IMPACT OF CONCRETE MIXTURE DESIGN PARAMETERS ON EARLY AGE CHARACTERISTICS AND LONG TERM PERFORMANCE OF BRIDGES AND PAVEMENTS

by

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ABSTRACT

AUSTIN LUKAVSKY. Impact of Concrete Mixture Design Parameters on Early Age Characteristics and Long Term Performance of Bridges and Pavements. (Under the direction of DR. BRETT TEMPEST)

The North Carolina Department of Transportation (NCDOT) maintains databases with information on the mixture design proportions, early age test results, and information about bridges and pavement sections throughout the state. Recent initiatives are supporting the development of performance-based specifications using these databases by identifying characteristics in the mixture design associated with an impact of the long term performance of concrete mixtures. The focus is on creating durable concrete, with characteristics like resistance to cracking, abrasion, and environmental conditions. To accomplish this, the analysis performed as part of this work was broken up into two different approaches, one for bridge decks mixtures and one for pavement mixtures. For each side of the analysis, it was advantageous to get an understanding of what concrete is being made, then to figure out how it is doing, so that characteristics that promote better performance can be promoted in new specifications, while characteristics that negatively impact performance can be avoided. Statistical software was used to perform four different analysis types on the data: stepwise regression and canonical correlation for analyzing how differences in mixture design proportions impact how close the early age test results match their design values, and t-test and group differences to determine trends in the mixture design proportions for under-performing and over-performing bridge decks and pavement section over its natural, no-maintenance lifespan.

When examining construction tolerances, the majority of the mixes accepted and used to create both bridges and roadways meet the standards created by the NCDOT. Therefore, while examining trends on individual mixture design characteristics impact on the early age test results is valuable, the prescriptive specifications are sufficient to design concrete when only those initial test parameters are considered. When performing that stage of the study (the impact of mixture design characteristics on the early age test results), the correlation values for both the bridge deck and the pavement analysis were not large enough to signify any definite trends. For the bridge deck side of the analysis, increasing the design values of the early age variables (air content and slump) made the target value harder to reach. The results from the comparison of mixture design characteristics to long term performance of bridge decks displayed that over-performing bridge decks tended to use more fly ash (significant at 90% confidence) and water amount (significant at 95% confidence) than bridge decks that were considered as under-performing, possibly indicating that workability may be one of the most important factors to the durability and performance of concrete. The same comparison could not be properly for concrete pavement performed due to limitations in the data linking procedure leading to an insufficient amount of data to perform a full analysis. Several modifications to the data collection and storage process are recommended to allow for stronger conclusions. The results from this study support the importance of data-driven decision making regarding future changes in specifications. The number of bridge decks considered as under-performing outnumber the number considered as over-performing, even though the early age targets are being met, indicating that those test results are not adequate for predicting the performance of concrete over its lifetime.

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CHAPTER 1 INTRODUCTION

1.1 Introduction to Performance Engineered Mixture Design

In an effort to better understand the early age and field performance of North Carolina concrete mixtures, as well as improve the specifications to which they are designed, this research was undertaken to link mixture design parameters with early age test results and long term performance. Trends identified as part of this work will help to identify the most important parameters to control in performance engineered concrete specifications, which are of interest to NCDOT, as well as other transportation departments across the United States.

Concrete mixtures for transportation infrastructure, whether intended for use in pavements or bridge decks, are designed to withstand harsh environmental conditions as well as user wear from vehicular tires. While concrete provides a cost-effective, long term solution to be used as the base of roadways, it is not an eternally durable product. Per AASHTO’s LRFD Bridge Design Specifications, the prescribed life span of a bridge structure is 75 years, while in some cases it can be as high as 100 years (AASHTO 2018). The first edition of this guide was not released until 1997, and as such the bridges built before it follow the traditional NCDOT standard 50-year design life. Many of North Carolina’s bridges were built before the release of the AASHTO guide and are beginning to reach or exceed their initially expected 50-year lifespan. In the 2013 ASCE Report Card for North Carolina’s Infrastructure, it was reported that about 33% of the 18,169 bridges and culverts that are reported to the NBI are 50 years or older (ASCE 2013). The average age for the entire NBI is 39 years, alluding to the significant aging of the concrete infrastructure in North Carolina. In the 2016 Maintenance Operations and Performance Analysis Report (MOPAR), the NCDOT found that of the roughly 13,500 bridges in the state, 13% are labeled as structurally deficient (SD) in 2016 (NCDOT 2016). While this is a decrease from 2013, it still describes the current state of the bridge infrastructure. The breakdown of SD bridges by age is shown in Figure 1-1:

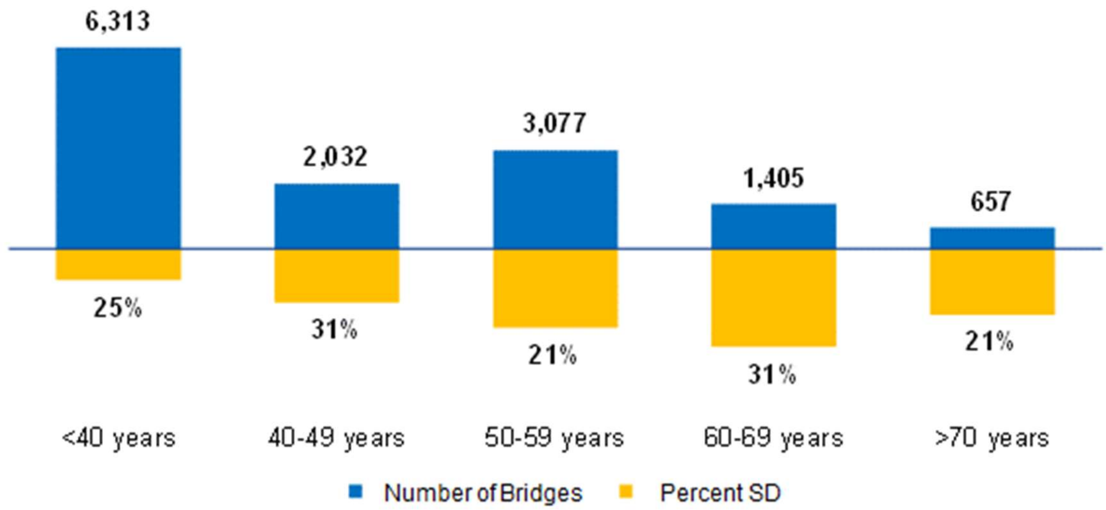

Figure 1-1: Structurally Deficient Bridges by Age (NCDOT 2016)

Mitigation of this deterioration and extend the service life of these structures requires a substantial amount of funding, which is difficult in a time where budgets are becoming increasingly stretched due to continuous new construction and increasing maintenance needs (Rodewald 2018). For the bridges in North Carolina, costs including maintenance, deficiencies investments, etc. add up very quickly. When compared to the annual budget, the amount required in these categories exceeds it by about $281 million (ASCE 2013). As such, taking more care in the early stages of a project, specifically in the mixture design, can help cut down on lifetime maintenance and replacement costs.

To improve the condition of the state's concrete infrastructure, as well as to reduce the need to spend money on maintenance costs over the life span of a bridge or pavement, new ways of specifying concrete mixtures are being considered. Current specifications mainly focus on three characteristics: slump, air content, and 28-day compressive strength. While these parameters have all proven to be useful methods and have historical data that justifies their use, many states are looking into the possibility of adding the element of durability performance-based specifications to the concrete mixture design approval and acceptance criteria. Recent advances in testing technology have allowed for the shift towards not only having early age data, but also performance data as qualifying factors in how a concrete mixture is designed and accepted. Taking advantage of this shift in technology, as well as identifying the appropriate performance tests and targets, will ensure that the NCDOT makes strides to improve.

While tests like surface resistivity can give good indication on how the concrete mixture will perform in a certain category (in this case, permeability and resistance to chemical penetration), one of the best indicators of how a concrete mixture will perform over years of use is through long term performance data gathered by inspectors. Linking the materials and mixture proportions as well as the early age test data to long term performance will help identify trends associated with poor, acceptable, and superior performance, providing NCDOT guidance for improving specifications and understanding the potential performance of concrete elements based upon initial mixture designs. It will also help reveal which components of a mixture and proportioning characteristics are the most important to the life span of the concrete.

1.2 Research Significance

Over the years, thousands of mixture designs have been approved by the NCDOT. While not all these mixtures have been used, each was designed with a specific application and construction considerations in mind. While there are recommendations on how to design a mixture to perform as required for a certain lifespan, there has not been a comprehensive study correlating long term performance of those mixtures to initial characteristics. Early age test data has been heavily relied upon for suggesting the long term performance.

The current NCDOT specifications used for concrete are based on years of experience and provide prescriptive limits on the amount and type of materials that should be used to make concrete that meets requirements. These strength-based prescriptive specifications often use more cementitious materials than necessary, and do not always provide the desired life span for the concrete (Taylor et al. 2014). As a result, the focus for concrete mixture design has shifted from prescriptive specifications to specifications based on how concrete has performed over its lifetime.

With the push toward performance-based specifications and the desire to find links between the mixture design and long-term performance, correctly identifying performance trends should allow for improved concrete mixtures. Establishing these trends and encouraging improvements in mixture design will help potentially increase the lifespan of concrete bridge elements and pavements, reduce maintenance costs, and allow for safer roadways.

Due to the advancements in technology (not only in testing methods but also in concrete constituents such as admixtures and fly ash) and the subsequent changes to the way that concrete is designed, the ability to understand the long-term performance of concrete will provide useful impacts on the design process.

1.3 Objectives

The objectives of the research presented in this thesis are the following:

1. Establish linkages between the various NCDOT databases utilized by NCDOT to store data on approved concrete mixtures, early age test results, and performance data. If warranted, provide recommendations for modifications to recordkeeping procedures for those datasets that will allow for improved utility of these databases in the future. This should allow for the following sequence of actions to be performed:

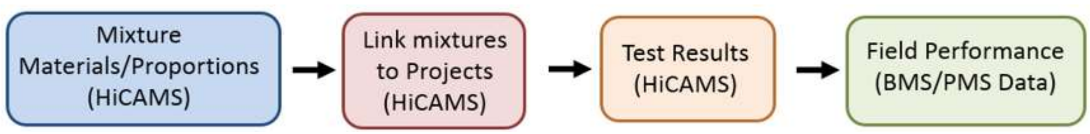

Figure 1-2: Potential Data Linking Sequence

2. Perform analysis to determine how the mixture design proportions impact the ability to meet required early age testing targets.
3. Identify the characteristics of mixtures that can be associated with different field performance. Some materials, proportions, and other characteristics may have more impact on the long term performance than others.
4. Provide recommendations for the modification of concrete mixtures based on the mixture parameters that tend to have an impact on the long term performance of those mixtures.

1.4 Organization of Thesis

This thesis consists of 8 chapters. The first chapter introduces to the topic of performance engineered mixture design, as well as presents why this is an important initiative to improve concrete infrastructure. The second chapter is a literature review that describes important characteristics of durable concrete, from its performance requirements to the components used for the concrete themselves. The third chapter describes the databases utilized by NCDOT for storing mixture designs, early age test results, and performance information, and the process of combining them for use in this study. Because the long term performance analysis required further manipulation beyond the initial combining of the databases, as well as the introduction of deterioration models, these additional considerations are outlined in the fourth chapter. The fifth chapter outlines the specific parameters used for the models. The results are broken down into two chapters, with Chapter 6 focusing on the analysis of bridge data and Chapter 7 focusing on the analysis of pavement data. The eighth and final chapter provides the main conclusions from the data analysis, as well as recommendations for considerations in the design of concrete mixtures and for the gathering and storing of data for use in future versions of a study similar to this one.

1.5 Additional Information

The research performed for this thesis was performed as part of a larger project commissioned by the NCDOT, with the end goal of improving specifications for concrete mixture design. The other part of this project includes a field and a lab component, aimed at modifying the overall testing requirements for concrete early age data. The combination of the work performed for this thesis, along with the findings of the laboratory and field components will facilitate the development of a “roadmap” towards performance-engineered concrete specifications.

CHAPTER 2 LITERATURE REVIEW

2.1 Performance Requirements for Durable Concrete

Concrete, as a general rule, has proven itself to be a durable, useful, cost efficient material in the construction industry. Because of this, it is the standard material not only for many roadways and bridges, but also in residential and commercial construction. As a well-designed concrete mixture can have a long service life, it lends itself well to the transportation industry, where large scale and frequent replacements are not desirable. In order to retain strength, stability, and safety, concrete must be able to withstand a plethora of performance requirements. According to Bryant Mather in the 2013 Transportation Research Board (TRB) Durability Circular publication, "Durable concrete is that which resists the forces in that environment that tend to cause it to deteriorate prematurely without requiring excessive effort for maintenance" (Mather 2013).

2.1.1 Resistance to Cracking

Visible cracking occurs in concrete when the applied tensile pressure from a variety of sources exceeds the tensile strength of the concrete. While there are several different reasons why concrete may crack, these reasons are be sorted into three categories: mechanical loading, volumetric stability, and environmental loading and durability (Transportation Research Board 2006).

Over time, concrete will inevitably crack. As a result, there are methods that allow this issue to be addressed in a way that the life of the structure is not compromised. Correct material selection and proportioning, as well as proper construction practices, can lead to a reduced likelihood or amount of cracking, therefore leading to more durable concrete.

2.1.1.1 Mechanical Loading

Under the mechanical loading category, micro-cracking occurs immediately after sufficient loading is applied. If the bond between the aggregates and the cement paste is not strong enough, or the load is too high, these cracks will get larger and localize until they form larger, visible cracking. Cyclic loading, or fatigue, is the second contributed to mechanical loading failure. Progressive cracking occurring each time the concrete is loaded and unloaded builds on each other until the cracks become visible.

2.1.1.2 Volumetric Stability

Volumetric stability includes cracking from settlement and shrinkage, as well as from temperature differentials during curing. *Settlement cracking* occurs as freshly mixed concrete settles and encounters restraint. Plastic settlement cracking occurs most commonly occurs at changes in cross section, and has been observed to occur in the construction of reinforced slab and bridge decks. Uniform settlement does not cause plastic cracking (as no tensile force is built up in the concrete), but differential settlement can lead to cracking. In research performed by Weyers et al. it was determined that clear cover depth, as well as rebar size and spacing, are the major contributors to differential cracking (Weyers et al. 1982). Larger bars (and as a result, greater spacing) and smaller cover amount lead to larger cracking.

Shrinkage occurs both in fresh concrete as well as in hardened concrete. In fresh concrete, cracking can occur within a few hours of placement. High capillary stress development near the surface is caused when the bleeding rate is exceeded by the surface evaporation rate (Cohen et al. 1989) as a result of factors such as high temperatures, high winds, low ambient humidity, and mixture design (ACI 1999). As the amount of shrinkage is directly related to the amount of water loss, the higher the evaporation the more cracking occurs. The relationship between shrinkage over time and curing conditions in normal strength concrete (Holt and Leivo 2000) are shown in the flowing graph:

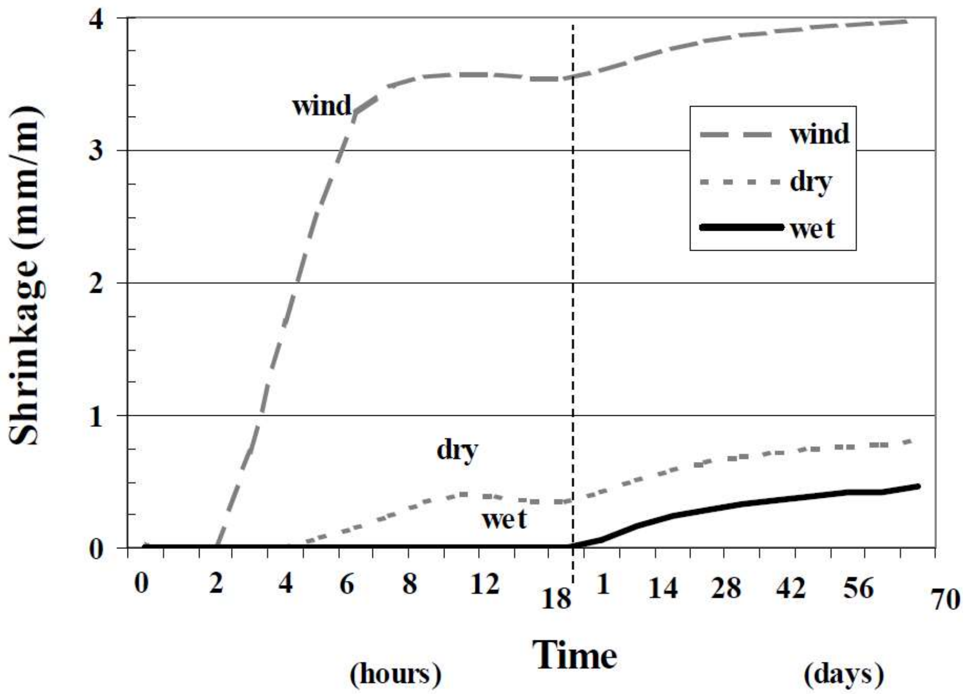

Figure 2-1: Combined Early Age and Long-term Shrinkage for Three Different Curing Conditions (Holt and Leivo 2000)

Autogenous shrinkage typically occurs when the water-to-cementitious materials (*w/cm*) ratio is below 0.42, and there is no loss of moisture (otherwise it could be considered as drying shrinkage). This type of shrinkage has been linked to several factors, and is known to occur at higher rates with higher temperatures, cement fineness, and cement content (ElSafty and Abel-Mohti 2013). Cracking in hardened concrete can result from the internal stress built up over time. If there is restraint on the free movement of concrete (the most common condition for concrete, particularly reinforced concrete, to exist in), cracking resulting from dying shrinkage is a concern. The amount of drying shrinkage that occurs is also related to aggregate type, as well as the cement paste content in the concrete (ElSafty and Abel-Mohti 2013). Using methods such as contraction joints and shrinkage-compensating admixtures can help prevent drying shrinkage for being a durability concern.

Temperature differences in concrete lead to tensile stresses, which in turn can lead to cracking. This *thermal cracking* can be reduced by controlling the rate at which the concrete cools, increasing the early age tensile strength, and reducing the maximum internal core temperature (ElSafty and Abel-Mohti 2013). This is primarily an issue in the first few days of the concrete's lifespan, as that is when the most changes in temperature occur.

2.1.1.3 Environmental Loading and Durability

The environmental loading factor of freezing and thawing is a major concern for concrete transportation structures, as this can cause internal cracking. The hydraulic pressure created by the pore water freezing (and thus expanding) and thawing can damage the concrete from the interior.

Corrosion in concrete occurs when chlorides, whether from the environment or from other sources (such as deicing salts), penetrate through the concrete and react with the reinforcing steel. Corrosion products are expansive, and cause tensile pressure within the concrete around the reinforcing steel. The corrosion threshold for typical reinforcing steel ranges from 1-2 lb/yd^3 (0.6 – 1.2 kg/m^3) (Linquist et al. 2006). In order to maintain concentrations of less than this amount, the concrete must be able to resist the ingress of chloride.

Research performed in Kansas found that typical salt applications for the state included a 23% NaCl salt brine solution, applied to bridge decks when frost is expected and the temperature existing between 15 to 32 °F. This is the same solution used on North Carolina bridges during similar storm conditions. Lindquist et al. found that in un-cracked concrete, even after 12 years, the chloride content at a depth of 3.0 inches (76 mm) was less than the low end of the allowable amount. At cracks however, at the same depth of 3.0 inches, the average chloride concentration exceeded the threshold for reinforcement, no matter the deck type.

Low concrete permeability aids in keeping chlorides from ingressing into the concrete. Reducing the water to cementitious ratio (*w/cm*) also leads to lower concrete permeability (Peyton et al. 2012). The current standard method for determining concrete permeability is the rapid chloride permeability test (RCPT), but due to the length of time needed to perform this test (over a day from start to finish), different approaches are being examined. This had led to the development of the surface resistivity test.

2.1.2 Resistance to Deleterious Substances

Durable concrete must have adequate resistance to deleterious substances in order to be considered useable on a project. A deleterious substance is any material in the aggregate that will be detrimental to the concrete. According to ASTM C33, this material list includes the following: clay lumps, friable particles, chert (SSD specific gravity less than 2.40), material finer than 75 µm (No. 200) sieve, and coal and lignite.

- Clay lumps are anything from fine-sand sized particles to larger lumps of clay. These particles experience breakdown with the freezing and thawing, as well as during the wetting and drying of the concrete they are embedded in. When these clay lumps weather away, it can leave pockets and pop-outs on the surface of the concrete (Forster 2006).
- Friable particles are the aggregate pieces with low bonding strength between the grains of that aggregate, such as sandstone. The breakdown of these particles can lead to more fines in the concrete, which can cause freeze-thaw damage if it occurs after the concrete is in place. Friable particles at the surface detract from the abrasion resistance, and can leave pockets on the surface of the concrete (Forster 2006).
- Chert particles with SSD specific gravity of 2.40 are susceptible to frost and can result in the concrete cracking.
- Material finer than the 75 μm sieve are generally known as silt and clay, while this list can also include dust from the fracturing of the aggregates. These fines become an issue as they are intermixed with the large aggregate, leading to an excessive amount of fine aggregate in the mix. This then leads to a larger water demand, which can cause drying shrinkage due to the lack of water.
- Coal and lignite, while usually associated with shale (not commonly used in concrete), can also be associated with other rock types. These organic materials can reduce the concrete strength, create pits in the surface of the concrete, and can cause staining on the surface.

The NCDOT has specifications for the maximum amount of these deleterious substances. For fine aggregates, the amount must not exceed 2.0% by weight for natural sand or 1.0% by weight for manufactured sand. For coarse aggregate, the amount must not exceed 3.2% by weight (NCDOT 2018).

2.1.3 Strength

Strength of concrete is its ability to resist rupture under an applied load. This strength comes from the bond between the paste (cementitious materials and water) to the aggregates. The specified strength type is different based on the project type, with construction projects indexing the design to compressive strength, while flexural strength tends to be a more necessary characteristic in pavement mixtures. In order to determine the compressive strength, a set of cylinders (in many cases, 3 cylinders, but this is dependent on the project) are created for the mixture, cured for a desirable number of days, and then loaded in compression until failure. An average of the compressive strengths becomes the known strength of the mix. This average strength must either equal or exceed the required strength for the project. Specifications for compressive strength often utilize an age of 28 days for acceptance testing, although other ages such as 7 days or 56 days are commonly utilized depending on the concrete mixture type and construction objectives.

Careful control of the strength capacity of a concrete mixture to ensure it does not excessively exceed the required strength is important. Excess compressive strength is not always a positive thing, as this typically comes from an increased cement content. For monolithic bridge decks, crack densities have been shown to rise 0.16-0.49 m/m^2 as compressive strength increased from 31-45 MPA (4500-6500 psi) (Darwin et al. 2004).

This increased likelihood of cracking stems from higher shrinkage (drying, autogenous, and plastic) in high paste content concrete. Higher compressive strengths can also lead to higher tensile strengths, increasing the changes that the reinforcement yields, as well as a higher modulus of elasticity, causing additional internal restraint (Frosch et al. 2003). Increases in the cement content also results in higher heat of hydration and increased risk of thermal cracking, as well as lower creep (Wright et al. 2014). An increase in strength does have a positive effect on abrasion resistance, as the two are positively related (Papenfus 2003).

2.1.4 Abrasion Resistance

For concrete mixtures to be used in a roadway situation, abrasion from car tires is an important factor when considering the durability of a mix. The abrasion resistance of concrete is defined as "the ability of a surface to resist being worn away by rubbing and friction" (ACI 2000). The ability of the concrete to resist this wearing comes from several factors: compressive strength, aggregate properties, surface finishing, curing, and use of surface hardness or toppings (Hadchiti and Carrasquillo 1988). Concrete with higher workability will often have lower abrasion resistance, so a relatively low water to cement ratio at the top of the concrete is the best possible situation. This can be achieved by using water reducing admixtures, taking steps to prevent bleeding, or avoiding the addition of water while finishing. Proper curing procedures are also necessary. In cases where water curing may not be practical, curing compounds that seal moisture in the concrete can be used (ACI 2001). As the compressive strength of concrete is the most important factor to the abrasion resistance, air entrainment (which reduces the compressive strength) decreases the abrasion resistance of the concrete. Any finishing that will be done on the concrete should be done after bleedwater has evaporated, as applying it before would decrease the strength of the upper layer.

2.2 Characteristics of Durable Concrete

Beyond the specifications for how durable concrete must perform, there are several qualifications for the mixture design of the concrete itself, from the proportioning to the materials themselves. Creating standards in these categories, and following the guidelines for each, allows for the production of uniform concrete. As testing procedures are created assuming compliance with the requirements, different concrete mixtures can be compared using the same standards.

2.2.1 Materials

Concrete is comprised of several individual components: cement and other supplementary cementitious materials (SCMs), aggregates (both fine and coarse), water, and other admixtures or compounds that will be added to help the concrete perform in a certain way. Information about and specifications for those components as they should exist to contribute fully to durable concrete are detailed in this section.

2.2.1.1 Cement

Cement is a fine powder that, when mixed with water, creates the paste that binds the aggregates together in concrete. The properties of cement that have the highest influence on durability performance are its chemical composition, particle size distribution, and reaction kinetics (and the consequential improvement of concrete strength resulting from these reactions).

Portland cement, a combination of tricalcium silicate ($3CaO*SiO_2$) and dicalcium silicate ($2CaO*SiO_2$) primarily (as well as tricalcium aluminate ($3CaO*Al_2O_3$) and tetracalcium aluminoferrite ($4CaO*Al_2O_3*Fe_2O_3$)), is a hydraulic compound that reacts with water to produce a paste that binds the solid components of the concrete together. This reaction forms two compounds, calcium hydroxide ($Ca(OH)_2$) and calcium silicate hydrate (H_2CaO_4Si, or as it is more commonly written, C-S-H). Calcium hydroxide helps lead to the potentially higher pH of the concrete pore fluids, increasing chemical durability (Dyer 2014). C-S-H makes up the largest portion of hardened Portland cement and is the largest contributor to the strength and stiffness of the concrete.

The particle size depends on the required strength class. The finer the particle size distribution, the faster the reaction occurs. Typical mean particle size is 20 µm.

There are six different types of Portland cement, based on their required use.

- Type I cement is for general purpose concrete
- Type II (MS) cement, which limits the amount of C_3A to help combat sulfate attack
- Type II (MH) cement, which limits the heat of hydration, and is intended for use in more massive elements
- Type III cement, which is used when high early strength is required, and if useful for precasting with high turnaround rates
- Type IV cement, which has a low rate and amount of heat generated
- Type V, which is more restrictive than Type II in C_3A amount to provide higher resistance to sulfate attack

2.2.1.2 Supplementary Cementitious Materials (SCM)

In addition to using cement to create the paste to bind the aggregates, several different SCMs (also known as pozzolans) can be used. These materials can not only aid in the binding process, but have also been linked to several performance benefits. The main three (fly ash, ground granulated blast-furnace slag, and silica fume) will be discussed in this section.

In general, the SCM's improve the workability of the concrete. Certain ones, such as silica fume, may contribute to a more rigid concrete during construction (and as a result, decrease the workability), so adjustments must be made to the mixture design to combat this. Concretes using fly ash and/or silica fume have been shown to have less bleeding and segregation than mixtures without, but concrete using ground slag tends to have higher bleeding (with no effect to the segregation) (Kosmatka et al. 2002). Other benefits include potential reduction of heat of hydration and improved finishability.

Alkali silica reaction (ASR) is a major concern when considering durability of concrete. The predominant source of alkalis in concrete is from the Portland cement. When those alkalis react with the silica present in the aggregates, the reaction product is a gel that can swell with the addition of water. This swelling causes cracking in concrete, allowing the ingress of more water, repeating the process. In order for a SCM to be helpful in ASR remediation (as they are well known to be useful for), it must meet a certain minimum amount. Those amounts are shown in Table 2-1.

Table 2-1: Range of Minimum Replacement Levels Required for Different Supplementary Cementing Materials to Control Expansion due to ASR (Page and Page 2007)

Type of SCM	Level required (%)
Low-calcium fly ash (< 8% CaO)	20 to 30
Moderate-calcium fly ash (8–20% CaO)	25 to 35
High-calcium fly ash (> 20% CaO)	40 to 60
Silica fume	8 to 12
Slag	35 to 65
Metakaolin (calcined kaolin clay)	10 to 20

2.2.1.2.1 Ground Granulated Blast-furnace Slag (GGBS)

In order to remove the silicon, magnesium, and aluminum impurities present in iron ore in the production of iron metal, limestone is added to the blast furnace. Blast-furnace slag is a coproduct of this addition, and floats to the top of the molten iron. After being cooled, the slag is then ground up to produce GGBS.

While it is not a specific hydraulic material, GGBS undergoes a "latent hydraulic reaction," meaning it reacts with water to produce C-S-H gel but only with exposure to high pH conditions. As such, the presence of Portland cement is necessary to activate the GGBS. While the initial reaction is slower than Portland cement, at 28 days the strength is typically comparable.

One of the largest benefits that comes from GGBS is an increased resistance to sulfate attack. The use of slag cement decreases the C_3A content while also decreasing the permeability of the concrete. In concrete using a slag cement content of greater than 60-65%, research has proven that high sulfate resistance was present (ASCE 2018). However, the alumina content of the slag cement must be known, as higher alumina content can adversely affect the sulfate resistance.

GGBS can also help prevent the expansion caused by alkali-silica reaction. Slag cement achieves this by reducing the total alkalis present while also consuming some in the reaction, leaving less to be able to react with the aggregates. For concrete with highly reactive aggregates, higher amounts of GGBS may be needed.

2.2.1.2.2 Fly Ash

During the processes of burning coal, clays and other inorganic material present within the coal are melted, then solidify as they are cooled by the exhaust fumes of the coal plant. This creates fine, hollow, fine, spherical particles which are trapped before they can disperse into the atmosphere.

Fly ash is made primarily of silicate glass containing silica, calcium, iron, and alumina. Crystalline compounds can also be present, as well as minor constituents such as sulfur, sodium, magnesium, potassium, and carbon.

Fly ash to be used in concrete must conform to the specifications in AASHTO M 295 and ASTM C618. For general use purposes, Class F and Class C are the most common types of fly ash, with Class F typically having more carbon content than Class C. Siliceous fly ash results in a pozzolanic reaction with CH, with C-S-H gel and calcium aluminate hydrates as the result.

Fly ash requires less water than concrete using only Portland cement, allowing for increased workability, as well as lower *w/cm* ratio which increases the strength. However, depending on the fly ash, sometimes it can increase the water demand by up to 5% (Gebler and Klieger 1986).

One of the most documented benefits of fly ash is its ability to reduce the impact of the alkali-silica reaction. Fly ash helps combat this by reducing the alkalinity of the pore solution through alkali binding, and also increases the amount of CSH produced (Shafaatian 2012).

2.2.1.2.3 Silica Fume

Silica fume is the byproduct of the production of silicon or ferrosilicon alloy. In the reduction process of high-purity quartz with coal in an electric arc furnace, silica fume rises as an oxidized vapor from the 2000°C furnace. When it cools, it is condensed and processed to ensure controlled particle size. The particles are spherical like fly ash and are extremely fine with an average diameter of 0.1 µm, about 100 times smaller than cement particles.

2.2.1.3 Aggregates

The bulk of the strength of the concrete comes from the aggregates, which comprise roughly 60% to 80% of the volume of the mixture. Naturally occurring aggregates include rocks and minerals. The weathering of rocks produces the stone, gravel, sand, silt, and clay used in concrete. The nature of the particles and the grading of the aggregates in concrete influence the workability of fresh concrete, as well as their impact on the strength and durability of the hardened concrete.

The characteristics of the particles, which includes shape, surface type, and porosity, affect how the bond between the concrete paste and the aggregates themselves, as well as the mixture proportions. For example, rounded aggregates require less water than more angular course aggregate for equal slump (Mamlouk and Zaniekwsi 2011).

Deleterious chemical reactions between certain susceptible aggregates to the paste is another important consideration in durable concrete. The most common reaction, alkali-silica reaction (ASR), occurs between the OH^- ion associated with the alkalis

(Na_2O and K_2O) from the cement and the siliceous content present in aggregates. The gel formed in the concrete by this reaction promotes cracking, leading to higher permeability. Careful selection of non-reactive aggregates, as well as remediation methods such as using fly ash when use of reactive aggregates cannot be avoided, are important to ensure that ASR does not become a durability issue.

2.2.1.4 Other Materials

Various chemical admixtures may be used to increase the durability of concrete. Water-reducing admixtures and superplasticizers lower the water content, and as a result to *w/cm* ratio, which results in lower permeability to potentially dangerous elements. Corrosion inhibitors improve corrosion resistance from chloride by reducing the corrosion rate, but caution must be used since these have only been tested over short-term, which can be misleading (Berke et al. 1997). Air-entraining mixtures improve the freeze-thaw resistance of concrete. Shrinkage-reducing admixtures reduce drying shrinkage in restrained concrete (Nmai and Kraus 1994).

2.2.2 Proportions

Proportion control of the materials used to make concrete is an important step to ensure that the most economical and practical mixture is batched, with the desire to fulfill the requirements of the project for which it will be used. According to ACI 211.1, the following is the basic structure that is followed when determining the proportions for a mixture (ACI 2009):

- Choose a slump
- Choose a maximum aggregate size
- Estimation of mixing water and air content

- Selection of water-cement or water-cementitious materials ratio
- Calculation of cement content
- Estimation of coarse aggregate content
- Estimation of fine aggregate content
- Adjustment for aggregate moisture

These steps are a basic guideline to designing a mixture. Specific information about several of these steps, as well as details about their importance, is provided in the sections that follow.

2.2.2.1 Water to Cementitious Materials Ratio (*w/cm*)

Simply put, the *w/cm* ratio is the mass of the water in the mixture divided by the mass of the cementitious material. The use of this ratio in relation to determining the strength of the concrete was recognized in about 1918 by Duff Abrams. Table 2-2 is a table included in ACI 211.1 comparing the relationship between *w/cm* to compressive strength of concrete.

Table 2-2: Relationship Between Water-Cement or Water-Cementitious Materials Ratio and Compressive Strength of Concrete (ACI 2009)

Compressive strength at 28 days, psi	Water-cement ratio, by weight	
	Non-air-entrained concrete	Air-entrained concrete
6000	0.41	-
5000	0.48	0.40
4000	0.57	0.48
3000	0.68	0.59
2000	0.82	0.74

2.2.2.2 Aggregates

The two major components of aggregates that are important in terms of proportioning are the gradation (particle size distribution) and the nature of the particles (shape, porosity, surface texture), as both play a major role in the workability of the fresh concrete and the strength of the hardened concrete (Ramakrishnan 2013).

Proper (optimized) gradation leads to economical mixtures, as less water and cementitious material are required to fill inter-aggregate spaces. Using larger aggregates reduces the required amount of paste and can help decrease shrinkage, but there are also limits on how large the aggregates can be based upon construction considerations such as minimal spacing between reinforcing bars. Ensuring consistent gradation will keep uniformity between mixtures on a project, which can help ensure the concrete performs as intended.

Gradation of the aggregates also has a strong influence on the workability of the concrete. The maximum aggregate size should not exceed three-fourths of the clear space between reinforcing rods/wire, prestressing tendons, or sets of bars. It should also not exceed one-fifth of the minimum distance between the sides of the forms (Ramakrishnan 2013). This allows to concrete to flow through the forms without concern of clogging around the reinforcing material. For fine aggregate, the grading depends on the work, the richness of the mixture, and the size of the coarse aggregate.

ACI 211.1 provides guidelines for how much coarse aggregate is to be used, as shown in Table 2-3:

Table 2-3: Volume of Coarse Aggregate Per Unit Volume of Concrete (ACI 2009)

Nominal Maximum Size of Aggregate, mm	Volume of Dry-Rodded Coarse Aggregate* per Unit Volume of Concrete for Different Fineness Moduli of Fine Aggregate			
	2.40	2.60	2.80	3.00
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76

*Volumes are based on aggregates in oven-dry-rodded conditions as described in ASTM C29

2.2.2.3 Entrained Air

For concrete exposed to deicing chemicals as well as freeze thaw cycles, entrained air must be used to allow for durability, as well as improves the workability of the concrete. Air entrainment can be controlled by using air-entrained Portland cement or by adding air-entraining admixtures. North Carolina standards dictate that an air content of 5.0% plus or minus 1.5% in freshly mixed concrete (NCDOT 2018). The recommended amount of air content is dependent on the maximum aggregate size, as well as the exposure level of the concrete. These recommended air content values are shown in Table 2-4.

Table 2-4: Approximate Air Content Requirements for Different Levels of Exposure (ACI 2009)

	Air Content (%)							
Max. size (mm)	9.5	12.5	19	25	37.5	50	75	150
Mild Exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate Exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe Exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

2.2.2.4 Water Content

The water demand of a mixture is determined by a range of conditions: the *w/cm* ratio, the size, gradation, and shape of the aggregates, the air content, slump, any admixtures, etc. Factors like increasing air content and using water-reducing admixtures can decrease the overall water need, while increasing the cement content or slump increase the water required for the mixture (Kosmatka 2013). The project requirements, as well as the available materials for achieving it will be the baseline for determining the amount of water needed for the mix.

2.2.2.5 Cementitious Materials Content

The overall cementitious materials content required for the mixture is determined by the *w/cm* ratio and the water content. Depending on exposure conditions and other factors, a minimum cementitious materials amount may be required. Proportioning should, in general, seek to limit the amount of cementitious material used, as this makes the mixture more economical (cementitious materials are often the costliest base component of the mixture). This can be achieved by using any of the following, or a combination of: the stiffest possible mixture, the largest nominal aggregate size allowed, the optimum fine-coarse aggregate ratio, and a uniform distribution of aggregate (Kosmatka 2013). Pozzolans and slag can be proportioned into the cementitious materials content depending on the requirements for the final concrete product.

Table 1000-1 in the NCDOT Standard Specifications includes the following ranges of required values for cement content, based on the mixture type. A condensed version of those requirements are listed in Table 2-5.

Table 2-5: Range of Required Cement Contents for Different Mixture Types (NCDOT 2018)

Class of Concrete	Minimum (lb/cy)	Maximum (lb/cy)
AA	639	715
AA-Slip Form	639	715
A	564	677
Latex Modified	658	658
Pavement	526	-
Prestress	564	-

2.2.3 Construction

Construction techniques can be the difference between a mixture performing as it should or should not, as a design on paper is only as good as it is made in the field. There are several steps a mixture goes through, starting from batching at the concrete plant to final finishing and curing. Ensuring proper care in each of these steps will allow for the concrete to be as durable as possible.

During batching, all the individual constituents of the concrete mixture are measured out as specified by the selected mixture design. The facility that houses this process must be designed to maintain the integrity of the mixing process, with any devices being used to weigh or measure by mass or volume being checked regularly to ensure accuracy. Aggregate stockpiling at the plant must be done in a way that it is able to maintain uniform gradation and moisture content, as this will prevent aggregate contamination and allow for consistent concrete. Knowledge of the moisture content of the aggregates is vital to the batching process, as it influences how much water needs to be added or removed from the mixture design.

Proper concrete mixing ensures that the final product is a homogenous blend of the materials used. The mixing duration must be long enough to produce a proper blend as well as for the development of the air-void system. The sequence of loading materials into the mixer, as well as the efficiency of the mixer itself are the factors that affect the performing of the mixing operation. ASTM C94 outlines the proper mixing procedure to ensure uniform concrete production.

Transportation to the site is the next factor to affect the concrete's field performance. Transportation from the mixer should be done with minimal impact to the original design conditions (such as slump, *w/cm* ratio, air content, etc.). Different drum colors can help with this, as darker colors can help retain solar energy in colder regions and light colors can help prevent excess heat gain in warmer regions (Lane 2013).

Guidelines for proper concrete placement are outlined in ACI 304R, 304.1R, 304.2R, 304.4R, and 304.5R. Avoiding segregation between the coarse aggregate and the mortar is necessary, and any mixtures that will be pumped into place must have the air content change taken into account during the design phase. Proper consolidation helps remove excess voids in the concrete and increases its durability. Guidance on consolidation can be found in ACI 309R.

Finishing and curing are the final steps in the construction process. Finishing should be performed with as little manipulation as possible, as overworking the concrete surface may reduce the surface air content and cause fine aggregates to rise to the top, increasing the cracking potential. Saw cutting of the groves and joints should be delayed until the concrete is strong enough to prevent coarse aggregate movement. Curing helps maintain proper temperature and moisture conditions in the concrete and help prevent the development of excessive volumetric stresses.

2.3 Linking Material Characteristics and Early Age Test Data to Field Performance

The need for advances in predicting the long term performance of a mixture design has prompted several states to direct funds to research projects on creating performance related standards as well as performance prediction modeling. In this section, approaches for that modeling will be presented, along with information on what is needed to create these models.

2.3.1 Types of Variables

Within the datasets used for this study, there are many different variables available. These include (but are not limited to) the following:

- Materials used in the mixture design, and the respective amounts of each
- Particular material types (for example, different types of pozzolans)
- Names of suppliers of mixture materials
- Early age test results, such as air content, slump, compressive strength, and/or flexural strength
- Measurements of either the bridge deck or the pavement section, such as length, width, etc.
- Information about the location, structure type, and main material type of bridges
- Information about the location, age, and rating of pavement sections

Any variables used in the modeling process can be divided into different types. *Continuous* (also known as *interval* or *quantitative*) variables take on any value within the range, as they are measured on a smooth scale rather than a stepping scale. The precision of the data is limited to the measuring equipment, not the method of collecting it. Variables in the mixture design data set that fit this category include cement content, aggregate content, and others.

Discrete variables can be numbers or labeled as numbers, but there is no smooth transition from category to category or value to value. They can also denote or describe non-numeric *qualitative* values, such as material type, bridge system, superstructure type, etc. (all categories in the BMS Network Master).

The distinction between continuous and discrete variables is not always apparent, especially in cases were the difference between discrete values is small and where the continuous variables are cut at certain limits (Tabachnick and Fidell 2007).

2.3.2 Types of Models

The goal of the modeling process in this study is to determine relationships between variables, whether it be the individual components of the mixture design to the long term performance inspection values or the amount of impact fly ash has on slump or anything in between. Therefore, modeling procedures that compare these individual variables, or fields, are the most valuable to this research. Using the modeling decision tree in Tabachnick's "Using Mutlivariate Statistics", the first modeling type to be used in canonical correlation, which shows the relationship between large sets of variables. Regression modeling can then be used to get more specific on the impact of a single field.

2.3.3 Identification of Significant Predictor Variables

Due to the number of variables present in the mixture design and early age data sets, determining the significant predictor variables, and their individual weights of importance, is necessary for the overall analysis of the data. To do this, *Canonical Correlation* can be used to find the relationship between sets of data.

Canonical correlation is a method for determining the relationship between two sets of variables. In this technique, if one set is known to be the predictor or independent set, and the other is known to be the criterion or dependent set, then the goal is to determine how the first effects the second.

Consider the following two equations:

$$W_1 = a_{11}X_1 + a_{12}X_2 + \cdots + a_{1p}X_p \tag{2.1}$$

$$V_1 = b_{11}Y_1 + b_{12}Y_2 + \cdots + b_{1p}Y_p \tag{2.2}$$

Where: W_1 = Linear combination of the *X* variables

V_1 = Linear combination of the *Y* variables

C_1 = The correlation between W_1 and V_1 (canonical correlation)

The goal of the two sets of equations is to find the values for a_{11} , $a_{12}, \ldots, a_{1p}$ and b_{11} , $b_{12}, \ldots, b_{1p}$ such that C_1 exists at its maximum value.

This step is then repeated for W_2 and V_2, and so on and so forth until W_m and V_m. In summary, the objective of canonical correlation is to identify the *m* set of canonical variates, (W_1 , V_1), (W_2 , V_2),… (W_m , V_m) such that the corresponding canonical correlations, C_1 , C_2 , … ,C_m are maximized (Sharma 1996).

The next step is determining the statistical significance of the canonical correlations. The null and alternative hypotheses for assessing this significance are:

$$H_o: C_1 = C_2 = \cdots = C_m = 0 \qquad (2.3)$$

$$H_a: C_1 \neq C_2 \neq \cdots \neq C_m \neq 0 \qquad (2.4)$$

To test this hypothesis (the null states that all canonical correlations are equal to zero), a number of test statistics can be used. However refined the final values from the canonical correlation are, they not useful unless they can be practically interpreted. This is a common issue associated with use of this method. The results have been described as "…often mathematically elegant but uninterpretable" (Tabachnick and Fidell 2007), which makes them difficult for inclusion in this study. Because of this, the results procured from the data while using this method are not the most directly useful.

While it is a very useful process and can be done by hand, the number of computations lead it to be impractical to be completed by hand. Several software packages are available that can perform canonical correlation, such as SAS, SPSS, MATLAB, and SYSTAT. Since most books use the SAS® software package, that one will be used for this research.

2.3.4 Regression Analysis

Regression analysis is the use of statistical methods to determine the relationship between a dependent variable and several corresponding independent variables. If such a relationship exists, mathematical models can be used to find it. For a simple linear regression model, only one independent variable exists, meaning that the dependent variable changes at a constant rate as the independent variable changes. This can be shown as the equation of a straight line. Ideally, this line will "fit" the data in the scatter plot, but not everything will fall perfectly on said line. To demonstrate this, the sample coefficient of determination R^2 is used. R^2 indicates how well the equation fits the data, and ranges in value from 0 to 1 (with higher values indicating a better fit) (Dowdy et al. 2004).

$$Y' = A + BX \tag{2.5}$$

Where: Y' = Predicted value (dependent variable)

A = The value of Y when X is equal to zero

B = The slope of the best-fit line

X = Value from which Y' is predicted (independent variable)

In order to solve for the equation, values for both A and B must be determined. B is the bivariate regression coefficient, and is the ratio of the covariance of the variables (X and Y) and the variance of the one from which predictions are made (X), as well as the slope of the best fit line (Tabachnick and Fidell 2007). Once B has been determined using equation 2.6, the value of the x-intercept, A, can be found using equation 2.7

$$B = \frac{N\sum XY - (\sum X)(\sum Y)}{N\sum X^2 - (\sum X)^2} \tag{2.6}$$

Where: B = Bivariate regression coefficient

X = Independent variable

Y = Dependent variable

$$A = \bar{Y} - B\bar{X} \quad (2.7)$$

Where: A = X-intercept

X = Mean of the predicted variable

Y = Mean of the predictor variable

Multiple regression is an extension of the principles of simple linear regression, with the largest difference being the use of multiple independent variables instead of just one. Instead of one single bivariate regression coefficient, each independent variable has their own, in an effort to cause Y to be as accurate as possible. As such, the regression equation looks like the following:

$$Y' = A + B_1X_1 + B_2X_2 + \cdots + B_kX_k \quad (2.8)$$

Where: Y' = Predicted value (dependent variable)

A = The value of Y when all X values equal zero

B_n = Regression coefficient for the n-th variable

X_n = n-th independent variable

k = Number of independent variables

With an inflated number of variables, the relationship between the individual variables can cause portions of the equation to become redundant. This is known as multicollinearity, where one or more of the independent variables are highly correlated with each other. If not addressed, multicollinearlity is problematic in the final model because these variables represent redundant information and are not all needed. If left in the final model, they will inflate the size of the error terms, and can weaken the analysis (Tabachnick and Fidell 2007). To measure the scale of the impact of multicollinearity, a variance inflation factor (VIF) should be computed for each independent variable during the regression analysis. VIF is calculated using the following equation:

$$VIF_j = \frac{1}{1 - R_j^2} \qquad (2.9)$$

Where: VIF_j = Variance Inflation Factor (for variable j)

R^2_j = Coefficient of Determination (for variable j)

In this equation, the coefficient of determination (R^2) is determined from the regression of each independent variable on the other independent variables that are being tested (Rawlings et al. 1998). Variables that show high correlation with other variables included in the model must be removed one at a time, rerunning the linear regression analysis each time to generate updated VIF values for the remaining independent variables. With a commonly used threshold of 10 as the target value (Rawlings et al. 1998), the previously mentioned step should be performed until all VIF values are below the threshold.

In some cases, the regression analysis may call for the removal of seemingly important variables, labeling them with higher VIF values. While statistically it may make sense to remove them, knowledge of typical concrete property influencers may contradict this. Accordingly, at a certain level, multicollinearity can be ignored. Paul Allison wrote that there are at least three situations in which a high VIF value is not an issue and can be ignored (Allison 2012):

1. The variables with high VIFs are control variables, and the variables of interest do not have high VIFs.

2. The high VIFs are caused by the inclusion of powers or products of other variables.

The variables with high VIFs are indicator (dummy) variables that represent a categorical variable with three or more categories. By these guidelines, any time that a variable was slated for removal but still fit one of these three situations, can be kept in the dataset.

In regression modeling with noisy, high-variability data, the *R* value (and thus the R-squared value) may be lower than expected. *R*-squared represents the variability, or the scatter around the regression line. Low R^2 values become an issue when trying to create precise predictive equations, but doesn't mean the variables are unrelated. Even in cases where the R-squared is low, low *P* values can still indicate the relationship between the significant predictors and the response variable. (Minitab Blog Editor 2014). Therefore, in cases where predictive equations are not necessary, but determination of variable relationships are, low R-squared values are acceptable, but attaining the highest R-squared value possible will still be preferable.

While regression can be performed by hand, when analysis is being performed with a large set of data it would become tedious, and the potential for mistakes is higher. As such, there are several computer programs that can aid in these calculations and can provide a best-fit equation for the data. Common computer programs for this include Minitab, MATLAB, SAS, SPSS, and SYSTAT. Each program has its benefits (from more output data to better user interface), but all can handle large amounts of data when performing regression analysis.

2.3.5 T-Test

The t-test is a statistics method for determining if the difference in the mean of two groups are significantly different from each other; i.e., is the amount of difference significant when considering the sample size and the standard deviation of each group. In this case, the null and alternative hypothesis are written as the following:

$$H_0 : \mu_1 = \mu_2 \tag{2.10}$$

$$H_a : \mu_1 \neq \mu_2 \tag{2.11}$$

Where μ_1, μ_2 are the means of the respective groups of data

To test the null hypothesis, values for the t-value must be computed with the information provided in the dataset. There are two potential equations for finding the t-value that will be used in this study: one for equal variance, also known as the Student's t (Eq. 2.12), and one for unequal variance, also known as Welch's t (Eq. 2.14) (NIST/SEMATECH 2012).

Student's t:

$$T = \frac{\overline{Y_1} - \overline{Y_2}}{s_p\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} \tag{2.12}$$

Where:

$$s_p = \sqrt{\frac{(N_1 - 1)s_1^2 + (N_2 - 1)s_2^2}{N_1 + N_2 - 2}} \tag{2.13}$$

Welch's t:

$$T = \frac{\bar{Y}_1 - \bar{Y}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \tag{2.14}$$

Where: $N_1, N_2 =$ Sample sizes

$\bar{Y}_1, \bar{Y}_2 =$ Sample means

$s_1^2, s_2^2 =$ Sample variances

At a significance level "α", the null hypothesis that the two means are equal is rejected if $|T| > t_{1-\alpha/2}$ at the calculated degree of freedom (υ). This degree of freedom is calculated using Eq. 2.15 if the variances are equal, and using Eq. 2.16 if the variances are not equal.

$$\upsilon = N_1 + N_2 - 2 \tag{2.15}$$

$$\upsilon = \frac{\left(\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}\right)^2}{\frac{\left(\frac{s_1^2}{N_1}\right)^2}{(N_1 - 1)} + \frac{\left(\frac{s_2^2}{N_2}\right)^2}{(N_2 - 1)}} \tag{2.16}$$

Where: $N_1, N_2 =$ Sample sizes

$s_1^2, s_2^2 =$ Sample variances

If the null hypothesis is rejected, the difference in the means between the groups is considered to be significant. If the final result is to fail to reject the null hypothesis, the difference between the means is not large enough to be significant at the given confidence level.

Any of the calculations that need to be done to determine the t-value, as well as the degree of freedom, can be determined using a variety of computer programs, with

Microsoft Excel being used for this study. Variance of the mean can be assumed as equal if the data allows for it, but for this study the variance will be checked and not assumed. This can be performed in Minitab, as a command under the ANOVA family.

2.3.6 Group Difference Modeling

Similar to the results obtained from the t-test, performing group comparisons using One-Way ANOVA allows for testing the difference in the mean between pairs of groups. The error rate for the comparison can range between 0.001 (99.999% confidence) and 50 (50% confidence) (Minitab 2018). Within the Minitab software, there are four options for data groups with assumed equal variance (Tukey, Fisher, Dunnett, and Hsu MCB), and one for data groups with unequal variance (Games-Howell). For this research, the following will be used:

- Dunnett's Method: Used to create confidence intervals for group differences between means of each factor and the mean of a singular control group. If an interval contains zero, then there is no significance in the difference between the means. This method assumes equal variance between the data groups.
- Games-Howell: The only available group comparison method available on Minitab for groups with equal variance not assumed, the method provides a similar confidence interval between the means. If that interval contains zero, the there is no significance in the difference between the means.

These methods provide not only the written confidence intervals, but also graphs to allow for easy interpretation. Since these methods will be used in conjunction with the t-test, and therefore are a secondary check rather than the main analysis method, the mathematical derivations of these methods will not be discussed.

2.3.7 Review of Previous Studies

In a field investigation performed by the department of civil and environmental engineering at The Pennsylvania University, researchers used field data to identify factors that contributed to (increasing or reducing) early age cracking the state bridge decks, as well as assessing the long-term durability effects of those cracks. This study was performed by combining data from older bridges as well as from newly constructed decks. In attempting to establish trends between various mixture design factors and early-age cracking of various concrete classes, it was determined that higher cementitious material content results in higher probability of cracking in early-age concrete (as displayed by Class AAA bridge decks, which are high cement level mixtures). Use of one-way analysis or variance (ANOVA) also implied that 7-day compressive strength significantly affected the crack density at the 0.05 significance level. Higher compressive strengths at the time tended to lead to higher likelihood of cracking (Manafpour et al. 2016).

2.4 Research Needs

As this project is dealing with linking concrete mixture design data, early age test results, and performance data, there is not currently any type of existing framework for performing the analysis, nor a clear pathway laid out by previous studies. The idea of using a combination of correlation and regression to determine predictor variables has been applied before ((Rose et al. 1989), see Section 5.1.1), but has not been used to examine the data presented in this research. As a result, the focus will not only be on establishing trends between concrete mixture materials and proportions, early age test results, and field performance, but focus will also be placed on establishing framework and methodology to support similar analyses in the future, if desired.

CHAPTER 3 DATA SOURCES AND CONDITIONING

3.1 Process Map

Figure 3-1 gives an overview of the basic process followed for both the bridge deck and pavement analysis, and provides the section number of this thesis corresponding to that portion of the analysis. For the statistical methods, the basic descriptions are in Chapter 2. For each step, the corresponding section number with more information is included.

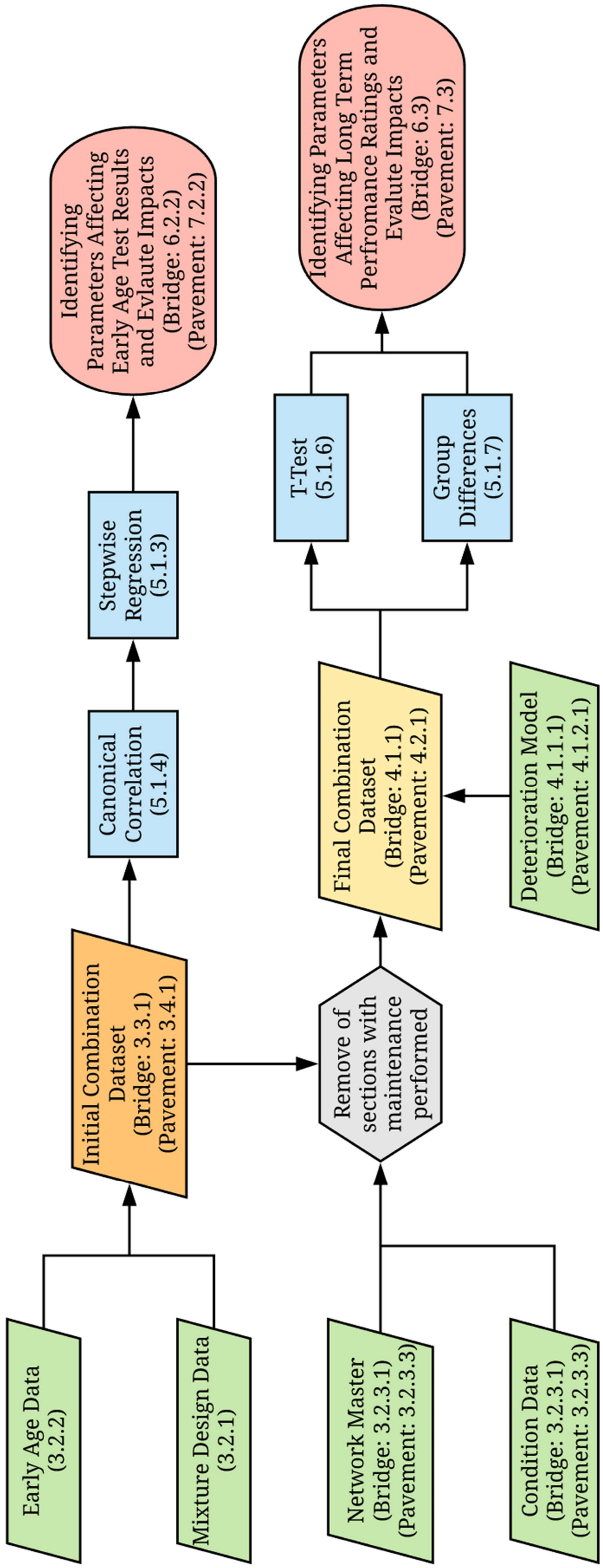

Figure 3-1: Modeling Procedure Process Map

3.2 Data Sources

Typical modeling procedures utilize a dataset to facilitate development of equations (or models) to predict one or more variables based upon others. This can be performed utilizing a number of techniques to accomplish a variety of goals, ranging from use of all the inputs leading to one output (such as regression analysis) or determining the relationship between multiple inputs and multiple outputs (such as canonical correlation). Any errors in these databases, either because of data recording, sorting, or labeling can lead to errors in the final models. Data conditioning should be performed to ensure the chances of incorporating errors into the model are reduced, as the end goal is to create an accurate model.

Records kept by the NCDOT, including inspection reports, maintenance records and approved mixture designs, are stored in databases. This allowed records to be queried and exported to a spreadsheet application (such as Microsoft Excel) for use in this analysis. While there is some crossover between the databases, each house different data aimed at supporting one of three key needs of NCDOT: 1) approved mixture designs, 2) early age test data for acceptance, and 3) condition data to track performance an identify maintenance, repair, rehabilitation, and replacement needs. The following sections detail the content of the databases that were used in this study, and how they were utilized in the analysis. Throughout this chapter, all the columns or categories present in the databases will be called "fields," and individual cells or lines of data will be called "records."

3.2.1 Concrete Mixture Database

Maintained by the NCDOT, the concrete mixture database is a list of all designs submitted to for approval since 1999. It contains information about each mixture, including the proportions and materials used, the producer of the materials and the concrete itself, the class of the concrete, the mixture ID, the status of the mixture design (active or expired), dates accepted/expiring, etc. The corresponding spreadsheet, where all the fields are housed, provides the mixture design values that will be used as the "Mixture Design" variables in the modeling procedures performed.

3.2.2 Concrete Test Data

For each project related to North Carolina bridges, a record of test results for fresh and hardened concrete is included in the central concrete test data spreadsheet. This spreadsheet includes the early age test data (slump, air content, and 28-day compressive strength), as well as information such as the contract number, material description, sample data, site description, county, and route number for bridges between 1999 and 2018. Due to the large number of projects (nearly 4000 unique site descriptions), as well as multiple tests performed on each, the original version of this spreadsheet was large (over 200,000 records). For the purposes of this study, this database will be referred to as the "Bridge Early Age Data" database.

There is a similar version of this sheet for the concrete pavement test data. For this database, in addition to the results of fresh concrete testing, the early age test data includes both flexural strength and compressive strength, with records spanning from 2000-2018. Due to the fact that concrete pavement (or at least the use of concrete as the wearing surface) is not as widely constructed as asphalt pavement, and the propensity to use a common mixture design for a single project, the original spreadsheet included 29 individual roadways, and only had around 7,400 records for concrete pavement projects. For the purposes of this study, this database will be referred to as the "Pavement Early Age Data" database.

3.2.3 Performance Data

NCDOT utilizes several databases to house records on bridge and pavement condition and maintenance, repair, and rehabilitation (MR&R) actions performed. These databases contain other information including location, current condition, etc. The Bridge Management System (BMS) is a collection of databases maintained by the NCDOT with such information about North Carolina bridges. Similarly, the Pavement Management System (PMS) is utilized to store performance data for the state's pavements. In order to link the long term performance of the bridges and pavements to the mixture designs and early age test data, performance data from the BMS and PMS was incorporated into the analysis.

3.2.3.1 BMS Network Master

The Network Master is sourced from the BMS, and it contains information about the location (county, intersection features, latitude, and longitude), structure number, and route number for each NCDOT-maintained bridge in the state. This dataset is updated annually to ensure accuracy. The version of the Network Master used for this project was exported in February 2018 to an Excel spreadsheet. At the time of export, it included 21,835 records, divided among 3965 bridges and culverts.

3.2.3.2 BMS Element Data

In order to create uniformity in the way that inspection data was recorded and reported, AASHTO created the Bridge Element Inspection Guide Manual. The goal of the manual is to "completely capture the condition of bridges in a simple was that can be standardized across the nation while providing the flexibility to be adapted to both large and small agency setting" (AASHTO 2010). The element set includes two different element types, the National Bridge Elements (NBE) and the Bridge Management Elements (BME). NBE represents the primary structural components of bridges, such as the deck, superstructure, substructure, bridge rail, bearings, etc. BME includes the other bridge components such as joints, wearing surfaces, protective systems, and other non-structural elements. All elements, no matter what type, have a standard number of condition states, comprised of good, fair, poor, and severe.

3.2.3.3 Pavement Management System (PMS)

The pavement management system (PMS) database is one of three parts in the Pavement Management Unit (the other two being Data Collection and Pavement Design & Analysis), a unit responsible for the design, testing, and monitoring of the pavements in the NCDOT network. The PMS is utilized to store and analyze pavement condition data, maintain records for the construction or maintenance of NCDOT roadways, and support analysis of pavement data to assist in the optimization of department funds.

For this study, the PMS Network Master was used. Within the Network Master roadways are divided into smaller sections. For each section, details such as location, length, surface type, and condition are provided. The version of the Network Master used for this project was exported in February 2019 to an Excel spreadsheet, and was prescreened to remove sections of roadway that do not have concrete as the upper layer. At the time of export, it included 3,610 records, divided amount 29 roadways.

3.2.3.4 Long Term Pavement Performance (LTPP) Database

As pavement performance data is one of the major research areas of the Strategic Highway Research Program (SHRP), the Long-Term Pavement Performance (LTPP) program was established to aid in this effort. Managed by the Office of Infrastructure Research and Development, the LTPP program includes a variety of smaller studies, but also includes two fundamental classes of studies: the General Pavement Study (GPS) and the Specific Pavement Studies (SPS). Collecting data on several different modules on all active sites, the LTPP Information Management System (IMS) is the central database where the data is stored.

Fifty sections of roadway involved in this study exist in North Carolina, located in areas throughout the state. The database includes information such as average climate, weather, traffic estimates, signs of distress, cracking, fracture, deflection, etc. for most if not all of those sections of pavement. This database provides more detail regarding the specific distresses observed in the concrete pavement, and will help in the evaluation of their long term performance.

While the information in this database is useful, its potential for use in accomplishing the objectives of this study is limited. Pavement sections that are included in the LTPP database tend to be experimental in nature, and as such are not reflective of typical NCDOT roadways. Therefore, the data will not be included on its own, but will provide secondary verification for information present in the PMS database.

3.3 Data Conditioning for Bridge Decks

In order to optimize the data storage, remove unnecessary information, and create a more concise database for analysis purposes, the individual data sources were merged. Due to the large amount of early age data present, functions available within Excel were utilized to help with the process. This early age data, while including a short description of the project, did not have structure numbers directly linked to each test record. As such, the spreadsheet was cross-referenced with the BMS spreadsheet in the following fields: county, route number, and site description. Spelling errors, non-standard abbreviation techniques, and labeling commonly caused issues with cross-referencing. The site description field was not recorded in a consistent manner from project to project, an issue that was more pronounced in some counties, and often included misspellings or abbreviation errors. In cases where this was observed, the record was modified to be consistent with the rest of the recordkeeping and to facilitate cross-referencing efforts.

3.3.1 Creation of Central Datasets

Combining information from the three databases (the concrete mixture database, the early age data database, and Network Master database [which includes both information about the bridge or pavement section, as well as its current condition rating]) into central databases, one for bridge mixtures and one for pavement mixtures, was essential to support the modeling process, as it allowed for the necessary data to be readily accessible. Within the original databases, there are a large number of informational fields present for the bridges. However, not all of it existed in a format that was beneficial for use, nor was all of it actually useful for this analysis. Therefore, creation of the central datasets also included removal of fields deemed not useful.

The creation of the databases was performed according to the following process. The first dataset was created to determine the relationship between mixture designs and available early age data for those mixtures. In the “Bridge Early Age Data” database, each test record is linked to a mixture design; as such, a mixture was labeled as used if its mixture ID existed in the “Bridge Early Age Data” datasheet. All mixtures that could not be linked to a test record were filtered out. For each individual test record, the corresponding mixture data was imported into the sheet. This newly created datasheet will be known as the “Bridge Initial Combination Dataset”.

The second dataset was created to find the link between any bridges having records in all three databases: mixture design, early age test results, and long term inspection data. An initial list of known structures was determined using the process outlined in 3.2.1.1. Once this list was created and records in the “Bridge Initial Combination Dataset” were linked to structure numbers (where possible), additional data was imported from the corresponding datasets, using the mixture ID to queue the corresponding mixture design and using the structure number to link the inspection data for that structure. This combination dataset is labeled as the “Bridge Final Combination Dataset”.

3.3.1.1 Structure Numbers

Every bridge owned by NCDOT is identified by a six-digit structure number. The six digits are broken down as follows: the first two numbers are the county code (00 through 99, representing each of North Carolina’s counties in alphabetical order), and the last four digits represent the individual bridge’s ID number within the county. Although including a brief site description for the site where the concrete was used, the early age test data did not include the structure number of the bridge built at that site. As such, the use of data from other datasets was necessary to link a structure number to each test record.

Since the data set is quite large, condensing it by removing any that were not related to this project. Any class B mixtures (Concrete Class B and Concrete Class B, Curb & Gutter) where removed, as they were not the focus of this study.

The first approach was to determine the structure number based on phrases included in the description column. The BMS data included an "Intersection Features" field, with phrases that were nested into the site description field of the "Bridge Early Age Data" database. Comparing these two fields using equations within Excel allowed for the structure number to be determined for routes with a single bridge, if the site description field contained a phrase present in the intersection feature field

This approach was successful for 38,173 sets of test data out of 158,806 sets, or about 24%. However, due to the fact that the method of labeling the intersection details was often vague, several of these have the potential of referring to multiple bridges across the same feature.

At this point, the data was re-sorted into counts of individual unique site descriptions, yielding a final count of 3259 records. Visual inspection and historic cost data, along with the previously mentioned methodology, had a combined success rate of 1855 site descriptions with at least one structure number attached to it. 107 have been identified as "Two Bridge Projects", with two structures being attached to the site description. Those records were kept in the dataset, as it is common enough that bridges for different directions of traffic are labeled as separate even though they would have been constructed together.

Even with the level of success achieved, there were still several more projects that were very difficult to attach a structure number to. As such, different ways of eliminating data have been proposed, either because they cannot be found or they will not be useful to the final dataset. Tables 3-1 and 3-2 detailed the parameters that where employed in the filtering of the data.

Table 3-1: Initial Filtration Parameters

Filtration Parameter	Reason for Removal
Batch Project	• Batch projects are identified as any project having three or more structures bundled under the same site description • Due to the large potential for error, eliminating these batch projects removes a level of ambiguity that results from so many projects referencing the same test results • Searches performed for common phrases such as “various”, “bridges”, and “sections” helped uncover many of them, but visual inspection was also important to identify them
Culverts	• Culverts were not considered in the scope of this project, any projects related to just culverts will be eliminated. • If a culvert it mentioned in the site description but it is in addition to a bridge, it is kept in the dataset.
Vague/Confusing Site Descriptions	• With no easy Excel-determined link between the site description and the BMS Network Master, each individual site description was inspected • In many cases, the description was either vague or could not be readily interpreted. • For example, a site description of “NC-18” could refer to any of the bridges on NC-18, meaning that the risk of error in determining the structure number was too high.

Since a large amount of data could not be linked to a structure number due to a variety of the previously mentioned potential errors, manual inspection became the best route to try and identify useful records. The BMS Network Master includes the latitude and longitude locations of each NCDOT maintained bridge in the state. Using the Google Maps software, layers were created to display the location of every listed bridge in the Network Master, totaling nearly 14,000 individual points (as shown in Appendix A, Figure A-6).

At this point, it became a search-and-find operation, using the key words in the site description to aid in locating the appropriate bridge. Due to spelling errors, county errors, route errors, and other record keeping anomalies, this proved to be a difficult task.

Another common issue is that a bridge could be called out in the site description, but either none exist at that location or the Network Master does not include it. This led to a number of records being excluded from the dataset due to the inability to find a linkage. In this process, two new methods of data elimination were used:

Table 3-2: Secondary Filtration Parameters

Filtration Parameter	Reason for Removal
Suggested for Removal (Mixed Reason Category)	• Descriptions that didn't seem to include new bridge construction (such as "GRADING, DRAINAGE, WIDENING AND RESURFACING ON SR 1301 (BOONE STATION DRIVE) AT SR 1226 (UNIVERSITY DRIVE)") • Locations were there was no bridge in the BMS Network Master database and no specific bridge name or number was mentioned (such as "BRIDGE OVER CABLE CREEK AND APPROACHES ON SR-1320.") • Specifically named intersections where no bridge existed
Roadways	• A section of roadway was named in the site description, which held anywhere from zero to multiple bridges. • Since no exact accurate bridge could be determined using this description, these were removed to eliminate some potential for error.

Even with this manual sorting process, much of the data had to be excluded from the dataset due to the inability to match it with a structure. In the end, a total of 1973 site descriptions that were linked to a structure number, with 114 of those being considered as "Two-Bridge" projects. In all, there were just over 2000 bridges that were able to be linked to one or more concrete mixture designs. While it is unfortunate that so much data had to be excluded from the analysis, ensuring accuracy in linking the mixture design to a structure number was far more valuable than keeping all of the data. The final dataset (the "Bridge Initial Combination Dataset") used for the analysis included a total of 36,766 records divided between 1551 bridges, providing a fairly robust database capable of meeting the analysis goals for the project.

3.3.1.2 Variables

Every database used in this analysis contains many variables pertaining to the bridges, giving information from inspection data to bridge location. Since not all of these variables will ultimately help with the desired models, decisions were made to determine which variables should be included in the analysis and which should be removed from the dataset and excluded from the analysis. Creating a concise yet large enough dataset is important, as too much data would clutter the analysis but not enough could reduce areas in which it could be potentially useful. The first step in the decision making process was to compile a list of all available variables between the databases. This list is shown in Table 3-3.

Table 3-3: Fields Available in the Bridge Databases

Field	Mixture Design	Early Age	Network Master	Field	Mixture Design	Early Age	Network Master
Mixture Design ID	X	X		Sample Status		X	
Status	X			Sample Date		X	
Date Accepted	X			Producer Name		X	
Date Expired	X			Age at Test, days:		X	
Class of Concrete	X	X		Air Content [%]:		X	
Mortar Content	X			Slump [in]:		X	
Cement Amount	X			Avg. Comp. Strength [psi]:		X	
Pozzolan Amount	X			Description		X	
Pozzolan Type	X			County		X	X
Fine Aggregate Amount	X			Route type		X	
Fine Aggregate Spec Gravity	X			Route Number		X	X
Coarse Aggregate Amount	X			Location		X	
Coarse Aggregate Spec Gravity	X			Station From		X	
Water Amount	X			Station To		X	
Maximum Water	X			Substructure Condition			X
Latex Modifier (gal.)	X			Bridges			X
Air Content	X			Bridge Class			X
Slump	X			Deck Condition			X
W/CM Ratio	X			Superstructure Condition			X
Max W/CM Ratio	X			Division#			X
Yield	X			Tier ID			X
Paste Content	X			Structure Type			X
Aggregate Content	X			Structure Type			X
Water Reducer	X			Facility Carried			X
Retarder	X			Intersected Features			X
Superplasticizer	X			Structure Number			X
Corrosion Inhibitor	X			Maintenance History			X
CNI Amount (gal)	X			TIP Bridge No.			X
Silica Fume Amount	X			Bridge Replacement Status			X
Comment	X			Replacement Status (TIP)			X
Contract Number		X		PRI			X
Concrete Mixture ID		X		Sufficiency Rating			X

Table 3-3: Fields Available in the Bridge Databases (continued)

Field	Mixture Design	Early Age	Network Master	Field	Mixture Design	Early Age	Network Master
Deficiency Points			X	Service Type On			X
Structurally Deficient			X	Span Type			X
Approach Roadway Width			X	Service Type Under			X
Functionally Obsolete			X	Superstructure Type			X
Posted TTST			X	Substructure Type			X
Bearing Grade			X	Latitude			X
Posting Score (#)			X	Longitude			X
BHI			X	Structure Type Main			X
BHI Score (#)			X	Structure Type Approach			X
Average Index (BMS)			X	Deck Structure Type			X
Temp Structure Designation			X	Culvert Type			X
Detour Length			X	Service Type			X
Bridge Age			X	Sorting Code			X
Year Built			X	Scour Critical Bridge			X
Estimated Remaining Life			X	Last Routine Inspect. Date			X
Bridge Length (NBIS)			X	Structure Appraisal			X
National Highway System			X	Deck Geometry Appraisal			X
Strahnet Designation			X	Approach Align. Appraisal			X
Deficient			X	Underclearance Appraisal			X
Green Line Route			X	Waterway Adequacy Appr.			X
Posted?			X	Culvert Condition			X
Functional Classification			X	Paint Condition			X
ADT			X	Min. Vert. Clearance Over			X
Structure Length			X	Max Clear. Under Bridge			X
Bridge Deck Width			X	Water Depth			X
Bridge Roadway Width			X	Height Crown to Bed			X
Through Lanes On			X	City			X
Min. Clearance Under Bridge			X	Bridge Name			X
Replacement Cost			X	Road System			X
MAINT RESP			X	Traffic Direction			X
Owner			X	Bridge System			X

Table 3-3: Fields Available in the Bridge Databases (continued)

Field	Mixture Design	Early Age	Network Master	Field	Mixture Design	Early Age	Network Master
Annual User Costs			X	Wearing Surface Type			X
Consider Replacement?			X	Wearing Surface Grade			X
Built By (Orig)			X	Substructure Material (Det)			X
Project No. (Orig)			X	Vert. Underclearance Goal			X
Func. Class (Sys. Under)			X	NCB_Deck_Width_GL_ID			X
ADT Year			X	Bridge Type			X
Percent ADT Truck			X	Bearing Grade (#)			X
ADT (Under)			X	SD CALC			X
ADT Year (Under)			X	UNDET_BHI_ID			X
Milepoint			X	SD CALC ANAL			X
Att.			X	UNDET BHI SCORE			X
Comments			X				

Many of the variables only exist in one database, as they are relevant only to that database's purpose. Some, such as "Site Description" and "Intersection Features" are similar but not identical, so they were kept separate in this list and within the central dataset.

Since not all of the variables are important to this analysis, or may not be in a useable form, the following is a list of reasons why variables were eliminated:

1. Lack of data: for some fields, many if not all of the records were blank, and as such are not useful.
2. Specific location information, such as city and route number, were important in linking records between databases, but could not be useful in analysis.

3. Items unrelated to this study, such as cost, culvert information, paint condition, etc. are not related to the condition of the structure itself, and were removed.
4. Items like substructure type, while important, are all coded differently, and were not utilized.

Table 3-4 is the list of categorical and continuous variables that remained after filtration are in the following list, with the variable, variable type, and source of information noted (MD = Mixture Design, EA = Early Age, NM = Network Master). Detailed descriptions of these variables are located in Appendix B.

Table 3-4: Variables in Central Dataset

Variable	Variable Type	Source
Structure Number	Continuous	NM
Class of Concrete	Categorical	MD, EA
Mortar Content	Continuous	MD
Cement Amount	Continuous	MD
Cement Producer	Categorical	MD
Pozzolan Amount	Continuous	MD
Pozzolan Producer	Categorical	MD
Pozzolan Type	Categorical	MD
Fine Aggregate Amount	Continuous	MD
Coarse Aggregate Amount	Continuous	MD
Water Amount	Continuous	MD
Maximum Water	Continuous	MD
Air Content (Design)	Continuous	MD
Age at Test	Continuous	EA
Compressive Strength	Continuous	EA
Air Content (Actual)	Continuous	EA
Slump	Continuous	EA
Substructure Condition	Continuous	NM
Deck Condition	Continuous	NM
Superstructure Condition	Continuous	NM
PRI	Continuous	NM
Sufficiency Rating	Continuous	NM
BHI Score (#)	Continuous	NM
Bridge Age	Continuous	NM
ADT	Continuous	NM
Structure Length	Continuous	NM
Bridge Deck Width	Continuous	NM
Through Lanes On	Categorical	NM
Superstructure Type	Categorical	NM
Structure Type Main	Categorical	NM
Deck Structure Type	Categorical	NM
Structure Appraisal	Categorical	NM
Bridge System	Categorical	NM
ADT Year	Continuous	NM
Wearing Surface Type	Categorical	NM
Substructure Material (Det)	Categorical	NM

3.3.2 Treatment of Outliers

Before performing the analysis, any values that were seen as suspect were removed or edited. Values were flagged if:

- The value was way larger or smaller than typical values (typically for mixture design proportions or early age data). If this occurred, the value was examined more closely. In some cases, the value was listed in dissimilar units (cm instead of inches, etc.), and could be fixed. If a reason for that value could not be determined, the record was removed to prevent the possible introduction of error.
- The value was of the wrong type, i.e. categorical variables in continuous fields. These values were either translated into continuous values or removed from the dataset.
- If the value reflected a potential error in data logging or retrieval, it was removed. For example, if the average compressive strength was listed as "0", it may have not been recorded. As such, records of this type were removed.

3.4 Data Conditioning for Pavements

In order to optimize the data storage, removing unnecessary information, and create a more concise database for analysis purposes, the individual data sources were merged. Due to the large amount of early age data present, functions available within Excel were utilized to help with the process. Details on this process, as well as issues that arose during data conditioning, are discussed in the following section.

3.4.1 Creation of the Central Datasets

Creating central datasets was essential in supporting the modeling process, as it allowed for the necessary data to be readily accessible. Within the original databases, there is a large amount of information in a variety of fields for the pavement sections. However, not all of it is useful or needed for this analysis.

The creation of the datasets was performed according to the following process. The first dataset was created to determine the relationship between the mixture designs and the available early age data. Within the “Pavement Early Age Test Data” database, each test is linked to a mixture design ID. If that mixture design ID was incorrectly recorded, or not present in the “Mixture Design” database, those test results were removed from the combination dataset (the "Pavement Initial Combination Dataset”).

The second dataset was created to find the link between sections of pavement for which all necessary fields are available: mixture design, early age data, and long term performance data (or anything pertaining to that performance). An initial list of pavement sections with all this known information was determined using the process outlined in 3.3.1.1. Once this list was created and links between the data were determined, additional relevant data was imported from corresponding databases to create the “Pavement Final Combination Dataset”.

3.4.1.1 Pavement Sections

Unlike the bridge data sourced for this study, the early age dataset for pavements was not large, with only around 7500 records prior to any filtration or conditioning. With the completion linking the early age data to and their respective mixture designs, the next step was to find a way to link performance and maintenance data to those records. Within the “Pavement Early Age Data” dataset, there are 44 unique contract numbers. These contracts range from 2000 to 2018. The contract numbers were linked to 29 unique roadways, in 16 different counties.

In order to only maintain information about the pavement sections that can potentially be examined in this study (information such as size, location, traffic amount, etc.), each record within the early age test result dataset was linked to its corresponding Network Master section. To accomplish this, fields that exist in both databases were examined (either as the exact same field or very similar fields). Both have the route type and number (although they are written differently), as well as general information about the section of roadway that the mixture was used for.

Within the Network Master, the route number is coded as an eight-digit number. Table 3-5 provides a breakdown of what each digit stands for:

Table 3-5: NCDOT Route Number Guide (NCDOT)

X	X	X	XXXXX
Type of Route	Special Route	Directional Code	Route Number
1 = Interstate	0 = Regular	0 = Inventory	
2 = US	1 = Alternate	4 = Southbound	
3 = NC	2 = Bypass	6 = Westbound	
4 = Secondary	7 = Spur	8 = Inner	
	8 = Truck	9 = Outer	
	9 = Business		

Within the "Pavement Early Age Data" dataset, the type of route and the actual route number are listed. As such, this was used as the first step in linking the early age tests will an actual section of roadway.

Before matching early age data to roadways, it was important to eliminate any potential sections of roadway that should not be included. Pavement is made up of several different layers:

- The subgrade is the existing soil on the site.

- A subbase level when necessary, typically comprised of crushed aggregate or engineered fill.
- Depending on the project, a base level may be used to help support the roadway. This is typically a concrete layer.
- The wearing surface is the uppermost layer of the pavement. It is the layer that is in contact with any vehicles, is the first to experience external environmental impact such as rain and snow, and is typically the first to show wear.

Since this project is focusing on concrete used for pavements, the wearing surface of the pavement section should be concrete (as opposed to any other wearing surfaces, such as asphalt). As such, any pavement sections that did not indicate that concrete was the surface layer were removed from the dataset.

With this filtration complete, the next step was a general comparison of the data to determine how many roadways had mixture design data, early age data, and location data from the Network Master. The mixture design and early age data were already linked, so within the Network Master, the "Route" field was broken down into its individual pieces (with "Type of Route" and "Route Number" being the important components) and the "County" field was broken down into "County Number" and "County Name". All records that did not belong to a roadway listed in the Network Master were filtered out of the database.

While this step gave a general overview of pavement sections to focus on, it does not filter out any particular sections of those roads that exist in the Network Master but have no early age tests associated with them (and thus, no mixture design data). Also, for any given roadway, there could be a single mixture design, or several mixture designs, attached to it. This is illustrated in Table 3-6:

Table 3-6: Number of Pavement Mixtures for Roadways Containing Early Age Data

County	Route Type	Route Number	Total Number of Mixture Designs	Number of Unique Mixture Designs
Buncombe	Interstate	40	6	5
Cabarrus	Interstate	85	16	14
Davidson	Interstate	85	8	8
Durham	Interstate	85	2	2
Forsyth	Interstate	40	2	2
Forsyth	US	52	3	1
Guilford	Interstate	40	1	1
Guilford	Interstate	85	1	1
Guilford	Interstate	785	2	2
Iredell	Interstate	40	1	1
Mecklenburg	Interstate	485	17	16
Nash	Interstate	95	1	1
Rowan	Interstate	85	9	9
Vance	Interstate	85	16	15
Wake	US	1	6	5
Wake	Interstate	540	10	9
Wake	NC	540	5	4
Yadkin	Interstate	77	10	10

In the table, each the number of mixture designs present is broken down by the number used on that roadway, as well as the number of unique mixture designs used. For example, the first record is I-40 in Buncombe County. There are six unique mixture ID's associated with the early age testing for that roadway, but only five are unique, meaning that one has the exact same mixture proportions as another.

Within the Network Master, every roadway is broken up into smaller sections, with the beginning and end location for that section being described in the fields "Begin

MP" and "To MP". These individual sections are then given a rating by the NCDOT, and additional information about those sections are provided. Since the roadways are all broken up this way, the concrete early age test data should match to a certain section of roadway. Determining the specific location on the roadway of individual test records is the best way of linking how the mixtures used to create that concrete impacts performance. However, with the current data recording methodology, this link is not possible.

Within the "Pavement Early Age Data" database, each recorded is assigned a few possible location descriptors: "Location", "Location Description", and "Station From" (as well as information such as route type and number). "Location" had a large variety of descriptor types, ranging anywhere from a single non-descript number to the lane in which the mixture was used. As such, the information tended to point to the mixture's location in the cross section of the roadway, but not to the location on the length of the road. 'Location Description" gave a general description of the roadway, with no specific breakdown of the location within the roadway. "Station From" was the most promising of the three, as it describes the construction stationing. However, it cannot be linked to the sections described in the Network Master "Begin MP" and "To MP", as the data is recorded differently and cannot be correlated.

Since accurate locations for the early age tests could not be determined, there was no way to determine the sections in which a specific pavement mixture design was used. As such, roadways that used multiple mixture designs had to be eliminated to avoid potential data corruption.

Ultimately, there were only six roadways that could be used, as shown in the Table 3-7:

Table 3-7: Final Roadways for Pavement Performance Consideration

County	Route Type	Route Number	# of NM Road Sections	# of NM Records
Durham	Interstate	85	16	74
Forsyth	US	52	6	23
Guilford	Interstate	40	18	76
Guilford	Interstate	85	39	201
Iredell	Interstate	40	5	19
Nash	Interstate	95	33	157

Note: NM = Network Master

As mentioned previously, each roadway within the Network Master is broken down into smaller sections. The number of sections present for each roadway is listed in the "# of NM Road Sections" field. For each section, there could be records of observations, as well as assigned NCDOT Pavement Ratings, for multiple years. This is better shown in the "# of NM Records" field, which is the number of condition ratings assigned to sections of the roadway over time. Each one of these sections has a defined beginning and end, and are assigned a "Section Management Number". Due to the amount of fluctuation in the beginning and end points, every time these points changed a new section label was given.

All of the individual entries in Network Master for the six roadways where transferred to a new sheet, and matched with the concrete mixture ID. Finally, the mixture proportions for each of those mixtures were added to the sheet, linking the concrete mixture design to the stretch of roadway that it was utilized on.

Secondary filtration was then applied to the dataset to remove any records that may have been added to the final dataset. For many of the sections of roadway, while originally a concrete pavement, an AC (asphalt concrete) overlay or reconstruction was performed to improve the condition or meet the needs of the area (specific reasons for this construction are not listed in the Network Master). This is recorded in the "RSC" field. Therefore, any records that indicate that an AC overlay was used were removed, as well as any future records for that roadway. Historical records for those roadways, when the surface was still concrete, were maintained in the dataset. Any records with a blank in the "RSC" field are removed, as it is unknown if AC construction was performed.

At this point of time, the dataset was complete to support the analysis that will be performed in this study (named the "Pavement Final Combination Dataset"). This dataset provided a clear link between the concrete mixture design and the section of roadway that it applies to (since the whole roadway uses the same design). The early age test results could not be maintained in this final dataset, as linking these records to individual sections could not be performed due to the fact that there was no accurate way of linking an early age test record to an individual section of roadway (i.e., determine which milepoints it was located between).

Another issue present within the database was the lack of accuracy between MP locations. Because each roadway is broken up into smaller segments for analysis, each is assigned a start and end in the "Begin MP" and "End MP" fields. The values in these fields are not consistent throughout the years, and need to be broken up further. For example, for Management Section # 464798677 (I-85 in Guilford County), in 2014 and 2015 the beginning and end MP's were recorded as 14.805 and 15.649 respectively. In

2016, they were changed to 14.179 and 15.179 respectively, increasing the condition rating of this "section" from 51.105 to 67.362. As such, while the sections on either side get larger or smaller based on how much extra in included in this section, the section must be considered as separate starting in 2016.

Recommendations for modifying the data collection and recordkeeping techniques, as well as rationale behind those suggested modifications, are listed in Chapter 8, Section 2.

3.4.1.2 Variables for Pavements

Each database used in this analysis contained multiple variables pertaining to the pavement sections, providing a variety of information ranging from compressive strength to the pavement location. Since not all of these variables will aid in the analysis and will only cause extra noise in the model, decisions were made to decide which should be included and which should be removed. The first step in that process is to compile a list of all available variables between the datasets, shown in Table 3-8.

Table 3-8: List of Variables Present in the Pavement Databases

Field	Mixture Design	Early Age	Network Master	Field	Mixture Design	Early Age	Network Master
Mixture Design ID	X	X		Disposition		X	
Status	X			Date Made		X	
Date Accepted	X			Producer		X	
Date Expired	X			Req. Flexural Strength		X	
Class of Concrete	X	X		Avg. Flexural Strength		X	
Mortar Content	X			Req. Compressive Strength		X	
Cement Amount	X			Avg. Compressive Strength		X	
Pozzolan Amount	X			Station From		X	
Pozzolan Type	X			Location		X	
Fine Aggregate Amount	X			Contract Description		X	
Fine Aggregate SG	X			Location Description		X	
Coarse Aggregate Amount	X			County		X	X
Coarse Aggregate SG	X			Route Type		X	
Water Amount	X			Route Number		X	
Maximum Water	X			Route			X
Air Content	X			Lane Direction			X
Slump	X			Lane Direction			X
W/CM Ratio	X			Lane			X
Max W/CM Ratio	X			Begin MP			X
Yield	X			To MP			X
Paste Content	X			Length			X
Aggregate Content	X			Year			X
Water Reducer	X			System			X
Retarder	X			From Description			X
Superplasticizer	X			To Description			X
Corrosion Inhibitor	X			JCP Section			X
CNI Amount (gal)	X			CRC Section			X
Silica Fume Amount	X			AC Section			X
Comment	X			BST/Slurry Section			X
Report ID		X		Surface Type			X
Contract Number		X		Last Rehab Year			X

Table 3-8: List of Variables Present in the Various Pavement Databases (continued)

Field	Mixture Design	Early Age	Network Master	Field	Mixture Design	Early Age	Network Master
Pavement Age			X	AC Ravel Index			X
Surf Contract			X	AC PCS Rut Index			X
RSC			X	NC Trans Index			X
Management Section #			X	AC Patch Index			X
Width			X	JCP Fault Index			X
Number of Lanes			X	JCP Longitudinal Index			X
Curb			X	JCP Joint Seal Index			X
Shoulder Type			X	JCP Corner Break Index			X
Shoulder Width			X	NC Pump Index			X
Paved Shoulder Rating			X	JCP Spall Index			X
Shoulder Dropoff Rating			X	PCC Patch Index			X
Shoulder Lane Joint Rating			X	NC Surface Wear Index			X
Unpaved Shoulder Rating			X	CRC Punchout Index			X
Unpaved Shoulder Width			X	CRC Longitudinal Index			X
Condition Survey Year			X	CRC Narrow Crack Index			X
NCDOT Rating Number			X	CRC Y Crack Index			X
Profiler Data Year			X	NC Ride Rating Index			X
Avg Left/Right IRI			X	IRI Index			X
Profiler Rutting			X	County Owner			X
AADT			X	District			X
AC Alligator Index			X	Division			X
AC Bleed Index			X	Statewide Owner			X
AC Oxi Index			X	Structure Year			X

Many of the variables only exist in one database (such as pozzolan amount only existing in the mixture design dataset). Some, such as “Route” and “Route Number” are similar but ultimately do not exactly match, so they were kept separate in this list.

Since not all of the variables are important to the analysis, or may not be in a useable form, the following is a list of reasons why variables were eliminated:

1. Lack of data: for some fields, many if not all of the records were blank, and as such are not useful.
2. Specific location information, such as city and route number, were important in data linking but did not support the goals of the analysis.
3. Items unrelated to this study, such as comments, county owner, user update, etc. are not related to the condition of the structure itself, and were removed from the dataset.
4. Variables within the Network Master that are dependent variables themselves, since as any of the index ratings, and therefore were removed.
5. Variables such as “AC Patch Index” and “JCP Corner Spall”, which are included in the calculation for the roadway condition were removed due to the fact that they are already considered within that condition rating. To save computing time and effort, they were removed prior to analysis.

Table 3-9 is the list of categorical and continuous variables that remained after filtration are in the following list, with the variable, variable type, and source of information noted (MD = Mixture Design, EA = Early Age, NM = Network Master).

Table 3-9: Analysis Variables in the Pavement Datasets

Variable	Variable Type	Source
Class of Concrete	Categorical	MD, EA
Mortar Content	Continuous	MD
Cement Amount	Continuous	MD
Pozzolan Amount	Continuous	MD
Pozzolan Type	Categorical	MD
Fine Aggregate Amount	Continuous	MD
Fine Aggregate Spec Gravity	Continuous	MD
Coarse Aggregate Amount	Continuous	MD
Coarse Aggregate Spec Gravity	Continuous	MD
Water Amount	Categorical	MD
Air Content	Continuous	MD
Slump	Continuous	MD
W/CM Ratio	Continuous	MD
Yield	Categorical	MD
Paste Content	Categorical	MD
Aggregate Content	Continuous	MD
Required Flexural Strength	Continuous	EA
Average Flexural Strength	Continuous	EA
Required Compressive Strength	Continuous	EA
Average Compressive Strength	Continuous	EA
System	Categorical	NM
Pavement Age	Continuous	NM
NCDOT Rating Number	Continuous	NM
AADT	Continuous	NM
Section ID	Categorical	NM

This is a list of all of the variables considered in the various stages of analysis for the pavement sections, but is not necessarily reflective of the list used at each stage of the analysis. Due to the limitations in linking to specific roadway sections, the early age data could not be included in the long term performance analysis, and therefore was not included in that database. Detailed descriptions of these variables are located in Appendix B.

3.4.2 Treatment of Outliers

Before performing the analysis, any values that were seen as suspect were removed or edited. Values were flagged for further consideration if:

- The value was way larger or smaller than typical values (typically for Mixture design proportions or early age data). If this occurred, the value was examined further. In some cases, the value was listed in the wrong units (cm instead of inches, etc.), and could be fixed. If a reason for that value could not be determined, it was removed to prevent potential error.
- The value was of the wrong type, i.e. categorical variables in continuous fields. These values were either translated into continuous values or removed from the dataset.
- If the value reflected a potential error in data logging or retrieval, it was removed. For example, if the average compressive strength was listed as "0", it may have not been recorded. As such, records of this type were removed.

3.5 Summary of Datasets

Since there are multiple steps to this study, as well as multiple components in each of those steps, several individual datasets were created. While they are similar and may contain much of the same data, each database is used for a different component of the analysis.

3.5.1 Bridge Mixture Designs to Bridge Early Age Data (Bridge Initial Combination Dataset)

While there are several more concrete mixture designs than structures they can be attached to, only the ones that could be linked to a specific structure (as well as fitting all other necessary criteria, such as concrete types included in the study) were kept for this dataset. While it may seem advantageous to keep all of the early age data in the final dataset, the possibility for inducing error increases when a specific structure and element cannot be determined for a concrete mixture that has been tested. As such, and early age data not linked to a bridge was removed. This dataset includes every useful early age test record, as well as the mixture design components for each early age test record. The completed dataset includes 40,743 entries.

3.5.2 Bridge Mixture Design to Early Age Data to Performance Data (Bridge Final Combination Dataset)

This dataset provides the base for comparing concrete mixture designs to their actual long term performance. As such, only records of mixtures with the mixture design, early age testing, and long term data exist within the dataset, with all of these categories tied to a structure number. Network Master values are also included here, as they are influencing factors to the long term performance. The result was a database with 1719 bridges, and a total of 39,807 entries when multiple test records for a single bridge were accounted for.

3.5.3 Pavement Mixture Designs to Early Age Data (Pavement Initial Combination Dataset)

The pavement mixture design to early age dataset contains all viable early age data for pavement mixtures (with compressive strength and flexural strength data for each), linking each early age record to its corresponding mixture design components. While the mixtures have the same general variables as in the bridge mixtures, it is important to note that the early age test results report different result types. Other useful information (although not essential to the analysis) is also included, such as county, route number, contract number, etc. to allow for this dataset to be the base of the performance dataset. The completed dataset includes 7,424 entries.

3.5.4 Pavement Mixture Design to Performance Data (Pavement Final Combination Dataset)

The pavement mixture design to performance data dataset was originally intended to also contain the early age test data, but due to data linking limitations it could not be included. As such, only the sections of roadway for roads with a single mixture design could be used. This dataset includes all the applicable sections of roadway with JCP as the top layer from the Network Master, as well as the mixture designs for those roadways. Other non-essential information such as county, route number, etc. were still included in the dataset in case further filtration was required. The completed dataset includes 407 entries.

CHAPTER 4 LONG TERM PERFORMANCE CONSIDERATIONS

4.1 Data Processing for Long Term Performance Analysis

With the creation of the larger databases for long term performance considerations, additional filtration and condensing was performed to condition the data into a format more appropriate to the selected model forms. The following sections detail this filtration process, including details on the deterioration models used as a standard for the long term performance.

4.1.1 Data Condensing for Bridge Performance

Within the "Bridge Final Combination Dataset", a categorical variable could include anywhere from two to hundreds of different category descriptions. Within each of those categories, the population for each may not be equally distributed, and as such some may not be useful for the analysis. When examining the categorical variables to be included in this part of the project, the following table was created to pair them down into fewer, more manageable categories. These groupings for the categorical values can be seen in Table 4-1.

Table 4-1: Grouping of Categorical Variables for Bridge Fields

Categorical Variable	Original Group	Grouping 1	Grouping 2
Structure Type Main Material	Concrete	Concrete	
	Concrete Continuous		
	Prestressed Concrete	Prestressed Concrete	
	Prestressed Concrete Continuous		
Structure Type Main Design	Slab	Stringer/Multi-Beam or Girder	Girder & Floor-beam System
	Stringer/Multi-beam or Girder		
	Girder and Floorbeam System	Girder & Floorbeam System	
	Tee Beam	Other	Other
	Box Beam or Girders - Multiple		
	Box Beam or Girders - Single or Spread		
	Frame (except frame culverts)		
	Orthotropic		
	Truss - Deck		
	Truss - Thru		
	Arch - Deck		
	Arch - Thru		
	Suspension		
	Stayed Girder		
	Movable - Lift		
	Movable - Bascule		
	Movable - Swing		
	Tunnel		
	Culvert (includes frame culverts)		
	* Mixed types		
	Segmental Box Girder		
	Channel Beam	Channel Beam	
	Other		
Deck Structure Type	Concrete Cast-in-Place		
	Concrete Precast Panels		
Bridge System	Interstate		
	Primary		
	Secondary		

Table 4-1: Grouping of Categorical Variables for Bridge Fields (cont.)

Categorical Variable	Original Group	Grouping 1	Grouping 2
Wearing Surface Type	Monolithic Concrete	Monolithic Concrete	
	Integral Concrete	Integral Concrete	
	Low Slump Concrete	Low Slump Concrete	
	Latex Concrete or similar additive	Other	
	Epoxy Overlay		
	Bituminous		
	None	None	
Superstructure Type	Various Original Longer Descriptions	PPC	Precast
		Precast	
		Prestressed	
		RC/PPC	
		RC/Precast	
		RC/Prestressed	
		RC	RC
		RC/Ibeam	
		Steel	Steel
		RC/Steel	
		Timber/Steel	
		Timber	Timber
		RC/Timber	
		Steel/Timber	
		Other	Other
		RC/Other	

The mixture design data did not contain a substantial number of outliers since it contains information that is not derived by experimental means. However, some missing or miss-entered values were removed from the dataset. In cases where the condition rating of a bridge deck was recorded as “N”, or had no condition rating listed, those records were removed from the dataset.

Natural deterioration of the concrete used for a bridge deck can be observed until any corrective activity such as repairs or new construction occur. With the goal of determining how to remove the need for maintenance for a greater period of time, a database of maintenance actions on bridges was obtained from NCDOT, and bridges with maintenance data indicating significant actions (ranging from major patching to reconstruction) for the bridge deck were removed. This allows for the study to focus on how the concrete performed prior to any maintenance actions, and determine what materials influenced the bridge decks life span before any such corrective activity.

4.1.1.1 Comparison with Bridge Deck Deterioration Model

Deterioration of the bridge components can be linked to a number of factors, such as age, daily traffic, environmental conditions, design specifications, wearing surface, etc. Physically, this deterioration is seen through the condition of the bridge, with noticeable damage such as steel corrosion or concrete cracking or spalling being easily observable. Deterioration modeling is a way of linking the influential components to the observed deterioration of the bridge.

This analysis employed a model of expected bridge deterioration in order to differentiate between structures that either exceeded or fell short of typical service life expectations for North Carolina. Deterministic deterioration models are be based on statistical measures like mean, standard deviation, and linear regression coefficients (Goyal 2015).

For the major components of a bridge (deck, superstructure, and substructure), the NCDOT has an assigned condition rating through the inspection process. This rating can be compared to the predicated value at that age in a deterioration model created for the state bridges, and then that difference can be statistically modeled against the material properties. The dissertation "Development of a Survival Based Framework for Bridge Deterioration Modeling with Large-Scale Application to the North Carolina Bridge Management System" (Goyal 2015) contains the deterministic deterioration models created for NCDOT maintained bridges for different bridge components, broken down by individual material type (concrete, steel, or timber). These models, updated in 2015, are overly pessimistic, and typically the components would remain within a condition rating for long than predicted within the model. For a concrete deck, the deterministic deterioration model is shown in Figure 4-1. This model was created independently from the work done in this present study, but as the work performed on Goyal's dissertation was based on data obtained from North Carolina bridges and is used by the NCDOT in applicable decision making processes, it was used in this study.

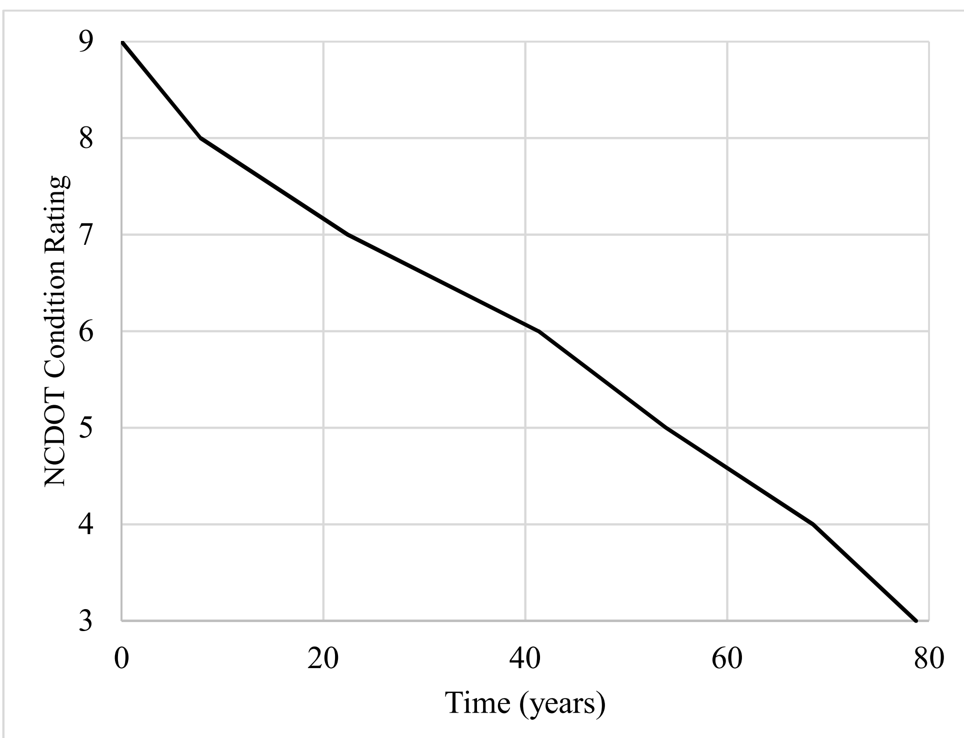

Figure 4-1: Concrete Deck Deterministic Model (Goyal 2015)

As a reminder, the rating for any part of the structure is a value between 0-9, and a condition rating of "N" implies that it is not applicable. The definitions of those ratings, taken directly from the FHWA Coding Guide ((FHWA 1995) are as follows:

N NOT APPLICABLE

9 EXCELLENT CONDITION

8 VERY GOOD CONDITION - no problems noted.

7 GOOD CONDITION - some minor problems.

6 SATISFACTORY CONDITION - structural elements show some minor deterioration.

5 FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling or scour.

4 POOR CONDITION - advanced section loss, deterioration, spalling or scour.

3 SERIOUS CONDITION - loss of section, deterioration, spalling or scour have seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.

2 CRITICAL CONDITION - advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored it may be necessary to close the bridge until corrective action is taken.

1 "IMMINENT" FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.

0 FAILED CONDITION - out of service - beyond corrective action.

The difference between the actual bridge condition rating and the rating expected from the model was calculated for each of the available bridge records. For multiple linear regression modeling, the independent variables included the mixture design parameters and the early age properties. The dependent variable was represented by the difference between the expected (modeled) and actual condition rating.

To support the analysis, two categories were considered: bridges that can confidently be seen as under-performing by reaching a lower condition rating at an accelerated pace, and bridges that can confidently be seen as over-performing by maintaining a condition rating higher than expected for their age. This can be done by removing the "middle group": bridges that reach the expected condition rating within a certain age range bracketing the expected age. To do this, four different approaches were considered:

1) Using standard deviation for each condition rating, and considering everything within one standard deviation as performing adequately, while everything greater than one standard deviation would be considered over-performing or under-performing and analyzed.
2) Considering the range of acceptable time to be reach the condition state as 10% of the expected age. For example, for Condition Rating 8, it is expected

to take 7.8 years to reach this level. As such, the acceptable range would be $7.8 \pm 0.1*7.8$, or 7.8 ± 0.78. This leads to an increasingly larger window of acceptable behavior over time, which is consistent with the trends in the standard deviation analysis.

3) Alternatively, the acceptable age could be taken as a standard amount from either side, such as an overall range of 10 years. This would lead to a more uniform reduction, but may not take into account the idea that the standard deviation changes over time.

4) Since the ratings drop so suddenly (there is no incremental steps, such as a rating of 6.7 or 8.3), the third proposed method takes into account the idea that in the time frame between two condition states, the deck should spend about half of this time span closer to one condition rating, and the second half closer to the other. For example, the spread between 9 and 8 is 7.8 years, so theoretically the rating should be closer to 9 for the first 3.9 years, then closer to 8 for the next 3.9 years). As such, if it reaches a definite rating of 8 before that 3.9 years, it should be considered underperforming.

After considering the different benefits of the methods, the fourth method of filtration was chosen. For the first method, the standard deviations increased with age (maxing out at nearly 20 years for Condition Rating 6), and lead to the elimination of a large amount of the data (bridges considered performing as expected). While the 10% method incorporated the idea shown in the standard deviation method, the range for the lower condition ratings was too large (statistically the standard deviation increased until it reached condition rating 6, then started to decrease). The 10-year method (or any fixed number of years) is useful but was judged to be more appropriate for a model where the original line is more linear and the age gaps are not varying so much. The time halfway method accounts for the gradient between condition states and seems to be the most realistic of the three, so it was chosen. This is shown graphically in Figure 4.2.

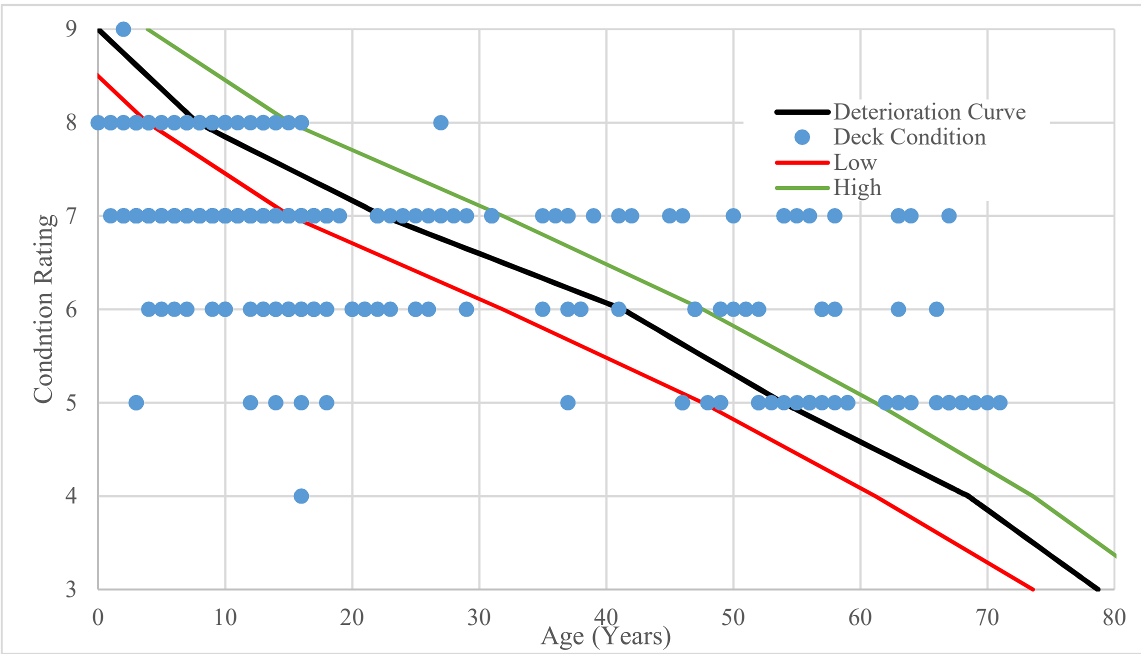

Figure 4-2: Proposed Bridge Deck Removal by Time Halfway Between Condition Ratings

When applied to the data, the amount of data in each category is shown in Table 4.2, and the number of bridges per condition rating that fall into those categories is shown in Table 4.3.

Table 4-2: Number of Bridge Decks within Specified Ranges

Range	# of Bridges	# of Records
Under	283	12077
Inside	120	4783
Over	49	861

Table 4-3: Number of Bridges per Condition Rating within Specified Ranges

Rating	# of Bridges		
	Under	Inside	Over
9	0	1	0
8	12	34	3
7	230	62	22
6	31	7	11
5	9	16	13
4	1	0	0
3	0	0	0

Overall, the majority of the bridges that are being included in this study are considered to be under-performing. Condition rating 7 has the highest number of under-performing bridges, with many of them reaching this condition before 10 years (it is expected to reach this condition rating closer to 22 years). Condition Rating 6, which had the highest standard deviation, also has much higher numbers of bridges outside of the expected region (considered either under-performing or over-performing) than inside it.

Class AA concrete mixtures were identified as the mixtures used for the concrete deck, based on the amount of compressive strength in comparison with the other available mixture types and all other concrete classes were removed. To control for any cases where a bridge used multiple mixtures (as determined by examining for bridges with early age tests for multiple mixture designs), any bridge with more than one unique mixture was removed. Due to the level of uncertainty of how much concrete was actually constructed using that mixture design, where that mixture is located on the bridge, and how the condition of the section with that mixture is separate from the entire bridge deck, this filtration decreases the possibility of incorrectly assigning a level of impact to the wrong mixture design.

Several potential modeling techniques were available for analyzing the data as are described in the following list:

1. ANCOVA

   In ANCOVA, also known as the Analysis of Covariance, the main effects and interactions of independent variables (IV's) are assessed after dependent variable (DV) values are adjusted for differences associated with one or more covariates (CV's). The attractiveness of this method includes increasing the sensitivity of the main effects and interactions by reducing the error term, which is adjusted by the relationship between the DV and the CV's (and hopefully reducing that error), as well as adjusting the means on the DV themselves to what they would be if all subjects has equal values for their CV(s) (Tabachnick and Fidell 2007).

   Having the ability to adjust for variables such as age and ADT would be helpful, but unfortunately for this method, it takes every continuous variable as a covariate. This means that the dependent variable (in this case, the difference between the expected and actual condition rating) would be adjusted for every continuous variable, while only be compared to the categorical ones. Since the mixture design proportions are mostly continuous, ANCOVA would not be able to produce useful results.

2. General/Stepwise Regression

   Condensing the analysis down to just the mixture design variables as the independent variables, and using the difference between the expected and actual condition rating as the dependent variable in theory should determine which mixture design characteristics are most related to performance (either under-performing or over-performing). This approach was attempted. However, three general issues emerged to indicate this approach was problematic:

1. Too many variables were removed at the beginning of the analysis
2. Too many variables violated the VIF threshold of 10
3. When VIF was met, all of the variables turn out to be statistically insignificant with a p>0.05.

Since the number of samples are low, as well as well as minimal variation in the variables and a reduced overall number of variables, the results from this method were inconclusive.

To simplify the data down to a more manageable level, categorical variables such as superstructure type, wearing surface type, etc. were removed or converted to continuous where possible. For example, instead of using “Pozzolan Type” as a categorical variable, new fields were created for each pozzolan type. This is better shown in Table 4-4.

Table 4-4: Example of Converting a Categorical Variable into a Continuous Variable

Pozzolan Amount	Pozzolan Type
172	Class F Fly Ash
0	No Pozzolan
110	Class C Fly Ash
172	Class F Fly Ash
319	GGBFS

→

Pozzolan Amount	Class C Fly Ash Amount	Class F Fly Ash Amount	GGBFS Amount
172	--	172	--
0	--	--	--
110	110	--	--
172	--	172	--
319	--	--	319

Since the early age data was relatively accurate to the prescribed or required amount (see Section 6.1), as well as the fact that not all bridges have an equal number of early age records, the early age records were also removed. This left the original mixture design parameters (with the pozzolan amount field divided into fields and amount for each type), the condition rating, and the difference in anticipated condition rating (from the model) and the actual condition rating. With the data now divided into under-performing and over-performing bridge decks mixtures (based on the condition rating), the mean design value for each variable was calculated. During this process, it became evident that in some cases, the mean for certain variables tended to be higher in the over performers, and in some cases the mean of certain variables was higher in the under performers (the means were never equal for any variable). Because the design values for each mixture design parameter do not fluctuate much, the difference in the means tended to be low. In statistical analysis, visual inspection alone is not accurate enough to determine which differences were actually significant.

This led to the use of two corresponding types of analysis for comparing the mean and standard deviation of two groups: t-test and group difference modeling. The theory behind these methods is explained in greater detail in Sections 2.3.5 and 2.3.6, and the specific application of those methods for this research, including specified confidence levels, is outlined in Sections 5.1.6 and 5.1.7.

4.1.2 Data Condensing for Concrete Pavement Performance

Before the pavement data from the various NCDOT databases could be used in modeling, it was pre-processed. The process used to combine information from several pertinent databases is outlined in Chapter 3, Section 3. For this part of the project, information pertaining to mixture design components, early age test data, and demographic data such as age, location, ADT, etc. was used.

At this stage in the analysis, the field “System” was removed, as there are only two types present in the six roadways that were included in the final dataset (Interstate and US), with five out of six being defined as Interstate. This stage of the analysis was intended to include the early age data, but due to limitations in the data processing, the results from the early age tests could not be linked to individual sections of the roadway. As a result, any mention of the early age data in this section will be for future studies where it could be possibly used.

4.1.2.1 Comparison with Concrete Pavement Deterioration Model

As part of the work done for NCDOT Project 2011-01 [Development and Validation of Pavement Deterioration Models and Analysis Weight Factors for the NCDOT Pavement Management System (Phase I: Windshield Survey Data)], JCP performance models were created. This model will be used as a base for the predicted condition of a roadway, plotted against the age of that section of roadway. The model uses the following Sigmoidal equation (Chen et al. 2014):

$$y = \frac{a}{1+e^{-\frac{x-b}{c}}} \quad (4.1)$$

Where: $y =$ Estimated pavement rating

$x =$ Pavement age

$a, b, c =$ Model parameters

For JCP: $a = 200$

$b =$ -0.144846685

$c =$ -29.8908026

For the pavements used in this study, the curve created from the model parameters is shown in Figure 4-3:

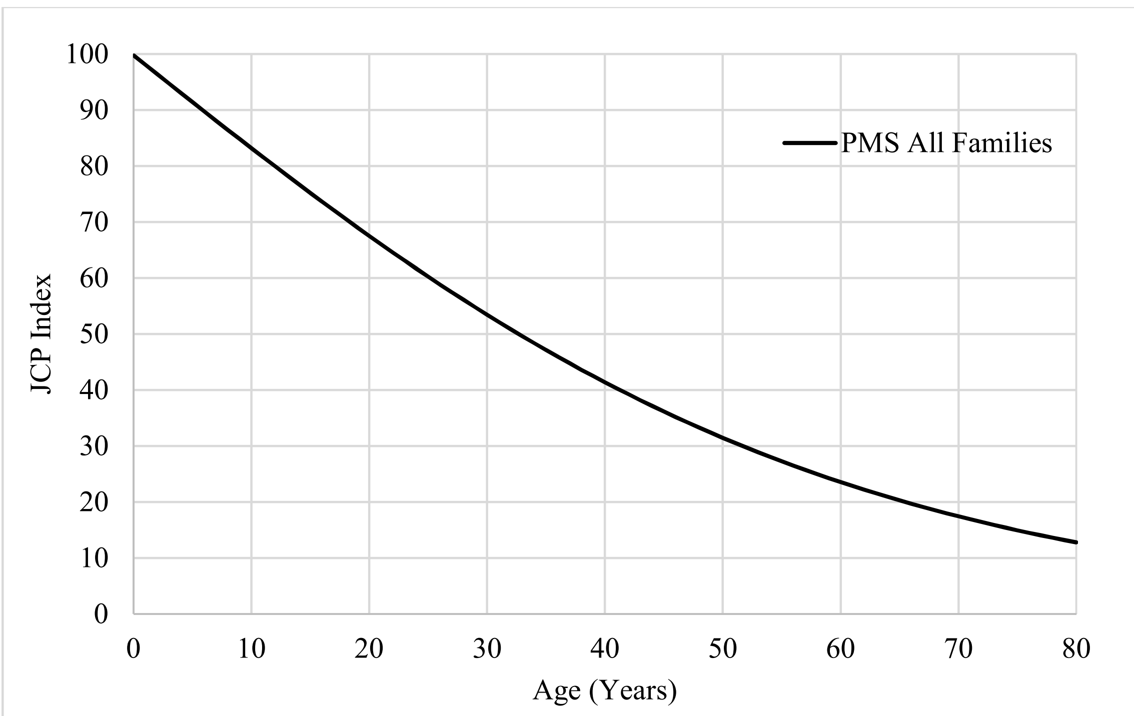

Figure 4-3: Sigmoidal Performance Model Parameters for JCP Pavements

The condition ratings for each section of pavement, as they changed over the time period for which rating data was available, were graphed against this deterioration curve. The following figure (Figure 4-4) shows the result of this graphing. Please note that while there are many colors present, no single color represents all of one roadway (for example, not all of the blue markers correspond to records from I-85 in Durham). Markers of the same color near each other are from the same section of roadway (the condition rating stays fairly stable, and as such most sets of markers will appear to be in a straight horizontal line).

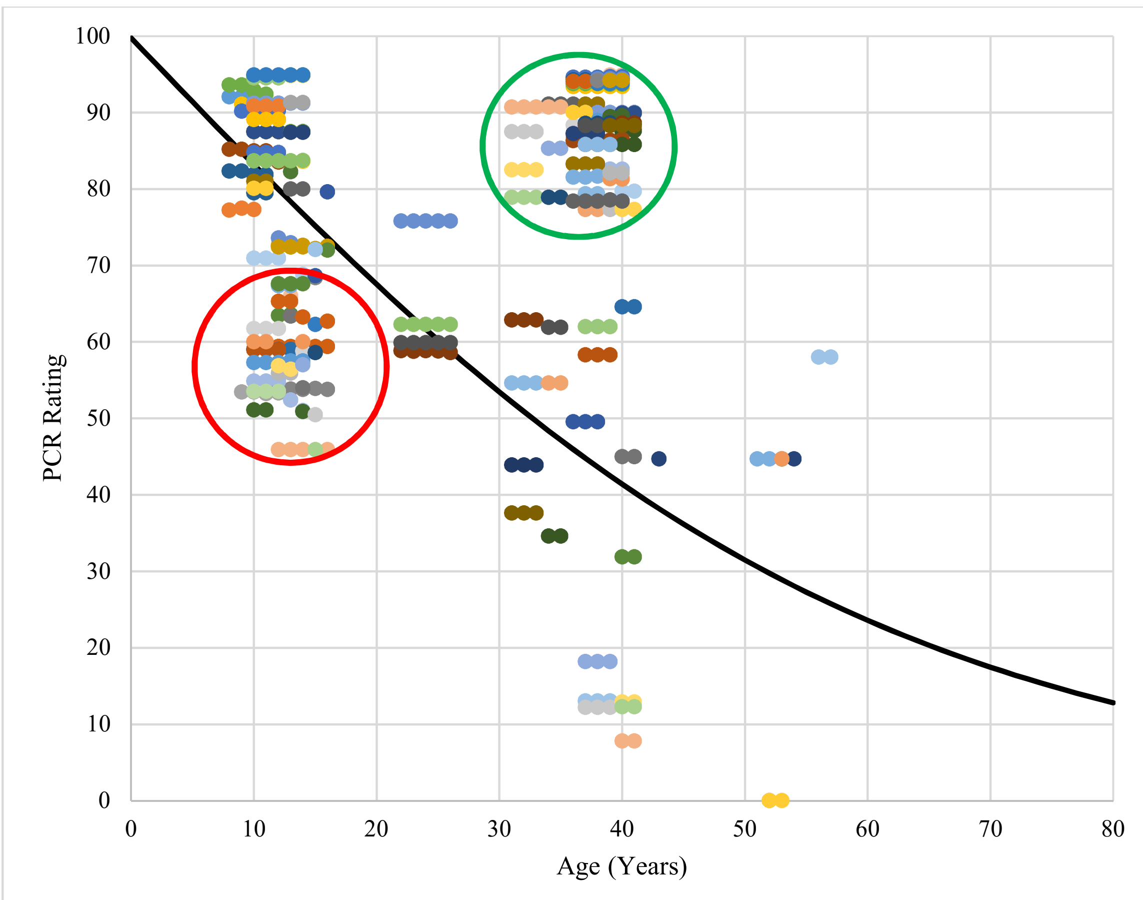

Figure 4-4: Pavement Roadway Section Condition Ratings plotted with Established Deterioration Model

Since this section of the analysis is more prescriptive of the way that the analysis should be performed instead of descriptive on the exact condition of roadways (due to the limited spread of data), the method for determining high and low performers is more general. Since the data tended to form a few groups, the sections of roadway in the green circle were defined as the over-performing sections, and the ones in the red circle were defined as the under-performing sections of roadway. To provide a better overview of the categories, the following is a rough description of what is considered as over- and under-performing:

- Over-performing: sections of roadway between the ages of 30 and 45 years and have a condition rating of greater than 75
- Under-performing: sections of roadway that reach a condition rating of lower than 70 before reaching the age of 20 years

Breaking down the data into these two categories, the number of sections (and the corresponding number of records) included in each performance category are shown in Table 4-5.

Table 4-5: Pavement Sections per Condition Category for Analysis

Data Type	# of Over-performing	# of Under-performing
Individual Sections	54	29
Individual Records	143	78

Since these sections are spread out between only six roadways (see Table 3-8), and each of those roadways only used one mixture design, there are five unique mixture designs represented in the final dataset.

CHAPTER 5 MODELING PARAMETERS

5.1 Overview of the Modeling Process

The new models created in the course of this study, and the information that they provide, are intended to be used by the NCDOT to evaluate the effectiveness of concrete mixture specifications to ensure durability and long, maintenance free service life. Modifications to these specifications could directly impact the way that producers will design the concrete mixtures in the future by enabling greater performance-based specifications. To support these new specifications, data gathered by the NCDOT linked to previously accepted mixture designs, early age testing of those designs, and the long term performance of the roadways featuring those designs were compared using modeling techniques such as stepwise regression and canonical correlation. The models were used to highlight aspects of the concrete mixtures that, based on historic data, have the most significant impacts on long term performance. For this work, multiple models were developed. The overall process is outlined in Chapter 3, in Figure 3-1.

5.1.1 Model Development Process

Research performed linking specific concrete early age test results to the mixture design served as a base for the modeling process. In a study from the civil engineering department at Queen's University, Kingston, Ontario, Canada, researchers studied the factors affecting strength and durability of concrete with various cement types (Rose et al. 1989). While this is not exactly the same aspect of performance that was studied in this analysis, the modeling procedure for defining the relationship between mixture design components and early age properties is applicable. The Queens University study consisted of two parts: a correlation analysis, and a regression analysis.

To define relationships between mixture design variables and early age characteristics, a hybrid of canonical correlation and stepwise regression was employed. First, canonical correlation was performed using the SAS software (SAS Institute Inc. 1994). All categorical and continuous variables available in the condensed dataset were input as possible predictors. The SAS software determined how the variables were related to each other, as well as to the final dependent variable. The results from the correlation analysis were taken into consideration when performing stepwise regression on the data in Minitab (Minitab 2017), a user friendly statistical software program that allowed easy modification of input values while performing regression analysis. Again, all usable categorical and continuous variables were included as possible predictors, and with each computational step, the statistically-significant variables were added or removed based on their significance. Significance was determined using both p-values and VIF, a process outlined in Section 5.1.3.

To determine the relationship between concrete mixture design and long term performance, the procedure was different. All of the records were compared to a deterioration curve, dividing the records into groups that exceeded or fell short of performance expectations (see Section 4.1.1.1 for bridges and Section 4.1.2.1 for pavements). The two outer cases (under and over performing) were compared to each other using a t-test method. This provided an indication of which characteristics of the groups are significant to influencing performance. Thus, it was determined which mixture design components were not only the most influential, but also how sensitive the outcome is to increasing or decreasing their magnitude. These results were also evaluated with the group difference modeling option in Minitab.

5.1.2 Preparation of the Databases

Before the data provided in the various NCDOT databases could be used for modeling, it was pre-processed (consolidated, filtered, and formatted). The process used to complete this task is described in Chapter 3. For this project, two main databases were used, one for the bridge data and one for the pavement data.

5.1.3 Stepwise Regression

An overview of stepwise regression as a statistical method is provided in Section 2.3.4. For this study, the stepwise function in Minitab (Minitab 2017) was used to examine the data. This function can perform multiple different methods: forward and backward stepwise regression, as well as a combination of both. With the forward pass method, the program initially begins with one predictor variable, and continues to add predictor variables into the model in one at a time until the target alpha value has been reached. The backward elimination method does the opposite of this, starting will all possible predictor variables included in the model and removes them one at a time until the alpha value is reached. The combination stepwise procedure, the method chosen for this study, adds predictor variables one at a time, removing any that become statistically irrelevant during the process. The alpha value sets the threshold value from the minimum amount of significance required for a variable to be kept in the regression equation.

For this project, stepwise regression was chosen with an alpha value of 0.05. This allowed for the terms to be examined, and either be removed by the program if they were deemed statistically irrelevant due to a p-value that exceeded the threshold, showed how the variables interacted with each other, and allowed for manual elimination by considering the VIF value.

The Minitab software package includes built-in parameters for aiding in inclusion of categorical values in the analysis. To do this, the program creates several different models for each group within the categorical variables. There is also a second option, where a single model is developed, and each categorical case is treated as a binary variable. For example, the superstructure of a bridge deck can be steel, timber, or concrete (to simplify for the purpose of this example). Instead of creating three separate equations for each, Minitab can present one singular equation where each possible option for a categorical value is represented by a set of binary variables. Between these two methods, the one that fit the data better and allowed for ease of analysis was chosen.

While performing multiple linear analysis, a multicollinearity check was performed on all of the independent variables. Minitab generates the Variance Inflation Factor (VIF) as a component of the regression model. For this study, a VIF threshold value of 10 was strictly enforced, unless a variable could be labeled as an exception to this rule (See Section 2.3.4). Within the categorical values, there is always a possibility that an individual group would have a p-value of greater than the threshold value of 0.05, or a VIF value above the threshold of 10. When this occurred, there were two options:

1. If the population for those groups were relatively small compared to the data set, they could be left alone. Since the end goal is not to create a predictive equation, but rather to determine the most influential factors, removing them was of little importance if it did not impact other variables.

2. If the number of individual variables in a category was low, and one or more violated the threshold values, and keeping them in would cause other continuous variables to violate the threshold values, then they were removed. An example of this is in the modeling for “Difference in Compressive Strength” for pavement mixtures, were the VIF values on both pozzolans were high or over 10, and were also causing the VIF for the “Pozzolan Amount” variable to exceed 10.

Because of the potential for large amounts of variance in the data, the R-squared value for any stage of the analysis may be small. While a low R-squared value is not preferable, they can still be considered as acceptable. The p-value must always meet the required threshold of $p < 0.05$ for a variable to remain in the regression equation.

5.1.4 Canonical Correlation

An overview of stepwise regression as a statistical method is described in Section 2.3.3. Within the SAS software (chosen for this side of the analysis because Minitab does not have a canonical correlation function), CANCORR find a canonical variable between two sets of data, such that the correlation between the canonical variables is maximized. This correlation is known as the first canonical correlation. Typically, these coefficients are normalized such that each canonical variable has a variance of one. CANCORR then continues to determine the second set of canonical variables, and produces the second highest correlation coefficient. This process is repeated until the number of pairs of canonical variables equal the number of variables of the smaller group (i.e. the number of fields).

As part of the calculation process, canonical correlation determines the correlation between the data: Between individual IV’s and themselves and other IV’s, between individual DV's and themselves, and between individual IV's and individual DV's. Mathematically and practically, this is the easiest information to use in tandem with the stepwise regression analysis.

5.1.5 Relationship between Stepwise Regression and Canonical Correlation Results

While stepwise regression and canonical correlation are processed separately, identifying the relationship between the two methods to determine the final results was necessary. Canonical correlation was performed first, since the results are separate from regression and provide an overview of how the variables relate to each other.

Since the variables often do interact and overlap with each other, the results of the stepwise regression will have variables with VIF values that exceed the threshold value of 10. Determining the correct ones to remove is made easier when using the knowledge base created from the correlation analysis. For example, the Figure 5-1 shows the results from Minitab after a few variables have already been removed:

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-6499	626	-10.38	0.000	
Mortar Content	-318.0	35.7	-8.91	0.000	69.89
Cement Amount	7.963	0.385	20.68	0.000	97.15
Pozzolan Amount	7.189	0.459	15.68	0.000	126.05
Fine Aggregate Amount	3.710	0.202	18.34	0.000	48.67
Fine Aggregate Spec Gravity	-808	143	-5.64	0.000	1.48
Coarse Aggregate Amount	0.6497	0.0508	12.79	0.000	5.13
Air Content	274.6	89.1	3.08	0.002	1.06
Slump	-79.80	3.85	-20.71	0.000	3.42
W/C Ratio	5101	315	16.22	0.000	18.99

Figure 5-1: Stepwise Regression Results Before Removal of Cement Amount

In its current state, five of the variables have a VIF value greater than 10, indicating that one (or more) should be removed. For instance, "Pozzolan Amount" appears to be the most obvious choice for removal, as it has the highest VIF value. However, when examining the correlation results, "Pozzolan Amount" is the third highest in correlation with the difference between design and actual flexural strength. These correlation results are shown in Table 5-1.

Table 5-1: Correlation Results for Comparison between IV's and Difference in Flexural Strength

Variable	Correlation to DiffinFlexuralStrength	Correlation Rank
Fine Aggregate Amount	0.4533	1
Mortar Content	0.396	2
Pozzolan Amount	-0.3242	3
Cement Amount	0.3226	4
Coarse Aggregate Amount	-0.2749	5
Yield	0.2302	6
Water Amount	0.223	7
W/CM Ratio	0.1838	8
Coarse Aggregate Spec Gravity	0.1557	9
Fine Aggregate Spec Gravity	0.1402	10
Slump	0.0887	11
Aggregate Content	-0.0309	12
Paste Content	0.0241	13
Max W/CM Ratio	0.0223	14
Air Content	0.0143	15
Maximum Water	0.0032	16
Latex	0	17

Since the variable, "Cement Amount," is ranked lower but still has a very high VIF, it is removed instead. These two variables have a high negative correlation between each other (around -0.6), so removing one will potentially help decrease the VIF value of the other. As such, "Cement Amount" was removed from the regression equation. Figure 5-2 shows the results of this action on the VIF values of the remaining variables:

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-25588	1045	-24.48	0.000	
Mortar Content	376.7	13.3	28.40	0.000	9.56
Pozzolan Amount	-2.2487	0.0698	-32.24	0.000	2.89
Fine Aggregate Amount	-0.4515	0.0557	-8.11	0.000	3.65
Fine Aggregate Spec Gravity	988	134	7.38	0.000	1.28
Coarse Aggregate Amount	0.7265	0.0507	14.34	0.000	5.05
Slump	-50.10	3.34	-15.01	0.000	2.54
W/C Ratio	-1321	118	-11.21	0.000	2.64
Yield	632.9	32.6	19.39	0.000	1.16

Figure 5-2: Stepwise Regression Results after the Removal of Cement Amount

As shown, removal of this one variable allowed all of the other variables to now have a VIF value of under the threshold value of 10. As a side note, in this situation, removal of "*W/CM* Ratio" (ranked 8th in correlation) instead of removing "Cement Amount" caused "Pozzolan Amount" to be removed from the regression equation. Because "Pozzolan Amount" (ranked at #3) is a higher correlated variable than "Cement Amount" (ranked at #4), that result is less useful (as maintaining as many highly ranked variables is the end goal). Other potential issues include causing important variables to violate the VIF or p-value threshold, as well as causing the coefficient itself to violate the p-value threshold. This process of removal will be applied to all instances of analysis similar to the example above.

5.1.6 T-Test

An overview of the theory and equations behind the t-test is described in Section 2.3.5. Since the equations used for this test are not overly complicated nor are they extensive, this procedure can be performed in Microsoft Excel. In order to minimize the potential for calculation error, individual pieces of the larger equations should be evaluated separately then combined for the final calculation.

For this project, equal variance between the means of the individual groups was not assumed, in an effort to cause the final results to provide a clearer picture of the trends in the mixture design proportions. Therefore, the group variance was tested in Minitab. Within Minitab, under the ANOVA umbrella there is an option for "Test for Equal Variance". All variables considered in the t-test and in the group difference modeling procedure were checked using this test, at each relevant confidence level.

Because there is potential for a variable to have either have or not have equal variance, both t-values and degrees of freedom were calculated for both cases. This allowed for the correct evaluation to be performed at each confidence level. The t-test was be administered at three different confidence levels: 95%, 90%, and 80% to allow more opportunities for variables to be maintained as significant, as well as rank the overall level of importance of certain variables.

Once all the t-values were calculated, they were compared to the values found in a typical t-distribution probabilities chart. As this is a two tailed test, it is important to remember to divide the α that corresponds with the confidence level by 2. If $|T| > t_{1-\alpha/2}$, then the null hypothesis that the means are essentially the same is rejected. The values for $t_{1-\alpha/2}$ can be determined by manual inspection.

5.1.7 Group Differences

The primary function of including the group differences is as a secondary check to the t-test. A brief description of the test is described in Section 2.3.6. Since there are three potential confidence level chosen for this study (95%, 90%, and 80%), the tests must be performed for each variable at each level, as is necessary to examine all of the variables.

If at any confidence level, the variance switches from equal to not equal (as determined through the “Test for Equal Variance” option in Minitab, outlined in Section 4.1.6), then for that variable at that confidence level and any lower confidence level, it was examined using the Games-Howell Method (Minitab 2018). If the variance stays equal (or can be assumed to be equal), then the Dunnett Method is used (Minitab 2018).

The results from this test should mirror the results determined using the t-test. If they do not, then the procedure for both tests should be examined for that variable to make sure that there are no errors in either the calculation or comparison of the t-value, nor errors in performing the group difference analysis.

CHAPTER 6 BRIDGE DECKS

The NCDOT monitors and maintains nearly 22,000 bridges, culverts, and overhead signs in the state, and stores records of characteristic and condition data in the BMS in a database called the "Network Master." The analysis performed in this section only uses the portion of those bridges that can be linked to concrete mixture design(s), as well as early age concrete test data.

6.1 Construction Tolerances for Bridge Concrete Mixtures

Concrete is designed to meet several prescriptive specifications. During construction these are checked by three primary early age tests: air content, slump, and compressive strength. In Chapter 10 of Standard Specifications for Roads and Structures, the NCDOT presents their threshold values for all three components tested at early age. As it is difficult to get the exact air every time, a tolerance of ±1.5% of the target air content (5.0%) to allow for more mixtures to be approved. For slump and compressive strength, the minimum values depend on the concrete type, and are found in Table 1000-1 (NCDOT 2018). A summary of the relevant components of that table are shown in Table 6-1.

Table 6-1: Excerpt from NCDOT Table 1000-1

Type of Concrete	Air (%)		Max Slump (in)		Strength (psi)	
	Between X of target 5.0%		Vibrated	Non	Day	Min *f'c*
Class AA	-1.5	1.5	3.5	-	28	4500
Class AA, Slip-form Barrier Rail	-1.5	1.5	1.5	-	28	4500
Drilled Shaft	-1.5	1.5	7	9	28	4500
Class A	-1.5	1.5	3.5	-	28	3000
Latex Modified Concrete	-1.5	1.5	6	-	7	3000
Flowable Fill	-1.5	1.5	-	-	56	150
Pavement	-1.5	1.5	1.5	-	28	4500
Prestress	-1.5	1.5	8	-	-	-
High Early-strength Patching Mix	-1.5	1.5	-	-	-	-
Class AAA	-1.5	1.5	-	-	-	-

Deviation outside of the specified air content range, as well as mixtures that fail to meet the maximum slump and minimum compressive strength requirements, can lead to performance issues, as there is an increased likelihood that the concrete cannot be adequately placed and consolidated (for low slumps) or exhibit segregation or other issues (for high slumps).

To assess the quality of the concrete used for bridge deck projects in North Carolina as compared to their design specifications, Figure 6-1 shows the percent of mixtures accepted with air contents that fit the specified range (5.0 ± 1.5%), broken down by concrete type:

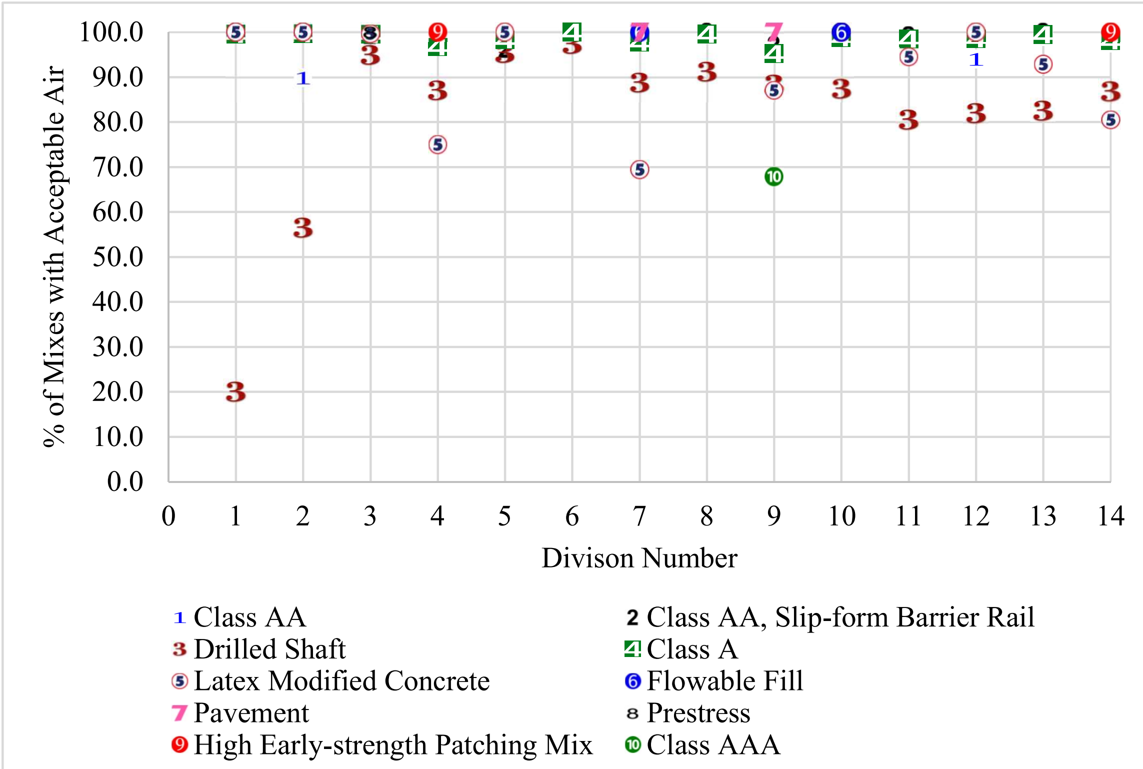

Figure 6-1: Percent of Accepted Mixtures with Adequate Air Content, Divided by Concrete Type

Ideally, all of the mixture types would have a "% of Mixtures with Acceptable Air" value of 100%, but in many cases, this was not true. While some concrete types tended to be mostly accurate (such as Class A), others varied dramatically (such as Drilled Shaft). These variances can lead to an increased potential for freeze-thaw damage (in the case of low air) or strength or permeability issues (in the case of high air).

The same type of analysis was performed on both the slump and compressive strength, comparing the NCDOT maximum/minimum requirements to the accepted slump and compressive strength. These are shown in Figures 6-2 and 6-3:

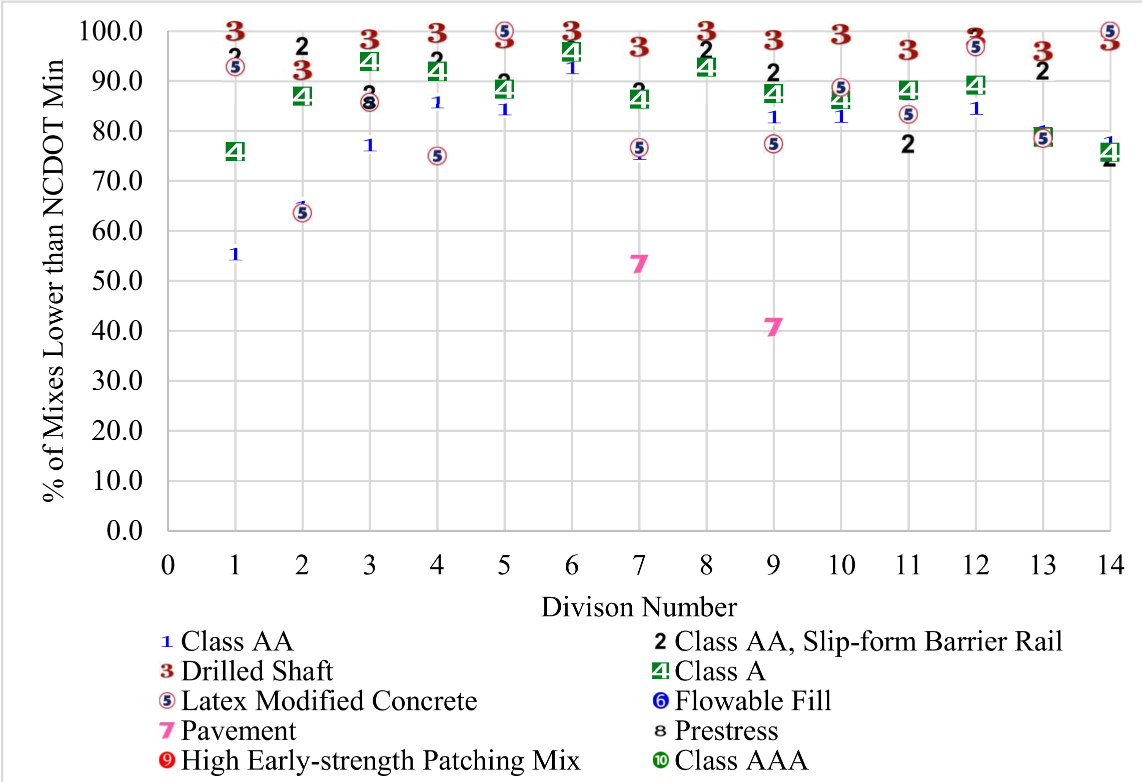

Figure 6-2 Percent of Accepted Mixtures with Adequate Slump, Divided by Concrete Type

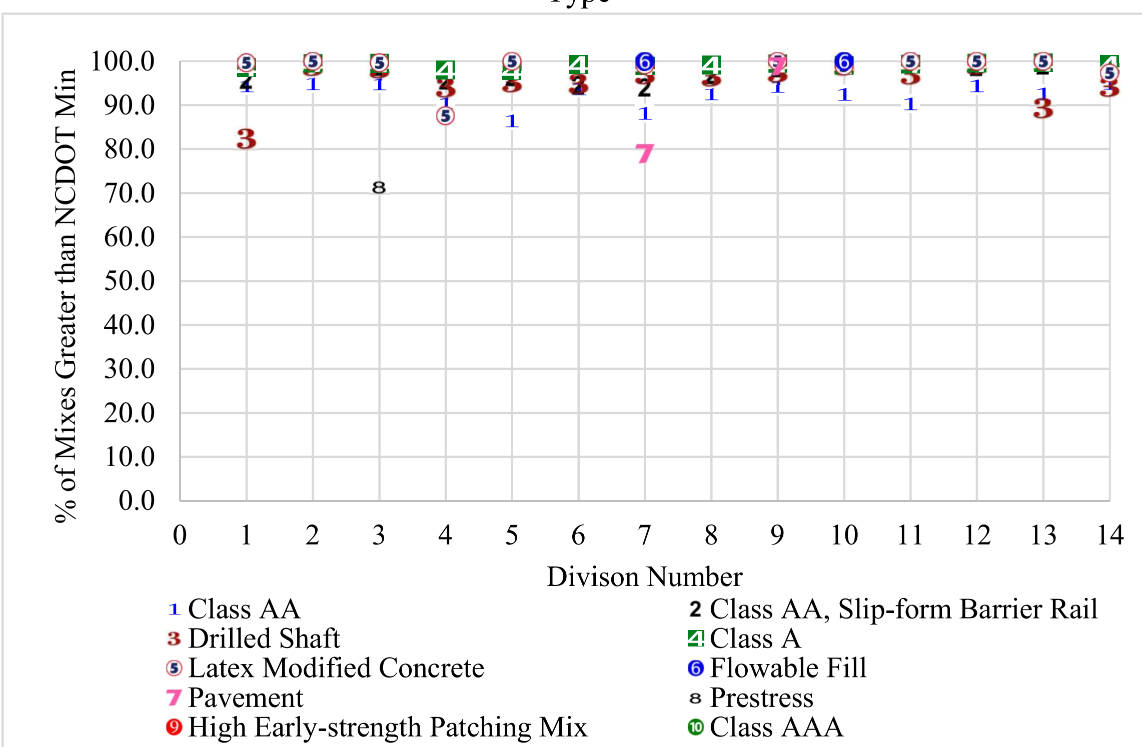

Figure 6-3 Percent of Accepted Mixtures with Adequate Compressive Strength, Divided by Concrete Type

With the exception of a few outliers, most of the accepted mixtures comply with the standards and specifications set by the NCDOT. Table 6-2 and corresponding graph in Figure 6-4 provide a summary of the data. This summary is broken down in a way to show the number of data points for each concrete type for each early age test.

Table 6-2: Percent of Mixtures Meeting Early Age Test Targets from NCDOT Specifications

	Concrete Type		Total Number	% Within Target Range
Air	1	Class AA	15073	97.5
	2	Class AA, Slip-form Barrier Rail	1878	99.1
	3	Drilled Shaft	8581	89.1
	4	Class A	13913	98.4
	5	Latex Modified Concrete	949	94.0
	6	Flowable Fill	2	100.0
	7	Pavement	102	100.0
	8	Prestress	7	100.0
	9	High Early-strength Patching Mix	18	100.0
	10	Class AAA	28	67.9
Slump	1	Class AA	15073	79.8
	2	Class AA, Slip-form Barrier Rail	1878	90.4
	3	Drilled Shaft	8581	98.2
	4	Class A	13913	86.9
	5	Latex Modified Concrete	949	86.2
	7	Pavement	102	42.7
Compressive Strength	1	Class AA	15073	92.5
	2	Class AA, Slip-form Barrier Rail	1878	97.4
	3	Drilled Shaft	8581	96.5
	4	Class A	13913	99.1
	5	Latex Modified Concrete	949	99.4
	6	Flowable Fill	2	100.0
	7	Pavement	102	95.1

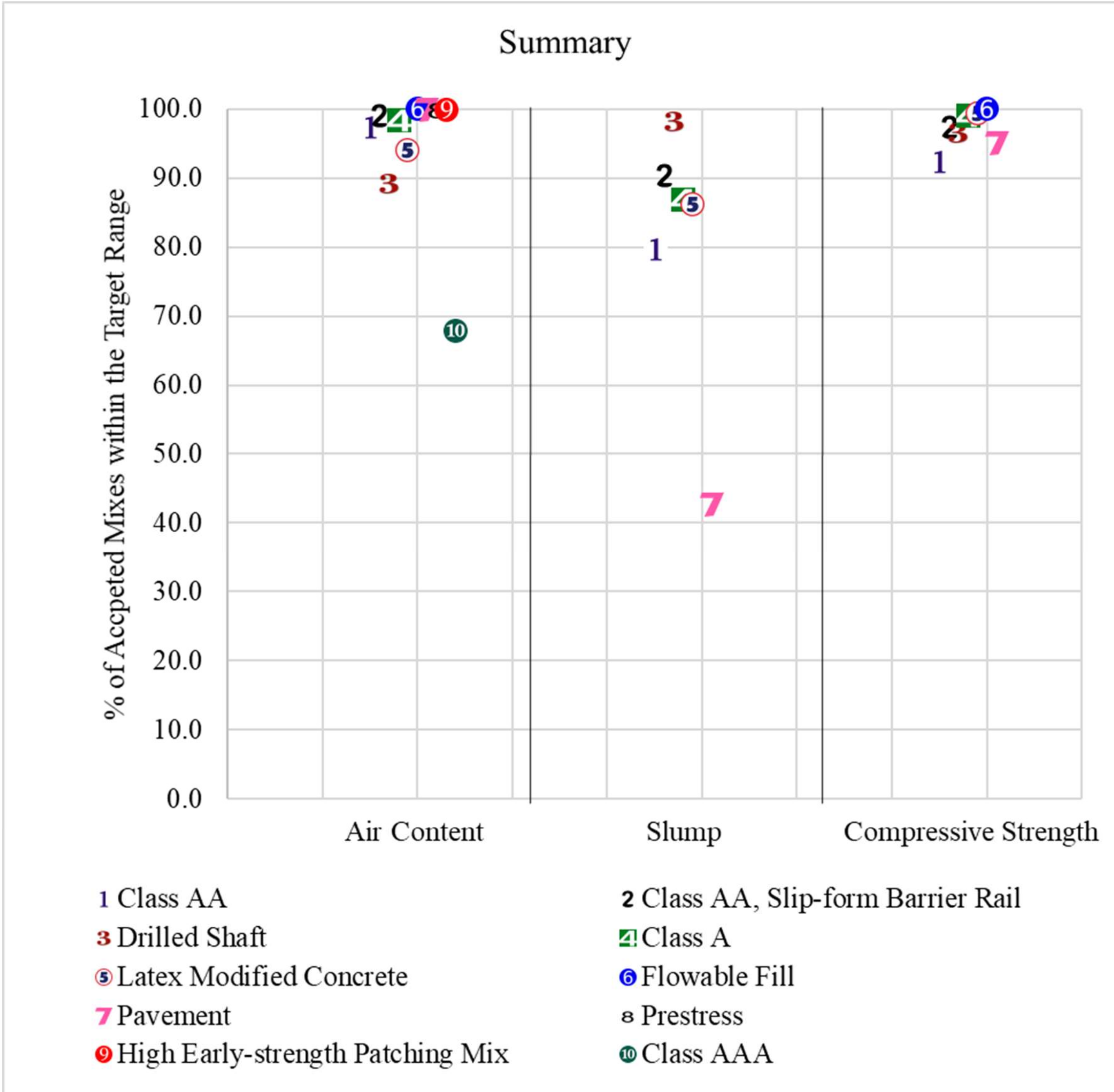

Figure 6-4: Percentage of Mixtures Meeting Early Age Test Targets from NCDOT Specifications

6.2 Statistical Analysis of Mixture Proportions to Early Age Data for Bridge Deck Mixtures

With the completion of the combined database (outlined in Chapter 3 Section 2), statistical regression for the comparison of mixture design components to each of the early age components (air content, slump, and compressive strength) was performed to identify which of the bridge mixture design variables were most influential to the fresh early age concrete properties. In multiple linear regression modeling, there are the two sets of variables: the independent variables, represented by the mixture design information, and the dependent variables, represented by the early age properties. The data pertaining to this was imported from Excel into Minitab, to allow for the performance of multiple linear regression.

To examine trends in the mixture design proportions as compared to early age properties, the following mixture design variables were selected based on the screening described in Section 3.2.1.2:

- Class of Concrete
- Mortar Content
- Cement Approved Producer
- Cement Amount
- Pozzolan Approved Producer
- Pozzolan Amount
- Pozzolan Type
- Fine Aggregate Amount
- Fine Aggregate Spec Gravity
- Coarse Aggregate Amount
- Coarse Aggregate Spec Gravity
- Water Amount
- Latex Modifier (gal.)
- Air Content
- Slump
- W/CM Ratio
- Yield
- Paste Content
- Aggregate Content

Several of the variables used in the independent variable side of the regression modeling where categorical instead of continuous, linearly related data and required special treatment. For the "Class of Concrete", Minitab has an option of including categorical variables, creating a final equation for each unique value in that variable set (as such, a different equation was created for each concrete class type). While this was useful for the analysis, the remaining categorical variables (Cement Approved Producer (CP), Pozzolan Approved Producer (PP), and Pozzolan Type (PC)) did not require their own equations. Therefore, instead of inputting these variables as categorical, the data structure, "binary variable," was used to reduce the number of produced regression equations. Each of these three categorical variables were broken down (i.e. a column was made in the spreadsheet for CP1, CP2, CP3, and so on for all three), and a value of 1 was used to indicate that the column applied, or 0 if it did not (Pardoe N.D.). This allowed for the inclusion of different potential individual producers or pozzolan types that may have an impact, while removing those who did not.

When checking for multicollinearity using the VIF value, variables like “Air Content” and “Slump” tended to be related to a VIF value of over 10. As these fall under the exceptions outlined by Dr. Allison (Allison 2012), they are allowed to remain in the analysis as long as they comply with all other requirements, such as having a p-value less than 0.05 (based on having an alpha of 0.05). If any variable (including the two mentioned above) violates the p-value requirement it is removed, but if it does not violate the p-value and does violate the VIF, it is further examined using the situations listed in Section 5.1.3.

Since the end goal of the analysis was to determine the mixture components that are most significantly correlated to an out-of-specification result, a separate column was created for the difference between the specified value of a characteristic and the measured value of the characteristic.

Theoretically, the early age values should fall into the ranges specified by the NCDOT; therefore, using the data to create equations to predict these values based on the mixture design proportions are not the end goal. Determination of the mixture proportion factors that are correlated with deviation from the design value is the focus of this study:

as such, the results from canonical correlation and the results from stepwise regression modeling can be compared to see what factors are indicated as being influential in both.

Data on incidental conditions such as mixing time, actual temperature, etc. were not available for inclusion in the analysis. As such, the following assumptions will be made:

- The prescribed mixing times are followed during the mixing of the concrete
- The surrounding air temperature during the mixing process was between 50°F and 95°F (10°C to 30°C) (except where other temperatures are required by Articles 420-8, 420-9 and 420-15) (NCDOT 2018), as prescribed in Division 10.
- The concrete is mixed using the prescribed amounts, and the number of times that was exceed for water content (i.e. approaching maximum water content) is minimal and can be disregarded.

6.2.1 Comparison of Values from Different Analysis Types

To determine which components are most influential towards causing incorrect early age values, Canonical Correlation was performed using the SAS software, while Stepwise Regression was performed in Minitab.

The decision to include the three categorical values that were "converted" into continuous using the "zero-one indicator method" ("Cement Producer", "Pozzolan Producer", "Pozzolan Type") in the analysis lead to complications that did not positively impact the interpretability of the results. Not all of the individual values were shown to have a strong impact on the early age data, but a few in each did. Because of this, all three are marked as useful and important factors, but were taken out of the correlation and regression analysis, as including each makes the data harder to read and interpret.

The following section is broken down by the early age parameter that was examined (difference in air content, slump, and compressive strength). Each section has a condensed version of the results from the canonical correlation results and the stepwise regression results. The first column is the rank of the absolute value of the correlation values, the second is the individual mixture design component analyzed, and the third is that variable's correlation to the independent variable.

In the correlation column, several are highlighted. These are the variables that remained in the regression equation after removing variables that violated the p-value and VIF requirements (except in cases where violating VIF is permitted, as discussed above).

Correlation results can be interpreted as having three different types of relationships between variables:

1. -1 to 0: Correlations falling in this range indicates a negative relationship between the variables. This means that as one increases, the other decreases.
2. 0: A correlation value of 0 indicates no relationship at all
3. 0 to 1: Correlation coefficients in this range indicate a positive relationship between the variables. This means that as one increases, the other increases as well.

The closer to 1 in the positive and -1 in the negative region indicates a stronger relationship between the two: i.e. “Paste Content” has a stronger correlation to the difference in air content than “Yield” does.

6.2.2 Results and Interpretation

The top correlation values in all three analysis types (difference in air content, difference in slump, and difference in compressive strength) are included in the regression equation, as these are the most important factors contributing to this difference. The results for each independent variable, as well as the practical interpretation is discussed in this section.

Table 6-3: Correlation and Regression Results for Difference in Air Content

Correlation Rank	Variable	Correlation to Air Content Difference
1	Design Air Content	-0.1417
2	Design Slump	0.1282
3	Paste Content	-0.1217
4	Fine Aggregate Amount	0.1108
5	Aggregate Content	0.0812
6	Coarse Aggregate Amount	-0.0786
7	Mortar Content	0.063
8	Latex Amount	0.0536
9	Coarse Aggregate Specific Gravity	-0.044
10	Water Amount	-0.0425
11	Yield	-0.0308
12	W/CM Ratio	-0.0122
13	Cement Amount	0.0089
14	Pozzolan Amount	-0.0025
15	Fine Aggregate Specific Gravity	0.0013

*Highlighted cells indicate variables present in the final regression equation

1. The design air content has a negative relationship with the difference between the design and actual air content values. This relationship means that the higher the design air content, the harder it is to actually achieve. Therefore, increasing the

design air content increases the likelihood that the actual air content will be less than the design.

2. The design slump value has a positive relationship with the difference between the design and actual air content values. Practically, this means that when the design slump is increased, there is more potential for the air content within the concrete to be larger than design value.
3. The paste content, a combination of the design cement, pozzolan, water, and air amounts, has a negative relationship with the difference between design and actual air contents. This agrees with the first factor (as air content is a component in the paste content).
4. The increase in fine aggregate amount has a positive relationship with the difference between design and actual air content. Since well-rounded particles in the fine aggregate can lead to higher air entrainment, increasing the amount of fine aggregate should positively increase the amount of air in the concrete. This relationship also indicates that suppliers in North Carolina tend to provide fine aggregate more in the middle size fractions (passing through the No. 30 sieves but retained in the No. 50), as lab testing has shown that in general, increasing the amount retained at the No. 100 sieve instead of the No. 50 sieve leads to decreased air content (Malisch 1996)

Of these top four most significant and influential variables, two are positively correlated and two are negatively correlated. Increasing the design air content and the paste content lead to a negative difference between design and actual air content, while design slump and fine aggregate content lead to a positive difference between the design and actual air content. Neither of these cases are preferable. These are some of the issues than can arise from either the air content being too low (the negative relationship) or being too high (the positive relationship):

Negative: If the air content of the concrete is too low, the workability is impacted. If a decrease in air content leads to less workable concrete, anything from the uniformity of the concrete to its finish can be negatively affected. The freeze-thaw capacity of the concrete can also become an issue, as there is not enough room for the concrete to expand without the potential of cracking. Freeze-thaw as a durability concern is discussed in Section 2.1.1.3.

Positive: While any increase in air content increases the workability of the concrete, it also increased the number of voids present in the concrete. This could increase the permeability of the concrete, which may lead to a higher likelihood of damage by water freezing in the pores left by the entrained air.

Table 6-4: Correlation and Regression Results for Difference in Slump

Correlation Rank	Variable	Correlation to Slump Difference
1	Design Air Content	0.3956
2	Design Slump	-0.2347
3	Cement Amount	-0.2154
4	W/CM Ratio	0.092
5	Water Amount	-0.0912
6	Paste Content	0.0907
7	Yield	0.0788
8	Latex Amount	-0.0691
9	Fine Aggregate Amount	-0.0676
10	Aggregate Content	-0.0669
11	Fine Aggregate Specific Gravity	-0.0428
12	Coarse Aggregate Specific Gravity	-0.0422
13	Pozzolan Amount	0.0309
14	Mortar Content	-0.0305
15	Coarse Aggregate Amount	0.0043

*Highlighted cells indicate variables present in the final regression equation

1. The design air content had a relatively strong positive correlation with the difference between design and actual slump values. This agrees with the results from the difference in air content values, and practically means that an increase in the air content (whether or not it was designed that way) leads to a higher slump, sometimes higher than desired.
2. The design slump has a negative relationship with the difference between the design and actual slump value, indicating the same principle as shown with the relationship between design air and the difference between design and actual air content: if the design value is increased, the likelihood of that value not being met is also increased. Practically, this is not a currently a major concern for North Carolina bridges (as for most concrete types, at least 80% of the accepted

mixtures are within the required range), but if the design slump is increased too much it could become an issue.

3. The cement content has a negative relationship with the difference between design and actual slump, meaning that adding more cement to the mixture decreases the slump. Logically, this makes sense since an increase in cement content tends to makes the mixture stiffer.
4. The *w/cm* ratio has positive relationship with the difference between design and actual slump amount, meaning that as the ratio is increase (either by water content increasing or cement value decreasing), the mixture becomes more workable and the slump itself increases.

While it is useful to identify the factors influencing performance, it is equally important to understand the impact that their influence on the mixture can have on the construction and on the final bridge. Practically, these negative or positive differences play a role in the performance of the concrete in the field, namely:

Negative: If the slump value is lower than needed, the strength of the concrete may increase, but there are other issues that can present themselves. Lower slump means decreased workability, increasing the likelihood that the concrete is not well placed in the formwork and there could be more gaps around rebar, where the concrete couldn't be properly consolidated.

Positive: A positive impact, leading to a slump value greater than the design value, means that the concrete is easier to work with and will flow through the formwork and around rebar much easier. However, this can lead to segregation in the concrete, leaving the upper portion of the concrete more susceptible to cracking. The overall strength of the concrete is also then decreased.

Table 6-5: Correlation and Regression Results for Difference in Compressive Strength

Correlation Rank	Variable	Correlation to Compressive Strength Difference
1	Fine Aggregate Amount	0.2819
2	Paste Content	-0.2526
3	Mortar Content	0.2189
4	Coarse Aggregate Amount	-0.2018
5	Latex Amount	0.2
6	Pozzolan Amount	-0.1733
7	W/CM Ratio	0.1535
8	Water Amount	-0.121
9	Design Slump	0.1092
10	Aggregate Content	0.1051
11	Fine Aggregate Specific Gravity	0.0805
12	Design Air Content	-0.0651
13	Yield	-0.0558
14	Coarse Aggregate Specific Gravity	-0.0296
15	Cement Amount	0.0273

*Highlighted cells indicate variables present in the final regression equation

The "design" compressive strength is equal to the NCDOT minimum 28-day compressive strength from NCDOT Division 10, outlined earlier in Section 4.2.1. Within the dataset, most of the difference records are positive, indicating the minimum strength capacity is usually exceeded. Therefore, when there is a negative correlation, it does not always indicate that increasing one variable or another will cause the compressive strength to fail to match the minimum requirement; instead, it can indicate that it will lower the increase in compressive strength. If the design values for compressive strength vary from the minimum required values, then this portion of the study is not as accurate.

1. The amount of fine aggregate in the mixture design has a relatively strong positive correlation to the change in compressive strength, indicating that increasing the amount of fines in a mixture tends to increase the strength, in many cases above the design compressive strength. The specific gravity of the fine aggregate, and thus the size of the fine aggregate, is not as important to the strength capacity, but increasing the total volume of fines tends to lead to higher increases in compressive strength.
2. Since the paste content has a negative relationship with the difference in compressive strength, increasing the paste content increases the chance that the compressive strength will not be as high. Paste content is a combination of cement content (positive), pozzolan amount (negative), water amount (negative), and latex (positive). The two positives, cement content and latex, are either very lowly correlated or not present in many of the mixtures, which is why the negatives control this variable.
3. While mortar content is a combination of cement amount and pozzolan amount, the relationship between this variable and the difference in compressive strength is positive. This indicates that increasing the mortar content, by way of increasing the cement amount and not the pozzolan amount, tends to lead to higher compressive strengths.
4. The coarse aggregate amount has a negative relationship with the difference between design and actual compressive strength, which is logical because too many large particles can increase the likelihood of void spaces, as well as decrease the space available for the binding paste.

During construction, producers are often conservative and target a compressive strength that is higher than is called for in the design documents as an insurance against failing to meet the required strength. As a result, the compressive strength tended to be above the minimum (as indicated in Section 6.1). No matter what the contributing factor, increasing the compressive strength well above the requirements is not always preferable because it may be linked to excessive cement content. Concrete with highly increased compressive strengths also can indicate unnecessary spending on materials.

6.3 Statistical Analysis of Mixture Design/Early Age Data to Long Term Performance for Bridge Deck Mixtures

Before the bridge data from the multitude of NCDOT databases was used in modeling, it was pre-processed using the processes outlined in Sections 3.3 and 4.1.1. For this portion of the project, information pertaining to mixture design components, early age test data, bridge qualities (such as ADT, year built, etc.), and maintenance data was used.

To determine the components that have the most influence on how a bridge performs over its lifetime, the following list of variables was chosen based on the data conditioning and filtration process described in Section 3.2.1.2:

- Class of Concrete
- Mortar Content
- Cement Amount
- Pozzolan Amount
- Pozzolan Type
- Fine Aggregate Amount
- Fine Aggregate Specific Gravity
- Coarse Aggregate Amount
- Coarse Aggregate Specific Gravity
- Water Amount
- Air Content
- Slump
- w/cm Ratio
- Yield
- Paste Content
- Aggregate Content

The following set of tables detail the results from applying the t-test and group difference modeling to the bridge deck data. The groups were divided into two sub-groups, one for the over-performing and one for the under-performing structures.

The following notes apply to the information in Tables 6-6, 6-7, 6-8, and 6-9:

- The left aligned, normal variables are the individual mixture components, the indented variables are sub-categories of the main variable, and the italicized variables are calculated characteristics of the individual mixture components.

- Class C fly ash and GGBFS, while both used, do not contain enough records at this stage of the analysis to warrant inclusion in the analysis. Therefore, while the presence of these variables is maintained in the table, many of the fields for them will be blank.
- Class F fly ash was treated separately from the other variables. Since there are three possible types of pozzolan (or there were cases that pozzolans were not used), it is not a constant consideration in the mixture design (unlike, for example, water amount, which has a non-zero value for every mix). To correct for this, the zero records were filtered out for the analysis of this variable. 86.67% of the under-performing bridges and 75% of the over performing bridges used Class F fly ash in their mixture design, and while these represent nearly all of the mixtures, the zero records skewed the data. Thus, this variable was examined only for records with a prescribed amount of Class F fly ash.

Table 6-6: Comparison of Mean and Mode Values between Under and Over Performing Bridge Decks

Variable	**Under-Performing Bridge Decks**		**Over-Performing Bridge Decks**		**Mean Difference**	**Mode Difference**
	Mean	Mode	Mean	Mode		
Mortar Content (cu.ft.)	16.30	16.36	16.27	16.39	-0.04	0.03
Cement Amount (lbs)	574.73	572.00	554.55	572.00	-20.18	0.00
Pozzolan Amount (lbs)	142.54	172.00	164.00	172.00	21.46	0.00
Class C Fly Ash (lbs)	---	---	110.00	---	110.00	---
Class F Fly Ash (lbs)	162.63	172.00	168.80	172.00	6.18	0.00
GGBFS (lbs)	192.00	---	319.00	---	127.00	---
Fine Aggregate (lbs)	1056.76	1205.00	1028.50	1041.00	-28.26	-164.00
Fine Aggregate S.G.	2.64	2.64	2.64	2.63	-0.01	-0.01
Coarse Aggregate (lbs)	1826.82	1800.00	1805.65	1800.00	-21.17	0.00
Coarse Aggregate S.G.	2.74	2.74	2.70	2.67	-0.04	-0.07
Water Amount (lbs)	32.59	33.00	33.37	33.00	0.78	0.00
w/cm Ratio	0.38	0.39	0.39	0.39	0.01	0.00
Yield (cu.ft.)	27.01	27.05	27.04	26.78	0.03	-0.28
Paste Content (%)	36.67	34.81	37.20	37.16	0.53	2.34
Aggregate Content (%)	63.33	65.19	62.80	62.84	-0.53	-2.34

Table 6-7: Equal Variance Results and Corresponding Calculated t-value and D.o.F.

Variable	**Equal Variance**			**t**		**df**	
	95%?	**90%?**	**80%?**	Equal	Non	Equal	Non
Mortar Content (cu.ft.)	YES	YES	YES	0.38	0.44	138.00	29.00
Cement Amount (lbs)	NO	NO	NO	1.51	0.96	138.00	20.00
Pozzolan Amount (lbs)	YES	YES	YES	-1.51	-1.23	138.00	22.00
Class C Fly Ash (lbs)	---	---	---	---	---	---	---
Class F Fly Ash (lbs)	YES	YES	YES	-1.67	-3.52	117.00	72.00
GGBFS (lbs)	---	---	---	---	---	---	---
Fine Aggregate (lbs)	YES	YES	YES	1.44	1.36	138.00	24.00
Fine Aggregate S.G.	YES	NO	NO	0.72	1.44	138.00	100.00
Coarse Aggregate (lbs)	YES	YES	YES	1.05	1.20	138.00	28.00
Coarse Aggregate S.G.	YES	YES	NO	1.83	2.48	138.00	36.00
Water Amount (lbs)	YES	YES	YES	-2.05	-2.22	138.00	27.00
W/CM Ratio	YES	YES	YES	-1.76	-1.98	138.00	28.00
Yield (cu.ft.)	NO	NO	NO	-1.34	-0.67	138.00	19.00
Paste Content (%)	YES	YES	YES	-1.74	-1.84	138.00	26.00
Aggregate Content (%)	YES	YES	YES	1.74	1.84	138.00	26.00

Table 6-8: t-test Mean Difference Significance Results

Variable	**Table t-value**			**Significant at:**			**Mean Change**
	95% α =0.05	**90%** α =0.1	**80%** α =0.2	95%?	90%?	80%?	
Mortar Content (cu.ft.)	±1.96	±1.645	±1.282	NO	NO	NO	DEC.
Cement Amount (lbs)	±2.086	±1.725	±1.325	NO	NO	NO	DEC.
Pozzolan Amount (lbs)	±1.96	±1.645	±1.282	NO	NO	YES	INC.
Class C Fly Ash (lbs)	---	---	---	---	---	---	INC.
Class F Fly Ash (lbs)	±1.96	±1.645	±1.282	NO	YES	YES	INC.
GGBFS (lbs)	---	---	---	---	---	---	INC.
Fine Aggregate (lbs)	±1.96	±1.645	±1.282	NO	NO	YES	DEC.
Fine Aggregate S.G.	±1.96	±1.662	±1.291	NO	NO	YES	DEC.
Coarse Aggregate (lbs)	±1.96	±1.645	±1.282	NO	NO	NO	DEC.
Coarse Aggregate S.G.	±1.96	±1.645	±1.306	NO	YES	YES	DEC.
Water Amount (lbs)	±1.96	±1.645	±1.282	YES	YES	YES	INC.
W/CM Ratio	±1.96	±1.645	±1.282	NO	YES	YES	INC.
Yield (cu.ft.)	±2.093	±1.729	±1.328	NO	NO	NO	INC.
Paste Content (%)	±1.96	±1.645	±1.282	NO	YES	YES	INC.
Aggregate Content (%)	±1.96	±1.645	±1.282	NO	YES	YES	DEC.

Table 6-9: Group Difference Mean Difference Significance Results

Variable	Dunnett Method Significant? 95%?	90%	80%	Games-Howell Significant? 95%?	90%	80%
Mortar Content (cu.ft.)	NO	NO	NO	EV	EV	EV
Cement Amount (lbs)	UV	UV	UV	NO	NO	NO
Pozzolan Amount (lbs)	NO	UV	UV	EV	NO	NO
Class C Fly Ash (lbs)	UV	UV	UV	EV	EV	EV
Class F Fly Ash (lbs)	NO	YES	YES	EV	EV	EV
GGBFS (lbs)	UV	UV	UV	EV	EV	EV
Fine Aggregate (lbs)	NO	NO	YES	EV	EV	EV
Fine Aggregate S.G.	NO	UV	UV	EV	NO	YES
Coarse Aggregate (lbs)	NO	NO	NO	EV	EV	EV
Coarse Aggregate S.G.	NO	YES	UV	EV	EV	YES
Water Amount (lbs)	YES	YES	YES	EV	EV	EV
W/CM Ratio	NO	YES	YES	EV	EV	EV
Yield (cu.ft.)	UV	UV	UV	NO	NO	NO
Paste Content (%)	NO	YES	YES	EV	EV	EV
Aggregate Content (%)	NO	YES	YES	EV	EV	EV

Note: If a cell has "UV" (Unequal Variance), then the Games-Howell Method was performed instead, and if a cell has "EV" (Equal Variance), the Dunnett Method was performed instead.

6.3.1 Interpretation of Results

Since there are several tables of results, this section will be broken down by table. Within this section, if a variable is identified as being important, this indicates that the difference in the mean value of the characteristic between the under-performing and over-performing bridge groups is significant. Therefore, a significant variable is one that the difference in the mean is significant.

Table 6-6 provides an overview of the mean and mode for each variable used in the concrete mixture design process, as well as the direction in which the mean changed when going from the under-performing mixtures to the over performing mixtures. Also included in Table 6-6 is the mode value (the most commonly occurring value). The specific amounts and trends in Table 6-6 will be referenced when discussing that variable, if it is considered as significant.

The results between Table 6-7 and Table 6-8 (the t-test and the group differences test), while presented slightly differently, are essentially the same. Only one variable, “Water Content” is significant at a 95% confidence level. When moving on to the 90% confidence level, five more become significant: “Class F Fly Ash”, “Coarse Aggregate S.G.”, “*w/cm* Ratio”, “Paste Content”, and “Aggregate Content”.

- The amount of water present in the mixture (the variable “Water Content”) is highlighted by the data as the most important variable, with the mean increasing from under-performing to over-performing. With its relationship to other variables, this result is logical. The values for paste content and the *w/cm* ratio (both of which are significant at the 90% confidence level) are both increased by an increase in the water amount, and the means for both of these variables increased from under to over performing bridge decks. Increasing the water amount also increases the mortar content, but mortar content has a mean that has decreased from under-performing bridges to over-performing bridges. While this appears to disagree with the water amount results, the difference in means for mortar content is not considered as significant at any of the three reported confidence levels. As such, an increase in the water amount does not cause a significant enough increase in the mortar content for the mortar content results to negate the influence of the water amount.
- The amount of water in the mixture is also correlated with the amount of fly ash used in the mixture (with Class F fly ash being considered as significant at the

90% confidence level). Since the mean for the Class F fly ash is shown to be increasing from under-performing bridges to over-performing bridges, the increase in water amount could be representative of the amount needed to hydrate it fully. Fly ash can either increase or decrease the required water amount. For the bridges in North Carolina that were included in this study, Table 6-10 shows the relationship between the mean water amount used in mixtures with Class F fly ash and those that do not.

Table 6-10: Comparison of Mean Water Amounts for Under/Over-Performing Bridges that Contain or Do Not Contain Class F Fly Ash

Cementitious Material	Mean Water Amount (lbs)	
	Under	Over
With Fly Ash	32.55	33.49
Without Fly Ash	32.88	33.00

The mean of the water amount increases with use of fly ash in the over-performing bridge decks, while the mean of the water amount decreases with fly ash use in the under-performing bridge decks. Combining the results of Table 6-10 and the discussion above it, increasing the amount of fly ash should lead to an increase in the water amount.

- In laboratory and field settings, increasing the fly ash has been proven to increase the overall durability of the concrete by decreasing the permeability and reducing the alkali-silica reaction (Shafaatian 2012). The results of this study confirm this, as the mean amount of fly ash is greater for the over performing bridges. This indicates that increasing the fly ash amount does help improve durability of concrete not only in the lab, but also over the lifetime of a bridge while in service.

- The specific gravity of the coarse aggregate is a significant variable at the 90% confidence level (and also at the 80% confidence level, where the variable no long has equal variance). The difference in the mean of the specific gravity is not large (only a decrease of 0.04 from under to over), but the mode value is decreased even more (2.67) for the over performers while for the under performers the mode is the same at as the mean (2.74).
- AASHTO PP 84-17 lists several strategies for improving concrete durability (AASHTO 2017). While this document is written primarily for pavements, the ideas presented in it are generally applicable to all concrete.
  1. If shrinkage cracking caused by volume change due to changes of moisture (hygral volume change), then either the volume of paste should be limited to 25% or the unrestrained volume change should be less than 420 microstrain at 28 days.
  2. For freeze-thaw durability, the water to cementitious material ratio (*w/cm*) should be less than 0.45, and the air content should be either between 5 and 8 percent or greater than 4 percent with a SAM number less than 0.20 using TP 118.
  3. To reduce joint damage due to deicing chemicals when $CaCl_2$ or $MgCl_2$ is used, either SCM's should replace at least 35% of the cement by volume, or a sealer should be used consistent with M 224.

For the bridge decks included in this study:

1. The volume of paste was consistently higher than this recommended minimum (typically in the low 30's rather than around 25%). While

this is typically the case for bridges (with higher slumps and a decreased maximum coarse aggregate size), this value is still high. Furthermore, the mean of the paste content for the over performing bridges was higher than for the under-performing bridges, and the mode value is also much higher. At a 90% confidence level this difference between the means became significant. As such, for the North Carolina bridges that were included in this study, lowering the paste content may not be beneficial for performance considerations.

2. For Class AA bridge deck mixtures, the air content is designed for either 5% or 6% air content, and with a tolerance of ±1.5%, 97.5% of the early age tests confirmed that this range was met. Therefore, the majority would fit either the greater than 4% or the between 5% and 8% requirement. For the *w/cm* ratio, the maximum included in this study was 0.43, falling below the recommended maximum. With a mean of 0.38 for the under-performing bridges and a mean of 0.39 for the over-performing bridges, at a 90% confidence level the difference in means is significant, but does not indicate that continuing to elevate the *w/cm* ratio will lead to better performance.
3. In the calculation for the volume of paste in a mix, AASHTO assumes that the specific gravity of the cement is 3.15, and that the specific gravity of the fly ash is 2.62. The maximum design value for cement within the bridges chosen for this part of the study is 715 lbs.

$$V_{Cement} = \frac{X(lbs\ cement)}{S.G._{cement} * \gamma_{water}} = \frac{715 lbs}{3.15 * 62.4 lbs/ft^3} = 3.64\ ft^3$$

With a specific gravity of 3.15, this is roughly 3.64 ft^3 of cement. In order to replace at least 35% of this volume with SCM's, the chosen SCM must occupy 35% of 3.64 ft^3, or 0.35*3.64 = 1.27 ft^3. As such, the minimum amount of fly ash (the most commonly used SCM in North Carolina) would be:

$$X(lbs\ fly\ ash) = \frac{V_{fly\ as}}{S.G._{fly\ as}\ * \gamma_{water}} = \frac{2.62 * \frac{62.4 lbs}{ft^3}}{1.27 ft^3} = 128.4\ lbs$$

The minimum amount of Class F fly ash included in a mixture design for the over performing bridges is 163 lbs, exceeding this amount. The mean difference between the amount of Class F fly ash used increased from under to over performing bridge decks (from 162.6 lbs to 168.8 lbs), and this difference is significant at the 90% confidence level. 25% of the mixtures in the under-performing category are below 163 lbs. As mentioned previously, at least 75% of the mixtures use fly ash, and since it has been shown that use of Class F fly ash above the recommended minimum, as well as an increase between the means from under to over performing bridges, continuing to add at least 35% replacement of cement with SCM's is recommended.

CHAPTER 7 CONCRETE PAVEMENT

7.1 Construction Tolerances for Concrete Pavements

While pavement mixtures have similar categories for early age requirements as bridge mixtures, not all of them are recorded. Therefore, it is assumed that slump and air content fits in (or generally fits) the required ranges.

In Division 10 of Standard Specifications for Roads and Structures, the NCDOT states that for pavements, “Use a mix that contains a minimum of 526 pounds of cement per cubic yard, a maximum water cement ratio of 0.559, an air content in the range of 4.5 to 5.5 percent, a maximum slump of 1.5", a minimum flexural strength of 650 psi at 28 days and a minimum compressive strength of 4,500 psi at 28 days. ” (NCDOT 2018). This is consistent with the NCDOT minimum compressive strength for Concrete Class AA, Concrete Class AA Slip-Form, and Drilled Pier. The following are the minimum required values for early age pavement concrete:

- Flexural Strength = 650 psi (minimum)
- Compressive Strength = 4500 psi (minimum).

Several of the mixtures in the dataset were not designed to meet the initial threshold value of 650 psi, with only 405 out of 4942 recorded mixtures designed for this threshold. Learned through personal communication with Brian Hunter, the State Laboratory Operations Manager for the NCDOT Materials & Tests unit, this is due to the fact that prior to 2002, the specifications called for 550 psi at 14 days, which was then raised to 600 psi before settling at the current target of 650 psi at 28 days (Hunter 2019).

Since the age of testing is not included in the database, it will be assumed that these mixtures that require a lower flexural strength are measured at 14 days.

For mixtures that require a flexural strength of lower than 550 psi, many indicate that the purpose was for concrete repair, or something similar. In this case, the strength requirement is a 3-day strength requirement, since the roadway needs to be operational as soon as possible. Therefore, because of the variance in strength requirements and the unknown date of testing, the listed required strength will also be the assumed NCDOT required strength for flexural strength tests.

Due to the limited amount of data, and the fact that the data is not well distributed by division (with several divisions not represented in the dataset), North Carolina pavement mixtures accepted during construction was not be separated by division for analysis. The following is a summary, in both tabular and graphical form, showing the percentages of mixtures accepted that meet NCDOT standards, separated by test type and concrete type.

The following table (Table 7-1) and its corresponding graph (Figure 7-1) display a summary of the data. This summary is presented in a manner that shows the number of data points for each concrete type for each early age test. Just over 750 records for Concrete Pavement – E have a reported flexural strength value of 0. Since no flexural strength is listed, these records are considered as outliers and were removed. There are two different "types" of pavement represented here, "M" and "E". These stand for "Metric" and "English" and refer to other components of the contract. The mixture design and test results are all in US customary units, so while they are separated

Table 7-1: Percentage of Mixtures Meeting Early Age Test Targets from NCDOT Specifications

	Concrete Type		Total Number	% Within Target Range
Flexural Strength	1	Concrete Pavement - M	2564	94.27
	2	Concrete Pavement - E	1596	91.29
	3	Concrete Pavement- Beams - E	25	100.00
Compressive Strength	2	Concrete Pavement - E	1545	96.76
	3	Concrete Pavement- Beams - E	938	99.04

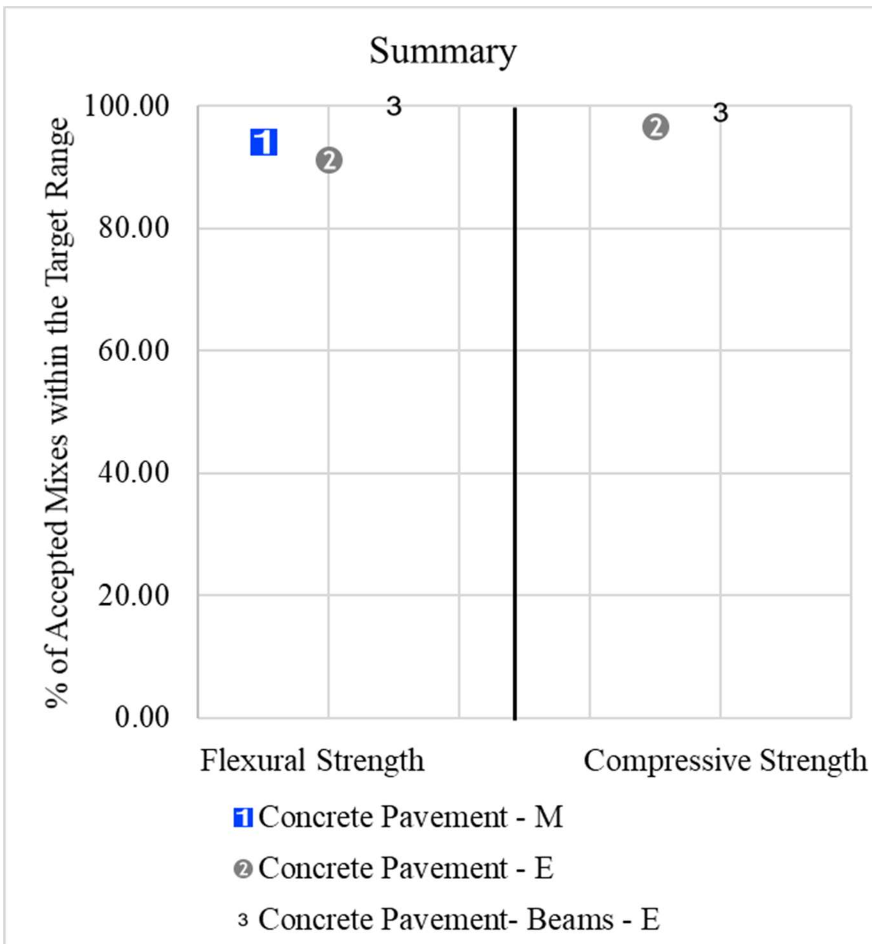

Figure 7-1: Percentage of Mixtures Meeting Early Age Test Targets from NCDOT Specifications

7.2 Statistical Analysis of Mixture Design to Early Age Data for Pavement Mixtures

With the completed databases, statistical regression for the comparison of mixture design components to each of the early age components (flexural strength and compressive strength) was performed to identify which components of the pavement mixture were most influential to the important early age concrete properties. In multiple linear regression modeling, there are the two sets of variables: the independent variables, represented by the mixture design information, and the dependent variables, represented by the early age properties. The data pertaining to this was imported from Excel into Minitab, to allow for the performance of multiple linear regression.

To determine the most influential mixture design variables for each of the early age properties, the following mixture design components were selected based on the filtration performed in Section 3.3.1. While the list is very similar to the one used for bridge deck mixtures, decisions made during that portion of the analysis are reflected in the early removal of some potential variables.

- Class of Concrete
- Mortar Content
- Cement Amount
- Pozzolan Amount
- Pozzolan Type
- Fine Aggregate Amount
- Fine Aggregate Spec Gravity
- Coarse Aggregate Amount
- Coarse Aggregate Spec Gravity
- Water Amount
- Air Content
- Slump
- *w/cm* Ratio
- Yield
- Paste Content
- Aggregate Content

The two categorical variables included at this stage of the analysis, "Pozzolan Type" and "Class of Concrete", both are heavily reduced from the number present in the bridge deck study. Both were left as categorical predictors in Minitab, and each individual variable type in the category were given their own equation. In both the analysis for the difference in flexural strength and the difference in compressive strength, these variables were removed as they violated the VIF threshold value of 10. “Pozzolan Type” was highly related to “Pozzolan Amount,” so it was removed to allow “Pozzolan Amount” to remain in the dataset, while “Class of Concrete” is related to many of the variables. Therefore, any special considerations for categorical variables was unnecessary for this portion of the project.

Unlike in the early age data for bridge mixtures, all of the individual mixtures were made either to be tested for flexural or for compressive strength. While a project could use the same mixture design ID for testing broth flexural and compressive strength, these tests were never performed on the same mixture. As such, analysis software like SAS and Minitab had a difficult time recognizing the data format and length. To correct for this, the early age database was separated into two, one for flexural strength test results and one for compressive strength test results.

To facilitate for concrete mixing conditions that are not available in the dataset, the following assumptions were made:

- The prescribed mixing times are followed during the mixing of the concrete
- The surrounding air temperature during the mixing process was between 50°F and 95°F (10°C to 35°C) (except where other temperatures are required by Articles 420-8, 420-9 and 420-15) (NCDOT 2012), as prescribed in Division 10.
- The concrete is mixed using the prescribed amounts, and the number of times that was exceed for water content (i.e. approaching maximum water content) is minimal and can be disregarded.

7.2.1 Comparison of Values from Different Analysis Types

In working towards the end goal of determining which parameters of the pavement mixture designs are most influential to the concrete strength (flexural and compressive), and how those variables interact to either cause the strength to be more or less than designed, canonical correlation was performed using the SAS software package, while stepwise regression was performed in Minitab.

The following section presents the results separated by the early age test variable examined (difference in flexural and different in compressive strength) and shows the condensed version of the results from canonical correlation and stepwise regression, combining them into a single table for each independent variable.

As mentioned at the end of Section 7.1, around 750 of the records (out of about 5000) have a flexural strength of 0 recorded. Without any notes indicating why this number was recorded, it is impossible to tell if these records are the result of a bad concrete mixture (and therefore not having measurable flexural strengths) or if the value was not recorded. These records were removed before analysis.

With correlation results, there are three different definitions for the relationships between variables:

1. -1 to 0: Correlations falling in this range indicates a negative relationship between the variables. This means that as one increases, the other decreases.
2. 0: A correlation value of 0 indicates no relationship at all

3. 0 to 1: Correlation coefficients in this range indicate a positive relationship between the variables. This means that as one increases, the other increases as well.

The closer to 1 in the positive and -1 in the negative region indicates a stronger relationship between the two: i.e. "Mortar Content" has a stronger correlation to the difference in flexural strength than "Yield" does.

7.2.2 Results and Interpretation

Table 7-2: Correlation and Regression Results for Difference in Flexural Strength

Correlation Rank	Variable	Correlation to Flexural Strength Difference
1	*w/cm* Ratio	0.158
2	Pozzolan Amount	-0.153
3	Water Amount	0.133
4	Yield	-0.122
5	Fine Aggregate Amount	0.122
6	Mortar Content	0.114
7	Coarse Aggregate Amount	-0.107
8	Cement Amount	0.105
9	Fine Aggregate Specific Gravity	0.103
10	Design Slump	-0.017
11	Aggregate Content	-0.008
12	Coarse Aggregate Specific Gravity	-0.007
13	Paste Content	0.007
14	Design Air Content	0.005

*Highlighted cells indicate variables present in the final regression equation

1. *w/cm* Ratio is the top correlated variable, with a positive relationship to the difference in flexural strength. This is backed up by the fact that Water

Amount is also positively correlated, as an increase in the *w/cm* ratio indicates either an increase in water amount or a decrease in cement content.

2. Pozzolans have been shown by numerous studies to increase the compressive strength of concrete (as confirmed in the difference in compressive strength column). Their impact on flexural strength has not been studied as widely, but some research suggests that it can increase the flexural strength in laboratory conditions (Akbulut 2006). For North Carolina concrete, only Class C Fly Ash and Class F Fly Ash are used. The correlation results, as well as the negative regression sign, indicate that for mixtures in the state, increasing the pozzolan amount leads to lowered (but not necessarily lower than required) flexural strength. Given that pozzolans hydrate more slowly than cement, and the test date is not currently adjusted for fly ash mixtures, this finding could be expected.
3. Yield has a negative relationship with the change in flexural strength, indicating that the more concrete is made in the batch, the lower the difference will be. Yield is positively correlated with another negative variable, coarse aggregate amount, which indicates that the two may be associated: as design amount of coarse aggregate amount increases, the overall yield also increases, and the overall difference in flexural strength decreases.
4. Fine aggregate amount has a positive correlation with flexural strength, indicating that increasing the fine aggregate content typically increases the strength above the design amount. This, combined with the fine aggregate specific gravity (positively correlated at #9 in the list, and also included in the

regression equation) indicate that for North Carolina mixtures, increasing the fine aggregate content as well as ensuring good gradation increase the concretes flexural strength.

Of these top three variables, two exhibit positive correlations and one exhibits a negative correlation. Increasing the water amount, and thus the *w/cm* ratio, tends to increase the difference in flexural strength. However, increasing the pozzolan amount does not tend to lead towards higher flexural strength for North Carolina mixtures. This could be due to the fact that fly ash begins to show its full impact on the strength of concrete after the initial 28-day strength test (Harison et al. 2014), so its full impact cannot be seen at the stage that concrete is typically tested at.

If the flexural strength is too low, then the concrete at the bottom face (also known as the tension face) will begin to crack over time. This cracking causes more strain on the reinforcing steel, which can then lead to failure. As such, ensuring proper flexural strength is important to maintaining overall strength and stability for the concrete pavement.

For most of the projects included in this study, the minimum compressive strength requirement is exceeded. For the dataset analyzed for this portion of the study, 97.6% of the mixtures either met or exceeded that minimum value. Therefore, while a negative correlation indicates that as one variable increases the other decreases, it does not indicate that increasing a variable like “Slump” (which has a negative correlation to the difference between design and actual) will cause the compressive strength to be below the required amount. It may be more important to look at the factor that cause the strength to decrease, as excessive strength is not always useful.

Table 7-3: Correlation and Regression Results for Difference in Compressive Strength

Correlation Rank	Variable	Correlation to Compressive Strength Difference
1	Fine Aggregate Specific Gravity	-0.273
2	Pozzolan Amount	0.217
3	Design Air Content	0.185
4	Aggregate Content	-0.171
5	Coarse Aggregate Specific Gravity	0.168
6	Yield	0.157
7	Fine Aggregate Amount	-0.153
8	w/cm Ratio	-0.147
9	Paste Content	0.146
10	Cement Amount	-0.103
11	Mortar Content	0.094
12	Design Slump	-0.065
13	Coarse Aggregate Amount	0.041
14	Water Amount	0.005

*Highlighted cells indicate variables present in the final regression equation

The state of North Carolina can be broken down into 3 different "regions": mountains, piedmont, and coastal. This breakdown is shown in the following image:

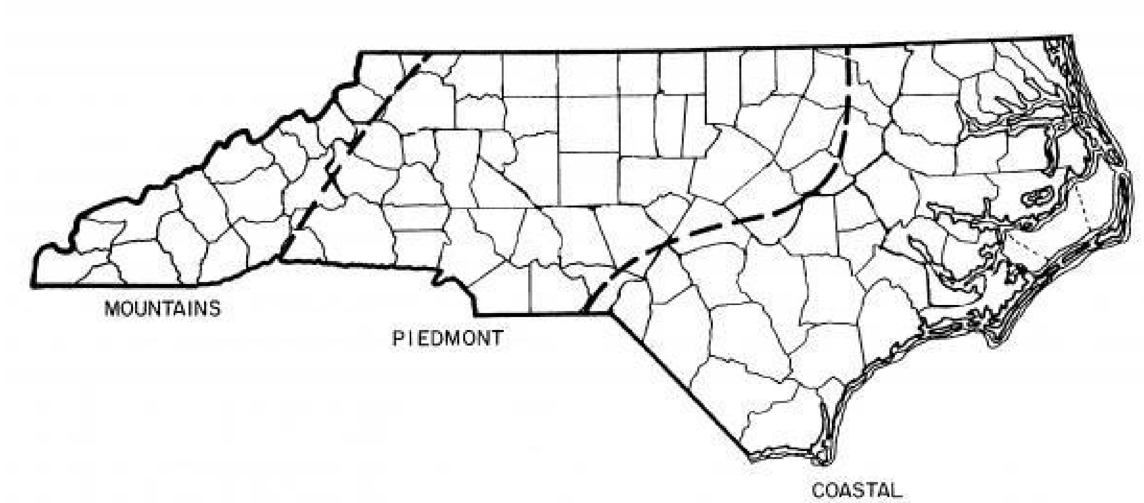

Figure 7-2: Regional Map Showing the Mountain, Piedmont, and Coastal Regions of North Carolina (Moore and Bradley 2018)

Because the use of rigid concrete as pavement is not currently widespread, the dataset is not large. The compressive strength test results in the early age database are entirely from only four different piedmont divisions and so the results are not representative of the variety of materials used across the state.

1. Fine aggregate specific gravity has a negative relationship with the difference between actual and required compressive strength. As the highest correlated variable, changes in the specific gravity of the fine aggregate tend to lower the difference in compressive strength. There can be many reasons for the difference in specific gravity of the fine aggregates used in the state, including the producer who obtains it, or if it is natural or manufactured sand. Since the producer of the fine aggregate, or the place that it is obtained is unknown, it is difficult to attribute this result to a specific type of fine aggregate or to a specific supplier. The specific gravity of manufactured sand is higher than that of natural sand (Megashree et al. 2016), so the results indicate that the use

of manufactured sand leads to a lower difference in compressive strength. Manufactured sand has been show to lead to higher compressive strengths (Vijayaraghavan and Wayal 2013), and these results do not necessarily contradict that. A negative correlation here means that while the compressive strength can still be larger than the design value (as it is in most cases), use of higher specific gravity fine aggregate leads to an overall lowered compressive strength.

2. Similar to common research findings, pozzolan amount has a positive correlation to the difference between design and actual compressive strength. Fly ash is the only pozzolan present in the pavement mixture designs, and has been shown to increase the later-age strength of concrete at the correct replacement amounts (Harison et al. 2014). As such, this result agrees with other research performed on the subject.
3. Increasing the air content as a positive relationship with the difference amount, indicating that concrete designed for higher air content levels tend to have higher strength capacities. The design air contents for the mixtures used in this study range from 4.9% to 6.1%, which is not a large difference. Since over 95% of the data falls within the 5.0±0.1%, the cases where the air content was higher are very few, and other components of the mixture that the air content correlates to could have also aided in increasing the compressive strength.

During construction, the conservative approach is to have a compressive strength that is higher than originally designed for. For the early age test records examined in the course of this study, the compressive strength tended to be above the minimum. No matter what the contributing factor, increasing the compressive strength well above the requirements is not always preferable. Concrete with highly increased compressive strengths can be an indicator of excess unnecessary spending on cementitious materials, and greater cementitious contents are often associated with durability problems such as cracking due to shrinkage.

7.3 Statistical Analysis of Mixture Design to Long Term Performance for Pavement Mixtures

The process for obtaining the final dataset used in this portion of the study is outlined in Sections 3.3.1 and 4.1.2, and the process for comparing the mixture design components to the long term performance is outlined for the bridge deck records. This includes the following steps:

- Reducing the dataset to include only continuous variables
- Finding the mean, standard deviation, mode and variance for the under-performing and over performing roadway sections for each field
- Determining if the means have equal variance
- Computing the t-value and compare it with a t-table
- Performing group differences to compare results with the t-test

Within the data reduction process, the overall dataset became significantly smaller. While it is possible to perform all of these steps on the final pavement dataset, the results will not be conclusive. If every record indicated a separate mixture design, then the overall number of records would be enough in that hypothetical situation, but since only 5 separate mixture designs could be confidently tied to specific roadway sections, the analysis cannot be accurately performed. Technically, the minimum number of records to perform a t-test is 2 (since the degree of freedom must be 1 or greater, and degree of freedom is calculated using the n-1 equation when considering equal variance), but having such a low number does not always provide strong results. When using small sample sizes, a statistically significant finding is more likely to be a false positive than when the same test is performed for a large sample (Winter 2013).

Consider Table 7-4, which shows the results of calculating the t-value for each mixture design variable. A few overall notes about the final dataset and about how Table 7-4 is formatted:

- The records were reduced, so instead of individual road sections, only one record for each mixture design was used. Because the analysis does not take the numeric difference between the actual condition rating and the expected condition rating, the only information that will be used is the mixture design components that lead to the mixture existing for a road that under-performed or over-performed.
    - The analysis was performed using each individual roadway record (so 143 records of over-performing and 78 records for under-performing, but due to the bias, the inability to correct for the fact that some mixture designs have more roadway records (leading to over representation of some mixtures), and the fact that there is such a small number of mixture designs (and thus not much variance), all of the variables were considered significant, even at a 99.99% confidence level.

- The t-value is the same for both equal and non-equal variance, so it is shown as a single column
- The degree of freedom was either 4 for equal variance or in the range of 2-4 for non-equal variance. Since decreasing the degree of freedom decreases the chance that a variable will be significant, variance is only checked on the fields that are significant assuming equal variance.
- The left aligned, normal variables are the individual mixture components and the italicized variables are combinations of the individual mixture components.

Table 7-4: Results from t-test for Pavement Data

Variable	t-value	95%	90%	80%
Mortar Content	-1.023	NO	NO	NO
Cement Amount	-1.343	NO	NO	NO
Fly Ash Amount	0.714	NO	NO	NO
Fine Aggregate Amount	1.369	NO	NO	NO
Fine Aggregate Spec Gravity	2.828	YES	YES	YES
Coarse Aggregate Amount	1.271	NO	NO	NO
Coarse Aggregate Spec Gravity	0.692	NO	NO	NO
Water Amount	-1.635	NO	NO	YES
W/CM Ratio	0.551	NO	NO	NO
Yield	-1.009	NO	NO	NO
Paste Content	-2.025	NO	NO	YES
Aggregate Content	2.025	NO	NO	YES

The results using the current limited amount of data are not very conclusive. The only variable with a significant difference in the means is "Fine Aggregate Specific Gravity", which only contains values ranging from 2.60-2.64. As this difference is not large, this variable could be committing a Type I error (rejecting the null hypothesis when it is in fact true) due to the small sample size. The others that do become significant only become so at the 80% confidence level. Therefore, the only potential conclusions from this dataset is that because the number of samples is so low, there is a high chance of a false positive (with variable Fine Aggregate Specific Gravity), and that strong conclusions on the effect of the individual variables cannot be made. Other factors that should also be included but where either not available in the database or could not be used for this condensed version of the study include treatment of the subgrade, climate, and traffic level.

A larger database is necessary to obtain results for analysis of pavement concrete mixtures. Recommendations for modifications in the data collection and storage that would allow for a sufficiently larger database are outlined in Section 8-2.

CHAPTER 8 CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

For analysis of both bridge concrete and pavement concrete mixtures, early age test results, and performance data, the availability of useable data and the ability to link records from different databases became a major challenge of this study. On the pavement side, this was even more pressing; the lack of useable data made results inconclusive. The data conditioning and filtration processes (and the recommendations for streamlining it for future analyses) became a major activity in this study. While the deterioration model with created using the same database as used in this study, the filtration performed in this study caused the model to be less representative of the final dataset. Therefore, even with the addition of tolerances around the deterioration curve, the results can indicate trends but are not completely conclusive.

Many external factors, such as transportation of the concrete to the site, batching, mixing times, finishing, and curing can influence the durability of concrete but are assumed to be adequate, as there are no fields in the database for these items. Therefore, the ability to determine the concrete quality at the construction site could only come from the early age data. When focusing just on the construction side of either the bridge decks or pavements, the consistent trend showed that the target ranges on the early age tests set by the NCDOT are being met. This allows for a higher chance for the concrete to behave as designed, as long as the material proportions are also being batched as indicated.

Within the mixture design to early age analysis for bridges, the mixtures used for NCDOT maintained bridges followed relatively common tends: as the air content is increased, the mixture is more fluid, leading to a lower slump, as well as the inverse of this statement, and increasing the cement amount causes the mixture to be stiffer. The compressive strength difference results did not highlight common trends (such as having cement content as the one of main influencers), but increasing the fine aggregate amount can lead to better mixture gradation, and too much paste can lead to a less economical mixture as well as leading to a decrease in compressive strength.

The results from the long term performance of the bridge decks are very intriguing. Since only one mixture type was examined (Class AA), the amount of variance in the design values are not large overall. In fact, between the under-performing and over-performing bridges, several even have the same mode value. The important conclusions from this analysis are that:

- Water amount, which has a ±1.0% tolerance, should favor the higher end of the design value spectrum. As the only variable that is significant at the 95% confidence level, the difference in the mean is 0.78lbs per cubic yard, which is outside of the available range of tolerance. Both the under-performing and over-performing bridge mixtures have a mode of 33.00lbs per cubic yard, but the under-performing bridges have several mixture designs with values that bring the overall average down. This increase in the water amount is useful in conjunction with the recommended increase in the fly ash (see the next bulleted conclusion), as over-performing bridge decks with fly ash used more water than bridge decks that did not use fly ash or that were under-performing. As such, water amount should favor the higher side.

- The importance of water amount may be a factor of the amount of "trim water" used in a mixture. The approved maximum amount listed in the mixture design sheet may not be the actual amount added, as sometimes water is held off during the initial mixing and added in if needed. To this effect, there is also a maximum water amount that is allowed to be added to the mixture.
- In the case of fly ash, there is not an immediate difference between the number of bridges that include it in the mixture design and bridges that do not. The percent of bridges that do not use pozzolans is nearly the same for under-performing bridges and over-performing bridges (for the bridges included in this dataset, 12.5% of the under-performing bridges and 10% of the over-performing bridges do not use a pozzolan). When it is used, there is a clear trend that higher replacement values tend to perform better. Both the under-performing and over-performing bridge decks have a mode of 172lbs of fly ash utilized in the mixture, and both have a mean under this value. As such, moving towards the replacement value of 172lbs of fly ash could increase the overall performance of the bridge deck. AASHTO recommends 35% replacement of cement with fly ash, which equates to around 130lbs per cubic yard. With the recommended value of 172lbs per cubic yard, the AASHTO recommendation is exceeded.

- Paste content and aggregate content are related to one other (as one goes up, the other goes down proportionally), and so the difference in the mean quantities in over performing or underperforming bridges is significant for both at the same confidence level (90%). While the difference in the mean paste content of under-performing bridge decks and the mean of the over-performing bridge decks is only 0.53% (around 0.14 ft^3 for a 1 yd^3 mixture), the difference in the mode values for the under-performing bridge decks and the mode of the over-performing bridge decks is even larger (2.34%, or 0.63 ft^3). The clear trend for North Carolina bridge decks is that a certain level of increasing the paste content is useful in improving the performance of the bridge deck (and at the same rate, decreasing the aggregate content). Since fly ash and water content are both components of the paste content, increasing them would have the effect of increasing the paste content. While the percentage increase between the mean paste content for the over-performing bridge decks and the mean paste content for under-performing bridge decks might not be very large, the data demonstrates that the paste content percentage should not be drastically lowered, as would be implied by some recommendations for durability enhancement.
- Because information on the actual construction conditions is not included in the databases, the higher paste content value may be acting as a proxy indicator greater workability. Increased paste content would allow for improved placement and finishing. As such, the workability of the concrete

itself may be an important factor that is indicated by this study: concrete that is easier to work with can lead to better performance.

Due to the limited amount of data, and issues with determining links in the data, the results from the pavement side of the analysis are not as conclusive or potentially as useful. In the mixture design to early age analysis, the results seem to contradict other known or tested information. Increasing the *w/cm* ratio for concrete has not been linked to an increase in the flexural strength (in fact, higher strength concrete tends to use lower *w/cm* ratio, to create a stiffer mixture where only enough water as is necessary to hydrate the cement is available (Wight 2016). Increasing the pozzolan amount typically leads to higher strength (as shown in the compressive side of the analysis), but had a negative correlation in the flexural strength portion of the analysis.   This is expected due to that fact that at 28 days, the fly ash has not fully developed to its full potential in the concrete. As fly ash is used as a replacement for cement, the overall strength before it is fully developed would be slightly decreased.   The compressive strength side yielded that for North Carolina pavements, decreasing the specific gravity of the fine aggregate can increase the strength, while increasing the pozzolan content increases the strength.

The results from the pavement mixture design to long term performance section are not conclusive due to the extremely limited amount of data available. Suggestions on modifications to the data collection and storage techniques are outlined in Section 8-2, and if followed can aid in creating results similar to the bridge side of the same analysis type.

In summary, the amount of data present in the final dataset for the pavement analysis was adequate for developing models to determine trends in the impact of mixture design proportions to early age and long term performance. These results can allow for modifications to the concrete mixture design specifications, with the aim of creating concrete that is more durable based on actual performance. For the pavement analysis, the final dataset was too limited to allow for accurate analysis. Therefore, no specific conclusions can be confidently made from analysis of the pavement data. As displayed in the bridge deck analysis, accurate data can allow for the observations for tends in material proportions, and can provide opportunities to increase the concrete durability and therefore decrease overall maintenance costs over the lifetime of that pavement. Implementation of the recommendations from the bridge deck analysis can help increase the quality and durability of the concrete used in North Carolina.

8.2 Recommendations for Data Collection and Storage

One of the greatest challenges presented in this research was to find a link between the various databases that house the information about NCDOT maintained bridges and roadways, as well as conditioning the data. The end goal, as mentioned in Chapter 1, is to find a way for the individual databases to be able to be used in conjunction with each other. That proposed data linking sequence is summed up by the following figure:

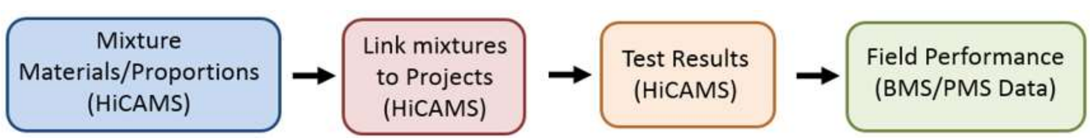

Figure 8-1: Potential Data Linking Sequence

The following section will detail the areas that could use improvement to not only aid in linking the data to improve usability, but also help streamline the analysis and remove potential roadblocks should this effort be undertaken again in the future.

8.2.1 Bridge Analysis

Within the early age database, there are a few suggestions on ensuring the data is readily useful for analysis.

- Some of the early age values are written as dates. This can be fixed by switching the column into the "Number" format, but it may be worth making sure that there is not an issue with the data importer
- Within the "Slump" category, there is a variety of ways the data is recorded. In the majority of cases, it is listed in inches with decimal points, the most efficient for data analysis. However, there are also the following other types also used:
  - Recorded in inches with a fraction (for example, 3 ½ instead of 3.5)
  - Recorded in millimeters
  - Recorded with an "O" instead of a zero
  - Recorded as various phrases such as "N/A" or "Omitted from Card" instead of just being recorded as blank
- To aid in the linking process, including either the structure number that the test record is linked to (the recommended choice) or at least include the latitude and longitude locations of the bridge where the mixture was placed. The "Site Description" field is useful when it calls out the exact structure number, otherwise it takes a manual check to determine the structure number.

The BMS Network Master houses all the information about the NCDOT maintained bridges, as well as their current condition ratings. Several fields in the BMS that could be edited to allow for them to be considered in future analysis.

- In the “Superstructure Type” and the “Substructure Type” fields, each include semi-detailed descriptions. Providing a simpler format for imputing these, or as a secondary field, is recommended. Since this field tends to be input by different people across the state, and there is no standard guideline to how they are written, their information is very difficult to include in the analysis. For example, in the “Superstructure Type”, reinforced concrete is written several different ways (ranging from R.C. to RC to Reinf. Conc. to Reinforced Concrete). Providing a secondary consistent labeling format would allow for these fields to be more suitable for use in a statistical analysis.
- The “Latitude” and “Longitude” fields are not in a suitable form for use in the analysis, and it is hard to tell exactly what the values represent. Modification of these fields to a more standardized format similar to other mapping standards such as GPS will increase the workability of the data.

8.2.2 Pavement Analysis

Pavement early age:

- As discussed in Section 3.3.1.1, the actual location on the roadway of the test sample is not easily found. Any of the fields that could give clues are either too general or pertain to labeling unique to eh project, which is not useful. Creating a field for either the latitude and longitude of the location of the sample, or more information about what sections of the roadway used the mixture that was tested would increase the number of records that could be used in this part of the analysis.

- In both the “Average Flexural Strength” and “Average Compressive Strength”, several of the records contain a 0. This could be an indication that the concrete was damaged, or that the test was not performed, but recording it as an actual tested value can have a negative impact on the analysis. In situations like this, it would be better to either leave it as blank, or with a “N/A” or “-“.

JCP Network Master:

- Consistency with how the milepoints are recorded (for both the Begin MP and End MP fields) is vital to ensuring the accuracy of the analysis. Currently, the exact beginning and end point of a roadway section may fluctuate year to year. While these fluctuations are not large, they could accidently add or subtract damaged patches from one roadway piece to another
- If the roadway is to be broken down into smaller pieces, a secondary way of ensuring that a section (and only that section) is analyzed for a given condition rating. The “Mgmt. Section #” field helps identify a measured section (i.e. from MP 1.0 to MP 2.0 will be assigned one number, MP 2.0 to MP 3.0 will be assigned a number, etc.), but occasionally multiple sections will be assigned the same Management Section Number. This can lead to difficulties in analysis as it impacts the ability to accurately break up the sections. Figure 8-1 displays how the condition rating change for the sections as they are originally recorded, and then how the condition ratings change

after they are defined by the numeric beginning and end milepoints (instead of by management number).

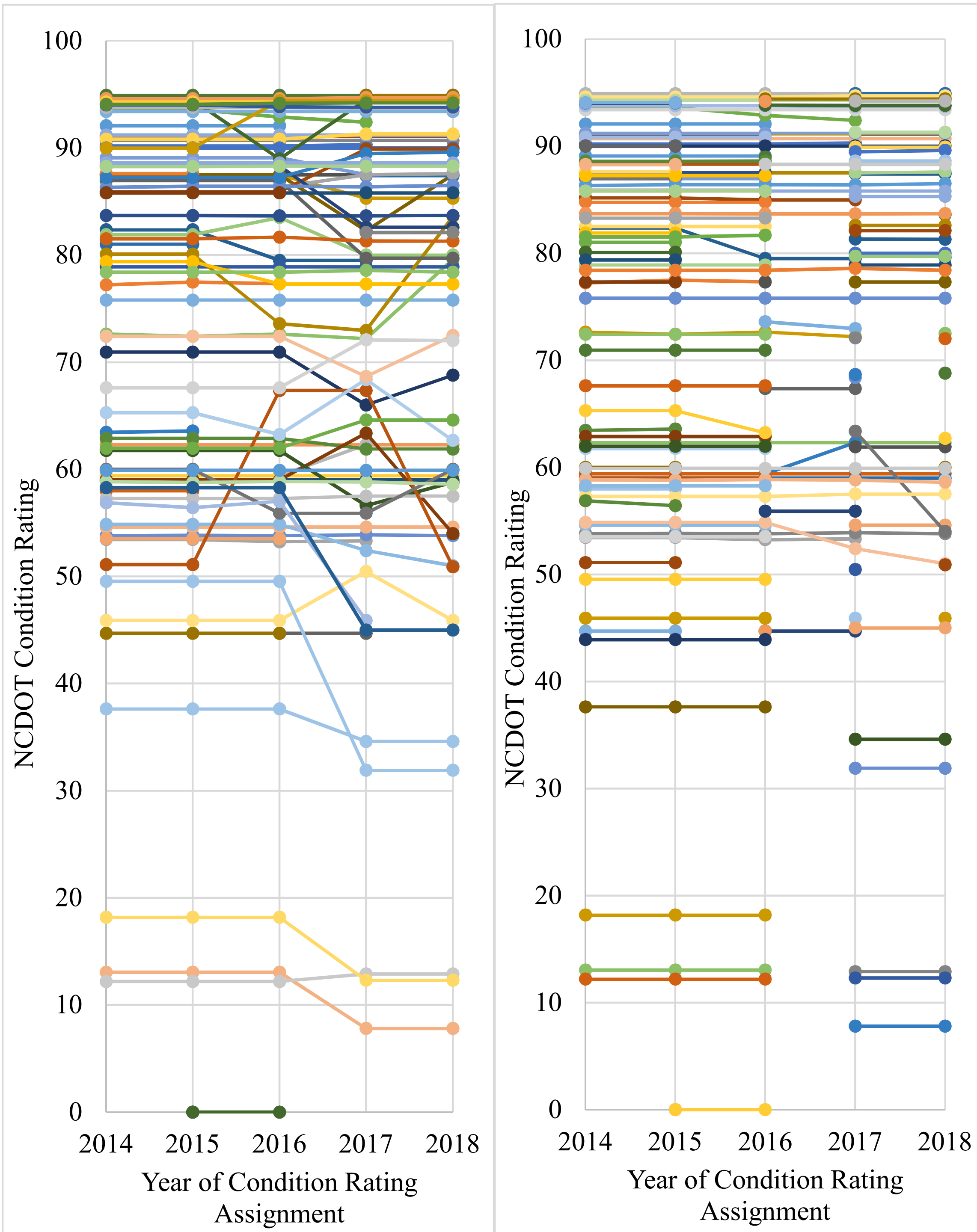

Figure 8-2: Comparison of Pavement Section Ratings for Original (Left) and Re-divided (Right) Sections

Re-dividing the sections based on the listed milepoints instead of the management number allows for a more accurate depiction of the deterioration of a roadway. If the sections are not re-divided, in some cases the condition rating goes up (even though no maintenance has been performed, and there should be no reason for an increase).

- Recording better information about the subgrade materials, such as type and treatment, would add a valuable addition to the database. Since the subgrade can have a large impact on a pavement section (cracking caused by settlement), this variable should be included in future variations of this study.

8.3 Summary

Performance based concrete mixture design specifications can help increase the lifespan of both bridges and pavements, and can also reduce MR&R actions. After merging and then filtering the array of databases available for this type of study and applying different statistical methods to these newly created datasets, trends in the data and how mixture design materials (and their proportions) affect the concrete's ability to meet early age and long term performance targets were identified. This process was more successful for the bridge deck portion of the analysis, as the level of uncertainty about the pavement data led much of it to be removed from the database. It is recommended that the stated conclusions be considered in the design of concrete to be used for concrete bridge decks in the state of North Carolina, as well as that the recommendations for modifying the collection and storage of pavement data be considered so that a similar level of success can be obtained on that portion of the study.

The results from this study support the importance of data-driven decision making regarding future changes in specifications. While the concrete is performing well in early age testing (meeting the threshold values the majority of the time), the performance of those mixtures over their lifetime indicate that the way that the concrete behaves in use must be taken into consideration. The number of bridge decks considered as under-performing far outnumber the number considered as over-performing, indicating that those early age test results are not adequate for predicting the performance of concrete over its lifetime.

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APPENDIX A ASSORTED FIGURES

1	Substructure Condition	Bridges	Bridge Cla	Deck Condition	Superstructure Condition	Division#	Tier ID	County	Structu	Structure Type	Facility Carried	Intersected Features
2	5	B080 0063		5	4	9	Regional	79 - ROW/	0	0 - Bridge	NC150	KERR CREEK
3	N	B032 0552		N	N	5	Statewide	31 - DURH	L	8 - Cantilever Sign Structu	CANTILEVER SI	I85 NB
4	N	B032 0567		N	N	5	Statewide	31 - DURH	S	14 - Overhead Sign struct	OVERHEAD SIG	US15/501 NB
5	6	B092 0224		7	7	5	Sub-Regional	91 - WAKE	0	0 - Bridge	SR2508	MARKS CREEK
6	6	B011 0206		6	5	13	Statewide	10 - BUNC	0	0 - Bridge	I-240 EBL	ACCESS RD.,HOMINY
7	N	B040 0096		N	N	2	Sub-Regional	39 - GREE	C	1 - Reinforced concrete b	SR1422	BR. OF CONTENTNEA
8	7	B036 0351		6	7	12	Statewide	35 - GAST	0	0 - Bridge	US321 N	SOUTHERN RAILWAY
9	N	B085 0295		N	N	9	Sub-Regional	84 - STOK	C	1 - Reinforced concrete b	SR1908	EURINS CREEK
10	7			6	7	10	Regional	59 - MECK	H	6 - A structure carrying a	PROSPERITY C	I485 (FUTURE)
11	5	B086 0291		5	5	11	Sub-Regional	85 - SURR	0	0 - Bridge	SR2012	FLAT SHOAL CREEK
12	7	B001 0013		7	7	7	Sub-Regional	0 - ALAMA	0	0 - Bridge	SR1530	HAW RIVER
13	N	B032 0551		N	N	5	Sub-Regional	31 - DURH	S	14 - Overhead Sign struct	OVERHEAD SIG	NC157/SR1322
14	N	B100 0308		N	N	13	Sub-Regional	99 - YANC	P	12 - Pipe culvert, either n	SR1200	LITTLE CRABTREE CRI
15	N	B053 0017		N	N	8	Regional	52 - LEE	C	1 - Reinforced concrete b	NC42	LITTLE POCKET CREE
16	8	B093 0080		8	8	5	Sub-Regional	92 - WARF	0	0 - Bridge	SR1314	HAWTREE CREEK
17	4	B081 0040		7	6	13	Regional	80 - RUTH	0	0 - Bridge	NC226	N. FORK FIRST BROAI
18	7	B031 0004		5	7	3	Statewide	30 - DUPL	0	0 - Bridge	US117	GOSHEN SWAMP
19	6	B090 0054		6	7	10	Sub-Regional	89 - UNIO	0	0 - Bridge	SR1002	GOURDVINE CREEK

Figure A-1: Screenshot of the 2018 BMS Network Master

1	Mix Design ID	Statu	Date Accepted	Date Expire	Class of Concrete	Mortar Content	Cement Amoun	Pozzolan Amount	Pozzolan Type	Fine Aggregate Amount	Fine Aggregate Spec Gravity	Coarse Aggregate Amount	Coarse Aggregate Spec Gravity	Water Amount	Maximum Water	Latex Modifier (gal.)	Air Conten	Slump	W/C Ra
2	3011VFH8660DE	Active	1/6/1999	12/31/2075	Class A	16.05	451	136	Class F Fly A	1113	2.63	1900	2.78	33	36		6	3.5	0.46
3	3011VFH8660CE	Active	1/6/1999	12/31/2075	Class A	16.43	451	136	Class F Fly A	1175	2.63	1940	2.94	33	36		6	3.5	0.46
4	3011VFH8660E	Active	1/6/1999	12/31/2075	Class A	15.82	451	136	Class F Fly A	1075	2.63	1940	2.78	33	36		6	3.5	0.46
5	3081VFE8660AE	Active	1/6/1999	12/31/2075	Class A	16.14	451	136	Class F Fly A	1106	2.63	2000	2.95	34	36		6	3.5	0.48
6	3011VOH7310DE	Active	1/6/1999	12/31/2075	Class A	16.05	564	0	No Pozzolan	1151	2.63	1900	2.78	34	36		6	3.5	0.50
7	3011VOH7310BE	Active	1/6/1999	12/31/2075	Class A	16.43	564	0	No Pozzolan	1213	2.63	1940	2.94	34	36		6	3.5	0.50
8	3011VOH7310CE	Active	1/6/1999	12/31/2075	Class A	16.43	564	0	No Pozzolan	1213	2.63	1940	2.94	34	36		6	3.5	0.50
9	3011VOH7310AE	Active	1/6/1999	12/31/2075	Class A	15.82	564	0	No Pozzolan	1113	2.63	1940	2.78	34	36		6	3.5	0.50
10	3081VOE7310CE	Active	1/6/1999	12/31/2075	Class A	16.14	564	0	No Pozzolan	1165	2.63	2000	2.95	34	36		6	3.5	0.50
11	1411VFD8660AE	Active	1/8/1999	12/31/2075	Class A	15.82	451	136	Class F Fly A	1075	2.63	1940	2.78	33	36		6	3.5	0.46
12	1921VF4092CCBE	Active	1/8/1999	12/31/2075	Class A	17.25	451	136	Class F Fly A	1282	2.65	1540	2.53	33	36		6	3.5	0.46
13	1921VF4092CCE	Active	1/8/1999	12/31/2075	Class A	17.25	451	136	Class F Fly A	1282	2.65	1540	2.53	33	36		6	3.5	0.46
14	1921VF4092CE	Active	1/8/1999	12/31/2075	Class A	17.25	451	136	Class F Fly A	1282	2.65	1540	2.53	33	36		6	3.5	0.46
15	1921VF4092WCCBE	Active	1/8/1999	12/31/2075	Class A	17.25	451	136	Class F Fly A	1282	2.65	1540	2.53	33	36		6	3.5	0.46
16	1921VF4092WCEE	Active	1/8/1999	12/31/2075	Class A	17.25	451	136	Class F Fly A	1282	2.65	1540	2.53	33	36		6	3.5	0.46
17	2701VF4092CE	Active	1/8/1999	12/31/2075	Class A	17.25	451	136	Class F Fly A	1282	2.65	1540	2.53	33	36		6	3.5	0.46
18	1871VFK8660BE	Active	1/8/1999	12/31/2075	Class A	15.76	451	136	Class F Fly A	1070	2.63	1950	2.78	34	36		6	3.5	0.48
19	1331VFP8660AE	Active	1/8/1999	12/31/2075	Class A	15.97	451	136	Class F Fly A	1079	2.63	1920	2.79	34	36		6	3.5	0.48

Figure A-2: Screenshot of the NCDOT Mixture Design Database

1	Sample ID	Contract Number	Concrete Mix ID	Sample Status	Sample Date	Material Description	Producer Name	Age at Test, days:	Air Content [%]:	Slump [in]:	Avg. Comp. Strength	Desc
2	115191	C104634	1111VO62082LUE	Meets Specs	12/16/1999 0:00	Concrete, Class B	Chandler Concrete Co.	28	5.7	3	5020	NC 86 From North of SR 1730 to Sou
3	115737	C105114	931VFP03AVE	Meets Specs	12/20/1999 0:00	Concrete, Class A	S & W Ready Mix Concrete Co.	28	5.5	3	4650	BRIDGE OVER STONEY CREEK & APPI
4	115920	C105193	24MVF61096LUE	Meets Specs	12/14/1999 0:00	Concrete, Class B	Chandler Concrete Co.	28	4.5		3920	SR-1943 (TROLLINGER RD) IN GRAH
5	117092	C104954	1102VOAAC441E	Meets Specs	1/5/2000 0:00	Concrete, Class AA	Argos USA LLC	28	7.4	1.75	5930	BRIDGE OVER HORSEPEN CREEK ANI
6	118486	C104807	2252VO7207E	Meets Specs	1/17/2000 0:00	Concrete, Class AA	Southern Concrete Materials	28	7.5	3	4540	US 23 From SR 1318 at Laurel Creek
7	119196	C105064	2422VO6AA64131E	Meets Specs	2/1/2000 0:00	Permanent Anchored W	Carolina Precast Concrete Co.,	14	5.8	2	5970	I-40 FROM WEST OF SR-1850 (SAND
8	119300	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			6705	I-95 From South of NC 72-711 to the
9	119301	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			6720	I-95 From South of NC 72-711 to the
10	119302	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			6960	I-95 From South of NC 72-711 to the
11	119303	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			6605	I-95 From South of NC 72-711 to the
12	119304	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			6610	I-95 From South of NC 72-711 to the
13	119305	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			6490	I-95 From South of NC 72-711 to the
14	119306	C104706	136RVFP13AAVBRE	Meets Specs	1/31/2000 0:00	Concrete, Class AA	S & W Ready Mix Concrete Co.	28			7100	I-95 From South of NC 72-711 to the
15	119450	C104501	112VO7207E	Meets Specs	2/2/2000 0:00	Concrete, Class AA	Southern Concrete Materials	28	5.5	3.5	5330	Bridge Over Swannanoa River, Sou
16	119467	C105212	1052VO7207E	Meets Specs	2/2/2000 0:00	Concrete, Class AA	Southern Concrete Materials	28	0.73	6.5	7880	BRIDGE OVER GREEN RIVER & APPR
17	119469	C105212	1052VO7207E	Meets Specs	2/2/2000 0:00	Concrete, Class AA	Southern Concrete Materials	28	0.57	7	7200	BRIDGE OVER GREEN RIVER & APPR
18	119486	C105212	1052VO7207E	Meets Specs	2/2/2000 0:00	Concrete, Class AA	Southern Concrete Materials	28	2	6	6920	BRIDGE OVER GREEN RIVER & APPR

Figure A-3: Screenshot of the NCDOT Cylinder Database

1	County	Route	Lane Direction	Lane	Begin MP	To MP	Length	Year	System	From Description	To Description	JCP Section	CRC Section	AC Section	BST/Slurry Section	Surface Type	Last Rehab
2	011-Buncombe	10000026	Increasing	1	24.498	25.435	0.937	2014	Interstate			Yes	No	Yes	No	JCP	
3	011-Buncombe	10000026	Increasing	1	25.435	26.435	1.000	2014	Interstate			Yes	No	No	No	JCP	
4	011-Buncombe	10000026	Increasing	1	26.435	27.435	1.000	2014	Interstate			Yes	No	No	No	JCP	
5	011-Buncombe	10000026	Increasing	1	27.435	28.244	0.809	2014	Interstate			Yes	No	No	No	JCP	
6	011-Buncombe	10000040	Increasing	1	5.130	7.082	1.952	2014	Interstate			Yes	No	Yes	No	JCP	
7	011-Buncombe	10000040	Increasing	1	7.082	7.635	0.553	2014	Interstate			Yes	No	No	No	JCP	
8	011-Buncombe	10000040	Increasing	1	7.635	8.470	0.835	2014	Interstate			Yes	No	No	No	JCP	
9	011-Buncombe	10000040	Increasing	1	8.470	10.121	1.651	2014	Interstate			Yes	No	Yes	No	JCP	
10	011-Buncombe	10600026	Increasing	1	0.903	2.112	1.209	2014	Interstate			Yes	No	No	No	JCP	
11	011-Buncombe	10600026	Increasing	1	2.112	3.112	1.000	2014	Interstate			Yes	No	No	No	JCP	
12	011-Buncombe	10600026	Increasing	1	3.112	4.012	0.900	2014	Interstate			Yes	No	Yes	No	JCP	
13	011-Buncombe	10600040	Increasing	1	21.594	23.100	1.506	2014	Interstate			Yes	No	Yes	No	JCP	
14	011-Buncombe	20600070	Increasing	1	18.526	18.711	0.185	2014	US			Yes	No	No	No	JCP	
15	011-Buncombe	21000074	Increasing	1	10.568	10.691	0.123	2014	US			Yes	No	No	No	JCP	
16	011-Buncombe	21000074	Increasing	1	10.691	11.015	0.324	2014	US			Yes	No	Yes	No	JCP	
17	011-Buncombe	21600074	Increasing	1	11.418	11.719	0.301	2014	US			Yes	No	No	No	JCP	
18	011-Buncombe	21600074	Increasing	1	11.719	11.841	0.122	2014	US			Yes	No	Yes	No	JCP	
19	013-Cabarrus	10000085	Increasing	1	0.000	0.534	0.534	2014	Interstate			Yes	No	No	No	JCP	
20	013-Cabarrus	10000085	Increasing	1	0.534	1.534	1.000	2014	Interstate			Yes	No	No	No	JCP	

Figure A-4: Screenshot of the NCDOT JCP Network Master

	A	B	C	D	E	F	G	H	I	J
1	Report ID	Contract N	Concrete Mix ID	Disposition	Date Made	Material Type	Producer	Required Flexural S	Average Flexural S	Required Compressi
2	1	C105064	120TVFP1201HPE	Meets Specs	8/22/2000	Concrete for Concrete Pavement	Argos USA LLC,	600	632	
3	2	C105064	120TVFP1201HPE		8/28/2000	Concrete for Concrete Pavement	Argos USA LLC,	600	654	
4	203	C200211	404TVFM39E	Meets Specs	7/1/2002	Concrete for Concrete Pavement	APAC-Georgia	600	642.5	
5	304	C200211	404TVFM39E	Meets Specs	7/2/2002	Concrete for Concrete Pavement	APAC-Georgia	600	656	
6	305	C200211	404TVFM39E	Meets Specs	7/2/2002	Concrete for Concrete Pavement	APAC-Georgia	600	715.5	
7	306	C200211	404TVFM39E	Meets Specs	7/2/2002	Concrete for Concrete Pavement	APAC-Georgia	600	723	
8	307	C200211	404TVFM39E	Meets Specs	7/2/2002	Concrete for Concrete Pavement	APAC-Georgia	600	663.5	
9	308	C200211	404TVFM39E	Meets Specs	7/3/2002	Concrete for Concrete Pavement	APAC-Georgia	600	679	
10	309	C200211	404TVFM39E	Meets Specs	7/3/2002	Concrete for Concrete Pavement	APAC-Georgia	600	665	
11	310	C200211	404TVFM39E	Meets Specs	7/3/2002	Concrete for Concrete Pavement	APAC-Georgia	600	690.5	
12	311	C200211	404TVFM39E	Meets Specs	7/4/2002	Concrete for Concrete Pavement	APAC-Georgia	600	671.5	
13	312	C200211	404TVFM39E	Meets Specs	7/4/2002	Concrete for Concrete Pavement	APAC-Georgia	600	665	
14	313	C200211	404TVFM39E	Meets Specs	7/4/2002	Concrete for Concrete Pavement	APAC-Georgia	600	637	
15	314	C200211	404TVFM39E	Meets Specs	7/5/2002	Concrete for Concrete Pavement	APAC-Georgia	600	665	
16	315	C200211	404TVFM39E	Meets Specs	7/5/2002	Concrete for Concrete Pavement	APAC-Georgia	600	670	
17	316	C200211	404TVFM39E	Meets Specs	7/5/2002	Concrete for Concrete Pavement	APAC-Georgia	600	689	
18	317	C200211	404TVFM39E	Meets Specs	7/5/2002	Concrete for Concrete Pavement	APAC-Georgia	600	622.5	

Figure A-5: Screenshot of the NCDOT Pavement Early Age Test Results

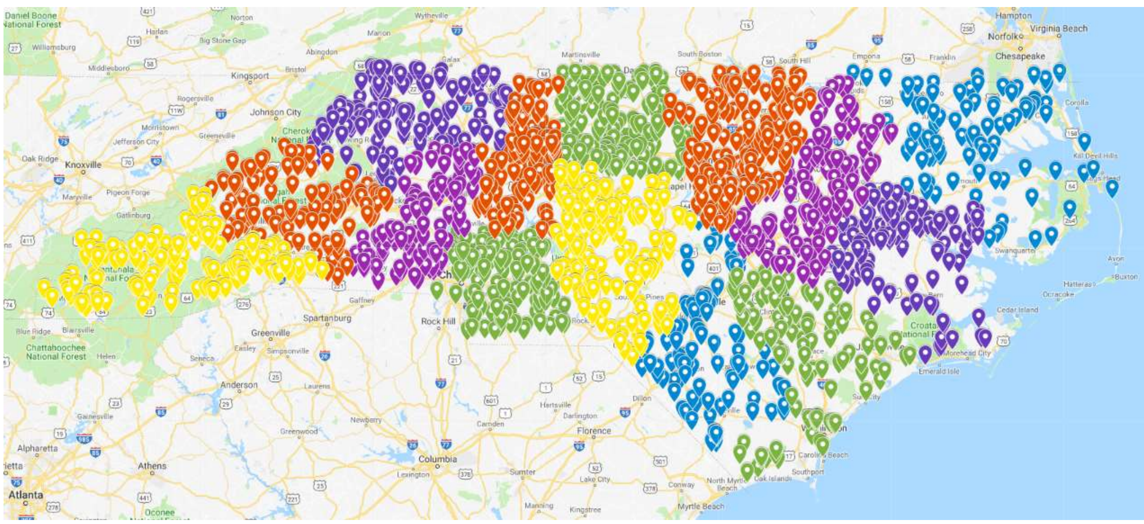

Figure A-6: Located NCDOT Bridges Colored by Division

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.901708	7.87%	7.82%	7.77%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	12.20	1.16	10.54	0.000	
FineAggregateAmount	0.000687	0.000063	10.96	0.000	2.68
FineAggregateSG	-0.478	0.157	-3.04	0.002	1.10
CoarseAggregateSG	-0.2110	0.0390	-5.42	0.000	1.11
WaterAmount	-0.04299	0.00571	-7.53	0.000	15.65
AirContent	-0.6513	0.0169	-38.45	0.000	34.06
Slump	0.02448	0.00747	3.28	0.001	13.12
WCRatio	2.426	0.335	7.24	0.000	11.77
Yield	-0.2192	0.0286	-7.66	0.000	1.34
AggregateContent	-0.02189	0.00659	-3.32	0.001	6.92
Class of Concrete					
Class AA	0.1826	0.0255	7.17	0.000	6.64
Class AA, Slip-form Barrier Rail	-0.2174	0.0385	-5.64	0.000	3.03
Class AAA	0.390	0.174	2.24	0.025	1.04
Drilled Shaft	-2.3674	0.0799	-29.63	0.000	43.14
High Early-strength Patching Mix	0.768	0.321	2.39	0.017	1.02
Latex Modified Concrete	-1.021	0.104	-9.78	0.000	11.93
Pavement	-0.2638	0.0954	-2.76	0.006	1.07
Prestress	0.119	0.522	0.23	0.820	1.01

Regression Equation

```
Class of Concrete
Class A                           AirDiff = 12.20 + 0.000687 FineAggregateAmount
                                            - 0.478 FineAggregateSG
                                            - 0.2110 CoarseAggregateSG - 0.04299 WaterAmount
                                            - 0.6513 AirContent + 0.02448 Slump
                                            + 2.426 WCRatio - 0.2192 Yield
                                            - 0.02189 AggregateContent

Class AA                          AirDiff = 12.38 + 0.000687 FineAggregateAmount
                                            - 0.478 FineAggregateSG
                                            - 0.2110 CoarseAggregateSG - 0.04299 WaterAmount
                                            - 0.6513 AirContent + 0.02448 Slump
                                            + 2.426 WCRatio - 0.2192 Yield
                                            - 0.02189 AggregateContent

Class AA, Slip-form Barrier Rail  AirDiff = 11.98 + 0.000687 FineAggregateAmount
                                            - 0.478 FineAggregateSG
                                            - 0.2110 CoarseAggregateSG - 0.04299 WaterAmount
```

Figure A-7: Model Summary for the Difference in Air Content for Bridges

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.870109	22.53%	22.48%	22.40%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	18.73	1.19	15.69	0.000	
CementProducer	0.002451	0.000855	2.87	0.004	1.10
CementAmount	-0.000960	0.000110	-8.72	0.000	3.75
PozzolanProducer	0.00905	0.00122	7.44	0.000	2.01
FineAggregateAmount	0.000034	0.000061	0.55	0.583	2.76
FineAggregateSG	0.463	0.152	3.05	0.002	1.10
CoarseAggregateSG	-0.0586	0.0385	-1.52	0.127	1.17
WaterAmount	-0.11286	0.00679	-16.63	0.000	24.06
AirContent	-0.0279	0.0169	-1.66	0.097	38.35
Slump	-0.27861	0.00734	-37.95	0.000	14.24
WCRatio	6.005	0.363	16.56	0.000	14.83
MaxWC	-0.367	0.344	-1.07	0.286	13.48
Yield	-0.4088	0.0300	-13.62	0.000	1.56
AggregateContent	-0.09850	0.00742	-13.27	0.000	9.49
Class of Concrete					
Class AA	0.3809	0.0413	9.21	0.000	18.85
Class AA, Slip-form Barrier Rail	-0.3877	0.0490	-7.91	0.000	5.22
Class AAA	-0.216	0.168	-1.28	0.200	1.05
Drilled Shaft	1.1128	0.0792	14.05	0.000	48.08
High Early-strength Patching Mix	-0.271	0.315	-0.86	0.389	1.05
Latex Modified Concrete	-1.479	0.136	-10.86	0.000	21.80
Pavement	0.1953	0.0929	2.10	0.036	1.09
Prestress	-1.205	0.507	-2.38	0.017	1.02

Regression Equation

Class of Concrete

```
Class A          SlumpDiff = 18.73 + 0.002451 CementProducer
                             - 0.000960 CementAmount
                             + 0.00905 PozzolanProducer
                             + 0.000034 FineAggregateAmount
                             + 0.463 FineAggregateSG
                             - 0.0586 CoarseAggregateSG
                             - 0.11286 WaterAmount - 0.0279 AirContent
                             - 0.27861 Slump + 6.005 WCRatio - 0.367 MaxWC
                             - 0.4088 Yield - 0.09850 AggregateContent
```

Figure A-8: Model Summary for the Difference in Slump Amount for Bridges

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
982.529	10.82%	10.80%	10.76%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	3074	821	3.75	0.000	
MortarContent	140.4	17.2	8.16	0.000	6.04
PozzolanAmount	-0.8045	0.0826	-9.74	0.000	1.48
FineAggregateAmount	0.3216	0.0999	3.22	0.001	5.94
CoarseAggregateAmount	-0.6023	0.0639	-9.43	0.000	3.33
WCRatio	2868	123	23.23	0.000	1.39
Yield	-92.0	28.5	-3.23	0.001	1.15
PasteContent	-49.06	3.76	-13.06	0.000	3.02

Regression Equation

FCDiff = 3074 + 140.4 MortarContent - 0.8045 PozzolanAmount + 0.3216 FineAggregateAmount
- 0.6023 CoarseAggregateAmount + 2868 WCRatio - 92.0 Yield - 49.06 PasteContent

Figure A-9: Model Summary for the Difference in Compressive Strength for Bridges

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
68.2874	7.41%	7.26%	7.03%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2197	374	5.88	0.000	
Pozzolan Amount	-0.1363	0.0207	-6.59	0.000	1.85
Fine Aggregate Amount	0.0803	0.0147	5.44	0.000	1.43
Fine Aggregate Spec Gravity	35.5	46.8	0.76	0.449	1.25
Water Amount	4.561	0.650	7.01	0.000	1.65
Slump	0.62	1.12	0.55	0.582	2.29
W/C Ratio	90.9	48.6	1.87	0.062	3.54
Yield	-91.6	12.1	-7.54	0.000	1.16

Regression Equation

Difference in Flexural Strength = 2197 - 0.1363 Pozzolan Amount
+ 0.0803 Fine Aggregate Amount
+ 35.5 Fine Aggregate Spec Gravity + 4.561 Water Amount
+ 0.62 Slump + 90.9 W/C Ratio - 91.6 Yield

Figure A-10: Model Summary for the Difference in Flexural Strength for Pavements

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
637.935	21.56%	21.31%	21.07%

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	-26033	2640	-9.86	0.000	
PozzolanAmount	-4.297	0.612	-7.03	0.000	9.95
FineAggregateAmount	-2.953	0.253	-11.67	0.000	2.83
FineAggregateSpecGravity	-2460	342	-7.19	0.000	2.56
CoarseAggregateSpecGravity	2868	206	13.89	0.000	1.80
AirContent	424.6	83.7	5.08	0.000	1.42
Slump	-204.2	32.5	-6.28	0.000	1.15
WCRatio	-7049	703	-10.02	0.000	5.70
Yield	1124.3	92.5	12.16	0.000	1.77

Regression Equation

DifferenceinCompressiveStrength = -26033 - 4.297 PozzolanAmount - 2.953 FineAggregateAmount
- 2460 FineAggregateSpecGravity
+ 2868 CoarseAggregateSpecGravity + 424.6 AirContent
- 204.2 Slump - 7049 WCRatio + 1124.3 Yield

Figure A-11: Model Summary for the Difference in Compressive Strength for Pavements

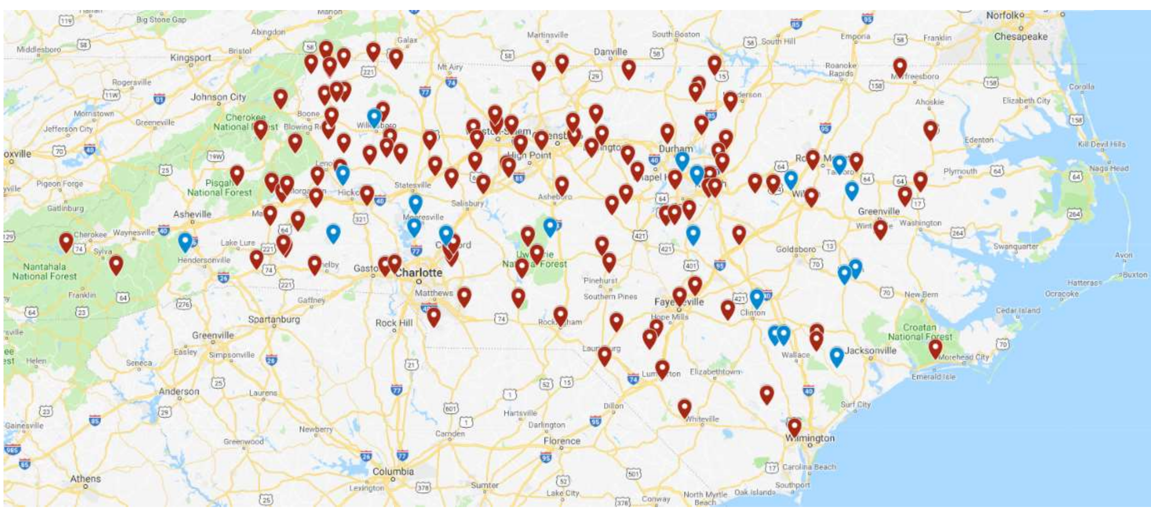

Figure A-12: Locations of Bridges Included in the Long Term Performance Analysis (with red representing the under-performing bridges and blue representing the over-performing bridges)

APPENDIX B VARIABLE DESCRIPTIONS

B-1. Bridge Deck Variables

B-1.1 Continuous Variables

Variables considered to be continuous for this analysis were typically numerical measurements of some sort, in units of pounds, days, percentage, etc. Many of these variables have been described previously in this thesis. Many of the data types retrieved from the BMS Network Master are defined in the 1995 NBI Recording and Coding Guide, first published by the Federal Highway Administration (FHWA 1995).

B-1.2 Previously Discussed Variables

Since many of the variables that fall into this category are components of the concrete mix, they have already been discussed earlier in this paper. These include structure number, concrete class, mortar amount, pozzolan type/amount, fine/coarse aggregate amount, water amount, compressive strength, air content, and slump.

B-1.3 Substructure Condition

The substructure condition is a rating to describe the physical condition of pier, abutments, piles, fenders, footings, or other related components. All of the previously mentioned elements are inspected for visible signs of distress, such as cracking, misalignment, collision damage, corrosion, and section loss. Ratings are given on a scale from “0” to “9” (with N also being included as non-applicable), with “9” representing excellent condition and “0” is completely failed and out of service.

B-1.4 Deck Condition

This category includes the rating for the overall condition of the deck. The inspection for concrete decks includes cracking, spalling, leaching, scaling, delamination, chloride contamination, potholing, and any type of depth failure (full or partial). Steel and timber decks have their own conditions as well, but as they are not related to this study, they will not be included. The condition of the wearing surface, protective system, joint expansion devices, curbs, sidewalks, bridge rail, parapets, and other such related items are not considered in this part of the bridge evaluation. Ratings of the deck condition given on a scale from "0" to "9" (with N also being included for culverts and other structures without decks), with "9" representing excellent condition and "0" is completely failed and out of service.

B-1.5 Superstructure Condition

The superstructure includes the physical condition of all the structural members, which are to be inspected for signs of distress such as cracking, section loss, malfunction, deterioration, and misalignment of bearings. The conditions of the bearings themselves, as well as the joints, paint systems, etc. are not included in the rating. Any failure components are given special attention, as failure can lead to collapse of a span or of the full bridge. On bridges where the deck is integral to the superstructure, the corresponding rating may be lower than the deck condition rating where the girders have damage. Ratings of the deck condition given on a scale from "0" to "9" (with N also being included for culverts and other structures without decks), with "9" representing excellent condition and "0" is completely failed and out of service.

B-1.6 PRI

The PRI, or Priority Replacement Index, is the system the NCDOT uses for ranking bridge replacement projects and interstate maintenance projects. This rating is significantly influenced by measures such as bridge condition, ADT (average daily traffic), and some safety items. Several of the fields included in the PRI analysis are double counted, while other characteristics that may actually be important are not included. For a bridge, the PRI can be a maximum of 120 points, with priority being given to bridges with higher scores. (Lane et al. 2016)

B-1.7 Sufficiency Rating

Evaluating a bridge on four different factors, the sufficiency rating is a percentage that indicates the sufficiency of a bridge to remain in service, with 100% being an entirely sufficient bridge. Each factor used in the equation have different weights, with that individual weigh shifting based on the parameters included within in. The NBI has the following graph (Figure 3-1) that demonstrates the basic ideas included:

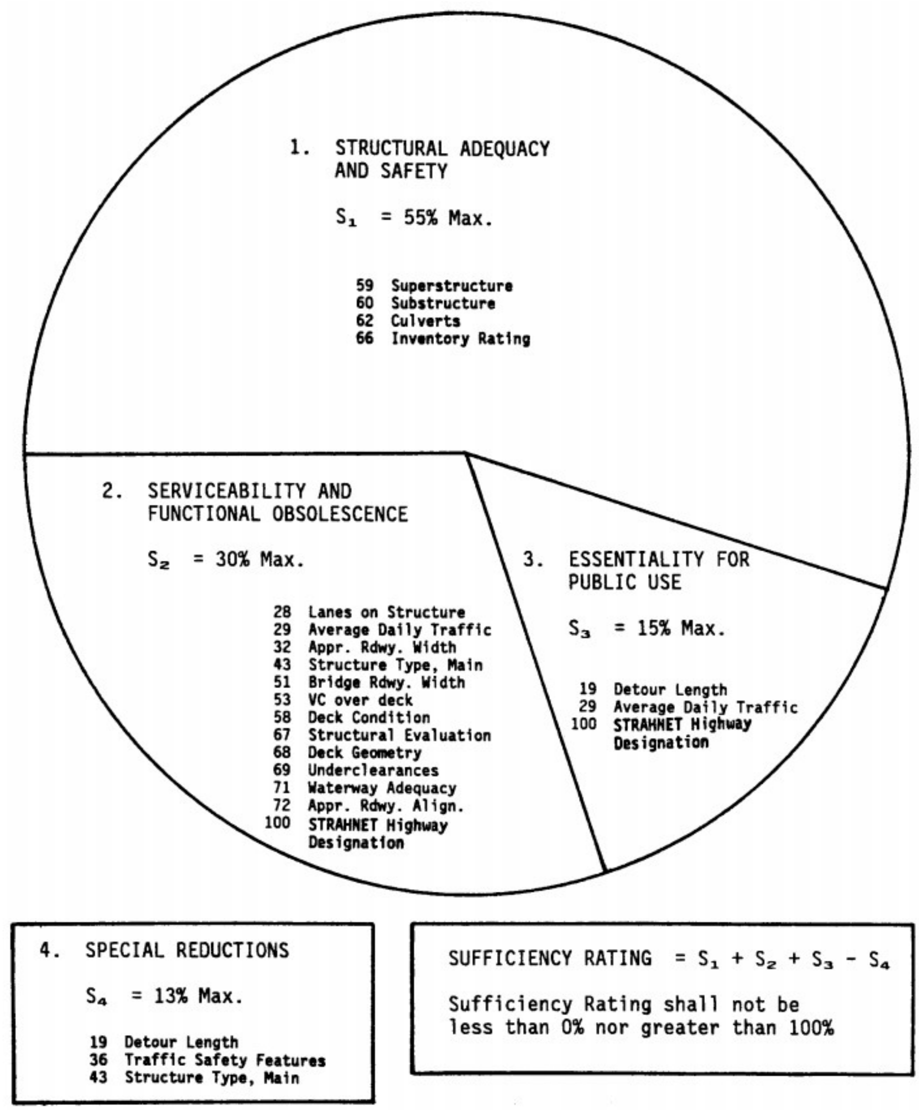

Figure B-1: Summary of Sufficiency Rating Factors (FHWA 1995)

For each piece of the pie chart, the rating of the individual components are evaluated to determine the amount of total percentage from that category will be used to determine the sufficiency rating. Some categories, such as Average Daily Traffic (ADT), are included in multiple factors. As such, this rating system is not considered to be highly accurate or useful, but since no alternative has been accepted, this rating is still used.

B-1.8 BHI Score

The BHI, or Bridge Health Index, is a way to identify which structures in the system are the most deteriorated and are in the most need of repair work. This measure only examines the condition of the structural elements of the bridge, and does not factor in function information such as traffic or capacity. A bridge is considered to be in good condition with a score of equal to or over 6 (on a scale from 1 to 9), but a low score does not correlate to an unsafe bridge (as the definition for "good" condition is not clearly defined, and a low score does not mean the bridge is falling apart) (NCDOT 2010).

B-1.9 Bridge Age

The bridge age is calculated as the difference between the year the bridge was build and the year it was inspected; i.e., the time the bridge has been in service. In theory, the older the bridge is, the more wear it will have be subjected to. Using this category can help correlate which components of the mixture design will cause the bridge to be in better condition than others over the same time period.

B-1.10 ADT / ADT Year

The ADT, or Average Daily Traffic, is a measure of the average volume of the bridge in a 24 hour time period. While this is an important number, it is not economically or logistically practical to maintain permanent counting stations, so instead a temporary counter is deployed for a period of time ranging from a few hours to a week. The determined hourly traffic volume is extracted, factored based on the day and time of year that the count was taken, then the ADT is determined (FHWA 2015).

Not all values in this category reflect how traffic is at present day. There is a category for the year in which the ADT was last determined, ranging from the current year to 30 years ago. Because the potential change in ADT from the time that it was recorded to the present is not known, this category is included to see how much non-recent data impacts the analysis.

B-1.11 Structure Length

The recorded structure length is the length of roadway supported by the bridge structure, measured either from paving notch to paving notch or back to back of the back walls of abutment. This value is given it meters, recorded to the nearest 0.1 meter. In the NCDOT BMS database, the recorded lengths are measured in imperial units, as confirmed by the field "Span Type". In this field, the measurements are given as a description, and as Network Master does not have specific units attached to the "Structure Length" field, the comparison of the two fields ensures accuracy.

B-1.12 Bridge Deck Width

The bridge deck width is to be recorded as a 4 digit metric value to the nearest 0.1 meter, and represents the out-to-out width of the structure. If the structure is a through structure, the record is the lateral clearance between superstructure members, exclusive of flared areas for ramps. The NCDOT BMS provides these values in feet instead of meters, so the format is different than the NBI description. Figure 3-2 helps to clarify exactly where the measurements are taken for this field:

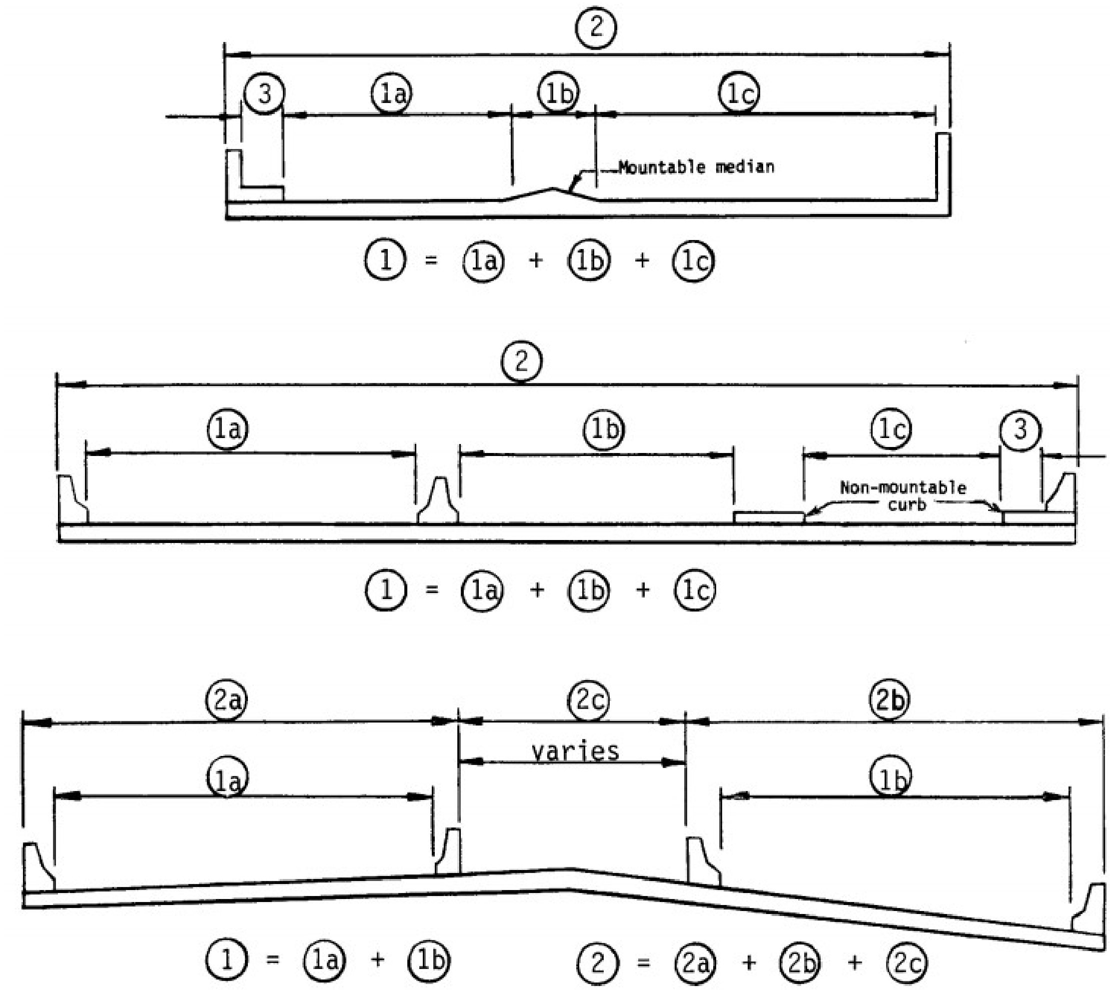

Figure B-2: Bridge Deck Width Examples (FHWA 1995)

B-1.13 Bridge Roadway Width

The recorded bridge roadway width is the most restrictive minimum distance between curbs or rails on the roadway for the structure. For double decked structures or ones with closed medians, this value is the sum of the restricted minimum distances for all roadways attached to the structure. The following figure (Figure 3-3) displays this more graphically.

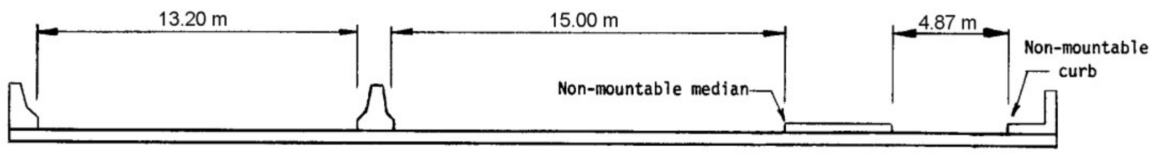

Figure B-3: Roadway Width Example (FHWA 1995)

NBI prescribes for the values to be determined using metric units (to the nearest 0.1m), but to stay consistent the values in the NCDOT BMS are recorded in terms of feet.

B-1.14 Categorical Values

Since not every value is numeric, determining how to include categorical values is important to ensure accuracy in the data. Categorical values are typically a subcategory for main ones; for example, “Pozzolan Type” is related to “Pozzolan Amount”.

B-1.15 Through Lanes On

Through lanes on is the number of lanes running across the bridge, ranging from 1 to 9. Typically, bridges do not include the upper end of this range, but there is one with 7 and one with 9 in the state. These atypical values were verified by satellite map images to ensure accuracy.

B-1.16 Superstructure Type

One a bridge, the area that gets the load directly applied to it (which then next transfers the load down to the substructure) is known as the superstructure. Typically, this will be the slab and the girders that support it. There is no uniform way that the superstructure is coded in the Network Master (since each gives a description unique to the jobsite), so these records were filtered to be more workable.

B-1.17 Structure Type Main

As a way of tracking the material type of the main structure, this field was added to house such records. These records are a 3-digit code comprised of two segments; the first (1 digit) is the kind of material and/or design (concrete, concrete continuous, steel, etc.), and the second (2 digits) is the type or design and/or construction (such as slab, tee beam, box beam, etc.). Since this project is on concrete bridges, all non-concrete bridges will be filtered out here.

B-1.18 Deck Structure Type

This field records the deck system of the bridge. In cases where more than one system is present, the most predominant will be coded. Bridges are coded 1 through 9 depending on material type, and labeled as "N" for filled culverts or arches with the approach roadway section carried across the structure. As concrete cast-in-place (code 1) and concrete precast panels (code 2) are the only ones that pertain to this topic, all others will not be used.

B-1.19 Structural Appraisal

In order to evaluate a bridge in relation to the level of service it can provide to a highway system. They are rated on a scale from "0" to "9", with "0" signifying that the bridge is closed and "9" that it is superior to present desirable criteria. Knowledge of the inventory rating (also known as the capacity rating) is vital to this rating. The following (Table 3-5) is the table used for determining the structural appraisal code.

Table B-1: Rating by Comparison of ADT and Inventory Rating (FHWA 1995)

Structural Evaluation Rating Code	Inventory Rating Average Daily Traffic (ADT)		
	0-500	501-5000	>5000
9	>32.4 (MS18)	>32.4 (MS18)	>32.4 (MS18)
8	>32.4 (MS18)	>32.4 (MS18)	>32.4 (MS18)
7	27.9 (MS15.5)	27.9 (MS15.5)	27.9 (MS15.5)
6	20.7 (MS11.5)	22.5 (MS12.5	24.3 (MS13.5)
5	16.2 (MS9)	18.0 (MS10)	19.8 (MS11)
4	10.8 (MS6)	12.6 (MS7)	16.2 (MS9)
3	Inventory rating < 4 and requires corrective action		
2	Inventory rating < 4 and requires replacement		
0	Bridge closed due to structural condition		

B-1.20 Bridge System

The bridge system defines what road type the bridge exists on. There are three different types present in the BMS Network Master database: Interstate, Primary, and Secondary. The values will be coded, and correspond with the traffic data.

B-1.21 Wearing Surface Type

The wearing surface is the road way surface of a bridge. It is a layer placed on the bridge deck and is the only part of the bridge that comes in contact with traffic. Within the BMS Network Master, it is coded as a 3-digit code comprised of three parts: type of wearing surface, type of membrane, and deck protection.

B-1.22 Substructure Material

The bridge substructure, which controls its connection to the soil and thus supports major structural elements and the bridge deck, plays an integral role in the life of the bridge. Knowledge on the materials used in this substructure is valuable, as substructure performance can lead to issues such as cracking. These materials are labeled within the BMS Network masters, and are also coded for values between 0-7.

B-2. Pavement Variables

B-2.1 Continuous Variables

Variables considered to be continuous for this analysis were typically numerical measurements of some sort, in units of pounds, days, percentage, etc. Many of these variables have been described previously in this paper. Other variables are either self-explanatory, easy to define, or defined in the 1995 NBI Recording and Coding Guide (FHWA 1995).

B-2.2 Previously Discussed Variables

Since many of the variables that fall into this category are components of the concrete mix, they have already been discussed earlier in this paper. These include structure number, concrete class, mortar amount, pozzolan type/amount, fine/coarse aggregate amount, water amount, compressive strength, air content, and slump.

B-2.3 Construction History Variables

Within the maintenance records, there are several variables that relate to the extent of work performed. Since each is simple to define and/or related to another one, these variables will be presented as bullet points rather than as individual sections.

- Lane: This defines the number of lanes that the work was performed on.
- Number of Lanes: The total number of lanes for that roadway section.

- Begin/End MP: The milepost at which the maintenance work started and stopped.
- Year Completed: The year that the work was performed. This value will be compared to when the roadway was completed to determine how much time passed after construction prior to maintenance work.
- Material 1/2/…/n: The material placed at the site, with the number indicating what layer it is (with 1 being the top layer)
- Thick 1/2/…/n: The thickness of the material with the corresponding material number.
- Inside/Outside Shoulder Width: If there is a shoulder (an emergency stopping lane on either side of the main lanes), the width of that shoulder is recorded here.

The variables from this database were used to determine if any maintenance had been performed on a section of roadway, specifically the sections that used JCP as the top layer.

B-2.4 Pavement Age

Pavement age is the length of time that has passed since the last major construction (whether it be initial construction or repairs) for a section of roadway. In theory, the older that the pavement section is, the more likely that it needs repairs/has already been repaired. This value is reset anytime repair work is performed to the roadway.

B-2.5 AADT

Annual average daily traffic, or AADT, is a measure to help determine the amount of wear on the pavement. The value itself is the total annual traffic on the roadway divided by 365, so the final units are vehicles/day.

B-2.6 NCDOT Rating Number

The NCDOT rating number is value somewhere between 0-100 describing the overall condition of the road, with 100 being a perfect rating. From the calculated weights (Table 3-11), the rating number can be calculated using the following equation:

$$PCR = 0.111 * TRNSVRS\_CRK + 0.111 * LNGTDNL\_CRK + 0.2087 * CON\_PATCH + 0.208 * ASPHLT\_PTCH + 0.098 * TRNSVRS\_SPLL + 0.098 * LNGTDNL\_JNT\_SPLL + 0.066 * CRNR + 0.098 * FAULT$$

Table B-2: Weight Factors for JCP NCDOT Rating Number

Distress	**Weight Factor**
Transverse Cracking (TRNSVRS_CRK)	0.111
Longitudinal Cracking (LNGTDNL_CRK)	0.111
PCC Patch (CON_PATCH)	0.208
Asphalt Patch (ASPHLT_PTCH)	0.208
Transverse Joint Spalled (TRNSVRS_SPLL)	0.098
Longitudinal Joint Spalled (LNGTDNL_JNT_SPLL)	0.097
Corner Break (CRNR)	0.066
Joint Fault (FAULT)	0.098

B-2.7 Categorical Variables

Since not every value is numeric, determining how to include categorical values is important to ensure accuracy in the data. Categorical values are typically a subcategory for main ones; for example, “Pozzolan Type” is related to “Pozzolan Amount”.

B-2.8 System

The roadway system is the lettering system used to designate the class of the roadway. Within the Network Master database there are four different designations: Interstate, NC (North Carolina), US (United States numbered highway), and SR (service road).

B-2.9 Section ID

This field is an expansion of the original "Section Management #" field. Within the original field, each "section" of roadway was assigned a separate number. Since the beginning and end point of these sections were not kept consistent throughout the years (and in some cases included multiple sections), the records were re-divided to reflect the true individual sections. As such, the sections needed to be assigned new identification numbers, which are included in this field.