5"	3000 psi	4500 psi	2.D.1
3YHE52	Y (Repairs Only)	48 hrs	0.42	750	2 – 5"	3000 psi	4000 psi	2.D.2
3RHE52	R (Repairs Only)	48 hrs	0.42	750	2 – 5"	3000 psi	4000 psi	2.D.3

* Supplementary Cementitious Materials allowed.
‖ Adjust slump in accordance with 2461.3.G.7.a,"Concrete Placed by the Slip-form Method."

State of New York Department of Transportation (NYSDOT)

Similarly, NYSDOT has developed more advanced standards inclusive to SCMs. Waste materials are encouraged and at times required for concrete mixtures in this state, as long as the waste material is performance verified, readily available, and does not harm the environment as stated in Section 106-05 entitled "Recycled Materials (NYSDOT, 2019). Pozzolanic material is required as a partial replacement for portland cement in Class DP, G, and HP concrete in New York, and is allowed as partial replacement for all concrete classes except Class F as stated in Section 501-2.02 "Material Requirements" (NYSDOT, 2019). Class DP concrete is a mixture of cement, fly ash micro-silica, fine and coarse aggregate, air entraining agent admixture and is used for concrete structures. Class G concrete is a low shrinkage fiber-reinforced structural concrete. Class HP is High Performance concrete utilized for concrete structures (NYSDOT, 2019). Table 2.7 shows concrete classes and allowable amounts of cement substitution with fly ash for each class (NYSDOT, 2019).

Table 2.8: New York Allowable Pozzolan Substitutions (NYSDOT, 2019)

Concrete Class Specified	Substitute Cement by Mass With	Class Substitution Allowed
A, C, E, H	15-20% Class F Fly Ash (711-10)	HP[1]
I, J	15-20% Class F Fly Ash (711-10)	-
D	15-20% Class F Fly Ash (711-10)	DP[1]
G[2] and GG[2]	20% Class F Fly Ash (711-10)	-
F	No Substitution Allowed	-

NOTES:
1. Class HP and DP concrete may be substituted to mitigate ASR as listed above. Classes HP and DP require the replacement of portland cement with 20% pozzolan and 6% microsilica. The pozzolan may be either Class C or F Fly Ash (§711-10) or Ground Granulated Blast Furnace Slag (§711-12).
2. Classes G and GG require the replacement of portland cement with 20% pozzolan. The mitigation of ASR in Classes G and GG must be accomplished using Class F Fly Ash (§711-10).

In regards to allowing loads on newly constructed bridges and roads, compressive strength results are used to determine when loading can begin unless otherwise stated by the regional engineer (NYSDOT, 2019). Even if early loading is requested, the regional engineer will base decision for loading on compressive strength results. Table 2.8 shows minimum wait times for loading based on the structure type, but are not applicable for concrete with fly ash, GGBFS, or concrete placed in ambient temperatures less than 60 degrees Fahrenheit as stated in Section 555-03.08 (NYSDOT, 2019).

Table 2.9: Minimum Time for Form Removal and Loading Limitations for Substructures in N.Y. (NYSDOT, 2019)

SUBSTRUCTURE ELEMENT	STRIPPING (2)	FORMING NEXT PLACEMENT	LOADING
All Footings	2 days	2 days	4 days before next placement
Abutment stems, backwalls	2 days if less than 10 feet (avg.). Add 1 day for each additional 5 feet to 5 days, maximum.	2 days	5 days before placing backwall on stem. 7 days before backfilling, 14 days before placing superstructure loads. (3)
Pier Columns, Pier Plinths	2 days if less than 10 feet high (avg.). Add 1 day for each additional 5 feet.	4 days – columns 2 days if forming pedestal	Columns – 7 days before placing cap beam. Plinth- 2 days before pedestal placement. 21 days before placing superstructure loads. (3)
Pier cap beams	8 days (bottom) 3 days (sides)	2 days	5 days before pedestal placement. 21 days before placing superstructure loads. (3)
All pedestals	2 days	—	7 days (class A) 3 days (class F) (4)
Wingwalls or Retaining walls	Same as abutment stems.	—	14 days before backfilling (3)
Arch centers Centering under beams	8 days	—	14 day (3)

All construction vehicles must be in accordance with the Vehicle and Traffic Law Section 385, along with complying with the limits provided by the contract (NYSDOT, 2019). Any vehicles or equipment over the legal gross weight limits, must be approved and operate under Section 385 as well (NYSDOT, 2019). In addition, any over-weight equipment must be approved by the contract Engineer prior to loading structures (NYSDOT, 2019).

When class C concrete is specified for pavements, Section 502-3.18 states roads can be opened to construction traffic and equipment 7 days after placement, or 3 days if contract Engineer approves and test cylinders prove to have a minimum compressive strength of 2500 psi in accordance with Section 502-3.18C (NYSDOT, 2019). As far as general traffic, if placed between June 1 and September 15, roads can be opened after 10 days, and if placed outside this window general traffic is allowed after 15 days according to the same section (NYSDOT, 2019). If the contract Engineer approves, the roads can be opened within 4 days if cylinders tested in accordance with Section 502-3.18C reach a minimum compressive strength of 3,000 psi (NYSDOT, 2019). Also in section 502-2.02 of the standard specifications, High Early Strength (HES) Concrete can be used when early age opening is required or requested (NYSDOT, 2019). Table 2.10 provides the HES concrete mix requirements, which includes opening roads to traffic (NYSDOT, 2019).

Table 2.10: N.Y. High Early Strength Concrete Requirements (NYSDOT, 2019)

Property	Minimum	Desired	Maximum
28 Day Compressive Strength	4000 psi	-	-
Opening Compressive Strength	2500 psi	-	-
Freeze-Thaw Loss (Test 502-3P, 3% NaCl)	-	0.0 %	3.0 %
Plastic Air Content	5.0 %	6.5 %	8.0 %
Hardened Air Content	5.0%	6.5 %	8.0 %
Water – Cement Ratio (w/c)	-	-	0.44
Slump[2]	1 in	-	6 in

Florida Department of Transportation (FLDOT)

FLDOT requires fly ash in all classes of concrete except for use of the following in an “aggressive” environment: Class I (3,000psi), Class I (3,000psi pavement), and Class II (3,400psi) as stated in Section 346-2.3 (FLDOT, 2019). In the same section, it states that SCMs may be used as an equal weight replacement for portland cement within total cementitious limitations, meaning the total of SCM and portland cement must stay within limits (FLDOT, 2019). Table 2.11 describes the concrete mixture proportions for cementitious materials based on application, the environment conditions are considered aggressive unless otherwise noted (FLDOT, 2019). Section 346-4 includes a master proportion table shown as Table 2.11, limiting the amount of total cementitious material and w/c ratio sorted by class of concrete (FLDOT, 2019). In Section 346-2.2, FLDOT specifies cement types for structures based on environmental use as shown in Table 2.12 (FLDOT, 2019). Also, FLDOT specifies minimum 28-day strength and slump target values for each class of concrete, as shown in Table 2.13 with emphasis on Class I (pavement) and Class II (bridge deck) as those at pertinent to this research (FLDOT, 2019). It should be noted that FLDOT conducts resistivity testing as permeability indicator as per AASHTO T358 testing method (FLDOT, 2019).

Table 2.11: Maximum Permissible FLDOT Cementitious Materials and Mixture Proportions (%) (FLDOT, 2019)

Application	Portland Cement	Fly Ash Type F	Slag	Highly Reactive Pozzolans		
				Silica Fume	Metakaolin	Ultra-Fine Fly Ash
General Use	70-82	18-30				
	66-78	15-25		7-9		
	66-78	15-25			8-12	
	66-78	15-25				8-12
	30-40	10-20	50-60			
	30-75(1)		25-70(1)			
	30-50		50-70			
	36-43		50-55	7-9		
	33-42		50-55		8-12	
	33-42		50-55			8-12
Precast Prestressed	70-85(1)	15-30(1)				
	70-82	18-30				
	66-78	15-25		7-9		
	66-78	15-25			8-12	
	66-78	15-25				8-12
	30-40	10-20	50-60			
	30-50		50-70			
	36-43		50-55	7-9		
	33-42		50-55		8-12	
	33-42		50-55			8-12
Drilled Shaft	63-67	33-37				
	38-42		58-62			
	30-40	10-20	50-60			
Mass Concrete	50-82(2)	18-50(2)				
	50-65(3)	35-50(3)				
	66-78	15-25		7-9		
	66-78	15-25			8-12	
	66-78	15-25				8-12
	30-40	10-20	50-60			
	30-50		50-70			
	36-43		50-55	7-9		
	33-42		50-55		8-12	
	33-42		50-55			8-12

(1) Slightly Aggressive and Moderately Aggressive environments.
(2) Concrete Core Temperature $T \leq 165°F$.
(3) Concrete Core Temperature $T \geq 165°F$.

Table 2.12: FLDOT Concrete Master Proportions (FLDOT, 2019)

Class of Concrete	Minimum Total Cementitious Materials Content pounds per cubic yard	Maximum Water to Cementitious Materials Ratio pounds per pounds*
I	470	0.53
I (Pavement)	470	0.50
II	470	0.53
II (Bridge Deck)	611	0.44
III	611	0.44
III (Seal)	611	0.53
IV	658	0.41**
IV (Drilled Shaft)	658	0.41
V (Special)	752	0.37**
V	752	0.37**
VI	752	0.37**
VII	752	0.37**

*The calculation of the water to cementitious materials ratio (w/cm) is based on the total cementitious material including cement and any supplemental cementitious materials that are used in the mix.
** When silica fume or metakaolin is used, the maximum water to cementitious material ratio will be 0.35. When the use of ultrafine fly ash is required, the maximum water to cementitious material ratio will be 0.30.

Table 2.13: FLDOT Cement Use by Environmental Classification (FLDOT, 2019)

Component	Slightly Aggressive Environment	Moderately Aggressive Environment	Extremely Aggressive Environment
Bridge Superstructures			
Precast Superstructure and Prestressed Elements	Type I or Type III	Type I, Type IL, Type II, Type III, Type IP, or Type IS	Type II (MH), Type IL, or Ternary Blend

Component	Slightly Aggressive Environment	Moderately Aggressive Environment	Extremely Aggressive Environment
Bridge Superstructures			
Cast In Place	Type I	Type I, Type IL, Type II, Type IP, or Type IS	Type II (MH), Type IL, or Ternary Blend
Bridge Substructures, Drainage Structures and other Structures			
All Elements	Type I or Type III	Type I, Type IL, Type II, Type IP, or Type IS	Type II (MH), Type IL, or Ternary Blend

Notes:
1. Cements used in a more aggressive environment may also be used in a less aggressive environment.
2. Type III cement may be used in an Extremely Aggressive Environment for precast superstructure and prestressed elements when the ambient temperature at the time of concrete placement is 60°F and below.

Table 2.14: FLDOT Concrete class, Compressive Strength, and Slump Requirements (FLDOT, 2019)

TABLE 3 Concrete Class, Compressive Strength, and Slump		
Class of Concrete	Specified Minimum Strength (28-day) (psi)	Target Slump Value (inches) (c)
Structural Concrete		
I [(a)]	3,000	3 [(b)]
I (Pavement)	3,000	2
II [(a)]	3,400	3 [(b)]
II (Bridge Deck)	4,500	3 [(b)]
III [(e)]	5,000	3 [(b)]
III (Seal)	3,000	8
IV [(d)(f)]	5,500	3 [(b)]
IV (Drilled Shaft)	4,000	8.5
V (Special) [(d)(f)]	6,000	3 [(b)]
V [(d)(f)]	6,500	3 [(b)]
VI [(d)(f)]	8,500	3 [(b)]
VII [(d)(f)]	10,000	3 [(b)]

(a) For precast three-sided culverts, box culverts, endwalls, inlets, manholes and junction boxes, the target slump value and air content will not apply. The maximum allowable slump is 6 inches, except as noted in (b). The Contractor is permitted to use concrete meeting the requirements of ASTM C478 4,000 psi in lieu of Class I or Class II concrete for precast endwalls, inlets, manholes and junction boxes.
(b) The Engineer may allow a maximum target slump of 7 inches when a Type F, G, I or II admixture is used. When flowing concrete is used, the target slump is 9 inches.
(c) For a reduction in the target slump for slip-form operations, submit a revision to the mix design to the Engineer. The target slump for slip-form mix is 1.50 inches.
(d) When silica fume, ultrafine fly ash, metakaolin, or a ternary blend cement is used in Class IV, Class V, Class V (Special), Class VI, or Class VII concrete, ensure that the concrete meets or exceeds a resistivity of 29 KOhm-cm at 28 days, when tested in accordance with AASHTO T358. Submit three 4 x 8 inch cylindrical test specimens to the Engineer for resistivity testing before mix design approval. Take the resistivity test specimens from the concrete of the laboratory trial batch or from the field trial batch of at least 3 cubic yards. Verify the mix proportioning of the design mix and take representative samples of trial batch concrete for the required plastic and hardened property tests. Cure the field trial batch specimens similar to the standard laboratory curing methods. Submit the resistivity test specimens at least 7 calendar days prior to the scheduled 28 day test. The average resistivity of the three cylinders, eight readings per cylinder, is an indicator of the permeability of the concrete mix.
(e) When precast three-sided culverts, box culverts, endwalls, inlets, manholes or junction boxes require a Class III concrete, the minimum cementitious materials is 470 pounds per cubic yard. Do not apply the air content range and the maximum target slump shall be 6 inches, except as allowed in (b).
(f) Highly reactive pozzolans may be used outside the lower specified ranges to enhance strength and workability. Testing in accordance with AASHTO T358 is not required.

For any road, street, or bridge (including temporary bridges owned by FLDOT), equipment cannot be operated in excess of maximum weights specified in Florida Highway Control, Commercial Motor Vehicle Manual, or in excess of posted lower weight limits established legally as per Section 7-7.2 of the FLDOT specification manual (FLDOT, 2019). Fresh concrete must be cured continuously for 72 hours (FLDOT, 2019). Unless the project engineer approves earlier opening, fresh concrete must be cured at least 14 days prior to opening structures to traffic (FLDOT, 2019). The project contractor can open any portion of a structure to vehicular or pedestrian traffic as long as the project engineer approves as per Section 7-15. Generally the engineer will approve early opening to traffic only if concrete samples made in accordance with ASTM C31 and tested in accordance with ASTM C39 prove to be at least 2,200 psi as stated in Section 350-16 (FLDOT, 2019). The pavement must be protected from all operations (including construction equipment loading) until specified time has elapsed (FLDOT, 2019). For bridge decks and slabs, concrete must be wheeled in order to avoid construction loading, and concrete has to cure for at least 14 days prior to opening road to traffic or approved by project engineer with a verified minimum compressive strength of 1,600 psi as per Section 400-17.1 (FLDOT, 2019).

Iowa Department of Transportation (IowaDOT)

In the Standard Specifications, IowaDOT states in Materials I.M. Section 491.17 that all fly ash and GGFBS must be selected from an approved source and must be in accordance with AASHTO M 295 (IowaDOT, 2015). As per standard section 4108.01 fly ash must be either Class F or Class C, and Class F must be tested for pozzolanic activity with lime (IowaDOT, 2015). The allowable fly ash and slag substitution is dependent on the type of mixture and purpose of mixture (IowaDOT, 2015). For low traffic pavements class A-mixtures are used, while for most pavement and bridge decks class-C mixtures are used (IowaDOT, 2015). For bridge deck overlays, blended cements, slag, and fly ash is required in the mixtures as per standard IM-529, “Portland Cement Concrete Proportions” and the maximum w/cm ratio is 0.42 (IowaDOT, 2015). Any concrete made using class V aggregates, which are fine and coarse feldspathic rocks, must follow Section 4117, “Class V Aggregates for Portland Cement Concrete” shown below in Table 2.15 (IowaDOT, 2015). Fly ash is limited to a substitution rate of 20% and slag is limited to a rate of 20%, with up to 50% total mineral admixture substitution for concrete structures as per section 2403, “Structural Concrete” (IowaDOT, 2015). For concrete bridge decks, as stated in section 2412 of the standard specifications, the maximum allowable substitution rates shown in Table 2.16 are adhered (IowaDOT, 2015). For concrete pavements mixtures, fly ash is limited to a substitution rate of 20% and GGFBS is limited to 35% with a maximum of 40% total mineral admixture as per standard section 2301, "Portland Cement Concrete Pavement" (IowaDOT, 2015). For blended cements such as Type IP or IS, only fly ash is permitted as a substitution (IowaDOT, 2015).

Table 2.15: IowaDOT Cement Types and Substitution for Portland Cement Concrete with Class V Aggregates (IowaDOT, 2015)

Cement Type	Min. Required Substitution	Max. Allowable Substitution
Type I, Type II	20% Class F Fly Ash	25% Class F Fly Ash
Type I, Type II	25% GGBFS	35% GGBFS
Type IS, IP	---	20% Class C Fly Ash

Table 2.16: IowaDOT Maximum Allowable Substitution Rates for Concrete Bridge Decks (IowaDOT, 2015)

Cement Type	Maximum Allowable Substitution[a]	Time Period
Type I, Type II	35% GGBFS 20% Fly Ash	March 16 through October 15
Type IS, IP	0% GGBFS 20% Fly Ash	March 16 through October 15
Type I, II, IS, IP	0% GGBFS 0% Fly Ash	October 16 through March 15

Construction equipment and other external loads must be simple compressive loads only for concrete structures, and must not exceed allowable loads designated by the designer (IowaDOT, 2015). Prior to loading concrete structures unless otherwise noted, the concrete must reach the ages shown in Table 2.17, and reach a minimum of 575 psi flexural strength as per section 2403 (IowaDOT, 2015). For concrete pavements, the maturity method can be used to expedite and determine when loads can be applied. The maturity method was discussed in Chapter 2, Section 2.1.1.3. Otherwise pavements must be in accordance with the age and strengths shown in Table 2.18 (IowaDOT, 2015).

Table 2.17: IowaDOT Minimum Age Requirements for Loading Concrete Structures (IowaDOT, 2015)

Portland cement (Type I and Type II with or without Class C fly ash)	7 calendar days
With Class F fly ash substitution	8 calendar days
Class M mix (with or without Class C or Class F fly ash)	3 calendar days
If strength is not determined (regardless of type of cement or class of fly ash)	14 calendar days

Table 2.18: Minimum Flexural Strength for Opening Concrete Pavements (IowaDOT, 2015)

Strength Class of Concrete	Minimum Age	psi (MPa)
A	14 calendar days[(a)]	500 (3.45)
B	14 calendar days	400 (2.80)
C	7 calendar days[(b)]	500 (3.45)
M	48 hours[(c)]	500 (3.45)
(a) 10 calendar days for concrete 8 inches (200 mm) thick or more. (b) 5 calendar days for concrete 9 inches (230 mm) thick or more. (c) Pavement may be opened for use prior to 48 hours when minimum flexural strength requirements are met.		

Illinois Department of Transportation (IDOT) and Illinois Tollway Authority

The Illinois department of transportation (IDOT) and Illinois Tollway standard specifications are summarized together since the Illinois Tollway follows IDOT with the exception of the supplemental specifications provided by the Tollway for special provisions. There are no supplemental provisions for portland cement concrete, thus the following specifications apply to both IDOT and the Illinois Tollway Authority. Section 1020.04 states that portland-pozzolan cement, portland limestone cement or any other combination of finely divided minerals and cement, must contain at least 400 pcy of OPC (IDOT, 2016). Class PV is designated for paving mixtures and BS is designated for bridge structure mixtures as shown in Table 2.19. Table 2.19 present the mix design criteria for bridge and pavement mixtures in Illinois (IDOT, 2016). For PV and BS class mixtures Class F fly replacement rates are not to exceed 25%, and limited to 30% for Class C fly ashes as per section 1020.05 (c)(1) in the IDOT standard specifications.

Table 2.19: Mix Design Criteria for IDOT (IDOT, 2016)

TABLE 1. CLASSES OF CONCRETE AND MIX DESIGN CRITERIA											
Class of Conc.	Use	Specification Section Reference	Cement Factor cwt/cu yd (3)		Water / Cement Ratio lb/lb	Slump in. (4)	Mix Design Compressive Strength (Flexural Strength) psi, minimum Days			Air Content %	Coarse Aggregate Gradations (14)
			Min.	Max			3	14	28		
PV	Pavement Base Course Base Course Widening Driveway Pavement Shoulders Shoulder Curb	420 or 421 353 354 423 483 662	5.65 (1) 6.05 (2)	7.05	0.32 - 0.42	2 - 4 (5)	Ty III 3500 (650)	3500 (650)		5.0 - 8.0 (5)	CA 5 & CA 7, CA 5 & CA 11, CA 7, CA 11, or CA 14
PP	Pavement Patching Bridge Deck Patching (10)	442					3200 (600) Article 701.17(e)(3)b.				CA 7, CA 11, CA 13, CA 14, or CA 16
	PP-1		6.50 6.20 (Ty III)	7.50 7.20 (Ty III)	0.32 - 0.44	2 - 4	at 48 hours			4.0 - 7.0	
	PP-2		7.35	8.20	0.32 - 0.38	2 - 6	at 24 hours			4.0 - 6.0	
	PP-3		7.35 (Ty III) (8)	7.35 (Ty III) (8)	0.32 - 0.35	2 - 4	at 16 hours			4.0 - 6.0	
	PP-4		6.00 (9)	6.25 (9)	0.32 - 0.50	2 - 6	at 8 hours			4.0 - 6.0	
	PP-5		6.75 (9)	6.75 (9)	0.32 - 0.40	2 - 8	at 4 hours			4.0 - 6.0	
RR	Railroad Crossing	422	6.50 6.20 (Ty III)	7.50 7.20 (Ty III)	0.32 - 0.44	2 - 4	3500 (650) at 48 hours			4.0 - 7.0	CA 7, CA 11, or CA 14
BS	Bridge Superstructure Bridge Approach Slab	503	6.05	7.05	0.32 - 0.44	2 - 4 (5)		4000 (675)		5.0 - 8.0 (5)	CA 7, CA 11, or CA 14 (7)
PC	Various Precast Concrete Items Wet Cast Dry Cast	1042	5.65 5.65 (TY III)	7.05 7.05 (TY III)	0.32 - 0.44 0.25 - 0.40	1 - 4 0 - 1	See Section 1042			5.0 - 8.0 N/A	CA7, CA11,CA 13, CA 14, CA 16, or CA 7 & CA 16
PS	Precast Prestressed Members Precast Prestressed Piles and Extensions Precast Prestressed Sight Screen	504 512 639	5.65 5.65 (TY III)	7.05 7.05 (TY III)	0.32 - 0.44	1 - 4			Plans 5000 3500	5.0 - 8.0	CA 11 (11), CA 13, CA 14 (11), or CA 16

IDOT specifies in section 107.29 that the project engineer will determine when/if a concrete pavement or structure is to be opened to regular traffic (IDOT, 2016). Also section 707.17 (c)(5) of IDOT's standard specifications states pavements will not be opened to regular traffic until 650 psi flexural strength is met or 3,500 psi compressive strength is met (IDOT, 2016). If these tests are not conducted, concrete pavements cannot be opened until 14 days after placement for OPC, and 28 days for concrete mixtures with fly ash or GGFBS. This section mentions all traffic (including construction traffic) should be limited to legal axle loads (IDOT, 2016). For structural concrete (i.e. Class BS concrete in this case) a minimum of 4,000 psi compressive strength or required flexural strength as determined by the project engineer must be met prior to loading concrete structures. As shown in Table 2.19, this is to be tested at 14 days. As per the minimum curing schedule shown in section 1020.13, pavements must cure at least 3 days, and bridge decks must cure at least 7 prior to opening to traffic (IDOT, 2016).

It should be noted that although concrete strength is a traditional method to ensure a pavement or bridge component can be subjected to traffic or other loads, the potential for a component to be distressed is also affected by other factors such as base thickness/strength, subgrade strength and reinforcement. Similarly, although concrete strength has been somewhat linked to durability at times, other performance variables are just as essential in determining durability, such as shrinkage as discussed in this report.

2.3.2 Shrinkage

Although strength is one of the primary variables studied when determining concrete durability, other variables such as shrinkage resistance should be accounted for as well in order to accurately determine concrete durability (AASHTO 2018, Cackler et al., 2017). For instance, cracking due to shrinkage can be detrimental to a concrete structure and may not occur until years after the concrete has been in service. As improved specifications are developed it is imperative to ensure these specifications do not impose unreasonable risk to any parties involved (owner, contractor, etc.) (Cackler et al., 2017). As part of the PEM initiative, several SHAs have been developing and implementing shrinkage specifications to help measure concrete performance.

Prior to the AASHTO PP 84-17 specification, unrestrained axial shrinkage was specified using volume of paste calculations to determine change of paste volume over time. The volume of paste could not change more than 25% as discussed in the "Performance Engineered Concrete Mixtures" presentation Van Dam at the Arizona Pavement/Materials Conference (2017). Currently, AASHTO's PP 84-19, suggests several driving factors influencing concrete durability performance and shrinkage is one of those factors (Cackler, 2017). As shown in Figure 2.1 AASHTO PP 84-17 included the ring test for unrestrained length change (AASHTO, 2017). The current AASHTO PP 84-19 (shown in Figure 2.2) specification eliminated this test, as it intensive, and ASTM C157 is specified as the most sophisticated testing measurement for shrinkage. It is expected that as improvements are made to the ring testing method, the dual ring test could return to standards if proven feasible. Although all concrete experiences shrinkage to some extent, shrinkage is a more critical concern in dry locations, and is listed as having prescriptive and performance implementation options (AASHTO, 2019). Per AASHTO PP 84-19, unrestrained volume change tested in accordance with ASTM C157, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete" (the most sophisticated of the approaches suggested) is limited to 420 micro-strain at hardened concrete age of 28 days in section 6.4.1.2 (AASHTO, 2019). AASHTO T 160 and ASTM C157 are jointly owned standards and are very similar.

Table 2.20: AASHTO PP 84-17 Performance Specifications (AASHT, 2017)

<table>
<tr><th>Mixture parameter</th><th>Traditional acceptance criteria</th><th>Property</th><th>Specification reference</th><th>Specified Test</th><th>Selection Details</th><th>Mixture Qualification</th><th>Acceptance</th><th>Selection Details</th></tr>
<tr><td rowspan="2">Concrete strength</td><td rowspan="2">yes</td><td>Flexural Strength</td><td>6.3.1</td><td>T 97</td><td rowspan="2">Choose either or both</td><td>Yes</td><td>Yes</td><td rowspan="2">Choose either or both</td></tr>
<tr><td>Compressive Strength</td><td>6.3.2</td><td>T 22</td><td>Yes</td><td>Yes</td></tr>
<tr><td colspan="9">6.4 Reducing Unwanted Slab Warping and Cracking Due to Shrinkage (if cracking is a concern)</td></tr>
<tr><td rowspan="4">Reducing unwanted slab warping and cracking due to shrinkage</td><td rowspan="4">no</td><td>Volume of Paste</td><td>6.4.1.1</td><td>-</td><td rowspan="4">Choose one</td><td>Yes</td><td>Yes</td><td rowspan="4">Choose only one</td></tr>
<tr><td>Unrestrained Volume Change</td><td>6.4.1.2</td><td>T 160</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Unrestrained Volume Change</td><td>6.4.2.1</td><td>T 160</td><td>Yes</td><td>Yes</td></tr>
<tr><td>Restrained Shrinkage</td><td>6.4.2.3</td><td>TP-363-17 (Dual Ring)</td><td></td><td></td></tr>
</table>

Table 2.21: AASHTO PP 84-19 Performance Specifications (AASHTO, 2019)

Specification	**Property**	**Specified Test**	**Specified Value**		**Mixture Qualification**	**Acceptance**	**Selection Details**
6.3.1	**Flexural Strength**	T 97	4.1 Mpa	600 psi	Yes	Yes	Choose either or both
6.3.2	**Compressive Strength**	T22	27.5 Mpa	4,000 psi	Yes	Yes	
6.4 Reducing Unwanted Slab Warping and Cracking Due to Shrinkage (if cracking is a concern)							
6.4.1.1	**Volume of Paste**	-	≤25%		Yes	No	Choose only one
6.4.1.2	**Unrestrained Volume Change**	T 160	420	At 28 days	Yes	No	
6.4.2.1	**Unrestrained Volume Change**	T 160	360, 420, 480	At 91 days	Yes	No	

More comprehensive means of ensuring shrinkage performance is met include other established and emerging tests. For example, shrinkage variation can be controlled by using an F factor and porosity measures, or mixture proportion observation (AASHTO, 2019). Other shrinkage tests under evaluation for inclusion in AASHTO PP 84 include several forms of a restrained ring test (AASHTO, 2017), although these tests have been removed from the current version of AASHTO PP 84. In other published guidance regarding shrinkage requirements, research suggested the change in length due to drying shrinkage should be less than 0.04% at 28 days and 0.05% at 90 days for concrete mixtures (Mokarem et al., 2203). In research performed for NCDOT, drying shrinkage test results (performed in accordance with ASTM C 157) indicated that concrete mixtures made with OPC and concrete mixtures made with PLC both met the threshold of 0.04% at 28 days, with minimal differences in shrinkage probability between the two types of mixtures. The mixtures in this research were tested at 56 and 112 days. The results at these ages suggest the threshold of 0.05% or less at 90 days (Cavalline et al., 2018). In addition, all of the mixtures met AASHTO PP 84-17 (the first AASHTO PEM Standard Specification) shrinkage recommendation, which suggested limit of 200-423 $\mu\varepsilon$ with the exception of one mixture (Cavalline et al. 2018).

NCDOT

NCDOT standard specifications state in section 420-15 to properly cure concrete structures for a minimum of seven days and take all necessary precautions to avoid shrinkage cracking including wind screens, temporary liquid moisture barriers, or early application of wet coverings (NCDOT, 2018). In hot weather, concrete temperatures must be controlled to prevent plastic cracking and as stated in section 1078-9 of the standard specifications, if shrinkage cracks occur during or after placement, the project engineer determines if removal or remediation is required (NCDOT, 2018). Otherwise, there is no specific target or testing required for unrestrained shrinkage.

LaDOTD

The LaDOTD standard specifications state in section 901.11.2 that concrete placed in high temperatures (hot weather) must be designed, placed, and cured properly to avoid plastic shrinking (LaDOTD, 2016). The only target specification for shrinkage is for undersealing or slab-jacking pavements and for structural concrete patching, where the shrinkage after four days must not change more than 0.13 percent in length and no more than 0.07 percent in length as per ASTM C157 testing procedure (LaDOTD, 2017).

NYSDOT

NYSDOT standard specifications state in section 718-06, for High Performing (HP) concrete length change due to shrinkage must be less than 600 microstrain tested in accordance with AASTHO T160-97, “Standard Method of Test for Length Change of Hardened Hydraulic Cement Mortar and Concrete” (ASTM C157) at 56 days (NYSDOT, 2018). For other concrete classes, there is no specified target maximum for shrinkage.

IowaDOT

The IowaDOT standard specifications do not specify target or standards for shrinkage resistance for concrete pavements and structures except for ultra-high performing concrete. For this type of concrete the initial shrinkage (tested after initial set) should be less than 766 micro-strain tested in accordance with ASTM C150, as stated in special provisions section 150289 (IowaDOT, 2015).

(IDOT) and Illinois Tollway Authority

In the Standard Specifications for Road and Bridge Construction, IDOT specifies shrinkage targets for the following concrete applications. For rapid hardening cement, shrinkage is limited to 0.050 percent in accordance to ASTM C 596, "Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement" (IDOT, 2016). Other than concrete mixtures using rapid hardening cement, targets for shrinkage specification were not found in the IDOT specifications or the supplementary specifications for the Illinois Tollway.

An ACI webinar about the Illinois Tollway Authority, discusses implementation of performance specifications in current and future projects and shrinkage is discussed (Gancarz, 2018). For HPC (structural concrete use) contractors have two options for shrinkage mitigation. The first option is to use shrinkage reducing admixtures at a rate of 1.5 gallons/cy and limit the cementitious materials to less than 605 lb/cy total cementitious material content or the other option is to provide test results of the ring test (ASTM C 596) proving drying shrinkage has been mitigated (Gancarz, 2018). For pavements and structures, the Illinois Tollway has identified reduced cementitious material contents, and increased use of SCMs as essential to producing durable concrete mixtures (Gancarz, 2018).

2.4 Research Needs

The movement towards PEM will likely result in state highway agencies constructing pavements and structures with mixtures that utilize increased quantities of SCMs. Concretes with SCMs tend to gain strength more slowly than concretes with OPC, so provisions for early age opening to construction and regular traffic will need to be considered as NCDOT encourages movement towards PEM specifications. With specifications increasing the allowable amount of fly ash, as well as PLC, NCDOT has the opportunity and need to improve specifications to ensure the benefits of SCMs are achieved without contractors fearing that they may not meet early-age strength requirements for construction vehicles and general opening to traffic.

Additionally, as NCDOT aims to reduce cracking in concrete infrastructure, PEM guidance and other sources provide performance targets for unrestrained shrinkage testing that could be utilized in specifications.

Since concrete quality and project costs are influenced by construction in addition to provisions required to ensure mixtures meet agency (and designer) requirements for concrete performance, standard specifications for N.C. should be examined to determine performance variables most impactful to the people working directly with concrete, the contractors. Since contractors control how concrete is vibrated, placed, cured, etc. it is essential that the standard specifications consider not only designer variables but constructability as well (Cackler et al. 2017).

The previous sections of this chapter presented current NCDOT specifications for concrete transportation structures, along with a summary of other SHA specifications for concrete made with SCMs, as well as prescriptive and performance provisions addressing concrete strength and shrinkage. The goal of summarizing other pertinent state specifications was to provide insight into potential approaches that could be useful in development of recommendations for modifications to the current NCDOT specifications.

CHAPTER 3: METHODOLOGY

3.1 Introduction

To define and implement specifications for durable concrete, the proper testing methods, performance targets, and standard approaches must be identified. As discussed in Chapter 2, the PEM initiative has identified current standards and testing methods that can serve as guidelines and best practices to assist in establishing specifications, targets, and performance criteria and ensuring durable concrete performance can be constructed (AASHTO 2018). As a part of this project, utilizing current PEM methods and standards along when testing an array of concrete mixtures (very good, reasonable, and likely lesser quality), performance targets will be identified for NCDOT to use in specifications for concrete pavements and bridges. To support and determine specifications for compressive strength and shrinkage, the mixture matrix and testing program described in this chapter was developed and implemented to assist in meeting the research objectives: developing specifications for 1) early-age strength and 2) shrinkage for performance engineered concrete. In addition to discussing the laboratory and testing methods, this chapter describes the materials used, proportions, and fresh concrete sampling procedures are described.

3.2 Development of Concrete Mixture Matrix

Since mixture proportioning is one of the main characteristics that control quality and performance results, the mixture matrix was developed in a manner that explored a range of potential concrete materials and proportions. Cementitious material content, w/cm ratio, and fly ash content were identified as key drivers of concrete performance, and were varied to provide a mixture matrix of 24 mixtures capable of supporting specification targets and durable concrete performance goals. These variables also represent characteristics historically utilized by NCDOT for bridge and pavement construction (Class AA) acceptance.

The w/cm ratios 0.37, 0.42, and 0.47 were chosen to represent low, mid-range, and high w/cm ratios representative of lower than typical, typical, and higher than typical values used in Class AA bridge and pavement field applications. For cementitious content, three values were chosen to represent different types of Class AA bridge mixtures and pavements. For low cement content bridge deck mixtures and paving mixtures, 600 pcy was used. For typical bridge mixtures (typical w/cm ratio) the mid-range cement content of 650 pcy was used. For high cement content bridge mixtures 700 pcy was used. These material proportions remained constant as the water, fine, and coarse aggregates were calculated. Mixture proportions are shown in Table 3.1. Each part of the mixture ID is specific to the proportioning content, where the first letter represents w/cm ratio, the middle number represents cement content, and the last number represents fly ash content as shown in Table 3.1.

The fly ash substitution rates, cementitious material contents, and w/cm ratios for each of the 24 concrete mixtures are shown in Figure 3.1. Ten of the twenty-four mixtures included zero percent fly ash substitution (“straight cement” mixtures), ten mixtures included twenty percent fly ash, and the remaining four mixtures included thirty percent fly ash as a substitute for cement. Recently, NCDOT changed their specifications to increase the maximum allowable fly ash content from 20 to 30%. Since incorporation of fly ash into concrete mixtures has been shown to provide improved durability performance, it was essential for the mixture design to include mixtures at both replacement rates to compare concrete performance in the tests.

In addition to the fly ash substitution rate, the second number shown in each box represents the amount of fly ash in pounds per cubic yard (pcy) of concrete. On the other hand, total cementitious material in pcy was varied as shown as the first number in each colored box in Figure 3.1. Mixtures with higher cementitious material (such as structural concrete members) are shown in orange, mixtures with mid-range cementitious content are shown in yellow, and mixtures with lower cementitious material (such as concrete pavements) are shown in green. Essentially the mixtures are grouped by low, medium, and high w/cm ratios commonly used in bridge and pavement mixtures. In addition, NCDOT recently decided to allow use of portland limestone cement (PLC), a more sustainable alternative to original portland cement (OPC). Therefore, so three of the twenty-four mixtures include portland limestone cement (PLC) instead of original and are shown in Figure 3.1 as light green colored boxes. Fine and coarse aggregate proportions remained constant to focus on performance impact of fly ash, cementitious material content, and w/cm ratios.

Figure 3.1: Concrete Mixture Matrix with Supplemental Information

3.3 Mixture Design

As described in the previous section and shown in Figure 3.1, NCDOT and the research team selected 24 mixtures for the overall project of building and maintaining longer lasting (more durable) concrete structures. Based on the cementitious materials contents, twelve of the mixtures were aimed at meeting Class AA bridge deck mixture requirements, and twelve of the mixtures could likely be used for pavement structures (Biggers, 2019). Materials, including fly ash, coarse and fine aggregates, water, and admixtures were all kept constant to focus on the target characteristics explored in the mixture matrix.

All mixtures except for three contained OPC Type I/II cement from LafargeHolcim in Holly Hill, S.C. Three mixtures contained Type I/II PLC cement from a location used in previous research for NCDOT RP 2015-03 (Cavalline et al. 2018).

As shown in Figure 3.1, cementitious material contents, w/cm ratios, and fly ash substitution rates were the parameters chosen to vary during laboratory testing. The mixtures were proportioned based on ACI 211.1 mixture proportioning guidance and the selected w/cm ratio for each mix. Coarse aggregate content was calculated to be 1,659 pcy using ACI 211.1 guidelines, while fine aggregate amounts ranged from 1,022 and 1,434 pcy. Depending on the fly ash replacement rate and w/cm ratio required for each mix, cement content ranged from 420 and 700 pcy. Fly ash content depended on the cement content and ranged from 0 to 180 pcy. Based on ACI 211 procedures, water content ranged from 222 and 329 pcy as shown in Table 3.1.

Table 3.1 Concrete Mixtures and Proportions

Mixture ID	Mixture Characteristics			Mixture Proportions (pcy)					
	Mixture Type	Cement Type	w/cm ratio	Fly Ash Replacement (%)	Cement	Fly Ash	Coarse Aggregate	Fine Aggregate	Water
H-700-0	Class AA (high and medium cm content	OPC	0.47	0	700	0	1659	1072	329
H-560-140				20	560	140	1659	1072	329
H-650-0				0	650	0	1659	1175	305.5
H-520-130				20	520	130	1659	1129	305.5
H-600-0				0	600	0	1659	1277	282
H-480-120				20	480	120	1659	1235	282
H-420-180				30	420	180	1659	1214	282
M-700-0			0.42	0	700	0	1659	1163	294
M-560-140				20	560	140	1659	1114	294
M-650-0				0	650	0	1659	1259	273
M-520-130				20	520	130	1659	1214	273
M-600-0				0	600	0	1659	1356	252
M-480-120				20	480	120	1659	1313	252
M-420-180				30	420	180	1659	1292	252
M-600P-0		PLC		0	600	0	1659	1356	252
M-480P-120				20	480	120	1659	1313	252
M-420P-180				30	420	180	1659	1292	252
L-700-0	Class AA (low cm content) and Pavement	OPC	0.37	0	700	0	1659	1254	259
L-560-140				20	560	140	1659	1205	259
L-650-0				0	650	0	1659	1344	240
L-520-130				20	520	130	1659	1298	240
L-600-0				0	600	0	1659	1434	222
L-480-120				20	480	120	1659	1392	222
L-420-180				30	420	180	1659	1370	222

3.4 Materials Description and Characterization

This section outlines additional information about concrete material sources and properties that have been tested experimentally and/or by manufacturer or supplier. Cementitious materials, coarse and fine aggregates, and chemical admixtures used for each concrete mixture are described.

3.4.1 Cementitious Material

OPC, PLC, and fly ash are the cementitious materials used in the laboratory testing program. portland cement (OPC) is most commonly used in concrete mixtures, and was used for twenty-one of the mixtures in the testing program. It was sourced from a LafargeHolcim cement plant in Holly Hill, SC and shipped to UNC Charlotte. The OPC used from this plant was Type I/II cement meeting ASTM C150, “Standard Specification for Portland Cement (ASTM, 2019). Appendix A, Figure A.1 contains the mill reports for the OPC used in the laboratory testing program. PLC Type IL cement was used for three of the twenty-four mixtures and was sourced from the same plant in Holly Hill, SC. The PLC Type IL cement was in accordance with ASTM C595, “Standard Specification for Blended Hydraulic Cements” and was produced using less than fifteen percent added limestone (ASTM, 2019). The OPC mill reports are applicable to the PLC and shown in Appendix A, Figure A.1.

The fly ash used in the testing program was sourced from Belews Creek Power Plant in Belews Creek, NC and is classified as Class F fly ash. Additional information about the fly ash is available in Appendix A, Figure A.2.

3.4.2 Coarse Aggregate

The coarse aggregate selected for this program was in accordance with NCDOT specification 1014-2, “Aggregate for Portland Cement Concrete – Coarse Aggregate” (NCDOT, 2018). The aggregate was in accordance with ASTM C33, “Standard Specification for Concrete Aggregates” as well (ASTM, 2018). In previous studies to assist NCDOT with concrete research, the research team collaborated with NCDOT to choose a quarry representative to the aggregates most commonly used for North Carolina bridges and pavements in the Piedmont region. No. 67 aggregate from Wake Stone – Triangle Quarry in Cary, NC was used. Aggregate hoppers with two cubic yard capacity was used to help research team members and a quarry representative collect the aggregate and transport it back to UNC Charlotte. Aggregate properties amongst other information is shown in Appendix A, Figure A.3-A.5 and Table A.1.

3.4.3 Fine Aggregate

The fine aggregate chosen for this program was selected in a manner similar to the coarse aggregate and in accordance with NCDOT specification 1014-1, "Aggregate for Portland Cement Concrete – Fine Aggregate" as well as ASTM C33 (NCDOT, 2018 and ASTM, 2019). Since fine aggregate is not a key variable in the mixture matrix, the same type of fine aggregate (a natural silica sand) was used for each mixture. The fine aggregate selected is commonly used in NC bridge and pavement concrete mixtures, and has been used in previous research projects (Biggers, 2019). The fine aggregate was sourced from the Lemon Springs, NC natural sand pit. Additional information about fine aggregate properties are shown in Appendix A, Figure A.6 and Table A.2.

3.4.4 Chemical Admixtures

The chemical admixtures used for this project include air entraining admixture (AEA) and mid-to-high range water-reducing admixture (WRA) both of which are readily available in the Southeast construction market and are commonly used in mixtures submitted to NCDOT for approval. Both admixtures were chosen to ensure the desired maximum slump of 3.5 inches and air content of 5 to 6 percent was obtained. NCDOT standard specification 100-2(C), "Portland Cement Concrete for Pavement – Slump" requires maximum slump of 3 inches (NCDOT, 2018), but variations up to 3.5 inches were tolerated in order to maintain w/cm ratios per the mixture matrix shown in Figure 3.1. In addition NCDOT standard specification 1000-3(B), "Portland

Cement Concrete for Pavement – Air Content" states allowable air content of 5 ± 1.5 percent but a 1 percent variation in range (target: 5.0% to 6.0%) was used for this project in order to more efficiently observe how material proportions impact the quality concrete properties, without complicating the variability of the test results with changes due to a wide range of air content variation (NCDOT, 2018).

Both admixtures are products produced by Badische Anilin- und Soda Fabrik (BASF) and have the following characteristics. The AEA selected for this project is called MasterAir AE 200 and was used in all twenty-four mixtures for the testing program. A dosage between 0.125 and 1.5 fluid ounces per hundredweight (cwt) of cementitious material was recommended by BASF (BASF, 2019). The actual range of dosage for the concrete mixtures in this testing program was 0.42-2.99 to obtain required air content of 5-6 percent. The mid-range WRA selected for this project is the MasterPolyheed 997, and was used for eighteen of the twenty-four mixtures to improve workability. Other mixtures were workable without the WRA, which was a characteristic attributed mainly the w/cm ratio. It was recommended by BASF to use a dosage range of 5-15 fluid ounces/cwt of cementitious material for most mixes (BASF, 2019). The high levels required for some of the mixtures were necessary to maintain the desired w/cm ratio and/or cementitious material content per the mixture matric. Additional details can be found in Biggers (2019).

3.5 Testing Program

The testing program needed to encompass practical testing methods currently used in NCDOT standard specifications, as well as emerging tests included in the PEM initiative. Each mixture described in the matrix was tested in fresh and hardened states depending on the appropriate ASTM and AASHTO test procedures. Although compressive and flexural strength tests were of primary interest to research presented in this thesis, a range of tests were included in the experimental program to support the overall objectives of the broader research project. Testing procedures for strength had to also encompass testing for bridge decks along with pavements.

Modulus of rupture (MOR) testing was only performed on lower cementitious content (pavement) mixtures, since the more cumbersome beams used for this test are only required for pavement mixtures. Table 3.2 entitled "Laboratory Testing Program" shows the testing type, standard applicable, test age of specimen, and how many specimens were collected.

Table 3.2: Laboratory Testing Program

	Test Name	Standard	Testing age(s) in days	# of Specimens taken
Fresh	Air Content	ASTM C231	Fresh	1
	SAM number	AASHTO TP 118	Fresh	2
	Slump	ASTM C143	Fresh	1
	Fresh Density (Unit weight)	ASTM C138	Fresh	1
	Temperature	AASHTO T 309	Fresh	1
Hardened	Compressive Strength	ASTM C39	3,7,28,56,90	3 each age
	Modulus of Rupture (flexural Strength)	ASTM C78	28	2
	Modulus of Elasticity and Poisson's Ratio	ASTM C469	28	2
	Hardened air content	ASTM C457 (automated)	N/A	2
	Resistivity	AASHTO T 358	3,7,28,56,90	3 each age
	Formation factor (Bucket Test)	Protocol by J. Weiss	35	2
	Shrinkage	ASTM C157	Per Standard	3
	Rapid Chloride Permeability	ASTM C666 (procedure A)	28,90	2

3.6 Batching and Mixture Procedure

A six cubic foot (cf) portable drum mixer was utilized to batch all concrete mixtures. The testing program allowed researchers to evaluate multiple mechanical and fresh concrete properties, as well as durability performance tests. The size of each batch was calculated depending on the test type, specimens that needed to be cast, and estimated waste. For mixtures requiring MOR testing (low cementitious content/pavement mixtures) batch sizes of 4.11 cf was calculated, and for the other twelve mixtures 2.79 cf was calculated (Biggers, 2019). To account for waste, the larger size (pavement) mixtures were batched in two 2.65 cf portions, and the other non-paving mixtures were batched in 3.0 cf portions. In order to ensure consistency between specimens, three specimens were sampled for compressive strength testing at each age.

All concrete mixtures were batched according to ASTM C685, "Standard Specification for Concrete Made by Volumetric Batching and Continuous Mixing" (ASTM, 2017). All specimens from non-paving mixtures shown in Table 3.2 were made from a single batch of concrete. The paving mixtures were batched in two separate portions. For the first batch, enough material was batched to allow for fresh properties testing, (2) specimens for hardened air content, (15) 4in x 8in cylinders for compressive strength testing, (2) 6in x 12in cylinders for modulus of elasticity (MOE) testing, (2) 4in x 6in cylinders for Rapid Chloride Permeability Testing (RCPT), and (2) specimens for formation factor testing. For the second batch enough material was batched for fresh property testing, (2) beams for hardened air content, (2) for MOR, and (3) for shrinkage testing.

3.7 Testing of Fresh Concrete Properties

This section outlines several testing procedures for fresh concrete. Several of these properties have been included in the PEM initiative as important to performance properties. Slump, fresh air content, and unit weight are also discussed. For fresh air content the Super Air Meter (SAM) was used along with the SAM number to correlate how the concrete responds to freeze-thaw conditions based on the air void system within the concrete (DeGraaf and Ley, 2018). Thus the SAM number will estimate the air bubble size distribution in fresh concrete (DeGraaf and Ley, 2018).

3.7.1 Slump

Slump was measured in accordance with ASTM C143, "Standard Specification for Slump of Hydraulic-Cement Concrete" for all fresh concrete mixtures. As mentioned earlier, deviation from the target slump of 3.5 inches was allowed due to the goal of maintaining a constant w/cm ratio, and could also be attributed to the design characteristics of each mixture. Similar to field applications, slump was also used to monitor quality. For example, mixtures made with less cementitious materials should have lower slumps than those of higher cementitious materials. Since the lower w/cm ratio mixtures contained less cementitious materials, these mixtures were more difficult to work with; however, WRAs were added to these mixtures to ensure easier workability.

3.7.2 Air Content

Freeze-thaw stresses are mitigated by proper air bubble distribution throughout the concrete so air content is an essential tool in predicting concrete durability (Kosmatka and Farney, 1998). Fresh air content was measured by ASTM C231, "Standard Test Method for Air Content of Freshly Mixed Concrete" by the Pressure Method" and an air content range of 5-6 percent was acceptable for this testing program (ASTM, 2017). Typical air content targets range from 4.5-6 percent for normal exposure conditions usually depending on nominal aggregate size (Kosmatka and Farney, 1998). The range for target air content in this laboratory testing program was chosen because it allows less deviation amongst the air content in the mixtures promoting consistency. The research team will be able to observe the parameters discussed instead of deviations in air content. Also, this tight air content range was utilized in previous research studies for NCDOT, and the research team desired to maintain consistency between data collected as a part of this study and data collected from previous studies (facilitating comparison) (Biggers, 2019). To reach the target air content range the research team used an AEA, along with testing the fresh concrete with the SAM and SAM number. SAM test procedures are discussed in AASHTO TP 118 (AASHTO, 2017).

3.7.3 Unit Weight

Unit weight can be used as an indicator of batching issues, such as air content or incorrect mixture proportions, and was measured on fresh concrete prior to any other testing (Biggers, 2019). Unit weight of each fresh concrete mixture was tested by ASTM C138, "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete" (ASTM, 2017). The SAM equipment that was used in air content testing was also used for unit weight testing since the weight and volume of the portion used was known. Since each mixture contained different material proportions, the unit weights varied, and the research team used unit weight as a quality check.

3.8 Preparation and Curing of Test Specimens

Each specimen was prepared in accordance with ASTM C192, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory" (ASTM, 2018). In order to release forms without damaging the concrete, form release was applied to the casings before handling fresh concrete. Although multiple members of the research team helped with batching and sampling the concrete, consistency was generally maintained during sampling preparation, with each type of specimen made by the same individual. This was performed in order to reduce variability that may occur due to human influence. Each specimen was cured in continuous misting conditions in accordance with ASTM C511, "Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes" (ASTM, 2019).

3.9 Testing of Hardened Concrete

The hardened concrete testing program is shown in Table 3.2 in the section of the table entitled, "Hardened." Mechanical properties such as compressive, flexural strength (typically for pavement mixtures only), and shrinkage historically have been depended on to predict concrete performance. This section provides an overview of these mechanical properties.

3.9.1 Compressive and Flexural Strength

For compressive strength testing, specimens were tested in accordance with ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" (ASTM, 2018). The specimens made for compressive strength were size 4in x 8in cylinders, with testing at 3, 7, 28, 56, and 90 days. NCDOT standard specifications section 1000-3 states a minimum of 4,500 psi strength for Class AA pavements and bridge decks by 28 days (NCDOT, 2018).

For flexural strength testing, specimens were tested in accordance with ASTM C78, "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Three-Point Loading)" (ASTM, 2018). This testing method utilizes the modulus of rupture (MOR) to evaluate the tensile strength of concrete after 28 days of curing. NCDOT standard specification section 1000-3 states that 650 psi average flexural strength must be reached by 28 days for pavements (NCDOT, 2018). As described previously, since half of the mixtures represent pavement mixtures, beam specimens were made and tested for these 12 mixtures only.

3.9.2 Volumetric Shrinkage

To determine shrinkage properties for this testing program, unrestrained shrinkage testing was used in accordance with ASTM C157, "Standard Test Method for Length Change of Hardened Hydraulic Cement Mortar and Concrete" testing procedures (ASTM, 2017). For shrinkage testing, three specimens size 4in x 4in x 11in were cast in order to obtain an average. To embed the gage studs into the specimens, the studs were placed in the mold prior to casting concrete. The concrete cured for 28 days after molding removal and transferred to an environmental chamber, which is temperature controlled at 73 degrees Fahrenheit (˚F) (with ±3˚F tolerance) and relative humidity controlled at 50% (with a ±4% tolerance). The results from this testing are correlated to potential volumetric contractions in the concrete due to causes other force and temperature using ASTM C157 (ASTM, 2017). The test results chapter of this report will further discuss shrinkage specifications in comparison with shrinkage testing results.

CHAPTER 4: TEST RESULTS

A summary of the results of the testing discussed in Chapter 3 are presented in this chapter. As stated earlier in this report, the mixture identifications for each mixture represent proportions, w/cm ratios, and cementitious materials. For instance, for mixture identification label "H-700-0", H represents the w/cm ratio, the first number 700 represents the cement content, and 0 represents the fly ash content. The w/cm ratios chosen for this project are "H" for high w/cm ratio of 0.47, "M" for mid-range/normal w/cm ratio of 0.42, and "L" for low w/cm ratio of 0.37, which are directly related to industry standards/expectations. The cement content for the mixtures vary from 420-700 pcy, and the fly ash contents vary from 0-180 pcy to show zero, twenty, and thirty percent fly ash content.

4.1 Fresh Concrete Test Results

The results of the fresh concrete testing mentioned in Chapter 3 are discussed in this section. Slump, fresh air content, unit weight, and SAM number was tested as a part of the fresh concrete testing program. To ensure the laboratory testing was in compliance with the guideline criteria mentioned, every mixture was tested. For each mixture the target air content was 5-6%, and admixtures were utilized in different dosages to ensure target air content was met. As discussed previously, this target range was held constant to ensure air content would not impact results and to adhere to the same constraints as previous projects so the data could be compiled and compared. Table 4.1 presents a summary of the fresh testing results. All of the test results will be discussed more thoroughly later in this section.

Table 4.1: Fresh Concrete Test Results

Mix ID	Slump (in.)	Air Content (%)	Unit Weight (pcf)
H-700-0	8.0	5.2	137.1
H-560-140	8.0	5.2	136.4
H-650-0	6.5	6.0	141.4
H-520-130	7.0	5.5	138.0
H-600-0	2.5	5.8	138.7
H-480-120	3.0	6.0	139.4
H-420-180	3.8	6.0	136.1
M-700-0	5.0	5.5	141.6
M-560-140	4.3	6.0	136.6
M-650-0	2.5	5.7	142.4
M-520-130	3.0	5.5	139.7
M-600-0	1.0	6.0	140.5
M-600P-0	1.5	5.0	139.6
M-480-120	2.0	6.0	138.1
M-480P-120	0.8	5.5	141.1
M-420-180	1.0	5.1	140.5
M-420P-180	1.5	5.9	137.0
L-700-0	2.3	6.0	143.9
L-560-140	1.8	5.0	140.3
L-650-0	1.0	6.0	141.8
L-520-130	1.0	5.0	141.6
L-600-0	1.0	5.5	142.6
L-480-120	0.8	5.5	142.0
L-420-180	1.0	5.2	142.0

4.1.1 Slump

Table 4.1 shows the slump test results for this testing program. As described in Chapter 3, each mixture had different characteristics requiring different WRA doses to achieve target slump. Although the target slump for this testing program was 3.5 inches, there were several mixtures deviating significantly from the target slump. These mixtures were, however, accepted, since the w/cm ratios is the focus of the evaluation. Mixtures with higher w/cm ratios had the highest slump values and tended to be more workable than those with lower w/cm ratios. Less WRA was used for most of these mixtures, as the higher water content associated with the high w/cm ratio provided the workability. Five of the higher w/cm ratios and one mid-range w/cm ratio (H-700-0, H-560-140, H-650-0, H-520-130, H-600-0, and M-700-0) required no WRA at all (Biggers, 2019). On the other hand, the mixtures with low cement content and w/cm ratio of 0.37 required more WRA resulting in slumps lower than the target. In addition to adhering to designated w/cm ratio, concrete workability was observed as well. Even with the deviations from the target slump, each mixture workability allowed for consolidation of the test specimens.

4.1.2 Fresh Air Content

The fresh concrete air content results are shown in Table 4.1. It is assumed that the variations of air content are due to the varying dosages of AEA added to each mixture to achieve the target air content of 5-6% depending on the mixture characteristics. Fly ash content, material temperatures, and WRA dosages also impact air content other than AEA dosage. For instance, 18 mixtures required more AEA than others and 15 of these mixtures contained fly ash or portland limestone cement (Biggers, 2019).

4.1.3 Unit Weight

Table 4.1 shows the unit weight test results for this testing program. As shown, unit weights varied from 136.1-143.9 pounds per cubic foot (pcf), due to the different materials and proportions of each mixture. The data shows that there is relationship between unit weight and w/cm ratio. For instance, the lowest unit weights of the testing program were mixtures that had either a high w/cm ratio, low cement content, contained fly ash or portland limestone cement, or a combination of mentioned characteristics. Out of the ten lowest unit weights, six of the ten had a high w/cm ratio of 0.47, and seven of the ten contained fly ash. As expected six out of ten of the mixtures containing only cement had were in the top ten highest unit weights for all mixtures. The four remaining mixtures containing only cement mixtures had medium to high w/cm ratios resulting in lower unit weights, and with one of those four contained PLC. To graphically present these differences, Figure

4.1 shows the mixtures unit weights separated by fly ash content and cementitious material content color coded in the same way as the design matrix shown in Figure 3.1 to differentiate high, medium, and low w/cm ratios.

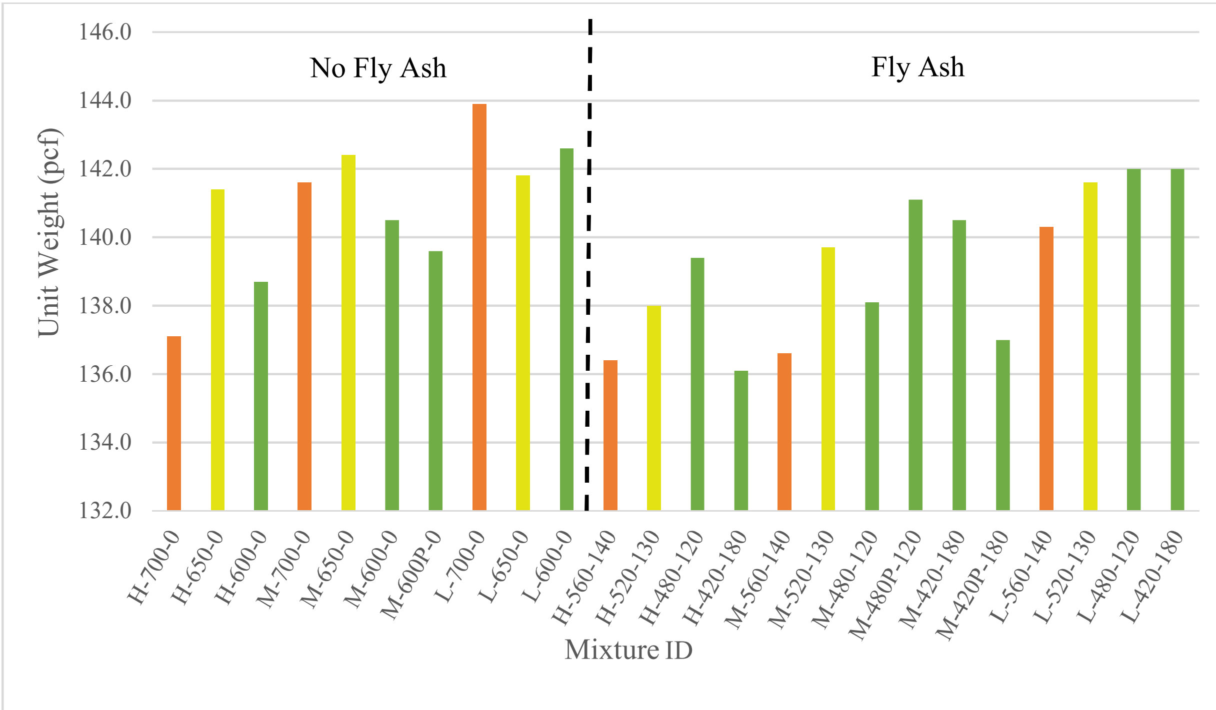

Figure 4.1: Fresh Concrete Unit Weight Results (from Biggers, 2019)

4.2 Testing of Hardened Concrete

The hardened concrete testing program presented in Chapter 3 will be provided in this section of this thesis. It is separated by mechanical properties and durability properties tested as part of the experimental program. The mechanical properties discussed in Section 4.2.1 include compressive strength and MOR data (flexural strength). Flexural strength testing was conducted only on the mixtures containing lower cementitious material contents, those similar to NCDOT pavement mixtures. For durability performance, shrinkage testing results will be presented in section 4.2.2. Results of other tests performed as part of this larger research study, including surface resistivity and rapid chloride ion permeability, are presented in Biggers (2019).

4.2.1 Compressive and Flexural Strength

Compressive strength test results for 3 days, 7 days, 28 days, 56 days, and 90 days are shown in Table 4.2 along with MOR test results. As mentioned in the last section only the 10 mixtures resembling NCDOT pavement mixtures were the only ones tested for MOR.

Table 4.2: Mechanical Property Test Results Related to this Thesis

Mixture Identification	Compressive Strength (psi)					MOR* (psi)
	3-day	7-day	28-day	56-day	90-day	
H-700-0	3,810	4,394	5,379	6,140	6,381	-
H-560-140	3,461	3,950	4,994	5,961	6,087	-
H-650-0	4,276	5,232	6256	7135	7556	-
H-520-130	3,705	4,323	5,319	6,921	7,233	-
H-600-0	3,750	4,309	5,494	5,887	6,302	744.6
H-480-120	2,784	3,150	3982	4418	5148	808.3
H-420-180	2,446	3,417	4328	4869	5521	724.4
M-700-0	5,088	5,679	6,688	7,531	8,168	-
M-560-140	4,019	4,854	5688	6114	6322	-
M-650-0	5,192	5,935	6,739	7,223	8,221	-
M-520-130	4,258	5,129	6,375	7,705	8,416	-
M-600-0	4,526	5,362	5,873	6,418	7,995	821.8
M-480-120	4,167	4,895	5390	5832	6483	726.3
M-420-180	3,991	4,260	5,007	5,590	6,216	726.5
M-600P-0	4,661	5,212	6,284	6,841	7,098	809.0
M-480P-120	4,249	5,314	6,415	6,967	7,215	719.9
M-420P-180	3,852	4,288	5,091	5,418	6,004	680.6
L-700-0	5,921	7,550	7,856	8,762	9,237	-
L-560-140	5,045	5,267	6,729	7,316	7,808	-
L-650-0	6,984	7,367	7,991	8,251	9,113	-
L-520-130	5,194	6,005	7,203	7,591	8,062	-
L-600-0	5,698	6,471	7,010	7,427	7,936	816.9
L-480-120	5,510	6,184	6,814	7,101	7,650	718.1
L-420-180	5,264	5,716	6,228	6,693	7,063	815.4

*tested for low cementitious content (pavement-type) mixtures

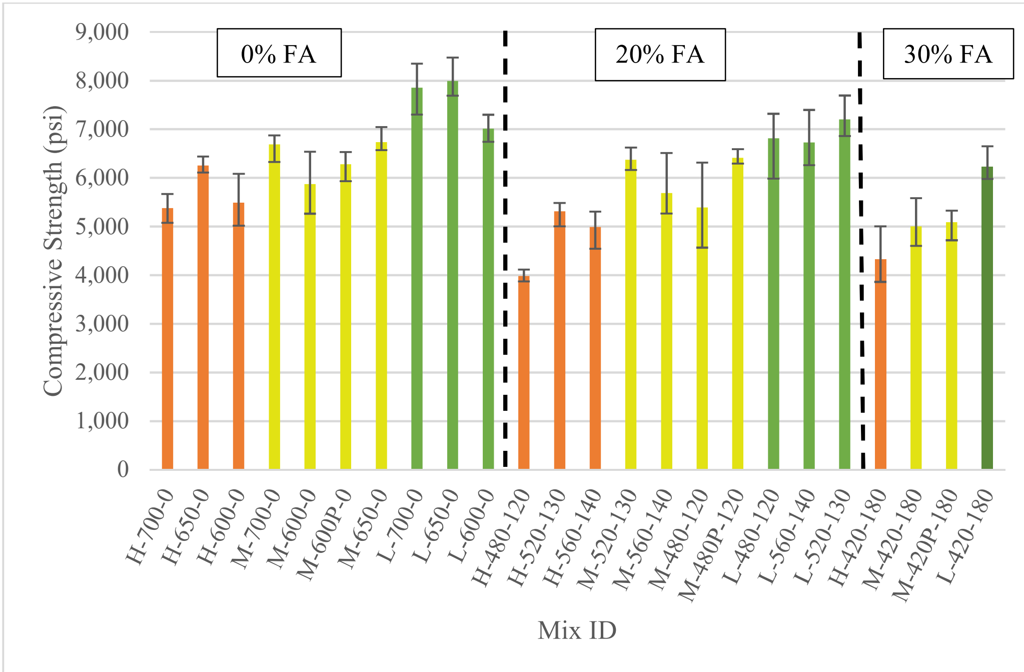

Figure 4.2: 28-day Compressive Strength Specimen Variance for each Mixture

Figure 4.2 shows the ranges between the tests results of the three samples tested for compressive strength at 28-days in this project's laboratory program. As shown the ranges for compressive strength test results were not excessively large, and the mixture with the highest variance, M -480-120 had one of the lower 28-day strengths. For this mixture each specimen was approximately 1,000 psi stronger, this variation could be due to specimen preparation.

Compressive strength testing was conducted at the ages of 3, 7, 28, 56, and 90 days using three test specimens per testing day. The results presented in Table 4.2 show the average strength of the three specimens tested at each age for each mixture. Figure 4.3 graphically shows the compressive strength test results separated by mixtures that do not contain fly ash and mixtures that do contain fly ash. Figure 4.4 graphically shows the mixtures grouped by higher than typical (0.47), typical (0.42), and lower than typical (0.37) w/cm ratios. NCDOT requires a 28-day compressive strength of 4,500 for class AA bridge decks and pavements and is represented by the solid black line shown in Figure 4.3 and 4.4 (NCDOT, 2018). As shown in grey, the only two mixtures out of the twenty-four not in accordance this standard are mixture identifications "H-480-120" and "H-420-180". This could be attributed to the fact that these two mixtures contained 20 and 30% fly ash replacement for cement and fly ash has the tendency to slow early strength gain; however, as shown in Figure 4.2 the first mixture surpasses 4,500 psi by 90 days and the second by 56 days.

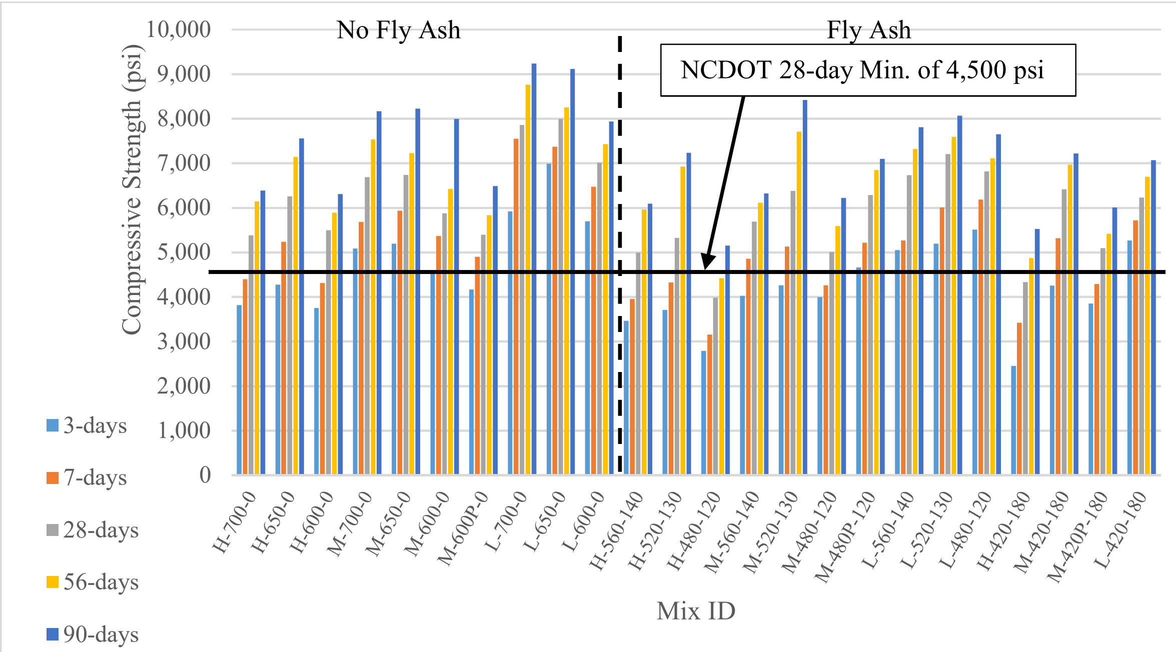

Figure 4.3: Compressive Strength Test Results Sorted by Mixtures with No Fly Ash and Mixtures Containing Fly Ash

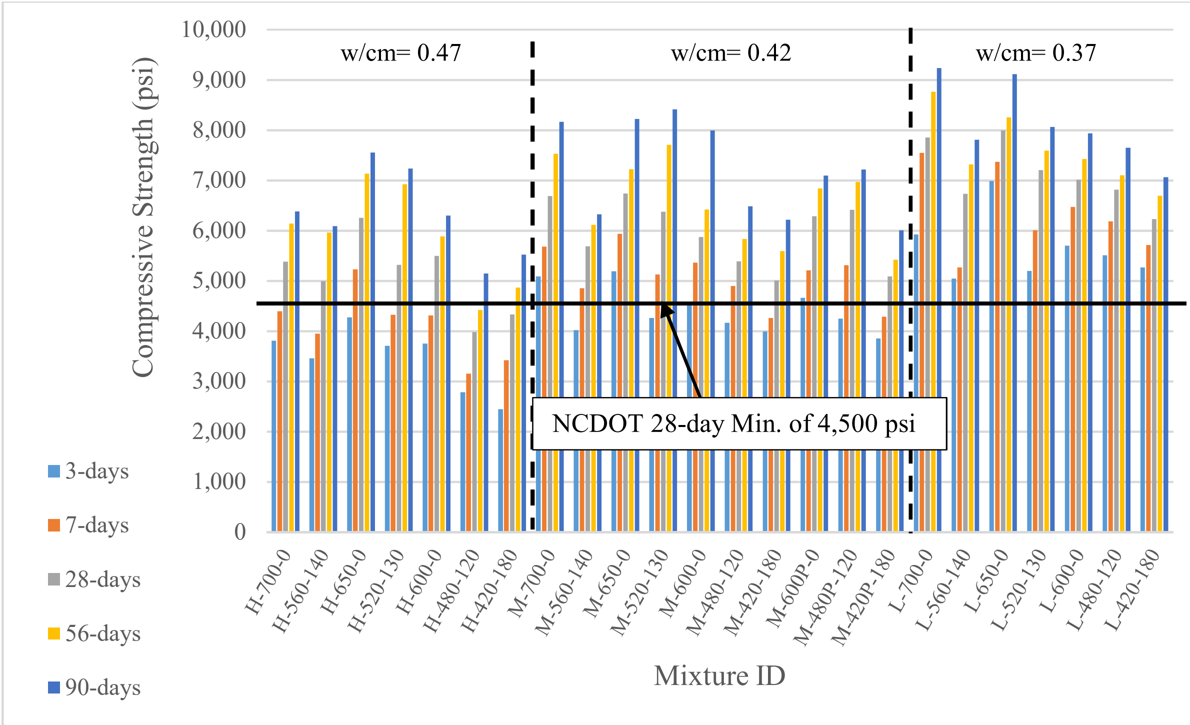

Figure 4.4: Compressive Strength Test Results Sorted by w/cm Ratio

Based on these twenty-four mixtures, as expected, the lower w/cm ratio the higher the strength as the mixtures with w/cm ratio of 0.37 had the highest overall strengths in comparison to the high and medium w/cm ratios. The mixtures with the low w/cm ratio of 0.37, contained some of the highest 28-day strengths for each testing age in comparison to the other w/cm ratios. This can be attributed to the fact that lower w/cm ratios tend to require less water than mixtures with higher w/cm ratios. As mentioned previously, two mixtures did not reach the NCDOT standard of 4,500 psi at 28-days. These were mixtures with the high w/cm ratio of 0.47. Outside of those two mixtures, all of the other high w/cm ratio mixtures met this standard. All of the mixtures well surpassed the standard by 90 days, and most (except the two mentioned) mixtures met this standard by 28 days. Out of the ten lowest compressive strengths at 28-days, six of them were high w/cm ratio mixtures.

For total cementitious materials, there were several differences in compressive strength results. Mixtures with cementitious content over 600 pcy had higher compressive strengths in comparison to those with 600 pcy. Mixtures containing 700 and 650 pcy had very similar results at each testing age. Since the two mixtures that did not reach the NCDOT 28-day strength requirement contained only 480 and 420 pcy of cementitious materials, the lower cementitious material contents could likely be the primary cause of the mixtures not reach the requirement in addition to the high w/cm ratio.

Looking at fly ash replacement, there were differences in strengths as well. For instance, mixtures with cement only (no fly ash) performed similarly for each w/cm ratio at each age in comparison to those with fly ash. The ten mixtures containing cement only had higher test results at each age and w/cm ratio with a few exceptions. This is due to the fact that fly ash reacts and hydrates slower than cement (Kosmatka and Wilson, 2016). Allowing these mixtures to cure longer would likely result in the mixtures with fly ash gaining more overall strength than the mixtures with just cement. One case where a fly ash mixture obtained higher compressive strength was M-480P-120 with w/cm ratio of 0.42. It should be noted this mixture contained PLC instead of OPC, supporting the findings of previous research for NCDOT by this research team (Cavalline et al., 2018). Mixture L-600-0 a straight cement mixture with a low w/cm ratio of 0.37, had a lower 90-day compressive strength than some of the fly ash mixtures with the same w/cm ratio. This mixture with w/cm ratio of 0.37 contained only 600 pcy total cementitious material content without an SCM, which may be why the 90-day strength was lower. In addition, the mixtures with a w/cm ratio of 0.47 with fly ash performed similarly to mixtures with the same w/cm ratio and no fly ash. However, the compressive strengths of the non-fly ash mixtures were still higher than those with fly ash.

For flexural strength, the Modulus of Rupture (MOR) testing procedure was utilized to calculate flexural strength of the twelve pavement-type mixtures and the results are shown in Table 4.2. MOR testing was performed at 28-days in accordance with ASTM C78 on the mixtures shown in Figure 3.1. To graphically display the MOR results, Figure 45 shows the MOR results sorted by non-fly ash and fly ash mixtures and Figure 4.5 shows the MOR results sorted by w/cm ratio.

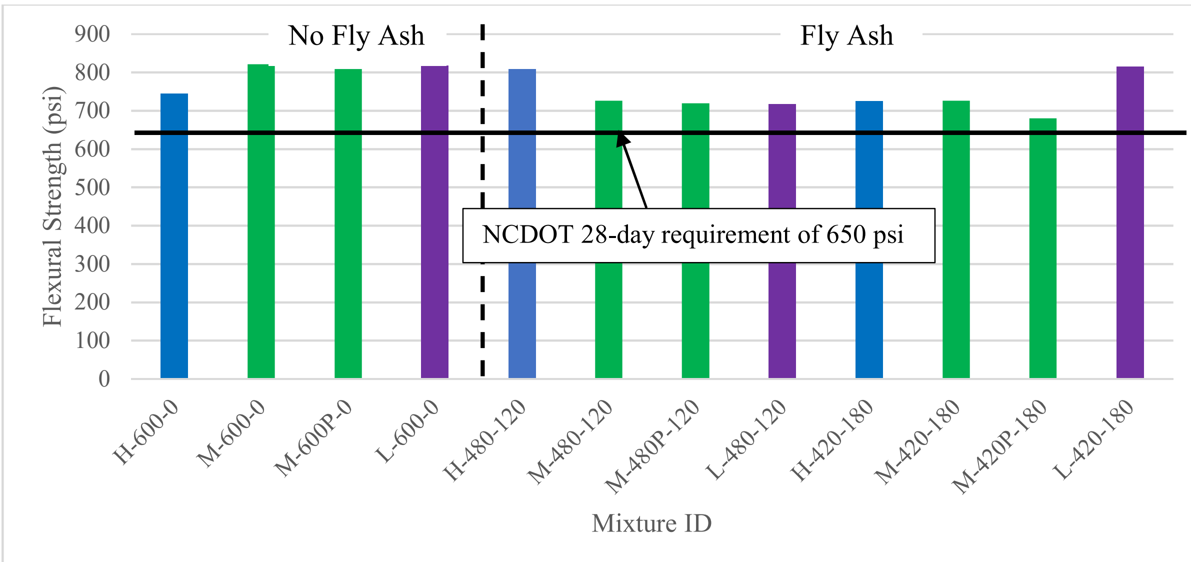

Figure 4.5: MOR Test Results Sorted by Non-Fly Ash and Fly Ash Mixtures

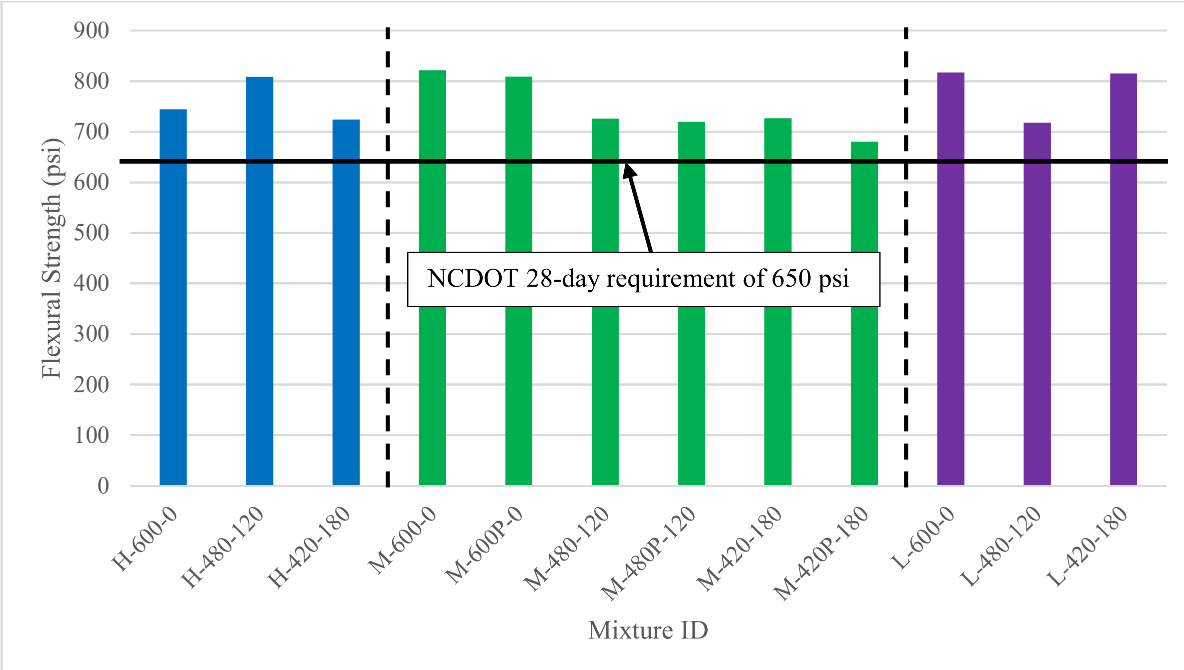

Figure 4.6: MOR Test Results Sorted by w/cm Ratio

For concrete pavement applications, NCDOT standard specifications require a minimum flexural strength of 650 psi at 28 days (NCDOT, 2018). As shown in Figure 4.5 and 4.6 all the pavement-type mixtures met this standard. For the high w/cm ratios, one of the fly ash mixtures, H-480-120, tested higher than the mixture with no fly ash. For the medium w/cm ratios, the flexural strengths were higher in the mixtures without fly ash in comparison to the ones with fly ash. For the low w/cm ratios the one of the mixtures with fly ash, L-420-180, had flexural strength test results almost equivalent to those of the ones without fly ash. Similar to the compressive strength results, use of the lower w/cm ratios produced the highest strength results overall. Out of the six highest flexural strength results, four of the mixtures did not contain fly ash and mixture M-600-0 had the highest overall flexural strength.

The challenge presented for contractors is meeting early strength requirements to proceed with construction schedules. As previously mentioned, NCDOT standard specifications state that concrete used for pavements and bridges must meet at least 3,000 psi or cure for 7 days prior to loading and opening to construction equipment and traffic. For opening to regular traffic 28-day strength targets must be met, or at least a compressive strength of 4,500 psi or flexural strength of 650 psi. Figure 4.7 shows the compressive strength results at 7 and 28 days with the construction compressive strength requirements for NC, while Figure 4.8 shows the flexural strength results (for pavement-type mixtures only) at 28 days with the standard requirement shown in black.

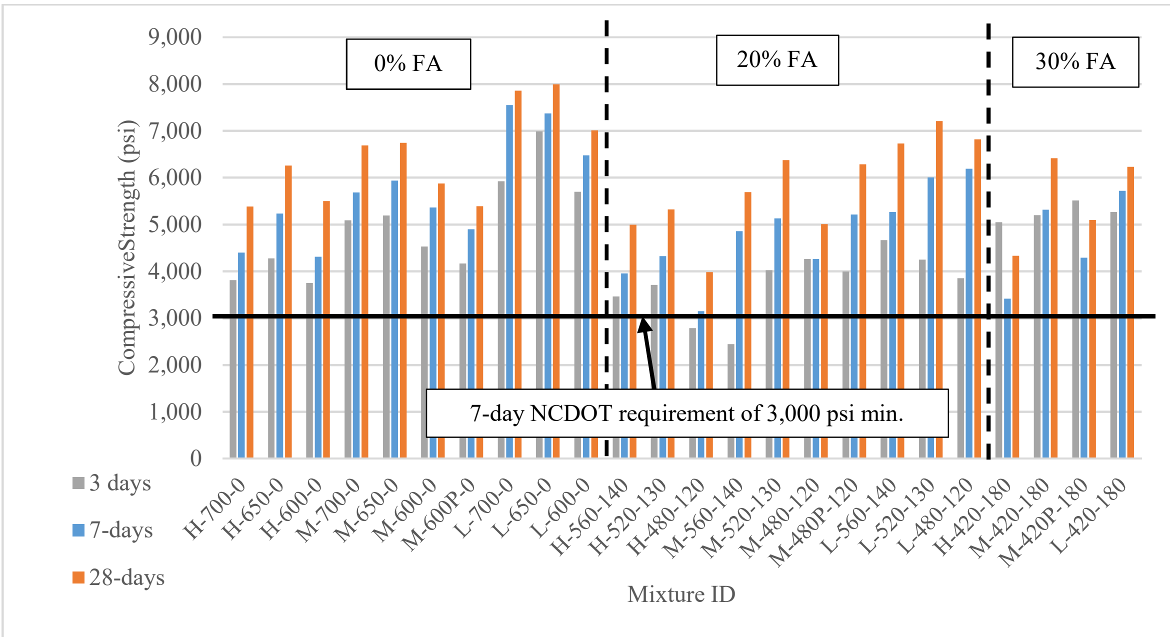

Figure 4.7: 3, 7, and 28-day Compressive Strength Test Results Sorted by Fly Ash Content

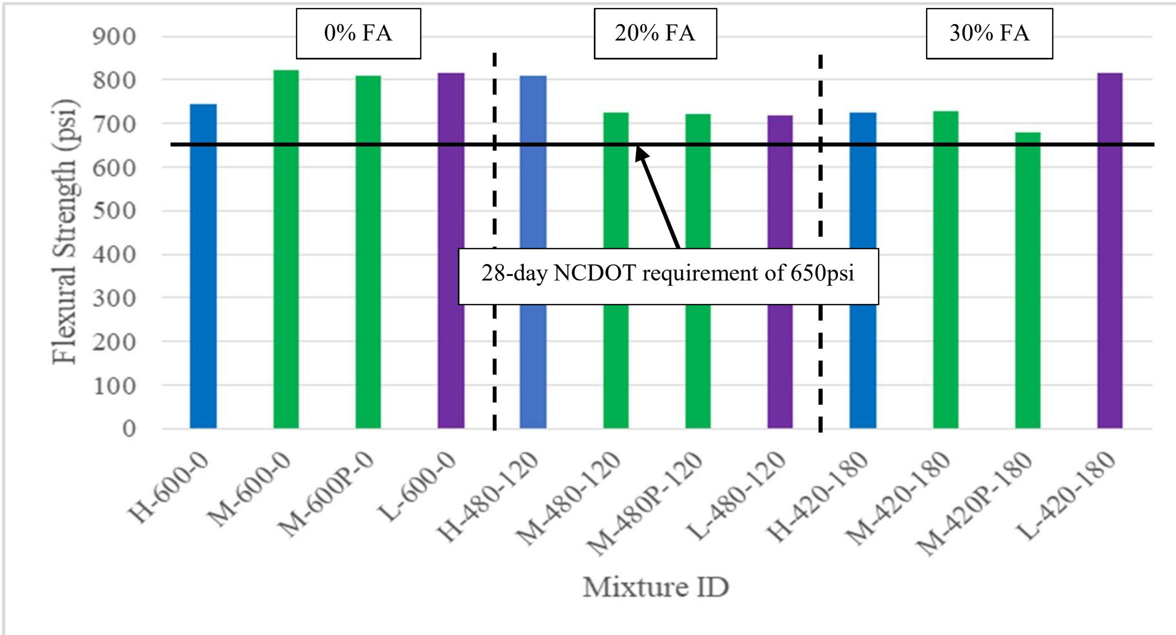

Figure 4.8: 28-day Flexural Strength Test Results for Pavement-type Mixtures Sorted by Fly Ash Content

As shown in Figure 4.7, most mixtures met the opening strength requirement of 3,000 at 3 days with the exception of two mixtures. These mixtures, H-480-120 and M-560-140, had 20% fly ash substitution rates, and reached 3,000 by 7 days. All mixtures met the 7-day specified compressive strength of 3,000, including the mixtures with a 30% fly ash substitution rate. The lowest 7-day strength was mixture H-480-120 with a compressive strength of 3,150 psi and this mixture had a 20% substitution rate, and the higher w/cm ratio of the three. The higher w/cm ratio could likely be the cause of the low early-age strength exhibited by the mixtures in this group, since the highest 7-day strengths belong to the lower w/cm ratio and the middle w/cm ratio. In addition, all of the pavement mixtures met the NCDOT 650 psi flexural strength requirement at 28 days, regardless of the fly ash substitution rate as shown in Figure 4.8. The lowest 28-day flexural strength was mixture M-420P-180 which contained PLC instead of OPC.

Previous research conducted on NC pavement mixtures by the research team had 6 PLC concrete mixtures. Of those PLC mixtures only 2 mixtures, M.BL.N.M and P.BL.B.M, did not meet the 650 psi requirement at 28 days. One of these mixtures did not contain fly ash which likely is the cause of not meeting the requirement (with a flexural strength of 610psi). The other mixture contained fly ash but also contained manufactured sand, which could have impacted the flexural strength (560psi) at 28 days (Cavalline et al., 2018).

4.2.2 Volumetric Shrinkage

To determine shrinkage characteristics of each mixture, changes in length were observed in three different specimens for each mixture. The testing procedure for volumetric shrinkage was in accordance with ASTM C157 as mentioned in Chapter 3. Testing was conducted at ages 4, 7, 14, 28 days and 8, 16, and 32 weeks for all mixtures except mixture identification H-650-0. For each mixture, three specimens were tested, and the average is reported. Measurements were recorded for up to 64 weeks but since the mixtures were batched throughout 2018, 64 weeks had not passed for most of the mixtures at the time of completion of this thesis. Since recommended PEM specification provisions in AASHTO PP 84 focus on timely performance criteria (not long-term results) for agency use, results presented in this thesis are appropriate for comparison to AASHTO PP 84 performance target recommendations and preliminary specification development. Additional analysis will be performed at later dates by the project team.

For each measurement age the average length change (in percent) of the three specimens were computed and are shown in Table 4.3. The shrinkage test results of each specimen at each day can be found in Appendix B, Table B.2. Figure 4.9 shows the 28-day shrinkage results sorted by non-fly ash and fly ash mixtures and Figure 4.10 shows the 28-day shrinkage results sorted by w/cm ratio in micro-strain (με). The 28-day maximum requirement of 420 με as suggested by AASHTO PP 84-19, is shown in Figure 4.9 and 4.10 by the solid black line (AASHTO, 2019).

Table 4.3: Unrestrained Shrinkage Test Results in Average Percent (%) Length Change

Mix ID	Percent Change in Length (%) (micro-strain)			
	28 day	**8 week**	**16 week**	**32 week**
H-700-0	0.0312 (312)	0.0382 (382)	0.0424 (424)	0.0504 (504)
H-560-140	0.0301 (301)	0.0376 (376)	0.0424 (424)	0.0937 (937)
H-520-130	0.0286 (286)	0.0342 (342)	0.0439 (439)	-
H-600-0-2	0.0261 (261)	0.0322 (322)	0.0429 (429)	0.0829 (829)
H-480-120-2	0.0258 (258)	0.0329 (329)	0.0420 (420)	0.0683 (683)
H-420-180-2	0.0246 (246)	0.0336 (336)	0.0439 (439)	0.0592 (592)
M-700-0	0.0322 (322)	0.0401 (401)	0.0498 (498)	0.0567 (567)
M-650-0	0.0310 (310)	0.0380 (380)	0.0462 (462)	0.0515 (515)
M-560-140	0.0318 (318)	0.0387 (387)	0.0448 (448)	0.1185 (1185)
M-520-130	0.0304 (304)	0.0389 (389)	0.0389 (389)	-
M-600-0-2	0.0274 (274)	0.0328 (328)	0.0378 (378)	0.0835 (835)
M-480-120-2	0.0279 (279)	0.0339 (339)	0.0401 (401)	0.0788 (788)
M-420-180-2	0.0292 (292)	0.0361 (361)	0.0415 (415)	0.0618 (618)
M-600P-0-2	0.0284 (284)	0.0355 (355)	0.0455 (455)	0.6340 (6340)
M-480P-120-2	0.0287 (287)	0.0348 (348)	0.0415 (415)	0.0638 (638)
M-420P-180-2	0.0269 (269)	0.0333 (333)	0.0390 (390)	0.0570 (570)
L-700-0	0.0314 (314)	0.0414 (414)	0.0513 (513)	-
L-650-0	0.0333 (333)	0.0401 (401)	0.0483 (483)	0.1140 (1140)
L-560-140	0.0347 (347)	0.0447 (447)	0.0546 (546)	-
L-520-130	0.0318 (318)	0.0414 (414)	0.0501 (501)	-
L-600-0-2	0.0298 (298)	0.0371 (371)	0.0430 (430)	0.0703 (703)
L-480-120-2	0.0304 (304)	0.0375 (375)	0.0437 (437)	0.0964 (964)
L-420-180-2	0.0309 (309)	0.0367 (367)	0.0419 (419)	0.0599 (599)

Figure 4.9 shows the ranges between the three samples tested for shrinkage for each mixture in this project's laboratory program. Although the variation between specimen measurements is not judged to be particularly excessive, it is noted that some of the highest average shrinkage results were mixtures that had large variances between specimens. L-650-0, M-520-130, and L-700-0 all had specimens resulting in wide ranges of length change.

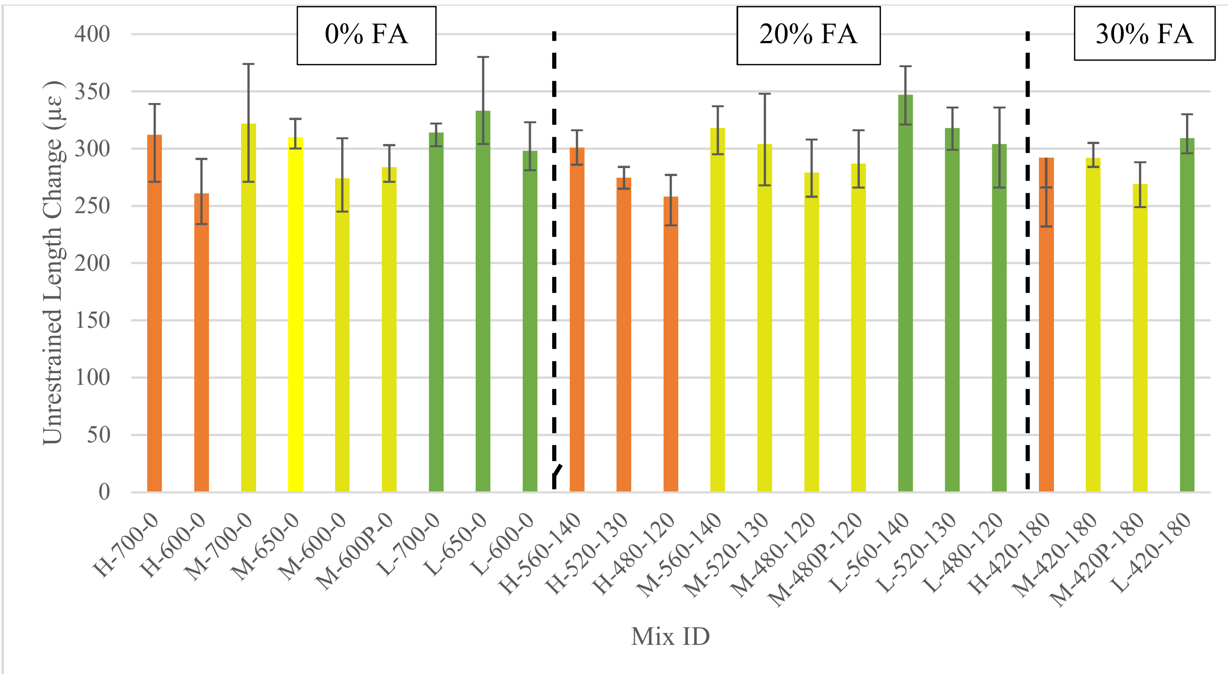

Figure 4.9: 28-day Unrestrained Shrinkage Variances for Original Mixtures

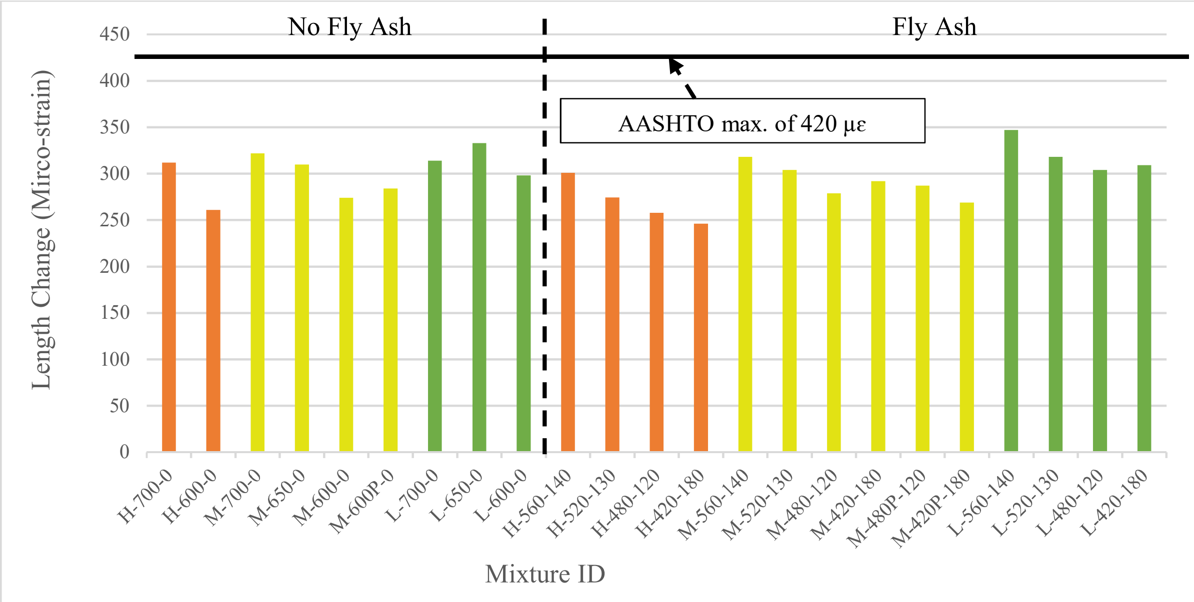

Figure 4.10: 28-day Shrinkage Results Sorted by Non-Fly Ash and Fly Ash Mixtures in Micro-strain (με)

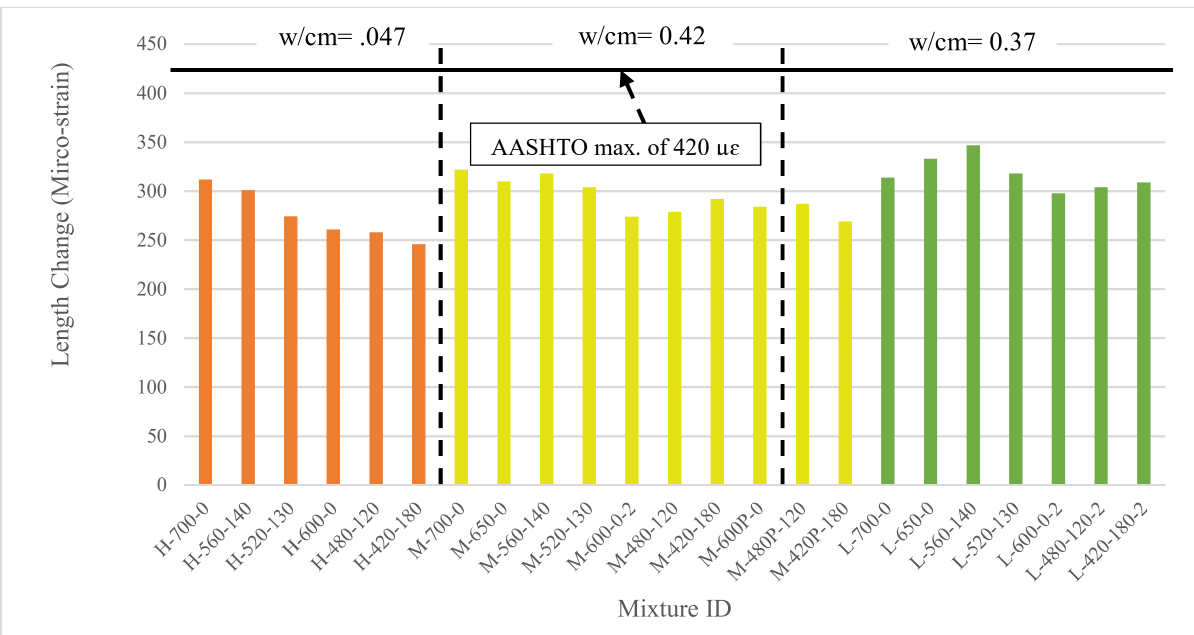

Figure 4.11: 28-day Shrinkage Results Sorted by w/cm Ratios in Micro-strain (με)

Based on Figures 4.10 and 4.11, mixtures containing fly ash generally results in less shrinkage at 28 days for each w/cm ratio except the lower one. For mixtures with the lower w/cm ratio of 0.37, those without fly ash tended to have less shrinkage at 28 days than those with fly ash. For instance, the mixture with the highest length change at 28 days was mixture L-560-140. Along with having the lower w/cm ratio, this mixture contained fly ash, but also contained 700 pcy total cementitious materials. This could likely be the cause of the high length change as the more cementitious material content, the more likely the structure is prone to cracking (Taylor et al. 2013). The two mixtures that had the smallest length change at 28 days was mixtures, H-420-180 and H-480-120, both of which had the higher w/cm ratio of 0.47. These mixtures had 30 and 20% fly ash replacement rates respectively, further supporting the fact that mixtures with SCMs tend to perform better (durability-wise) than mixtures made with straight cement. All of the mixtures met the 420με shrinkage limit suggested by AASHTO (AASHTO, 2019).

For mixtures of the same w/cm ratio containing PLC instead of OPC, performance results depending on fly ash content. For mixture M-420-180, which had a fly ash replacement rate of 30% was out performed by the PLC mixture M-420P-180 since it resulted in length change lower than the OPC mixture. On the other hand, mixture M-480-120 with a fly ash replacement rate of 20% had less change in length in comparison to the PLC mixture M-480P-120. Based on this data for mixtures of the same w/cm ratio, PLC mixtures with 30% fly ash replacement tend to perform better than PLC mixtures with 20% fly ash replacement rates.

4.3 Summary of Findings

The laboratory testing program used twenty-four mixtures to collect data for analyses to observe differences in mechanical properties based on proportioning and determine effects of proportioning and use of SCMs on durability performance by testing concrete durability characteristics. This section provides key findings of this testing program.

The observations for fresh concrete are discussed first. The mixtures containing lower w/cm ratios required more WRA than those with higher w/cm ratios and were less workable. In addition the mixtures with low cement contents had slumps lower than the target as expected due to less cement and water. Mixtures with fly ash and/or portland limestone cement required more AEA to reach target air content range, than cement-only mixtures. Mixtures with high w/cm ratios had the lowest unit weights overall, and mixtures with high cementitious materials had the highest unit weights overall.

The observations from hardened concrete testing provided mechanical and durability performance characteristics of the twenty-four mixtures. Although the testing program discussed in Chapter 3 and shown in Table 3.2 included compressive strength, modulus of rupture, modulus of elasticity, hardened air content, resistivity, formation factor, shrinkage, and rapid chloride permeability, only compressive and flexural strength (MOR) test results and shrinkage results are discussed in this thesis. Previous theses apart of this research project grants a discussion of all hardened concrete test results (Biggers, 2019). Mechanical properties are discussed first.

For compressive strength, as shown in Figure 4.3 all but two mixtures reached NCDOT's 28-day strength requirement of 4,500 psi (NCDOT, 2018). These mixtures contained 20 and 30% fly ash as a replacement for cement. Although these two mixtures did not reach 4,500 psi at 28-days, by 90 days one of the mixtures surpassed 5,000 psi and the other surpassed 5,500 psi in compressive strength both over the 4,500 psi requirement. As mentioned previously one of these mixtures had the higher w/cm ratio of 0.47, while the other was high in cementitious material. This finding supports the inclination that current NCDOT standard specifications for concrete infrastructure could be revised to consider specifying lower w/cm ratios and cementitious material content to improve durability performance. In addition to increased fly ash contents, these mixtures had the higher w/cm ratio (0.47).

For flexural strength, each w/cm ratio exhibited different results. Of the concrete mixtures with w/cm ratio of 0.47, the mixture with 20% fly ash replacement had the highest flexural strength. Of the concrete mixtures with w/cm ratio of 0.42 the mixtures with 20 and 30% fly ash obtained about the same strengths, and slightly higher than those of the same fly ash content and w/cm ratio with portland limestone cement instead of conventional cement. Mixtures with a w/cm ratio of 0.37 had the highest overall flexural strengths, and the mixture with 30% fly ash replacement was almost equivalent to the mixture without fly ash. Overall all mixtures readily met NCDOT's standard requirement of 650 psi for pavement mixtures (NCDOT, 2018).

All of the mixtures tested exhibited unrestrained shrinkage test results well under the 28-day AASHTO PP 84-19 suggested shrinkage limit of 420 με, which suggests these mixtures should be resistant to unrestrained shrinkage. The research findings presented show that fly ash mixtures tended to be more resistant to shrinkage than the non-fly ash mixtures, supporting the fact that SCMs such as fly ash enhance the overall performance of concrete. Mixtures with 30% fly ash replacement rates showed reduced shrinkage by 28 days in comparison to several of the 20% fly ash replacement rate mixtures, as expected. Overall, most of the mixtures were well under the recommended limit of 420 με and an unrestrained shrinkage limit of 350 με may be a more appropriate and readily achievable target for North Carolina concrete mixtures.

The highest length change for 28-days was mixture L-560-140 which was a lower w/cm ratio mixture containing 20% fly ash substitution rate. This mixture was a pavement-type mixture with a total of 700 pcy cementitious materials content which could attribute to the higher length change as unrestrained shrinkage is likely due to paste volume reduction. This supports AASHTO PP 84 guidance regarding reducing paste content through optimized aggregate gradations and lower cementitious material contents.

CHAPTER 5: DEVELOPMENT OF RECOMMENDED STRENGTH SPECIFICATION

5.1 Introduction

Provided in this chapter is a summary of current opening traffic and early-age strength requirements used by several SHAs in their standard specifications, along with analyses of compressive strength data using North Carolina concrete mixtures. A more complete review of other state agency strength recommendations is provided in Chapter 2. For additional support data for the NCDOT recommended early-age strength specifications for PEMs, the analyses presented in this section include data from previous research projects on bridge and pavement concrete batched and tested from UNC at Charlotte research team. This data set includes the 24 mixtures bathed and testing as part of the project supporting this thesis along with an additional 23 mixtures from previous research studies. It is noted that although the previous projects included more than 23 mixtures in the research program, the mixtures selected to include in this thesis for additional supporting information were selected due to having similar mixture materials and proportions (Cavalline et al., 2018, Ojo, 2018, and Cavalline et al., 2019).

Additional characteristics of the 23 mixtures are shown in Table 5.1. These mixtures were batched and tested prior to the current allowable fly ash substitution ratio. The specification for these mixtures were 1.2 lb. of fly ash per 1.0 lb. of cement instead of the current 1:1 ratio and these rates are noted with a "*" in the table (NCDOT, 2012). The table has been color coded to shown pavement mixtures in green and structural mixtures in orange. Mixtures with the higher w/cm ratio of 0.48 is shown in purple and mixtures with the lower w/cm ratio of 0.35 is shown in green. Each letter of the mixture identifications specify a variance parameter. The first letter designates what region the coarse aggregate was the sourced from. P is for piedmont, M is for mountainous, and C is for coastal region. The second letter designates type of cement used, as A is OPC source A, B is OPC source B, and BL is PLC. The third letter represents rather or not the mixture includes fly ash, N means no fly ash, A is source A fly ash and B is source B fly ash both as a 20% replacement rate for cement. The last letter of each mixture identification represents the fine aggregate type as N is for natural sand, and M is for manufactured sand (Cavalline et al., 2015). It should be noted that the strength and shrinkage results were impacted for the mixtures with manufactured sand. This will be discussed more thoroughly in Section 5.2.2.

Table 5.1 Characteristics and Properties of the Additional 23 Mixtures Included in the Expanded Dataset

Mixture ID	Mixture Characteristics			Mixture Proportions, pcy				
	Mixture type (Project Publication)	w/cm	Fly Ash Replacement Level (%)	Cement	Fly Ash	Coarse Aggregate	Fine Aggregate	Water
P.A.N.M.	Paving (NCDOT RP 2015-03, Cavalline et al. 2018)	0.48	0	574	0	1798	1260	275
P.B.N.M.		0.48	0	574	0	1798	1260	304
P.BL.N.M.		0.48	0	574	0	1798	1260	275
C.A.N.M.		0.48	0	574	0	1661	1260	275
C.B.N.M.		0.48	0	574	0	1661	1260	275
C.BL.N.M.		0.48	0	574	0	1661	1260	275
M.A.N.M.		0.48	0	574	0	1798	1260	275
M.B.N.M.		0.48	0	574	0	1798	1260	275
M.BL.N.M.		0.48	0	574	0	1798	1260	275
P.A.A.M.		0.48	20*	460	137	1798	1260	304
P.B.A.M.		0.48	20*	460	137	1798	1260	275
P.BL.A.M.		0.48	20*	460	137	1798	1260	304
P.A.B.M.		0.48	20*	460	137	1798	1260	304
P.B.B.M.		0.48	20*	460	137	1798	1260	275
P.BL.B.M.		0.48	20*	460	137	1798	1260	304
P.A.N.N.		0.48	0	574	0	1798	1184	275
P.B.N.N.		0.48	0	574	0	1798	1184	304
P.BL.N.N.		0.48	0	574	0	1798	1184	275
BC1	Paving (Ojo, 2018)	0.48	20*	460	137	1798	1094	291
BC2		0.48	20*	460	137	1798	1094	291
BC3		0.48	20*	460	137	1798	1094	291
CC	Bridge (Leach, 2017)	0.35	0	715	0	1720	1113	266
CF		0.35	20*	512	172	1720	1113	266

NOTE: * The specification for these mixtures were 1.2 lb. of fly ash per 1.0 lb. of cement instead of the current 1:1 ratio

5.2 Analysis of Relevant Requirements

To develop an early-age strength specification for PEMs in NC, existing AASHTO specifications along with several SHA specifications for early-age compressive and flexural strength were reviewed (Chapter 2) and summarized in this section.

5.2.1 Applicable Federal Standards

The federal standards applicable to this section include the FHWA's standard specifications for pavements and bridges, and AASHTO PP 84 which is specifically for PEMs

(AASHTO, 2019 and FHWA, 2014). Both the FHWA standard specifications and the AASHTO PP 84 specifications are summarized in Table 5.2 with the requirements for opening roads to construction equipment/traffic as well as regular traffic. The requirements are based on 4 in. by 8 in. cylinder specimens.

Table 5.2: Relevant FHWA and AASHTO standards to Support Development of Early-Age Compressive and Flexural Strength Specifications (FHWA, 2014; AASHTO, 2019).

Standard	**Concrete Type**	**Construction Equipment Requirement (psi)**		**Age**	**Regular Traffic (psi)**		**Age***
		Compressive	**Flexural**		**Compressive**	**Flexural**	
FHWA Standard Specifications	Pavement	3,000	550	7	4,000	550	28
	Bridge (Class A/AA)	loads <4,000 lbs. allowed after 7 days otherwise design strength must be met		---	4,500	---	28
AASHTO PP 84	Pavement	N/A	N/A	---	4,000	600	28
	Bridge	N/A	N/a	---	4,000	600	28

AASHTO PP 84-19 does not mention construction loading requirements, so this is indicated as "N/A" in Table 5.2. FHWA early-age requirements for pavement mixtures are comparable to several SHAs specifications for early age strength as discussed in the next section.

5.2.2 Applicable State Specifications

To help develop standard specifications that are appropriate and sensible, SHAs with current early-age strength targets were reviewed in detail (Chapter 2). Early-age strength and opening concrete structures and pavements for eight states are summarized in Table 5.3. The requirements summarize include special provisions for high performing concrete, high early strength, and general specifications.

Table 5.3: Relevant SHA standards to Support Development of Early-Age Compressive and Flexural Strength Specifications

State/ Standard	Concrete Type	Construction Equipment Requirement (psi)		Age (days)	Regular Traffic (psi)		Age* (days)
		Compressive	Flexural		Compressive	Flexural	
Louisiana DOTD	B and D paving	3,000	550	7	3,000	only if Engineer req.	14
	HES mod. A1 paving	3,000	-	4 hrs.	4,500	-	28
	Class A1, A2, A3 bridge deck (A/AA)	4,000	-	14	4,500	only if Engineer req.	28
Minnesota DOT	Class A paving	3,000	500-350 (depends on slab thickness)	7	4,500	-	28
	HES Grade F paving or structural	3,000	-	48 hrs.	4,500	-	28
	Y bridge deck	100% req. strength	500	7	4,000	-	28
New York DOT	Class A, C paving	2,500	-	3,7	4,000	600	28
	HES Class F paving or structural	2,500	-	-	4,000	-	28
	Class A or project specified	depends on project	-	-	depends on project	-	28
Florida DOT	Class A paving	2,200	-	14	3,000	550	28
	Class II bridge deck	1,600 if verified by Engineer	-	14	4,500	-	28

Iowa DOT	Class A paving (unless otherwise noted in contract)	depends on project	500	14	specified by project, approved by engineer		
	HES Class M paving	depends on project	500	48 hrs.	specified by project, approved by engineer		
	Class A bridge deck	depends on project	550	7	specified by project, approved by engineer		
Illinois DOT	PV paving	3,500	650	7 or 14	min of 3,500 or 650 by 14 days prior to loading		
	BS bridge deck	4,000	675	14	min of 4,000 or 675 by 14 days prior to loading		
Virginia DOT	A3 paving	maturity method	600	14	3,000	600	28
	HES Class A4	3,500	-	7	3,500 must be achieved in 7 days prior to loading		
	A4 bridge deck	maturity method	-	14	4,000	-	28
West Virginia DOH	Class A paving	maturity method or prove 28-day strength met		4,6,8	3,000	500	28
	Class H bridge decks	3000 or maturity method	-	7	4,000		28

*28-days is not the requirement wait time for opening to regular traffic, it represents the age where the concrete should reach the strength required.

Specification provisions shown in Table 5.3 are summarized from the standard specifications for each state for concrete pavements, bridge decks, and high-early strength (HES) concrete for paving and structural concrete. Several of the concrete strength requirements for opening pavements and structures are similar, but are not specific to PEMs. Concrete age at time of testing dates varies by state, but most SHAs required more conservative standards for bridge decks and structural concrete than those for concrete pavements. More specifically, most states require a higher strength for opening concrete bridge decks and structures to traffic in comparison to opening pavements. For example, NCDOT currently requires a strength of at least 4,500 psi or 650 psi flexural strength for structures in comparison to 3,000 psi for concrete pavements (NCDOT, 2018). For three of the state specifications summarized, pavements were tested at 7 days prior to loading to determine strength development and further opening to traffic (LaDOTD, 2016, MnDOT, 2016, and NYSDOT, 2019). LaDOTD requires a compressive strength of 3,000 psi prior to opening pavements to loading (construction and regular traffic) or flexural strength of 550 psi at 7 days (LaDOTD, 2016). MnDOT requires at least 3,000 psi compressive strength at 7 days to open pavements to construction and regular traffic with a 28-day strength minimum of 4,500 psi (MnDOT, 2016). Other states, such as New York, begin strength testing at 3-day for concrete pavements with a strength requirement of at least 2,500 psi (NYSDOT, 2019). West Virginia allows concrete testing for pavements at 4 days requiring 28-day strength gain (WVDOH, 2017). IDOT, FLDOT, and VDOT all require 14 days for pavement opening (IDOT, 2017, FLDOT, 2016, and VDOT, 2016). IDOT requires 3,500 psi (compressive) and 650 psi (flexural), FLDOT requires 2,200 psi (compressive), and VDOT 600psi (flexural) strength (IDOT, 2017, FLDOT, 2016, and VDOT, 2016). VDOT and WVDOH allow verification of 28-day strength at ages shown in Table 5.3 by the maturity method for opening pavements and bridge structures to construction (VDOT, 2016 and WVDOH, 2017).

HES concrete mixtures were included to help support the development of the compressive and flexural strength specifications. Out of the nine state specifications selected to support this thesis, four of them have specifications for HES. Each of the four states shown with HES standard specifications vary in compressive and flexural strength requirements. For HES mixtures the opening strength requirements were expected to be obtained in 4 to 48 hours (LaDOTD, 2016, MnDOT, 2016, and IowaDOT, 2015).

The most aggressive specifications for opening strength requirements for concrete bridges and pavements were either for the HES mixtures or for bridge deck mixtures of the SHAs specifications reviewed. As mentioned earlier most of the HES mixtures require 3,000 psi by 4 to 48 hours (VDOT, 2016, MnDOT, 2016 and LDOTD, 2016). Minnesota DOT had the most aggressive requirement of 4,000 psi for bridge decks at 7 days (MnDOT, 2016). Illinois and Louisiana were the second most aggressive requirements of 4,000 psi at 14 days to allow loading on concrete bridge decks (IDOT, 2017 and LDOTD, 2016). After reviewing the summary of state early-age and opening age compressive and flexural strengths shown in Table 5.3, most SHAs had similar targets.

5.3 Development of Performance Targets for Early Age Strength Specification Provisions

Currently NCDOT specifies an early-age strength requirement to open to traffic of 3,000 psi or 650 psi for pavements and 4,500 psi for bridges and structural concrete (NCDOT, 2018). The research presented in this thesis shows that 4,500 psi for structural mixtures is generally achievable by the fly ash-containing mixtures, although there could be risk of higher SCM mixtures not achieving this strength by 28 days in field conditions. In addition, as discussed in Chapter 2, many states, including VDOT, have implemented 4,000psi as a structural target for opening strength (Jones, 2017). VDOT utilizes the maturity method to verify early-age strength for opening to regular traffic (VDOT, 2016). Research in this study supports that an opening to traffic strength of 3,000 psi and 650 psi for NC paving mixtures is achievable. As noted, however, verification of early-age compressive strength does not ensure concrete structures will not be damaged from external loads.

To further discuss the findings and compare to target values, Class A/AA mixtures must meet the 28-day required strength of 3,000 psi. All of the pavement mixtures except H-480-120 and H-420-180 also surpass 3,000 psi at the age of 3 days as shown in Figure 5.1, may be appropriate for NC pavement mixtures. The color coding matches the color coding used throughout this report and represent each w/cm ratio level used. Figure 5.2 shows the 3-day, 7-day, and 28-day compressive strength results sorted by fly ash content to depict the impact of fly ash on concrete performance. One of the previous research projects included in the expanded dataset contains 20% fly ash replacement and has compressive testing data at 7 and 28-days for pavement-type mixtures (Ojo, 2018). The other dataset to be used in the expanded dataset has mixtures with 0 and 20% fly ash replacement rates, with compressive testing results at 28-days (Cavalline et al. 2015). Figure 5.3 displays the expanded dataset with 3-day, and 7-day compressive strength results sorted by fly ash content. Figure 5.4 displays the expanded dataset with 28-day compressive strength results sorted by fly ash content.

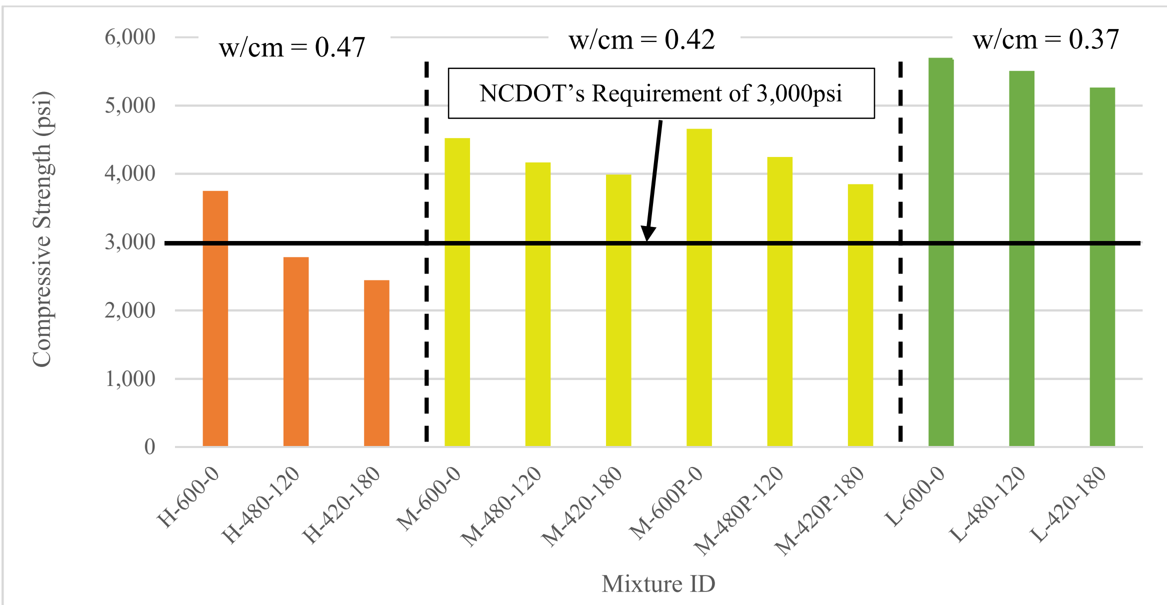

Figure 5.1: 3-day Compressive Strength of Pavement Mixtures with NCDOT's 28-day Requirement

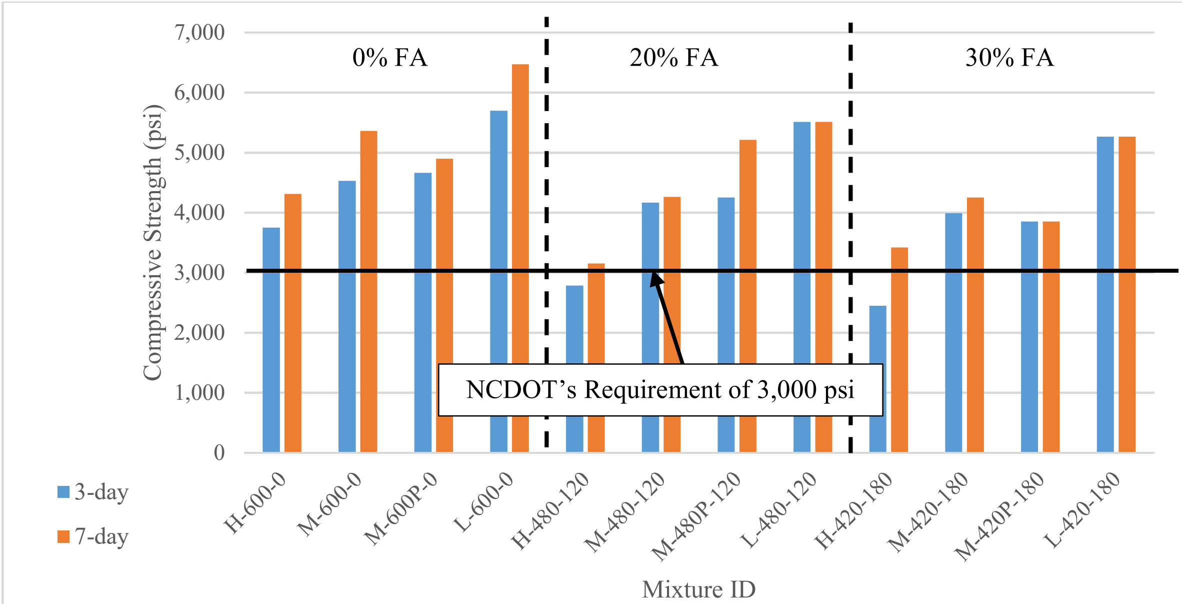

Figure 5.2: 3 and 7-day Compressive Strength of Pavement Mixtures Including the Extended Dataset Sorted by Fly Ash Content with NCDOT's 28-day Requirement

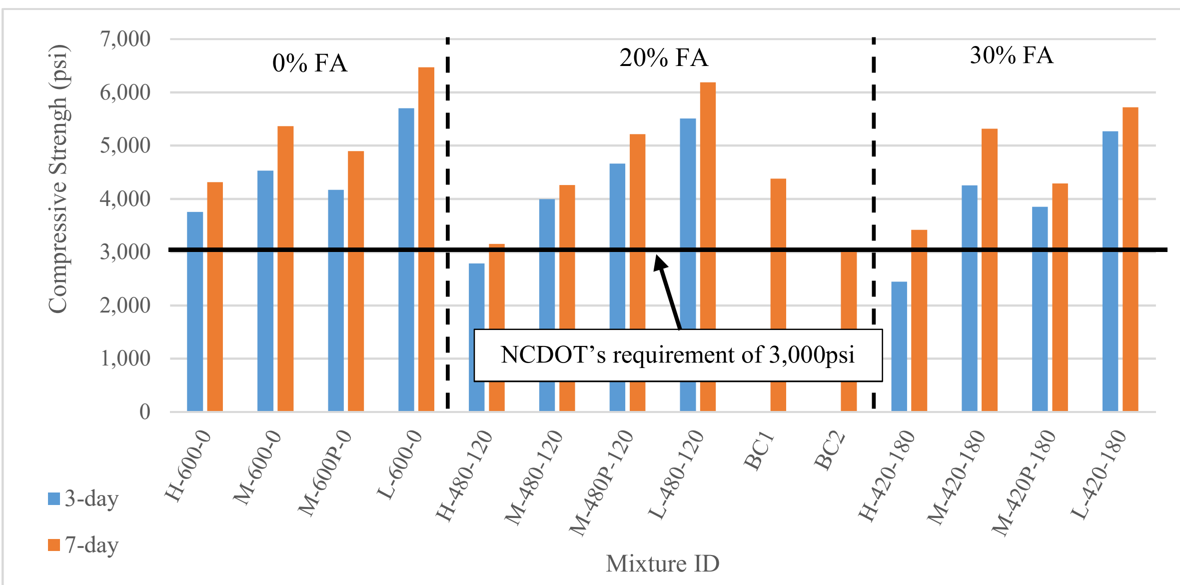

Figure 5.3: 3 and 7-day Compressive Strength of Pavement Mixtures Including the Extended Dataset and NCDOT's 28-day Requirement Sorted by Fly Ash Content

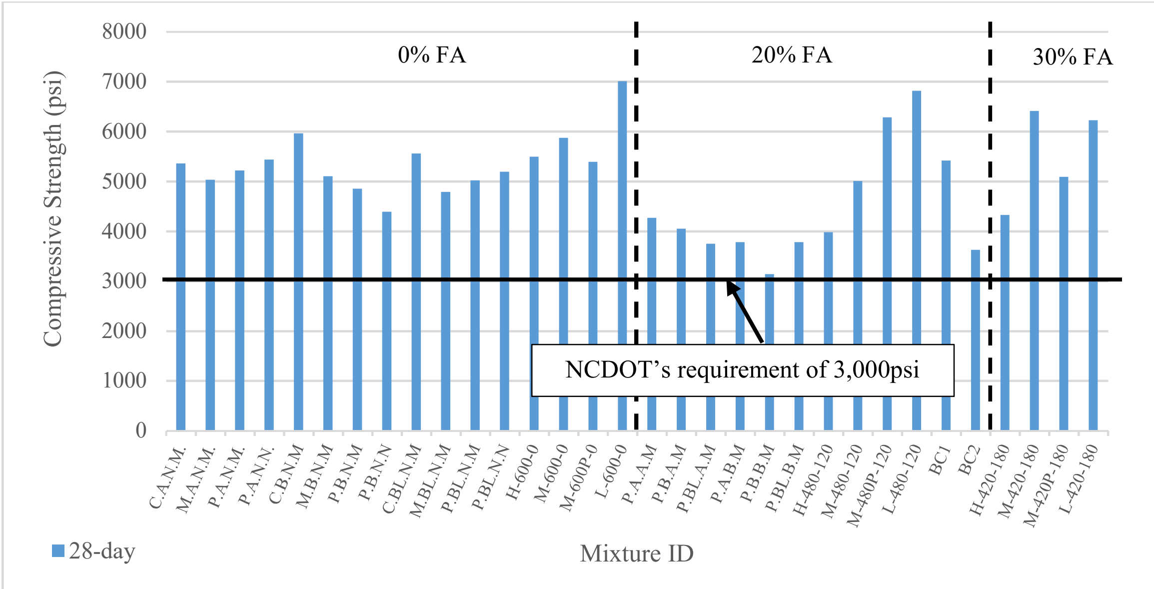

Figure 5.4: 28-day Compressive Strength of Pavement Mixtures Including the Extended Dataset and NCDOT's 28-day Requirement Sorted by Fly Ash Content

As shown in the Tables above, NCDOT's 28-day strength requirement is met as early as 3-days for several mixtures. Allowing contractors to use the maturity method to determine when pavements are strong enough to open to traffic, could help with future use of this specification. Further analyses of the expanded dataset is discussed subsequently, supporting findings from this project's experimental program.

In addition to compressive strength, NCDOT specifies 650 psi flexural strength at 7 days prior to any construction or traffic loading on concrete pavements. MOR data was collected for pavement-type mixtures at 28 days for this research project as well as the ones included in the expanded dataset shown in Figure 5.5 (Cavalline et al. 2015). As shown in the figure below, there are only four mixtures that do not reach this flexural strength by 28- days. These include Mixture M.A.N.M., P.B.A.M., P.A.B.M., and P.BL.B.M. All of these mixtures were batched using manufactured sand which could have possibly contributed to this result, although it is noted that other manufactured sand mixtures met the target (Cavalline et al., 2015). Three of these mixtures contain 20% fly ash as a substitute for cement and all of them have a w/cm ratio of 0.48 which may attribute to the low strength values (Cavalline et al. 2015),. As shown in Figure 5.5, all of the mixtures included in this research met 650 psi by 28-days even those with 30% fly ash substitution rates.

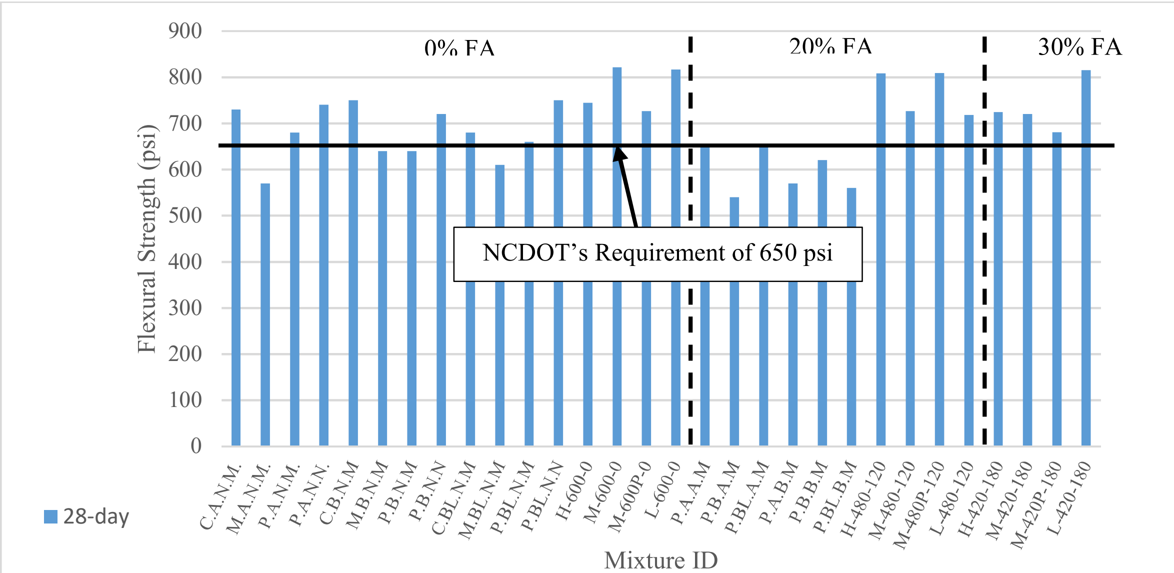

Figure 5.5: MOR Test Results at 28-days Including Expanded Dataset Sorted by Fly Ash Content with NCDOT's Flexural Strength Requirement

For concrete structures in Virginia, Virginia's Class A4 (bridge construction use) must meet 4,000 psi (28-day strength) prior to any traffic loading (construction and regular) (VDOT, 2016). The maturity method is often used to verify 28-strength prior to opening (VDOT, 2016). The 7-day compressive strengths of the structural mixtures in this laboratory program are summarized in Figure 5.6 with VDOT's 4,000 psi and NCDOT's 4,500 psi requirement shown in black. These results are color coded designated the w/cm ratios consistent with the rest of the report. All of the structural-type mixtures passed 4,000 psi within 7 days, except H-560-140. This mixture surpasses 4,000 psi by 28 days, so it is almost certain even this mixture will have at least 4,000 psi by 14 days. Figure 5.7 shows the 3, 7, and 28 day compressive strength results for the structural mixtures sorted by fly ash content. Previous research conducted by the research team is included in the expanded dataset shown in Figure 5.8. The previous research in the expanded dataset includes two structural concrete mixtures (bridge structures), one without fly ash “CC” and the other “CF” with a 20% fly ash replacement rate (Leach, 2018, Cavalline et al., 2019).

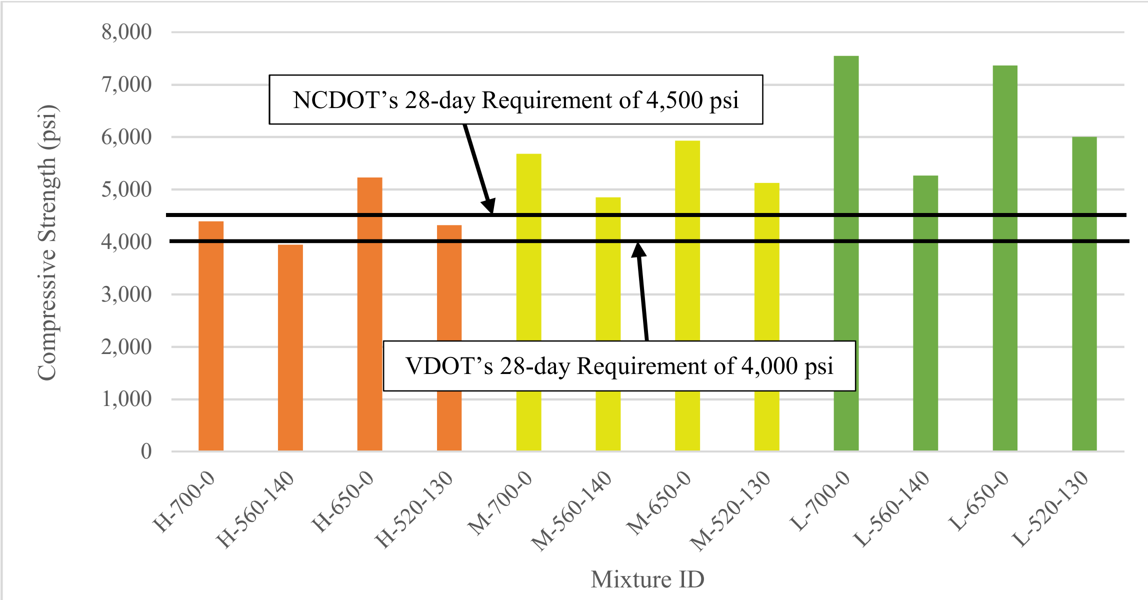

Figure 5.6: 7-day Compressive Strength of Structural Mixtures with VDOT’s and NCDOT’s 28-day Requirement

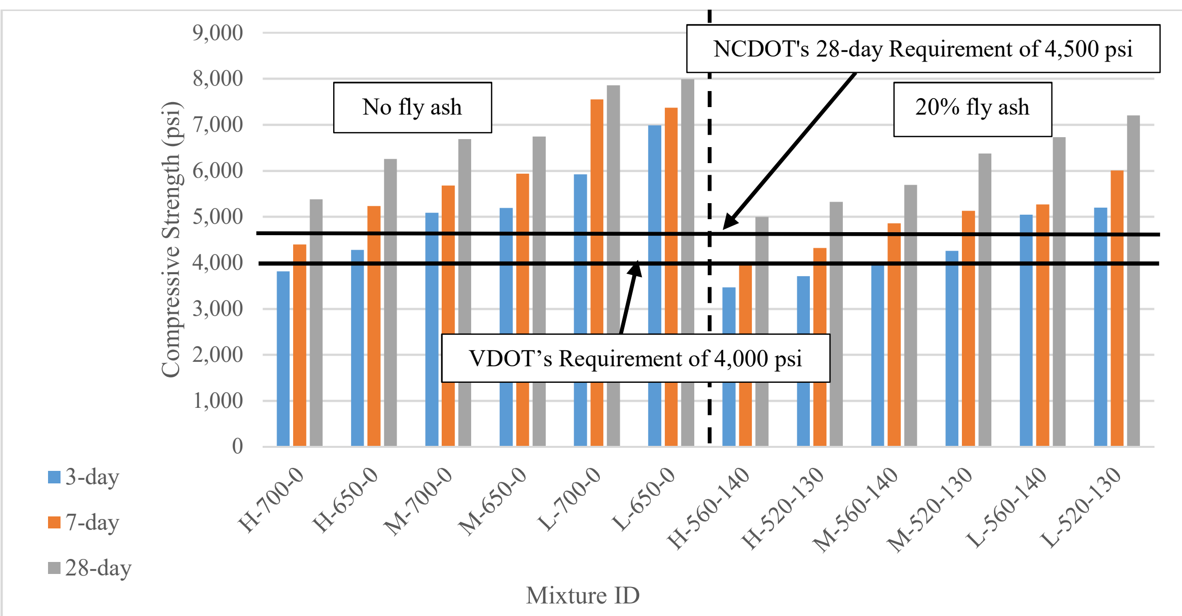

Figure 5.7: 3, 7, and 28-day Compressive Strength of Structural Mixtures with VDOT’s and NCDOT’s 28-day Requirement Sorted by Fly Ash Content

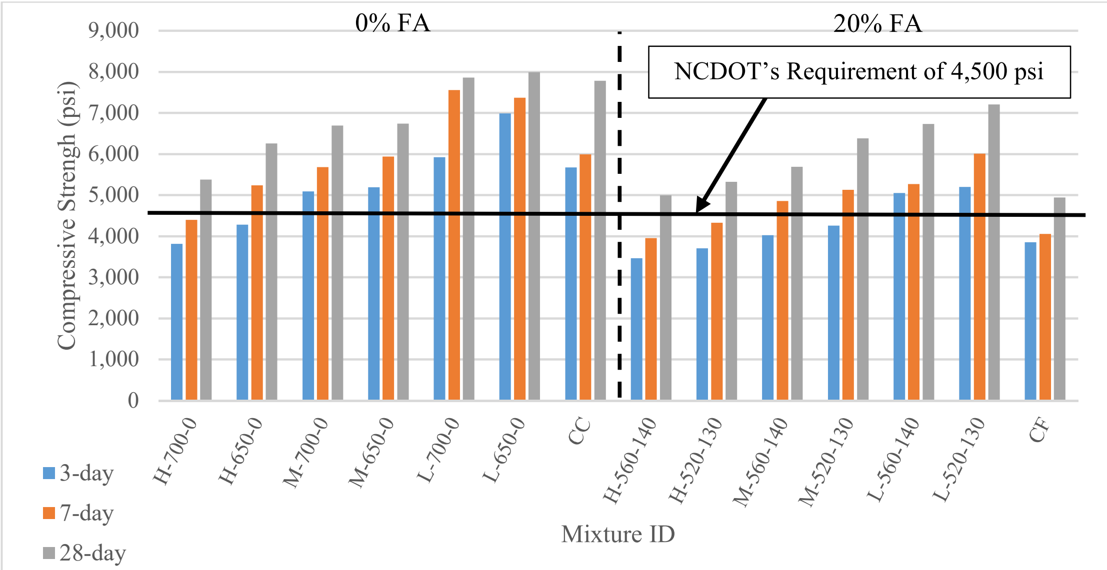

Figure 5.8: 3, 7, and 28-day Compressive Strength of Structural Mixtures Including the Expanded Dataset with NCDOT's 28-day Requirement Sorted by Fly Ash Content

Additional analysis was performed to determine how practical the targets of 3,000 psi compressive strength, or 650psi flexural strength (pavements) and 4,500 psi and 4,000 psi compressive strength (structural concrete-bridges) are for use as early age strength targets. Below is a series of tables which show the mixtures in the expanded dataset that passed and failed these target values. For each target, the percentage of mixtures in the expanded dataset that passed the (compressive strength) target specification requirement at 3- and 7-days was determined and is shown in Table 5.4 for pavement mixtures. Table 5.5 shows which mixtures pass the 3,000 psi specification and which do not. It should be noted that mixtures batched and tested from one previous research project on pavement concrete does not have 3 or 7-day compressive strength values, so those were omitted in this table (Cavalline et al. 2015). Also, the mixtures labeled BC1 and BC2 do not have 3-day compressive strength values so only the 7-day values are included in this analysis (Ojo, 2018). Table 5.6 shows the mixtures and percentage of mixtures passing the (flexural strength) requirement at 28-days, while Table 5.7-5.8 show which mixtures pass 650, and 600 psi requirements and which do not. It should be noted that BC1 and BC2 did not have flexural values for 28 days so these mixtures were omitted (Ojo, 2018). For bridge mixtures, this is shown in Tables 5.9-5.11. It should be noted the color yellow represents a mixture with 20% fly ash replacement rate, while the color green represents a mixture with 30% fly ash replacement rate.

Table 5.4: Analysis of Pavement Mixtures Passing Selected Performance Targets at 3 Days and 7 Days (Compressive Strength)

Target Values	**3,000 psi**		**2,500 psi**	
Age	3 days	7 days	3 days	7 days
Mixtures passing target value	H-600-0	H-480-120	H-600-0	H-420-180
	M-600-0	BC1	M-600-0	BC1
	M-600P-0	BC2	M-600P-0	BC2
	L-600-0	H-420-180	L-600-0	
	M-480-120		L-480-120	
	M-480P-120		H-480-120	
	L-480-120		M-480-120	
	M-420-180		M-480P-120	
	M-420P-180		M-420-180	
	L-420-180		M-420P-180	
			L-420-180	
Percent Passing	71%	100%	79%	100%

Table 5.5: Pavement Mixtures Passing and Failing at 3 and 7-days for Performance Target 3,000psi

Target Values	**Meeting 3,000 psi target**		**Not Meeting 3,000 psi**	
Age	3 days	7 days	3 days	7 days
Mixture Identification	H-600-0	H-480-120	H-480-120	
	M-600-0	BC1	M-480-120	
	M-600P-0	BC2		
	L-600-0	H-420-180		
	M-480-120			
	M-480P-120			
	L-480-120			
	M-420-180			
	M-420P-180			
	L-420-180			
Percent Passing	71%	100%	83%	100%

As shown in Tables 5.4 and 5.5 at 3 days, three of out four mixtures with 30% fly ash replacements rates met the requirement of 3,000 and the fourth one met it by 7 days. For the 20% fly ash substitution rate, three out of six mixtures reached or passed 3,000 psi at 3 days, while the other three met this specification target by 7 days.

Table 5.6: Analysis of Pavement Mixtures Passing High-Low Performance Targets (Flexural Strength)

Target Values	**650 psi**	**600 psi**	**550 psi**	**500 psi**
Age	28 days	28 days	28 days	28 days
Mixtures passing target value	C.A.N.M.	M.B.N.M.	M.A.N.M.	P.B.A.M.
	P.A.N.M.	P.B.N.M.	P.BL.B.M.	
	P.A.N.N.	M.BL.N.M.	P.A.B.M.	
	C.B.N.M.	P.B.B.M.		
	P.B.N.N.			
	C.BL.N.M.			
	P.BL.N.M.			
	P.BL.N.N.			
	H-600-0			
	M-600-0			
	M-600P-0			
	L-600-0			
	P.A.A.M.			
	P.BL.A.M.			
	H-480-120			
	M-480-120			
	M-480P-120			
	L-480-120			
	H-420-180			
	M-420-180			
	M-420P-180			
	L-420-180			
Percent Passing	73%	87%	97%	100%

Table 5.7: Pavement Mixtures Passing and Failing at 28-days for Performance Target 650 psi Flexural Strength

Target Values	**Meeting 650 psi target**	**Not Meeting 650 psi target**
Age	28 days	28 days
Mixture Identification	C.A.N.M.	M.A.N.M.
	P.A.N.M.	M.B.N.M.
	P.A.N.N.	P.B.N.M.
	C.B.N.M.	M.BL.N.M.
	P.B.N.N.	P.B.A.M.
	C.BL.N.M.	P.A.B.M.
	P.BL.N.M.	P.BL.B.M.
	P.BL.N.N.	P.B.B.M.
	H-600-0	
	M-600-0	
	M-600P-0	
	L-600-0	
	P.A.A.M.	
	P.BL.A.M.	
	H-480-120	
	M-480-120	
	M-480P-120	
	L-480-120	
	H-420-180	
	M-420-180	
	M-420P-180	
	L-420-180	
Percent Passing	73%	27%

Tables 5.6 and 5.7 show the results of the expanded dataset for flexural strength, as well as the percentage of pavement mixtures meeting the requirements set in the Tables. About 75% of the pavement mixtures in the expanded dataset met the requirement of 650 psi at 28 days for flexural strength. Similar to the compressive strength results the mixtures that did not meet this standard

were mixtures made with fly ash and/or manufactured sand. Based on these results typical pavement mixtures with and without fly ash easily meet this requirement at 28 days.

Table 5.8: Analysis of Structural Mixtures Passing Selected Compressive Strength Performance Targets

Target Values	**4,500 psi**			**4,000 psi**			**3,500 psi**		
Age	3 days	7 days	28 days	3 days	7 days	28 days	3 days	7 days	28 days
Mixtures passing target value	M-700-0	H-650-0	H-700-0	H-650-0	H-700-0	H-560-140	H-700-0	H-560-140	
	M-650-0	M-560-140	H-560-140	M-700-0	H-520-130		H-650-0		
	L-700-0	M-520-130	H-520-130	M-650-0	CF		M-700-0		
	L-650-0		CF	L-700-0			M-650-0		
	CC			L-650-0			L-700-0		
	L-560-140			CC			L-650-0		
	L-520-130			M-560-140			CC		
				M-520-130			L-560-140		
				L-560-140			L-520-130		
				L-520-130			H-520-130		
							M-560-140		
							M-520-130		
							L-560-140		
							L-520-130		
							CF		
Cum. Percent Passing	50%	71%	100%	71%	93%	100%	93%	100%	

Table 5.9: Structural Mixtures Passing and Failing at 3, 7 and 28-days for Performance Target 4,500 psi Compressive Strength

Target Values	**Meeting 4,500 psi Target**			**Not Meeting 4,500 psi**		
Age	3 days	7 days	28 days	3 days	7 days	28 days
Mixtures passing target value	M-700-0	H-650-0	H-700-0	H-700-0	H-700-0	
	M-650-0	M-520-130	H-560-140	H-650-0	H-560-140	
	L-700-0	M-560-140	H-520-130	M-560-140	H-520-130	
	L-650-0		CF	M-520-130	CF	
	CC			H-560-140		
	L-560-140			H-520-130		
	L-520-130			CF		
Cumulative Percent Passing	50%	71%	100%	43%	71%	100%

Table 5.10: Structural Mixtures Passing and Failing at 3, 7 and 28-days for Performance Target 4,000 psi Compressive Strength

Target Values	**Meeting 4,000 psi Target**			**Not Meeting 4,000 psi**		
Age	3 days	7 days	28 days	3 days	7 days	28 days
Mixtures passing target value	H-650-0	H-700-0	H-560-140	H-700-0	H-560-140	
	M-700-0	H-520-130		H-520-130		
	M-650-0	CF		CF		
	L-700-0			H-560-140		
	L-650-0					
	CC					
	M-560-140					
	M-520-130					
	L-560-140					
	L-520-130					
Cumulative Percent Passing	64%	86%	100%	71%	93%	100%

Tables 5.9-5.11 show structural mixtures of the expanded dataset and the selected strengths. Table 5.10 shows that only 71% of the mixtures met 4,500 at 7 days, but 83% of the mixtures met the 4,000 psi at 7 days. This supports the fact that NCDOT mixtures with fly ash typically required a bit longer to reach opening strengths and NCDOT could consider: 1) specifying a lower strength or 2), allow testing at any age after 7 days of curing to provide contractors flexibility when using mixtures with SCMs.

Several findings from the test results can be used to support feasible opening compressive and flexural strength targets for pavements and bridges. A target of 3,000 psi at 7 days should be readily obtainable for concrete pavement mixtures. As shown in Table 5.5, mixtures H-480-120, and H-420-180 were the only mixtures out of the current research dataset that did not pass at 3 days, but these mixtures did pass by 7 days. Also these mixtures were the ones with the highest w/cm ratio, which has historically taken longer to gain strength. As mentioned previously, mixtures BC1 and BC2 were not tested at 3-day but by 7 days those mixtures reached over 3,000 psi. Based on the data obtained for flexural strength a target of 650 psi is obtainable as all mixtures in the current laboratory testing program passed 650 psi by 28 days. As shown in Table 5.7 there were several mixtures from previous research that did not reach 650 psi by 28 days. These mixtures all had a w/cm ratio of 0.48 and contained manufactured sand which has historically resulted in lower strength gain, in comparison to the mixtures included in the current program.

For structural mixtures, a target of 4,000 psi by 7 days or 4,500 psi by 7 days depending on the mixture use for opening structures to traffic. Most mixtures met 4,000 psi by 7 days with the exception of one mixture H-560-140. This mixture had a high w/cm ratio, and surpassed 4,000 psi by 28 days. For structures with higher loading applications, a target of 4,500 psi may pose issue for mixtures with SCMs. As shown in Table 5.10, mixtures containing fly ash reach well over 4,500 psi after 28 days. Using a target of 4,500 psi after bridge has cured for at least 7 days for more critical concrete structures or structures withstanding heavy loading is more feasible in respect to PEMs with SCMs. Targets explained for pavements and bridges allow for variety of mixture properties as well as types of concrete application.

5.4 Summary of Findings

- North Carolina's current early age strength targets for opening pavement and structural concrete to traffic seem reasonable. However, they could be modified slightly to ensure SCM mixtures are readily considered for use by contractors.
- A target of 3,000 psi for early age opening to traffic appears appropriate for pavement mixtures, since 3,000 psi was typically achieved by 7 days by pavement mixtures included in this research.
- All structural mixtures included in this laboratory testing program surpassed 4,500 psi by 28 days, although considering weather conditions, contractor scheduling, and the time it takes some of the concrete with SCMs to gain strength. By developing a specification target for mixtures used for less critical structural components and another target for more critical structural components, contractors may have an increased ability to both optimize concrete mixtures and meet their desired schedule. This approach aligns with NCDOT's use of Class A and Class AA concrete for structural uses.
- For structural mixtures a target of 4,000 psi was achieved for most mixtures earlier than 7 days, but 4,500 psi is achievable for all mixtures (even fly ash mixtures) by 28 days. So NCDOT could use 4,000 psi as an early target or use 4,500 psi as a 28-day target. Alternatively, NCDOT could specify a target of 4,000 psi at 14 days for mixtures used in less critical concrete structures, and 4,500 psi at 28 days for mixtures used for more critical structures, in which PEMs with significant SCM content may be an attractive option.

- Specification provisions should also allow contractors to demonstrate that strength targets are met using maturity methods before those ages.
- As this specification is implemented, depending on contractor and producer ability to meet these targets, the targets can be adjusted and made more aggressive. More aggressive targets could ensure NCDOT pavement and bridges are low maintenance and long-lasting.

5.5 NCDOT Shadow Specification for Strength

This section is suggested as a revision to sections of the NCDOT 2018 Standard Specifications for Roads and Structures in respect to opening pavements and bridges to traffic. For pavements, Section 700-13 "Use of New Pavement or Shoulder" in the Concrete Pavements and Shoulders chapter of the specifications was used to revise with suggested standards (NCDOT, 2018). Currently this section is presented as follows:

> 700-13 Use of New Pavement or Shoulder
>
> Traffic or other heavy equipment will not be allowed on the concrete pavement or shoulder until the estimated compressive strength of the concrete using the maturity method has exceeded 3,000 psi. Estimate the compressive strength of concrete pavement in accordance with ASTM C 1074 unless otherwise specified.

The suggested revision to include application of early-age compressive strength specification for opening concrete pavements to traffic for NCDOT is as follows:

> 700-13 Use of New Pavement or Shoulder
>
> Traffic or other heavy equipment will not be allowed on the concrete pavement or shoulder until the estimated or measured compressive strength has exceeded at least 3,000 psi. Pavement or shoulder can also be verified by using the maturity method to estimate concrete strength in accordance with ASTM C 1074 unless otherwise specified.

For structural concrete, Section 400-20 "Placing Load on Structure Members" in the Structural Concrete chapter of the specifications was used to revise with suggested standards (NCDOT, 2018). Currently this section is as follows:

Do not place vehicles or construction equipment on a bridge deck until the deck concrete develops the minimum specified 28 day compressive strength and attains an age of at least 7 curing days. Construction equipment is allowed on bridge approach slabs after the slab concrete develops a compressive strength of at least 3,000 psi and attains an age of at least 7 curing days. See Sub article 420-15(A) for the definition of “curing day.” Provide evidence that the minimum compressive strengths referred to above are satisfied by nondestructive test methods approved in writing or by compressive strength tests made in accordance with AASHTO T 22 and T 23.

The suggested revision to include application of earl-age compressive strength specification for opening bridge structures to traffic for NCDOT is as follows:

Do not place vehicles or construction equipment on a bridge deck until the deck concrete develops the minimum specified 28 day compressive strength or at least 4,500 psi and has been cured for a minimum of 7 days. For less critical structures the bridge deck must develop the minimum specified strength or at least 4,000 psi is after a minimum of 7 curing days. Construction equipment is allowed on bridge approach slabs after the concrete develops a compressive strength of at least 3,000 psi and attains an age of at least 7 curing days. See Sub article 420-15(A) for the definition of “curing day.” Provide evidence that the minimum compressive strengths referred to above are satisfied by nondestructive test methods approved in writing or by compressive strength tests made in accordance with AASHTO T 22 and T 23.

CHAPTER 6: DEVELOPMENT OF RECOMMENDED SHRINKAGE SPECIFICATION

6.1 Introduction

Provided in this chapter is a review of current shrinkage targets recommended by AASHTO, and other SHAs along with analyses of shrinkage data using North Carolina concrete mixtures. For additional support data for the NCDOT recommended shrinkage specifications for PEMs, the analyses presented in this section include data from previous research projects on bridge and pavement concrete batched and tested from UNC at Charlotte research team. This data set includes the 24 mixtures discussed throughout this thesis along with the additional 23 mixtures mentioned in the last section. As mentioned previously, the additional research project included more than 23 mixtures in the experimental program. However, the ones selected for inclusion in this thesis for additional supporting data were chosen due to having similar mixture materials and proportions. These proportions are shown in Table 5.1.

6.2 Analysis of Relevant AASHTO Requirements

To develop a shrinkage specification for PEMs in NC, existing AASHTO specifications along with several SHA specifications for shrinkage were reviewed (Chapter 2) and are summarized in this section of Chapter 5.

6.2.1 Applicable Federal Standards

The federal standards applicable to this section include the FHWA's Concrete Pavement Preservation Guide, specifications for pavements and bridges, and AASHTO PP 84 (Smith et al. 2014, FHWA, 2014, and AASHTO, 2019). The Concrete Pavement Preservation Guide has procedural recommendations for reducing shrinkage. For partial-depth concrete pavement repairs, shrinkage is noted as a problem when repairs are not cured and/or finished properly, but is normally not a major issue so the FHWA requires monitoring repairs for shrinkage as a preventative measure

(Smith et al. 2014). For dowel bar retrofitting, patching materials for concrete pavement are recommended to exhibit less than 0.13% length change after 4 days (Smith et al. 2014). For concrete overlays, it is recommended to avoid Type III cement as it is more susceptible to shrinkage (Smith et al. 2014). Fiber-reinforced concrete is recommended for concrete overlays due to the micro synthetic fibers that tend to reduce shrinkage and improve aesthetics (Smith et al. 2014).

In the FHWA Standard Specifications in Section 725.22 it states that expansive hydraulic cement grout must be observed for shrinkage characteristics (FHWA, 2014). For structural concrete, in Section 522 there are several placement recommendations to avoid shrinkage (FHWA, 2014). In AASHTO PP 84, limiting the volume of paste to no more than 25% is a currently recommended prescriptive specification provision for reducing shrinkage potential for pavement mixtures while SHAs could also choose to limit length change in micro-strain to 420 in accordance with ASTM C 157 testing method as a performance based specification (AASHTO, 2019). Table 6.1 summarizes applicable federal shrinkage specification recommendations. It is noted that the maximum 25% paste requirement is likely not appropriate for most structural concrete mixtures which require higher workability.

Table 6.1: Relevant FHWA and AASHTO Standards to Support Development of Unrestrained Shrinkage Specifications

<table>
<tr><th>Standard</th><th colspan="2">Requirement, AASHTO Acceptance (if Applicable)</th><th>Age</th></tr>
<tr><td>FHWA Concrete Pavement Preservation Guide - dowel bars retrofit</td><td colspan="2">length change (%)<0.13% (130 με) in accordance with ASTM C157</td><td>4 days</td></tr>
<tr><td>FHWA Standard Specifications hydraulic cement sanded grout</td><td colspan="2">Observe for shrinkage characteristics</td><td>N/A</td></tr>
<tr><td>FHWA Standard Specifications structural concrete</td><td colspan="2">Placement curing and finishing properly and observe/repair shrinkage cracks</td><td>N/A</td></tr>
<tr><td rowspan="2">AASHTO PP 84</td><td>Volume of paste<25%</td><td>420 micro-strain</td><td>28 days</td></tr>
<tr><td>Prescriptive limit suggested by AASHTO PP 84</td><td colspan="2">Accepted</td></tr>
</table>

The FHWA also grades performance of High Performance Concrete (HPC) for structural concrete and shrinkage is included in the criteria. Based on the grading system the lowest grade is given for concrete exhibiting unrestrained length change of 600-800 με, the middle grade for length change of 400-600 με, and the highest grade for length change less than 400 με (Russell et al., 2006). The AASHTO recommendation of less than 420 micro-strain is close to the highest grade for shrinkage as per FHWA HPC grading system.

6.2.2 Applicable State Specifications

To support the development of standard shrinkage specifications that are practical, current SHAs specification provisions for shrinkage targets were reviewed. Shrinkage requirements for concrete structures and pavements in several state agency specifications are summarized in Table

6.2. The requirements summarized include standard specifications, as there were no special provisions considering shrinkage for concrete bridges and pavements from the SHAs shown in Table 5.3. SHA specifications that did not include shrinkage targets were not included in this table.

Table 6.2: Relevant SHA standards to Support Development of Shrinkage Performance Specifications

State/Standard	Concrete Type	Unrestrained Shrinkage Limit (% length change unless noted)	Curing and/or construction requirements	Age (days)
Louisiana DOTD standard specifications	Rapid hardening concrete for dowel bar retrofit	<0.013 (130 με)	-	4
	Structural concrete patching material	<0.070 (700 με)	-	28
Minnesota DOT standard specifications	Type R3 - Rapid hardening concrete for dowel bar retrofit	<0.050 (500 με)	-	28
New York State DOT	High Performance Concrete for precast and pre-stressed bridge beams	s<600με	cured for the same time in lab as field	56
	PCC mix for precast repairs	<0.050 (500 με)	cured for the same time in lab as field	56
Florida DOT Standard specifications	Concrete using Petroleum Coke Class F fly ash	-	compare results with ASTM C618 Class F fly ash concrete	28
	Type Q - epoxy compound and repair materials for bridge/pavements	<0.012 (120 με)	water cured and compared to one day length	28
Virginia DOT standard specifications	Class A4 modified - low shrinkage (bridge deck, overlay)	<0.035 (350 με)	moist cured for 7 days prior to testing	28
West Virginia DOH standard specifications	Class S-P - self-consolidating and precast concrete	≤0.020 (200 με)	28-day cure per ASTM C157 then Air Storage for 28-days	56

The shrinkage targets shown are directly from the standard specifications from each SHA. These standards range from class A4 modified concrete to dowel bar retrofit. For most of the SHAs testing for shrinkage is at 28 days with the exception of Louisiana, New York, and West Virginia, which each test at 56 days for unrestrained shrinkage as per ASTM C 157 (ASTM, 2017). Since the dowel retrofit bars are not the focus of this thesis review of those shrinkage specifications in omitted. New York, Virginia, and West Virginia were identified as SHAs with concrete shrinkage specifications. For New York, the specified concrete class is HPC for precast and pre-stressed concrete bridge beams, where the unrestrained shrinkage is limited to 600 με tested at 56 days (NYSDOT, 2019). Considering the AASHTO limit of 420 με this is quite lenient, which could be due to the fact it is for precast concrete instead of cast-in-place. Virginia specifies shrinkage restrictions of 350 με at 28 days for Class A4 modified low shrinkage concrete to be used for bridge decks and overlays, which is stricter than the AASHTO recommended target limit (VDOT, 2016). This class of concrete is specifically for low shrinkage concrete, which is likely why it is stricter than AASHTO's recommendation. For West Virginia, the class of concrete is a self-consolidating mixture which are normally used for mass concrete structures (WVDOH, 2017). This class of concrete is limited to 200 με tested at 56 days, which is the strictest requirement of all of the shrinkage specifications relevant to concrete pavements and bridges mentioned in this report (WVDOH, 2017).

The shrinkage target chosen to support development of a proposed NCDOT shrinkage specification is the AASTHO PP 84 recommendation of 420 με (AASHTO, 2019). The collaborative efforts of the FHWA, NCC, PCA, and several other industry organizations to publish this durability performance based specification for concrete pavements has made this one of the leading specifications for PEMs (Cackler et al. 2017). NYSDOT and Virginia state specifications for shrinkage will be used to compare less aggressive and more aggressive standards with standard specifications.

6.3 Development of Performance Targets for Shrinkage Specification Provisions

The AASHTO PP 84 standard lists shrinkage as a key indicator of concrete pavement durability performance (AASHTO, 2019). This specification focuses on PEMs and concrete performance targets that are achievable for contractors and ensures durable concrete pavements for NC roads (Cackler et al. 2017). Although this specification is targeted towards concrete pavements, it will be used to evaluate structural mixture performance and identify feasible shrinkage targets for these types of mixtures. At 28 days unrestrained shrinkage is limited to 420 με, tested in accordance with ASTM C157 (AASHTO, 2019). To determine if this target is achievable with NC mixtures, previous research by the research team is included in the expanded dataset used in this thesis (Cavalline et al. 2015). The mixture properties of these mixtures are shown in Table 5.1 labeled as paving mixtures. Figure 6.1 shows the expanded dataset with concrete pavement mixtures sorted by fly ash content.

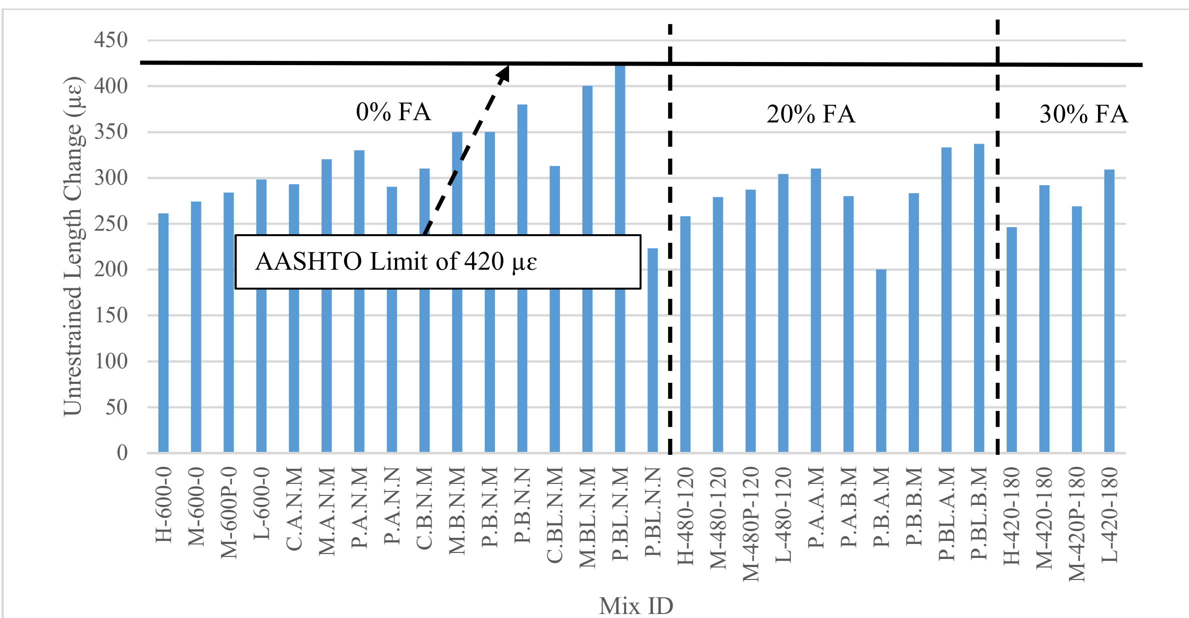

Figure 6.1: 28-day Average Unrestrained Volume Change (με) for Pavement Mixtures

As shown in Figure 6.1, only one mixture P.BL.N.M exceeded the recommended limit at 423 με. This mixture from the previous research project was a cement only pavement mixture with a w/cm ratio of 0.48. Research has shown that SCMs tend to help reduce shrinkage and cracking (Taylor et al. 2013). This supports the implementation of this target as the mixtures with fly ash tend to shown reduced shrinkage in comparison to the mixtures with cement only. The mixtures with the lowest length change is mixture P.B.A.M with a 20% fly ash replacement rate. As mentioned earlier in this report, this target represents the standard, while VDOT's limit for Class A4 modified mixtures (bridge overlays) of 350 με is the more aggressive target that can be used for more durable concrete applications and NYSDOT's limit for HPC mixtures (bridge structures) of 600 με represents a less aggressive standard (VDOT, 2016 and NYSDOT, 2019).

To determine the practicality of these targets for allowable shrinkage in pavements and structural mixtures further analyses were performed. Below is a series of tables that identify percentage of mixtures that passed the 28-day shrinkage limit targets for each level of standard aggression. This is shown for pavement and structural mixtures in Tables 6.3-6.5. For both pavement and structural mixtures, all mixtures included in the expanded dataset resulted in length change less than 600 με.

Figure 6.2 shows the ranges between the three samples tested for shrinkage for each mixture in this project's laboratory program. Although the variation between specimens measurements is not judged to be particularly excessive, it is noted that some of the highest average shrinkage results were mixtures that had large variances between specimens. L-650-0, M-520-130, and L-700-0 all had specimens resulting in wide ranges of length change.

Table 6.3: Analysis of Pavement and Structural Mixtures Passing Aggressive Unrestrained Shrinkage Targets

Target Values	350με	420με	600με
Age	28 days		
Mixtures passing target value	H-600-0	M.B.N.M.	P.BL.N.M
	M-600-0	P.B.N.N.	
	M-600P-0	P.B.N.M.	
	L-600-0	M.BL.N.M.	
	C.A.N.M		
	M.A.N.M		
	P.A.N.M		
	P.A.N.N		
	C.B.N.M		
	C.BL.N.M		
	P.BL.N.N		
	H-480-120		
	M-480-120		
	M-480P-120		
	L-480-120		
	P.A.A.M		
	P.A.B.M		
	P.B.A.M		
	P.B.B.M		
	P.BL.A.M		
	P.BL.B.M		
	H-420-180		
	M-420-180		
	M-420P-180		
	L-420-180		
Percent Passing	83%	97%	100%

Table 6.4: Pavement and Structural Mixtures Passing and Failing at 28-day "More Aggressive" Performance Target

Target Values	Under 350με target	Not Under 350με target
Age	28 days	28 days
Mixture Identification	H-600-0	M.B.N.M
	M-600-0	P.B.N.M
	M-600P-0	P.B.N.N
	L-600-0	M.BL.N.M
	C.A.N.M	P.BL.N.M
	M.A.N.M	
	P.A.N.M	
	P.A.N.N	
	C.B.N.M	
	C.BL.N.M	
	P.BL.N.N	
	H-480-120	
	M-480-120	
	M-480P-120	
	L-480-120	
	P.A.A.M	
	P.A.B.M	
	P.B.A.M	
	P.B.B.M	
	P.BL.A.M	
	P.BL.B.M	
	H-420-180	
	M-420-180	
	M-420P-180	
	L-420-180	

Table 6.5: Pavement and Structural Mixtures Passing and Failing at 28-day Standard Performance Target

Target Values	Under 420με target	Not Under 420με target
Age	28 days	28 days
Mixture Identification	H-600-0	P.BL.N.M
	M-600-0	
	M-600P-0	
	L-600-0	
	C.A.N.M	
	M.A.N.M	
	P.A.N.M	
	P.A.N.N	
	C.B.N.M	
	C.BL.N.M	
	P.BL.N.N	
	H-480-120	
	M-480-120	
	M-480P-120	
	L-480-120	
	P.A.A.M	
	P.A.B.M	
	P.B.A.M	
	P.B.B.M	
	P.BL.A.M	
	P.BL.B.M	
	H-420-180	
	M-420-180	
	M-420P-180	
	L-420-180	

Based on Tables 6.3-6.5, analyzing the mixtures in the expanded dataset a practicable shrinkage target can be determined. The suggested AASHTO PP 84 target of less than 420 με at 28 days proved to be attainable by all mixtures, with the exception of one that exceeded the limit by 3 με as shown in Table 6.4. This mixture was cement only and contained a higher w/cm ratio, and the high length change could be attributed to that. Although, one mixture did not pass, the other mixtures (pavement and structural) all are within this standard limit. The more aggressive target of

350 με could readily be used for concrete pavements and structures susceptible to undesirable shrinkage, or in applications where it is essential to limit shrinkage cracking and warping. Although this target was aggressive, only five mixtures were over this limit as shown in Table 6.5. These mixtures were a mix of piedmont and mountain coarse aggregate types, and all mixtures contained 1798 cy coarse aggregate in comparison to 1661 cy (Cavalline et al., 2018). In addition four of the five mixtures that were over the limit of 350 με contained manufactured sand, which could have attributed to the higher length change.

6.4 Summary of Findings

- To improve the quality of concrete performance, concrete pavement and bridge mixtures could be tested for unrestrained shrinkage using ASTM C157. Shrinkage is detrimental to both concrete pavements and structures due to undesirable cracking and volumetric change, so implementing shrinkage testing and target limits will encourage durable concrete mixtures.
- Analysis indicated that an unrestrained shrinkage a target limit of 420 με, as suggested by AASHTO PP 84, can be used for concrete pavements and bridges. For concrete mixtures susceptible to shrinkage or in applications where shrinkage is highly undesired, a more aggressive target of 350 με could be used.
- Both targets should not eliminate concrete mixtures made with SCMs. These targets are attainable by NC concrete mixtures for both bridges and pavements. Although unrestrained shrinkage testing was conducted at 4 weeks, 8 weeks, 16 weeks, 32 and 64 weeks, the test age of 28 days is recommended by AASHTO and several SHAs as a target age for testing due to convenience. To encourage use of higher SCM mixtures, a 56 day target could also be utilized.
- As this specification is implemented, target(s) could be adjusted depending on contractor and producer ability to test and limit shrinkage. More aggressive targets could ensure

NCDOT concrete pavement and bridge mixtures are durable, by keeping unrestrained shrinkage to a minimum.

6.5 NCDOT Shadow Specification for Shrinkage

This section is suggested as a revision to Section 1000-4 “Portland Cement Concrete for Structures and Incidental Construction” in the NCDOT Standard Specifications (NCDOT, 2018). Currently there are no shrinkage requirements by the NCDOT, so this section should be added to the laboratory tests Table shown in this chapter as well as a subsection as follows:

(A) Composition and Design (Add this Table to Specification in Replacement of Table found in Section 1000-4 (A))

Table 6.6: Laboratory Tests for Portland Cement Concrete for Structures and Incidental Construction

Property	**Test Method**
Aggregate Gradation	AASHTO T 27
Air Content	AASHTO T 152
Slump	AASHTO T 119
Compressive Strength	AASHTO T 22 and T23
Shrinkage	AASHTO T 160

(E) Shrinkage Requirements

Concrete should be tested for unrestrained length change at 28 days using AASHTO T 160. For normal concrete pavement and bridge applications, the length change in micro-strain is limited to 420 με. For concrete applications where enhanced provisions against cracking are desired, length change in micro-strain can be limited to 350 με at the engineer’s discretion.

The following table would be added or incorporated into Table 1000-1 with the following note:

Table 6.7: Suggested Addition to NCDOT Specifications for Roads and Structures

Class of Concrete	Shrinkage Limit (με) at 28 days
AA	420*
Pavement	420*
*For concrete where a reduction in cracking due to shrinkage is desirable, 350με could be used.	

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

Along with previous research projects, this project is a stepping stone that will help NCDOT specify durable concrete mixtures while allowing the contractor advantages associated with performance specifications. Previous projects varied materials to determine impact of material selection on concrete performance. This project focused on varying proportions to determine the influence of different proportions on durability performance (such as shrinkage) and mechanical properties (such as compressive and flexural strength).

This thesis presents the findings of testing of NCDOT concrete paving and structural concrete mixtures batched at UNC at Charlotte and describes the development of proposed early-age compressive strength specifications for opening pavements and bridges to traffic, and the development of shrinkage specifications considering PEMs. Using a review of other SHAs and federal specifications in use, along with analyses of laboratory supporting data from NC concrete mixtures, specification requirements for early age compressive strength for opening to traffic were confirmed and revised, and target limits for a specification for unrestrained shrinkage was developed.

This work supports an overall effort by the NCDOT to move towards PEM specifications to promote design and construction of pavements and bridge structures that are durable, sustainable, and long-lasting, and is in alignment with the FHWA's PEM initiative. The conclusions and recommendations presented in this thesis should be considered as preliminary recommendations for shadow specifications to be implemented on pilot projects to ensure they are the appropriate. This chapter summarizes the conclusions found from this research and test results. Also, recommendations for future research are provided in this section.

7.1 Conclusions

Resistance to shrinkage and early-age opening strength requirements were evaluated in this thesis based on the test results of 24 mixtures. Combining the results from this laboratory program with previous NC durability research projects allowed researchers to identify preliminary target shrinkage limits and early-age opening requirements that do not hinder use of mixtures that include SCMs. The key findings from the laboratory testing include:

- PLC mixtures do not need to be treated differently from ordinary portland cement mixtures in specification provisions. The test results presented in this research support the fact that mixtures containing PLC perform almost equivalent to OPC in most instances for standard NC paving and bridge mixtures. Processes producing PLC are energy saving and cost saving for producers in comparison to OPC, and as specifications improve PLC should prove to be a beneficial substitution for OPC.
- When comparing w/cm ratios, the w/cm ratios of 0.42 and 0.37 tended to have superior mechanical properties as well as durability characteristics over the higher w/cm ratios, confirming previous research recommending SHAs to lower required w/cm ratios in order to produce longer lasting concrete infrastructure. NCDOT could choose to prescribe a w/cm limit for mixtures to support overall performance improvements.
- At earlier ages, straight cement mixtures may perform mechanically better than fly ash mixtures, but as they age, mixtures containing fly ash with a typical (0.42) to low (0.37) w/cm ratio tend to outperform these mixtures.
- Comparing 20% and 30% fly ash replacement rates, there was little difference in long term compressive, flexural, and shrinkage results. It should be noted that in some cases, 20% fly ash replacement rate mixtures performed better than 30% and vice versa. This finding supports the increased replacement rate of 30% to achieve sustainability benefits, as well as reduced permeability and increased durability.

- Mixtures with fly ash tended to gain ultimate strengths surpassing current NCDOT standards of 3,000 psi for pavement mixtures and 4,500 psi for most structural mixtures. However, current standards for opening structures to traffic may be limiting, as fly ash mixtures can take longer to gain strength. Findings from this study indicated that in laboratory conditions, pavement mixtures with fly ash can regularly meet 3,000 psi in 7 days, some as early as 3 days. By 7 days most of the structural concrete mixtures met 4,500 psi, and all met 4,500 psi by 28 days.
- Current NCDOT specifications indicate that structural concrete should be tested after 7 curing days, and it is recommended that this provision be retained. A minimum required strength of 4,500 psi concrete strength can be verified through nondestructive testing methods such as the maturity method or conventional method of testing. As shown in VDOT's specifications as well as the Illinois Tollway, the maturity method has aided in determining in-place strength (VDOT, 2016; Gancarz, 2018). By keeping the required strengths the same, the transition to implementation should be smoother.
- Laboratory results indicate that 4,500 psi for structural concrete may be challenging to reach with mixtures made with SCMs at early ages. Mirroring other SHAs, allowing contractors to use the maturity method, as well as testing for strength at any age after concrete has cured for a minimum of 7 days, would allow SCM mixtures to meet this requirement. In addition, NCDOT could use separate provisions for less critical structures and more critical structures, allowing a specification with a lower opening strength requirement of 4,000 psi, which is used by several other SHAs. Based on the test results, 4,000 psi was achievable by more structural mixtures at 7 days than 4,500 psi.
- The research findings presented show that fly ash mixtures were more resistant to shrinkage than the non-fly ash mixtures, supporting the fact that SCMs such as fly ash enhance the

overall performance of concrete. Mitigating unrestrained shrinkage should prolong the service life of pavements and bridges, aligning with NCDOT's durable concrete initiative.

- Mixtures with 30% fly ash replacement rates showed reduced shrinkage by 28 days in comparison to several of the 20% fly ash replacement rate mixtures, as expected. Overall, most of the mixtures were well under the recommended limit of 420 $\mu\varepsilon$ and an unrestrained shrinkage limit of 350 $\mu\varepsilon$ may be a more appropriate and readily achievable target for North Carolina concrete mixtures.

Considering contractor feasibility and risk will be key in successful implementation of these standards. Since contractors are on tight schedules, specification targets should initially be readily achievable by concrete mixtures that have shown proven performance in the field. Test ages should also be specified within reasonable test periods as much as practical. Use of non-destructive test methods, such as the maturity method to determine strength of in place concrete, will allow contractors a readily implementable method of real-time testing to meet performance targets early and avoid delays.

For both early age strength and shrinkage, specification recommendations were integrated into NCDOT's current specifications in order to aid with implementation processes and provide minimum change to the currently accepted standards. It should be noted that strength is not the only indication of performance, as discussed there are several other factors that are essential to concrete durability and long-lasting pavements and structures, including shrinkage, resistivity, and corrosion resistance. Ultimately, performance targets should be linked to field performance over time.

7.2 Recommendations for Future Work

These specifications are recommendations for preliminary implementation and should be tested through use on a pilot project and/or trial mixtures. Research has shown concrete performs differently in place than the cylinders selected for testing. Use of these targets in pilot projects and in other shadow specification applications should allow NCDOT to reaffirm the targets are appropriate and will help alleviate some apprehension from contractors towards PEM tests and specifications.

It is noted that although the mixture matrix encompassed a selected group of key parameters for study, additional research using a broad range of materials and mixtures is needed to support these findings and to verify of the feasibility and reasonableness of these performance targets.

Other research could utilize these targets as potential values for use of pay incentives for contractors. Pay incentives are often used and given to contractors who exceed expectations and perform work well in a number of areas of construction. As implementation of these targets begin, pay incentives for contractors exceeding these targets or meeting the more aggressive targets mentioned could be considered to encourage more contractors to use higher-performing, more durable and sustainable mixtures. These recommendations should ultimately allow NCDOT to move towards longer lasting concrete infrastructure.

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APPENDIX A: SUPPLEMENTARY INFORMATION FOR CHAPTER 3

Version 6.42

Holcim

NSF

Material Certification Report

Material:	Portland Cement	Test Period:	14-Sep-2015
Type:	I-II(MH)	To:	15-Sep-2015

Certification

This Holcim cement meets the specifications of ASTM C150 for Type I-II(MH) cement, and complies with AASHTO M85 specifications for Type I-II(MH) cement.

General Information

Supplier:	Holcim (US) Inc.	Source Location:	Holly Hill Plant
Address:	2173 Gardner Boulevard Holly Hill, SC 29059		2173 Gardner Boulevard Holly Hill, SC 29059
Telephone:	803-496-2995	Contact:	Scott Poaps
Date Issued:	15-Dec-2015		

The following information is based on average test data during the test period.
The data is typical of cement shipped by Holcim; individual shipments may vary.

Tests Data on ASTM Standard Requirements

Chemical

Item	Limit[A]	Result
SiO_2 (%)	-	20.4
Al_2O_3 (%)	6.0 max	4.8
Fe_2O_3 (%)	6.0 max	3.3
CaO (%)	-	63.8
MgO (%)	6.0 max	1.6
SO_3 (%)	3.0 max[B]	3.1
Loss on Ignition (%)	3.0 max	1.6
Insoluble Residue (%)	0.75 max	0.23
CO_2 (%)	-	1.1
Limestone (%)	5.0 max	2.6
$CaCO_3$ in Limestone (%)	70 min	92
Inorganic Processing Addition (%)	5.0 max	0.0
Potential Phase Compositions[C]:		
C_3S (%)	-	54
C_2S (%)	-	17
C_3A (%)	8 max	7
C_4AF (%)	-	10
$C_3S + 4.75C_3A$ (%)	100 max	87.3

Physical

Item	Limit[A]	Result
Air Content (%)	12 max	6
Blaine Fineness (m^2/kg)	260-430	393
Autoclave Expansion (%) (C151)	0.80 max	0.05
Compressive Strength MPa (psi):		
3 days	10.0 (1450) min	29.0 (4210)
7 days	17.0 (2470) min	34.8 (5040)
Initial Vicat (minutes)	45-375	117
Mortar Bar Expansion (%) (C1038)		0.006
Heat of Hydration: kJ/kg (cal/g)[D] 7 Days (for informational purposes)	-	305 (73)

Tests Data on ASTM Optional Requirements

Chemical

Item	Limit[A]	Result
Equivalent Alkalies (%)	0.60 max	0.53

Physical

Item	Limit[A]	Result

Notes

[A] Dashes in the limit / result columns mean Not Applicable.
[B] It is permissible to exceed the specification limit provided that ASTM C1038 Mortar Bar Expansion does not exceed 0.020 % at 14 days.
[C] Adjusted per Annex A1.6 of ASTM C150 and AASHTO M85.
[D] Test result represents most recent value and is provided for information only. Analysis of Heat of Hydration has been carried out by CTLGroup, Skokie, IL. This data may have been reported on previous mill certificates.

Silo 18
9/14/2015
Grind 257-259

Additional Data

Inorganic Processing Addition Data

Item	Result[A]
Type	-
Amount (%)	-
SiO_2 (%)	-
Al_2O_3 (%)	-
Fe_2O_3 (%)	-
CaO (%)	-
SO_3 (%)	-

Base Cement Phase Composition

Item	Result
C_3S (%)	56
C_2S (%)	18
C_3A (%)	7
C_4AF (%)	10

By Scott Poaps, Quality Manager

Figure A.1: Original Portland Cement (OPC) Mill Report

TEC Services
Testing • Engineering • Consulting

Client: Mr. Jim Simon
Ash Venture LLC
188 Summerfield Court, Suite 201
Roanoke, VA 24019

Date: January 30, 2015
TEC Services Project No: TEC 14-1097
TEC Laboratory No: 14-1090

REPORT OF FLY ASH TESTS			
Date Sampled: DS 12/11-12/16	Start Date:	December 11, 2014	
Manufacturer: Belews Creek	End Date:	December 16, 2014	
	Date Received:	December 22, 2014	
		Specification (Class F)	
Chemical Analysis**	**Results**	**ASTM C618-12a**	**AASHTO M295-11**
Silicon Dioxide	**53.21**	----	----
Aluminum Oxide	**28.74**	----	----
Iron Oxide	**7.64**	----	----
Sum of Silicon Dioxide, Iron Oxide & Aluminum Oxide	**89.59**	70 % min.	70 % min.
Calcium Oxide	**1.74**	----	----
Magnesium Oxide	**0.92**		
Sulfur Trioxide	**0.38**	5 % max.	5 % max.
Loss on Ignition	**2.61**	6 % max.	5 % max.
Moisture Content	**0.10**	3 % max.	3 % max.
Available Alkalies as Na_2O	**0.42**	----	1.5 % max.*
Sodium Oxide	**0.11**	----	----
Potassium Oxide	**0.47**	----	----
Physical Analysis			
Fineness (Amount Retained on #325 Sieve)	**13.3%**	34 % max.	34 % max.
Strength Activity Index with Portland Cement			
At 7 Days: Control Average, psi: 4930; Test Average, psi: 3840	**78%**	75 % min.† (of control)	75 % min.† (of control)
At 28 Days: Control Average, psi: 6150; Test Average, psi: 5540	**90%**	75 % min.† (of control)	75 % min.† (of control)
Water Requirements (Test H_2O/Control H_2O) Control, mls: 242; Test, mls: 236	**98%**	105 % max. (of control)	105 % max. (of control)
Autoclave Expansion	**0.03%**	± 0.8 % max.	± 0.8 % max.
Specific Gravity:	**2.29**	----	----

† Meeting the 7 day or 28 day strength activity index will indicate specification compliance
* Optional Requirement
**Chemical Analysis performed by Wyoming Analytical

The results of our testing indicate that this sample complies with ASTM C618-12a and AASHTO M295-11 specifications for Class F pozzolans.

Respectfully Submitted,
Testing, Engineering & Consulting Services, Inc.

COMMONWEALTH OF VIRGINIA
BRIAN J. WOLFE
Lic. No. 402053518
1/31/15
PROFESSIONAL ENGINEER

Dean T. Roosa
Senior Laboratory Technician

Shawn McCormick
Laboratory Principal

Testing, Engineering & Consulting Services, Inc.
235 Buford Drive | Lawrenceville, GA 30046
770-995-8000 | 770-995-8550 (F) | www.tecservices.com

Figure A.2: Fly Ash Material Report

A.S.T.M. C 127 Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate

Date Sampled	Material	Control Number	Bulk - Dry	Bulk - Saturated Surface Dry	Apparent	Absorption	Laboratory	Technician	Comments
		Triangle							
April 4, 2018	# 67	T-1	2.632	2.644	2.663	0.4%	WSC Central	C. Gastiger	Dark Gray Material

Figure A.3: Coarse Aggregate Specific Gravity and Absorption Report

A.S.T.M. C - 131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine

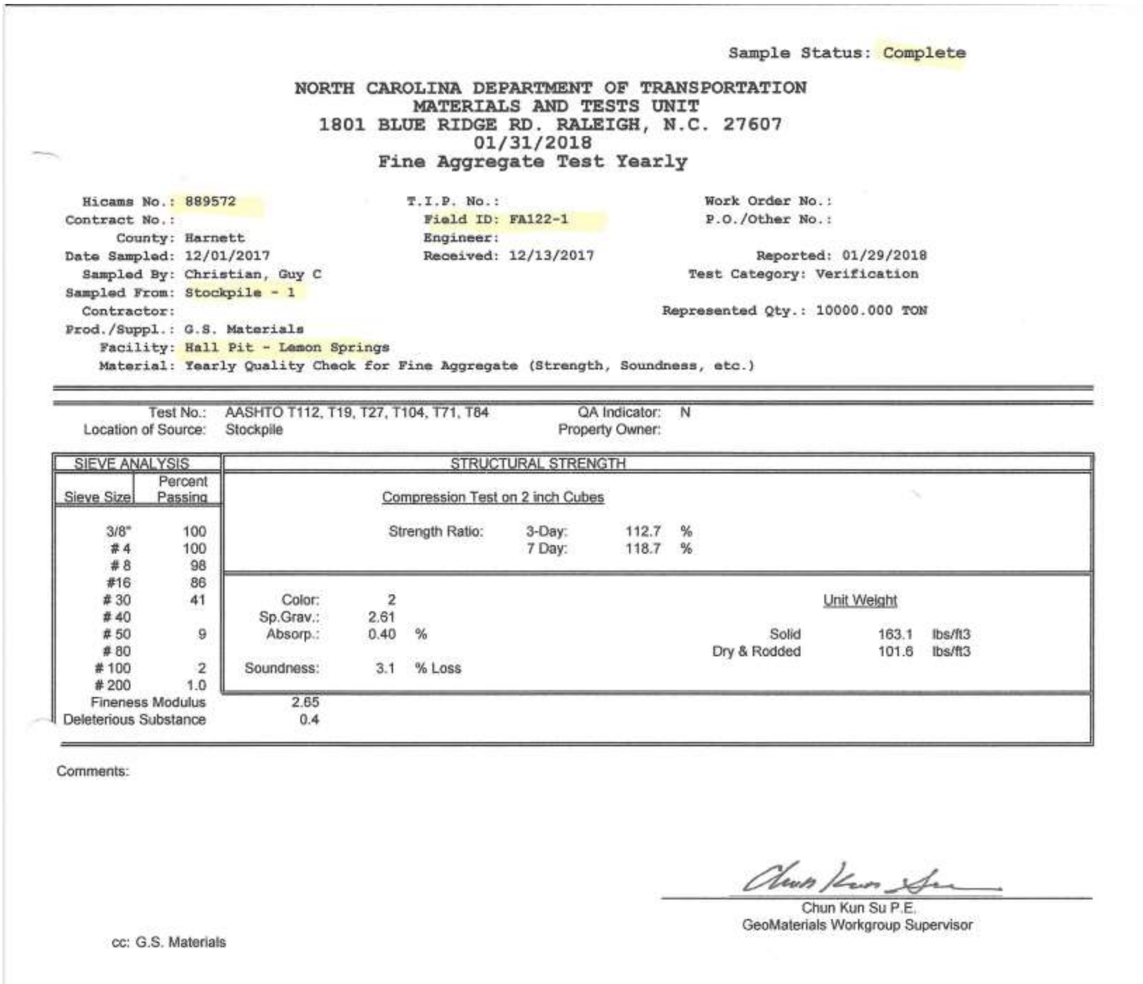
Date Sampled	Material	Control Number	Grading	Percent Loss	Laboratory	Technician	Comments
		Triangle					
April 4, 2018	# 67	T-1	B	47	WSC Central	C. Gastiger	Dark Gray Material

Figure A.4: Coarse Aggregate LA Abrasion Test Report

A.S.T.M. C - 136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregate

Date Sampled	Material	Control Number	Percent Passing															Soil Mortar			
			2"	1 1/2"	1"	3/4"	1/2"	3/8"	#4	#8	#10	#16	#30	#40	#50	#100	#200	LL	PI	#30	#40
		Triangle																			
April 4, 2018	# 67	T-1			100	98	59	36	5	3											

Figure A.5: Coarse Aggregate Sieve Analysis Report



Sample Status: Complete

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
MATERIALS AND TESTS UNIT
1801 BLUE RIDGE RD. RALEIGH, N.C. 27607
01/31/2018
Fine Aggregate Test Yearly

Hicams No.: 889572
Contract No.:
County: Harnett
Date Sampled: 12/01/2017
Sampled By: Christian, Guy C
Sampled From: Stockpile - 1
Contractor:
Prod./Suppl.: G.S. Materials
Facility: Hall Pit - Lemon Springs
Material: Yearly Quality Check for Fine Aggregate (Strength, Soundness, etc.)

T.I.P. No.:
Field ID: FA122-1
Engineer:
Received: 12/13/2017

Work Order No.:
P.O./Other No.:
Reported: 01/29/2018
Test Category: Verification
Represented Qty.: 10000.000 TON

Test No.: AASHTO T112, T19, T27, T104, T71, T84
Location of Source: Stockpile
QA Indicator: N
Property Owner:

SIEVE ANALYSIS

Sieve Size	Percent Passing
3/8"	100
# 4	100
# 8	98
#16	86
# 30	41
# 40	
# 50	9
# 80	
# 100	2
# 200	1.0

Fineness Modulus 2.65
Deleterious Substance 0.4

STRUCTURAL STRENGTH

Compression Test on 2 inch Cubes

Strength Ratio: 3-Day: 112.7 %
7 Day: 118.7 %

Color: 2
Sp.Grav.: 2.61
Absorp.: 0.40 %
Soundness: 3.1 % Loss

Unit Weight
Solid 163.1 lbs/ft3
Dry & Rodded 101.6 lbs/ft3

Comments:

Chun Kun Su P.E.
GeoMaterials Workgroup Supervisor

cc: G.S. Materials

Figure A.6: Fine Aggregate Report

Table A.1: Calculated Coarse Aggregate Properties

Property	Sample 1	Sample 2	Sample 3	Sample 4
Bulk Specific Gravity (bulk SG)	2.57	2.57	2.49	2.54
Bulk Specific Gravity (saturated surface dry)	2.61	2.62	2.56	2.6
Apparent Specific Gravity (apparent SG)	2.67	2.69	2.69	2.68
Absorption (%)	1.49	1.63	2.95	2.02

Table A.2: Calculated Fine Aggregate Properties

Property	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**
Bulk Specific Gravity (bulk SG)	2.58	2.54	2.58	2.56
Bulk Specific Gravity (saturated surface dry)	2.61	2.59	2.61	2.6
Apparent Specific Gravity (apparent SG)	2.66	2.67	2.68	2.67
Absorption (%)	1.26	1.91	1.52	1.56

APPENDIX B: SUPPLEMENTAL INFORMATION FOR CHAPTER 4

Table B.1: Compiled 28-day Strength Test Results

Mixture Identification	28 day compressive strength			Average Compressive Strength (psi)	Standard Deviation
	1	2	3		
H-700-0	5,075	5,669	5,394	5,379	297.3
H-560-140	4,544	5,131	5,306	4,994	399.1
H-650-0	6,113	6,440	6,216	6,256	167.2
H-520-130	5,446	5,007	5,483	5,312	264.8
H-600-0	5,016	5,381	6,085	5,494	543.4
H-480-120	3,870	4,114	3,962	3,982	123.2
H-420-180	3,862	5,007	4,114	4,328	601.7
M-700-0	6,330	6,874	6,860	6,688	310.1
M-560-140	5,284	5,270	6,510	5,688	711.9
M-650-0	6,600	7,046	6,572	6,739	265.9
M-520-130	6,162	6,626	6,337	6,375	234.3
M-600-0	5,264	5,813	6,541	5,873	640.6
M-600P-0	6,531	6,388	5,933	6,284	312.3
M-480-120	4,567	5,290	6,313	5,390	877.3
M-480P-120	6,358	6,294	6,593	6,415	157.4
M-420-180	4,835	4,602	5,584	5,007	513.1
M-420P-180	5,226	4,719	5,328	5,091	326.2
L-700-0	8,348	7,303	7,916	7,856	525.1
L-560-140	6,528	6,261	7,398	6,729	594.6
L-650-0	7,810	7,690	8,473	7,991	421.7
L-520-130	7,694	7,056	6,859	7,203	436.5
L-600-0	6,989	6,742	7,299	7,010	279.1
L-480-120	7,318	7,136	5,988	6,814	721.1
L-420-180	5,980	6,054	6,650	6,228	367.3

Table B.2: Shrinkage Test Results of Each Specimen at Each Day Tested

Mixture ID	Specimen ID	Shrinkage (Percentage)						
		4 day	7 Day	14 Day	28 Day	8 Week	16 Week	32 Week
H-700-0	1	0.0118	0.0136	0.0190	0.0271	0.0362	0.0404	0.0674
	2	0.0134	0.0160	0.0247	0.0339	0.0403	0.0441	0.0521
	3	0.0120	0.0148	0.0220	0.0326	0.0381	0.0427	0.0317
H-560-140	1	0.0140	0.0161	0.0233	0.0316	0.0398	0.0448	0.1088
	2	0.0122	0.0140	0.0208	0.0301	0.0371	0.0420	0.0860
	3	0.0116	0.0131	0.0189	0.0286	0.0359	0.0404	0.0864
H-520-130	1	0.0110	0.0121	0.0197	0.0284	0.0346	0.0442	-
	2	0.0104	0.0110	0.0188	0.0265	0.0338	0.0435	-
	3	Gauge Stud Broke Out						
H-600-0-2	1	0.0081	0.0092	0.0171	0.0258	0.0311	0.0413	0.0773
	2	0.0103	0.0117	0.0210	0.0291	0.0332	0.0441	0.0861
	3	0.0098	0.0103	0.0183	0.0234	0.0323	0.0433	0.0853
H-480-120-2	1	0.0110	0.0123	0.0202	0.0277	0.0348	0.0438	0.0778
	2	0.0099	0.0112	0.0189	0.0264	0.0326	0.0416	0.0706
	3	0.0064	0.0095	0.0149	0.0233	0.0313	0.0406	0.0566
H-420-180-2	1	0.0090	0.0110	0.0175	0.0240	0.0332	0.0440	0.0600
	2	0.0117	0.0129	0.0199	0.0266	0.0358	0.0452	0.0592
	3	0.0072	0.0094	0.0169	0.0232	0.0318	0.0425	0.0585
M-700-0	1	0.0151	0.0192	0.0303	0.0374	0.0431	0.0512	0.0591
	2	0.0127	0.0143	0.0224	0.0271	0.0350	0.0477	0.0543
	3	0.0136	0.0163	0.0256	0.0321	0.0422	0.0505	0.0567
M-650-0	1	0.0122	0.0148	0.0227	0.0300	0.0362	0.0448	0.0502
	2	0.0135	0.0167	0.0259	0.0326	0.0394	0.0479	0.0531
	3	0.0130	0.0162	0.0228	0.0304	0.0384	0.0459	0.0512
M-560-140	1	0.0147	0.0171	0.0251	0.0322	0.0399	0.0460	0.0950
	2	0.0122	0.0148	0.0209	0.0295	0.0386	0.0453	0.1383
	3	0.0121	0.0173	0.0272	0.0337	0.0376	0.0431	0.1221
M-520-130	1	0.0120	0.0138	0.0194	0.0296	0.0376	0.0444	-
	2	0.0136	0.0174	0.0231	0.0348	0.0399	0.0478	-
	3	0.0125	0.0153	0.0181	0.0268	0.0392	0.0458	-
M-600-0-2	1	0.0091	0.0111	0.0205	0.0268	0.0322	0.0374	0.0844
	2	0.0123	0.0130	0.0241	0.0309	0.0344	0.0396	0.0856
	3	0.0089	0.0101	0.0154	0.0245	0.0318	0.0364	0.0804
M-480-120-2	1	0.0096	0.0110	0.0202	0.0271	0.0330	0.0398	0.0798
	2	0.0084	0.0102	0.0197	0.0258	0.0321	0.0382	0.0782
	3	0.0132	0.0139	0.0216	0.0308	0.0366	0.0423	0.0783

Table B.2: Shrinkage Test Results of Each Specimen at Each Day Tested (Continued)

M-420-180-2	**1**	0.0111	0.0122	0.0207	0.0284	0.0350	0.0401	0.0601
	2	0.0127	0.0141	0.0219	0.0287	0.0372	0.0423	0.0623
	3	0.0125	0.0148	0.0234	0.0305	0.0361	0.0421	0.0631
M-600P-0-2	**1**	0.0118	0.0134	0.0221	0.0303	0.0371	0.0467	0.8913
	2	0.0104	0.0112	0.0202	0.0271	0.0346	0.0440	0.9120
	3	0.0105	0.0111	0.0210	0.0278	0.0348	0.0458	0.0988
M-480P-120-2	**1**	0.0099	0.0110	0.0200	0.0266	0.0323	0.0386	0.0616
	2	0.0105	0.0119	0.0210	0.0279	0.0350	0.0412	0.0632
	3	0.0126	0.0131	0.0232	0.0316	0.0371	0.0446	0.0666
M-420P-180-2	**1**	0.0120	0.0133	0.0215	0.0288	0.0338	0.0393	0.0593
	2	0.0097	0.0110	0.0198	0.0249	0.0316	0.0356	0.0506
	3	0.0122	0.0135	0.0211	0.0270	0.0345	0.0421	0.0611
L-700-0	**1**	0.0126	0.0148	0.0201	0.0302	0.0398	0.0502	-
	2	0.0148	0.0161	0.0209	0.0318	0.0420	0.0526	-
	3	0.0146	0.0183	0.0229	0.0322	0.0424	0.0511	-
L-650-0	**1**	0.0141	0.0173	0.0268	0.0315	0.0389	0.0480	0.1230
	2	0.0133	0.0158	0.0254	0.0304	0.0374	0.0456	0.1066
	3	0.0164	0.0203	0.0303	0.0380	0.0440	0.0513	0.1123
L-560-140	**1**	0.0180	0.0202	0.0255	0.0348	0.0457	0.0562	-
	2	0.0149	0.0177	0.0224	0.0321	0.0425	0.0527	-
	3	0.0178	0.0203	0.0256	0.0372	0.0459	0.0549	-
L-520-130	**1**	0.0129	0.017	0.025	0.0299	0.0384	0.0478	-
	2	0.0152	0.0202	0.0297	0.0336	0.0432	0.0521	-
	3	0.0145	0.0195	0.0284	0.0319	0.0426	0.0504	-
L-600-0-2	**1**	0.0098	0.0121	0.0201	0.0281	0.0355	0.0421	0.0761
	2	0.0114	0.013	0.0206	0.029	0.0372	0.0436	0.0686
	3	0.0142	0.0163	0.0217	0.0323	0.0386	0.0433	0.0663
L-480-120-2	**1**	0.0102	0.0125	0.0203	0.0310	0.0371	0.0438	0.0988
	2	0.0126	0.0162	0.0222	0.0336	0.0389	0.0449	0.0779
	3	0.0099	0.0112	0.0172	0.0266	0.0365	0.0424	0.1124
L-420-180-2	**1**	0.0137	0.0161	0.0234	0.0330	0.0384	0.0442	0.0612
	2	0.0129	0.0145	0.0210	0.0301	0.0361	0.0415	0.0635
	3	0.0094	0.0117	0.0195	0.0296	0.0356	0.0400	0.0550

Table B.3: Compiled 28-day Shrinkage Test Results

Mixture ID	28 Day (%)	28 day	Micro-strain	Average Micro-strain	Standard Deviation
H-700-0	0.0271	0.000271	271	312	36.1
	0.0339	0.000339	339		
	0.0326	0.000326	326		
H-600-0-2	0.0258	0.000258	258	261	28.6
	0.0291	0.000291	291		
	0.0234	0.000234	234		
M-700-0	0.0374	0.000374	374	322	51.5
	0.0271	0.000271	271		
	0.0321	0.000321	321		
M-650-0	0.0300	0.0003	300	310	14.0
	0.0326	0.000326	326		
	0.0304	0.000304	304		
M-600-0-2	0.0268	0.000268	268	274	32.4
	0.0309	0.000309	309		
	0.0245	0.000245	245		
M-600P-0-2	0.0303	0.000303	303	284	16.8
	0.0271	0.000271	271		
	0.0278	0.000278	278		
L-700-0	0.0302	0.000302	302	314	20.1
	0.0318	0.000318	318		
	0.0322	0.000322	322		
L-650-0	0.0315	0.000315	315	333	41.1
	0.0304	0.000304	304		
	0.0380	0.00038	380		
L-600-0-2	0.0281	0.000281	281	298	22.1
	0.0290	0.00029	290		
	0.0323	0.000323	323		
H-560-140	0.0316	0.000316	316	301	15.0
	0.0301	0.000301	301		
	0.0286	0.000286	286		
H-520-130	0.0284	0.000284	284	274.5	13.4
	0.0265	0.000265	265		
	-	-	-		
H-480-120-2	0.0277	0.000277	277	258	22.6
	0.0264	0.000264	264		
	0.0233	0.000233	233		

Table B.3: Compiled 28-day Shrinkage Test Results (Continued)

M-560-140	0.0322	0.000322	322	318	21.3
	0.0295	0.000295	295		
	0.0337	0.000337	337		
M-520-130	0.0296	0.000296	296	304	40.6
	0.0348	0.000348	348		
	0.0268	0.000268	268		
M-480-120-2	0.0271	0.000271	271	279	25.9
	0.0258	0.000258	258		
	0.0308	0.000308	308		
M-480P-120-2	0.0266	0.000266	266	287	25.9
	0.0279	0.000279	279		
	0.0316	0.000316	316		
L-560-140	0.0348	0.000348	348	347	25.5
	0.0321	0.000321	321		
	0.0372	0.000372	372		
L-520-130	0.0299	0.000299	299	318	18.5
	0.0336	0.000336	336		
	0.0319	0.000319	319		
L-480-120-2	0.0310	0.00031	310	304	35.4
	0.0336	0.000336	336		
	0.0266	0.000266	266		
H-420-180-2	0.0240	0.00024	240	246	17.8
	0.0266	0.000266	266		
	0.0232	0.000232	232		
M-420-180-2	0.0284	0.000284	284	292	11.4
	0.0287	0.000287	287		
	0.0305	0.000305	305		
M-420P-180-2	0.0288	0.000288	288	269	19.5
	0.0249	0.000249	249		
	0.0270	0.00027	270		
L-420-180-2	0.0330	0.00033	330	309	18.4
	0.0301	0.000301	301		
	0.0296	0.000296	296		