TRC2203

Low Shrinkage Concrete Mixtures for Arkansas

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University of Arkansas - Fayetteville
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16. Abstract

Drying shrinkage-induced cracking is a major concern for concrete bridge decks, compromising both durability and service life. This study, conducted for the Arkansas Department of Transportation (ARDOT), aimed to develop and evaluate low-shrinkage concrete mixtures using locally available aggregates. A literature review identified effective shrinkage mitigation strategies, including mixture optimization and the use of shrinkage-reducing or shrinkage-compensating admixtures. A field survey of approximately 100 Arkansas bridge decks constructed between 2016 and 2022 revealed that half had early-age cracking, often associated with high cement contents and poor aggregate gradation.

Laboratory testing was performed on mixtures using four coarse aggregate types (limestone, dolomite, sandstone, and gravel). Each was tested in Standard ARDOT S(AE) mixtures and three optimized mixtures: two reduced cement mixtures with aggregate gradation optimization, and a reduced cement mixture with 30 percent fly ash substitution. Results showed that optimized mixtures achieved equivalent or superior shrinkage and strength performance compared to standard mixtures. Limestone and sandstone aggregates yielded the best compressive strength, while sandstone showed the highest shrinkage values. Electrical resistivity testing indicated that optimized mixtures also offer potential improvements in durability if they include fly ash.

The study proposes specification changes aimed at mitigating early-age cracking and improving concrete durability while maintaining ARDOT performance standards. New mixture design recommendations are provided to facilitate the adoption of these practices in Arkansas bridge decks.

17. Key Words Drying shrinkage, Coarse Aggregates, Low-Shrinkage Concrete, Shrinkage-Reducing Admixture, Shrinkage-Compensating Admixture	18. Distribution Statement		
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

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

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

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LIST OF ABBREVIATIONS, ACRONYMS, AND SYMBOLS

ACI – American Concrete Institute

ARDOT – Arkansas Department of Transportation

ASTM – American Society for Testing and Materials

CSA – Calcium Sulfoaluminate

DOT – Department of Transportation

HRWR – High-Range Water-Reducing Admixture

LWA – Lightweight Aggregate

PCC – Portland Cement Concrete

RCPT – Rapid Chloride Permeability Test

SAP – Super Absorbent Polymer

SCM – Supplementary Cementitious Material

SRA – Shrinkage-Reducing Admixture

TRC – Transportation Research Committee

VDOT – Virginia Department of Transportation

w/c – Water to Cement Ratio

w/cm – Water to Cementitious Materials Ratio

EXECUTIVE SUMMARY

This final report for TRC2203 details an investigation into low-shrinkage concrete mixtures for use in bridge decks in Arkansas, focusing on drying shrinkage as a major cause of early-age cracking. A comprehensive study was conducted that included a literature review, a field survey of approximately 100 recently constructed bridge decks, laboratory testing of concrete mixes, and the development of mixture specifications tailored to local aggregates. The primary goal was to understand how aggregate mineralogy, gradation, and mixture design influence shrinkage and related performance properties such as bulk resistivity.

The bridge survey showed that nearly half of the evaluated bridge decks exhibited early-age cracking. Statistical analysis suggested a correlation between cracking and high cement contents, elevated paste volumes, and suboptimal aggregate gradations. Laboratory testing focused on four commonly used coarse aggregates in Arkansas (limestone, dolomite, sandstone, and gravel). For each aggregate type, concrete mixtures were produced in multiple configurations: standard S(AE), reduced cement, and reduced cement with fly ash substitution. Aggregate gradation was optimized using tarantula curve methods, and mixtures were evaluated for fresh properties, compressive strength, drying shrinkage, and electrical resistivity.

Results showed that reducing cement content by up to 15.4 percent and using optimized aggregate gradation achieved comparable or improved performance in shrinkage and strength. Fly ash substitution also provided performance benefits. Among aggregates, limestone and sandstone generally produced the highest strengths, while dolomite had the lowest. All tested low-shrinkage mixtures met ARDOT's strength and workability requirements. Based on findings, new mixture specifications and design recommendations were developed to improve concrete in Arkansas bridge decks.

CHAPTER 1. INTRODUCTION

PROBLEM STATEMENT

Concrete bridge decks are particularly prone to the appearance of cracks, especially at early-ages, and regardless of the structure type and location. While they affect the aesthetics of the bridges, cracks also reduce the service life of the structure by facilitating the ingress of water and harmful chemicals (e.g., deicing salts) into the concrete, thus leading to reinforcement corrosion, freezing and thawing damage, and other distresses. Numerous studies have concluded that early-age cracking (especially in the direction transverse to the road direction) results from a combination of different factors, with drying shrinkage being the primary cause. Drying shrinkage is inevitable in conventional concrete structures, rendering its mitigation complicated. Furthermore, multiple intertwined parameters influence the effect of drying shrinkage, starting with the design of the bridge deck itself, the concrete mix design and water to cement ratio, the type of aggregate used, the construction and curing procedures, and finally, the temperatures at the time of construction. While the project needs dictate the bridge deck structural design and construction procedures, the materials and curing procedures can easily be adapted to reduce the effect of drying shrinkage and mitigate the issue of early-age shrinkage cracking. This study focuses on the mixture design effects on drying shrinkage.

RESEARCH OBJECTIVES

The objectives, as proposed at the beginning of the project, are as follows:

1. Evaluate how coarse aggregate mineralogy and gradation influence the fresh properties and the long-term performance of concrete mixes.
2. Develop low-shrinkage concrete mixes and provide design specifications based on those of other states, tailored to the locally available coarse aggregates.

RESEARCH APPROACH

The research approach for the project follows five essential tasks used to meet the proposed goals of the project, which are described below.

Task 1 – Literature review: A literature review was conducted to first describe the causes of drying shrinkage and its influence on bridge deck cracking on one hand, and on the efficiency of low-shrinkage concrete in reducing bridge deck cracking on the other. This task involved gathering ideas related to materials, concrete mix proportioning, and performance standards.

Task 2 – Evaluation of recently constructed bridge decks: Bridge decks constructed between 2019 and 2022 were surveyed throughout the state with the help of local resident engineers' offices. The main parameters in the survey were the mix design proportions, materials sources, curing procedures, construction parameters such as temperature and humidity at the time of construction, cracking status, and length and direction of cracks. Additional construction documents were used to determine other construction parameters, when available, such as deck pour sequencing, curing procedures, and cracking information.

Task 3 – Development of low-shrinkage concrete mixtures: The work in this task is mainly organized into three subtasks: describing the materials used in the project, the mixture design process and the fresh and hardened properties of the concrete mixes following the Arkansas Department of Transportation (ARDOT) specifications, and the development of low-shrinkage concrete mixes.

Task 4 – Development of mixture specifications for local aggregates: Based on the results from Task 3, design suggestions are introduced to address concrete shrinkage from the standpoint of mixture design.

Task 5 – Development of recommendations for low-shrinkage concrete: Final recommendations are provided for producing low-shrinkage concrete to be used in concrete bridge decks in the state of Arkansas, based on the results obtained in Task 3 and available literature sources.

CHAPTER 2. LITERATURE REVIEW

DRYING SHRINKAGE AND TRANSVERSE CRACKING IN CONCRETE BRIDGE DECKS

Numerous studies have investigated the issue of early-age cracking in concrete bridge decks in an effort to pinpoint its exact cause, which is often difficult due to a combination of different parameters that may contribute to cracking. Most of these studies, however, have concluded that a combination of temperature-induced stresses and shrinkage are to blame, particularly drying shrinkage which primarily causes transverse cracking in restrained structures such as concrete bridge decks (MnDOT 2011; Krauss and Rogalla 1996). Figure 1 below shows transverse cracks on the surface of a bridge deck in Arkansas. Concrete bridge decks are restrained in the longitudinal direction by the girders and the rebar cage so when the deck attempts to shrink, the restraint leads to a buildup of stresses and, potentially, cracking.

Figure 1. Transverse Cracking on Concrete Bridge Deck Surface

Drying shrinkage results from moisture loss in concrete after it has hardened. Once hardened, much of the remaining moisture inside the concrete evaporates due to the sun and wind, leaving behind voids that constrict as the moisture leaves resulting in a volume reduction. Several factors influence the potential for drying shrinkage in concrete, including the ambient relative humidity, wind conditions, ambient temperature, the type and content of aggregate, the water content, and the water-cement ratio. The factors contributing to the concrete's drying shrinkage can be mitigated through various strategies, detailed in the following section. Primarily, this report focuses on mixture design strategies to reduce drying shrinkage.

SHRINKAGE MITIGATION STRATEGIES IN CONCRETE BRIDGE DECKS

While drying shrinkage is inevitable in portland cement concrete, several strategies can be used for shrinkage mitigation, and they are briefly reviewed here. For the purpose of this report, they are classified based on whether the strategy is based on the choice of materials, or other non-materials-related factors.

Non-Materials-Related Shrinkage Mitigation Strategies:

Non-materials-related mitigation strategies concern the design of the bridge deck, the curing procedures, and the construction practices, as summarized in this section.

Consider Advantageous Design Considerations

The structural design considerations that influence the appearance of cracks in concrete bridge decks are the degree of restraint of the bridge deck and its thickness. Generally, bridges with multiple spans, continuous, composite, and large steel girders exhibit more cracking than simply supported girders (MnDOT 2011; French et al. 1999). Similarly, the high surface area to volume ratio of thin concrete bridge decks leads to a more significant increase in drying shrinkage stresses in the concrete (Krauss and Rogalla 1996; MnDOT 2011). Therefore, increasing the thickness of the deck is another recommendation to reduce shrinkage. Of course, increasing thickness increases the dead load and may not be feasible, it also increases materials costs. The size and overall structural design of the substructure also may not be realistic to change solely for the purpose of reducing cracking.

Improve the External Curing Conditions of the Concrete

External curing is an essential step in shrinkage mitigation, as it helps prevent the loss of water from the surface of the concrete until the concrete has gained enough strength to resist shrinkage-induced stresses. Not only is the curing procedure important, but the duration of the curing is also significant. Adopting good curing practices can also enhance the microstructure of the concrete, thus improving its durability and strength (Schmitt and Darwin 1996; Leclair 1998; MnDOT 2011; Krauss and Rogalla 1996). The impact of curing duration has been further highlighted by Peyton et al. (2012), who studied five concrete bridge decks newly constructed in Arkansas, and found that although no correlations existed between the curing procedures for all the bridges, the two decks with the most cracks had either the longest time before the curing compound was applied or the longest time to final cure, as a result of curing inconsistencies. Additionally, ARDOT TRC1902 and TRC1903 highlighted the importance of bridge deck curing (Murray and Spann 2021; Heymsfield et al. 2023).

Adopt Better Construction Practices

Field studies indicate that construction practices that consider concrete temperatures as well as ambient conditions such as relative humidity, ambient temperature, and evaporation rate at the time of deck placement tend to reduce shrinkage and transverse cracking in bridge decks (French et al. 1999; MnDOT 2011; Krauss and Rogalla 1996). Casting concrete so that the initial hours of concrete setting are occurring at a cooler point in the day can reduce the rate of evaporation, reduce the internal concrete temperature, and prevent solar radiation from impacting the temperature and evaporation. Avoiding excessively windy or dry days is also a good approach. Finally, exercising some control of concrete temperature by using cooler materials, ice, or retarding admixtures can help reduce early-age shrinkage.

Materials-related Shrinkage Mitigation Strategies:

Materials-related strategies generally involve the use of aggregates with low-shrinkage potential, changes or optimization of the mix design, and the use of alternative materials aimed at reducing the inherent shrinkage strains in the concrete.

Optimization of the Mixture Design

Aggregates, especially coarse aggregates, act as a restraint against cement paste shrinkage (ACI Committee, 2001; Pickett, 1956). The aggregate type, gradation, size, mechanical, and physical properties have significant effects on the drying shrinkage of concrete. For example, concrete made with rounded and smooth aggregates like river gravel shrinks more than concrete made with angular and sharp-edged aggregates like crushed limestone. Other properties of aggregates that influence shrinkage in concrete are their specific surface area and their modulus of elasticity. Concrete made with a low modulus of elasticity aggregates exhibits more shrinkage compared to concrete made with aggregates having a higher modulus of elasticity, due to a decreased restraint of the paste shrinkage (ACI (American Concrete Institute), 2017; Delatte et al., 2006; Mehta & Monteiro, 2013; French et al., 1999; Krauss & Rogalla, 1996, David W. Mokarem, 2015). The specific surface area of an aggregate is inversely proportional to its size: the smaller the aggregate, the higher the specific surface area. Troxell et al. emphasized that low elastic modulus aggregates, such as gravel and sandstones, increase the drying shrinkage by a factor of 2.5, compared to aggregates with a higher elastic modulus, such as quartz or limestone (Troxell et al., 1958). In a broader sense, the absorption capacity of the aggregate affects concrete shrinkage, as investigated by Carlson in 1938 and reported in an American Concrete Institute (ACI) guide (ACI Committee 224 2001). In fact, the absorption capacity indicates the porosity of the aggregate and is therefore related to its stiffness or modulus of elasticity, with a low modulus of elasticity generally indicated by a higher absorption. The relationship between aggregate types, their water absorption capacity, and shrinkage after a year is shown in Table 1.

Table 1. Aggregate Types, Absorption and 1-year Shrinkage (ACI Committee 224 2001)

Aggregate Type	Specific Gravity	Absorption (percent)	1-year Shrinkage (percent)
Sandstone	2.47	5.0	0.116
Slate	2.75	1.3	0.068
Granite	2.67	0.8	0.047
Limestone	2.74	0.2	0.041
Quartz	2.66	0.3	0.032

The cement content is related to the maximum aggregate size, therefore there is a relationship between the amount of coarse aggregate in a mixture and the shrinkage experienced (Mehta & Monteiro, 2013, French et al., Krauss & Rogalla, 1996). Using larger aggregate sizes as well as a higher content of coarse aggregate contributes to reducing shrinkage in concrete (ACI (American Concrete Institute), 2017; Cleary & Delatte, 2008; Delatte et al., 2006; Hansen, 2011; Mehta & Monteiro, 2013). Investigating the relationship between the water-cement ratio, aggregate content, and shrinkage strains, Odman found in 1968 that the shrinkage magnitude of the concrete increases with the water-cement ratio of the mix, for a given aggregate content, with a more pronounced effect for lower aggregate contents (Odman 1968). His findings are shown in Figure 2 which illustrates the relationship between aggregate content, water-cementitious ratio, and shrinkage.

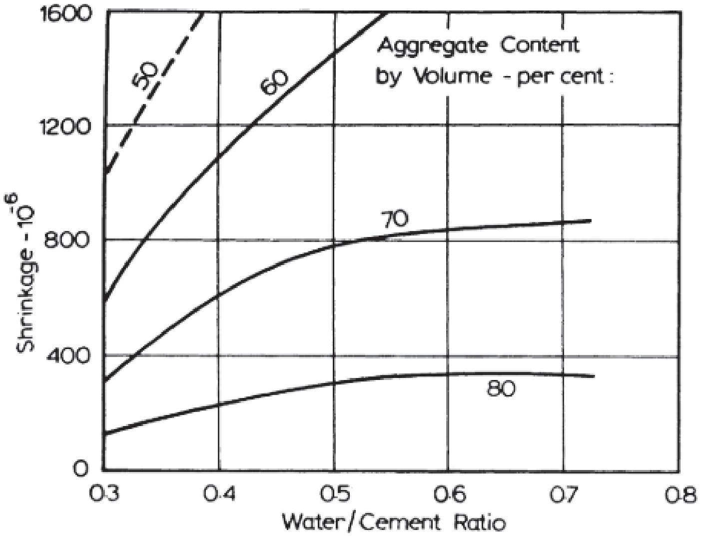

Figure 2. Relationship Between Water-Cement Ratio, Aggregate Content, and Shrinkage (ACI Committee 224 2001)

Error! Reference source not found. compares a notional cross section of a gap-graded concrete mixture (3-a) and a well-graded concrete mixture (3-b). The former generally performs poorly by being more prone to segregation and shrinkage because of the higher paste content required, unlike well-graded concrete mixtures where there is less total paste content and a stronger aggregate skeleton to reduce segregation and shrinkage (ACI Committee 325 2017; Krauss and Rogalla 1996). In light of the impact of the aggregate gradation on concrete properties like shrinkage, numerous studies have investigated the impact of gradation on concrete mixture properties, resulting in the creation of aggregate optimization models based on particle packing theories.

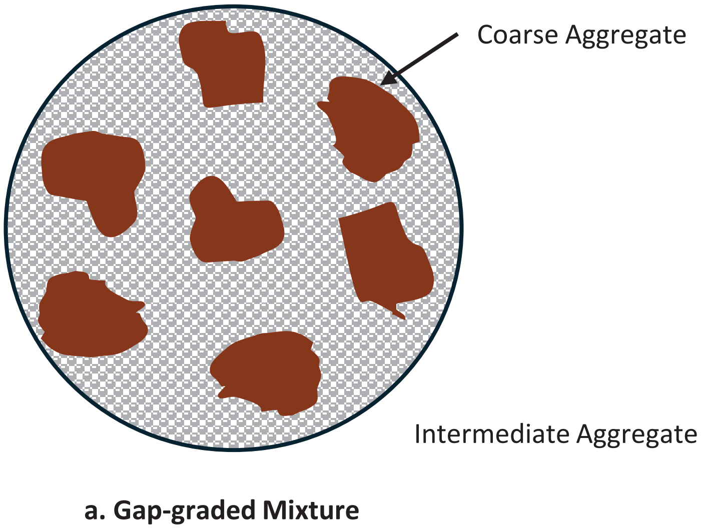

Figure 3. Concrete Mixtures: a. Gap-graded Mixture; b. Well-graded Mixture

Aggregate gradation optimization tools can be classified into two categories: experimental tools and theoretical tools, which can be subcategorized into empirical models and scientific models (Hu, 2022). The theoretical tools are summarized in Figure 4. The application of scientific tools is complex and involves parameters that are not readily available. Therefore, the following discussion only concerns empirical aggregate gradation optimization tools, which should be of use to typical concrete specifiers such as state departments of transportation.

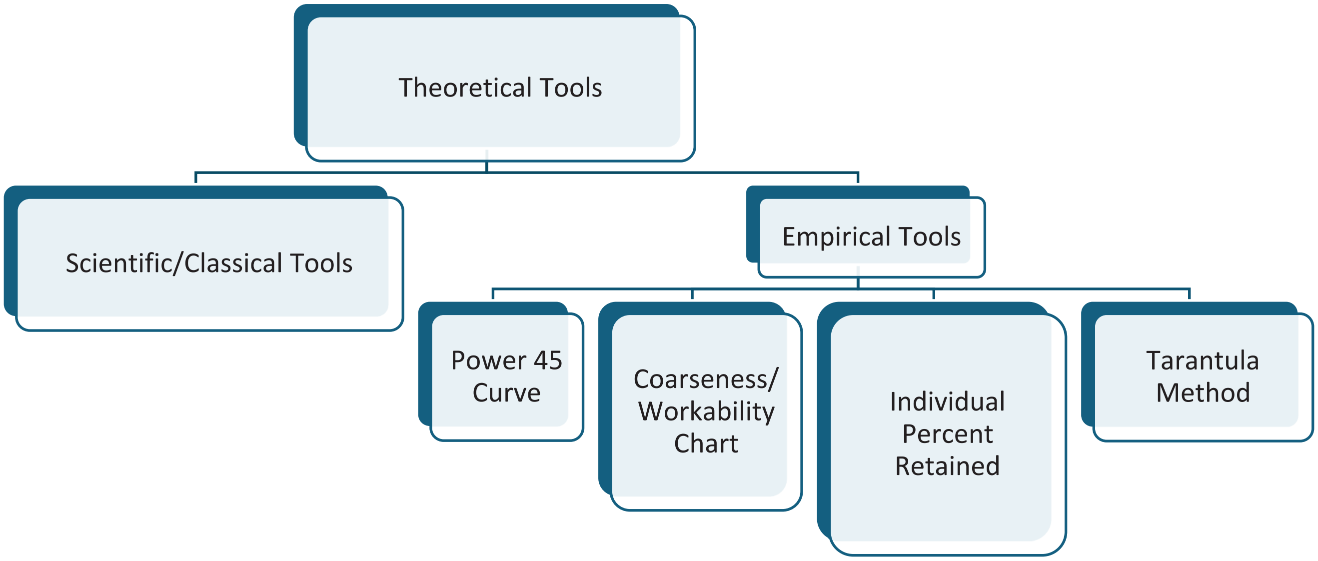

Figure 4. Classification of Theoretical Aggregate Gradation Optimization Methods

Power 45 Curve. The Power 45 curve is often used in the asphalt industry (Roberts et al. 1996), and was developed in the early 1900s by Fuller (Fuller and Thompson 1907). The combined aggregate gradation is plotted against the sieve size raised to the 0.45 power on the cumulative percent passing chart. A straight line, representing the maximum density of the combined aggregate gradation with the minimum amount of voids, is also plotted from the origin of the chart to the nominal maximum aggregate size (NMAS) (Marllon Daniel Cook, Ley, and Ghaeezadah 2016) An example of a concrete mixture is illustrated in **Error! Reference source not found.**, with the Power 45 Curve.

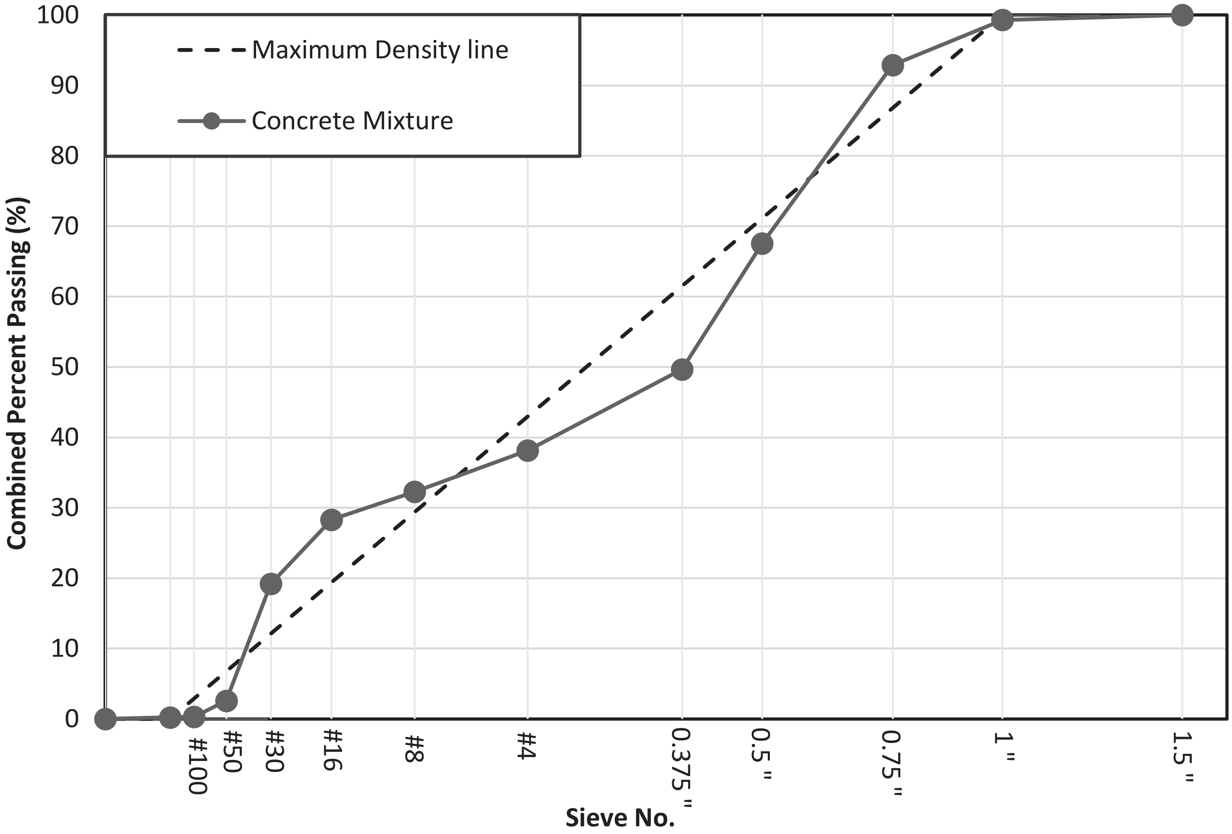

Figure 5. Power 45 Curve and a Concrete Mixture

Coarseness/Workability Factor Chart. Developed by Shilstone, the coarseness factor chart assumes that concrete aggregates are rounded or cubical in shape and uses two parameters to classify the combined gradation into categories that describe how workable the final mix will be (Shilstone 1990). These parameters are the coarseness factor (*CF*), and the workability factor (*WF*) calculated according to equations 1 and 2 (Ley and Cook 2014):

$$CF = \frac{Q}{R} * 100 \qquad \text{(Eq. 1)}$$

$$WF = W + 2.5 * \frac{(C - 564)}{94} \qquad \text{(Eq. 2)}$$

Where Q = the cumulative percent retained on the 3/8 inch sieve
R = the cumulative percent retained on the No. 8 sieve
W = the cumulative percent passing the No. 8 sieve
C = the cementitious material content (lb/yd^3)

The coarseness factor and workability factor are plotted on a graph divided into five zones, as shown in **Error! Reference source not found.**, to predict the workability of concrete mixtures. Zone II of the coarseness factor chart is usually considered an optimal area for improved constructability.

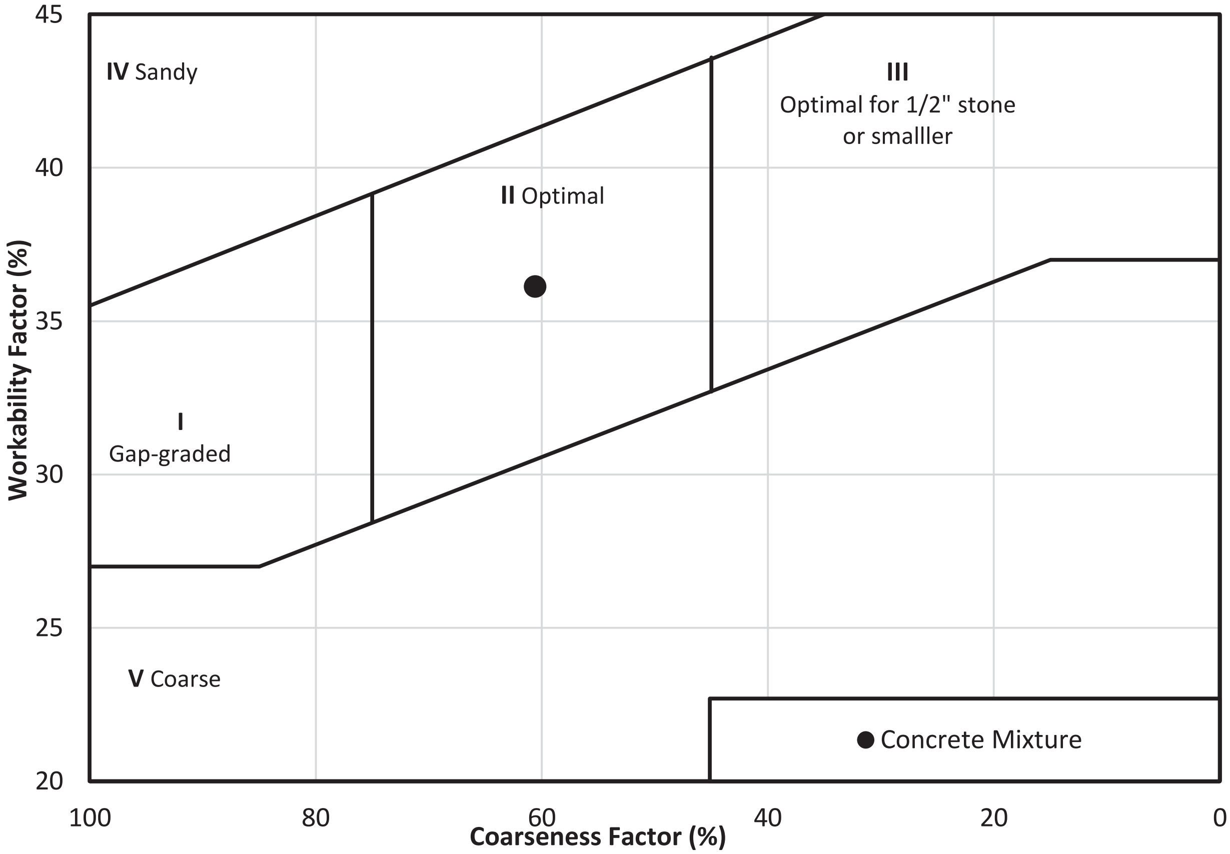

Figure 6. Coarseness Factor Chart

Individual Percent Retained (IPR) Chart and Tarantula Curves. The individual percent retained (IPR) chart, also called the 8-18 chart or haystack chart, plots the combined aggregate gradation against limits which indicate where the gradation may be excessive or lacking. Limits of 8 percent to 18 percent on each sieve size ranging from 1 inch to No. 30 are suggested (Shilstone 1990). It is the predecessor of the tarantula curve that was later developed at Oklahoma State University as a result of extensive research and review of field performance data, assessing the workability and aggregate gradation of more than 500 concrete mixtures and eight aggregate sources (Marllon D. Cook et al. 2013; Ley and Cook 2014). In the tarantula curve (Ley and Cook 2014), the upper and lower limits of the IPR have been changed empirically to reflect the impact of combined aggregate gradation on concrete workability, and recommendations are made for improved cohesion and workability. An example of the tarantula curve is shown in **Error! Reference source not found.**, with the recommended specified limits for cohesion, workability and finishability proposed by the researchers (Cook et al., 2013). Excessive amounts of coarse aggregates, from the 1.5 inch sieve to No. 4 sieve, can lead to segregation, and decrease the concrete strength due to poor gradation. Meanwhile, excess amounts of fine aggregates, from the No. 8 sieve to No. 200 sieve, increase the mixing water demand while reducing the workability of concrete. The figure also illustrates the recommended coarse sand limit (No. 8 to No. 30) which should be higher than 15 percent to ensure the cohesion of the concrete, and a recommended fine sand limit (No. 30 to No. 200) ranging from 25 percent to 40 percent, for pumped concrete.

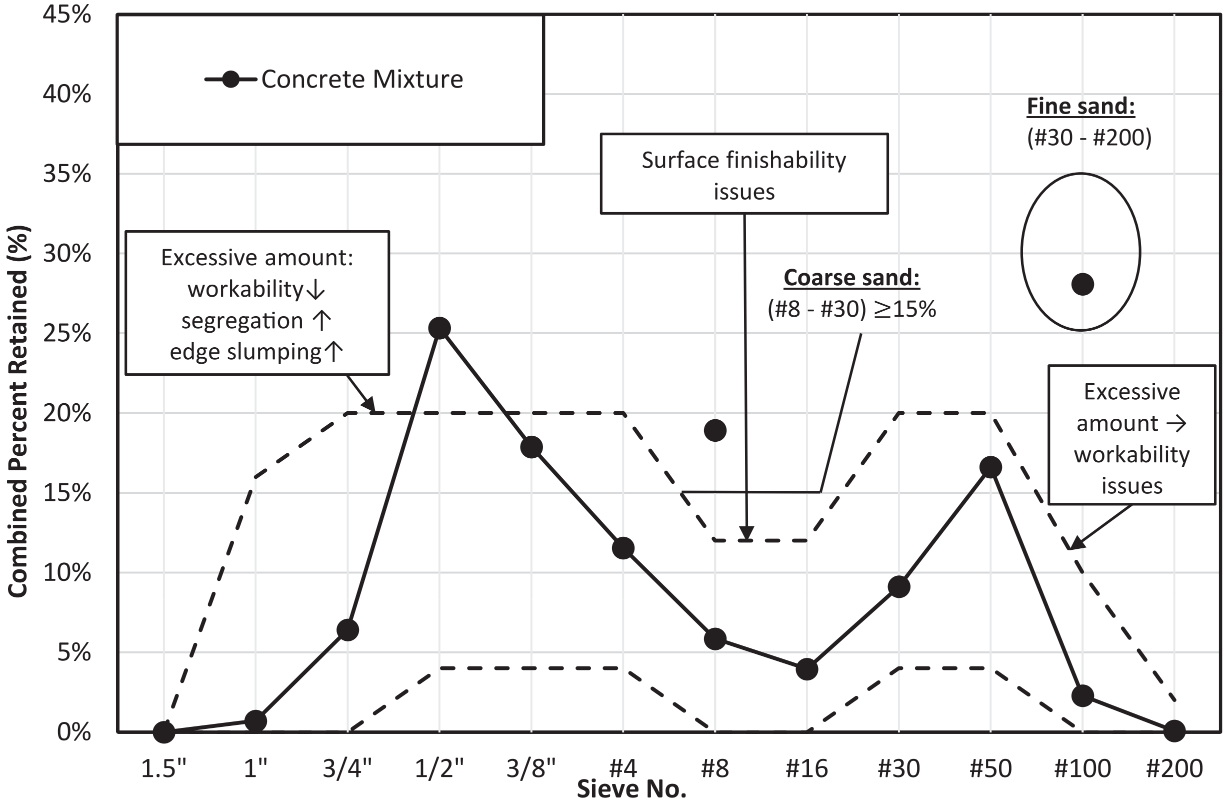

Figure 7. Tarantula Curve

Use of Mineral Admixtures

Silica fume and fly ash are typical mineral admixtures used in concrete construction. Due to their pozzolanic nature, they are reported to decrease the rate of hydration, thus reducing the concrete temperature (Deng et al., 2016; MnDOT, 2011). Lam (2005) notes that silica fume reduces the drying shrinkage in mortar and concrete. Investigating three different Class C fly ashes and one Class F fly ash, Tangtermsirikul (1995) reported lower drying shrinkage for the mixes with Class C fly ash than cement-only mixes, due to a reduction in the water demand. However, Gebler et al. (1986) found that portland cement-only concrete exhibited a similar drying shrinkage to concrete with fly ash. These results were further confirmed by Casillas et al., who found that adding fly ash to concrete resulted in similar or slightly higher drying shrinkage than control mixes without fly ash (2020).

Use of Internal Curing Agents

Drying shrinkage, as explained earlier, results from the loss of moisture in hardened concrete. The general hypothesis on the mechanism governing shrinkage is explained by moisture diffusion in concrete, which refers to the movement of water (or moisture) within the concrete or from the concrete to the surrounding environment. This process affects the durability and shrinkage of the concrete, as the water flows from areas of high moisture to low moisture, driven by differences in concentration. This phenomenon is more evident in concrete bridge decks because they have a higher surface-area-to-volume ratio and dry faster due to this higher exposure to the environment (Krauss and Rogalla 1996). As such, providing and maintaining a positive state of moisture in the concrete for as long as feasible, or until the strength is sufficient to resist shrinkage-induced stress, has been found to be an effective way of reducing early-age drying shrinkage cracking. A novel approach to provide this continuous moisture is through internal curing. Internal curing agents are used to provide some additional moisture to the concrete's interior, while maintaining the design water-cementitious materials ratio (ACI Committee 308 2012; Panwar and Jindal 2023). Lightweight aggregates (LWA) and super absorbent polymers (SAPs) can be used as internal water reservoirs that replace concrete paste moisture as it leaves the concrete surface (ACI Committee 308 2012). Lam (2005) found that using SAPs or LWAs tends to not only reduce the shrinkage and thermal deformation of concrete, but also its heat of hydration. However, the author also argues that SAP is more effective at reducing autogenous shrinkage rather than drying shrinkage (2005).

Lightweight aggregates (LWA) are specialized aggregates such as shale, slate, or expanded shale, clay, and slate, which have a bulk density less than 70 lb/ft^3 (Alexander and Mindess 2005; ACI Committee E701 2007). These aggregates' cellular structure increases their water absorption capacity, thus making them favorable for internal curing purposes, when they are pre-wetted or pre-soaked before being used in concrete. A study by Jones et al. (2020) found that using 300 lb/yd^3 of lightweight aggregates (shale and clay) led to a reduction in early-age drying shrinkage, especially when pre-soaked for at least one day, compared to concretes made with normal-weight aggregates. Although the authors stated that LWAs have a tendency to increase the drying shrinkage strains in concrete over longer time periods. The increase in ultimate drying shrinkage caused by LWA has been attributed to the lower modulus of elasticity of the lightweight aggregates in comparison to normal-weight aggregates, thus reducing the restraint against the cement paste shrinkage (Naik, Kraus, and Chun 2006).

Use of Specialized Admixtures

Numerous reports have documented the effectiveness of shrinkage-compensating admixtures and shrinkage-reducing admixtures (SRAs) in significantly reducing concrete shrinkage. Shrinkage-compensating concrete refers to concrete where the portland cement is partially replaced with shrinkage compensating cement (such as Type K cement), a material which experiences early-age expansion during curing, which counteracts later portland cement shrinkage. A study by Nair et al. (2016) found that using shrinkage-compensating concrete helped to minimize or eliminate shrinkage cracking in bridge decks. SRAs are chemical admixtures that reduce the total shrinkage experienced by the concrete by changing the surface tension of the water. Lam concluded that SRA significantly reduced drying shrinkage while extending the time between the appearance of cracks (2005). Nmai et al. (1998) reported a reduction in drying shrinkage of 50 to 60 percent in concretes using SRA, and those results were later confirmed by Gettu et al. (2002) who also found a significant reduction in drying shrinkage of concretes by 50 percent when SRA was used. Figure 8 below compares the drying shrinkage strain of portland cement concrete, concrete with Type K cement, and concrete using SRA.

Shrinkage-compensating admixtures induce controlled expansion in the concrete to offset shrinkage stresses and reduce cracking. The most commonly used expansive additive is Type K cement, which achieves the compensation effect through the expansive agents it contains. Type K cement is a combination of calcium sulfoaluminate (CSA) and calcium sulfate, which combine to produce ettringite crystals during early hydration (ACI Committee 223 2023). As a result of ettringite formation, the cement paste expands, generating compressive stresses that counteract the tensile stresses from drying shrinkage, and reduce cracking. The compressive stress generated is more important in restrained concrete members such as bridge decks. Although it is advantageous in reducing shrinkage cracking and improving the durability of concrete members, Type K cement presents a few drawbacks, such as being more expensive than portland cement and requiring different placement and mixture design considerations. Type K cement tends to accelerate hydration and needs a properly dosed retarder so that it doesn't affect the placement schedule. In addition, moist curing for at least seven days is needed to ensure that the expansive reaction occurs as intended.

Shrinkage-reducing admixtures are generally liquid additives that reduce the surface tension of water in the capillary pores of concrete, leading to a reduction in the capillary forces from shrinkage as the concrete dries, and a significant reduction in drying rates of the concrete (Bentz 2005). Similarly to Type K cement, SRA improves the durability of concrete structures and reduces shrinkage cracking but also has drawbacks like their expensive costs and potential effects on the setting times and workability of the concrete mixes. Furthermore, SRA's effectiveness requires following good mixing procedures, and a proper moist curing regimen, for at least seven days.

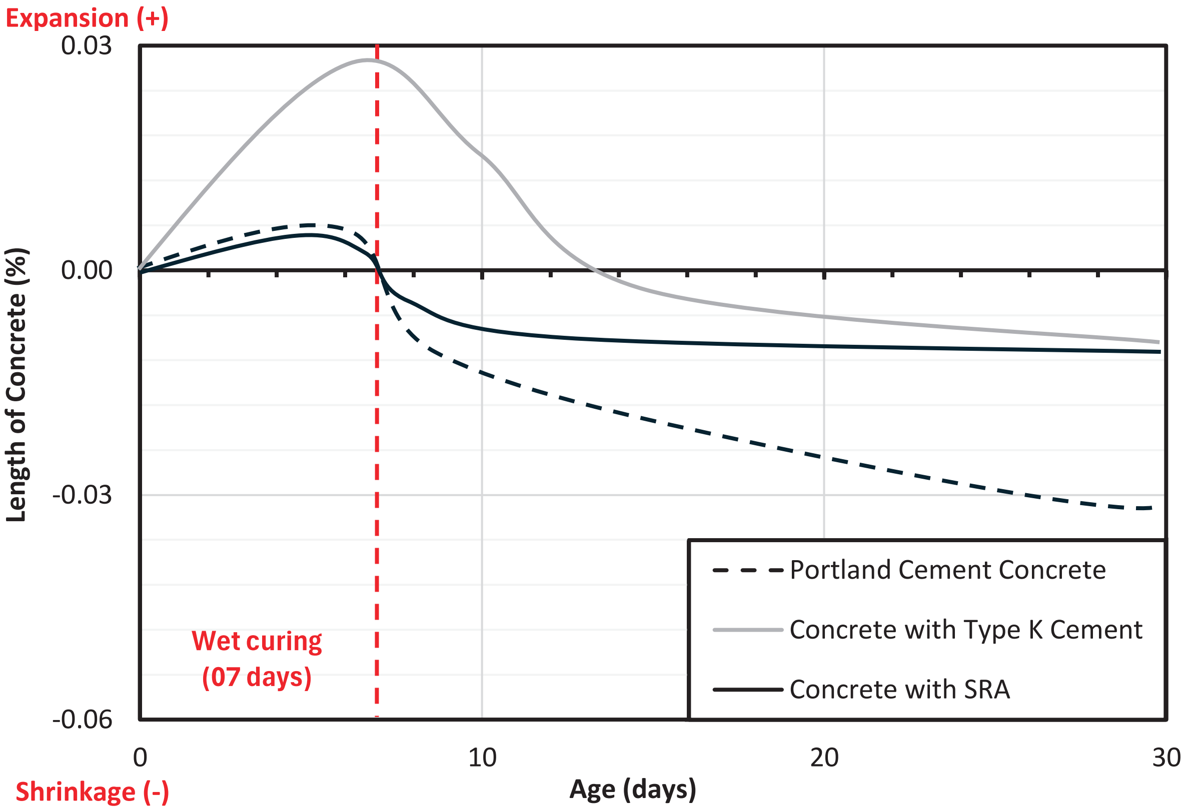

Figure 8. Comparison Between Portland Cement Concrete, Type K Cement and SRA

LOW-SHRINKAGE CONCRETE BRIDGE DECKS IN THE UNITED STATES

Although numerous states in the United States have reported a significant reduction in shrinkage strains by adopting one or a combination of the mitigating strategies reviewed here, only a few have updated their specifications to reflect those strategies. A few of those shrinkage specifications and low-shrinkage concrete mix designs gathered from national DOT specifications are briefly summarized below:

- **Alabama** limits the maximum shrinkage strain to 0.04 percent at 28 days (Alabama DOT 2022).
- **Arizona** limits the shrinkage of high-performance concrete to 0.04 percent after an initial seven-day curing period followed by 21 days of drying. Additionally, fibers may be used after approval (Arizona DOT 2021).
- **California** requires the use of fibers and shrinkage-reducing admixtures in concrete mixes used for bridge deck construction. Their specifications limit the shrinkage to 0.032 percent after 28 days of drying, with a wet curing period of 7 days. Additionally, for lightweight concrete used in structures, the drying shrinkage is limited to 0.04 percent after 14 days of drying, and shrinkage-reducing admixtures as well as fibers are not required (CalTrans 2023).
- **Delaware** requires the use of fibers, and shrinkage-compensating or shrinkage-reducing admixture for Class D concrete used in bridge decks (Delaware DOT 2024).
- **Virginia** specifies a low shrinkage (Class A4) modified concrete for bridge decks. The shrinkage for Class A4 concrete is limited to 0.035 percent at 28 days after an initial curing of 7 days. Other mitigation measures include the use of shrinkage-reducing admixture if the measured shrinkage

is greater than this shrinkage limit, or the use of lightweight aggregates, in which case no shrinkage-reducing admixture is necessary (Virginia DOT 2020).

- **Washington** specifies a maximum 28-day shrinkage of 0.032 percent, as specified in AASHTO T160, and allows the use of shrinkage-reducing admixtures (Washington DOT 2025). An additional provision allows the use of shrinkage-compensating concrete for patching materials, with a maximum shrinkage of 0.05 percent at 28 days.

The ARDOT specifications for S(AE) concrete used in bridge decks does not include a shrinkage limit; therefore the specifications and recommendations outlined in 0 will be based on and adapted from the specifications found in other states and augmented by the findings using local materials.

ELECTRICAL BULK RESISTIVITY OF CONCRETE

Concrete compressive strength is often used as a performance index to benchmark all other mechanical and durability properties of concrete. Similarly, the permeability of the concrete can be used as an indication of the overall durability of concrete, and the electrical bulk resistivity of concrete is a good measure of permeability. In effect, low-permeability concrete tends to have a higher resistivity, and vice-versa. Similar to shrinkage, aggregate properties significantly influence the resistivity of concrete. In general, using higher coarse aggregate contents will improve the resistivity of the concrete, by introducing electrical obstacles in the paste, thus increasing the tortuosity in the concrete rather than changing the porosity of the paste (Hou et al. 2017). Similar to compressive strength, porous and weak aggregates are more prone to crack propagation, thus increasing the conductivity of ions and reducing the resistivity of the concrete (Bentz et al. 2017). Larger aggregate sizes tend to increase the permeability of concrete, thus reducing its electrical resistivity (Mehta and Monteiro 2013). A study by Sengul (2014) compared the resistivity of concrete made with gravel and crushed limestone and concluded that coarse aggregate type, size, and content influence concrete's electrical resistivity. This study's results show that the concrete's electrical resistivity increases with an increase in the aggregate content, and that the increase in electrical resistivity was significantly noticeable for a minimum of 60 percent of coarse aggregate content. Moreover, the mixes with gravel had lower resistivities compared to the ones with crushed limestone, and this was attributed to the weaker interfacial transition zone between the aggregate and cement resulting from the smoothness and roundness of the gravel. Comparing the sizes of coarse aggregates, the author also found that at 40 percent and 60 percent coarse aggregate volume, the mixtures containing coarse aggregates sizes of 0.6 inch to 1.2 inch had resistivities 39 percent and 63 percent higher than mixtures containing coarse aggregates smaller than 0.16 inch (Sengul 2014).

While the ARDOT Specifications for S(AE) concrete used in bridge decks does not include permeability requirements, some DOTs specify current passed in the rapid chloride permeability test (RCPT). Others are beginning to use surface resistivity. The Virginia Department of Transportation sets a maximum 28-days permeability limit at 2500 Coulombs (based on the RCPT) which is equivalent to an electrical bulk resistivity of 75 Ohm-m (Spragg, Castro, et al. 2011; Virginia DOT 2020). Resistivity measurements are becoming more common in DOT specifications due to their ability to benchmark many durability properties and their correlation with desirable concrete properties.

CHAPTER 3. EVALUATION OF RECENT BRIDGE DECKS

The first step of the project consisted of surveying concrete bridge decks constructed between 2016 and 2022, determining how many showed early-age cracking, and determining the potential causes for cracking based on the mixture design and construction information. Approximately 100 bridge decks were investigated throughout the state of Arkansas. Figure 9 shows the distribution of the bridges investigated around the state and whether early-age cracking was observed.

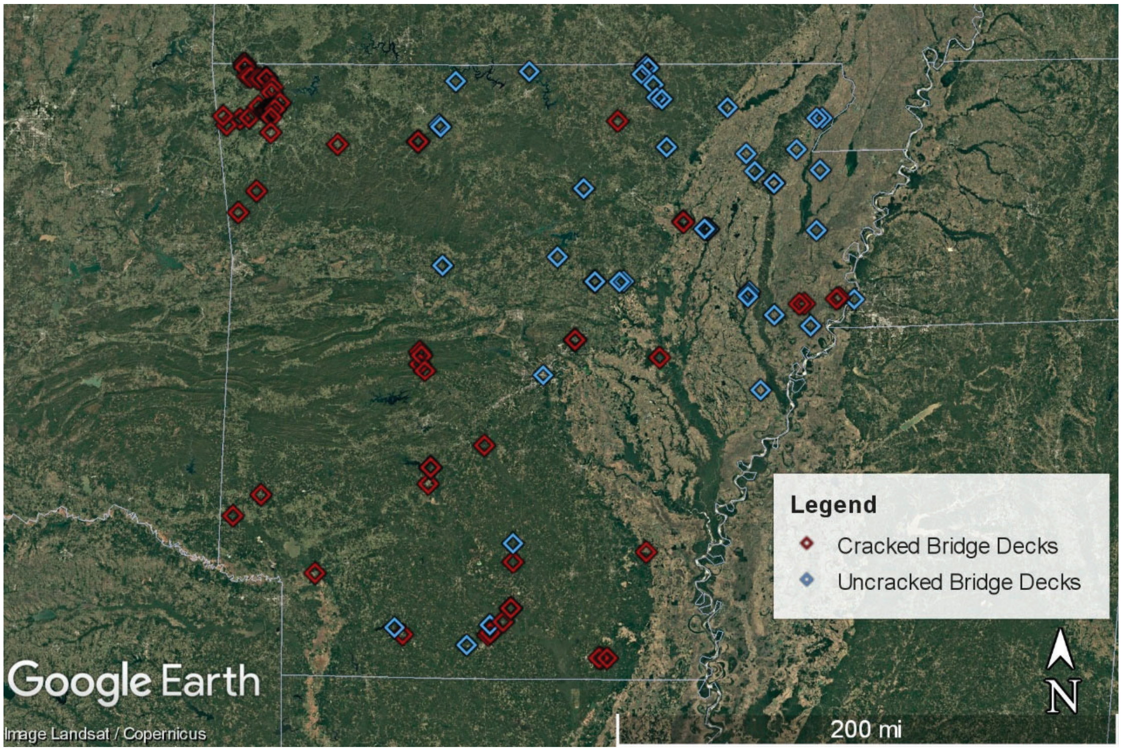

Figure 9. Location of Surveyed Bridge Decks

Roughly half of all bridge decks included in the survey experienced early-age cracking. A statistical analysis was performed to determine differences in mix design parameters, such as the average compressive strength, cementitious material content and aggregate contents, for example. The results are summarized in Table 2. The statistical analysis shows that the average reported strength was 45 percent higher than the specified compressive strength of 4000 psi at 28 days, and the coarse aggregate content ranged from 55 percent to 64 percent of the concrete's volume, with a median weight of 1800 lb/yd^3. Another important observation is that some bridge decks used 650 lb/yd^3 of total cementitious material, which is eight percent higher than the minimum required cement content of 611 lb/yd^3.

Table 2. ARDOT Survey: Mix Design Properties and Statistical Values

Properties	Minimum	Maximum	Mean	Median
Compressive strength at 28 days (psi)	4230	8465	5828	5772
Cement content (lb/yd3)	489	650	578	611
Fly ash, when used (lb/yd3)	122	130	123	122
Water (lb/yd3)	232	280	262	267
Water to cementitious materials ratio (w/cm)	0.38	0.45	0.42	0.43
Paste content (percent)	25	29	27	27
Coarse Aggregate (lb/yd3)	1622	1977	1801	1800
Fine Aggregate (lb/yd3)	1090	1434	1213	1214
Coarse Aggregate (percent)	55	64	60	60
Fine Aggregate (percent)	36	45	40	40
Air Content (percent)	4	7	5	5
Slump (inch)	3	7	4	4
Concrete Temperature (°F)	56	89	74	75
Ambient Temperature (°F)	39	88	63	62

The mineralogies of the coarse aggregates used in the bridges surveyed were also determined for 46 bridges, based on the available construction information, and they are summarized in **Error! Not a valid bookmark self-reference.**. Limestone, dolomite, sandstone and gravel were identified as the most used in bridge decks throughout the state. Therefore, these aggregate species were selected for the lab testing performed in this project. The type of coarse aggregate used in bridges was based almost entirely on local material availability to reduce transportation costs.

Table 3. Mineralogy of Coarse Aggregates used in Surveyed Bridges.

Coarse Aggregate Mineralogies Used	Number of Cracked Bridge Decks	Number of Uncracked Bridge Decks	Total
Limestone	8	5	13
Dolomite	4	9	13
Sandstone	5	5	10
Gravel	4	3	7
Syenite	2	0	2
Tuff	1	0	1
Total	**24**	**22**	**46**

The origin of each of the coarse aggregates selected for investigation in the project is shown on a map of Arkansas in Figure 10. The species were chosen based on how commonly they were used in bridge decks, otherwise the criteria used to select these specific quarries was their presence on the ARDOT qualified products list and their relative proximity to Fayetteville, AR.

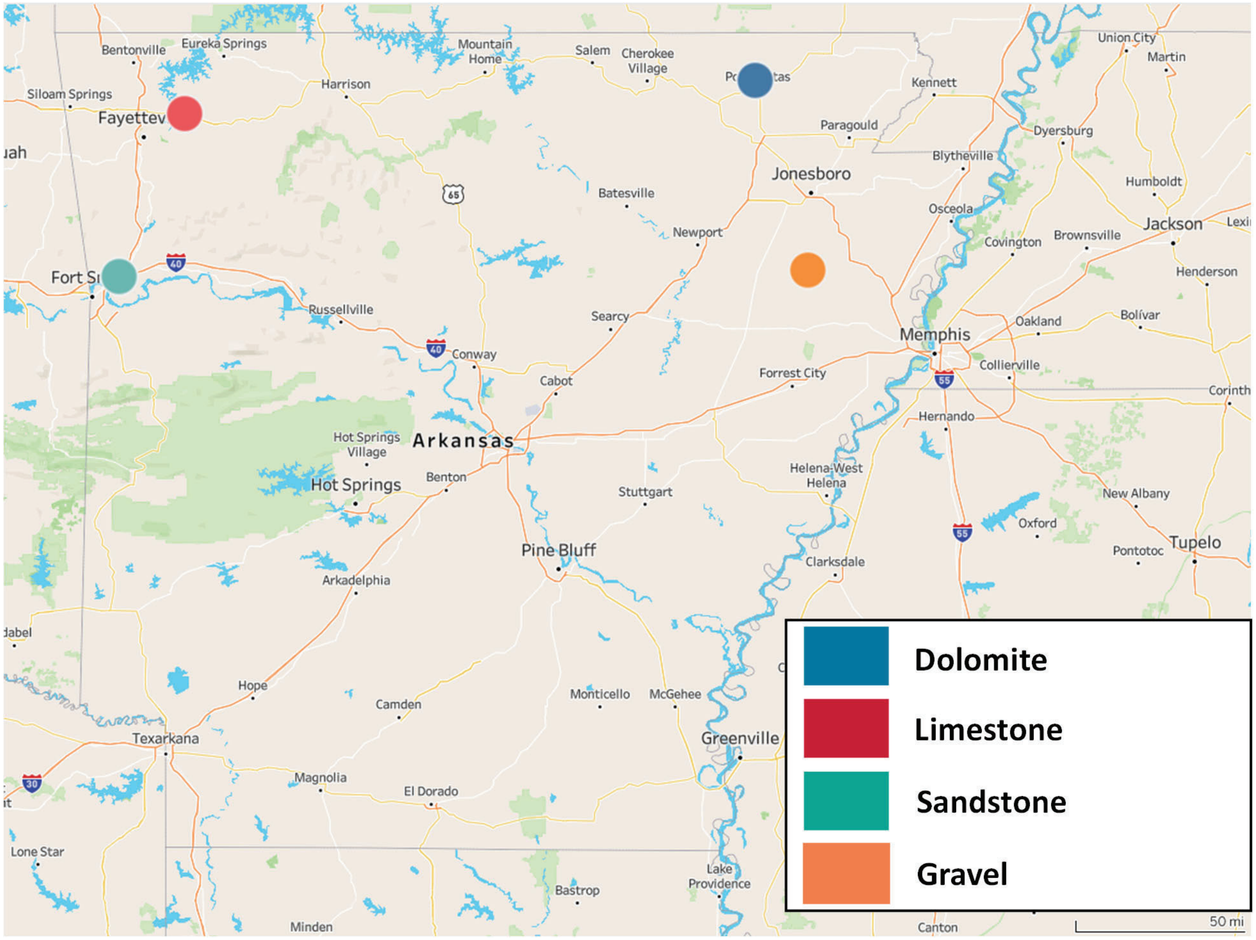

Figure 10. Coarse Aggregate Quarries Used in this Project

To compare the effect of aggregate gradation on the presence of cracking in the bridges in this survey, the coarse and fine aggregate gradations were obtained for all the bridge decks where that information could be found. From these gradations and mixture designs, the tarantula curves were plotted. The tarantula curves from a selection of cracked and uncracked bridges are shown in Figure 11 (cracked bridges) and in Figure 12 (uncracked bridges). Every bridge in this subset of bridges where the gradations and mix designs were obtained failed the tarantula limits on the coarse aggregate side. On the other hand, more of the uncracked bridges met the tarantula curve limits, though not all did. While this does not imply that the aggregate gradation directly leads to lower shrinkage, the research approach was adjusted to investigate varying the aggregate gradation to observe its effect on shrinkage. Even if the gradation doesn't directly affect shrinkage, a mixture with poor workability (as indicated on the tarantula curve) may require a higher water content to achieve the desired slump or may require more finishing effort and consolidation. These factors could contribute to higher shrinkage, construction delays which affect curing, or they may denote a generally poor concrete mixture, all of which could lead to early-age cracking.

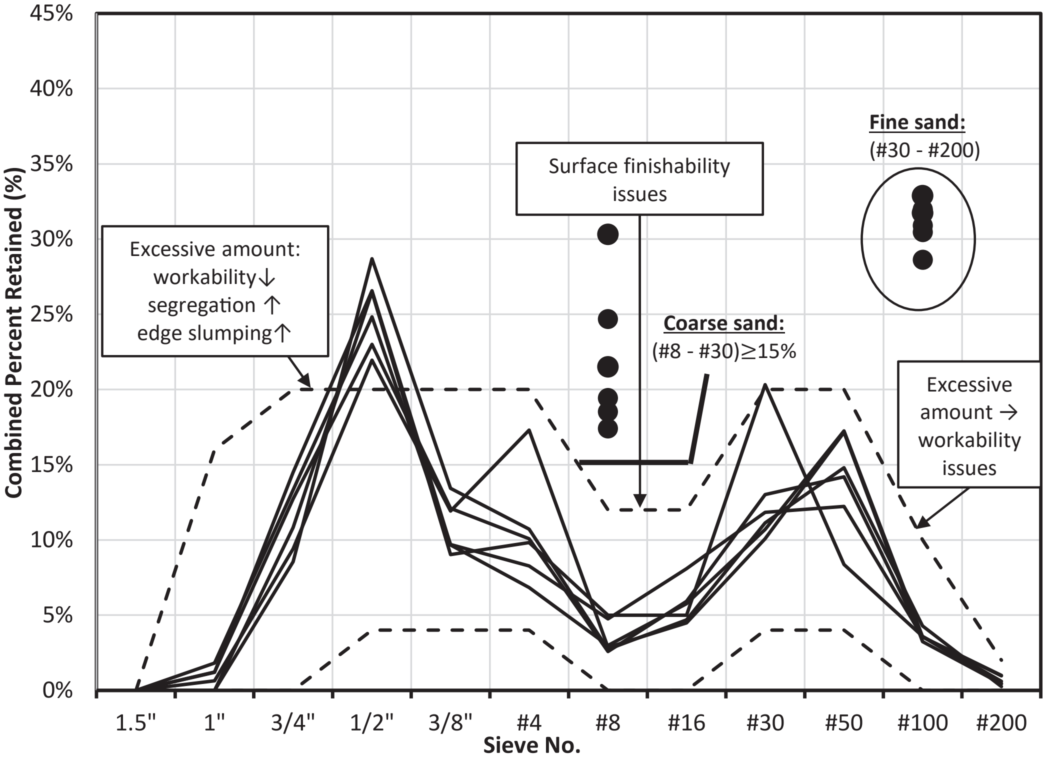

Figure 11. ARDOT Survey: Tarantula Curves - Cracked Bridges

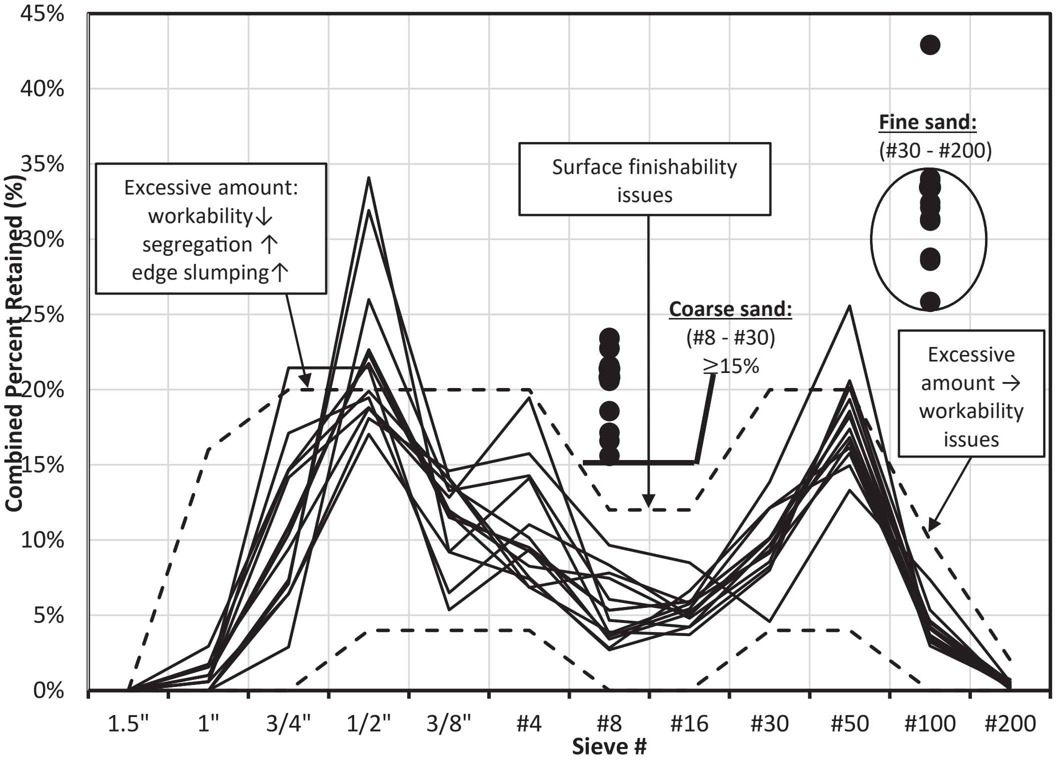

Figure 12. ARDOT Survey: Tarantula Curves - Uncracked Bridges

CHAPTER 4. DEVELOPMENT OF LOW–SHRINKAGE CONCRETE MIXTURES

This chapter describes the materials and methods used to understand the shrinkage of S(AE) concrete mixtures made using various common Arkansas coarse aggregate species and results of testing from these mixtures. The general approach was to perform a suite of tests on S(AE) concrete mixtures made with four Arkansas aggregate types which were most used in bridge deck concrete. Within each aggregate type, multiple mixtures were made: a "standard" mix with only one coarse aggregate gradation, a mix with a half a bag reduction in cement content and an optimized gradation incorporating an intermediate aggregate size, a mix with a full bag reduction in cement and optimized gradation, and a mix with a full bag reduction of cement, 30 percent fly ash replacement, and an optimized gradation. Typical fresh and hardened concrete properties were measured in addition to drying shrinkage for up to a year and several other novel properties. The methods and results of these initial mixtures are detailed in this chapter and were used to draw conclusions about the effect of optimized gradations on shrinkage and the shrinkage qualities of commonly used Arkansas aggregates.

MATERIALS USED IN CONCRETE MIXTURES

This section summarizes all the materials used to make the concrete mixtures in this study.

Cementitious Materials

Type I/II portland cement was used to make two standard S(AE) concrete mixes, but since the availability of regular Type I/II portland cement is dwindling, it was replaced with portland limestone cement for the remainder of the project. In addition, Class C fly ash and the shrinkage compensating cement, Type K cement, were also used. The Class C fly ash was obtained from the Flint Creek Power Plant in Gentry, AR sold by Charah Solutions, and Type K cement was obtained from the CTS Cement Corporation. An x-ray fluorescence (XRF) chemical analysis was conducted on these materials at the ARDOT Materials Laboratory for the portland limestone cement, Class C fly ash, and Type K cement, and the results are summarized in Table 4, in percentages. The Bogue Equation can be used to determine the phase composition of portland cement based on an XRF chemical analysis. The equation is not adapted to cementitious materials other than portland cement, therefore, the primary cement compounds for the Class C fly ash and the Type K cement are not provided. Additionally, the resulting alkali content of each cementitious material, also called Na_2O–equivalent or Na_2O_{eq} (Leming and Nguyeh 2000) was calculated using the equation (Eq. 3) below, based on the analysis results provided:

$$Na_2O_{eq} = Na_2O + 0.658\,K_2O \qquad \text{(Eq. 3)}$$

Where Na_2O = the percentage of sodium oxide in cementitious materials
K_2O = the percentage of potassium oxide in cementitious materials

Table 4. Chemical Compositions of the Cementitious Materials Used

	Chemical Notation	Portland Limestone Cement	Class C Fly Ash	Type K cement
Silicon Dioxide	SiO_2	19.3	36.56	11.53
Aluminum Oxide	Al_2O_3	4.20	18.59	15.00
Iron Oxide	Fe_2O_3	3.02	5.53	1.44
Calcium Oxide	CaO	63.3	24.68	47.43
Magnesium Oxide	MgO	2.00	4.71	0.82
Sulfur Trioxide	SO_3	2.99	1.43	14.98
Loss on Ignition	LoI	3.77	-	-
Sodium Oxide	Na_2O	0.18	1.5	0.23
Potassium Oxide	K_2O	0.53	0.44	0.48
Titanium Dioxide	TiO_2	0.26	1.44	0.55
Phosphorous Pentoxide	P_2O_5	0.07	1.02	0.06
Carbon Dioxide	CO_2	3.5	-	-

Primary Cement Compounds (Bogue Calculation) and Alkali Contents:

	Chemical Notation	Portland Limestone Cement	Class C Fly Ash	Type K cement
Tricalcium Silicate	C_3S	51.80	-	-
Tricalcium Aluminate	C_3A	6.10	-	-
Dicalcium Silicate	C_2S	16.25	-	-
Tetracalcium Aluminoferrite	C_4AF	9.2	-	-
Alkali content	Na_2O_{eq} (percent)	0.529	1.790	0.546

Admixtures

An air-entraining admixture (TERAPAVE® AEA) was used for all concrete mixes to increase the volume of entrained air to the specified range of 4 to 8 percent. A high-range water reducing admixture (HRWR, ADVA® Cast 575) was also used to reach consistent workability between mixtures, facilitate concrete placement, and decrease the water content when necessary. In addition, a shrinkage-reducing admixture (SRA, EUCON™ SRA XT) manufactured by Euclid Chemical was used to produce low-shrinkage concretes for selected coarse aggregate species. Depending on the ambient temperature at the time of mixing, concrete mixes containing shrinkage-mitigating admixtures such as Type K cement and EUCON™ SRA XT can set faster than regular portland cement concrete. Therefore, to allow enough time to perform all necessary tests on the fresh concrete, a set retarder and hydration-stabilizing admixture (MasterSet® Delvo) was used in mixes containing shrinkage-mitigating admixtures. The weight of the mixing water was adjusted accordingly whenever the liquid admixtures were used.

Aggregates

The aggregates used in the project were obtained from locations throughout the state. They were tested for their basic properties immediately following their acquisition. First, samples were batched and reduced to an appropriate sample size following ASTM D75/D75M (ASTM 2019) and ASTM C702/702M (ASTM 2018). After these steps, the aggregate samples were washed based on ASTM C117-23 (ASTM 2023a). Other basic aggregate properties evaluated include a sieve analysis or gradation and the specific gravity and absorption of the aggregates. The gradation or sieve analysis of the aggregate was performed according to ASTM C136/C136M-19 (ASTM 2014). The specific gravity and absorption of the rocks were determined using ASTM C127 (ASTM 2024). Those test results and the aggregate sources are presented next for the fine and coarse aggregates.

Fine Aggregate

The fine aggregate used in this project was river sand quarried in Van Buren, Arkansas. The absorption of the sand was 0.5 percent, and its fineness modulus ranged from 2.390 to 2.877. The acceptable gradation for the fine aggregate is illustrated in Figure 13. Sand from the Arkansas river is ubiquitous in concrete mixtures state-wide and while it is quarried in different parts of the state, it was assumed that the properties of the sand are relatively similar, so only one source was considered. All sand was used as-received, regardless of the gradation.

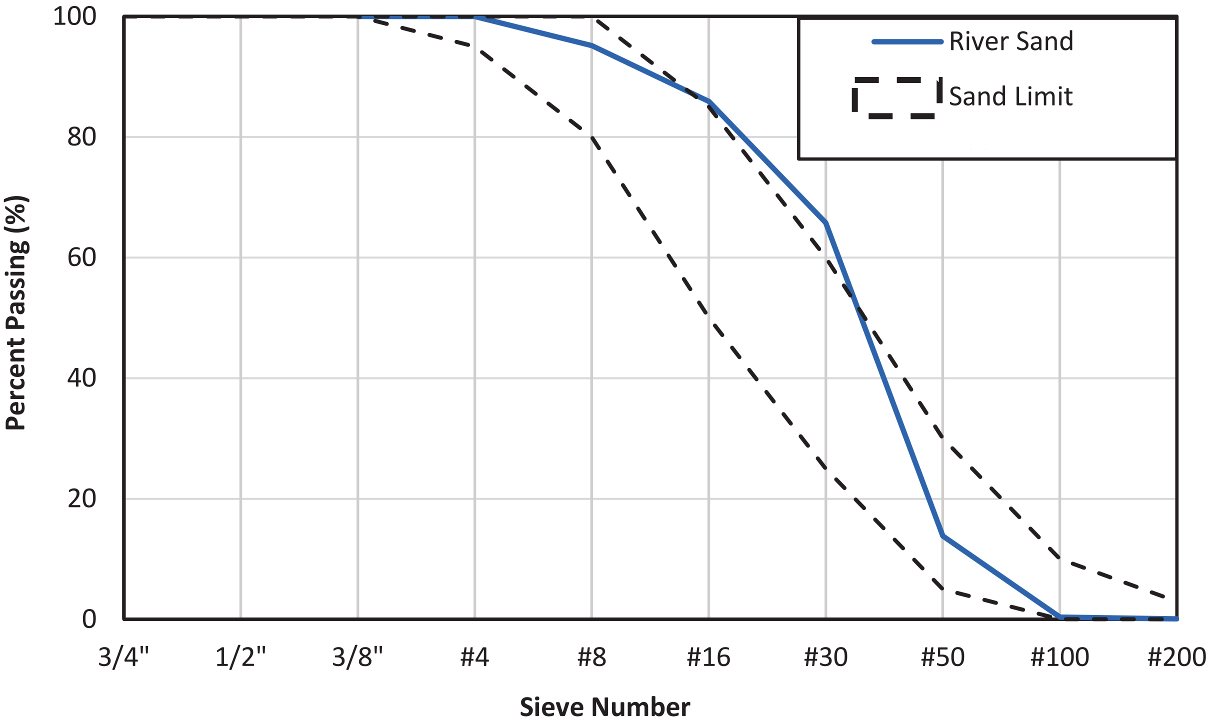

Figure 13. Fine Aggregate Gradation with Acceptable Limit Range

Coarse Aggregates

Based on the preliminary survey provided by ARDOT at the beginning of the project and described in 0, four Arkansas coarse aggregates were selected for the investigation: Limestone, Dolomite, Sandstone and Gravel. A description of the mineralogy of the coarse aggregate species used in the study follows:

- **Limestone** is a sedimentary rock composed mainly of the mineral calcite or calcium carbonate, $CaCO_3$.
- **Dolomite** is physically similar to limestone, although its main mineral, dolomite, or calcium magnesium carbonate $MgCa(CO_3)_2$, results from dolomitization, which is a geological process leading to the replacement of calcium ions with magnesium ions.
- **Sandstone** is a sedimentary rock composed of a framework of silicate grains, cemented together by either silicate minerals like quartz or non-silicate materials like calcite, clay minerals, feldspars, or hematite. Because of its constitutive makeup, sandstone is usually softer than limestone or dolomite, thus having a lower resistance to weathering.
- **Gravel** can be classified as a sedimentary rock; however, it is a mix of different rocks and minerals that can be quite variable and may contain limestone, dolomite, chert, etc. Therefore, it is difficult to give an exact and definitive description.

The aggregate gradations are plotted, by species of coarse aggregates, in Figure 14 for the #57 aggregate size, and Figure 15 and Figure 16 for the intermediate aggregate sizes. A #57 AASHTO gradation was selected due to its regular use in S(AE) concrete. In Figure 14, not all of the coarse aggregates met the #57 limits, but the aggregates were used as received. The figure demonstrates the variability of aggregate gradations and how coarse aggregates from different quarries may have different quantities retained on each sieve size. The use of optimized gradation methods can provide producers with more ability to adjust these gradations using blends of aggregate.

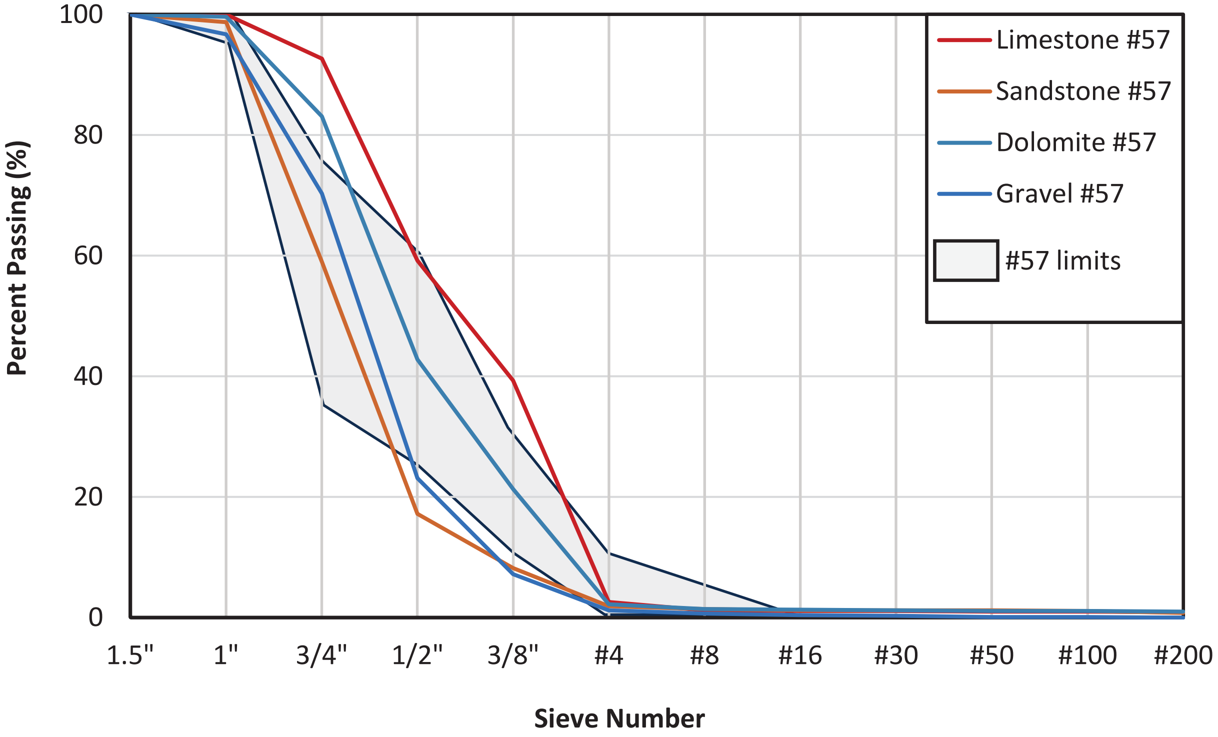

Figure 14. #57 Coarse Aggregates Gradations Plots and Size Limit

An intermediate size was selected to fill in the aggregate gradation and make the mixtures more uniformly graded. Since aggregate sizes are often driven by the demand for coarse aggregate used in asphalt paving, the intermediate size didn't always conform to the same gradation. Regarding the intermediate aggregates shown in Figure 15 and Figure 16, while they are sold under a certain grade size the actual gradation often differed, and two aggregates sold under the same grade could have differences in their gradations. As observed in Figure 15, the gravel chip class 2 nearly conforms to the #7 grade size, while the dolomite chip class 2 better fits the #8 grade size, in Figure 16. In addition, the intermediate limestone size illustrated in Figure 15 best fits within the #7 size limits. This highlights the necessity to understand the actual combined aggregates gradation whenever possible to ensure their consistency over time and adjust the concrete mix proportions to achieve the desired concrete properties.

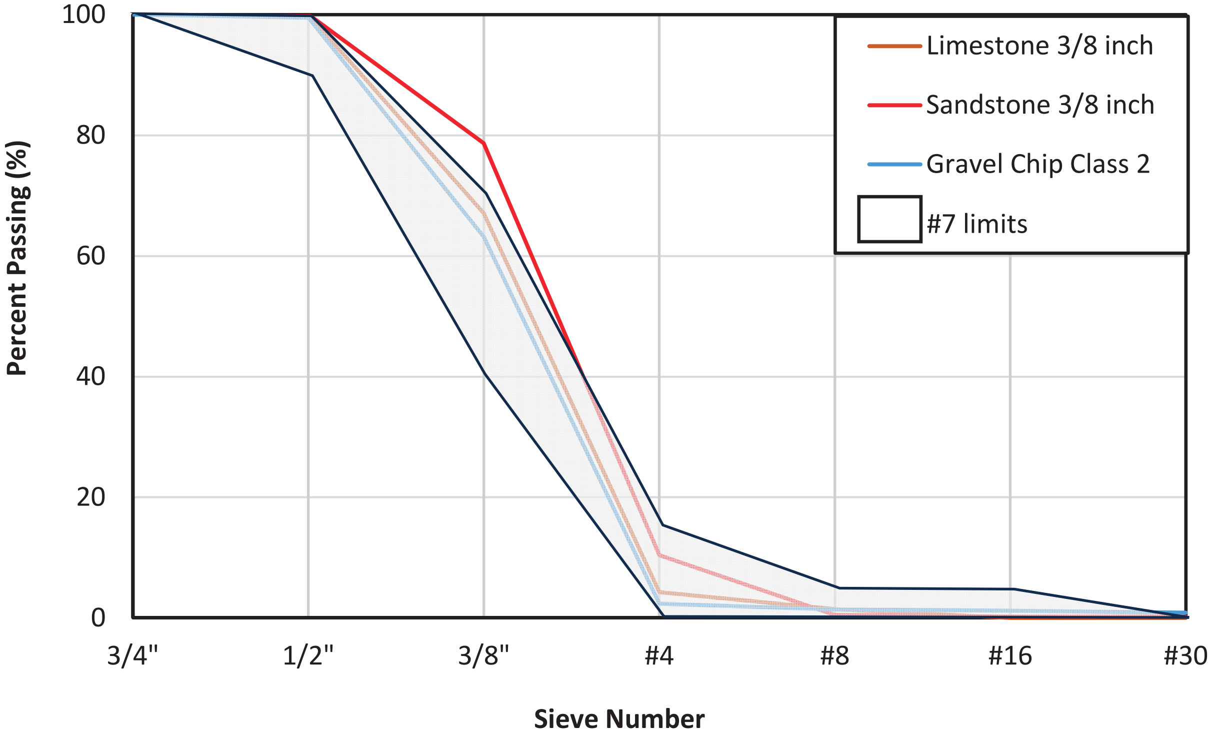

Figure 15. Intermediate Coarse Aggregates Gradation Plots and #7 Aggregate Size Limits

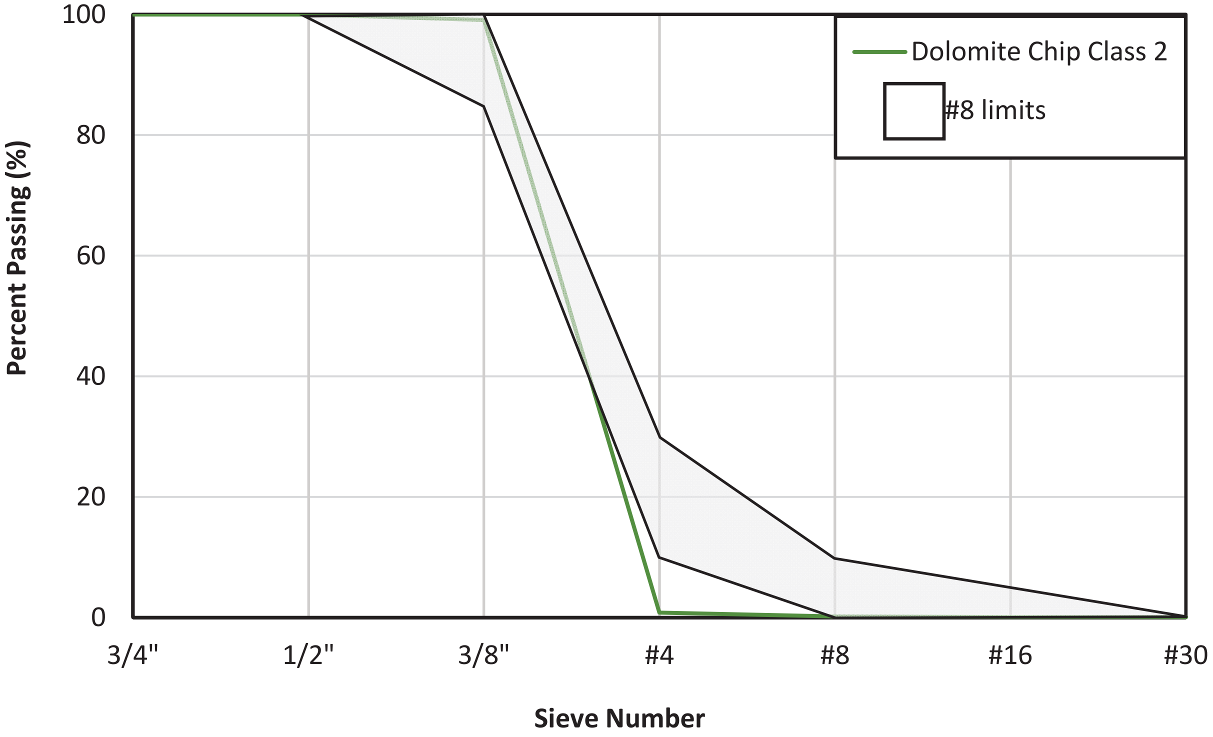

Figure 16. Intermediate Coarse Aggregate Gradation Plot and #8 Aggregate Size Limits

A summary of the specific gravities and absorption capacities of the coarse aggregates is presented in Table 5. The specific gravities of all coarse aggregates were fairly similar with the exception of dolomite, which had a slightly higher specific gravity. The absorption capacities, on the other hand, vary widely between coarse aggregate types and may also vary significantly for a specific aggregate type between different quarries or even over time. Regular sampling and testing should be performed to understand these changes over time. The sandstone had the highest absorption (2.2 percent for the intermediate size rock), while the absorption capacity of the intermediate limestone was the lowest (0.4 percent). These absorption capacities are directly related to the porosity and density of the coarse aggregate and will influence the resulting concrete density, stiffness, and resistivity.

Table 5. Specific Gravity and Absorption of the Coarse Aggregates

Aggregate Species	Gradation	Specific Gravity	Absorption (percent)
Limestone	#57	2.550	1.6
Limestone	Intermediate size	2.665	0.4
Sandstone	#57	2.510	1.8
Sandstone	Intermediate size	2.499	2.2
Dolomite	#57	2.733	1.1
Dolomite	Intermediate size	2.732	1.3
Gravel	#57	2.505	1.2
Gravel	Intermediate size	2.529	1.0

MIXTURE DESIGN AND TESTING OF CONCRETE MIXTURES

The selected aggregates were used to produce Structural Air-Entrained (S(AE)) concrete mixes, as specified by ARDOT (AHTD 2014), as well as optimized low-cement concrete mixes. They were tested for a range of fresh and hardened properties which are described further in this section.

Design Requirements and Approach

Structural Air-Entrained Concrete Mixes

Standard S(AE) concrete mixes were based on the requirements for concrete bridge decks, as specified by ARDOT (Arkansas State Highway and Transportation Department 2014). The design requirements are as follows:

- **Air Content:** 6 ± 2 percent
- **Slump:** 1 inch to 4 inch

- **Maximum water to cement ratio(w/c)**: 0.44
- **Minimum Cement Factor**: 6.5
- **Minimum 28-day Compressive Strength**: 4,000 psi

The standard ARDOT concrete mixes, or Standard S(AE) mixtures, were designed to roughly match the survey results provided by ARDOT and described above in Washington specifies a maximum 28-day shrinkage of 0.032 percent, as specified in AASHTO T160, and allows the use of shrinkage-reducing admixtures (Washington DOT 2025). An additional provision allows the use of shrinkage-compensating concrete for patching materials, with a maximum shrinkage of 0.05 percent at 28 days.

The ARDOT specifications for S(AE) concrete used in bridge decks does not include a shrinkage limit; therefore the specifications and recommendations outlined in 0 will be based on and adapted from the specifications found in other states and augmented by the findings using local materials.

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While the ARDOT Specifications for S(AE) concrete used in bridge decks does not include permeability requirements, some DOTs specify current passed in the rapid chloride permeability test (RCPT). Others are beginning to use surface resistivity. The Virginia Department of Transportation sets a maximum 28-days permeability limit at 2500 Coulombs (based on the RCPT) which is equivalent to an electrical bulk resistivity of 75 Ohm-m (Spragg, Castro, et al. 2011; Virginia DOT 2020). Resistivity measurements are becoming more common in DOT specifications due to their ability to benchmark many durability properties and their correlation with desirable concrete properties.

Chapter 3. Evaluation of Recent Bridge Decks. Thus, the cement content was set at 611 lb/yd^3, and the volume of coarse aggregate was fixed at 1800 lb/yd^3. The water/cement ratio was also fixed at 0.44. Aside from varying the mineralogy of the coarse aggregates used, the other design variables in all Standard S(AE) mixes are the volume of fine aggregates and the dosage of admixtures which were adjusted to achieve a mix design which attained the specified slump and air content. It is important to note that the Standard S(AE) concrete mixes only used #57 coarse aggregates.

Optimized Low-Cement Concrete Mixes

The standard S(AE) concrete mixes were then optimized using the tarantula curve. The coarse aggregates used are a combination of #57 coarse aggregates and intermediate coarse aggregates; the intermediate coarse aggregates were purchased at the same quarry as the #57 aggregate, and their size was based on quarry availability as described previously. In addition, the initial cement content of 611 lb/yd^3 used in the Standard S(AE) mixes was progressively reduced by half a bag and an entire bag of cement, corresponding to a reduction of 5.9 percent and 15.4 percent, respectively, to determine the effects of these changes on the suite of properties measured in the study. Furthermore, an additional mix category was done by reducing the cementitious materials content to 517 lb/yd^3 (corresponding to removing a bag of cement) and substituting 30 percent of the cement with Class C fly ash. The w/cm is fixed at 0.44 for all mixes. Similarly to the Standard S(AE) mixes, the dosage of admixtures used (TERAPAVE® AEA and ADVA® Cast 575) was adjusted to reach the desired slump and air content specified in the ARDOT Specifications (Arkansas State Highway and Transportation Department 2014). A summary of all the concrete mix categories studied in this section and their mix designs is provided below, in Table 6. The decision to hold the coarse aggregate weight constant was made to focus on the variable of gradation only. Using an optimized gradation, however, should increase the volume of coarse aggregate that can be used in a mixture without affecting workability – this increase in volume should reduce shrinkage strains, though this was not explicitly tested in this study.

Table 6. Concrete Mix Categories and Mix Design Proportions.

Mix Categories	Cementitious Material Types	Cementitious Materials Content (lb/yd^3)	Cementitious Materials Replacement Rate of Fly Ash (percent)	Coarse Aggregate (lb/yd^3	Fine Aggregate (lb/yd^3)
Standard S(AE)	Cement	611	0	1800	Variable
Cement Reduced by 5.9 percent	Cement	575	0	1850	Variable
Cement Reduced by 15.4 percent	Cement	517	0	1850	Variable
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Cement + Class C Fly Ash	517	30	1850	Variable

Aggregate Optimization

For each coarse aggregate mineralogy, the replacement rate of the intermediate coarse aggregate was adjusted to attempt to more closely fit the tarantula curve. It is worth mentioning that the aggregates were not sieved and recombined to a desired gradation, but they were rather used as received, as they would have been in the field. As an example of the effects of different coarse aggregate gradations and cement contents on the combined gradation, Figure 17 shows the tarantula curves for all the mixes containing limestone. While all the mixes are within the required amount for the coarse sand and fine sand portions of the combined aggregate gradations, the mixes with reduced cement, and fly ash substitution still have an excess of aggregates retained on the ½ inch and No. 4 sieves, thus indicating a risk of workability loss and segregation. For sandstone, only the standard S(AE) mix exceeded the limits; all the other mixes fit within the limits of the tarantula curve, which is desired for workability and finishability purposes. The gravel and dolomite mixtures similarly met tarantula limits except for the standard S(AE) mix. Some mixes did not meet the coarse sand requirement; this could indicate that the available sand makes it more difficult to optimize the gradation. The tarantula curves for the mixes using sandstone, dolomite, and gravel are provided in Appendix B. Even mixtures which do not meet the limits of the tarantula could have good workability characteristics, but widening the ability of mix designers to use different gradations and combine them as desired to meet the tarantula curve could provide more mix design options and improve concrete workability performance. Workability, specifically, was outside the scope of this project, but this project did investigate the effects of these optimized mix designs on hardened properties.

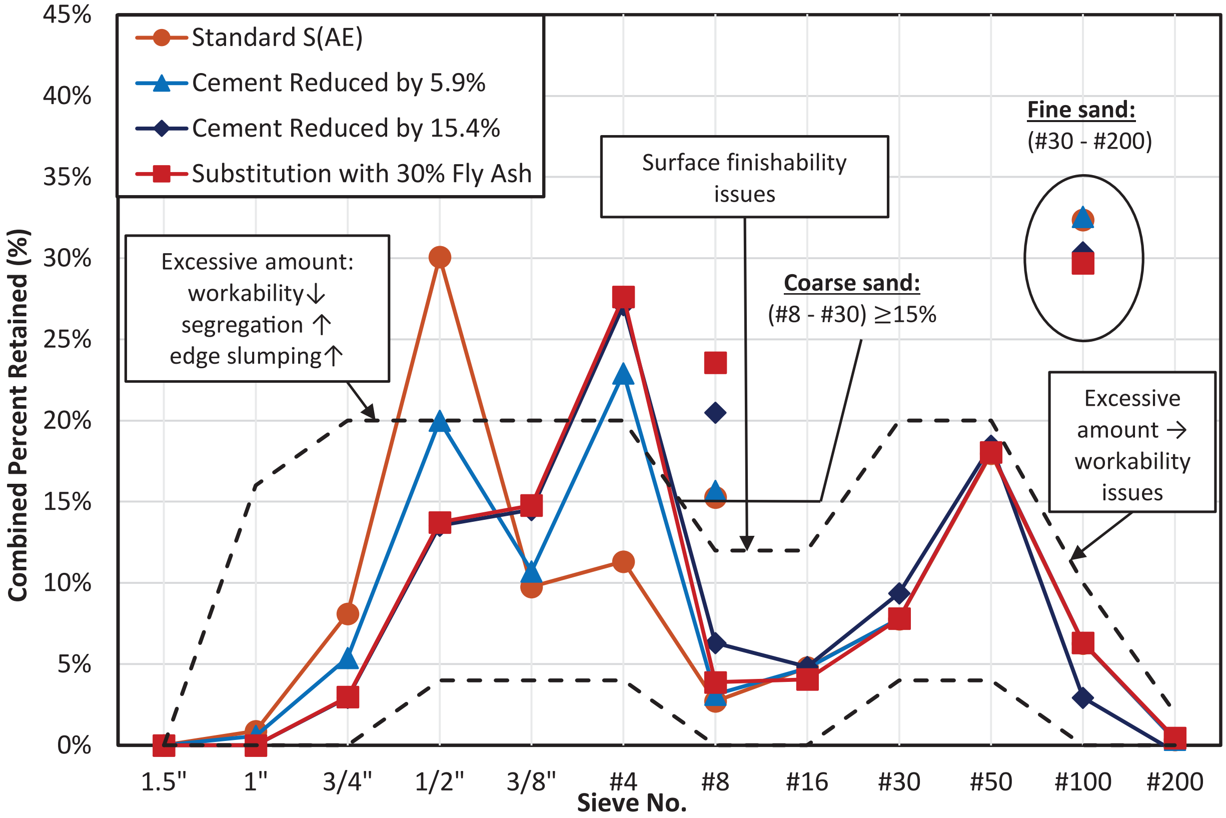

Figure 17. Tarantula Curves of All Mixtures Using Limestone Coarse Aggregate

MIXING PROCEDURES

The mixing procedure adopted for all mixtures was based on ASTM C192 (2024d). First, the coarse aggregates was added to the mixer, followed by half the mixing water mixed with the air-entraining admixture. The mixer was turned on, and the fine aggregate, cementitious materials, and remainder of the water was added, in that order. The mixer was then left to mix for three minutes, followed by a resting period of two minutes during which the high-range water reducer was added if needed, and finally the mixing resumed for three more minutes to ensure that the concrete was well mixed. The main difference between the mixing procedure adopted, and the one prescribed by ASTM C192 is that the latter recommends mixing for three minutes, a three-minute rest and finally two minutes of mixing.

RESULTS AND DISCUSSION

All results from the standard and optimized concrete mixtures are described here. A standard suite of mix characterization tests was performed in addition to some test methods not currently employed in the ARDOT specifications.

Fresh Concrete Properties

The Standard S(AE) and low-cement concrete mixes were tested for their fresh properties including temperature, slump, air content, and unit weight, and the results and methods are summarized below.

Slump

The slump test was conducted according to ASTM C143 (2020). As described previously, HRWR dosage was adjusted to attempt to make the mixtures fit the S(AE) requirement of a slump from 1 to 4 inches. To accommodate the different types of aggregates and gradations being used, mixes having a slump value up to 5 inches were also considered since this was not far out of the range and was not expected to significantly affect the hardened concrete properties. The results of the slump tests for all the mixes are summarized in Table 7 including the total coarse aggregate volume, HRWR dosage, and the combined aggregate absorption (sand plus all coarse aggregates, calculated as a weighted average). The highest slumps were obtained for mixtures using gravel since this aggregate has a rounded surface which affects its workability. Mixtures containing fly ash had higher slumps due to the rounded surface of individual fly ash particles. Due to the mix design philosophy used (maintaining a constant coarse aggregate weight in all mix designs), the total volume of aggregate is relatively similar across all mixtures. The use of aggregate optimization methods should allow designers to increase the total coarse aggregate volume of mixtures while maintaining adequate workability.

Table 7. Slump Results Summary

Mix Categories	Coarse Aggregate Mineralogy	Coarse Aggregate (percent)	Combined Aggregate Absorption (percent)	High Range Water Reducer dosage (oz./cwt*)	Slump (inches)
Standard S (AE)	Limestone	61.2	0.47	0.5	1.5
Standard S (AE)	Sandstone	64.9	1.74	0.5	1
Standard S (AE)	Dolomite	58.8	0.92	0	5
Standard S (AE)	Gravel	64.1	0.94	0.45	4.25
Cement Reduced by 5.9 percent	Limestone	61	0.49	0.5	1.75
Cement Reduced by 5.9 percent	Sandstone	64.6	1.56	0	3
Cement Reduced by 5.9 percent	Dolomite	59.5	0.93	0.5	2.5
Cement Reduced by 5.9 percent	Gravel	64.1	0.90	0	2.5
Cement Reduced by 15.4 percent	Limestone	60	0.49	0.35	1.75
Cement Reduced by 15.4 percent	Sandstone	62.2	1.52	0	1
Cement Reduced by 15.4 percent	Dolomite	57.3	0.91	0.23	1.5
Cement Reduced by 15.4 percent	Gravel	62.4	0.88	0.25	1.5
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Limestone	59.4	0.46	0.55	3.5
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Sandstone	63	1.40	0	3.25
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Dolomite	57.8	0.91	0.45	3.5
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Gravel	62.8	0.89	0	5

*oz./cwt = ounces of admixture per 100 lb cement

Fresh Air Content

The fresh air content of the concrete was tested following ASTM C231 (2024a) using a Type B pressure meter, and the test results are summarized in Table 8. The average air content of all mixtures was 5.8 percent with a coefficient of variation of 17.5 percent. It was desired to ensure similar air contents to remove this as a potential variable.

Table 8. Influence of the Aggregate Mineralogy on the Fresh Air Content

Mix Categories	Coarse Aggregate Mineralogy	Combined Aggregate Absorption (percent)	Paste Content (percent)	AEA dosage (oz/cwt*)	Air Content (percent)
Standard S (AE)	Limestone	0.47	26.6	0.45	6.0
Standard S (AE)	Sandstone	1.74	28.7	0.45	4.2
Standard S (AE)	Dolomite	0.92	27.5	0.45	6.2
Standard S (AE)	Gravel	0.94	27.5	0.25	5.2
Cement reduced by 5.9 percent	Limestone	0.49	25.9	0.45	7.1
Cement reduced by 5.9 percent	Sandstone	1.56	25.8	0.45	4.1
Cement reduced by 5.9 percent	Dolomite	0.93	25.9	0.45	7.5
Cement reduced by 5.9 percent	Gravel	0.90	25.9	0.73	5.2
Cement reduced by 15.4 percent	Limestone	0.49	23.2	0.39	5.3
Cement reduced by 15.4 percent	Sandstone	1.52	23.2	0.45	5.5
Cement reduced by 15.4 percent	Dolomite	0.91	23.2	0.40	6.0
Cement reduced by 15.4 percent	Gravel	0.88	23.2	0.45	4.5
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Limestone	0.46	24.5	0.55	6.2
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Sandstone	1.40	24.5	0.52	6.4
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Dolomite	0.91	24.5	0.58	5.7
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Gravel	0.89	24.5	0.45	7.1

*oz./cwt = ounces of admixture per 100 lb cement

Density

The density, or unit weight, of the fresh concrete was also measured following ASTM C138 (2013) and using the same vessel used in ASTM C231 (2024a). The vessel is first weighed, then filled with freshly mixed concrete according to the ASTM requirements. The density of the concrete is then determined by dividing the net weight of concrete by the volume of the container. The density values for each mix are presented below in Table 9. The lowest densities were obtained for the gravel and the highest for the dolomite. The density of concrete is directly related to the aggregate type. Since the volume of aggregate was different between mixtures and the weight of coarse aggregate was fixed between mixes, this value mostly varied based on the cement content and the sand content in this case.

Table 9. Density, or Unit Weight, of the Fresh Concrete Mixes

	Coarse Aggregate Mineralogy	Coarse Aggregate (percent)	Paste content (percent)	Density (lb/yd^3)
Standard S (AE)	Limestone	61.2	26.6	143.1
Standard S (AE)	Sandstone	64.9	28.7	146.7
Standard S (AE)	Dolomite	58.8	27.5	145
Standard S (AE)	Gravel	64.1	27.5	140.2
Cement reduced by 5.9 percent	Limestone	61	25.9	142.3
Cement reduced by 5.9 percent	Sandstone	64.6	25.8	143.9
Cement reduced by 5.9 percent	Dolomite	59.5	25.9	143.9
Cement reduced by 5.9 percent	Gravel	64.1	25.9	143.4
Cement reduced by 15.4 percent	Limestone	60	23.2	146
Cement reduced by 15.4 percent	Sandstone	62.2	23.2	142.8
Cement reduced by 15.4 percent	Dolomite	57.3	23.2	147.4
Cement reduced by 15.4 percent	Gravel	62.4	23.2	144.4
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Limestone	59.4	24.5	145.3
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Sandstone	63	24.5	141.7
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Dolomite	57.8	24.5	146.7
Cement reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Gravel	62.8	24.5	139.8

Temperature

The temperature of the fresh concrete mixtures was also evaluated using ASTM C1064 (2023b). The measured temperatures are summarized in Table 10 below, as well as the ambient and water temperatures measured on the day of mixing. It was desired to maintain consistency in fresh concrete temperature to avoid unintended variability in mix properties to excessively high or low concrete temperatures. The average concrete temperature was 70°F, with a coefficient of variation of eight percent indicating low variability between mixes.

Table 10. Fresh Concrete, Mixing Water and Ambient Temperatures

Mix Categories	Coarse Aggregate Mineralogy	Fresh Concrete Temperature (°F)	Water Temperature (°F)	Ambient Temperature (°F)
Standard S (AE)	Limestone	61.6	56.1	66.7
Standard S (AE)	Sandstone	61.9	56.2	65.7
Standard S (AE)	Dolomite	72.9	33.1	79
Standard S (AE)	Gravel	67.4	99.6	76.8
Cement Reduced by 5.9 percent	Limestone	68.2	61.3	67.1
Cement Reduced by 5.9 percent	Sandstone	60.3	62.1	61.9
Cement Reduced by 5.9 percent	Dolomite	65.5	32.2	75.6
Cement Reduced by 5.9 percent	Gravel	71.8	100.4	65.5
Cement Reduced by 15.4 percent	Limestone	71.3	59.8	66.2
Cement Reduced by 15.4 percent	Sandstone	72.9	72.0	75.6
Cement Reduced by 15.4 percent	Dolomite	74.9	76.7	71.1
Cement Reduced by 15.4 percent	Gravel	71.3	99.2	63.3
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Limestone	72.9	71.3	72.9
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Sandstone	77.0	75.1	75.2
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Dolomite	75.1	69.3	77.4
Cement Reduced by 15.4 percent + Substitution with 30 percent Fly Ash	Gravel	77.6	102.1	66.9

Hardened Concrete Properties

The standard S(AE) and low-cement concrete mixes were tested for compressive strength according to ASTM C39, unrestrained drying shrinkage by ASTM C157 and electrical bulk resistivity by ASTM C1876, and the results are presented below.

Compressive Strength

Immediately after casting cylinder samples, the samples were covered with plastic for 24 hours to set up and cure. After 24 hours had passed, all cylinders were demolded and transferred to a moist curing chamber held at 74°F and 100 percent relative humidity. At least three concrete cylinders were cast for each testing age. The testing ages of interest were 24 hours, seven days, and 28 days in accordance with ASTM C39/C39M (2024a). The results of these tests are presented in Table 11. The average one-day strength was 1,980 psi, the average seven-day strength was 4,400 psi and the average 28-day strength was 5,550 psi. The 28-day strengths exceeded the specified minimum of 4,000 psi by 39 percent on average and no mixtures failed to reach this minimum. Of the sixteen mixtures studied, twelve mixtures actually exceeded 4,000 psi compressive strength by seven days. There was no noticeable difference between the 28-day strengths even though the cement content was reduced. There was a noticeable difference, however, by aggregate type, with limestone and sandstone giving the highest strengths and dolomite the lowest.

Table 11. Influence of the Aggregates Mineralogy on the Compressive Strengths.

	Coarse Aggregate Mineralogy	Compressive Strength (psi) 24 hours	Compressive Strength (psi) 7 days	Compressive Strength (psi) 28 days
Standard S (AE)	Limestone	1800	4190	6130
Standard S (AE)	Sandstone	2240	5300	6440
Standard S (AE)	Dolomite	2630	3740	4820
Standard S (AE)	Gravel	2250	3360	4690
Cement reduced by 5.9 percent	Limestone	2000	4290	5820
Cement reduced by 5.9 percent	Sandstone	1940	4310	5480
Cement reduced by 5.9 percent	Dolomite	2340	3670	4860
Cement reduced by 5.9 percent	Gravel	1900	4680	5920
Cement reduced by 15.4 percent	Limestone	2290	5090	5640
Cement reduced by 15.4 percent	Sandstone	2510	4220	5420
Cement reduced by 15.4 percent	Dolomite	2540	4920	5090
Cement reduced by 15.4 percent	Gravel	2160	4670	5480
Cement reduced by 15.4 percent + substitution with 30 percent fly ash	Limestone	1200	4570	6260
Cement reduced by 15.4 percent + substitution with 30 percent fly ash	Sandstone	1250	4940	6360
Cement reduced by 15.4 percent + substitution with 30 percent fly ash	Dolomite	1510	4660	5540
Cement reduced by 15.4 percent + substitution with 30 percent fly ash	Gravel	1140	3800	4780

Figure 18Error! Reference source not found. plots the compressive strengths at 24 hours, seven days and 28 days for the Standard S(AE) concrete mixes and the optimized low-cement concrete mixes. As the graph shows, by reducing the cement content and optimizing the aggregate gradation, the specified strength requirement of 4,000 psi at 28 days is still met, even as early as seven days.

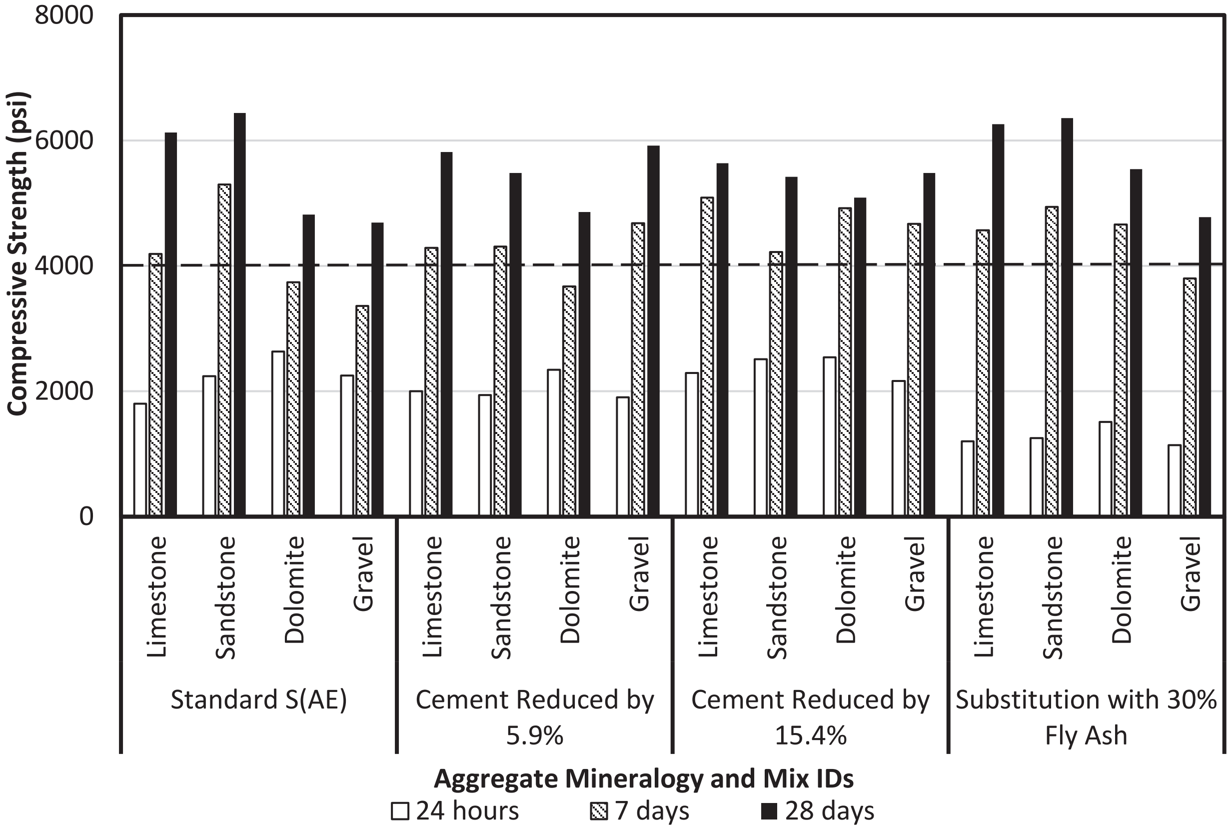

Figure 18. Compressive Strengths at 24 hours, 7 days and 28 days for the Standard S(AE) and Optimized Low-Cement Concrete Mixes

Furthermore, the 28-day compressive strengths for each aggregate type were compared to determine the effect of optimization, and aggregate type on strength, and the results are plotted in Figure 19. Overall, the mixes with limestone have the highest strength with an average of 5,960 psi, followed by the mixes with sandstone at an average of 5,930 psi, while the mixes with dolomite have the lowest strengths at 5,080 psi in average. The optimized low-cement concrete showed a slight decrease in compressive strength for the limestone and sandstone but exhibited an opposite effect on the dolomite and gravel where the strength was improved. Also, the concrete mixes with fly ash presented similar, or slightly higher compressive strengths compared to the standard S(AE) mixes, independently of the coarse aggregate mineralogy. The mixtures with fly ash would be expected to give higher strengths at later ages.

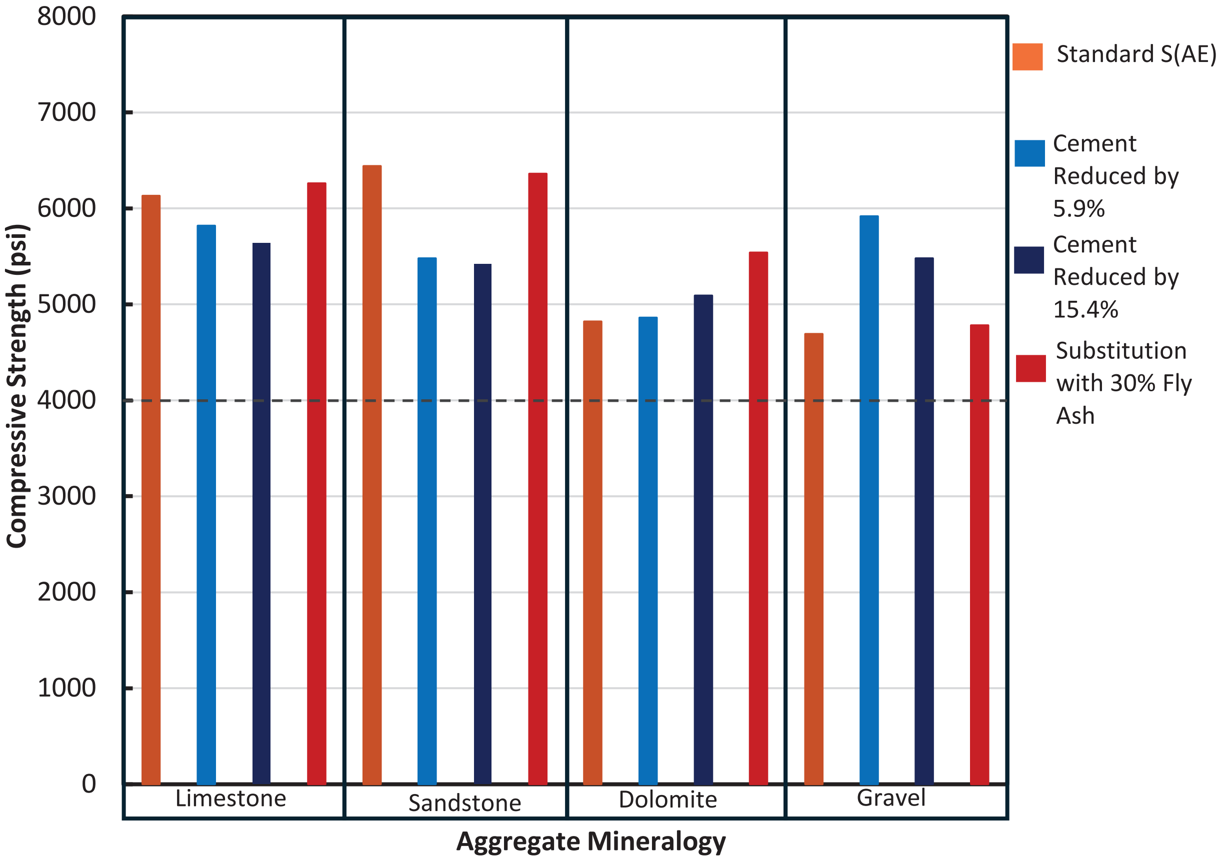

Figure 19. Compressive Strengths at 28-days by Coarse Aggregate Mineralogies

Drying Shrinkage

The long-term unrestrained or free drying shrinkage of the concrete mixes was tested according to ASTM C157 (2024d), using 4 inch x 4 inch x 11.25 inch prisms. The samples were cast in their molds, covered with plastic sheets and left for an initial curing period of 24 hours in a moist room at relative humidity of 100 percent; they were then demolded and placed in a lime-saturated bath for 28 days, including the initial curing time. At the end of the lime curing period, the samples were moved to a dry room held at 50 ± 4 percent relative humidity and 72°F for the remainder of the testing period. The change in strain was monitored regularly until the end of the testing period, which extended to 365 days. The timing of these measurements generally conformed to the requirements in ASTM C157. The ASTM requires a 28-day lime bath curing period, so this requirement was used in the testing detailed in this report to directly compare aggregate types. However, in a state specification, the curing period could be lessened to better represent the curing period used for bridge decks in the state. Furthermore, the shrinkage monitoring period could be shortened if strains are compared at the same age and if most of the early-age shrinkage is captured in the measurement period.

The drying shrinkage results for the Standard S(AE) and optimized low-cement concrete mixes are presented in graphs separated by coarse aggregate type in Appendix C. As an example, the drying shrinkage results for the mixes containing dolomite are plotted in Figure 20, from the age at demolding (zero days), to the end of lime curing (28 days) to the final measurements at one year of age. In general, all aggregate types showed a similar trend of a rapid rate of shrinkage in the first 56 days, followed by a reduced rate of shrinkage reaching a plateau by around 84 days to 112 days. On average, 28 days after being removed from the lime bath, 67 percent of the ultimate 365 day strain had been achieved. At 56 days this value was 83 percent. Potentially, DOTs can specify shrinkage at an earlier age, understanding that a significant portion of the shrinkage will have been reached at an earlier age.

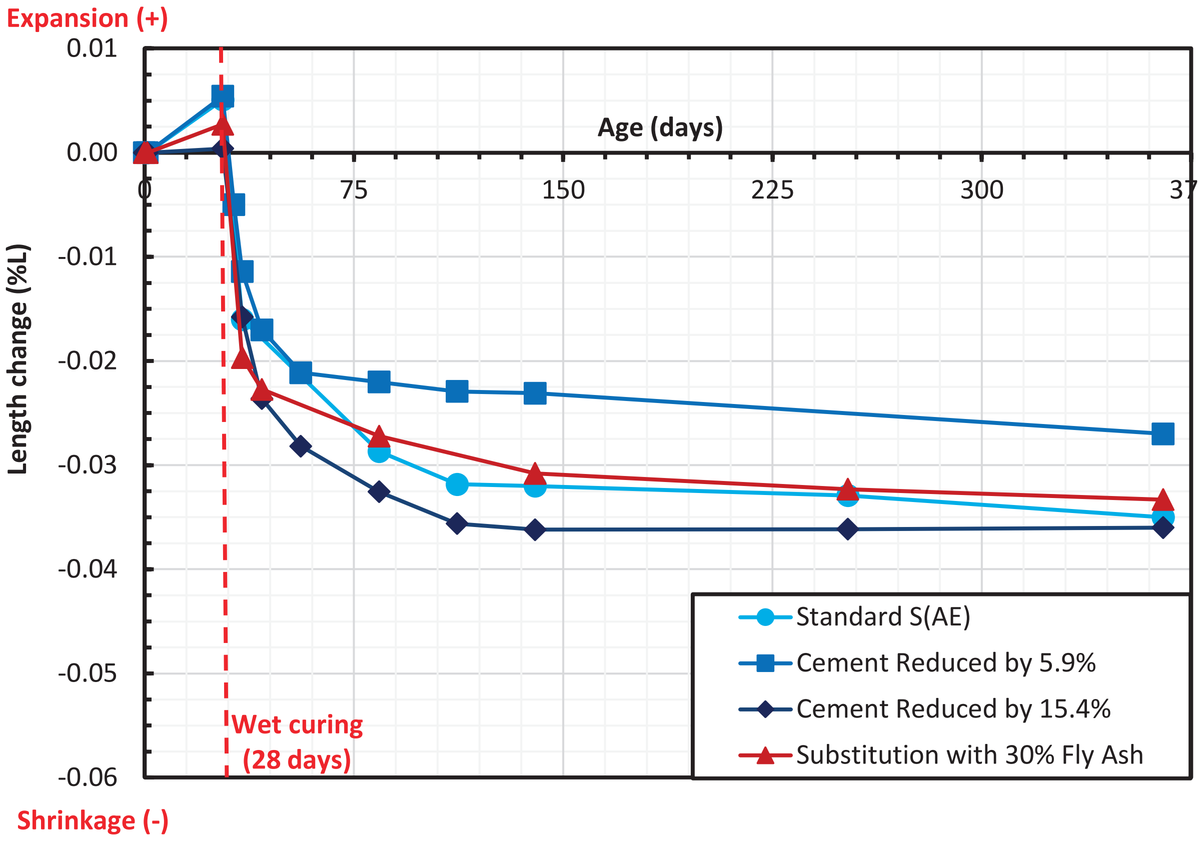

Figure 20. Drying Shrinkage of Mixes with Dolomite

The drying shrinkage curves for all aggregates and mix categories were used to determine the ultimate drying shrinkage, which was taken at 365 days. This value provides a direct comparison of the ultimate shrinkage for each concrete mixture. All the concrete mixes investigated here exceeded 80 percent of their ultimate shrinkage in 56 days after being removed from the lime bath. While ARDOT does not specify a shrinkage limit for S(AE) concrete, the Virginia Department of Transportation (VDOT) limits the 28-day shrinkage (meaning an initial wet curing period of 7 days followed by 21 days of drying shrinkage) to 0.035 percent for bridge deck concrete (Virginia DOT 2020). Figure 21 compares the shrinkage for all concrete mixtures at 56 days, 84 days and 365 days. The drying shrinkage magnitude for all the S(AE) and optimized low-cement concrete mixes are also compared to the VDOT limit in Figure 21. The shrinkage magnitude would be expected to be higher for these mixtures compared to the 28-day shrinkage specified by VDOT due to the longer drying time, however the longer curing time used in this study should reduce the shrinkage slightly. The only mixture which did not exceed the VDOT limit at 365 days was the mixture containing limestone. Clearly, the rock type strongly affects the ultimate shrinkage for S(AE) mixtures and sandstone and gravel have much worse shrinkage than limestone or dolomite. To be clear – this is not a reason to stop using these coarse aggregates, rather it may indicate the need for additional measures to reduce shrinkage when these sources are used. The standard S(AE) concrete mixes made with dolomite and gravel also showed more significant increases in their ultimate shrinkage magnitude at 365 days, unlike the mixes with limestone and sandstone, whose shrinkage was relatively unchanged between 84 days and 365 days. This shows that the rate of change of shrinkage is dependent on aggregate type and may influence the number of days of drying shrinkage that should be used in any potential specification. Limestone and sandstone are the most used aggregate types in Arkansas, and they had minimum and maximum ultimate shrinkage strains, respectively. Therefore, those aggregates were selected to develop the low-shrinkage concretes using shrinkage-mitigating admixtures, in the next section.

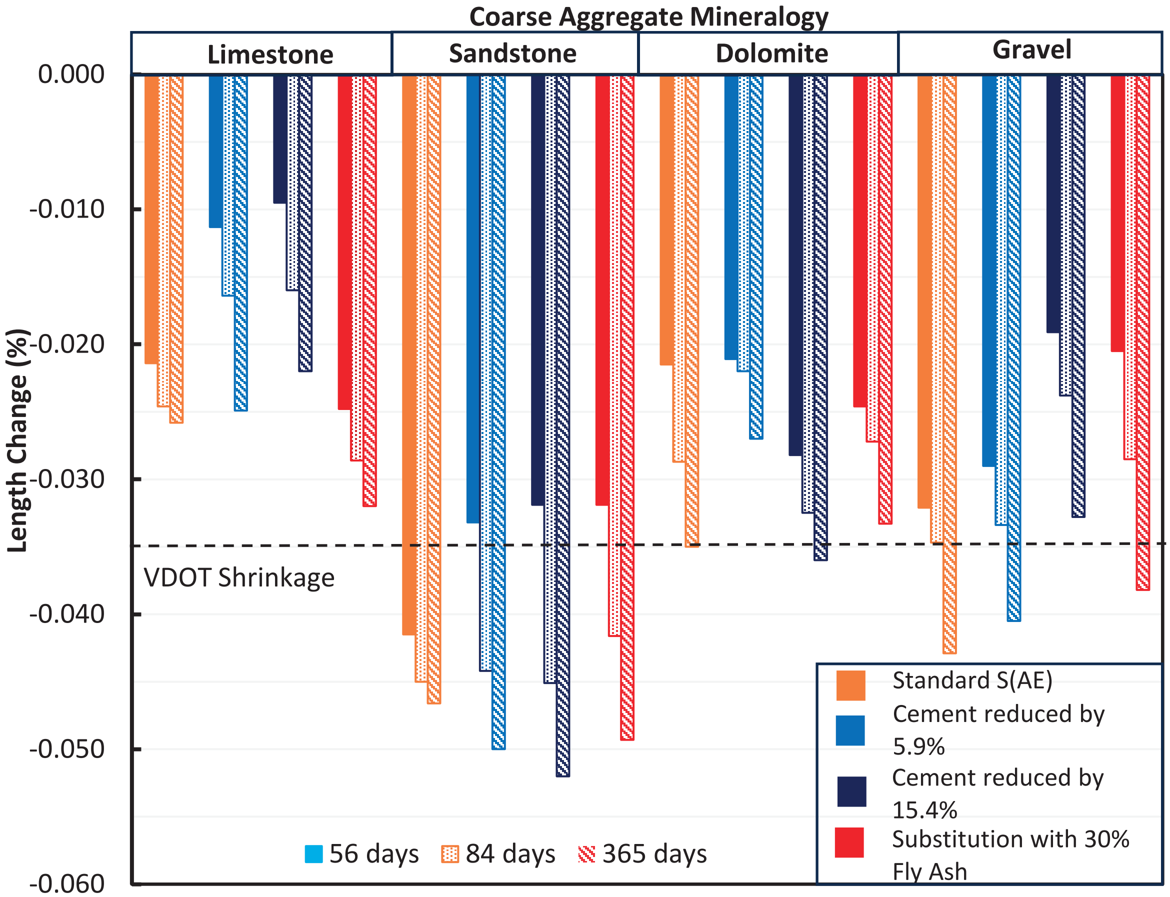

Figure 21. Length Change Comparison at 56 days, 84 days and 365 days for the Standard S(AE) and Optimized Low-cement Concrete Mixes

Referring to the sandstone shrinkage results at 365 days and the Virginia DOT limit of 0.035 percent, if 67 percent of the ultimate shrinkage was achieved at 28 days (corresponding to the age when shrinkage is measured in Virginia, all these mixtures would narrowly have a shrinkage value less than the limit.

Electrical Bulk Resistivity

The electrical bulk resistivity test was performed according to ASTM C1876 (ASTM 2024b). After curing the samples in a moist room for 21 days, they were placed for at least a week in a simulated pore solution made from deionized water, calcium oxide, potassium hydroxide, and sodium hydroxide to simulate the internal pore solution of the concrete. Although different aggregates with different chemical compositions were used for the concrete mixes, it was assumed that ions leaching from the concrete had no significant impact on the results. Electrical resistivity was measured by passing a current from an electrode at one end of the cylinder to the other end. The measured electrical bulk resistivity for the Standard S(AE) and optimized low-cement concrete mixes are illustrated in Figure 22, and compared to the equivalent 28-days Virginia DOT permeability limit for RCPT set at 2500 Coulombs, or 75 Ohm-m (the roughly equivalent limit for bulk resistivity). While mixture optimization led to a slight reduction in the electrical bulk resistivity, the concrete mixes with a 30 percent fly ash substitution had a significant increase in their electrical bulk resistivities at 90 days. If aggregate volume had been increased when cement was removed, this would likely lead to further improved resistivities. The electrical bulk resistivities of most of the concrete mixtures without fly ash, independently of the coarse aggregates, or cement content were below the 75 Ohm-m limit. The mixtures which do not reach the suggested permeability limit highlight a potential area for improvement in the ARDOT specifications.

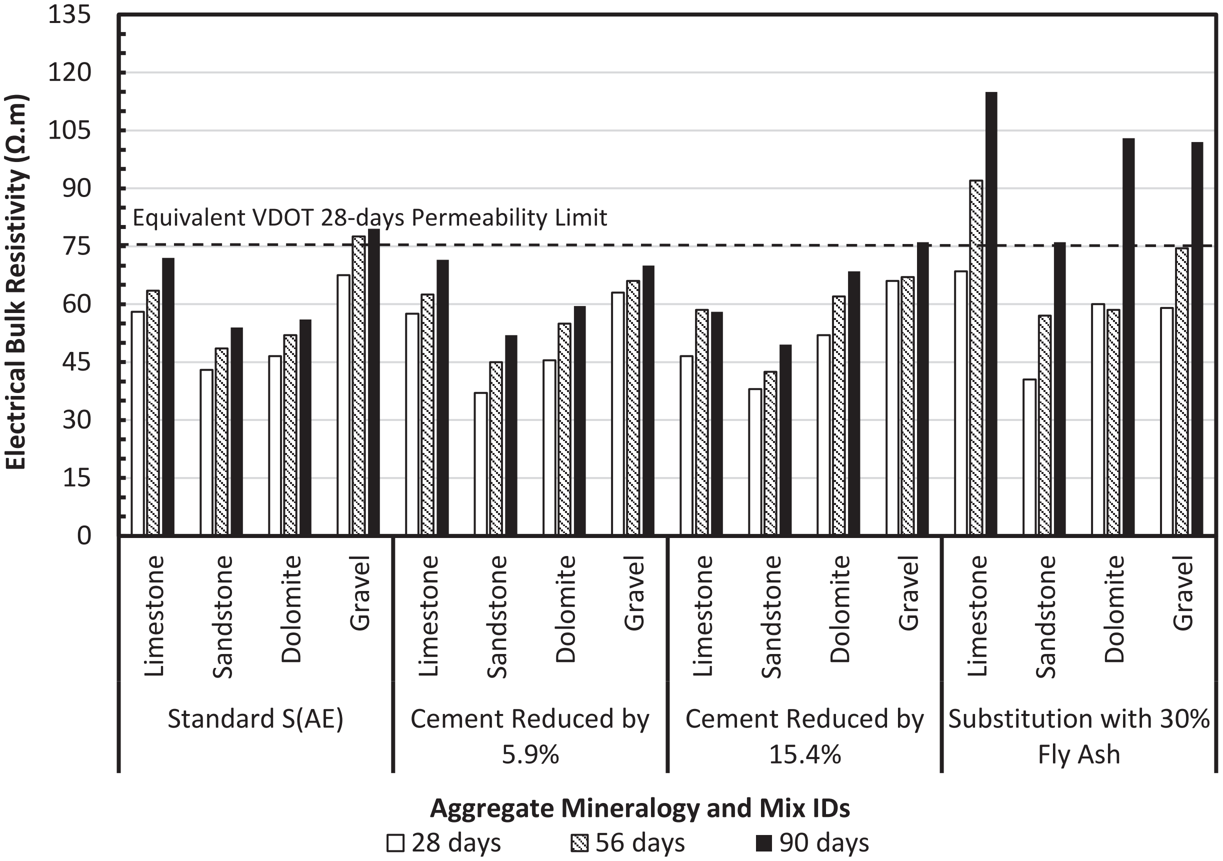

Figure 22. Electrical Bulk Resistivity Results for Standard S(AE) and Optimized Low-Cement Concrete

CHAPTER 5. DEVELOPMENT OF LOW-SHRINKAGE MIXTURES

The results in Chapter 4 showed that reducing the cement content and optimizing the mixture gradation did not significantly reduce the drying shrinkage of the investigated concrete mixes if the aggregate volume was kept the same, but that the aggregate type strongly affected shrinkage. Thus, additional mixes were done using shrinkage-mitigating additives: a shrinkage-compensating Type K cement additive named Komponent cement manufactured by CTS Cement, and a SRA manufactured and sold by Euclid Chemical under the name EUCON SRA XT.

MIX DESIGN APPROACH

The reduced shrinkage concrete mixes were designed using the tarantula curve, with a total cement content of 611 lb/yd^3, a water-cementitious materials ratio of 0.44, and a total coarse aggregate weight set at 1850 lb/yd^3 to facilitate comparison to the other mixtures. Additionally, only sandstone and limestone were used in developing those low-shrinkage mixtures, because they exhibited the highest and lowest shrinkage magnitudes, respectively. The details of the mix design are summarized below in Table 12.

Table 12. Mix Design Proportions for Low-Shrinkage Concrete Mixtures with Different Admixtures and Dosage.

Mix Categories	Cementitious Materials	Aggregate Type	TERAPAVE® AEA (oz/cwt)*	ADVA® Cast 575 (oz/cwt)*	MasterSet® Delvo (oz/cwt)*	EUCON SRA XT
Standard S(AE) with 20 percent Type K cement Replacement	Cement + Type K cement	Limestone	0.172	1.5	1	N/A
Standard S(AE) with 20 percent Type K cement Replacement	Cement + Type K cement	Sandstone	0.52	0	2	N/A
Standard S(AE) with 1 percent EUCON SRA XT	Cement	Limestone	0.5	0	2	1 percent of the cement weight
Standard S(AE) with 1 percent EUCON SRA XT	Cement	Sandstone	0.2	0	2	-

*oz./cwt = ounces of admixture per 100 lb cement

Aggregate Optimization

The tarantula curves for the developed low-shrinkage mixes are compared with their respective Standard S(AE) mixes, in **Error! Reference source not found.** and Figure 24, for the limestone and sandstone, respectively. The SRA and Type K cement mixtures had the same proportions of aggregate and so had the same combined gradations.

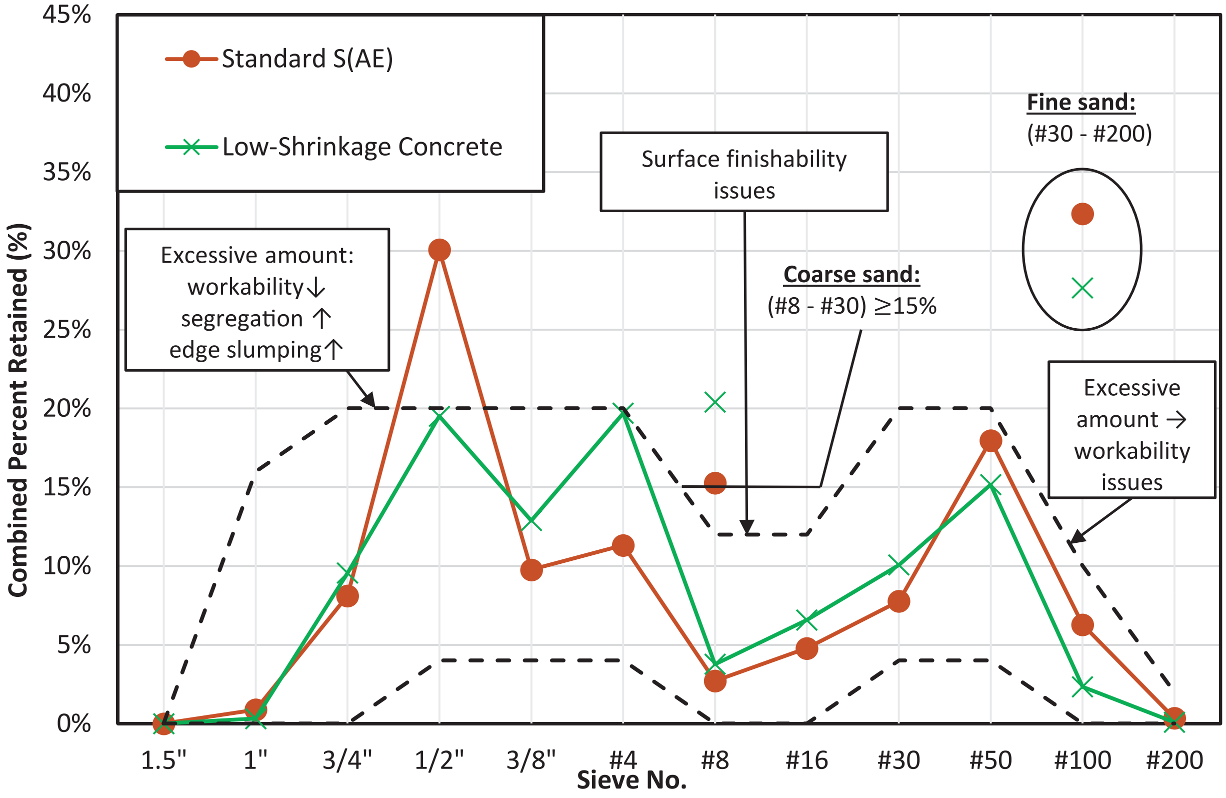

Figure 23. Tarantula Curves for the Standard S(AE) and the Low-Shrinkage Concrete Mixes, using Limestone

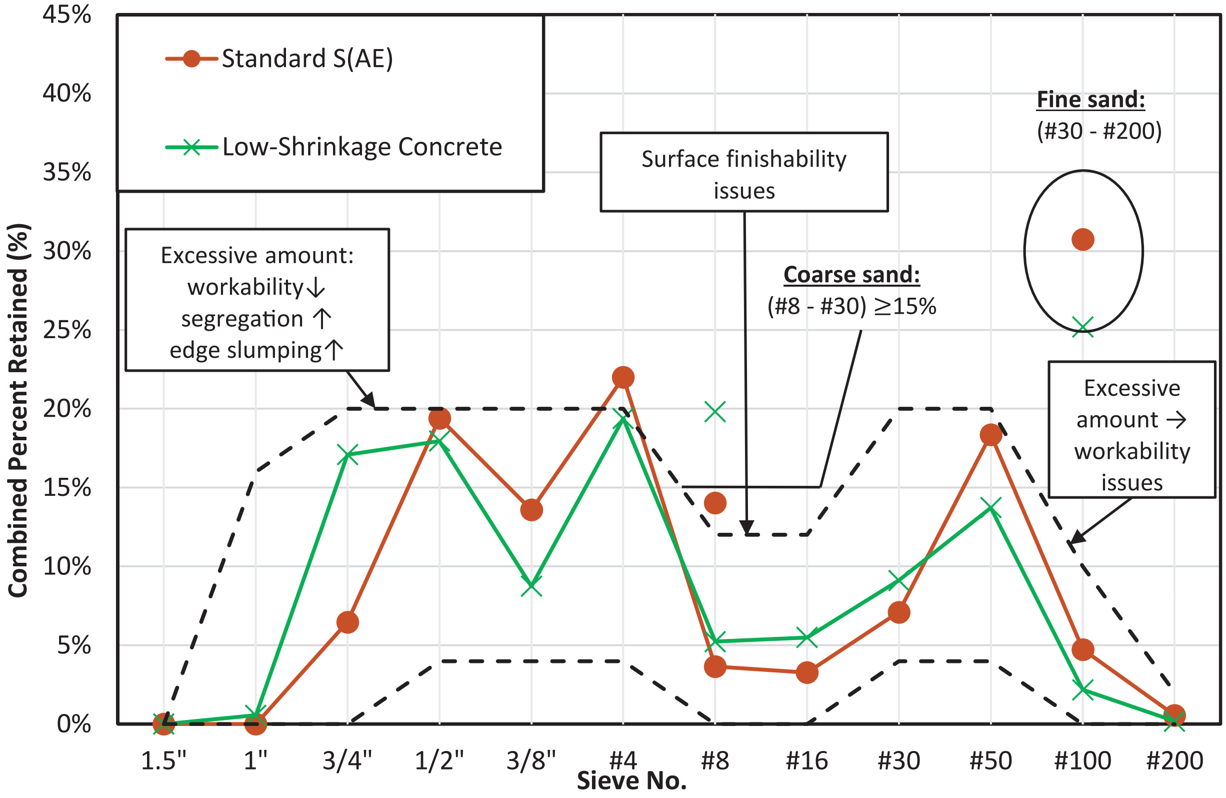

Figure 24. Tarantula Curves for the Standard S(AE) and the Low-Shrinkage Concrete Mixes, using Sandstone

DRYING SHRINKAGE TESTING

Like the standard and low-cement concrete mixtures, the low-shrinkage concretes were tested for unrestrained drying shrinkage, according to ASTM C157. In addition, the concretes containing Type K cement were also tested for restrained shrinkage, following ASTM C878, to evaluate the efficiency of the expansive agent in reducing drying shrinkage strains. However, because low-shrinkage mixes contain expansive agents that are active at very early-ages, the test methods referenced above were both modified to use vibrating-wire strain gauges (VWSGs) installed in 6 inch x 12 inch cylinders, as shown in Figure 25, instead of 4 inch x 4 inch x 11.25 inch prisms. This facilitated the rapid collection of data at an earlier age rather than using the physical length comparator gauge.

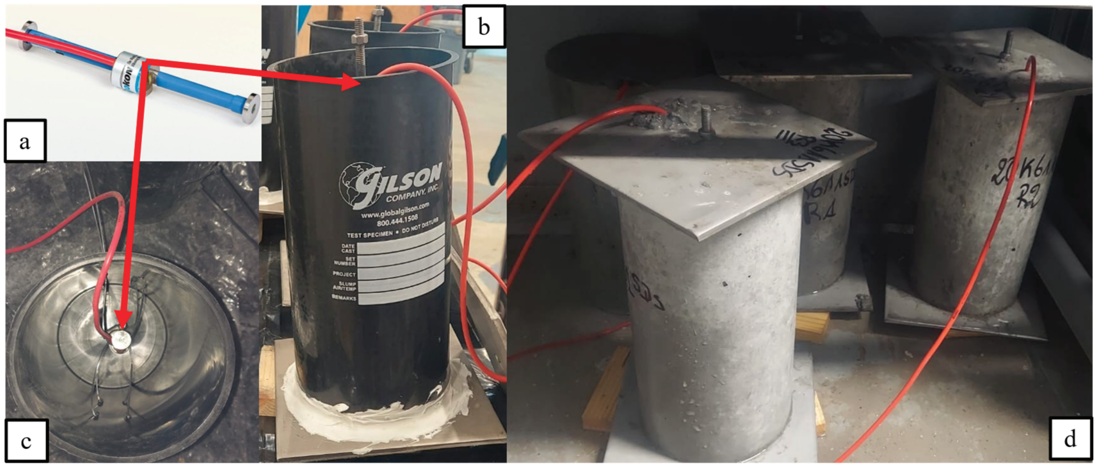

Figure 25. Low-Shrinkage Concrete Samples for Shrinkage Measurements: a- VWSG; b- Restrained Shrinkage Molds; c- Unrestrained Shrinkage Molds, d- Low Shrinkage Concrete Samples in Environmental Chamber

Independent of the testing methods, the samples were cast in their respective molds, covered with plastic sheets and left for an initial curing period of twenty-four hours in an environmental chamber at 100 percent relative humidity; they were then demolded and placed back in the environmental chamber until the end of the curing period of 28 days when the samples were placed in a dry room at 50 percent relative humidity, and the strains were monitored regularly until the end of the testing period.

RESULTS AND DISCUSSION

Results for the low-shrinkage concrete mixtures are presented here for the fresh and hardened concrete properties investigated.

Mixing Procedures

The mixing procedures adopted for the low-shrinkage concrete mixtures differed significantly from the mixing procedure of the standard and low-cement concrete, and were based on the manufacturer's recommendations, depending of the additive used. For the concrete mixes using Type K cement, all liquid admixtures were mixed with 20 percent of the mixing water, and were mixed thoroughly. Then, the coarse aggregates were added to the mixer, followed by the 20 percent of the mixing water that had been previously mixed with all liquid admixtures, followed by the fine aggregates, Type K cement additive, portland cement, and the remaining 80 percent of the water, in that order. The concrete was mixed continuously for 8 minutes, without rest and then discharged. For the concrete mixes with SRA, all liquid admixtures except the SRA were mixed thoroughly with half of the mixing water. Then, the coarse aggregates were added to the mixer with the portion of the water containing the admixtures, and the mixer was started. The fine aggregates were then introduced, followed by the portland limestone cement and the remainder of the water. The concrete was then mixed for three minutes, followed by a one minute break during which the SRA was added to the concrete, followed by five more minutes of mixing.

Fresh Concrete Properties

The low-shrinkage mixes were tested for their temperature, slump, air content, and unit weight, and the results are summarized in Table 13. The low-shrinkage concretes have higher slumps compared to their respective standard S(AE) mixes. In addition, the fresh air content is about the same, although the mix with sandstone and Type K cement had an air content of 8.5 percent, which is slightly higher than its standard S(AE) mix and mix with EUCON SRA, with the same aggregate. While this mixture slightly exceeded the maximum air content allowed by ARDOT, the mix was used for these tests since it was nearly meeting the ARDOT limits. The use of shrinkage mitigating admixtures may pose additional challenges in mixture design with regards to setting times, air content, and slump, and care should be taken when proportioning these mixtures to ensure that all desired mixture properties can be achieved as expected.

Table 13. Fresh concrete properties of Standard S(AE) and low-shrinkage concrete mixes

	Coarse Aggregate Mineralogy	Fresh concrete Temperature (°F)	Ambient Temperature (°F)	Slump (in)	Air Content (percent)	Unit Weight (lb/ft^3)
Standard S(AE)	Limestone	61.6	66.7	1.5	6.0	143.1
Standard S(AE)	Sandstone	61.9	65.7	1	4.2	146.7
Standard S(AE) with 20 percent Type K cement	Limestone	69.8	73.9	3.75	5.2	145.7
Standard S(AE) with 20 percent Type K cement	Sandstone	75.2	73.6	4.5	8.5	135.9
Standard S(AE) with 1 percent EUCON SRA XT	Limestone	70.1	69.8	3.5	6.3	144.2
Standard S(AE) with 1 percent EUCON SRA XT	Sandstone	73.6	65.2	4.25	5.0	141.9

Hardened Concrete Properties

The optimized concrete mixes were tested for compressive strength, unrestrained drying shrinkage, and bulk resistivity. The individual results are summarized in the following sections and compared with their Standard S(AE) counterparts.

Compressive Strength

The compressive strength results are compared in Figure 25, for the low-shrinkage concrete mixes and the standard S(AE) mixes. The low-shrinkage mixes all met the required 28-day strength of 4,000 psi by seven days. According to the manufacturer, Type K cement should increase the strength of a mixture by 10-15 percent. The mix with limestone and Type K cement showed an 18 percent increase in strength compared to the standard S(AE) mixture, while the mixture with sandstone and Type K cement had a sixteen percent decrease in strength. The sandstone mixture had a 8.5 percent air content compared to 5.2 percent for the limestone mix, this discrepancy likely led to the difference in strength. On the other hand, the low-shrinkage mixes with EUCON SRA XT show a decrease in strength at 28 days by nine percent and fifteen percent for the limestone and sandstone, respectively, compared to the standard S(AE) mixtures. Early-age (one day) strengths were improved by using Type K cement and SRA.

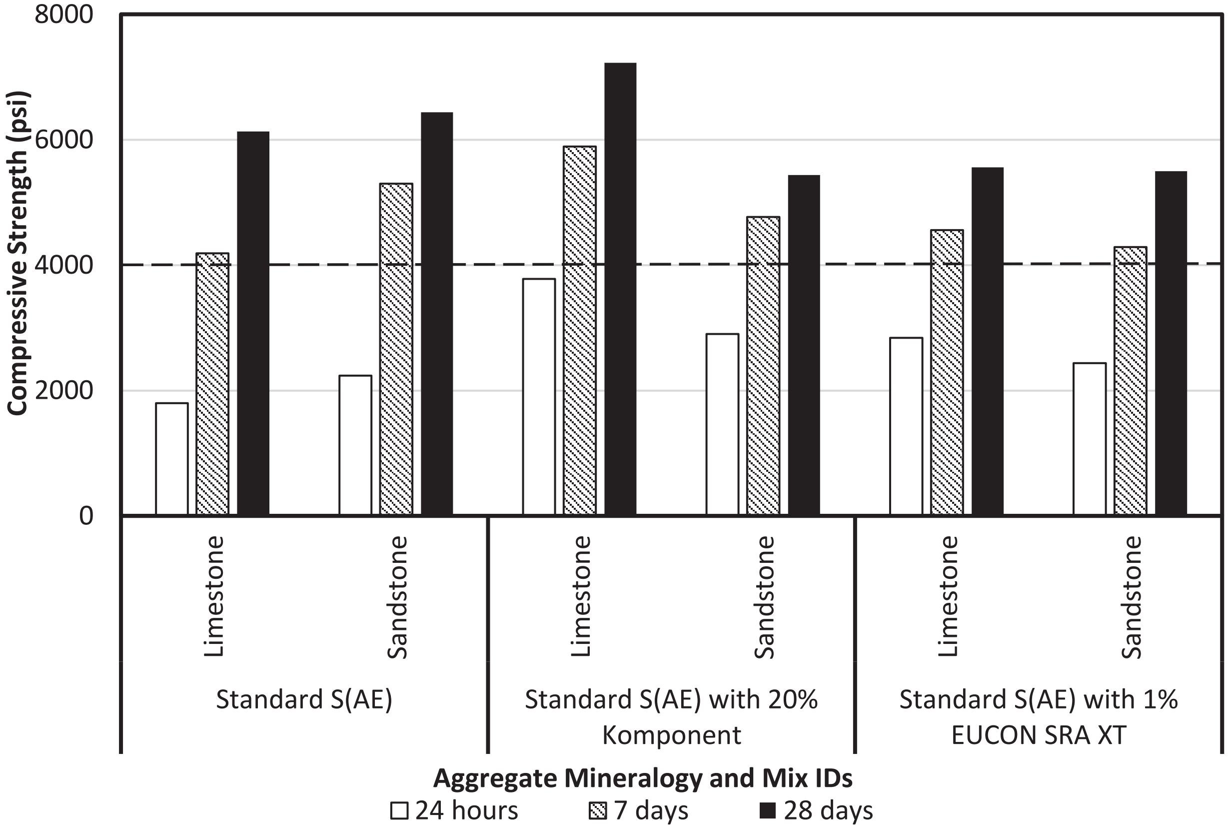

Figure 26. Compressive Strengths at 24 Hours, 7 Days and 28 Days for the Standard S(AE) and Low-shrinkage Concrete Mixes

Drying Shrinkage

The length change results for the low-shrinkage concrete mixes were compared with the Standard S(AE) mixes in Figure 27 and Figure 28, for the limestone and sandstone, respectively. For the mixtures using SRA and Type K cement, a full one-year set of data was not available, but in most cases the shrinkage plot has reached a plateau and the long-term shrinkage can be reasonably estimated. Figure 27 shows the raw shrinkage results for limestone mixtures containing type K cement (restrained and unrestrained shrinkage shown) and SRA compared to the standard S(AE) shrinkage results. For limestone, the standard drying shrinkage at 84 days was 246 microstrains, which was reduced to 71 microstrains for the Type K cement mixture and 43 microstrains for the SRA mixture. These reflect reductions in shrinkage of 71 percent when using type K cement and 82.5 percent when using SRA.

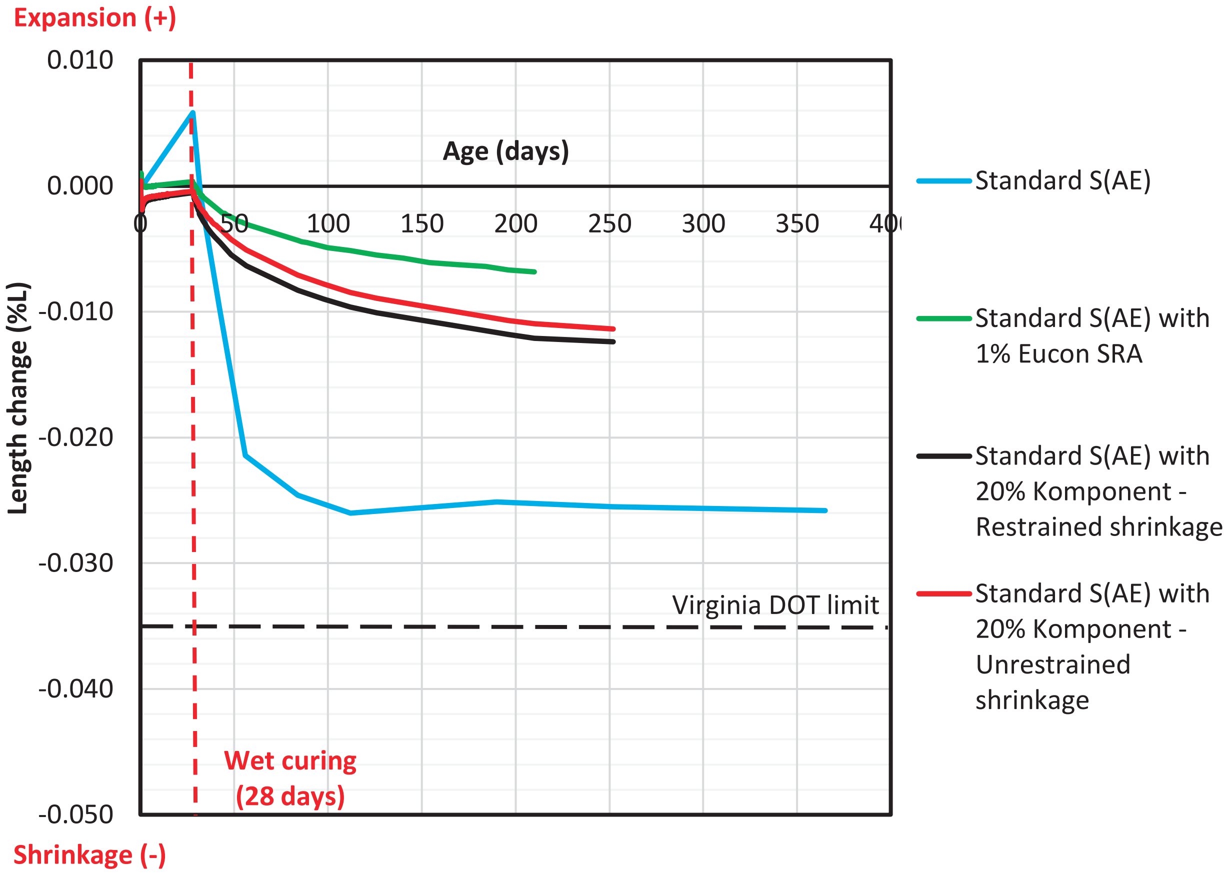

Figure 27. Length Change of Standard S(AE) and Low-shrinkage Concrete Mixes containing Limestone.

Figure 28 shows the raw shrinkage results for mixtures containing sandstone. The average shrinkage strain from three specimens is shown for the S(AE), type K (restrained and unrestrained samples), and SRA mixtures. At 84 days of age, the Type K cement contributes to reducing the drying shrinkage by approximately 320 microstrains, while the SRA reduced the shrinkage by 375 microstrains compared to the standard S (AE) mix at an age of 84 days. These shrinkage reductions represent 67 and 83 percent reduction from the standard mix shrinkage at these ages.

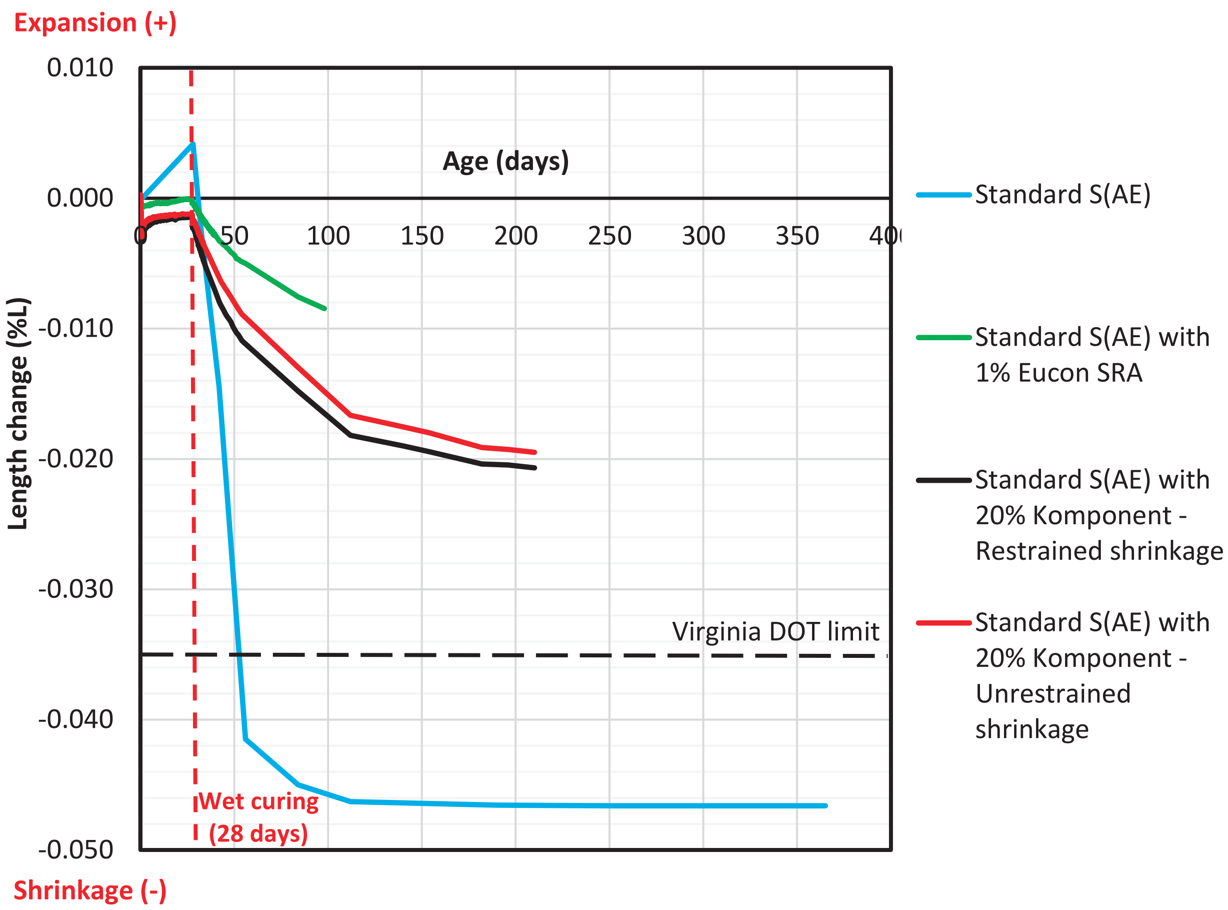

Figure 28. Length Change of Standard S(AE) and Low-Shrinkage Concrete Mixes Containing Sandstone

Figure 29 compares the drying shrinkage values between the standard S(AE) concrete mixes and the low-shrinkage concrete mixes using limestone and sandstone, at 84 days. The shrinkage reduction is noticeable when using shrinkage-mitigating admixtures for both types of coarse aggregates. The Type K cement reduced the shrinkage by 69 percent compared to the standard S(AE) mix at 84 days, and the SRA reduced the shrinkage by more than 83 percent.

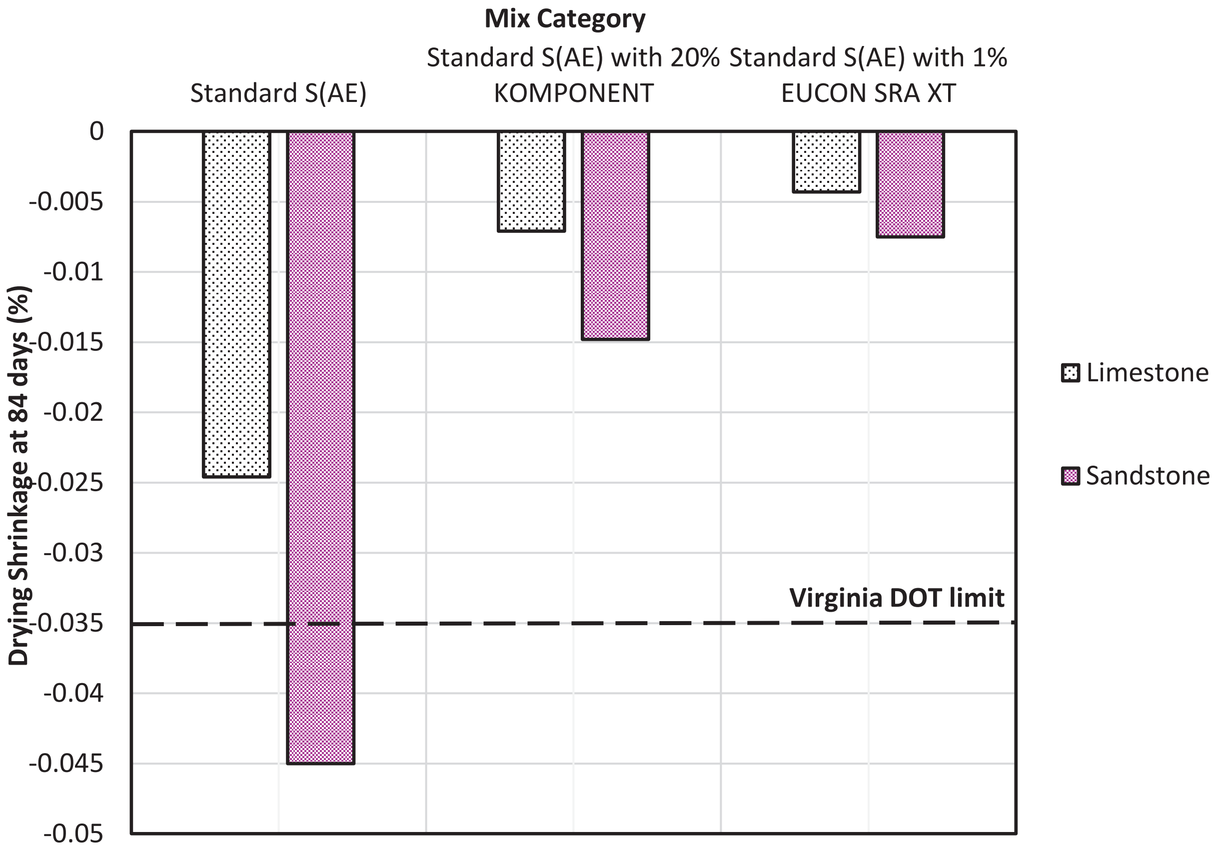

Figure 29. Drying Shrinkage Strains at 84 Days for the Standard S(AE) and Low-Shrinkage Concrete Mixes

Electrical Bulk Resistivity

The measured electrical bulk resistivity for the standard S(AE) and low-shrinkage concrete mixes are illustrated in Figure 30, and compared to the equivalent 28-days Virginia DOT permeability limit set at 2500 Coulombs for the RCPT test, converted to 75 Ohm-m in terms of bulk resistivity (Malakooti, Maguire, and Thomas 2018). While the mixture optimization by only reducing the cement content had little to no effect on the electrical bulk resistivity, all the concrete mixes that incorporated SRA or Type K cement had slightly higher resistivities than their companion standard S(AE) mixtures at 90 days. The low-shrinkage mixtures remained below the 75 Ohm-m target, even at 90 days with the exception of the limestone and SRA mixture.

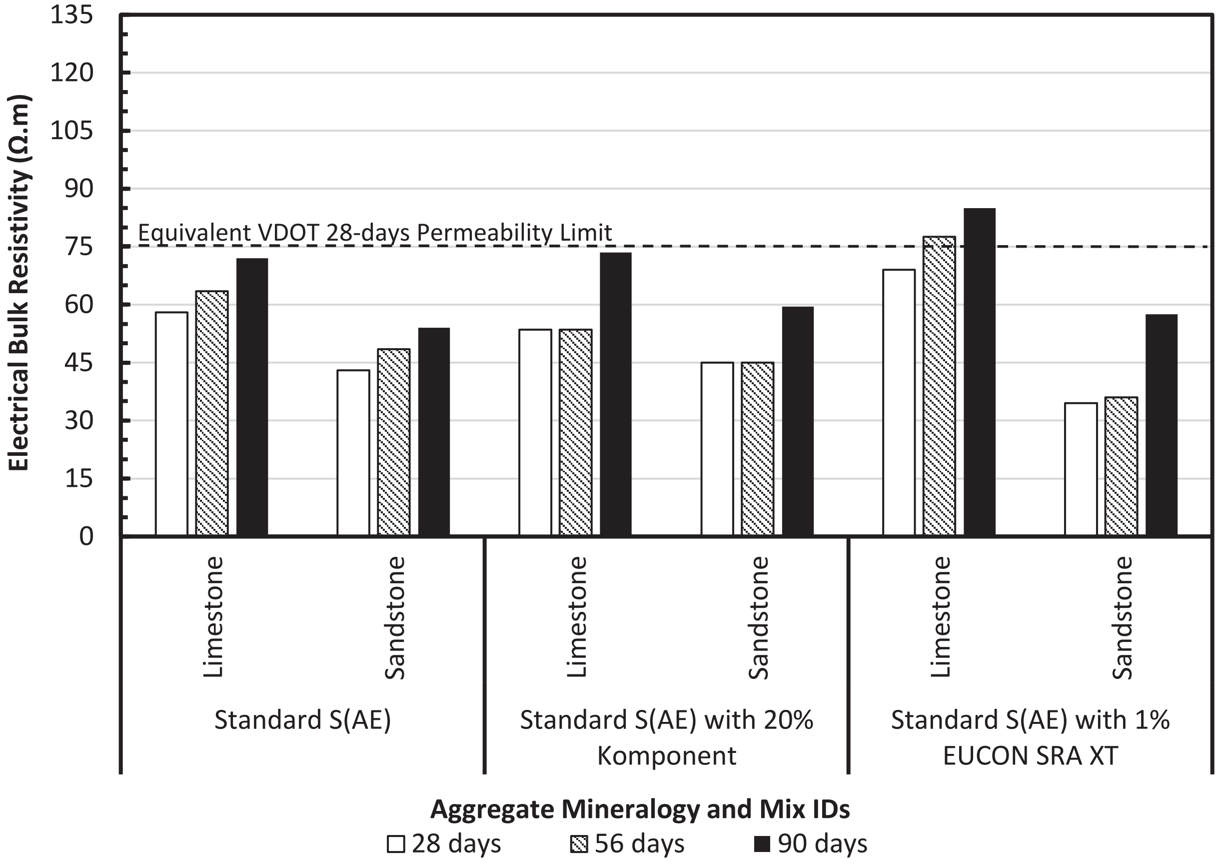

Figure 30. Electrical Bulk Resistivity Results for Standard S(AE) and Low-Shrinkage Concrete

CHAPTER 6. DEVELOPMENT OF MIXTURE SPECIFICATIONS FOR LOCAL AGGREGATES AND LOW SHRINKAGE CONCRETE

MIXTURE SPECIFICATIONS CONSIDERATIONS

The mixture specifications developed in this chapter are based on the results obtained throughout the study, for locally available aggregates. Recommendations and observations here are organized to attempt to incorporate changes that could be made based on the results of this study, prior ARDOT research, and other state specifications.

Cementitious Materials

Portland limestone cement will continue to be the primary cement provided by cement suppliers going forward. One change that can be considered by ARDOT is to eliminate or reduce the minimum cement content requirement. This work has shown that all mixtures, regardless of aggregate species and cementitious materials content, easily exceeded the minimum strength requirement, usually by 7 days. In terms of electrical resistivity, all mixtures tested were unable to reach the minimum threshold suggested by the Virginia DOT at 28-days, but there was little effect in terms of total cementitious content. The effect of cement content on shrinkage was negligible.

Admixtures

Type K cement and SRAs are powerful tools to significantly reduce the ultimate shrinkage of concrete. This report details the large reductions in shrinkage that were evident when either method was used. If shrinkage testing limits are established by ARDOT, the specifications could include allowances for the use of shrinkage compensating cements (ASTM C845 (2024g)) and SRAs (classified as class S admixtures in ASTM C494(2024f)) to provide producers with a method to reduce mixture shrinkage.

Aggregates

This report highlighted the large differences in concrete shrinkage that can be seen when using different aggregate mineralogies. Material availability and transportation costs mean that it may not be economical to source aggregates specifically to address shrinkage. In a vacuum, changing the gradation of the aggregate had no effect on shrinkage – however, in this study, the total coarse aggregate volume remained relatively fixed. In practice, if cement content was reduced and coarse aggregate volume was maximized using the tarantula or other combined gradation methods, the shrinkage of concrete should be lower due to higher aggregate restraint. It is suggested to change the gradation requirements to allow mixture designers more freedom to blend aggregates if the final mixture properties are acceptable.

Mix Design and Testing Methods

There are some considerations at the mixture approval stage to consider based on this report. Bulk resistivity was measured for the concrete mixtures in this study. Generally, when comparing the resistivity results in this study to comparable limits based on the RCPT test, the Arkansas mixtures were lower than is required despite uniformly high compressive strengths. This highlights a weakness of traditional specifications which assume compressive strength is a proxy for most durability related properties. Adopting bulk resistivity as an acceptance test is a tool to increase the durability and longevity of bridge deck concrete. The bulk resistivity test is easy to perform and relatively inexpensive after an initial investment in a resistivity meter.

Another consideration related to shrinkage is to specify a maximum shrinkage value from a shortened version of the shrinkage specification. Several states require shrinkage to be below a certain threshold after seven days of moist curing followed by 14 to 28 days of drying. Based on the results in this report, it is likely that the highest shrinkage mixtures using sandstone would be roughly at the limit specified by the Virginia DOT of 0.035 percent shrinkage. This would be a significant change to the mixture design approval process. Alabama, Arizona, California, Virginia, and Washington all require shrinkage data for bridge deck mixtures and could be used as models for a potential Arkansas specification. If concrete made with certain aggregates in state could not meet the shrinkage limit, Type K cement, SRA, or changes to the mix design could be incorporated (reducing water content, maximizing coarse aggregate volume with the tarantula or other gradation methods). The shrinkage test is not complicated to perform, but it does require a length comparator, steel molds, gauge studs, and a controlled drying shrinkage room, therefore it may be difficult to perform except for by the ARDOT lab or independent testing labs.

Finally, if Type K cement and SRA are allowed in the specifications, it is imperative that contractors design mixtures which can still be placed in a timely manner with the required fresh and hardened properties. These admixtures can affect setting time, strength, air content, and other important mixture properties. The Virginia DOT specification for low-shrinkage concrete requires the contractor to prepare (at contractor expense) a 3 yd^3 batch of the concrete for testing by an independent testing lab.

Curing

All else equal, properly curing bridge deck concrete is by far the most important intervention that could improve the quality of bridge decks in the state. As emphasized in the final reports for TRC1902 and TRC1903 (Murray and Spann 2021; Heymsfield et al. 2023), proper curing is a missing component of many bridge deck pours. Those final reports can be referred to for specific recommendations about curing – in short, on hot, windy days, fogging moisture over the bridge deck and preventing evaporation when the concrete is still plastic, or wet is highly recommended. Immediately after setting, when the concrete has gained enough strength to support hoses, burlap, and plastic sheeting, it is recommended to initiate moist curing for at least seven days or up to 14 days, ideally. Wax based curing compounds can be effective but are even more effective when used in conjunction with a proper 14-day cure. Finally, if Type K shrinkage compensating cement is used, moist curing is even more important. The method of action of Type K cement is to produce early expansion that offsets shrinkage. This expansion is only realized in a positive state of moisture. Curing is mentioned in the current ARDOT specifications, but it could be more clearly described and enforced more uniformly.

RECOMMENDATIONS FOR LOW-SHRINKAGE CONCRETE

This section will suggest a series of recommendations to be adopted by the Arkansas Department of Transportation, to reduce shrinkage cracking in concrete bridge decks. Table 14 below compares the current specifications for ARDOT compared with the Virginia DOT and Delaware DOT, and suggested future changes to the ARDOT specifications. The new specification could consider a new class of concrete for bridge decks so as to separate it from Standard S(AE) concrete. Based on the work in this report, reducing the required minimum cement content should have no significant effect on the properties measured here, so it is suggested to reduce it by one bag of cement. Requiring supplementary cementitious materials is a good idea because these materials reduce the heat of the concrete, improve the long-term durability, and reduce the cost from cement. We do not recommend requiring these materials, but other potential requirements could necessitate their use. This study found no ill effects of using a combined or optimized aggregate gradation. The use of blends of coarse aggregates would provide mix designers with another way to reduce the cost in cement of their mixes, improve fresh properties, and likely increase durability (as measured by bulk resistivity) and reduce shrinkage (if total aggregate volume is increased). Allowing producers to use any AASHTO M80 aggregate could be a good approach and this is the approach in Delaware. We suggest no change to the minimum strength requirement since this strength is used in structural design and all mixtures tested here easily exceed 4,000 psi. We recommend no change to the maximum w/c, however other changes in the specifications may encourage designers to use lower w/c. We recommend no change to the slump or air requirements

The major suggested changes are to require an accelerated shrinkage test for bridge deck concrete and to require bulk resistivity testing. Since early age shrinkage is a documented concern, providing test results for mixture designs to be used in bridge decks can be a way to improve any concrete around the state that may promote bridge deck cracking. The suggested test is a modified version of ASTM C157 with a reduced lime water curing duration of 7 days (or equivalent days to match the concrete bridge deck curing duration) and “ultimate” shrinkage measured at 28 days compared against 0.035 percent (350 microstrain). If a mixture failed this limit, the mix design could be adjusted using the following methods: 1) reduce the water content of the mix and achieve slump using water reducers, 2) increase the aggregate volume in the mixture through optimization methods, 3) use SRA or shrinkage compensating admixtures. The second major change is to consider incorporating bulk resistivity testing as a durability metric for concrete mixtures on a trial basis. This research showed that a typical Standard S(AE) mixture is likely to fall below established resistivity limits that are correlated with better long-term concrete performance. Incorporating a bulk resistivity minimum of 75 Ohm-m could lead mix designers to design more impermeable mixtures by reducing the w/c, increasing their use of supplementary cementitious materials, and maximizing the coarse aggregate content of their mixtures.

Table 14. Comparison between ARDOT and VDOT Specifications for Concretes to be Used in bridge decks

	Current ARDOT	**Virginia DOT**	**Delaware DOT**	**Suggested Future ARDOT**
Concrete Mix Designation	Structural Air-Entrained – S(AE)	Low-Shrinkage A4 Modified	Class D Concrete	S(AE) (or, Bridge Deck)
Minimum Cement Content (lb/yd^3)	611	None	None	Reduce to 517
Required Supplementary Cementitious Materials Content	None	-	15% Min. Fly Ash or 20% Min. Slag	None
Aggregate Requirements	AASHTO #57	AASHTO #7, 8, or 78 or as approved by the engineer	Conforms to AASHTO M80	Conforms to AASHTO M80
Minimum Compressive Strength at 28 days (psi)	4,000	4,000	4,500	4,000
Maximum w/cm	≤0.44	≤0.45	≤0.40	≤0.44
Maximum Permeability at 28 Days (coulombs/Ohm-m)*	Not Applicable	2500/75*	2000/100*	75 Ohm-m (measured by bulk resistivity)
Air Content (percent)	6 ± 2	6.5 ± 1.5	5.5 ± 1.5	6 ± 2
Slump (inch)	1 - 4	2 - 4	1-3	1-4
Maximum Shrinkage (microstrains) at 28 Days	None	350	None, but require shrinkage reducing admixture and fibers	350

*RCPT current passed is converted to resistivity based on limits in (Malakooti, Maguire, and Thomas 2018)

Low-Shrinkage concrete mixtures should be considered when the drying shrinkage at 28 days including the time of initial curing, and as measured by ASTM C157 (ASTM 2024d), exceeds 0.03 percent or 300 microstrains. The authors recommend the following mix designs, for shrinkage-compensating concrete and concrete with SRA, as presented in Table 1Table 15. If such mixtures are used, it is suggested that ARDOT require a verification test at contractor expense of the mixture where the same equipment to be used on the project is used to prepare test samples for an independent testing lab to verify the mixture meets slump, temperature, strength, shrinkage, and resistivity requirements.

Table 15. Mix Design Recommendations for Low-Shrinkage Concrete Mixtures

	Shrinkage-Compensating Concrete	**Concrete with Shrinkage-Reducing Admixture**
Minimum cement content (lb/yd^3)	517	517
Recommended water/cementitious ratio (w/c)	≤0.44	≤0.44
Type of admixture used: **Replacement Rate**	Shrinkage-Compensating Admixture: At least 19 percent by weight or volume of cement.	Shrinkage-Reducing Admixture: Less than two percent by weight of cement (or as recommended by manufacturer).
Air Content (percent)	4 - 8	4 - 8
Slump (inch)	2 - 5	2 - 5
Maximum shrinkage (microstrains) at 28 days*	300	300
Minimum compressive strength at 28 days (psi)	4000	4000

*Using suggested modified version of ASTM C157

Finally, bulk resistivity testing is fairly new and limits have not yet been established that are verified against field performance. The minimum resistivity suggested here is a conversion of existing RCPT limits from other researchers. We suggest rolling out bulk resistivity testing on a trial basis to evaluate the minimum of 75 Ohm-m and evaluate any unforeseen issues with such a limitation for concrete durability.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effect of various Arkansas coarse aggregates on the long-term shrinkage performance of Standard S(AE) concrete used in bridge decks. The purpose of the study was to examine the potential for early age cracking in bridge decks based on the type of aggregate used and to determine what methods can be used to reduce or eliminate the extent of cracking. Additionally, bulk resistivity testing was performed on all mixtures and the value of this test method was highlighted. Four different species of coarse aggregates widely used in Arkansas (Limestone, Dolomite, Sandstone, and Gravel) were investigated for mixtures with progressively reduced cement content made possible by optimizing the aggregate gradation. Some mixtures also incorporated a 30 percent fly ash replacement. The results for the fresh concrete properties were, for the most part, consistent between mixes. The drying shrinkage results, however, showed that the mixes with limestone and sandstone exhibited the lowest and highest drying shrinkage strains, respectively after a year of testing. Low-shrinkage concretes using both of these aggregates (limestone and sandstone) were produced using the typical minimum cement content of 611 lb/yd^3, and different shrinkage-mitigating admixtures:

- A Type K shrinkage-compensating cement additive, Type K cement, manufactured by CTS Cement, and used at a replacement rate of 20 percent by weight of cement;
- And a shrinkage-reducing admixture, EUCON SRA XT, manufactured by Euclid Chemical, and dosed at 1 percent by weight of cement.

The drying shrinkage results for the low-shrinkage concrete showed a reduction in drying shrinkage magnitude by around 69 percent for the mixes containing the type K cement additive and 83 percent for the mixes with SRA.

Other major conclusions are as follows:

- Many Arkansas bridge decks experience early age shrinkage cracks. Concrete mixtures which fell within the limits of the tarantula curve were less likely to show early age cracking. This is likely a secondary effect because these mixtures may require less mixing water to achieve good workability.
- Changing the gradation of the aggregate had minimal effect on properties (all mixtures contained roughly the same total volume of coarse aggregate) including slump, strength, shrinkage, and bulk resistivity.
- Sandstone consistently showed the highest shrinkage due to its low modulus.
- All mixtures, regardless of the reductions in cement content, consistently exceeded the minimum strength requirement, often by seven days of age.
- In spite of their high compressive strengths, mixtures without fly ash generally did not achieve minimum bulk resistivity based on similar RCPT test results. Reducing the w/c, improving the aggregate gradation, and using fly ash or other SCMs could improve mixture durability.

Suggestions were made for incorporation into the next iteration of the ARDOT Specifications. The proposed changes are as follows:

- Consider requiring a modified shortened version of ASTM C157 for concrete drying shrinkage for approval of bridge deck concrete mixtures. A maximum shrinkage of 0.035 percent or 350 microstrains is recommended based on practice in other states.
- Reduction in the required cement content and loosening of aggregate requirements is suggested to allow designers more freedom to improve mixture efficiency.
- Bulk resistivity is recommended, on a trial basis, with limits based on current research as a more direct way to specify concrete with improved durability. This would incentivize contractors to reduce w/c and use SCMs which are proven to improve the longevity and quality of concrete.
- Some mixture design suggestions are made to help incorporate SRAs and shrinkage compensating cements as an approach to mitigate high-shrinkage concrete mixtures.

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APPENDIX A: BRIDGE DECK SURVEY

Table A 1. Summary of Bridge Decks Surveyed in Project

District	Job #	Status	Bridge #	Job name	County
D1	BB0107	Cracked	A7025	Shearerville - Hwy 77	Crittenden
D1	BB0107	Cracked	07344	Shearerville - Hwy 77	Crittenden
D1	BB0113	Cracked	06939	Shell Lake STR. & Apprs.	St. Francis
D1	BB0114	Cracked	06940	Blackfish Lake Str. & Apprs.	St. Francis
D1	110574	No cracks	07444	Hwy. 350 Strs. & Apprs.	Cross
D1	110574	No cracks	07445	Hwy. 350 Strs. & Apprs.	Cross
D1	110217	No cracks	07320	Walnut Corner - Cypress Corner	Lee & Phillips
D1	BB0112	No cracks	06937	Fishing Lake Str. & Apprs.	St. Francis
D1	110574	No cracks	07446	Hwy. 350 Strs. & Apprs.	Cross
D1	110574	No cracks	07447	Hwy. 350 Strs. & Apprs.	Cross
D1	110617	No cracks	07467	Fifteenmile & Cutoff Bayous Strs. & Apprs.	St. Francis
D1	110617	No cracks	07488	Fifteenmile & Cutoff Bayous Strs. & Apprs.	St. Francis
D1	110702	No cracks	07496	Hwy.1B Str. & Apprs	St. Francis
D10	BR1610	No cracks	04935	Burlington Northern Santa Fe Railway (S)	CRAIGHEAD
D10	100824	No cracks	07407	BNSF Railroad Overpass (Hwy. 18) (S)	CRAIGHEAD
D10	100824	No cracks	07408	BNSF Railroad Overpass (Hwy. 18) (S)	CRAIGHEAD
D10	100841	No cracks	07438	CACHE RIVER RELIEF STR. & APPRS. (S)	GREENE
D10	100840	No cracks	07473	DITCH NOS. 1 & 47 STRS. APPRS. (S)	POINSETT
D10	100870	No cracks	07420	HWY. 34 STRS. & APPRS. (S)	GREENE
D10	101000	No cracks	07498	Village Creek STR. & APPRS. (S)	GREENE
D10	N/A	Cracked	N/A		
D10	100870	No cracks	07419	HWY. 34 STRS. & APPRS. (S)	GREENE
D10	CA1001	No cracks	07363	MONETTE BYPASS (S)	CRAIGHEAD
D10	100759	No cracks	A6021	BLACK RIVER STR. & APPRS. (S)	RANDOLPH
D2	020587	Cracked	07426	Ables Creek Str. & Apprs. (S)	Drew
D2	020534	Cracked	07321	Co. Rd. 411 - Why 425 (East of Crossett)	Ashley
D2	020534	Cracked	07322	Co. Rd. 411 - Why 425 (East of Crossett)	Ashley
D2	020534	Cracked	07323	Co. Rd. 411 - Why 425 (East of Crossett)	Ashley
D2	020562	Cracked	07362	Big Creek Str. & Apprs. (S)	Grant
D2		No cracks	N/A		
D3	030428	Cracked	07364	Burke Creek & Cossalot	Sevier
D3	BB0303	Cracked	07335	Red River East & West	Miller/Hempstead
D3	030415	Cracked	07378	Little River Strs Apprs.	Little River/Sevier
D3	030497	No cracks	030497	Mill & Bodcau Creeks	Miller
D4	040623	Cracked	07373	Natural Dam - North Strs & Apprs (S)	Crawford
D4	CA0903	Cracked	07277	Why 71 Interchange (Bella Vista Bypass)	Benton
D4	BB0413	Cracked	05945	Elm Springs Rd. Interchange Imprvts.	Washington
D4	040207	Cracked	06955	Devil's Den - West (S)	
D4	BB0414	Cracked	05692	Porter Rd - Hwy 112/71B Widening & Intching. Imp.	Washington
D4	BB0414	No cracks	A7380	Porter Rd. - Hwy 112/71B Widening & Intchng Imp	Washington
D4	BB0414	No cracks		Porter Rd. - Hwy 112/71B Widening & Intchng Imp	
D4	040641	No cracks		Middle Fork White River Strs Apprs	
D4	BB0414	No cracks		Porter Rd. - Hwy 112/71B Widening & Intchng Imp	
D4	BB0414	No cracks		Porter Rd. - Hwy 112/71B Widening & Intchng Imp	
D4	BB0414	No cracks		Porter Rd. - Hwy 112/71B Widening & Intchng Imp	
D4	BR7208	No cracks		West Fork White River (Woolsey) Strs & Apprs	
D4	CA0903	No cracks	07278	Hwy 71 Interchange (Bella Vista Bypass)	Benton
D4	CA0903	No cracks	07280	Hwy 71 Interchange (Bella Vista Bypass)	Benton
D4	CA0903	No cracks	07281	Hwy 71 Interchange (Bella Vista Bypass)	Benton
D4	040622	No cracks	07448	Washington Co. Line - South Strs & Apprs (S)	Crawford

Table A 1. Summary of Bridge Decks Surveyed in Project Continued

D4	040622	No cracks	07449	Washington Co. Line - South Strs & Apprs (S)	Crawford
D4	040622	No cracks	07450	Washington Co. Line - South Strs & Apprs (S)	Crawford
D4	040622	No cracks	07451	Washington Co. Line - South Strs & Apprs (S)	Crawford
D5	050344	No cracks	07443	English Creek Str. & Apprs. (S)	Fulton
D5	FA6713	No cracks	04933	South Big Creek Str. & Apprs. (S)	Sharp
D5	050341	No cracks	07431	Mill & Piney Creek Strs. & Apprs. (S)	Cleburne
D5	050230	Cracked	07301	Why 9 - S of Hwy 342 (Mammoth Spring) (S)	Fulton
D5	005836	Cracked	07289	White River Str. & Apprs. (Newport) (S)	Jackson
D5	005836	Cracked	00612	White River Str. & Apprs. (Newport) (S)	Jackson
D5		No cracks	07300		
D5		No cracks	07395		
D5		No cracks			
D5		No cracks	RE53		
D5		No cracks	07375		
D5		No cracks	07376		
D5		No cracks	07377		
D5		No cracks			
D5		No cracks	RE55		
D5		No cracks	04548		
D5		No cracks	07430		
D5	050230	No cracks	07299	Hwy. 9 - S of Hwy. 342 (Mammoth Spring) (S)	Fulton
D5	050280	No cracks	07429	Joy - Searcy (S)	White
D5	050274	No cracks	07337	Gut Creek Str. & Apprs. (S)	Fulton
D5	R50116	No cracks	07231	Little Raccoon Creek - Cove Prong Creek (S)	Stone
D5	050272	No cracks	07374	Cache River - Amagon Strs. & Apprs. (S)	Jackson
D5	050251	No cracks	07353	Hwy. 16 - Hwy. 67 (S)	White
D5	050275	No cracks	07394	Hardy - Ozark Acres Strs. & Apprs. (S)	Sharp
D6	BB0610	Cracked	07343	White River Bridge	Prairie County
D6	061507	No cracks	07436	Palarm Creek/Hwy 365	Pulaski
D6	061509	Cracked	A6466		
D6	061509	Cracked	A6467		
D6	060395	Cracked		Arch Street Bridge	
D6	061331	No cracks		Hwy 10/I-430 Interchange	Pulaski
D6	CA0608	No cracks		I-630	Pulaski
D6	061348	No cracks		MacArthur Overpass/Hwy 365	Pulaski
D6	061349	No cracks		Hwy 183	Pulaski
D7	70415	No cracks	07469	Bayou Derriseaux Str. & Apprs (S)	Cleveland
D7	70375	No cracks	07471	Alsobrook Slough Str. & Apprs (S)	Dallas
D7	70418	No cracks	07475	Halfway Creek Str. & Apprs. (S)	Bradley
D7	CA0703	Cracked	07406	Hwy 274 - North (Widening)(S)	Calhoun
D7	070282	Cracked	A6362	Ouachita River Str. & Apprs. (S)	Union & Calhoun
D7	070365	Cracked	07361	Hwy 79 No. - Co. Rd. 525 (Magnolia) (S)	Columbia
D7	070283	Cracked	07371	Bangs Slough - Hwy 172 (S)	Calhoun
D7	070283	Cracked	07372	Bangs Slough - Hwy 172 (S)	Calhoun
D7	070240	Cracked	07316	Ouachita River Str. & Apprs. (Arkadelphia)	Clark
D7	070280	Cracked	07261	El Dorado - Hwy 335 (S)	Union
D7	070280	Cracked	07262	El Dorado - Hwy 335 (S)	Union
D7	012307	Cracked	B7427	De Roche Creek Strs. & Apprs. (S)	Clark
D7	12307	No cracks	A7427	De Roche Creek Strs. & Apprs. (S)	Clark
D7	70415	No cracks	07470	Bayou Derriseaux Str. & Apprs (S)	Cleveland
D7	CA0705	No cracks	07409	Co Rd 27 - Hwy 79 (Widening)(S)	Columbia
D7	CA0706	No cracks	07410	Airport Dr - Hwy 82B (Widening)(S)	Union
D7	70380	No cracks	07466	Haynes Creek Str & Apprs (S)	Union
D7	CA0704	No cracks	A7400	Hwy 79 - South (Widening)(S)	Calhoun

Table A 1. Summary of Bridge Decks Surveyed in Project Continued

D7	CA0704	No cracks	B7400	Hwy 79 - South (Widening)(S)	Calhoun
D8	080506	Cracked	070428	Crooked Branch Str & Apprs (S)	Pope
D8	080504	Cracked	07437	Deer Creek Str & Apprs (S)	Montgomery
D8	012318	Cracked	07464, 07465	Middle Fork Saline River & Dry Run Creek Strs & Apprs (S)	Multiple
D8	080439	Cracked	07415, 07416	Bear Creek & So. Fourche La Fave River Strs & Apprs (S)	Perry
D8	080445	Cracked	070347	Cadron Creek Str & Apprs (S)	Van Buren
D8	80529	No cracks	07474	HECTOR, ISABELL & ALEWINE CREEKS STRS. & APPRS. (S)	Pope
D8	FA3610	No cracks	04944	PANTHER CREEK STR. & APPRS. (S)	Johnson
D9	090376	Cracked	07370	HWY.62/102 INTCHNG.IMPVTS. & 8th STREET WIDENING	Benton
D9	090551	No cracks	07495	Locust Creek Str. & Apprs. (S)	Marion
D9	BR0405	Cracked	04937	WILDCAT CREEK STR. & APPRS.	Benton
D9	BR0406	Cracked	04943	OSAGE CREEK STR. & APPRS. NO.2	Benton
D9	090508	Cracked	A7274	HWY.71 - CO.RD.34 (ADD'L LNS)(B.V. Bypass)	Benton
D9	009784	Cracked	04940	Buffalo River & Mill Creek Strs. & Apprs.	Newton
D9	CA0903	Cracked	07277	Hwy.71 INTERCHANGE (B.V. Bypass)	Benton
D9	CA0903	Cracked	07278	Hwy.71 INTERCHANGE (B.V. Bypass)	Benton
D9	CA0903	Cracked	07280	Hwy.71 INTERCHANGE (B.V. Bypass)	Benton
D9	090343	Cracked	07346	Hwy. 74 - Huntsville Strs. & Apprs	Madison
D9	CA0903	Cracked	07281	Hwy.71 INTERCHANGE (B.V. Bypass)	Benton
D9	CA0907	Cracked	07307	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07308	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07309	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07310	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07311	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07312	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07313	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07314	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	07315	HWY. 112 - I-49	Benton
D9	090406	Cracked	07393	HWY. 43 KCS RAILROAD OVERPASS (SILOAM SPRINGS)	Benton
D9	090402	Cracked	07421	LITTLE OSAGE CREEK STR. & APPRS.	Benton
D9	090508	Cracked	A7195	HWY.71 - CO.RD.34 (ADD'L LNS)(B.V. Bypass)	Benton
D9	090508	Cracked	A7196	HWY.71 - CO.RD.34 (ADD'L LNS)(B.V. Bypass)	Benton
D9	CA0905	Cracked	A7218	CO.RD.34 - Missouri St Line (B.V. Bypass)	Benton
D9	CA0905	Cracked	A7219	CO.RD.34 - Missouri St Line (B.V. Bypass)	Benton
D9	090508	Cracked	A7276	HWY.71 - CO.RD.34 (ADD'L LNS)(B.V. Bypass)	Benton
D9	090373	Cracked	07333	HWY.264 - PLEASANT GROVE RD.	Benton
D9	CA0907	Cracked	A7304	HWY. 112 - I-49	Benton
D9	090282	Cracked	07265	ILLINOIS RIVER STR. & APPRS.	Benton
D9	CA0907	Cracked	A7305	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	A7306	HWY. 112 - I-49	Benton
D9	CA0905	Cracked	B7218	CO.RD.34 - Missouri St Line (B.V. Bypass)	Benton
D9	CA0905	Cracked	B7219	CO.RD.34 - Missouri St Line (B.V. Bypass)	Benton
D9	CA0907	Cracked	B7304	HWY. 112 - I-49	Benton
D9	CA0907	Cracked	B7305	HWY. 112 - I-49	Benton
D9	BB0903	Cracked	07405	HWY. 71B INTCHNG. IMPVTS.	Benton
D9	009784	Cracked	07423	Buffalo River & Mill Creek Strs. & Apprs.	Newton
D9	CA0906	No cracks	07341	Maxie Camp Rd - Hwy 206	Boone
D9	CA0906	No cracks	07342	Maxie Camp Rd - Hwy 206	Boone
D9	009814	No cracks	07397	E. Pigeon Creek Str. & Apprs. (S)	Baxter

Note: Blank cells indicate information not available

APPENDIX B: COMBINED AGGREGATE GRADATIONS

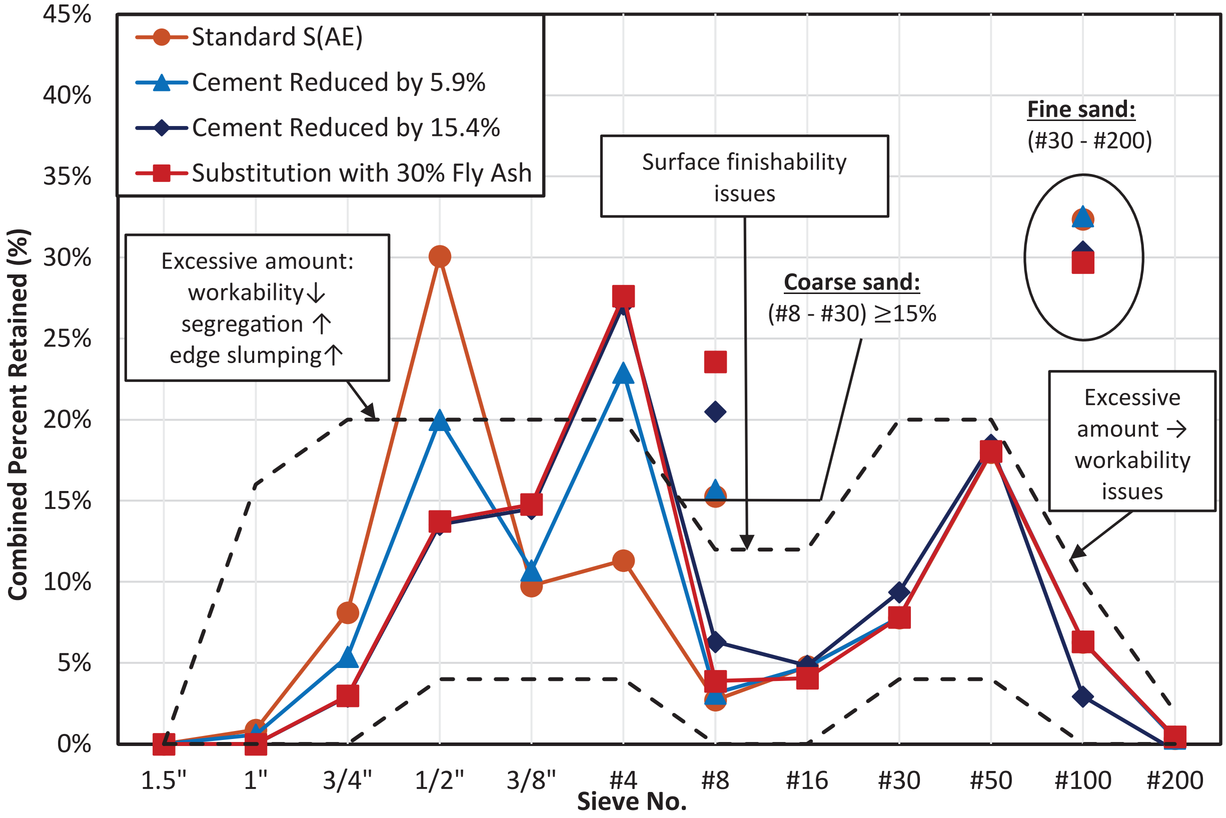

Figure B 1. Tarantula Curves for Standard S(AE) and Optimized Low-Cement Concrete Mixes using Limestone

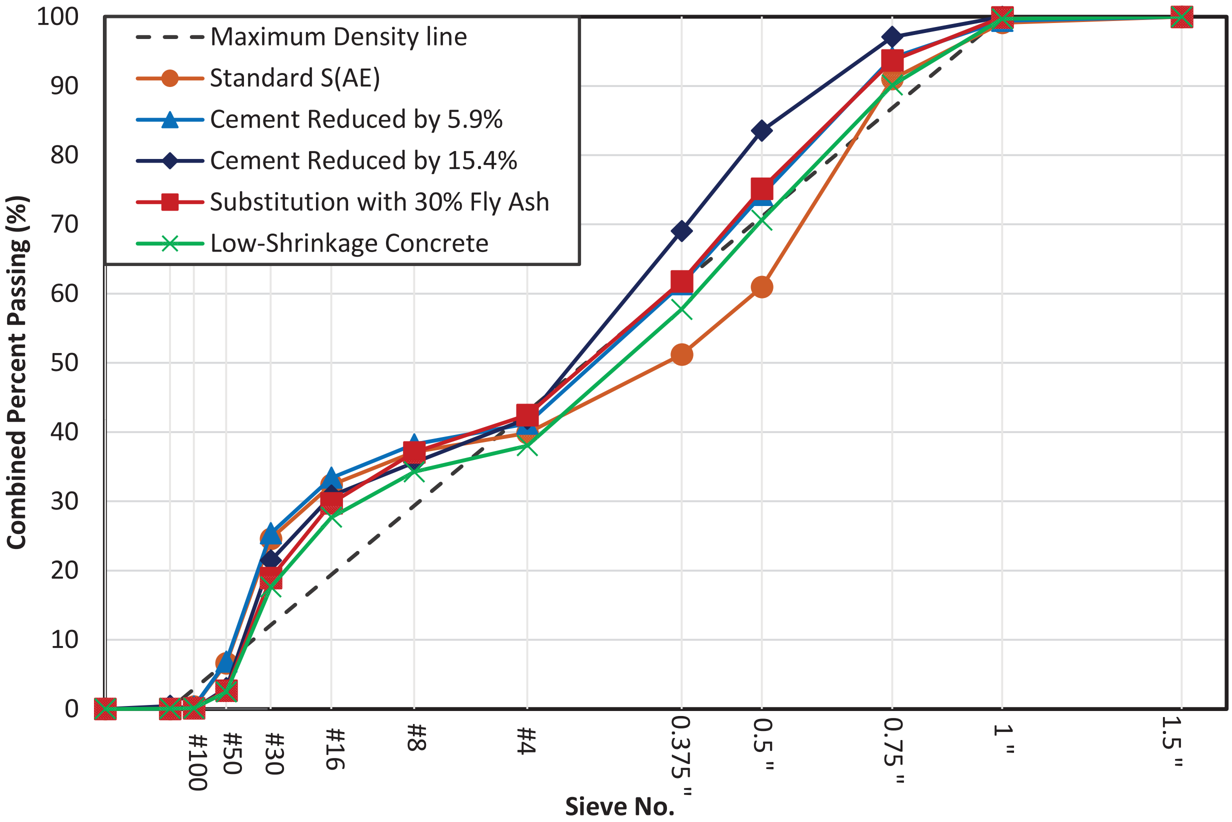

Figure B 2. Power 45 Curves for all Concrete Mixes using Limestone

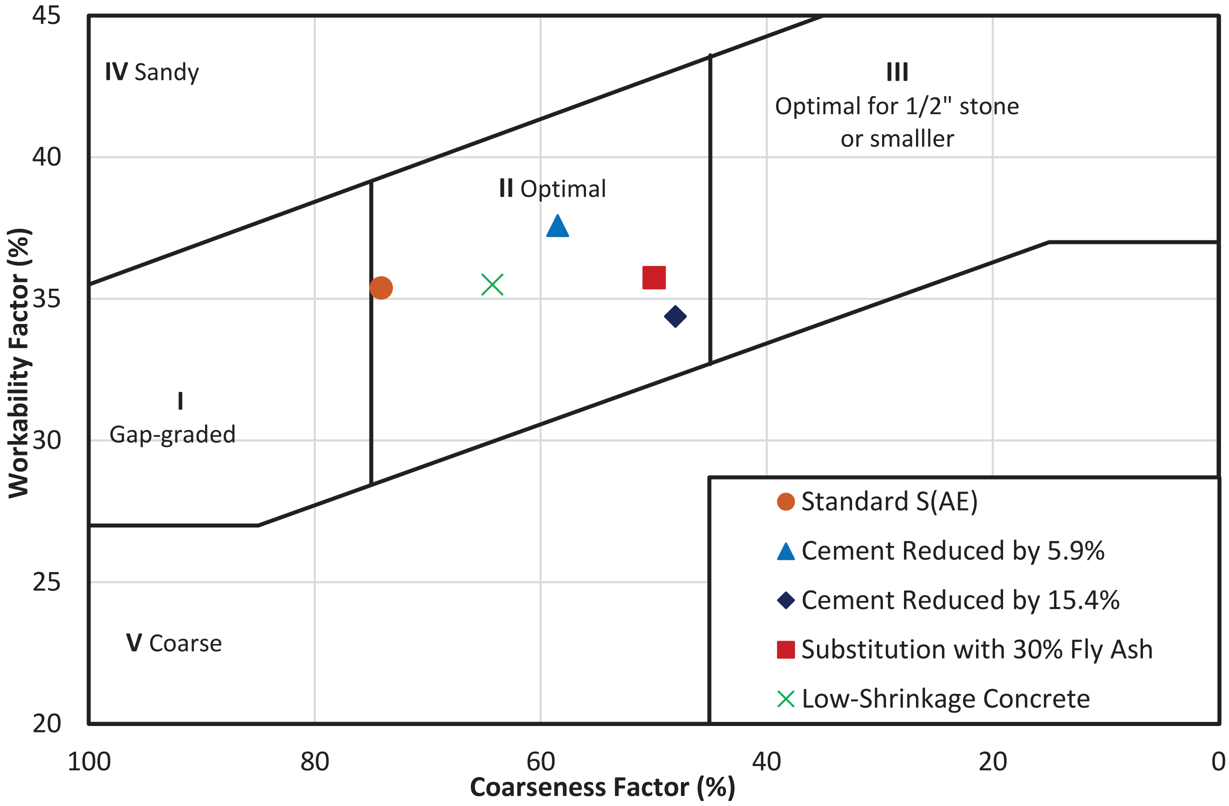

Figure B 3. Shilstone Plot (Coarseness Factor Chart) for all Concrete Mixes using Limestone

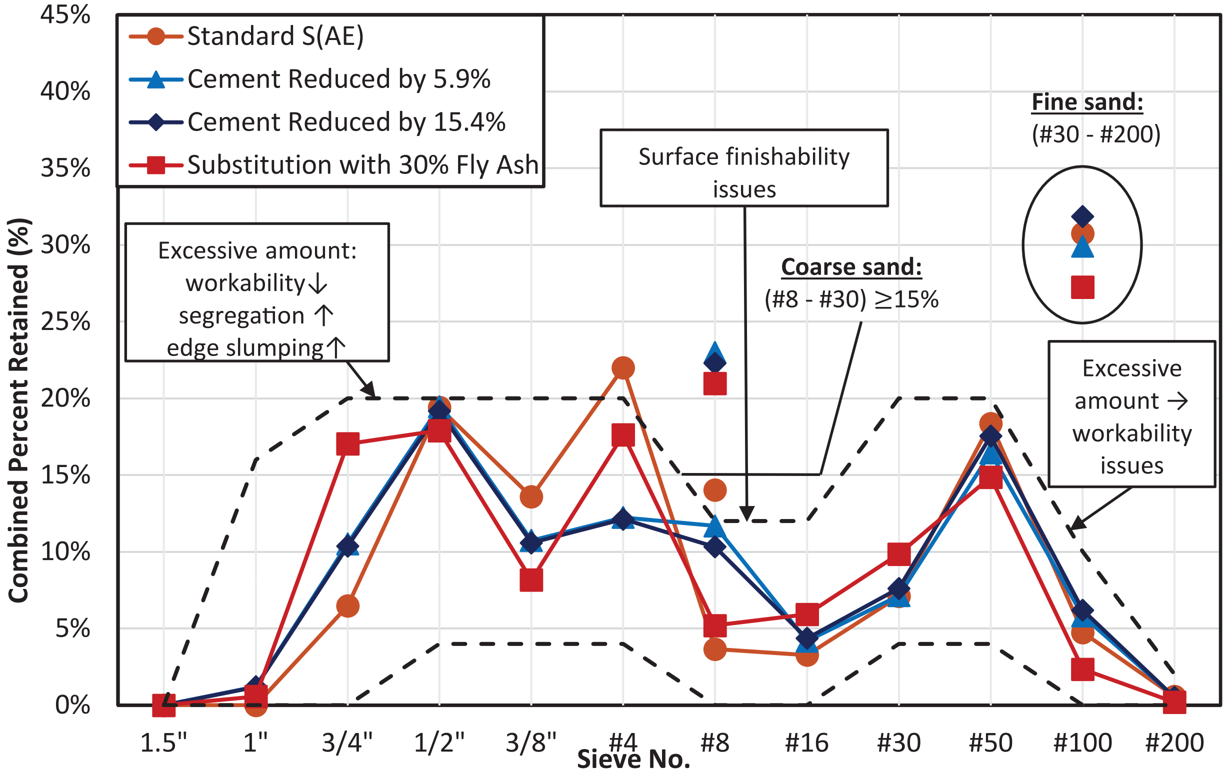

Figure B 4. Tarantula Curves for Standard S(AE) and Optimized Low-cement Concrete Mixes using Sandstone

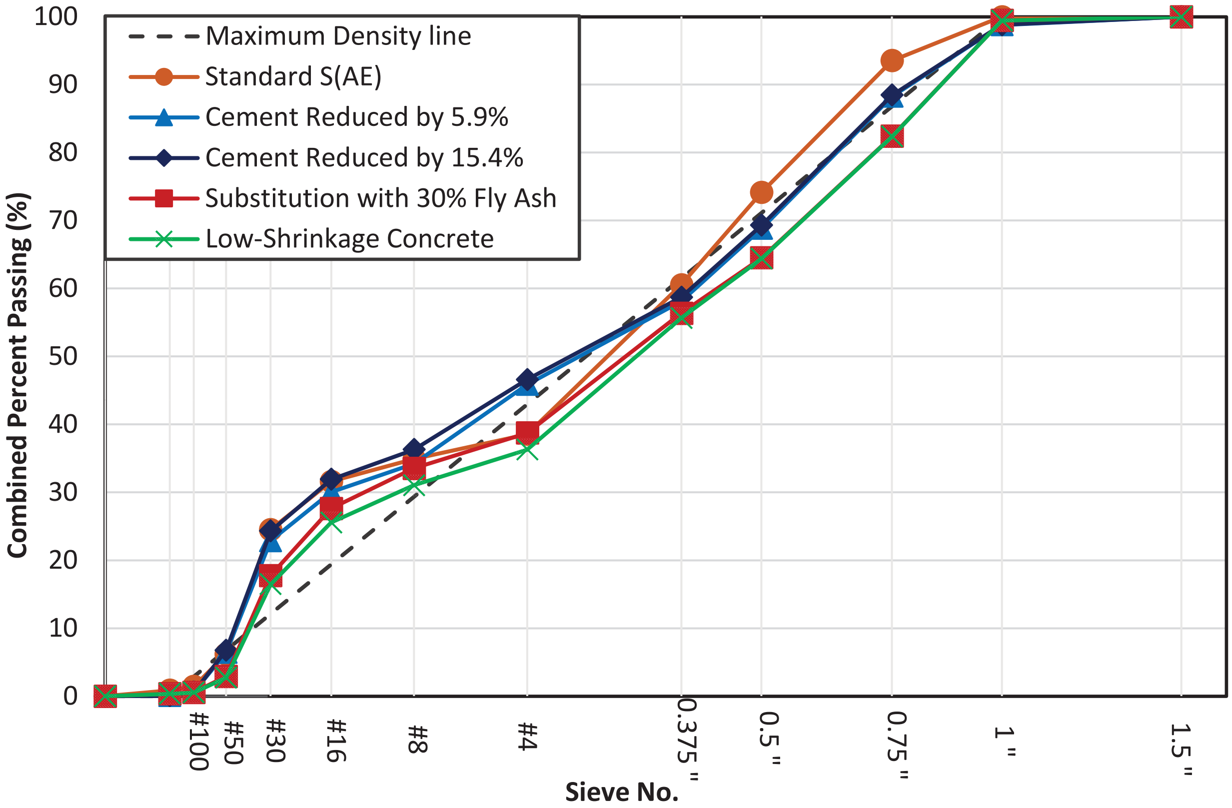

Figure B 5. Power 45 Curves for all Concrete Mixes using Sandstone

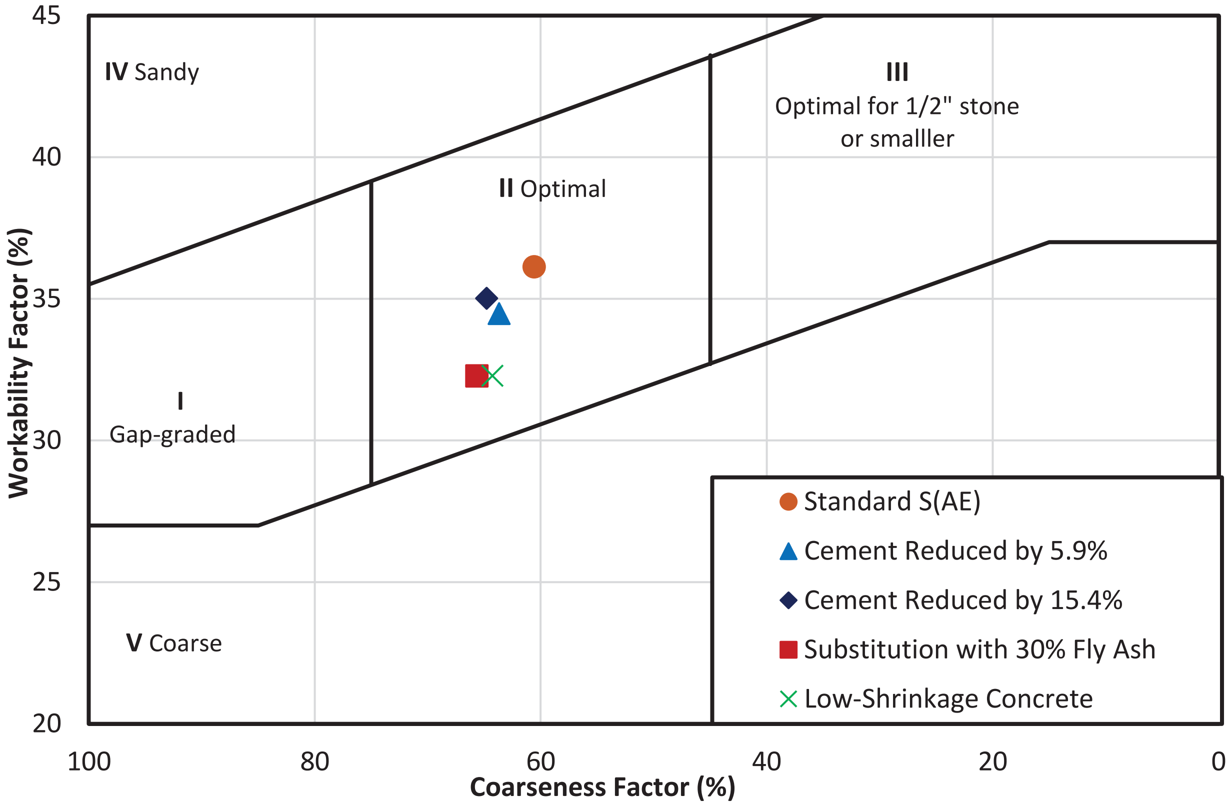

Figure B 6. Shilstone Plot (Coarseness Factor Chart) for all Concrete Mixes using Sandstone

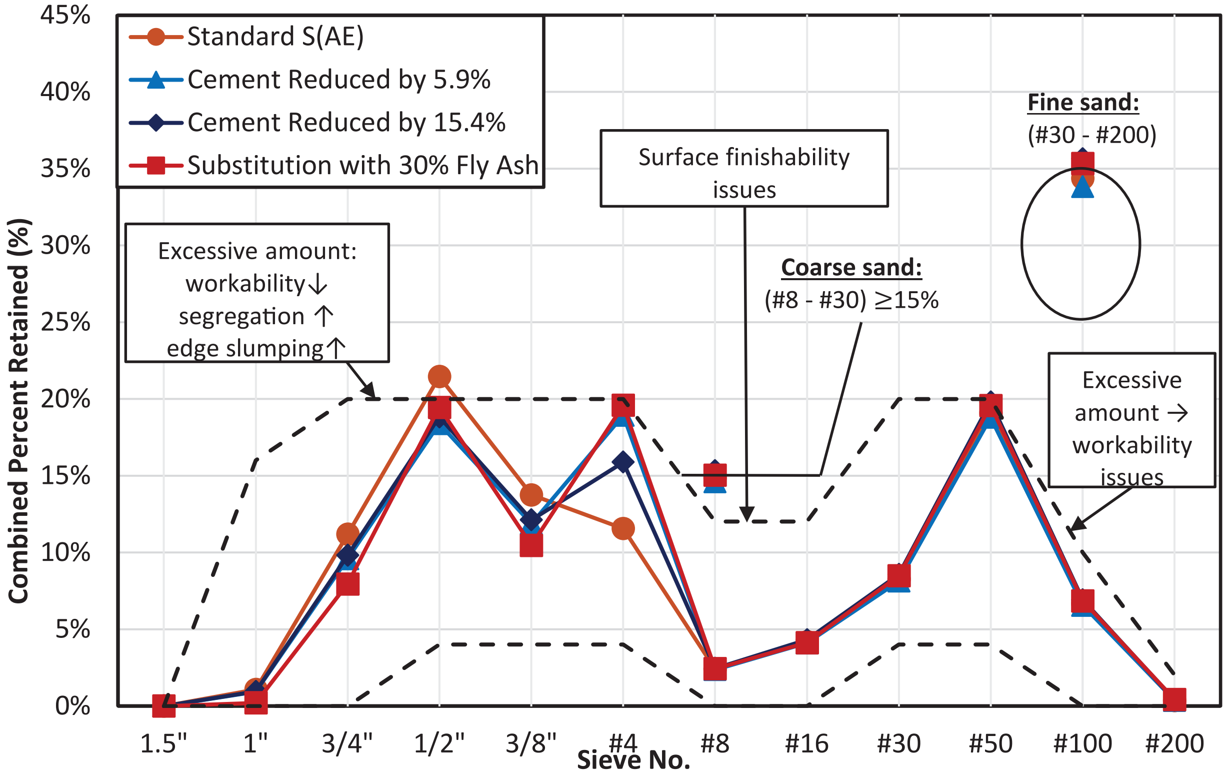

Figure B 7. Tarantula Curves for Standard S(AE) and Optimized Low-cement Concrete Mixes using Dolomite

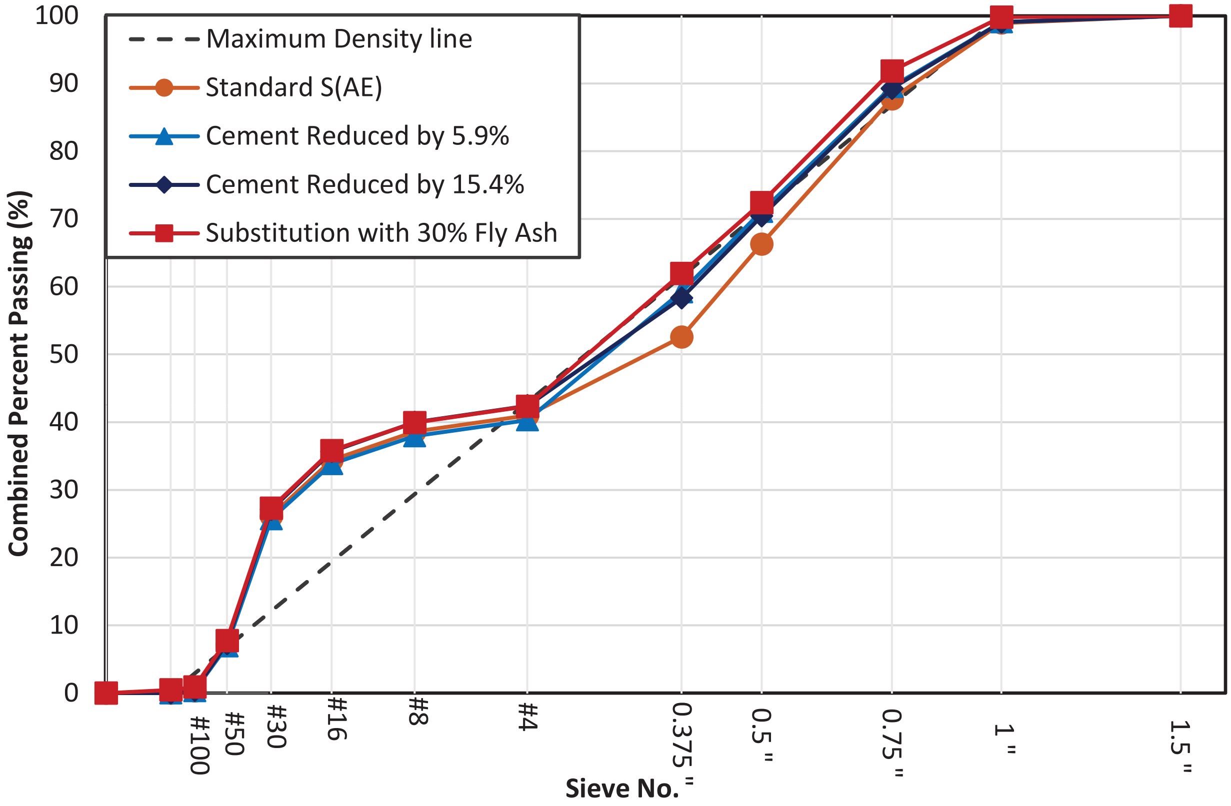

Figure B 8. Power 45 Curves for all Concrete Mixes using Dolomite

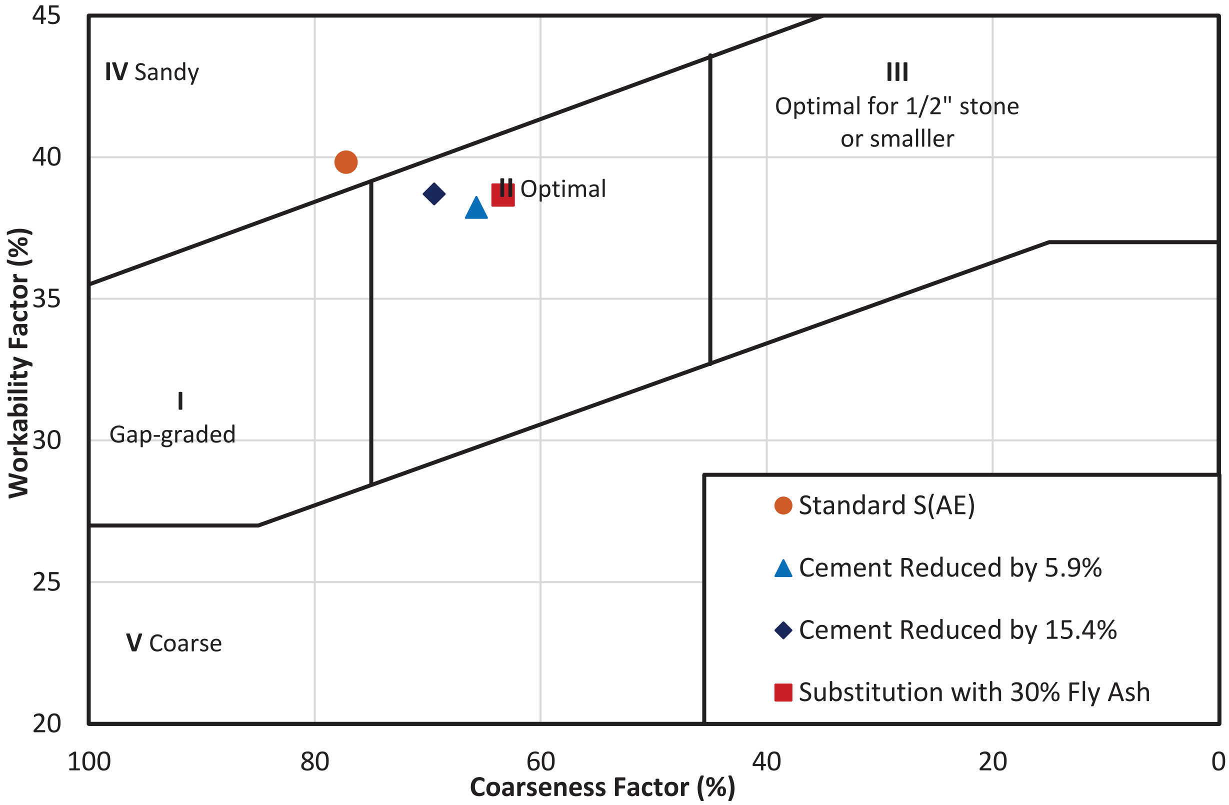

Figure B 9. Shilstone Plot (Coarseness Factor Chart) for all Concrete Mixes using Dolomite

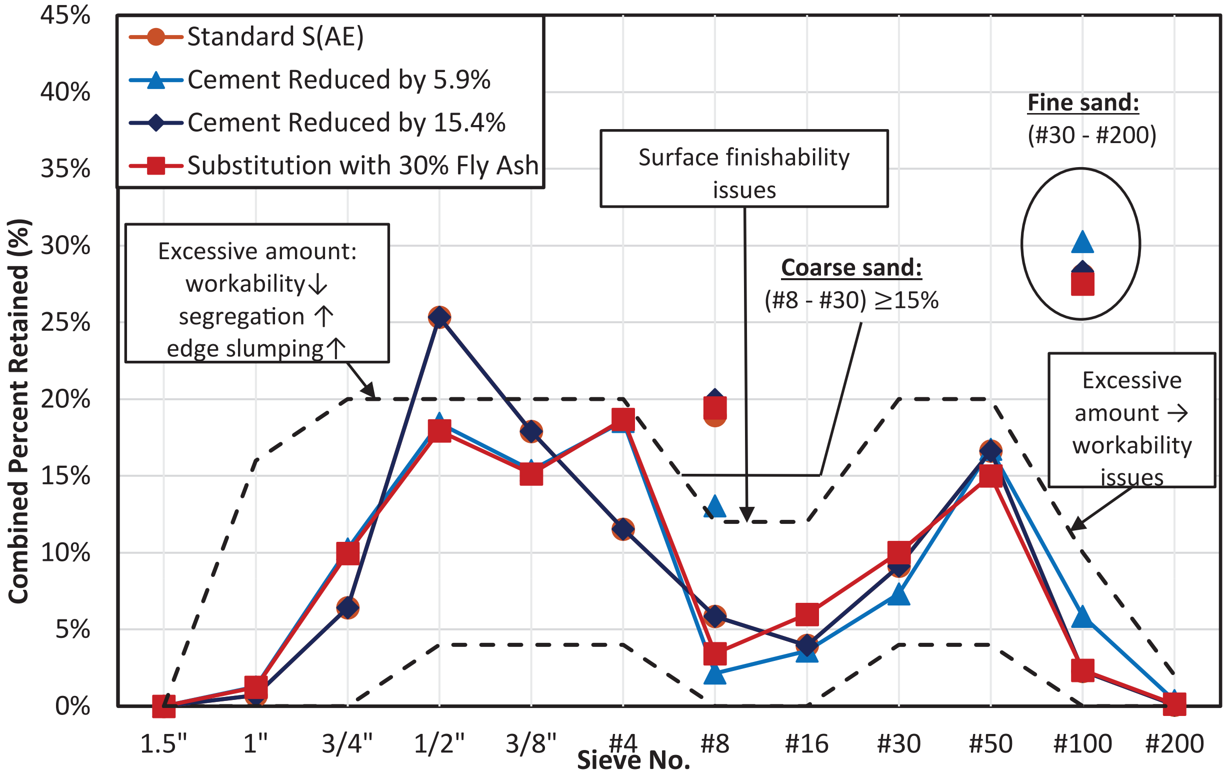

Figure B 10. Tarantula Curves for Standard S(AE) and Optimized Low-cement Concrete Mixes using Gravel

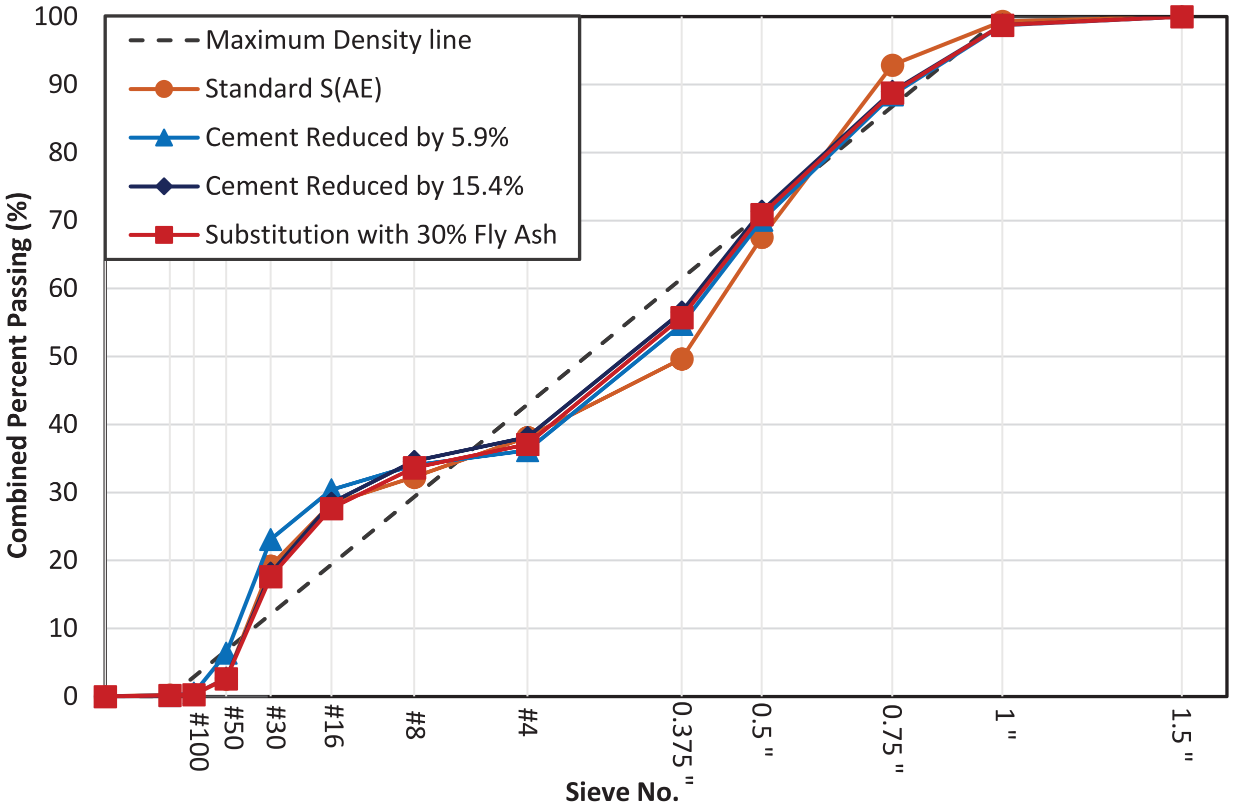

Figure B 11. Power 45 Curves for all Concrete Mixes using Gravel

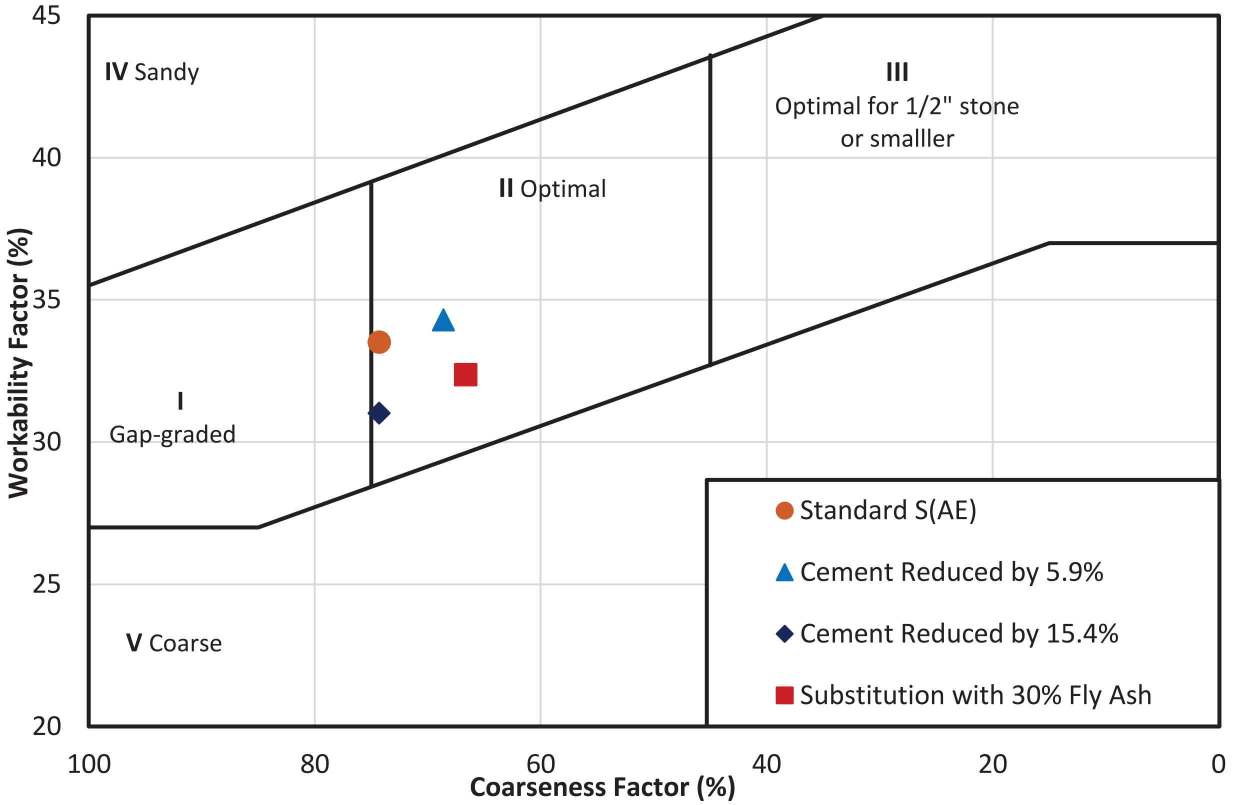

Figure B 12. Shilstone Plot (Coarseness Factor Chart) for all Concrete Mixes using Gravel

APPENDIX C: SHRINKAGE HISTORIES FOR ALL CONCRETE MIXES

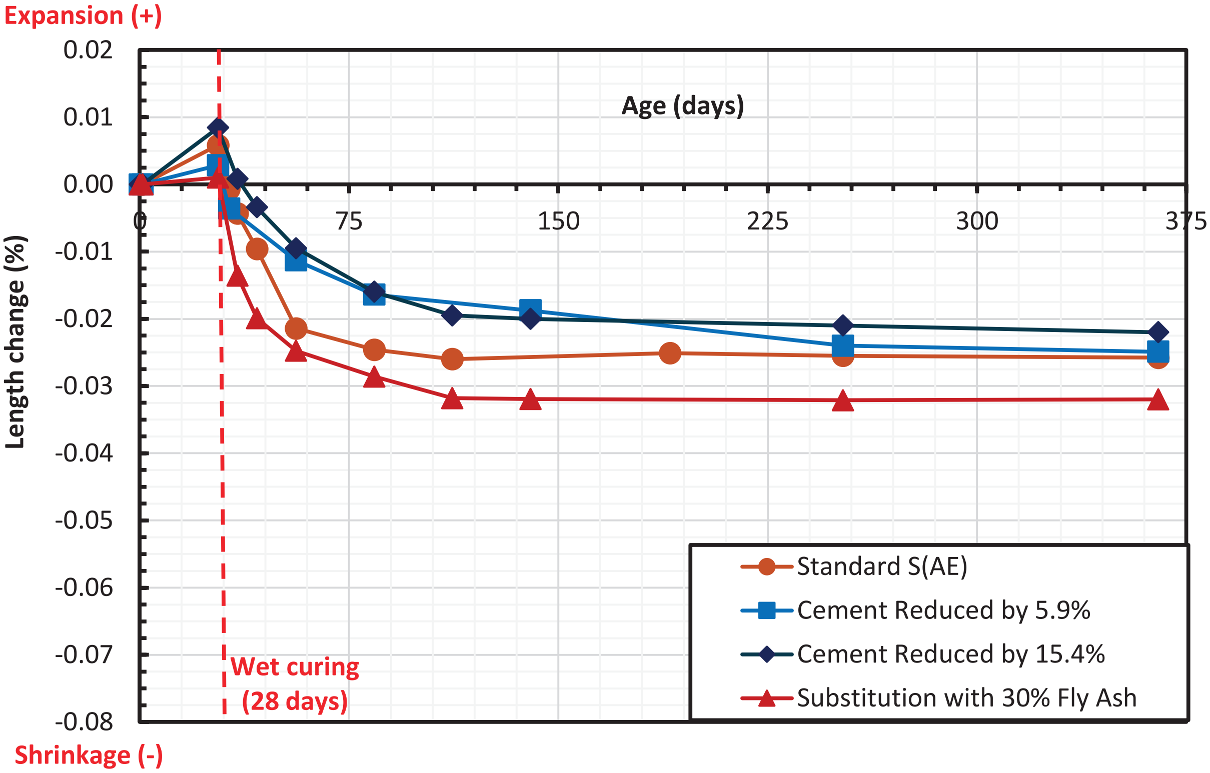

Figure C 1. Length Change History for Standard S(AE) and Optimized Low-cement Concrete Mixes using Limestone

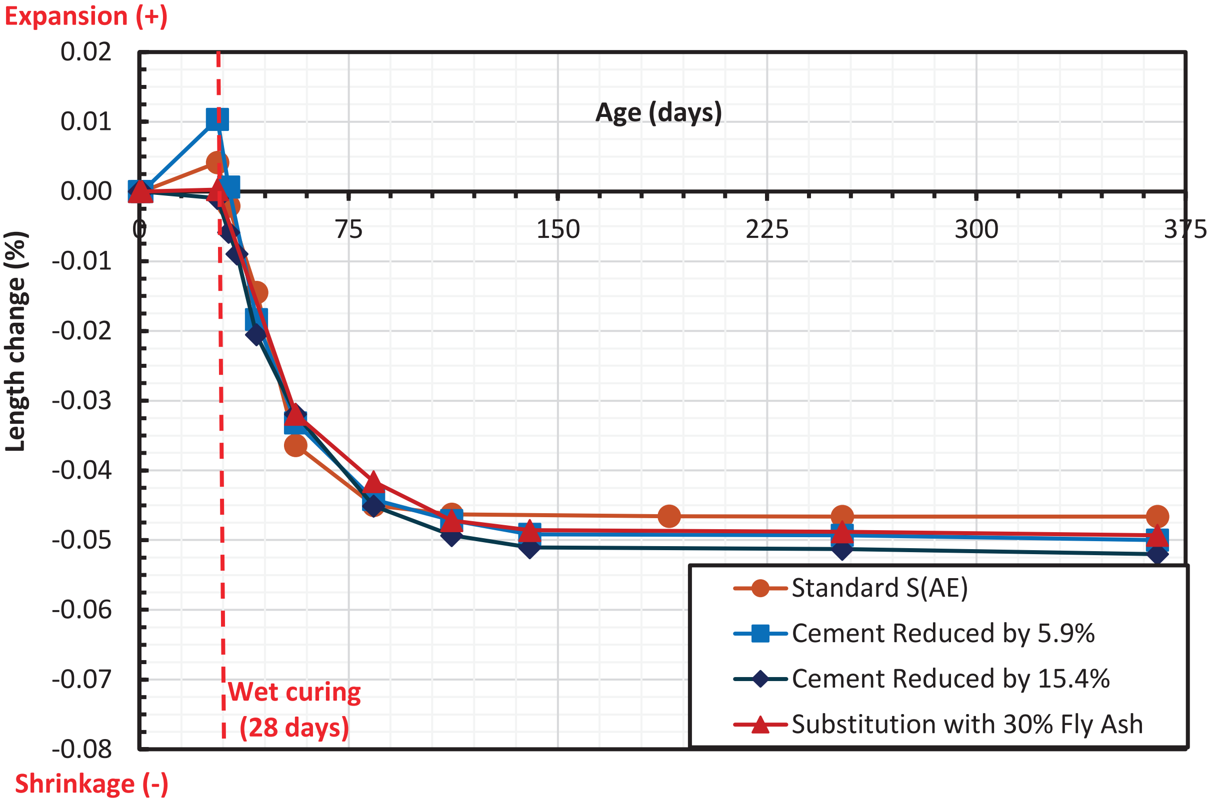

Figure C 2. Length Change History for Standard S(AE) and Optimized Low-cement Concrete Mixes using Sandstone

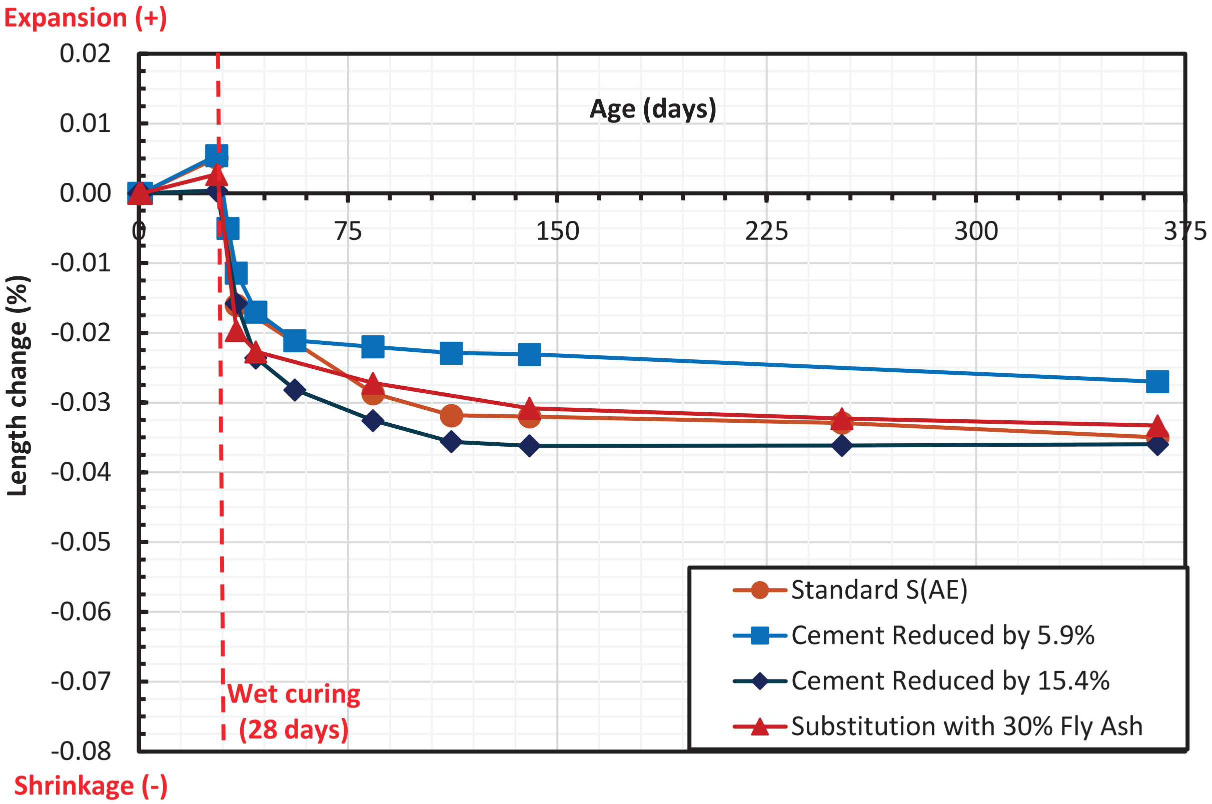

Figure C 3. Length Change History for Standard S(AE) and Optimized Low-cement Concrete Mixes using Dolomite

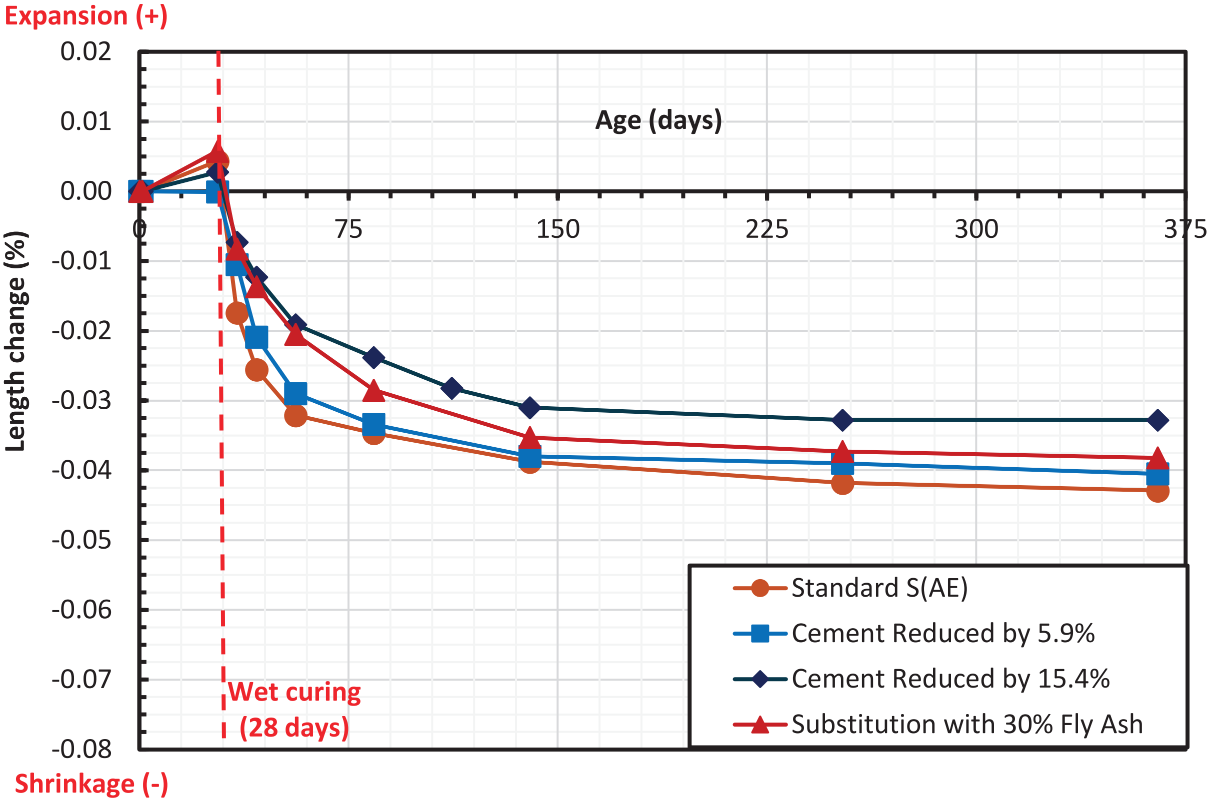

Figure C 4. Length Change History for Standard S(AE) and Optimized Low-cement Concrete Mixes using Gravel