Effects of Extended Discharge Time and Revolution Counts for Ready-mixed Concrete

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David Trejo
Jiaming Chen

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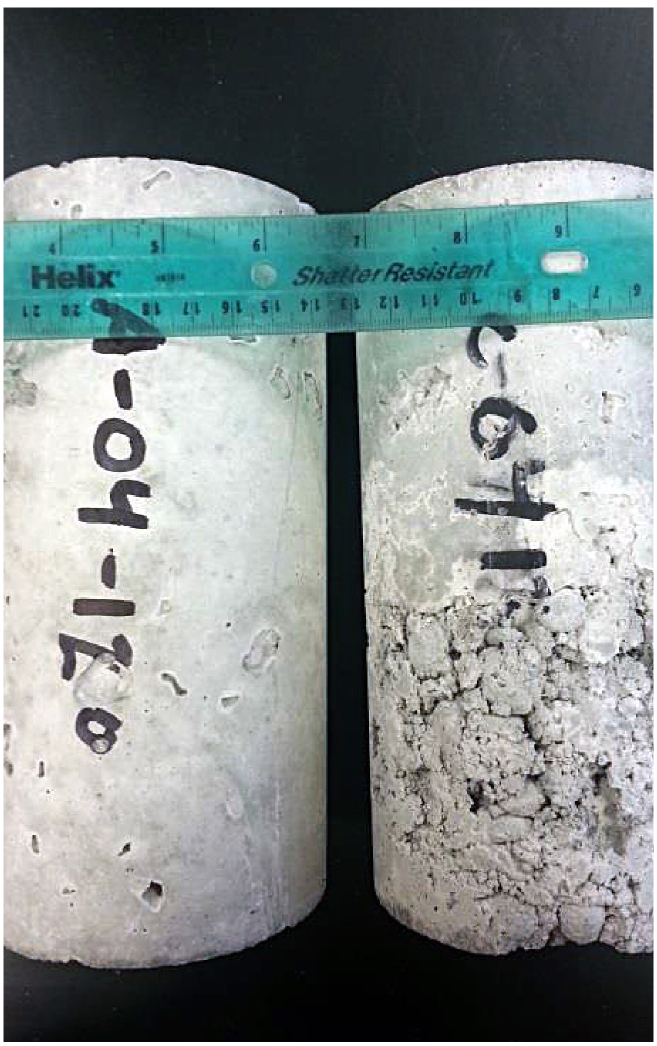

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The Kiewit Center for Infrastructure and Transportation

Effects of Extended Discharge Time and Revolution Counts for Ready-mixed Concrete

by

David Trejo, Ph.D. and Jiaming Chen

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16. Abstract

Specifications for ready-mixed concrete limit drum revolution and mixing time to 250 drum revolutions and/or 1.5 hours before discharge. These specifications have been in place for many years with the objective of ensuring the quality and performance of the finished concrete product; however, these limitations could potentially increase construction costs without additional benefits, especially when longer transport distances are required. Because there have been significant changes in concrete constituent materials (e.g., chemical admixtures) and equipment since these limits were first implemented, research is needed to assess the effects of time to discharge and drum revolution counts on concrete performance. The objective of this research program is to evaluate and verify whether existing specifications for mixing and transporting concrete are applicable for today's materials and equipment and if not, to identify key variables or tests that can ensure adequate placeability and good mechanical and durability characteristics. This study evaluated the influence of coarse and fine aggregate, supplementary cementitious materials quantity and type, chemical admixtures, temperature and mixing time and drum revolution on the mechanical and durability characteristics of concrete. Results indicate that existing specifications may be appropriate due to loss of workability. However, mixing time and drum revolution counts had no significant effects on the majority of mechanical properties and durability characteristics of ready-mixed concrete and results from this research indicate that existing specification limits are very conservative.

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration (FHWA) or the Washington State Department of Transportation (WSDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was David Trejo, Ph.D., P.E. (CA).

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Table of Contents

Page

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 GENERAL BACKGROUND

The performance and economy of our infrastructure is dependent on specifications used to construct it. Specifications that place restrictions on material suppliers and/or contractors can increase construction costs. These requirements and restrictions can increase the likelihood of improved performance, construction speed, or safety, thereby reducing the overall life-cycle costs. However, not all specifications can be correlated with performance. These specifications are typically older specification and often remnants of past prescriptive specifications. Specifications that do not provide improved performance, speed, or safety can result in unnecessary and higher costs with limited or no benefits, thereby limiting the value of these specifications.

Ready-mixed concrete (RMC) is used for many infrastructure systems. Specifications for the manufacture, transport, and placement of concrete have been established for some time. Concrete producers typically have established mixture proportions and mixing procedures with the objective of delivering a uniform concrete mixture to the job site. Concrete mixtures can be mixed in central mixers (central-mixed), in trucks (truck-mixed), or with a combination of both (shrink-mixed). The mixing process can influence the workability and longer-term performance characteristics of concrete and historical and existing specifications place limits on the mixing of concrete. As defined per ACI CT-13, workability is the property of freshly mixed concrete or mortar that determines the ease with whichh it can be mixed, placed, consolidated, and finished to a homogenous condition. This definition is used in this report. However, limits placed on mixing do not account for newer materials (e.g., chemical admixtures) and were developed when less efficient equipment was used to produce the concrete. The objective of this research is to identify and quantify the effects of concrete mixing variables, specifically mixing time and the number of concrete mixer drum revolutions counts (DRC), on concrete workability and performance.

The first self-discharging motorized concrete mixer was developed in 1916 (The Aberdeen Group 1962). Even with this motorized mixer, good mixing of concrete was limited due to the relatively low power output of the mixers. As a result of these limitations, the American Society for Testing and Materials (ASTM) published the first C94 specification in 1935, which required that the concrete be discharged within 90 minutes after mixing. Sometime later, limits on the number of truck drum revolutions were added to the specification. After WWII, heavier trucks with more powerful engines were available, making concrete production easier and more consistent. Water-reducing agents were introduced in the 1960's and superplasticizers were developed in the 1970s (California State Water Project 1964; Mehta and Monteiro 1993). In the 1990's polycorboxylate based admixtures became more popular than the naphthalene and melamine based chemical admixtures. In addition, more powerful set controlling admixtures have been developed. Although significant improvements in equipment and admixture technology have occurred, the mixing time and drum revolution count limits in many specifications have not been modified to recognize these changes. In fact, a search of the literature indicates limited research has been performed to assess how materials perform when mixed with modern equipment and materials. Whether the original requirements of ASTM C94 are still applicable is unknown.

1.2 OBJECTIVE AND SCOPE

The objectives of this research are to determine whether existing limits in the ASTM, Washington State Department of Transportation (WSDOT), and many other state's specifications are applicable. This research will identify key materials, environmental, and/or mixing variables that can be correlated with concrete workability, constructability, and performance (mechanical and durability). In this report, Chapter 1 contains the introduction, Chapter 2 includes a literature review on current specifications and the effects of mixing on cement-based systems, Chapter 3 provides an overview of the constituent materials and mixture proportions used in this research, Chapter 4 contains the experimental program, Chapters 5 and 6 present the results and analyses from the laboratory study, and Chapter 7 presents the results and analyses for the field study. Lastly, the conclusions and recommendations are provided in Chapter 8.

2. LITERATURE REVIEW

This chapter provides a review of the literature regarding the history of specifications for RMC and the effects of materials, mixing time, mixing drum revolutions, and mixing speed on RMC characteristics. The following sections review the progression of RMC specifications currently in place by the American Association State Highway Transportation Officials (AASHTO), ASTM, and state highway agencies (SHAs). The literature regarding the effects of RMC constituent materials and mixing variables on the fresh and hardened characteristics of concrete are then reviewed.

2.1 HISTORY

RMC has a long history of development. Kelly (2013) reported that the first concrete mixed offsite and delivered to the job site may have been in 1913, just one year before the establishment of committee ASTM C9—*Concrete and Concrete Aggregates*. When the National Ready-mixed Concrete Association (NRMCA) recognized the growth in usage of RMC in the late 1920s, they approached the ASTM C9 committee, requesting development of a specification for RMC. The first RMC specification was issued in 1933 as a tentative specification, ASTM C94-33T—*Tentative Specification for Ready Mixed Concrete.* In 1935, the committee provided the national standard, ASTM C94—*Standard Specification for Ready Mixed Concrete* addressing the purchasing, material requirements, batching and mixing, delivery, sampling, and testing of RMC.

A delivery constraint set by the first C94 specification was a maximum discharge time limit (specified as time of hauling) of 90 minutes. Discharge time in this specification was defined as either the time between the introduction of the mixing water and cement to complete discharge of the concrete or the time between the introduction of the cement to the aggregates until complete discharge of the concrete. The later definition was used when the fine aggregate (FA) and/or coarse aggregate (CA) contained moisture contents in excess of 6 percent and 3 percent by weight, respectively. The term "discharge" should not be confused with "placement." ACI Concrete Terminology (2013) defines the term placement as "the process of placing and consolidating concrete or a quantity of concrete placed and finished during a continuous operation." The term discharge only describes the initial step of concrete placement which is the motion to release or unload the fresh concrete from the concrete truck to the jobsite. Note that ASTM, AASHTO and many SHAs specify limitations for both discharge and placement of RMC. Details on these limitations are discussed in section 2.3.

In 1958, ASTM added a maximum of 300 truck drum revolutions to the C94 specification. Limited information is available on why this was added. Although time limits are still reported in ASTM, ASTM recently removed the drum revolution count (DRC) limit and now defers the drum revolution limit to the purchaser (ASTM C94-13b). This is likely a result of the inability to correlate mixture performance with drum revolution counts; limited information has been published on the influence of drum revolution counts on concrete performance. The limitation on discharge time remains unchanged since its first implementation in 1933. Despite the removal of the drum revolution counts limit by ASTM, many SHAs continue to enforce both drum revolution counts and discharge time restrictions. A review of commonly used methods to produce RMC follow.

2.2 METHODS FOR MIXING CONCRETE IN THE FIELD

The production of concrete consists of establishing a mixture proportion for concrete and then mixing these constituent materials to obtain a mixture with well distributed aggregate. Although there has been significant work in understanding the influence of constituent material types and proportions on RMC performance, much less work has been done to assess the influence of mixing on RMC properties. Several processes are commonly used to mix concrete. The mixing is typically classified into three general types: Stationary, Ready-mixed concrete, and mobile batcher mixed concrete (Kosmatka et al. 2002).

Stationary mixing is when the concrete mixing process is done at the jobsite. Stationary mixers are commercially available in different sizes up to 9.0 m^3 (12 yd^3).

Ready-mixed concrete is typically batched and mixed off the jobsite and then delivered to the jobsite in a concrete mixing truck. RMC can be manufactured by these methods:

1) Central-mixed concrete is a concrete mixed thoroughly in a stationary mixer that is then discharged into transporting equipment. This transporting equipment can be a truck agitator, a truck mixer operating at agitation speed, or a nonagitating truck.

For non-agitating trucks, the tendency of concrete segregation limits the distance it can be transported. ASTM C94/C94M—*Standard Specification for Ready-Mixed Concrete,* limits the volume of concrete charged into a truck with an agitator to 80 percent of the truck drum volume.

2) Shrink-mixed concrete is a concrete partially mixed in a stationary mixer with mixing completed in a concrete truck mixer during its travel to the jobsite. ASTM C94/C94M limits the volume of this concrete to 63 percent of the truck drum volume.

3) Truck-mixed concrete is a concrete mixed completely in a concrete truck mixer. The mixing constituents are batched at a plant, charged into the transporting truck, and mixed as the truck travels to the jobsite. The volume of all ingredients for this type of concrete should not be greater than 63 percent of the truck drum volume (TMMB 1996).

Another method to produce concrete is with the use of mobile batch mixers. The Portland Cement Association (PCA) reports that concrete produced with mobile batch mixers is volumetrically batched and the dry concrete constituents are continuously mixed prior to adding water and admixtures at the mixing trough (auger). This research will not assess concrete produced with mobile batch mixers.

A review of current ASTM, AASHTO, and WSDOT specifications for RMC production is presented in Section 2.3.

2.3 READY-MIXED CONCRETE SPECIFICATIONS

Much of the RMC produced today is transported to the job site with a concrete mixer truck. The RMC is then discharged from the truck. The concrete is then placed, consolidated, and finished by the workers at the jobsite. A typical timeline for RMC production is shown in Figure 2-1.

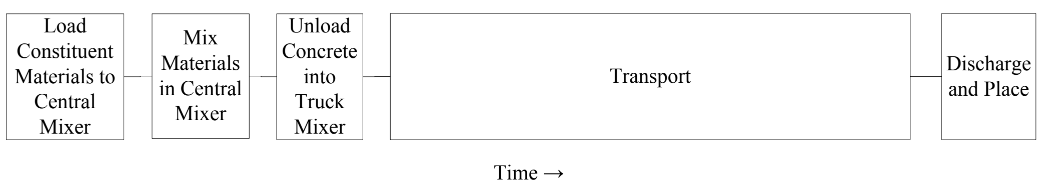


Figure 2-1. Timeline for Typical RMC Production.

Specifications are in place to ensure that concrete is mixed, transported, and placed such that it can achieve desired properties. Time and temperature limits for placement following ASTM C94 (2013) are shown in Figure 2-2. ASTM C94 defines concrete placement temperature as the temperature of the as-placed concrete. The specification specifies time and concrete temperature limits for discharge and placement, respectively, and minimum concrete temperature for placement as a function of section size. Minimum concrete temperatures for placement are required because low concrete temperatures during early ages can significantly reduce the rate of strength gain of the concrete and can influence the final concrete product, especially if freezing occurs (ACI 306 1966).

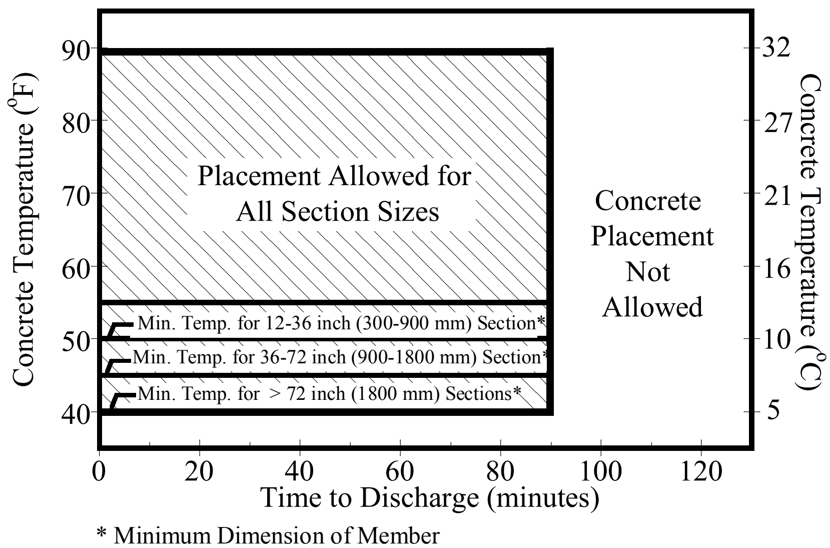


Figure 2-2. ASTM C94-13b Limits for RMC.

NRMCA Concrete In Practice (CIP) 27—Cold Weather Concreting (1998) reports that fresh concrete will freeze if its temperature falls below about 25 °F (-4 °C) at early ages. ACI 306 (1966) first proposed minimum temperature limits for concrete placement to provide protection against freezing and to ensure adequate strength development. If fresh concrete freezes, its mechanical properties can be significantly reduced and its durability will be adversely affected (NRMCA CIP 27 1998). The current minimum temperature limit specified by ASTM is 55 °F (13 °C). This value is much higher than the reported freeze temperature of concrete and NRMCA CIP 27 (1998) implies that a higher minimum temperature is required to ensure adequate strength development. Figure 2-3 shows the strength development of concrete cured at different temperatures (from 40 to 115 °F [4 to 46 °C]). The figure clearly shows that concrete cured at lower temperatures results in slower strength development and lower 28-day strengths. At 7- and 28-days, concrete cured at 40 °F (4 °C) gained only about 38 and 78 percent of the strength gained compared to the concrete cured at 70 °F (21 °C). However, larger section sizes can generate sufficient heat to obtain adequate strength and several standards recognize this. In all cases, care must be taken to prevent differential thermal strains which can result in cracks (ACI 306 1966).

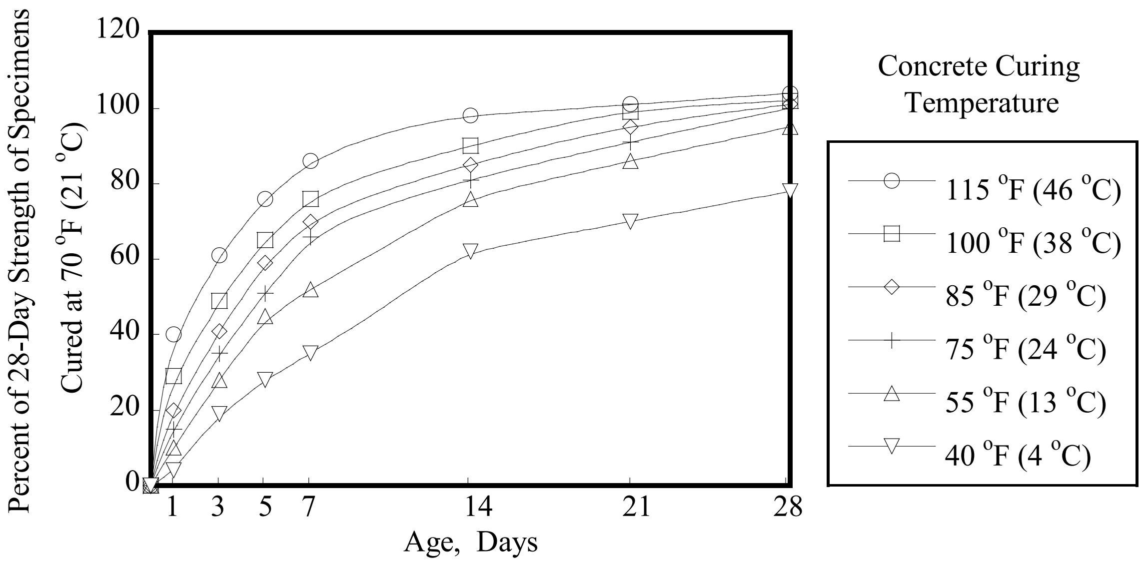


Figure 2-3. Influence of Casting and Curing Temperatures on Concrete Strength (after Concrete Manual 1975).

AASHTO M157—Standard Specification for Ready-Mixed Concrete (2011) *specifies discharge limits for RMC.* Figure 2-4 shows concrete discharge time limits and concrete temperature limits following AASHTO M157 (2011). AASHTO M157 defines concrete temperature as the temperature of the as-delivered concrete. The AASHTO specification also specifies the discharge of concrete based on concrete temperature and section size but with small differences to that of ASTM C94. The differences relate to the definition of section size. AASHTO classifies two types of section sizes: thin sections and heavy sections. AASHTO also specifies concrete temperature based on these section sizes. AASHTO also specifies minimum concrete temperature based on air temperature—lower air temperatures require higher concrete temperatures. Requirements are shown in Table 2-1. In addition to temperature and time limits, AASHTO also specifies that RMC must be discharged within 300 drum revolution counts (DRCs).

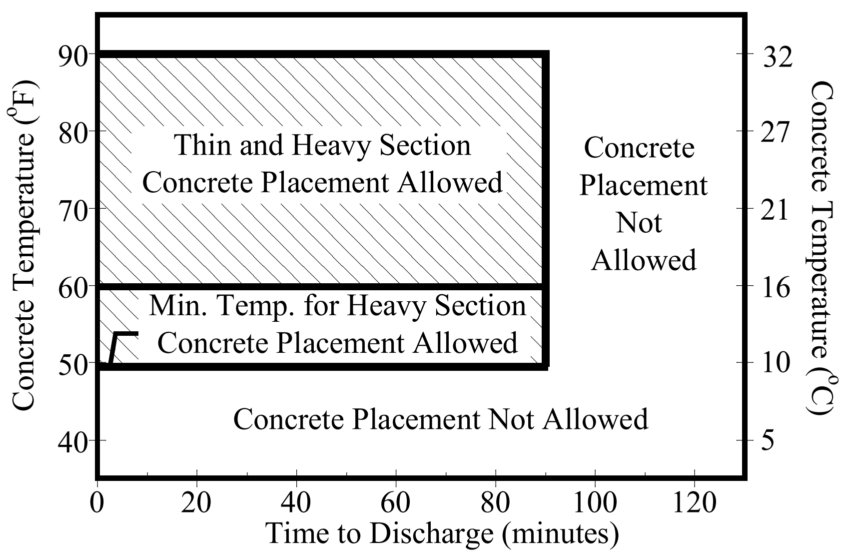


Figure 2-4. AASHTO M157-11 Limits for RMC.

Table 2-1. AASHTO Minimum Concrete Temperature for Placement.

Air Temperature, °F (°C)	Thin Sections and Uniform Slabs, °F (°C)	Heavy Sections and Mass Concrete*, °F (°C)
30 to 45 (-1 to 7)	60 (16)	50 (10)
0 to 30 (-18 to -1)	65 (18)	55 (13)
Below 0 (-18)	70 (21)	60 (16)

*Mass concrete is defined as any large volume of concrete where special materials or procedures are required to cope with the generation of heat of hydration and attendant volume change to minimize cracking (AASHTO Transportation Glossary 2009).

Climate conditions can be different for different regions and many SHAs have different specifications for RMC transport and placement. Figure 2-5 shows discharge time limits and concrete temperature limits for concrete placement as specified by WSDOT specification *M41-10—Standard Specifications for Road, Bridge, and Municipal Construction 2013*. WSDOT defines concrete temperature as the temperature of the concrete while it is being placed (compared to as placed and as delivered for ASTM and AASHTO, respectively). The time and placement temperature limits for WSDOT are different from that of ASTM and AASHTO. WSDOT limits discharge time to a maximum of 105 minutes (or 120 minutes with approval from engineer) if the concrete temperature is between 55 and 75 °F (13 and 24 °C). However, if concrete temperature is between 75 to 90 °F (24 to 32 °C) WSDOT lowers the discharge time maximum to 90 minutes.

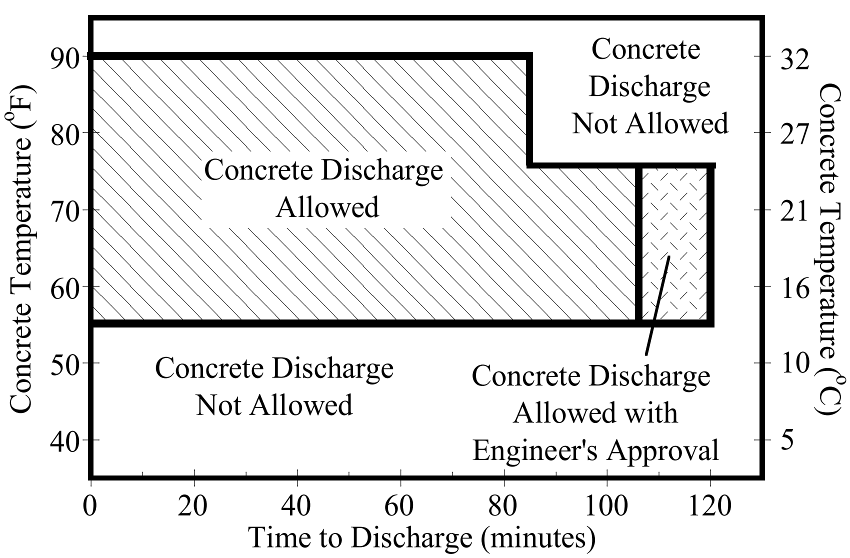


Figure 2-5. WSDOT Limits for RMC.

In addition to limits on discharge time and concrete temperature placement limits, SHAs also specify minimum and maximum drum revolution counts. The drum revolution requirements reported by transportation organization for SHAs and transportation organization in US territories for central-, shrink-, and truck-mixed concretes are shown in Table 2-2, Table 2-3, and Table 2-4, respectively. The limits used by the different agencies vary greatly.

Table 2-2. Truck Drum Revolution Limits for Central-Mixed Concrete.

US State and Territories	Maximum
Alabama, American Samoa, District of Columbia, Florida, Georgia, Guam, Hawaii, Idaho, Illinois, Iowa, Louisiana, Maryland, Michigan, Mississippi, Missouri, New Hampshire, New Jersey, New Mexico, Oklahoma, Pennsylvania, Texas, Vermont, West Virginia, Wisconsin, Wyoming	300
Alaska, Arizona, Arkansas, California, Colorado, Connecticut, Delaware, Indiana, Kentucky, Maine, Massachusetts, Montana, Nebraska, Nevada, New York, North Carolina, North Dakota, Ohio, Oregon, Rhode Island, South Carolina, South Dakota, Tennessee, Utah, Virginia	N.R.
Minnesota	150
Kansas	200
Washington	250

N.R.: No requirement.

Table 2-3. Truck Drum Revolution Limits for Shrink-Mixed.

US Territories	Minimum	Maximum
Alabama, American Samoa, District of Columbia, Florida, Georgia, Guam, Hawaii, Idaho, Illinois, Iowa, Kansas, Louisiana, Maryland, Michigan, Mississippi, Missouri, New Hampshire, New Jersey, New Mexico, Oklahoma, Pennsylvania, Texas, Vermont, West Virginia, Wisconsin, Wyoming	N.R.	300
Alaska, Arizona, Arkansas, California, Connecticut, Delaware, Indiana, Kentucky, Maine, Massachusetts, Montana, Nebraska, New York, Nevada, North Carolina, North Dakota, Ohio, Oregon, Rhode Island, South Carolina, South Dakota, Tennessee, Utah, Virginia	N.R.	N.R.
Colorado	20	N.R.
Minnesota	N.R.	150
Washington	70	320

N.R.: No requirement.

Table 2-4. Truck Drum Revolution Limits for Truck-Mixed.

US Territories	Minimum	Maximum
Alabama, American Samoa, District of Columbia, Florida, Guam, Hawaii, Idaho, Illinois, Iowa, Maryland, Michigan, Mississippi, Missouri, New Hampshire, New Mexico, Pennsylvania, Texas, Vermont, West Virginia, Wyoming	70 to 100	300
Alaska, Colorado	50 to 100	N.R.
Arizona, Massachusetts, North Dakota	70 to 100	N.R.
Arkansas	70 to 100	300
California	N.R.	250 or 300 with admixtures
Connecticut	60	N.R.
Delaware, Indiana, Montana, Nevada, Rhode Island, South Dakota, Tennessee	70 to 100	N.R.
Georgia,	70 to 150	300
Kansas	70 to 100	300
Kentucky	70	N.R.
Louisiana	70 to 130	300
Maine, Nebraska, Oregon	N.R.	N.R.
Minnesota	50 to 150	150
New Jersey	50 to 100	300
New York	100	N.R.
North Carolina, Ohio, South Carolina, Utah	70	N.R.
Oklahoma	70 to 125	300
Virginia	70 to 125	N.R.
Washington	70	320
Wisconsin	70	300

N.R.: No requirement.

Placing time or revolution limits on concrete mixing and placement can present challenges for contractors, especially when longer transport distances are required. Lobo and Gaynor (2006) noted that except for very soft aggregates, the revolution limits for mixing concrete is of "no practical consequence." The authors also noted that these limits were developed long ago when truck mixers were powered with separate engines that had only one slow mixing speed (6 rotations per minute [rpm]). Modern central plants and truck mixers have the capabilities to mix concrete constituents at significantly higher speeds than the older plants and trucks. The NRMCA approves the use of concrete truck mixers and WSDOT requires that trucks be certified by NRMCA. The NRMCA Truck Mixer Manufacturers Bureau (TMMB) 100-05 Standard—*Truck Mixer, Agitator and Front Discharge Concrete Carrier* (2009) requires that mixing speeds be in the range from 6 to 18 rpm and the agitating speed be not more than 6 rpm. The plant certification requires that truck mixers contain a plate showing mixing speed and that these mixing speeds be in the range of 6 to 18 rpm.

There are clear differences in concrete placement limits between WSDOT, ASTM and AASHTO specifications. Table 2-5 compares the differences between these specifications. Some specifications specify limits as a function of time and/or temperature, some as a function of section size, some as a function of mixing truck DRCs, and some require different combinations of these requirements. These differences in the specifications indicate that a better understanding of the influence of mixing parameters on concrete construction and performance is needed. Research is needed to identify mixing variables that influence RMC construction and performance.

Table 2-5. Comparison of ASTM, ASSHTO, and WSDOT Specification Requirements.

Standards	Maximum Time to Discharge, minutes	Maximum Drum Revolutions	Concrete Placement Temperature Range, °F (°C)	Minimum Concrete Temperature as a Function of Section Size?	Minimum Concrete Temperature Depending on Air Temperature?
ASTM	90	None	40 to 90 (4 to 32)	Yes	No
AASHTO	90	300	50 to 90 (10 to 32)	Yes	Yes
WSDOT	90 to 120	250	55 to 90 (13 to 32)	No	No

2.4 VARIABLES THAT POTENTIALLY INFLUENCE CONCRETE CHARACTERISTICS

The production of RMC, that is, the process of combining aggregate, cement, and water in a rotating drum, may seem to be a trivial task. However, many variables need to be considered to produce quality RMC. This research is focused on determining the influence of mixing parameters; specifically time and truck drum rotation on concrete performance. However, the influence of time and rotation on concrete performance could be dependent on the proportions of constituent materials, the characteristics of the constituent materials, and the environmental conditions during mixing, transport, and placement. To better understand the potential influence of these variables, a review of the literature follows.

2.4.1 Constituent Material Variables

RMC consists of four main constituents: water, cement, coarse aggregate (CA), and fine aggregate (FA). Supplementary cementitious materials (SCMs) and chemical admixtures are also commonly used to enhance concrete performance and reduce cost. Any change in proportion and/or characteristic of these constituent materials may have an effect of the performance of the concrete.

Of the four main constituents, aggregate makes up the bulk of the finished concrete product. Hudson (1999) reported that aggregate accounts for approximately 80 percent of the total volume of concrete and that aggregate characteristics (both fine and coarse) can significantly affect the performance of fresh and hardened concrete. Cement, SCMs and chemical admixtures can also influence fresh and hardened concrete characteristics. Data from Tennis and Bhatty (2006) indicate that different types of cement exhibit different setting times, rates of strength gain, and 28-day compressive strengths. It has been reported that the source of mixing water is rarely a factor in concrete performance as long as it is potable water. Changes in constituent materials can potentially influence mixing and concrete characteristics and how these constituent materials influence the mixing and the fresh and hardened characteristics of RMC is presented next.

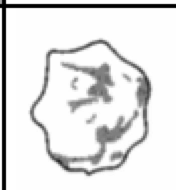
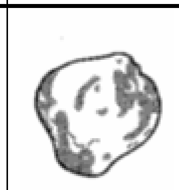
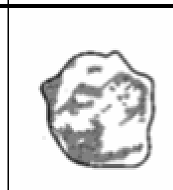
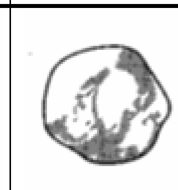
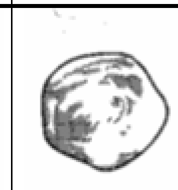
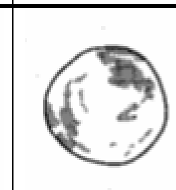
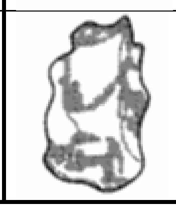
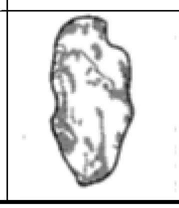
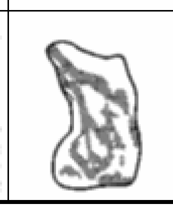
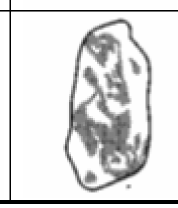
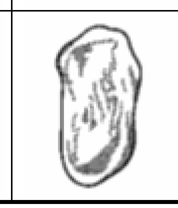
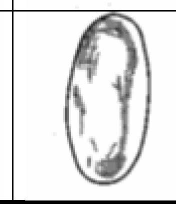
Because aggregate accounts for the majority of RMC, aggregate characteristics could likely significantly affect the fresh and hardened characteristic of concrete. Potentially influencing aggregate characteristics include maximum size aggregate (MSA), gradation, shape and texture, specific gravity (SG), and absorption.

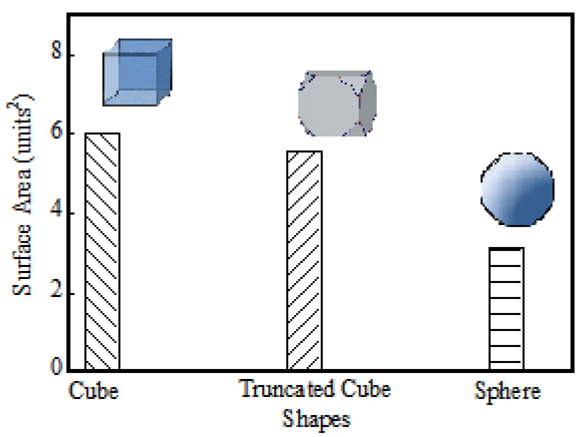
MSA is typically determined by the smallest screen opening which the entire aggregate are required to pass (ASTM 2013 and ACI 2013). MSA has been reported to affect the slump of RMC. Decreasing MSA results in increasing specific surface area. Concrete mixtures with smaller MSA will require higher paste contents to achieve similar workability as mixtures with larger MSA. Previous research has shown that concrete containing 1½ inch (38 mm) MSA requires less water than concrete containing ¾ inch (19 mm) MSA. Washa (1998) reported that because of the smaller specific surface area, larger MSA would lead to better workability for a given paste content. Cannon (2005) also reported that surface area and water requirements decrease with increasing MSA. MSA has also been reported to influence the entrapped air content of RMC. However, small changes in the entrapped air content has relatively little influence on the fresh and hardened characteristic and therefore will not be addressed here. Past research has reported a reduction in compressive strength with increasing aggregate size from ¾ to 1 ½ inch (19 to 38 mm). For a given water to cement ratio (w/c), the compressive strength has been reported to decrease with increasing MSA. Rao et al. (2012) reported that as MSA increases from 0.375 to 1 inch (10 to 25 mm) in a 0.40 w/c mixture (cement content was fixed at 600 lb/yd^3 [356 kg/m^3]), the 28-day compressive strength decreased from approximately 5100 to 4500 psi (35 to 31 MPa). The author provided no information on paste content.

The aggregate gradation is determined by passing aggregate through a series of standard screens with decreasing opening sizes. Gradation would be expected to significantly influence many concrete characteristics such as void content, packing density, and workability because gradation is directly related to surface area. Kosmatka et al. (2002) reported that aggregate void volume decreases when the two aggregate sizes are combined because the smaller aggregate size fills the voids between the larger aggregates. Larger void contents require more cement paste to fill these voids to produce a workable mixture. Aggregate gradation can influence workability of a mixture with a given cement content. Mehta (1993) reported that to produce concrete with good workability, optimal void content should not be the smallest possible void content but a void content somewhat above the minimum. Larrard (1999) and Dewar (1999) reported that there is a clear relationship between grading of aggregates and the voids content of aggregates. Although there is a clear relationship between void content, volume of paste, and workability, there is not a clear relationship between aggregate gradation and concrete strength. Shilstone (1990) reported that concrete containing both well-graded and poorly graded aggregate can achieve similar strengths. However, Cramer et al. (1995) reported that concrete containing well-graded aggregate can achieve increased strengths.

The ASTM D3398—*Standard Test Method for Index of Aggregate Particle Shape and Texture* provides a test method to quantify the shape and texture of an aggregate by establishing a single particle index (PI) number. This number ranges from 1 to 21. A higher PI value indicates a more angular and/or elongated aggregate with a rougher surface. According to Quiroga and Fowler (2003), aggregate can be classified as cubical, spherical, or flat and elongated. Round aggregate have minimal edges and corners whereas angular aggregate have well-defined edges and corners. Table 2-6 shows images of typical aggregate shapes. It has been well established that aggregate shape and texture influence both the fresh and hardened characteristics of concrete and that the effect on fresh characteristics is more significant. Angular, elongated, and rougher surfaced aggregates generally require more paste to produce workable concrete because these aggregates have larger surface areas. Figure 2-6 shows the relative surface area for aggregate shapes. As shown in Figure 2-6, a rounded aggregate has the least surface area. For similar mixtures with the same paste content, the mixtures with rounded aggregate (least surface area) should exhibit the highest workability because less paste is required to cover the smaller surface area of the rounded aggregate. Neville and Brooks (2008) reported that irregular shaped (not round) aggregate results in higher paste demands. In addition, angular, elongated and rough aggregate surfaces can interlock, resulting in higher internal friction between the aggregate, and reduced workability. Quiroga and Fowler (2003) reported that angularity of the CA is related to aggregate void content, and an increase in CA angularity results in increased water demands. Polat et al. (2013) tested slumps of four mixtures with different CA types; the authors reported that the slump of the concretes increased when the CA changed from elongated and flat to rounded. The shape and texture of an aggregate can also influence the hardened concrete characteristics. Neville and Brooks (2008) also stated that concrete containing flat particles yielded lower compressive strengths. Polat et al. (2013) also reported that CA shape has an influence on compressive strength and the concrete containing spherical aggregates produced concrete with higher compressive strengths. In addition, concrete containing flat aggregates resulted in concrete with lower compressive strengths.

Table 2-6. Visual Assessment of Particle Shape (Powers 1953).

		Very Angular	Angular	Sub-angular	Sub-rounded	Rounded	Well Rounded
Sphericity	Higher						
	Lower						



*All surface areas calculated using a maximum edge dimension of 1.

Figure 2-6. Surface Area for Different Aggregate Shapes.

There is little published information on the effect of shape and texture of FA; however, it is believed that the shape and texture can also affect the workability of concrete. Bloem and Gaynor (1963), Wills (1967), and Quiroga et al. (2002) reported shape and texture of FA have an influence on water demand, possibly even greater than that of the CA. Cannon (2005) reported that workability of a mixture is controlled by the flow characteristic of mortar because the total surface area of FA to be covered with paste exceeds that of the CA regardless of the maximum size aggregate. Jarvenpaa (2001) reported that the fine aggregate characteristics have significant influence in compressive strengths.

In addition to shape and texture, other aggregate characteristics may affect the fresh and hardened properties of concrete. Concrete containing aggregate with higher SG can also lead to higher compressive strength. Dobrowolski (1998) reported that poor performance has been observed for concrete containing low specific gravity aggregate such as shale, sandstone, and chert, particularly for concrete in cold climates.

Absorption is another aggregate characteristic that may influence concrete performance. Even though it is not used to proportion a concrete mixture, absorption is used to calculate the amount of water adjustment needed for a mixture. Little research has been done on absorption, but one would expect absorption has an effect on water requirements for a mixture. Sengul et al. (2002) reported that higher absorption results in better bonding between the aggregate and mortar, forcing fracture to occur through the aggregate and resulting in higher compressive strength. Popovics (1998) reported that surface popouts can occur for porous aggregate and aggregate porosity can affect concrete's durability because water in the voids of porous aggregate can freeze causing freeze-thaw damage. However, Forster (1994) stated that the relationship between absorption and freeze-thaw behavior still waits to be proven.

Depending on the desired performance of concrete, SCMs are often used in concrete for cost savings. Most of the SCMs used today are by-products of other industries. The use of these materials in portland cement concrete (PCC) provides many benefits, including making concrete more environmentally friendly, economical and with improved characteristics and properties. The typical SCMs used today are fly ash (Class C and Class F), metakaolin, silica fume, slag, and calcined shale. Literature reviews on Class F fly ash and slag performance are presented in this section as they were evaluated in this research.

Fly ash is a by-product of pulverized coal fired in electric power plants. Fly ash is the most widely used SCM in concrete. Fly ash consists of particles that are mostly spheres but some are hollow cenospherres that range in size between 1 to 100 microns (μm) (39.37 to 3937 μ-inch). Figure 2-7 shows fly ash as observed with a scanning electron microscope.

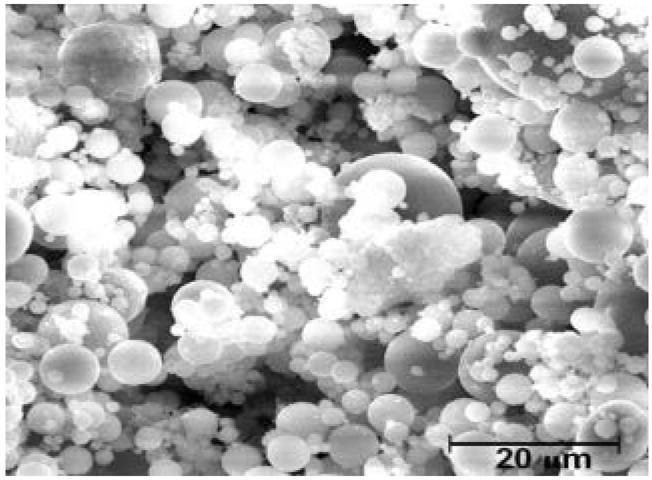


Figure 2-7. Fly Ash As Seen Under a SEM (Prasittisopin and Trejo 2013).

All aspects of concrete properties are affected when fly ash is use in concrete. Pasko and Larson (1962) and Naik and Ramme (1990) reported that when cement is partially replaced with fly ash the water required to produce the same slump can be reduced. This reduction in water is likely a result of the round shaped fly ash particles acting as ball bearings, resulting in a more workable mixture. The addition of fly ash also affects the hardened properties of concrete. Al-Manaseer et al. (1988) reported that increasing fly ash content (up to 50 percent by weight of cement) led to a slower strength gain, however, the 28-day compressive strength of concrete with and without fly ash was approximately the same. Zhang et al. (1999) investigated the effects of Class C and Class F fly ash on concrete strength. The authors reported that when 58 percent of the cement was replaced with fly ash, the 7-, 28-, and 91-day compressive strengths of the mixtures containing the fly ashes decreased when compared to those of the control mixtures.

Ground granulated blast-furnace (GGBF) slag is another widely used SCM. When used in concrete, GGBF slag can typically replace between 30 and 45 percent of the cement.

It has been established from past studies that the use of GGBF slag as a replacement for cement could lead to increased workability. Wood (1981) and Meusel and Rose (1983) reported that concrete containing GGBF slag showed improved workability and placeability when compared with concrete without GGBF slag. With regards to rate of slump loss, Meusul and Rose (1983) reported similar rates of slump loss were observed for mixtures with and without slag (50 percent replacement by weight of cement). Similar to fly ash, GGBF slag can also influence the hardened properties of concrete. Hogan and Meusel (1981) investigated the strength of mortar containing GGBF slag. The authors reported that the compressive strength gain of mortar containing 50 percent GGBF slag varied depending on the grade of the GGBF slag. AASHTO classifies GGBF slag by its reactivity. There are three classes of GGBF (from low reactivity to high): Grade 80, Grade 100, and Grade 120. The authors reported that concrete containing Grade 120 GGBF slag (50 percent replacement by weight of cement) resulted in similar compressive strengths at 1 to 3 days but exhibited increased compressive strengths between 7 and 28 days. At the same replacement level, concrete containing grade 100 GGBF slag resulted in lower strengths up to 21 days after casting and then obtained similar compressive strengths as the concrete without GGBF slag. Concrete containing Grade 80 GGBF slag exhibited lower compressive strengths up to 28 days after casting. Data from Zhang et al. (1999) contradict the results of Hogan and Meusel (1981). Zhang et al (1999) reported that when slag is added to a concrete mixture as a replacement of the cement, the compressive strength of concrete containing slag decreases at 7-, 28-, and 90-days after casting when compared to control specimens (no GGBF slag). It should be noted that the study by Zhang et al. (1999) incorporated 55 percent replacement levels by weight of cement. Even so, this indicates that hardened properties could be dependent on the characteristics of the GGBF slag, which is likely dependent on the source of the slag.

Chemical admixtures are materials used in concrete mixtures other than water, aggregates, cementitious materials, and fiber reinforcement. ACI CT (2013) defines chemical admixtures as materials used to modify the fresh, setting, or hardened properties of a cementitious mixture. Kosmatka et al. (2002) reported that there are 11 different types of admixture: air-entraining admixtures (AEA), water-reducing admixture (WRA), plasticizers, accelerating admixtures, retarding admixtures, hydration-control admixtures, corrosion inhibitors, shrinkage reducers, alkali-silica reactivity inhibitors, coloring admixtures, and miscellaneous admixtures. Miscellaneous admixtures include chemicals to alter the workability, bonding, damp-proofing, permeability reducing, grouting, gas-forming, anti-washout, foaming, and pumpability. Some of these admixtures can accelerate or retard the setting of a mixture, some can reduce water demand while maintaining the mixture's workability, some can introduce air bubbles in the mixture to enhance the long-term hardened properties and there are many other uses for admixtures. It is beyond the scope of this report to review all admixtures available on the market. Only commonly used admixtures that fit the objective of this research are reviewed here. The following sections will provide literature reviews on retarders, water-reducing admixtures (WRAs), and air-entraining admixtures (AEAs).

Kosmatka et al. (2002) reported that hardened concrete containing AEA can exhibit significant improvements in freeze-thaw performance compared to concrete without AEAs. Ghafoori and Barfield (2010) investigated the effects of hauling time on concrete containing AEAs and reported that total air content typically decreases with increasing haul times.

Nehdi and Al-Martini (2009) investigated the coupled effects of prolonged mixing and high temperatures on mixtures containing three different types of WRA: lingosulfonate, naphthalene sulfonate-, and carboxylates. The author's data indicated that longer agitation times (up to 110 minutes) tend to decrease slump. However, all three mixtures containing the different WRAs exhibited significantly less reduction in slump with increasing dosages of WRA. Ravina (1996) compared compressive strength of mixtures with and without WRA when mixed up to 180 minutes. The author's data indicated that for agitating up to 135 minutes, the compressive strength increased linearly but differed for the two different mixtures evaluated. Compressive strength of the mixture without WRA increased 3 percent per 45 minutes of agitating, and 4 to 5 percent for the group containing WRA.

Tuthill (1979) and Ravina Soroka (2002) reported higher slump losses for mixtures containing water reducing and retarding admixtures. Gaynor and Bloem (1962) tested five separate retarders and observed no delay in loss of slump. Vollick (1962) reported that using a WRA and water mixture to retemper the concrete to the original slump resulted in a lower increase in water-cement ratio (w/c) than when water only was added.

2.4.2 Mixing, Transportation, and Handling

Production of concrete can influence the homogeneity and uniformity of the concrete mixtures. The homogeneity and uniformity of concrete mixtures can affect the quality of the end concrete product. Lowke et al. (2005) reported that the degree of homogeneity of a concrete depends on the proportions of the constituent materials in the concrete, the velocity of the mixing tool, the geometry of the mixer, and the mixing sequence. During mixing, interactions between the mixer blade and constituent materials occur, creating a random and complex network of materials within the mixture. To understand the mixing process and its influence on concrete performance, a review of the cement paste system is provided first. This is followed by a review of the influence of concrete mixing.

2.4.2.1 Influence of Mixing Variables on Cement Paste Characteristics

Rheology is the study of flow. Flow properties of cement paste depend on the interaction of cement particles as they pass each other in suspension. The American Petroleum Institute (API) (2002) reported the rheology, thickening time, free water, fluid loss, and compressive strength could be all connected to a single parameter—specific mixing energy (SME). API (2002) reported that all of these properties can be optimized when SME is close to 5.5 KJ/kg (2.25 BTU/lb). The SME for a given mixture can be determined as a function of the mixing speed and mixing time using the following equation:

$$\frac{E}{M} = \frac{(k \times w^2 \times t)}{V} \qquad \text{2-1}$$

where E = Mixing energy (kJ [Btu])

M = Mass of cement paste (kg [lb])

k = Experimental constant = 6.4 x 10^{-9} (N.m/kg.m^3/rpm [pdl.ft/lb.ft^3/rpm])

w = Rotation speed (rpm)

t = Mixing time (minutes)

V = volume of cement paste (m^3 [ft^3])

Vidick and Schlumberger (1990) studied the effect of mixing energy on cement paste characteristics and reported that the most crucial step in mixing cement paste is deflocculation of the cement particles. The authors reported that mixing beyond deflocculation provided no added benefit. Mixing speed was studied by Vlachou and Piau (1997). The authors prepared portland cement (PC) pastes following the API specification (API 2002) and assessed the effect of mixing speed on fresh characteristics. One specimen was mixed and then kept at rest while other specimens were continuously stirred for 18 hours at 150 rpm. The authors assessed the rheology characteristics over an 18-hour period and reported that the setting time for the at-rest specimen was faster and the shear stress increased at a much slower rate when compared with the at-rest sample. SEM and X-Ray diffraction (XRD) studies indicated that mixing inhibits the hydration products from forming bonds, which leads to a more workable mixture for longer times. This research seems to contradict the current limits placed on time and drum revolution counts published in many specifications.

Yang and Jennings (1995) investigated the effects of mixing intensity on rheology and microstructure of cement pastes. The authors varied the mixing intensity by using various mixing methods: mixing paste by hand, mixing with a paddle mixer (ASTM 1998c), and mixing with a high energy mixer. The shear stress for each paste specimen was measured. The authors reported that the paste mixed with the high energy mixer exhibited lower peak shear stresses, indicating that faster mixing leads to better flow. The results from the microstructure study indicated that the pastes mixed by hand and with the paddle mixer exhibited agglomeration of the cement particles. No observable agglomerates were identified in the paste mixed in the high energy mixer.

The effects of increasing mixing energy (higher mixing speeds and longer mixing times) of PC paste was studied by Williams et al. (1999) and Rupnow et al. (2007). The authors reported that increasing the mixing energy improved flowability, decreased agglomeration, and provided greater structure break down. More importantly, the authors reported that when mixing energy reaches a certain level, further mixing was not necessary because the paste had already achieved some optimal homogeneity. Rupnow et al. (2007) also reported that optimal mixing energy varies based on the constituent materials and mixture proportions. The authors also reported that mixtures containing fly ash required less mixing energy to obtain homogeneity than mixtures containing cement only. As for compressive strength, Rupnow et al. (2007) reported that mixing energy had minimum effect on compressive strength. However, the authors did report that faster mixing speeds provide slightly higher compressive strength than that of the mixture mixed at slower mixing speed.

Much of the research in mixing of PC pastes indicates that mixtures will reach a homogeneous state at some minimum energy input and that further mixing adds little or no benefit to the mixtures. However, limited research has been performed to assess if some maximum mixing energy limits exist which could lead to increased heterogeneity of a mixture. It is reasonable to hypothesize that as cement hardens during mixing, the heterogeneity could increase. Figure 2-8 illustrates that there is likely an optimal mixing energy for achieving homogeneity and that over-mixing may reduce homogeneity. This supports the time and drum revolution limits required in many specifications.

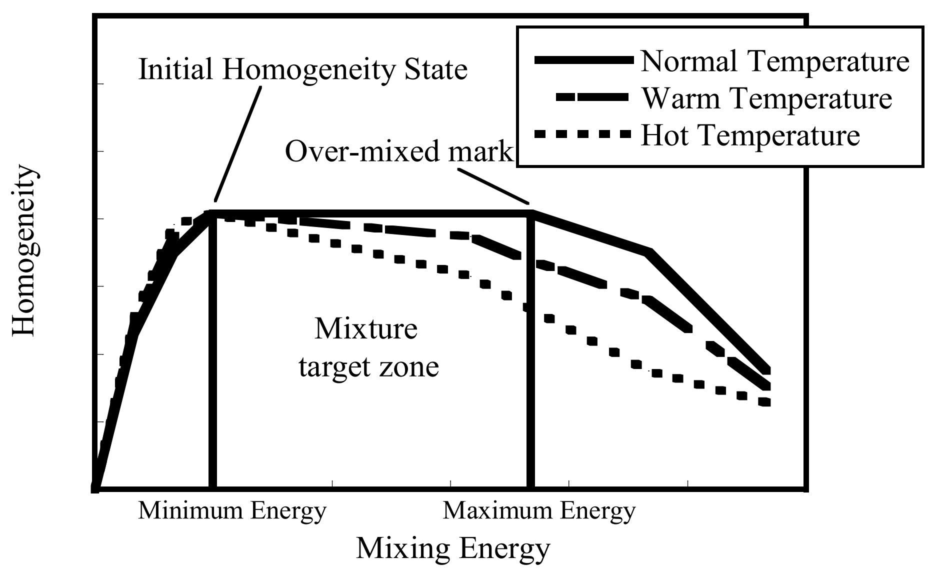


Figure 2-8. Optimal Mixing Zone.

2.4.2.2 Influence of Mixing Variables on RMC Characteristics.

Similar to cement paste, it has been reported that ready-mixed concrete (RMC) could be influenced by mixing variables. Bloem and Gaynor (1971) investigated factors that affect homogeneity of RMC. The authors used data from 200 mixtures and reported that increased number of truck drum revolution counts (TDRCs), increased drum rotation speed (rates higher than 10 rpm), and smaller batch sizes can lead to more homogeneous mixtures. The authors later investigated the effect of concrete truck mixer types on concrete properties and reported that agglomeration of constituent materials inside the concrete truck can result in non-uniformity of the concrete mixture. Gaynor (2006) later recommended mixing at high speeds to prevent agglomeration and to improve homogeneity. However, the author recommended mixing at 20 to 22 rpms, which is faster than the current values specified by NRMCA for truck mixers. Even so, this aligns with the findings reported by Yang and Jennings (1995) that higher mixing speeds result in improved homogeneity of the concrete mixture. Yang and Jennings (1995) reported similar findings for the cement paste.

Beitzel (1981) studied the influence of mixing time on the quality of the concrete. The author defined concrete quality as the uniform distribution of all the concrete constituents. Beitzel (1981) concluded that different concrete properties require different optimum mixing times, and there should be an upper and lower bound on mixing time. Lowke et al. (2005) reported that maximum flowability decreases with increased tool speed and prolonged mixing leads to loss of slump.

In addition to the fresh properties, the hardened properties of concrete as a function of mixing variables have been investigated. Ravina (1996) reported that the 7-, 28-, and 90-day compressive strength increased with increasing mix time up to 135 minutes for various mixtures. The author also noted the strength gain of these mixtures were linear. Kırca et al. (2002) studied the 7- and 28-day compressive strengths as a function of mixing time at a constant mixing speed. The authors reported increases in compressive strength as a function of mixing time and reported that the strength gain was a result of the loss of water due to evaporation, which led to a decrease in w/c ratio. The authors also reported that another possible reason for the increase in strength was that longer mixing times could have resulted in grinding of the cement particles, resulting in finer cement grains and more hydration.

2.4.3 Temperature

Tuthill (1979) reported that temperature has a significant effect on slump loss. A mixture that has no significant problems with slump loss in cold weather could have substantial issues in hot weather conditions. Ravina and Soroka (1994) reported that the rate of slump loss is greater for the mixtures mixed at 90 °F (32 °C) compared to mixtures mixed at 70 °F (21 °C). In addition, mixtures mixed at higher temperatures required more retempering water to revive the slump back to its initial slump. Here, retempering is defined as the addition of water and the remixing of a cementitious mixture to restore the workability to a condition in which the mixture is placeable or usable (ACI CT-13). ACI 304 (2000) reports that mixtures could exhibit slump loss during long distance deliveries in warm weather. In addition to slump loss, Gene (2006) reported that temperature can influence the workability of concrete; higher temperatures result in faster rates of workability loss.

The reason for reduced slump and workability at elevated temperatures is likely due to both the increases in hydration rate and the increases in rate of water evaporation. Nehdi and Al-Martini (2009) investigated changes in RMC properties during delivery under extremely hot weather and reported that concrete can lose about one-third of its initial slump over short durations.

2.4.4 Summary

Placing limits on concrete mixing and placement can present challenges to users, especially when longer traffic time and distance are required. According to Lobo and Gaynor (2006), the revolution limits for mixing concrete, except for very soft aggregates, has no practical consequences. The limits on mixing were established long ago when concrete mixers had only slow mixing-speeds and when synthetic chemical admixtures were not available. Chemical admixtures are now available that can modify and manipulate the characteristics and properties of concrete. Specifications of many state agencies as well as ASTM, AASHTO, and ACI 304R standards still limit time to discharge and truck drum revolutions for ready-mixed concrete. Based on the literature review there is no clear reason for specifying these limits. Research is needed to assess the influence of mixing time and drum revolution on the fresh characteristics and hardened properties of concretes containing different constituent materials.

3. MATERIALS, PROCEDURES, AND MIXTURE PROPORTIONS

3.1 INTRODUCTION

Variations in constituent materials can have a significant influence on the fresh and hardened characteristics of concrete. To ensure results from this research are representative of concrete in the State of Washington, the research team worked with WSDOT personnel to identify constituent materials to be used in the research program. Eleven different coarse aggregates (CA) were selected for the research program. Aggregates were selected based on distinctive characteristics, mainly SG, absorption, and source location. The following sections discuss constituent materials selection, and test procedures used in the laboratory program. The constituent materials evaluated and used in the research program include cement, fly ash, slag, aggregates (FA and CA), and chemical admixtures.

3.2 MATERIALS SOURCE SELECTION

Prior to procurement and characterization of the aggregates, a statistical analysis was performed using CA SG and absorption values from the WSDOT aggregate source approval (ASA) database. The mean and standard deviation (σ) of the SG and absorption were calculated for all approved sources. The SG and absorption of these aggregates were then categorized as low (L), medium (M) and high (H). Here, low is defined as a value less than two standard deviations from the mean ($<2\sigma$), medium is defined as a value within two standard deviations of the mean, and high is defined as a value of two standard deviations above the mean ($>2\sigma$). The researchers' objective was to select CA sources that included a wide range of characteristics. Also, aggregate types were selected from different geographical regions in Washington to ensure representation of aggregate variability. It should be noted that not all conditions are represented in this research. This research attempts to represent most conditions but is limited, as with all research, by time and available resources. Eleven CA sources and two FA sources were procured from throughout Washington. Another fine aggregate (FA) from Knife River (Corvallis, OR) was procured for the research. Figure 3-1 shows the aggregate source locations. Table 3-1 shows the aggregate source availability and their corresponding pit numbers per WSDOT Aggregate Source Approvals (ASA).

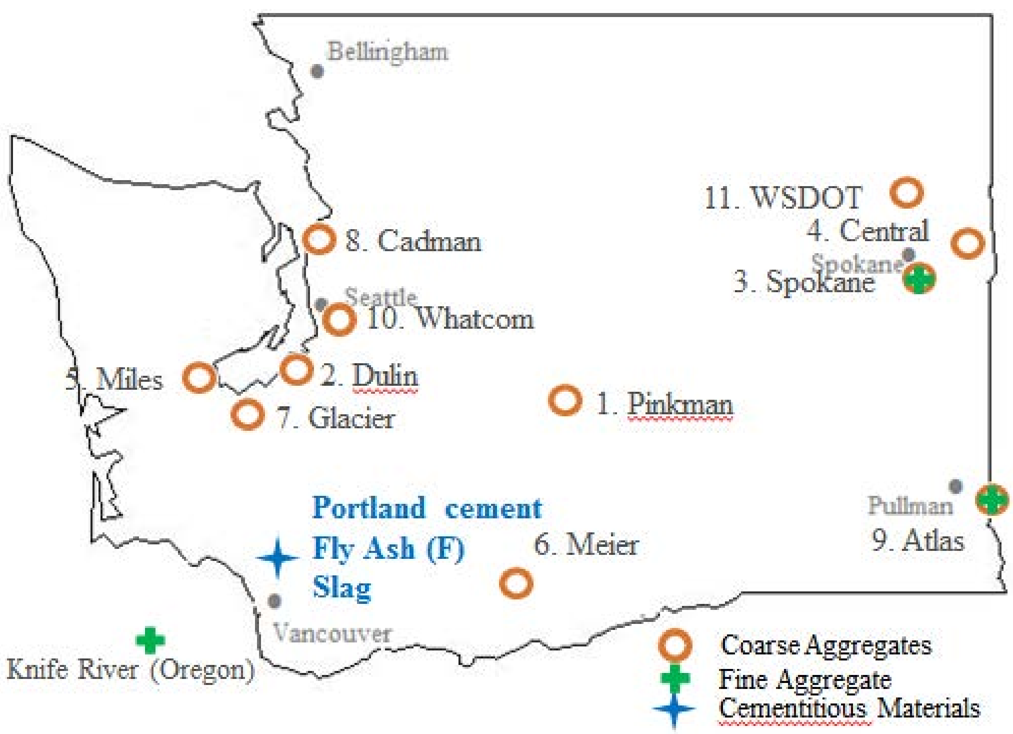


Figure 3-1. Material Sources Locations in the State of Washington.

Table 3-1. Procured Aggregate and Corresponding ASA Pit Number.

Number	Pit Number	Company Name	FA Procured?	CA Procured?
1	E353	Pinkham	No	Yes
2	L231	Dulin	No	Yes
3	C290	Spokane Rock Products	Yes	Yes
4	C173	Central Pre-Mix Concrete Co.	No	Yes
5	X49	Miles Sand & Gravel Co.	No	Yes
6	GT91	Maier's Enterprises	No	Yes
7	B335	Glacier Northwest	No	Yes
8	A460	Cadman, Inc.	No	Yes
9	ID4	Atlas Sand and Rock, Inc.	Yes	Yes
10	F194	Van Boven Gravel Co. (Whatcom)	No	Yes
11	C331	WSDOT	No	Yes

3.3 MATERIALS TEST PROCEDURES AND RESULTS

3.3.1 Cement

Type I/II PC was used for this research. The PC was assessed by the manufacturer following ASTM C114—*Standard Test Methods for Chemical Analysis of Hydraulic Cement.* The oxide analysis of the PC is shown in Table 3-2. The setting time was assessed using ASTM C191—*Standard Test Method for Time of Setting of Hydraulic Cement by Vicat Needle*. Initial setting time of the cement paste at normal consistency (w/c = 0.3) was 135 min and final setting time was 165 minutes. Table 3-7 shows the physical characteristics of the cement used in the laboratory study.

Table 3-2. Chemical Characteristics of Type I/II PC Used in Laboratory Testing.

Chemical Composition	Proportions (%)
SiO_2	20.3
Al_2O_3	4.8
Fe_2O_3	3.5
MgO	0.7
SO_3	2.8
CaO	63.9
Loss on Ignition	2.6
Insoluble Residue	0.11
CO_2	1.8
Limestone	3.2
CaCO3 in Limestone	97.8
Na_{eq}	0.54

Table 3-3. Physical Characteristics of Cement Used in Laboratory Study.

Physical Properties	Result
Blaine Fineness, ft^2/lb (m^2/kg)	1809 (371)
3-day, psi (MPa)	3870 (26.7)
7-day, psi (MPa)	4900 (33.8)
28-day, psi (MPa)	6450 (44.5)
Autoclave expansion (%)	0.02
Air Content of Mortar (%)	8

In addition, the setting time of cement mortar was investigated using Ottawa graded standard sand following ASTM C807—*Standard Test Method for Time of Setting of Hydraulic Cement Mortar by Modified Vicat Needle*. Results indicate that the setting time of the mortar is approximately 140 minutes.

3.3.2 Fly Ash

Class F fly ash is commonly used as a supplementary cementitious material (SCM) in RMC mixtures. Table 3-4 shows the chemical characteristics and Table 3-5 shows the physical characteristics of the fly ash used in the laboratory testing program as reported by the distributor. These values indicate that the fly ash met the Class F fly ash requirement of ASTM C618—*Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*.

Table 3-4. Chemical Characteristics of the Fly Ash Used in Laboratory Study.

Chemical Composition	Proportions (%)
SiO_2	49.4
Al_2O_3	16.4
Fe_2O_3	6.20
MgO	4.60
SO_3	1.00
CaO	13.9
Moisture Content	0.14
Loss on Ignition	0.24
Available $Na_2O_{eq.}$	1.20
Total $Na_2O_{eq.}$	4.79

Table 3-5. Physical Characteristics of the Fly Ash Used in Laboratory Study.

Physical Properties	Result
Fineness, ft^2/lb (m^2/kg)	118 (24.2)
Fineness by No. 325 (45-μm) sieve	3.0
Water Requirement (% of control)	98
Autoclave Expansion (%)	0.02
Density, mg/m^3 (lb/ft^3)	2.55 (159)

3.3.3 GGBF Slag

GGBF slag was also used in this research. Table 3-6 shows the chemical characteristics of the slag. Table 3-7 shows the physical characteristics of the slag. These results were reported by the distributor. The slag meets the physical and chemical requirements of ASTM C989—*Standard Specification for Slag Cement for Use in Concrete and Mortars*.

Table 3-6. Chemical Characteristics of GGBF Slag Used in Laboratory Study.

Chemical Composition	Proportions (%)
SiO_2	31.0
Al_2O_3	12.2
Fe_2O_3	0.8
MgO	4.8
SO_3	1.9
CaO	43.2
TiO_2	0.6
Loss on Ignition	2.1
Inorganic Process Addition	6.0
Sulfide Sulfur (% S)	0.7
Sulfate Ion (% as SO_3)	3.2

Table 3-7. Physical Characteristics of GGBF Slag Used in Laboratory Study.

Physical Properties	Result
Fineness, ft^2/lb (m^2/kg)	2391 (490)
Fineness by 45-µm (No. 325) Sieve	3.7
7-day Compressive Strength, psi (MPa)	3915 (27.0)
28-day Compressive Strength, psi (MPa)	5875 (40.5)
Specific Gravity	2.89
Air Content of Mortar (%)	4.5

3.3.4 Aggregates

3.3.4.1 Fine Aggregate

FA and CA make up the bulk volume of RMC and the characteristic of the aggregates could influence the concrete performance. Characterization tests were performed on all FA. Table 3-8 shows the characteristics and the corresponding test procedures used for the FA.

Table 3-8. Characteristics and Test Standards for FA.

Characteristic	Test Designation
Gradation	ASTM C136—Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
Relative Density and Absorption	ASTM C128—Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate
Aggregate Constituents	ASTM C40—Standard Test Method for Organic Impurities in Fine Aggregates for Concrete
Gradation	ASTM C117—Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
Concrete Aggregate	ASTM C33—Standard Specification for Concrete Aggregates

Figure 3-2 shows the gradation of the FAs used in this research. These gradations meet the requirements of ASTM C33.

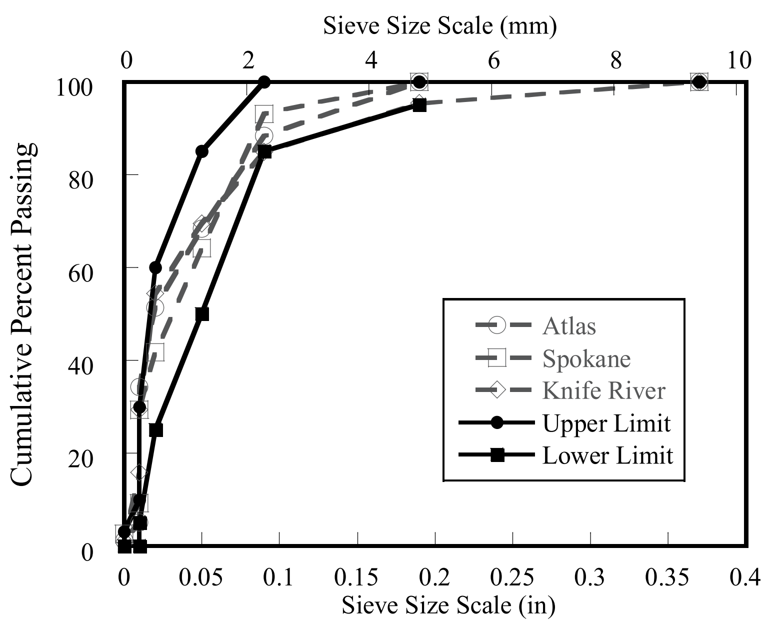


Figure 3-2. ASTM Limits and the Measured FA Gradation.

The SG and absorption of the FA were determined by laboratory testing and used for mixture proportion calculations. Results of SG and absorption tests on the FA as well as the reported values from manufacturers and/or Aggregate Source Approval (ASA) are shown in Table 3-9 and Table 3-10, respectively. Note that some variation was identified, which would be expected.

Table 3-9. Specific Gravity of FA.

Source	Results From Laboratory Testing	ASA Reported Value	Manufacturer Reported Value	Difference Between ASA and Laboratory Testing	Difference Between Manufacturer and Laboratory Testing
Atlas	2.79	2.68	2.68	4%	4%
Spokane	2.47	2.65	2.65	7%	7%
Knife River	2.47	No value	No value	Not applicable	Not applicable

Table 3-10. Absorption of FA.

Source	Results From Laboratory Testing	ASA Reported Value	Manufacturer Reported Value	Difference Between ASA and Laboratory Testing	Difference Between Manufacturer and Laboratory Testing
Atlas	4.9%	1.8%	2.4%	171%	104%
Spokane	3.8%	1.7%	3.0%	124%	27%
Knife River	3.1%	N.A.	N.A.	-	-

N.A.: not available

The amount of deleterious and organic impurities in the FA and the amount of fine particles were determined following ASTM C40, *Standard Test Method for Organic Impurities in Fine Aggregates for Concrete*. Results are shown in Table 3-11 and Table 3-12, respectively.

Table 3-11. Deleterious and Organic Impurities of FA.

Source	C40 Limit	Manufacturer Reported
Atlas	Passed	No color
Spokane	Passed	No value
Knife River	Passed	No value

Table 3-12. Results from Wet Sieving Showing Materials Passing No. 200 Sieve.

Source	Amount of Material Passing No. 200 Sieve by Washing
Atlas	1.20%
Spokane	1.58%
Knife River	1.30%

3.3.4.2 Coarse Aggregate

Similar to FA, CA makes up for a large portion of RMC. As such, characterization tests were performed on all CA used in the research. Table 3-8 shows the characteristics assessed and the corresponding test procedures used to assess the CA.

Table 3-13. Characteristics and Test Standards of CA.

Characteristic	Test Designation
Bulk Density	ASTM C29—Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate
Concrete Aggregate	ASTM C33—Standard Specification for Concrete Aggregates
Gradation	ASTM C117—Standard Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
SG and Absorption	ASTM C127—Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate
Gradation	ASTM C136—Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates
Aggregate Constituents	ASTM C142—Standard Test Method for Clay Lumps and Friable Particles in Aggregates
Particle Shape and Surface Texture	ASTM D3398—Standard Test Method for Index of Aggregate Particle Shape and Texture

The bulk density (unit weight) is defined as the mass of the coarse aggregate required to fill a specified-volume. Bulk density is a function of SG and packability of aggregate and is used for mixture proportioning. The rodding method for consolidation was used in this study. The unit weights of the coarse aggregates are shown in Table 3-14.

Table 3-14. Unit Weights of CA.

Source	Unit Weight lb/ft^3 (kg/m^3)
Central	102.04 (1634.5)
Atlas	100.14 (1604.0)
Spokane	94.18 (1508.6)
WSDOT	95.17 (1524.5)
Dulin	105.16 (1684.5)
Miles	106.04 (1698.5)
Whatcom	104.56 (1674.8)
Pinkham	106.48 (1705.6)
Maier	105.63 (1692.0)
Cadman	101.55 (1626.6)
Glacier NW	107.38 (1720.0)

Figure 3-3 to Figure 3-5 show the gradation and limits of the CA. The sieve analysis for the CA included sieve size #50 (300 µm), #16 (1.18 mm), #8 (2.36 mm), #4 (4.75 mm), $^3/_8$" (9.5 mm), ½" (12.5 mm), ¾" (19 mm), 1" (25 mm) and 1½" (37 mm). Of the 11 selected CAs, one met #56 grading, seven met #57 grading, and three met #67 grading following ASTM C33 limits.

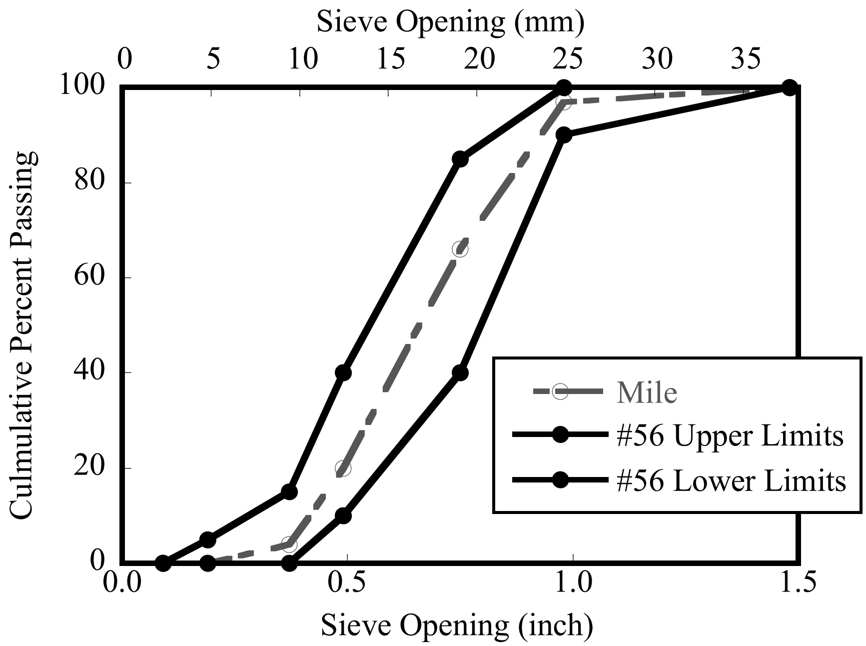


Figure 3-3. Gradation of #56 CA Used in Laboratory Research.

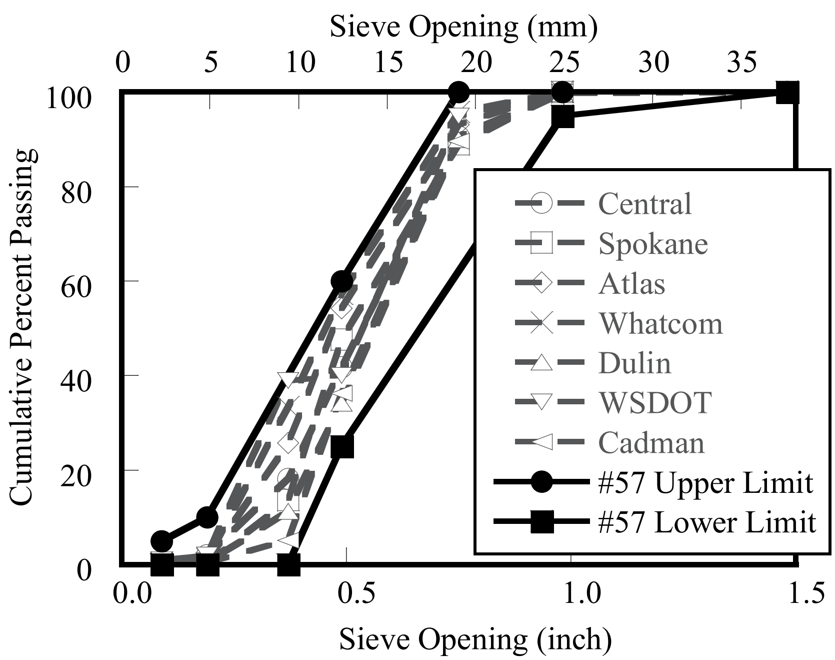


Figure 3-4. Gradation of #57 CA Used in Laboratory Research.

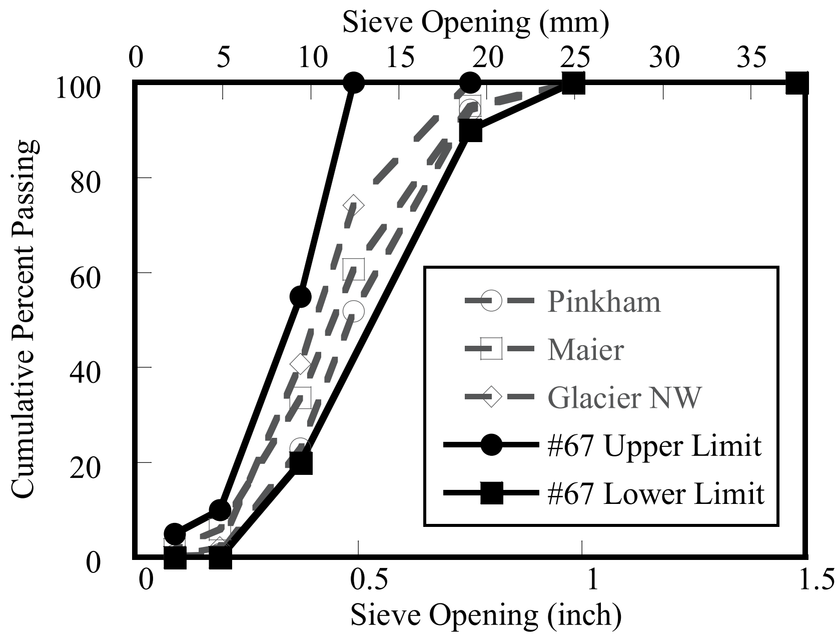


Figure 3-5. Gradation of #67 CA Used in Laboratory Research.

The SG and absorption values of the CA are shown in Table 3-15 and Table 3-16, respectively. The SG and absorption values for the CA were used to determine the mixture proportions per ACI 211.1.

Table 3-15. Specific Gravity of CA.

Source	Results From Laboratory Testing	ASA Reported Value	Manufacturer Reported Value	Difference Between ASA and Laboratory Testing	Difference Between Manufacturer and Laboratory Testing
Central	2.63	2.66	2.60	1%	1%
Atlas	2.71	2.73	2.74	1%	1%
Spokane	2.64	2.72	2.72	3%	3%
WSDOT	2.69	2.83	N.A.	5%	-
Dulin	2.58	2.68	N.A.	4%	-
Miles	2.67	2.77	N.A.	4%	-
Whatcom	2.69	2.78	N.A.	3%	-
Pinkham	2.69	2.71	N.A.	1%	-
Maier	2.82	2.80	N.A.	1%	-
Cadman	2.68	2.70	N.A.	1%	-
Glacier NW	2.68	2.69	2.69	0%	0%

N.A.: not available

Table 3-16. Absorption for CA.

Source	Results From Laboratory Testing	ASA Reported Value	Manufacturer Reported Value	Difference Between ASA and Laboratory Testing	Difference Between Manufacturer and Laboratory Testing
Central	0.9%	1.3%	1.3%	38%	38%
Atlas	1.4%	1.1%	1.7%	27%	18%
Spokane	2.7%	2.8%	2.5%	4%	8%
WSDOT	3.3%	1.9%	1.9%	42%	40%
Dulin	2.0%	1.2%	1.2%	31%	31%
Miles	1.3%	1.1%	1.7%	15%	38%
Whatcom	2.7%	2.8%	2.5%	4%	8%
Pinkham	1.2%	1.3%	N.A.	7%	-
Maier	0.6%	2.0%	N.A.	68%	-
Cadman	1.2%	1.1%	N.A.	3%	-
Glacier NW	0.9%	1.0%	1.2%	8%	33%

N.A.: not available

The amount of clay lumps and friable particles in the CA were assessed following ASTM C142, *Standard Test Method for Clay Lumps and Friable Particles in Aggregates*. This test assesses the undesirable constituents that could negatively influence water requirements, workability, and strength characteristics of RMC mixtures. The results from this testing is shown in Table 3-17.

Table 3-17. Clay Lumps and Friable Particle in CA.

Source	Results From Laboratory Testing	Manufacturer Reported
Central	1.25%	1.00%
Spokane	0.65%	N.A.
Atlas	0.59%	N.A.
Miles	1.21%	N.A.
Dulin	0.26%	N.A.
WSDOT	0.16%	N.A.
Northwest	0.21%	N.A.
Whatcom	0.31%	N.A.
Pinkham	0.96%	N.A.
Maier	0.31%	N.A.
Cadman	0.67%	N.A.
Glacier NW	0.01%	N.A

N.A.: not available

In addition to clay and friable particles, the shape and texture of the CA can also influence concrete characteristics. Particle shape and texture indices of CA were assessed following ASTM D3398, *Standard Test Method for Index of Aggregate Particle Shape and Texture*. Particles that tend to pack better typically result in lower index values. Results of the packing index (PI) values for the different CA used in this research are shown in Table 3-18.

Table 3-18. Particle Shape and Surface Texture and Type of CA.

Source	PI Value	Type
Glacier NW	6.1	Gravel
Dulin	6.2	Gravel
Pinkham	6.5	Gravel
Central	7.1	Gravel
Miles	7.1	Gravel
Maier	8.0	Crushed gravel
Whatcom	9.3	Crushed gravel
Atlas	10.0	Crushed gravel
Spokane	10.9	Crushed aggregate
Cadman	12.3	Crushed aggregate
WSDOT	13.1	Crushed aggregate

3.3.5 Chemical Admixtures

Three types of chemical admixtures (water reducing agent [WRA], retarder, and air-entraining agent [AEA]) were used in the laboratory study. Both Grace Construction Products and BASF Construction Chemicals LLC provided all of the chemical admixtures. Table 3-19 shows the chemical admixtures used in this study.

Table 3-19. Chemical Admixtures Used in This Study.

Chemical Admixtures	Manufacturer	
	BASF	Grace
WRA	Pozzolith 200n	WRDA 64
Retarder	Delvo Stabilizer (referred to as retarder B)	Daratard 17 and Recover (referred to as retarder A)
AEA	MB AE 90	Daravair AT 30

3.4 MIXTURE PROPORTIONS

Typical concrete in the state of Washington is 4000 psi (27.6 MPa) minimum. In consultation with WSDOT, it was determine that this research would focus on a 4000 psi (27.6 MPa) mixture, as this is common mixture used in the state. Specifically, a Class 4000 concrete was identified to be the control of this research. All of the mixtures were proportioned using ACI 211.1—*Standard Practice for Selecting Proportion for Normal, Heavyweight and Mass Concrete*. The absolute volume method was used. Because of the wide range of aggregate characteristics in the state, specifically SG, the initial mixture proportions had to be altered. Following the ACI procedure, the cement, water contents, maximum size aggregate, and target strength was constant for all initial proportions. With different SG values, the proportioning methodology required that the FA/CA change for the different mixtures. Constant paste volumes were maintained for mixtures containing angular CA and rounded CA (different paste volumes for each), and the FA/CA was altered depending on the SG of the CA. After these proportions were determined, trial mixtures were assessed.

It should be noted that a 4000 psi (27.6 MPa) mixture with a 4 inch (101 mm) slump was the target for this research. To achieve this slump, the researchers added or subtracted 10 lbs (4.5 kg) of water to alter the slump in 1 inch (25 mm) increments. The cement content was also modified to maintain the w/c ratio. Although most mixtures only required one modification, in some cases a second addition or subtraction of water and cement was required to achieve the target slump. Mixture proportions for the CA, chemical admixture, and SCM groups are shown in Table 3-20 through Table 3-22.

Table 3-20. CA Group Mixture Proportions for Laboratory Mixtures.

Mixture	Water lb/cy (kg/m^3)	Cement lb/cy (kg/m^3)	CA lb/cy (kg/m^3)	FA lb/cy (kg/m^3)
Pinkham	320 (190)	696 (413)	1725 (1024)	1158 (687)
Dulin	313 (185)	679 (403)	1704 (1011)	1143 (678)
Spokane	348 (206)	756 (449)	1664 (987)	1070 (635)
Central	318 (189)	692 (410)	1653 (981)	1198 (711)
Miles	298 (177)	647 (384)	1718 (1019)	1247 (740)
Maier	340 (202)	739 (437)	1752 (1040)	1124 (667)
GNW	310 (184)	674 (400)	1740 (1032)	1181 (701)
Cadman	310 (184)	674 (400)	1644 (976)	1285 (763)
Atlas	335 (199)	728 (432)	1622 (963)	1201 (713)
Whatcom	310 (184)	674 (400)	1725 (1024)	1297 (770)
WSDOT	340 (202)	739 (439)	1542 (915)	1194 (709)

Table 3-21. Chemical Group Mixture Proportions for Laboratory Mixtures.

Water lb/cy (kg/m^3)	Cement lb/cy (kg/m^3)	CA lb/cy (kg/m^3)	FA lb/cy (kg/m^3)	Chemical Admixture	Chemical Dosage oz (mL)
287 (170)	623 (370)	1725 (1023)	1298 (770)	WRDA64	85 (182)
284 (169)	618 (670)	1725 (1023)	1306 (775)	Pozzolith 200N	51 (141)
289 (171)	628 (373)	1725 (1023)	1289 (765)	Daratard 17	102 (201)
280 (166)	609 (361)	1725 (1023)	1325 (708)	Delvo Stabilizer	77 (181)
285 (169)	619 (368)	1725 (1023)	1304 (774)	Daravair AT 30	14 (73)
297 (176)	648 (383)	1725 (1023)	1253 (743)	MBAE 90	19 (91)

Note: all mixtures use Pinkham CA.

Table 3-22. SCM Group Mixture Proportions for Laboratory Mixtures.

Cement lb/cy (kg/m^3)	SCM	Water lb/cy (kg/m^3)	CA lb/cy (kg/m^3)	FA lb/cy (kg/m^3)	Fly Ash/ Slag lb/cy (kg/m^3)
470 (279)	Fly Ash	270 (160)	1725 (1023)	1345 (798)	118 (69)*
396 (235)	Fly Ash	260 (154)	1725 (1023)	1377 (817)	170 (101)**
539 (320)	Slag	310 (184)	1725 (1023)	1190 (706)	135 (80)*
404 (240)	Slag	310 (184)	1725 (1023)	1181 (702)	270 (160)***

Note: all mixtures use Pinkham CA. *20 percent replacement by weight. **30 percent replacement by weight. ***40 percent replacement by weight.

3.5 SUMMARY

A wide range of CAs and FAs were procured from the State of Washington. These constituent materials were characterized following ASTM standard procedures. All constituent materials met specification requirements for use in concrete in the State of Washington. Material characterization results were compared to those obtained from ASA and/or manufactures. The difference for SG results was minimal. Absorption values reported by the supplier were different from the reported ASA values and different for those determined in this assessment. Although the test standard for assessing adsorption (ASTM C128) has some subjectivity, aggregate sources are not homogeneous and constant and the difference is likely a result of changing sources in the quarries. The test values from laboratory testing will be used for the remainder of this report. Initial mixture proportions were determined following ACI 211.1. Trial mixtures were used to determine the final mixture proportions.

4. EXPERIMENTAL PROGRAM

4.1 INTRODUCTION

When water and cement are combined, a complex set of chemical reactions occur that result in time-dependent changes to the water-cement system. These chemical reactions between the water and cement, termed hydration, result in stiffening of the concrete and later contribute to the strength development and durability of the concrete. The quality of the concrete is dependent on the constituent materials in the concrete mixture, the manner in which the concrete is processed, transported, and placed, and the temperature of the concrete materials and surrounding environment during curing. This research will investigate the effect of conditions after water has been introduced to the cement and until the concrete has been placed. More specifically, this research will investigate the influence of mixing variables on concrete performance. The Portland Cement Association (2002) reports that excessive mixing of concrete may lead to excessive temperature rise, loss of entrained air, lower strength, and higher slump loss. A comprehensive experimental program is performed to determine the influence of mixing variables on concrete performance.

4.2 EXPERIMENTAL PLAN

The research team performed this research in four phases. Phase I included the procurement and characterization of the materials that were used in the research program. Phase II consisted of an extensive laboratory research program. Phase II was performed in two tasks. The objective of the first task (Phase II – Task 1) was to perform a general assessment to identify material, mixture, or environmental characteristics that, upon longer mixing times, different mixing speeds, and/or mixer revolution counts could affect the fresh or hardened characteristics of the concrete. This phase was followed by a second task (Phase 2 – Task 2) that investigated fewer materials, mixtures, and environmental conditions but investigated a larger number of fresh and hardened concrete characteristics. Following Phase II, a field assessment (Phase III) was performed to correlate the laboratory findings with the field findings. Phase IV included analyses, results (Chapters 5 and 6), and documentation of the research findings. A detailed description of each phase and task follow.

4.2.1 Phase I - Material Procurement and Characterization

The objective of this research project is to determine if mixing time, mixer revolution rate, and number of TDRCs influence the characteristics and properties of RMC. RMC is made from a wide variety of constituent materials under various environmental conditions and these variables can affect the characteristics and properties of the RMC. In an ideal world researchers would mix all different material combinations (aggregate type, aggregate size, cement types, SCM, admixtures, and even water) in actual concrete mixing trucks under different environmental conditions for different times and DRCs and would then assess the effect of these variables (material types, truck types, environmental conditions, mixing times, DRCs, etc.) on the constructability, mechanical properties, and durability characteristics of the concretes. The fact is our world is not ideal and time, budget, and reality constraints require that a systematic and cost-effective approach be taken to achieve the goals and objectives of the research.

Phase I of this research includes the procurement and assessment of materials. Eleven CA sources were identified and researchers arranged for the procurement and transport to the laboratories at Oregon State University (OSU). After receiving the materials at the laboratories, materials were characterized as described in Chapter 3 of this report.

4.2.2 Phase II - Experimental Laboratory Test Program

The experimental research consisted of two tasks – one task assessing the effects of several material types and proportions, environmental conditions, mixing time, and DRCs on a select number of early-age and hardened concrete characteristics. This approach allows for an assessment of a large number of materials and conditions such that material and environmental variables that may affect the concrete can be identified and further assessed in the Task 2 test program. Task 2 assessed a fewer number of materials, mixtures, and conditions but with more focus on the variables that were identified in Task 1 as influencing the early-age and hardened characteristics of the concrete.

4.2.2.1 Phase II – Task 1 General Laboratory Investigation

After materials were assessed, the fresh characteristics and hardened mechanical properties of concretes containing the 11 CA were assessed. A Class 4000 concrete mixture was assessed. One type of cement and the conditions shown in Table 4-1 were evaluated. The influence of aggregate type, cement quantity, chemical admixture manufacturer, admixture type, SCM replacement level, and temperature on the characteristics of concrete mixed at different times and drum revolutions was assessed.

Table 4-1. Experimental Plan for Phase II, Task 1.

CA Source	Cement Content	Fly Ash or Slag (%)	Mixing Time (min.)		Temperature °F (°C)
			@ 8 rpm	@ 15 rpm	
1	L, M, H	N	5, 15 & 60	15 & 60	~70 (21)
1	M	N	5, 15 & 60	15 & 60	~70 & 90 (21 & 32)
1	M	(20 & 30)*	5, 15 & 60	15 & 60	~70 (21)
1	M	(20 & 40)**	5, 15 & 60	15 & 60	~70 (21)
1	M	N	5, 15 & 60	15 & 60	~70 (21)
2	M	N	5, 15 & 60	15 & 60	~70 (21)
3	M	N	5, 15 & 60	15 & 60	~70 (21)
4	M	N	5, 15 & 60	15 & 60	~70 (21)
5	M	N	5, 15 & 60	15 & 60	~70 (21)
6	M	N	5, 15 & 60	15 & 60	~70 (21)
7	M	N	5, 15 & 60	15 & 60	~70 (21)
8	M	N	5, 15 & 60	15 & 60	~70 (21)
9	M	N	5, 15 & 60	15 & 60	~70 (21)
10	M	N	5, 15 & 60	15 & 60	~70 (21)
11	M	N	5, 15 & 60	15 & 60	~70 (21)

H: high L: low M: moderate N: none
*fly ash percentage replacement by weight of cement
**slag percentage replacement by weight of cement

Table 4-2. Experimental Plan for Phase II, Task 2.

CA Source	Cement Content	Chemical Admixture Manufacturer				Mixing Time (min.)	
		WRA	AEA	Retarder	Hydration Stabilizer	@ 8 rpm	@ 15 rpm
1	M	A & B	N	N	N	5, 15 & 60	15 & 60
1	M	N	A & B	N	N	5, 15 & 60	15 & 60
1	M	N	N	A & B	N	5, 15 & 60	15 & 60
1	M	N	N	N	N	5, 15, 60, 90 & 180	5, 15, 60, 90 & 180
1	M	N	N	N	A & B	5, 15, 60, 90 & 180	5, 15, 60, 90 & 180
1	M	N	N	B	B	5, 15, 60, 90 & 180	5, 15, 60, 90 & 180

A: Manufacturer A B: Manufacturer B H: high L: low M: moderate N: none
Note: all mixtures mixed at ~70 °F (21°C)

The fresh characteristics of all mixtures were assessed for slump (ASTM C143), slump loss, air content (ASTM C231), and unit weight (ASTM C231). The 28- and 56-day compressive strength values (ASTM C39) were assessed for each mixture and select mixtures were assessed for freeze-thaw performance (ASTM C666) and chloride transport (ASTM C1556). The setting time and temperature of all concrete mixtures were assessed following ASTM C403 and ASTM C1064, respectively. When applicable, the mixing procedure followed ASTM C192—*Standard Test Method for Making and Curing Concrete Test Specimens in the Laboratory.* The researchers assessed the initial setting time for select mixtures for different mixing times. Note that the concrete was mixed for as long as possible without allowing the concrete to set in the mixer.

4.2.2.2 Phase II – Task 2 Detailed Laboratory Investigation

Following the Phase-II Task 1 investigation, the research team assessed the results and identified variables that seemed to influence the fresh and hardened characteristics of concrete mixed for different times and drum revolutions. Knowing these variables, the researchers then generated a comprehensive research plan to further assess the influence of these variables on a wide variety of properties and characteristics. The properties and characteristics evaluated were compressive strength (ASTM C39) at 3, 7, and 28 day, modulus of elasticity (ASTM C469) at 28 days, modulus of rupture (ASTM C78) at 28 days, splitting tensile strength (STS) (ASTM C496) at 28 days, the diffusivity of the concrete following ASTM C1556, and freeze-thaw performance following ASTM C666.

4.2.3 Phase III - Field Assessment

To validate the laboratory findings, the research team worked with a concrete plant. A Class 4000 concrete mixture proportion provided by the plant was mixed in a central mixer and placed in a concrete mixer truck to continue mixing. Mixing was performed at three speeds: 4, 8, and 15 rpm. Samples were taken from the truck at predetermined mixing times (similar to those tested in the laboratory phase). Throughout the field study, environmental conditions were monitored; air content of fresh concrete, concrete temperature, and slump were assessed for each sampling. Specimens were also fabricated to assess the compressive strength, modulus of elasticity, modulus of rupture, splitting tensile strength, and chloride diffusivity.

4.2.4 Phase IV - Data Analysis and Documentation of the Research Findings

Statistical analyses were performed to identify the influence of the material characteristics, processing variables, and temperature on the early-age characteristics, mechanical properties, and durability characteristics. Using the test results and standard statistical analysis techniques, the research team identified potential correlations between constituent materials, mixing processes, and temperature with concrete characteristics.

4.3 METHODOLOGY FOR ANALYSIS

This section consists of methodologies to analyze the fresh and hardened characteristics of the concrete mixtures. Regression models were generated for slump as a function of mixing time and DRCs. These models are developed at the 95 percent confidence interval (CI). Various statistical tests were used in the analyses. The tests include the student t-test and ANOVA test. These tests were used to compare the means of the measured characteristics for the different mixtures types and mixing conditions. Results were analyzed using Minitab 16.1 (State College, PA). Each statistical test used in this research begins by setting up hypotheses (shown later). The p-value is a statistical value output by statistical tests that assesses how much evidence there is to accept or reject the hypothesis at a certain confidence level. Figure 4-1 shows a flow chart for the statistical analysis procedure used in this research. A description of the statistical test used in this research follows.

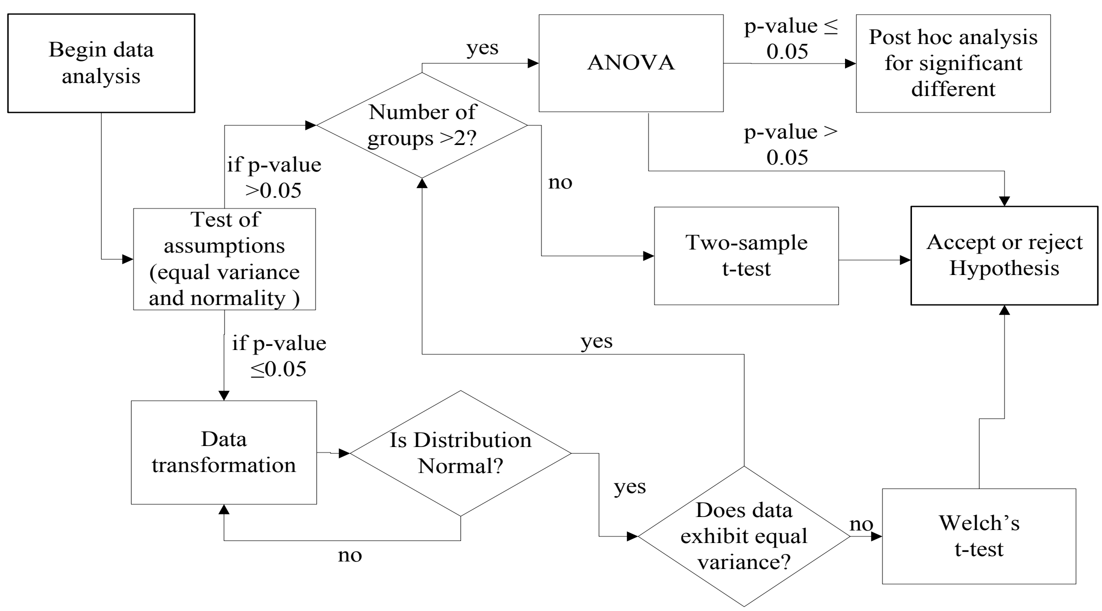


Figure 4-1. Outline for Statistical Analysis.

4.4 STATISTICAL TEST ASSUMPTIONS

The student t-test and ANOVA test are used to compare the means of different data sets. To properly utilize these statistical tests, there are assumptions that data sets should meet, specifically, independence, equal variance and normality. The following presents the test methods can be used to verify these assumptions. Data sets can sometimes be transformed by using arithmetic to meets the assumptions. In cases where assumptions cannot be met despite transformation, other non-parametric statistic tests are used.

4.4.1 Independence

Independency of data sets are achieved at the design stage of a research program with careful planning and experiment setup. All data in this research are independent and randomly obtained from the laboratory and field studies.

4.4.2 Test for Homogeneity of Variance

To assess the equality of variances in different observation groups, Levene's test is used to verify the assumption of equal variance. To use Levene's test, a null (H_0) and alternate (H_a) hypothesis must be defined. For this research the hypotheses are as follows:

$$H_0 : \sigma_i^2 = \sigma_j^2 = ... = \sigma_k^2 \quad (3.1)$$

$$H_a : \sigma_i^2 \neq \sigma_j^2 \text{ for at least one pair } (i, j) \quad (3.2)$$

where σ_x^2 is the variance of data set, x.

The test statistic for Levene's test can be determined as, W_{Levene}:

$$W_{\text{Levene}} = \frac{(N-k)}{(k-1)} \frac{\sum_{i=1}^{k} N_i (\overline{Z}_{i\cdot} - \overline{Z}_{\cdot\cdot})^2}{\sum_{i=1}^{k} \sum_{j=1}^{N_i} (Z_{ij} - Z_{i\cdot})^2} \quad (3.3)$$

where k = the number of different groups

N = the total number of the observations

N_i = the number of observation in the i^{th} group

Y_{ij} = the value of the j^{th} observation in i^{th} group

$$Z_{ij} = \begin{cases} \left|Y_{ij} - \overline{Y_{i\cdot}}\right|, \overline{Y_{i\cdot}} \text{ is the mean of } i^{th} \text{ group} \\ \left|Y_{ij} - \tilde{Y}_{i\cdot}\right|, \tilde{Y}_{i\cdot} \text{ is the median of } i^{th} \text{ group} \end{cases}$$

$Z_{..}$ = the overall mean of all Z_{ij}

$Z_{i.}$ = the overall mean of the Z_{ij} for i^{th} group.

4.4.3 Test for Normality

The normal distribution of data can be assessed for normality using the Ryan-Joiner test. This test is more reliable than the more common Shapiro-Wilk test when sample size is less than 50 observations. The hypotheses for this test are:

H_0 : there is no difference between the distribution of the group and a normal group

H_a : there is a difference between the distribution of the group and a normal group

The test statistic for normality test can be determined as W_{normal}:

$$W_{normal} = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{3.4}$$

where $x_{(i)}$ = the ith order statistic

$$a_i = \frac{m^{T}V^{-1}}{\sqrt{(m^{T}V^{-1}V^{-1}m)}}$$

where m^T = expected value of the order statistics and

V = covariance matrix

4.5 TWO-SAMPLE T-TEST

Independent, two-sample t-testing is used to compare the means of two groups of observations. The population is assumed to be normally distributed, independent, and co-variant. Because the sample sizes in this study are less than 30 and some sample sizes are unequal, a two-sample t-test with pooled variance can be used to compare means of the observed groups. The comparison is used to test two observed groups with the null hypothesis:

$$H_0 : \mu_1 = \mu_2 \tag{3.5}$$

$$H_a : \mu_1 \neq \mu_2 \tag{3.6}$$

The test statistic for this t-test can be determined as, $W_{t\text{-}test}$:

$$W_{t-test} = \frac{\overline{X_1} - \overline{X_2}}{s_{X_2X_1}\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}} \tag{3.7}$$

where $s_{X_1X_2} = \sqrt{\frac{(n_1-1)s^2{}_{X_1} + (n_2-1)s^2{}_{X_2}}{n_1+n_2-2}}$

$\bar{X}$ = average of data set

s = standard deviation

n = number of observations

A p-value can be obtained from statistics tables based on the determined test statistic. A decision on whether to accept or reject the null hypothesis can be made based on the p-value.

4.6 ANALYSIS OF VARIANCE (ANOVA)

ANOVA is a method to observe the different variance in a particular variable. It is interpreted as whether the mean of several groups are the same. Because the sample sizes of each group is less than 30, for this research ANOVA testing is a useful tool and can be used for data that are in groups of two or more. Compared to performing multiple t-tests, this reduces a chance of committing a Type I error, where a true null hypothesis is incorrectly rejected.

The data are considered to be independent, randomly-distributed, and normal and were analyzed using the F-test. The formal comparisons begin with a test of the overall null hypothesis:

$$H_0 : \mu_1 = \mu_2 = ... = \mu_a \tag{3.8}$$

$$H_a : \mu_1 \neq \mu_j \text{ for some } i \neq j \tag{3.9}$$

The test statistic for ANOVA can be determined as, W_{ANOVA},

$$W_{ANOVA} = \frac{\text{MMS between groups}}{\text{MSS within groups}} \qquad (3.10)$$

where MSS = mean sum of squares

A p-value can then be determined and a decision on whether to accept or reject the null hypothesis can be made based on the p-value. In the case that the H_0 is rejected, it can be concluded that the means of group populations are not equal. However, the conclusions from ANOVA tetsing are not specific to the individual groups. The post hoc analysis is used to specify information of each group.

4.7 POST HOC ANALYSIS

Post hoc or pair-wise analysis is an additional analysis of the differences among means to provide specific information on which means are significantly different from each other. The Tukey–Kramer method was used in this study. It compares all possible pairs of means and calculates as the minimum significant difference (MSD). If a greater difference than the MSD is observed between a pair of means, the pair of means is significantly different. This method can be used for the population with both equal and unequal sample sizes and the hypotheses are as follows:

$$H_0 : \mu_i = \mu_j \qquad (3.11)$$

The test statistic can be determined as W_{Tukey},

$$q_s = \frac{Y_A - Y_B}{\text{SE}} \tag{3.12}$$

4.8 LOGARITHMIC TRANSFORMATION

In the case that the assumptions are violated for normality testing and/or equal-variance, logarithmic transformation is used to transform the data. In this study, natural log transformations are used. The transformation generally allows a group of transformed data to be normal and have equal variance.

The transformed data are then tested against assumptions again using Levene and Ryan Joiner tests. If the group of transformed data has normality and equal variance, either two-sample t-test or ANOVA can be used to compare the means. However, if the group of transformed data is normal but does not exhibit equal variances, this group is tested using the Welch's t-test.

4.9 WELCH'S T-TEST

Unequal variance t-test or Welch t-test is used to determine the data with equal variances. It is an adaptation of unpaired two-sample t-test and it is insensitive to equality of the variance apart from whether the sample sizes are the same. The flowchart of statistical analysis is shown in Figure 4-1.

5. LABORATORY RESULTS AND ANALYSIS: EFFECT OF TIME ON CONCRETE CHARACTERISTICS

5.1 RESEARCH OBJECTIVES

Most specifications for the mixing, transportation, and placement of concrete place limits on the time to discharge and number of drum rotations. These limits have been put in place to help ensure the quality and performance of the finished concrete product. However, significant changes in both constituent materials and equipment have occurred since these limits were initially developed in 1933. If these limits do not correlate with workability, constructability, and performance of concrete systems, unnecessary constraints are placed on suppliers and contractors, which can lead to undue risks and higher construction costs. Therefore, the objectives of this research are to determine if existing limits in the WSDOT specifications are applicable to typical concrete mixtures used in the State of Washington and if not, to identify key material, environmental, and mixing variables that can be used to ensure good concrete workability, constructability, and performance (mechanical and durability).

This chapter presents the results from a laboratory study. This research assessed the concrete characteristics of concrete mixtures mixed for different mixing times, different DRCs, and different mixing speeds. Because performance was expected to vary significantly for mixtures with different constituents, the mixtures were grouped. The mixture groups are defined as: 1) mixtures containing each of the 11 different CA; 2) mixtures containing chemical admixtures, and; 3) mixtures containing SCMs. For each group of mixtures, the fresh concrete characteristics assessed included slump, air content of the fresh concrete, unit weight, and concrete temperature. The hardened concrete properties assessed included 28- and 56-day compressive strength, freeze-thaw performance, and chloride diffusivity. Statistical analyses were performed to test for statistical significance and differences in means of various concrete characteristics for the different mix times, DRCs, and mixing speeds on the fresh and hardened concrete characteristics.

Although some research has been performed on the effect of mixing time on concrete, the overall body of knowledge is incomplete and more information is needed to justify existing time limits currently included in many specifications. The influence of mixer speed is assessed. The following sections present information on the influence of mixing time and mixing speed on the fresh and hardened characteristics of three RMC mixture groups. Mixtures containing 11 different CA will be referred to as the CA group and mixtures containing chemical admixtures will be referred to as the admixture group. The chemical admixtures included WRAs, retarders, and AEAs. Mixtures containing Class F fly ash and slag will be referred to as the SCM group. The mixtures containing SCMs were evaluated at two replacement levels.

5.2 INFLUENCE OF MIXING TIME ON FRESH CHARACTERISTICS

5.2.1 Potential Influence of Constituent Material Characteristics on Slump Loss

The influence of CA and FA characteristics and cement content will be analyzed in the following sections.

5.2.1.1 Potential Influence of CA Characteristic

This section will assess if the CA characteristics have an influence on slump loss. Figure 5-2 through Figure 5-5 show the relationships between SG_{CA}, $absorption_{CA}$, PI_{CA}, and CA fineness modulus (FM_{CA}) on the slump loss. The FM_{CA} here is calculated as the sum of the cumulative percent weight retained on the ¾ inch (19 mm), 3/8 inch (9.5 mm), and #4 (4.75 mm) sieve. Larger CA FM values indicate larger average particle size.

The characteristics of the CA can influence the initial slump value of a mixture. Larger CA PI values indicate more angular and rougher surface aggregates. Therefore, a mixture with large CA PI values will typically requires more paste content to act as lubricant to produce concrete with the same slump value when compared to those mixtures containing aggregates with smaller CA PI values. In addition, the FM provides a general measure of the gradation and average particle size of an aggregate. Larger FM values indicate larger average aggregate sizes, smaller surface areas, and generally require lower cement contents for similar slumps. Lastly, because SG_{CA} and SG_{FA} both influence sand content in the mixture proportioning process, these characteristics can indirectly influence initial slump. Although aggregate characteristics can influence initial slump, the mixtures proportions here were modified to achieve a 4 inch (102 mm) slump. What is relevant is whether mixing time influences the rate at which the slump changes.

Figure 5-1 shows the mixing time versus slump for the CA group mixtures. Some mixtures exhibited an increase in slump values when mixed to 15 minutes. This is likely because the initial 5 minutes of mixing at 8 rpm did not produce a homogeneous mixture and the 15 minutes of mixing did. Rupnow et al (2007) reported that different mixtures require different minimum energy inputs to produce homogeneous mixtures. Therefore, the slump loss was calculated using the difference in slump between 15 and 60 minutes only.

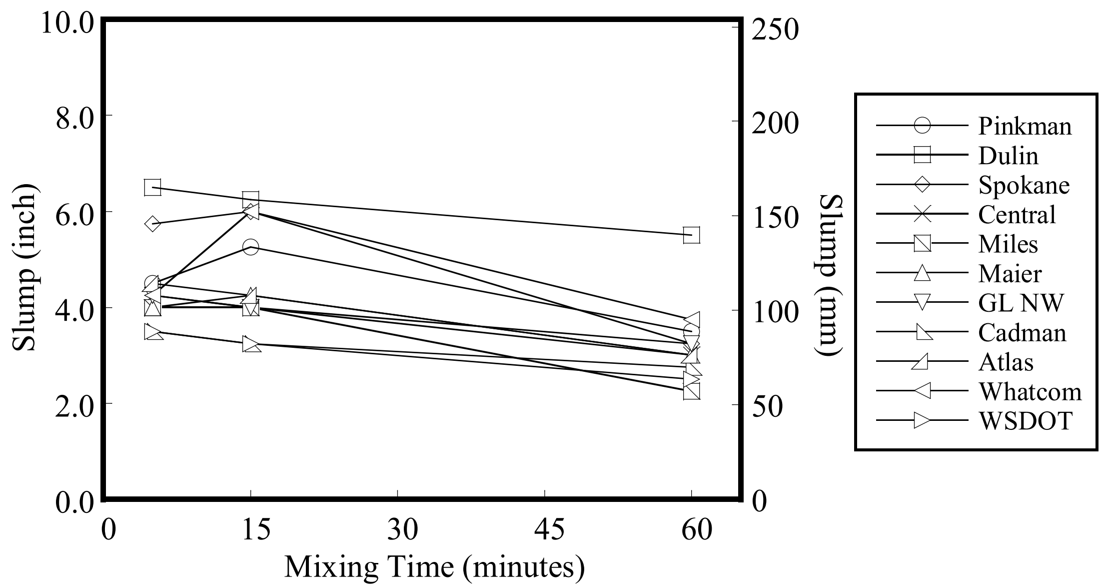


Figure 5-1. Mixing Time versus Slump for the CA Group.

Figure 5-2 shows the SG of the coarse aggregate for the CA mixture group versus slump loss of the mixtures containing those coarse aggregate. As shown in Figure 5-2, SG_{CA} is not significantly correlated with slump loss for mixtures mixed between 15 and 60 minutes of mixing at 8 and 15 rpm. This indicates that slump loss is not dependent on the SG_{CA}.

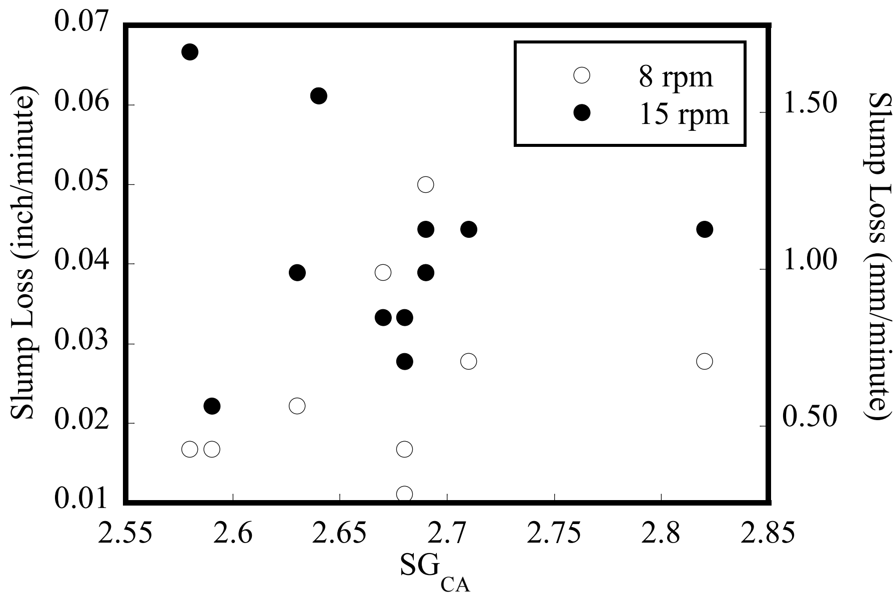


Figure 5-2. SG_{CA} versus Slump Loss.

Figure 5-3 shows coarse aggregate absorption values versus slump loss for mixtures containing those coarse aggregates. Figure 5-3 shows that the $absorption_{CA}$ is not significantly correlated with slump loss for mixtures mixed between 15 and 60 minutes at both mixing speeds (8 and 15 rpm). This also indicates that $absorption_{CA}$ does not significantly influence slump loss.

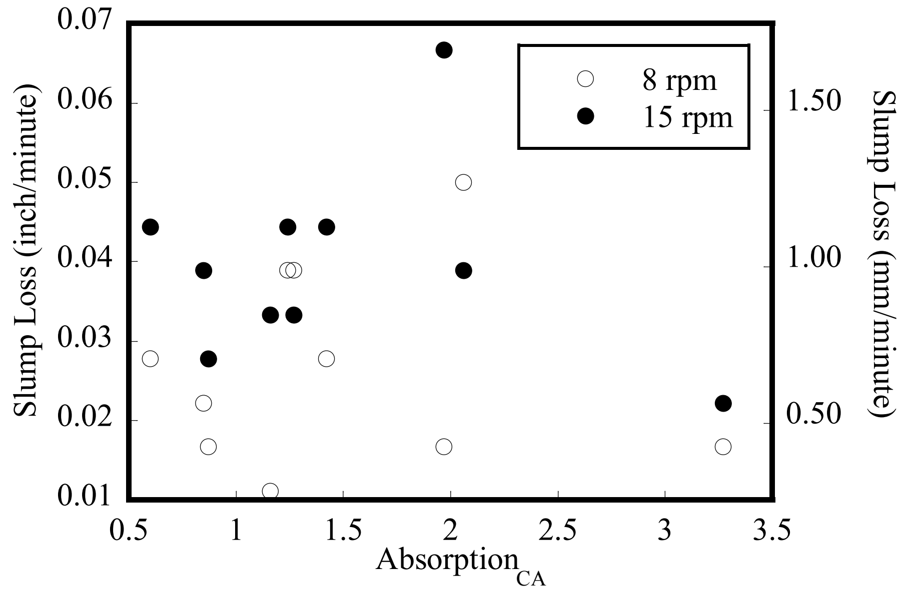


Figure 5-3. Absorption$_{CA}$ versus Slump Loss.

Figure 5-4 shows that the PI$_{CA}$ versus slump loss. Note here that larger values of PI$_{CA}$ indicate a rougher texture and more aggregate angularity. The figure indicates that PI$_{CA}$ is not significantly correlated with slump loss for mixtures mixed for up to 60 minutes at both 8 and 15 rpm. This indicates that PI$_{CA}$ likely has limited influence on slump loss.

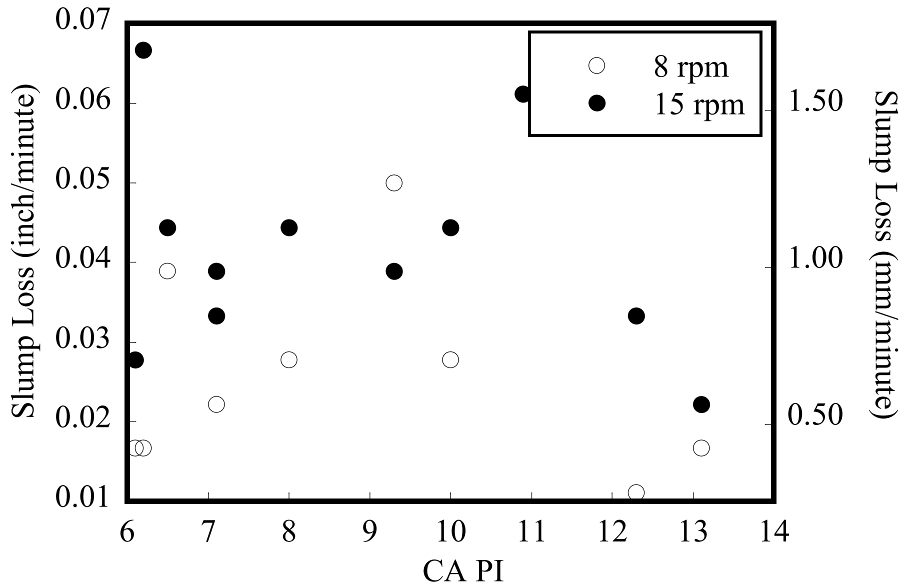


Figure 5-4. CA_{PI} versus Slump Loss.

Figure 5-5 shows the fineness modulus of the CA versus slump loss. The figure shows no correlation between FM_{CA} with slump loss for mixtures mixed between 15 and 60 minutes at both 8 and 15 rpm. This also indicates FM_{CA} is not correlated with slump loss.

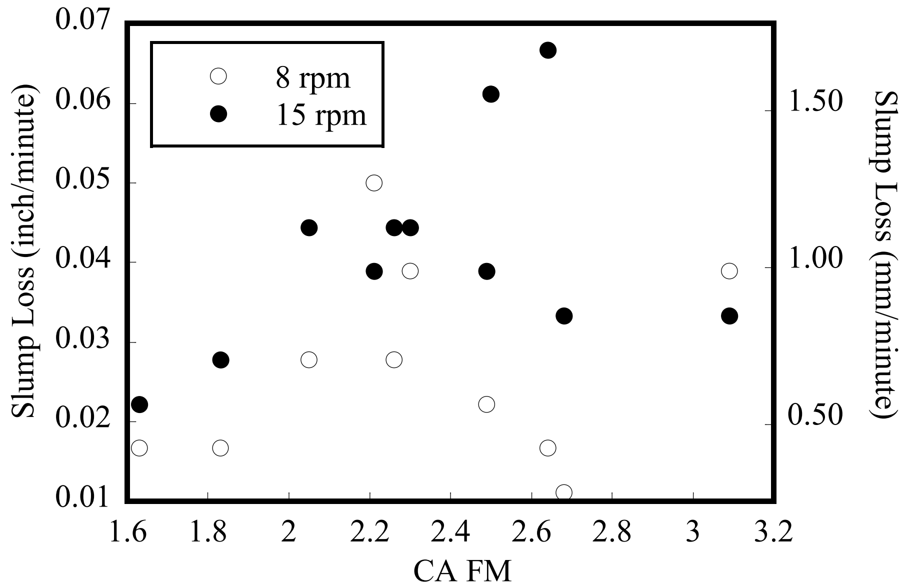


Figure 5-5. CA FM versus Slump Loss.

The results assessing the influence of aggregate characteristics on slump loss indicate that the CA characteristics have little correlation with slump loss. This is not to say that aggregate characteristics do not influence initial slump. It is well known the aggregate characteristics can influence initial slump values. However, in this research the objective was to begin with an initial slump value of 4 inches (102 mm). Because of this, mixture proportions were modified to achieve this initial slump value (see mixture proportioning in Chapter 3). One objective of this research project is to determine if characteristics of constituent materials influence slump loss. This information can be used to model slump loss as a function of mixing time. However, the results indicate that coarse aggregate characteristics do not influence slump loss and these characteristics will not be included in the model.

5.2.1.2 Potential Influence of Fine aggregate Characteristics

Similar to coarse aggregate, the influence of FA characteristics on slump loss weredassessed. The assessed FA characteristics included SG_{FA}, $absorption_{FA,}$ and FM_{FA}. Note that only three fine aggregates were assessed and data from this research are limited. Figure 5-6 through Figure 5-8 show the FA characteristics versus slump loss. This limited information indicates no strong correlation between the SG_{FA}, $absorption_{FA}$, and FM_{FA} and slump loss. Because of the limited correlation between fine aggregate characteristics and slump loss, fine aggregate characteristics will not be included in the model for slump loss.

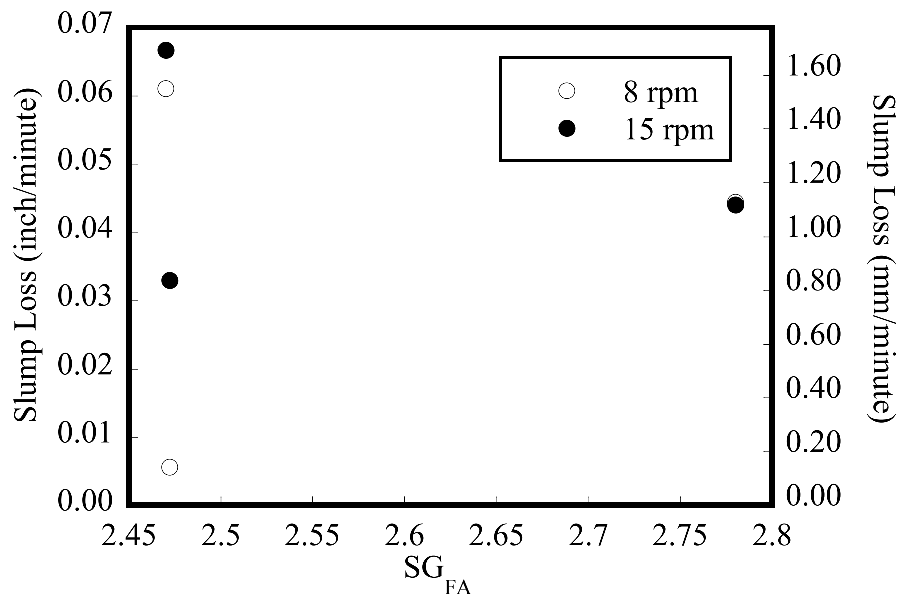


Figure 5-6. SG_{FA} versus Slump Loss.

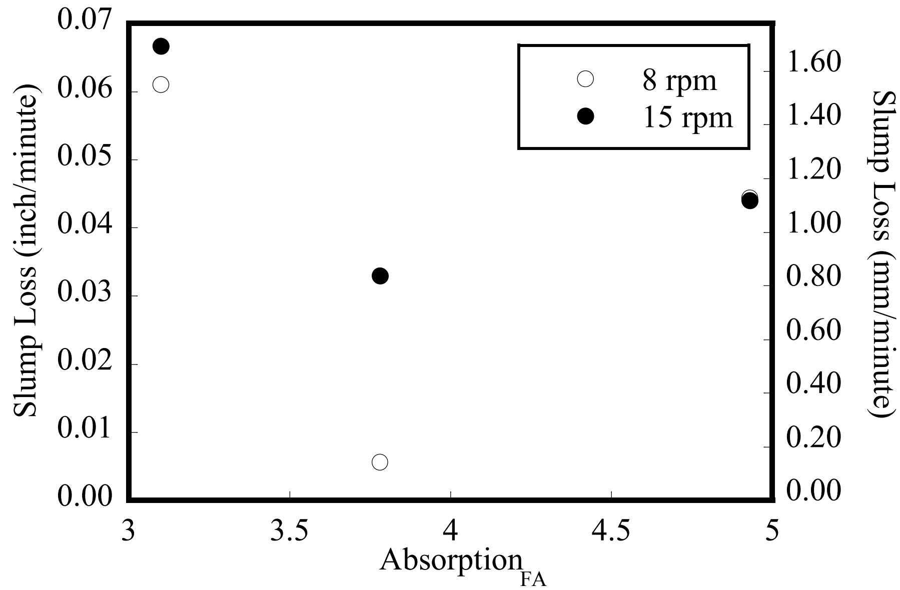


Figure 5-7. Absorption$_{FA}$ versus Slump Loss.

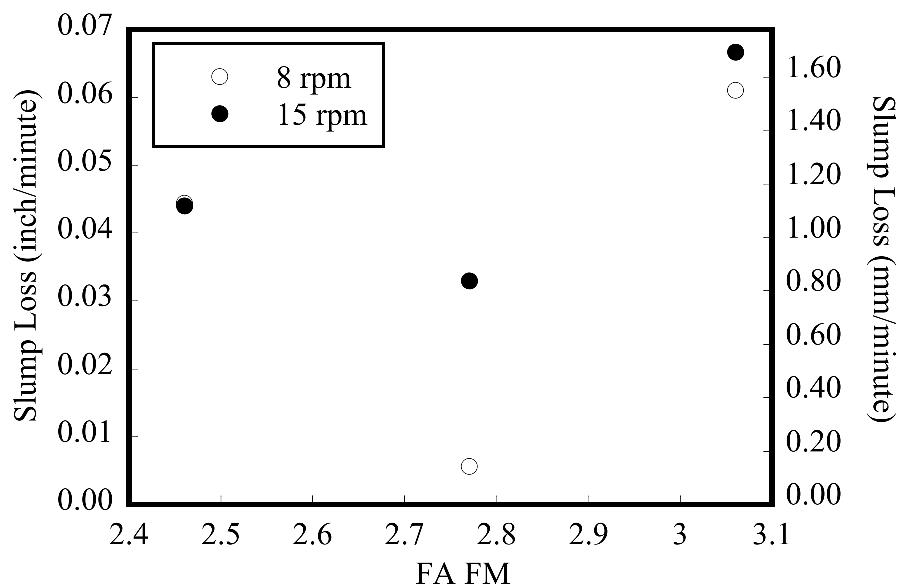


Figure 5-8. FM$_{FA}$ versus Slump Loss.

5.2.1.3 Potential Influence of Cement Content

This section assesses the influence of cement content on the slump loss. Cement contents ranged from 645 to 755 lb/yd^3 (383 to 448 kg/m^3). Because the hydration process is an exothermic reaction (heat generating reaction), it is believed that higher cement contents may lead to higher temperatures that could cause the concrete to stiffen faster (i.e., higher value of slump loss). However, it should be noted that the laboratory mixes were relatively small volumes and temperature of laboratory mixture are likely significantly different than the temperature of field mixtures (larger quantities).

Figure 5-9 shows cement content versus slump loss. As shown in the figure, no strong correlation between cement content and slump loss is observed when mixed at 8 and 15 rpm. Because of the weak correlation for the range and specimen volumes tested, cement content is likely not correlated with slump loss and will not be included in the model of slump loss versus time.

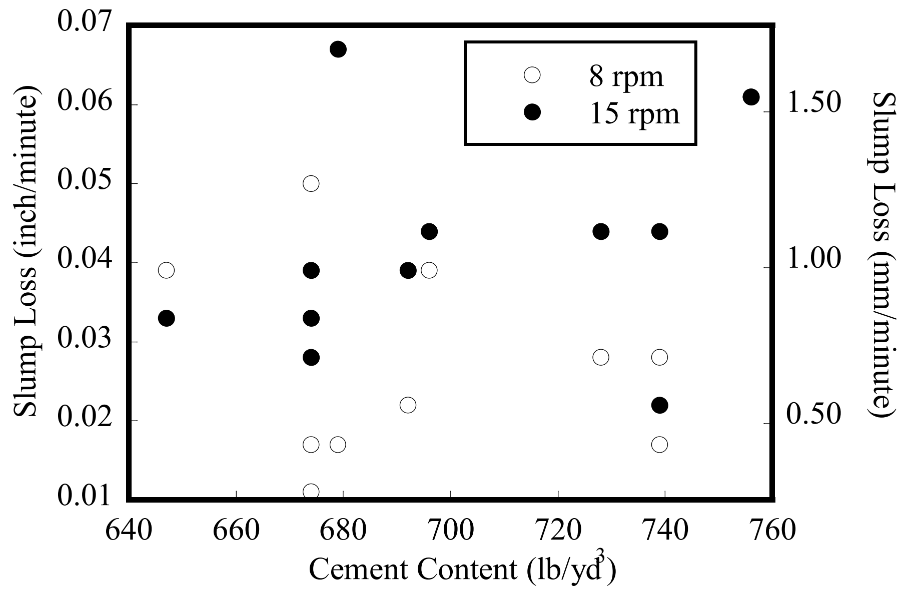


Figure 5-9. Cement Content versus Slump Loss.

The analyses on the influence of constituent materials on slump loss indicate there constituent materials have no significant influence on the slump loss of mixtures mixed in the laboratory.

5.2.2 Potential Influence of Initial Temperature of the Mixtures on Slump

Two concrete mixtures were mixed at different temperatures to assess the influence of constituent materials and fresh concrete temperature on the slump loss of concrete. Constituent material temperatures were maintained at 71 °F (22 °C) and 79 °F (25 °C) prior to mixing. The temperature of the constituent materials were measured at the beginning of each mixing sequence.

These mixtures were mixed for up to 60 minutes at 8 and 15 rpm and the slump was assessed at 5, 15, and 60 minutes. Table 5-1 shows the slump values for these mixtures and Figure 5-10 and Figure 5-11 shows mixing time versus slump values.

Table 5-1. Slump Values for Mixture with Different Initial Temperatures.

Time (minutes)	Initial Temperature °F (°C)			
	8 rpm		15 rpm	
	71 (22)	79 (26)	71 (22)	79 (26)
	Slump, inch (mm)			
5	4.50 (114)	3.75 (95)	4.50 (114)	3.75 (95)
15	5.25 (133)	4.25 (108)	4.25 (108)	3.25 (83)
60	3.50 (89)	2.50 (64)	2.25 (57)	2.25 (57)

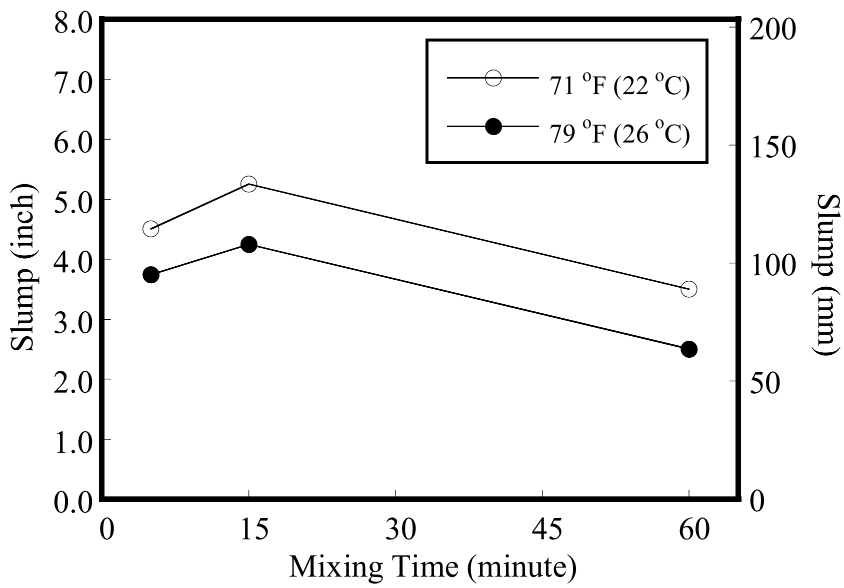


Figure 5-10. Slump Values for Mixtures Mixed at 8 rpm for Different Initial Concrete Temperature and Mixing Times.

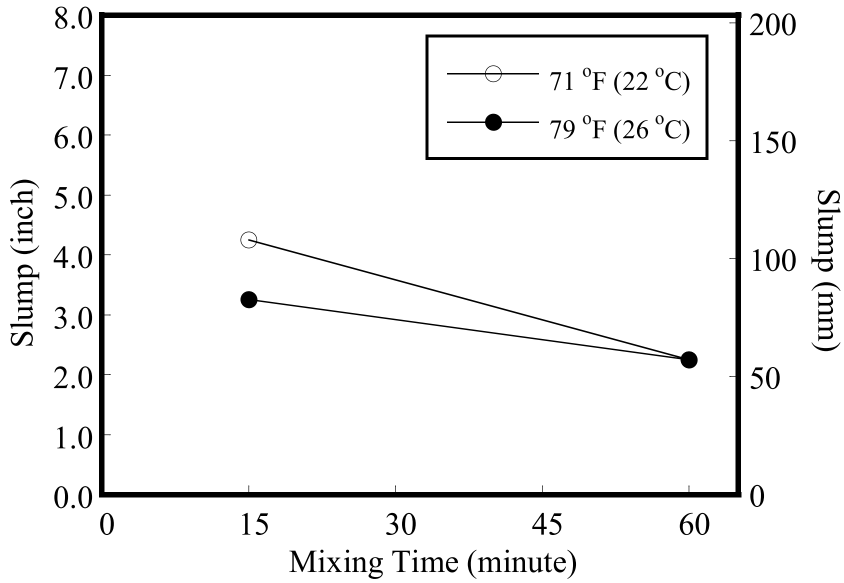


Figure 5-11. Slump Values for Mixtures Mixed at 15 rpm for Mixture with Constituent Materials at Different Initial Temperature and Mixing Times.

For the mixtures mixed at 8 rpm, an increase in temperature of approximately 8 °F (5°C) resulted in an approximated 20 percent decrease in slump at all mixing times. For the mixtures mixed at 15 rpm, the slump at 15 minutes of mixing time was reduced by approximately 25 percent. However, at 60 minutes of mixing, the slump values are similar for both mixtures regardless of the initial temperature. This is likely a result of the heat generated by the faster mixing speed and because mixing was performed in a mixing room at 70 °F (21°C).

The slump reduction factor, R_T, as a function of initial mixture temperature (T_0), when initial mixture temperature increased from 71 °F (22 °C) to 79 °F (25 °C) can be estimated as follows:

$$R_T = 1 - (\frac{T_0 - 71}{8})25\% \tag{5-1}$$

where R_T is the slump reduction factor in percentage and T_0 is the initial temperature between 71 and 79 °F (22 and 26 °C).

The effects of concrete temperature indicate that higher initial mixture temperatures lead to faster initial slump loss. An increase from 71 °F (22 °C) to 79 °F (25 °C) can results in 25 percent loss in slump.

5.2.3 Potential Influence of Mixing Time on Fresh Concrete Characteristics

The following sections assess the influence of mixing time on fresh concrete characteristics including air content, unit weight, temperature, and slump. These sections are followed by a section containing the analyses on the effects of mixing time on hardened properties.

5.2.3.1 Potential Influence of Mixing Time on Air Content

Limited information is available in the literature on the effect of mixing time on the air content of non air-entrained concrete. The following sections assess the influence of mixing time on the entrapped air content of the conventional mixtures (CA group) and mixtures containing SCM and non AEA chemical admixtures. In addition, an assessment is performed to determine the influence of mixing time on the air content of mixtures containing AEA.

CA Group

Table 5-2 shows the entrapped air content values for the CA group mixtures mixed at different times.

Figure 5-12 shows a box plot for these air contents. The box plot shows the mean, the first (25 percent) and third (75 percent) quartiles, and the outliers. Air contents range from 1.1 to 1.9 percent for all mixtures. Because AEA was not used in these mixtures, it was expected that only small changes in the air content would be exhibited. A statistical analysis shows that there is not a statistically significant difference between the means of the entrapped air contents for the CA group mixed for 5, 15, and 60 minutes at the 95 percent confidence level (ANOVA, p-value = 0.560). Results indicate that mixing time has no significant influence on the air content for mixture containing no air entrainment.

Table 5-2. Air Content of Fresh Concrete for CA Group for Different Mixing Time.

Aggregate Source	Fresh Concrete Air Content, %				
	Time of mixing, minute (8 rpm)			Time of mixing, minutes (15 rpm)	
	5	15	60	15	60
Dulin	1.3	1.2	1.4	1.2	1.4
Central	1.6	1.7	1.6	1.5	1.6
Spokane	1.3	1.2	1.5	1.2	1.3
WSDOT	1.0	1.5	1.5	1.5	1.7
Miles	1.4	1.1	1.5	1.1	1.4
Cadman	1.5	1.5	1.4	1.4	1.0
Glacier NW	1.4	1.1	1.6	1.3	1.2
Whatcom	1.1	1.2	1.2	1.0	1.3
Pinkham	1.3	1.9	1.4	1.4	1.7
Atlas	1.4	1.4	1.3	1.4	1.2
Maier	1.7	1.5	1.5	1.5	1.5

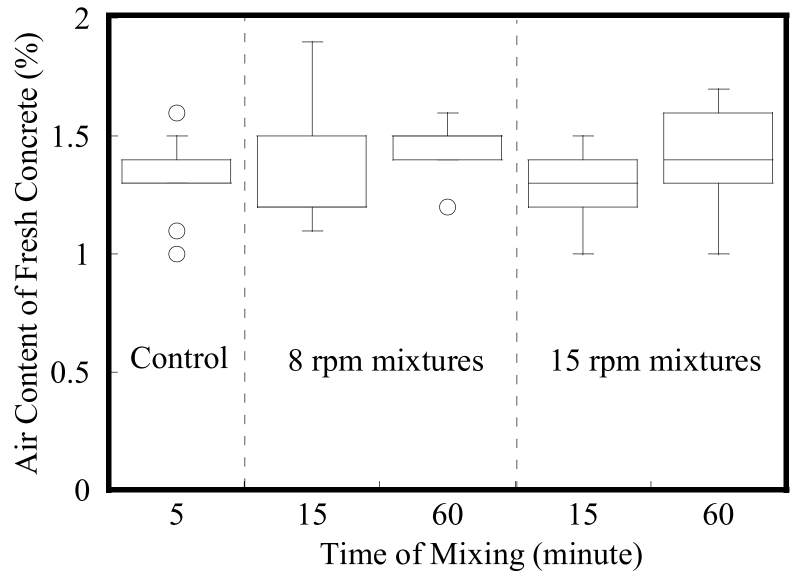


Figure 5-12. Box Plot for Air Content of Fresh Concrete for CA Group.

Admixture Group

The admixture group contains mixtures with WRAs, retarders, and AEAs. For the purposes of assessing air content of fresh concrete, the admixture group is separated into two sub-groups: mixtures with no air-entrainning admixtures and mixtures with AEA. Figure 5-13 and Figure 5-14 show box plots for the air contents of the fresh concrete for both subgroups mixed at 8 rpm and 15 rpm, respectively. For the 8 rpm mixtures, air contents ranged from 0.9 to 2.9 percent for the non-AEA mixtures and 4.6 to 9.0 percent for the AEA mixtures. For the 15 rpm mixtures, air contents ranged from 0.9 to 2.0 percent for the mixtures without AEA and 4.6 to 8.9 percent for the mixtures containing AEA.

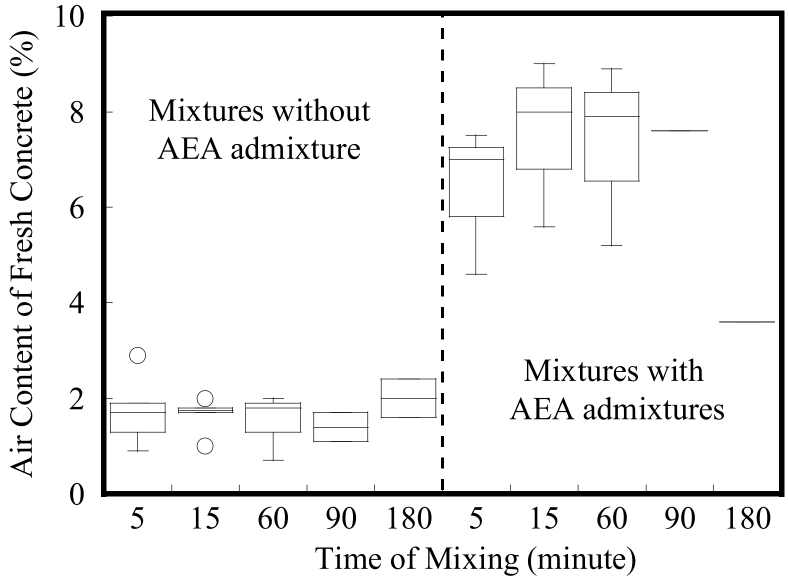


Figure 5-13. Box Plot for Air Content of Fresh Concrete for the Admixture Group Mixed at 8 rpm.

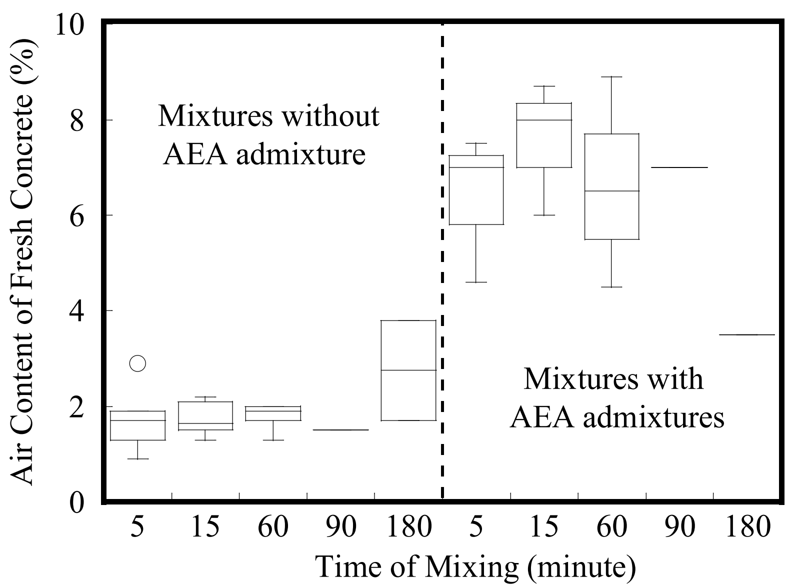


Figure 5-14. Box Plot for Air Content of Fresh Concrete for the Admixture Group Mixed at 15 rpm.

Table 5-3 shows the air content values of fresh concrete for the sub-group with no AEA mixed at 8 rpm and Figure 5-15 shows the box plot for the air content values of these mixtures with no AEA mixed at 8 rpm.

Table 5-3. Concrete Air Content of Fresh Concrete for Non-AEA Subgroup Mixed at 8 rpm.

Admixtures	Air Content of Fresh Concrete, %				
	Time of mix, minute				
	5	15	60	90	180
WRDA 64	0.9	1.8	1.9	N.A.	N.A.
Pozzolith 200N	1.8	1.7	1.7	N.A.	N.A.
Delvo	1.6	1.7	1.9	N.A.	N.A.
Daratard 17	1.9	2.0	2.0	N.A.	N.A.
Recover	1.3	1.0	1.3	1.1	1.6
Delvo (extended time)	2.9	1.80	0.7	1.7	2.4

N.A. = not available.

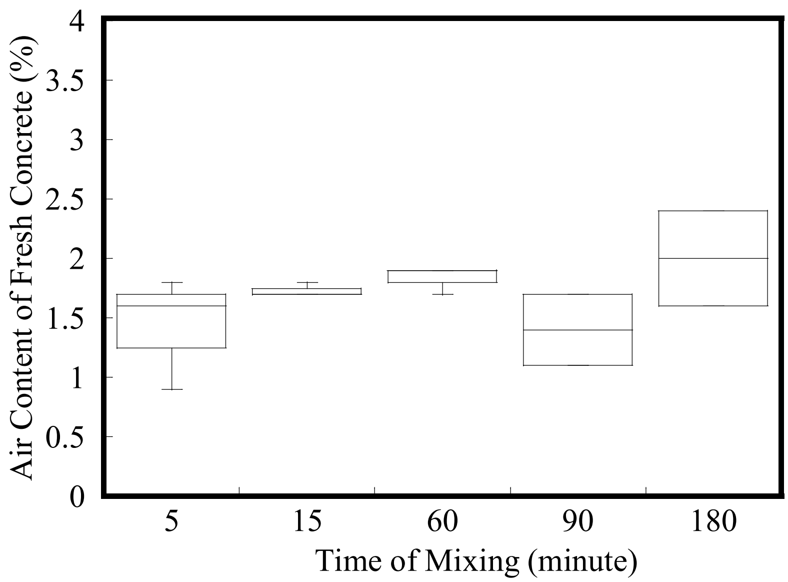


Figure 5-15. Box Plot for Sub-group with no AEA Mixed at 8 rpm.

A statistical analysis for the 8 rpm non-AEA mixtures shows that there is not a statistically significant difference between the means of the air contents of the fresh concrete mixtures for the admixture group mixed for 5, 15, 60, 90, and 180 minutes at 8 rpm (ANOVA, p-value = 0.850, 95 percent confidence level).

Table 5-4 shows the air content of fresh concrete for the sub-group mixtures containing no AEA mixed at 15 rpm and Figure 5-16 shows box plot for these data.

Table 5-4. Concrete Air Content of Fresh Concrete for Non-AEA Subgroup Mixed at 15 rpm.

Admixtures	Air Content of Fresh Concrete, %				
	Time of mix, minute				
	5	15	60	90	180
WRDA 64	N.A.	1.5	1.7	N.A.	N.A.
Pozzolith 200N	N.A.	1.7	1.8	N.A.	N.A.
Delvo	N.A.	1.6	2.0	N.A.	N.A.
Daratard 17	N.A.	2.2	2.0	N.A.	N.A.
Recover	N.A.	1.3	1.3	1.5	1.7
Delvo (extended time)	N.A.	2.1	2.0	1.5	3.8

N.A. = not available.

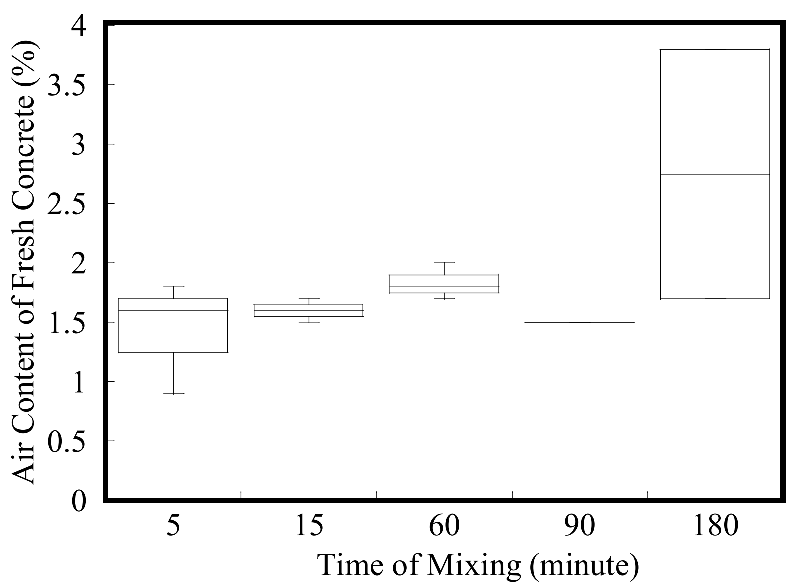


Figure 5-16. Box Plot for Subgroup with no AEA Mixed at 15 rpm.

Similar results were obtained for the non-AEA mixtures mixed at 15 rpm. The statistical analysis indicates that there is no statistically significant difference between the means of the air content of the fresh concrete mixtures for the admixture group mixed for 5, 15, 60, 90 and 180 minutes at the 95 percent confidence level (ANOVA, p-value = 0.399). Note that the air content for the mixtures mixed at 180 minutes exhibits larger variations and higher average air content value. This was caused by stiffening of the mixtures, likely leading to more entrapped air.

Table 5-5 shows the air content values of fresh concrete for the AEA sub-group mixed at 8 rpm and Figure 5-17 shows the box plot for these mixtures.

Table 5-5. Air Content of Fresh Concrete for Mixture Containing AEA Mixed at 8 rpm.

Admixtures	Air Content of Fresh Concrete, %				
	Time of mix, minute				
	5	15	60	90	180
MBAE 90	7.5	8.0	7.9	N.A.	N.A.
Daravair	4.6	5.6	5.2	N.A.	N.A.
Delvo and MBAE 90	7.0	9.0	8.9	7.6	3.6

N.A. = not available.

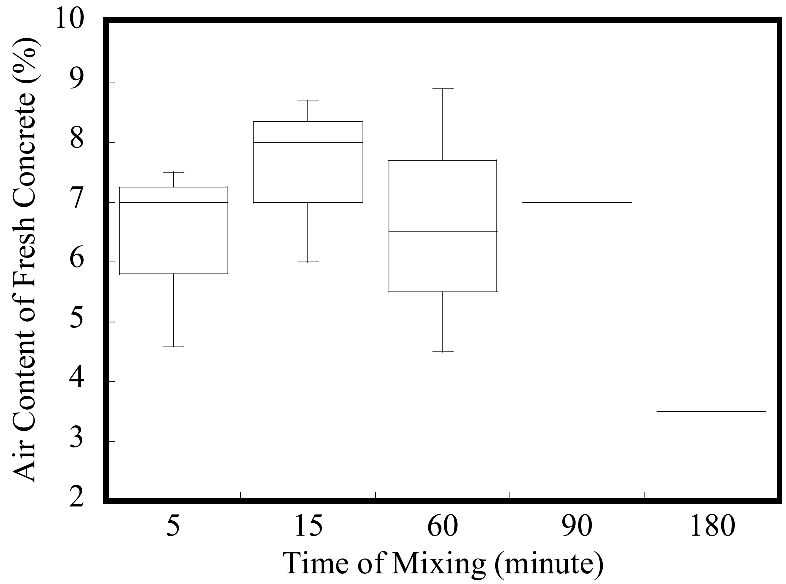


Figure 5-17. Box Plot for Sub-group with AEA Mixed at 8 rpm.

For the mixtures containing AEA, the statistical analysis for the 8 rpm mixtures shows that there is not a statistical significant difference between the means of the air contents for the mixtures mixed for 5, 15 and 60 minutes (ANOVA, p-value = 0.697). The mixtures mixed for 90 and 180 minutes could not be assessed in the statistical analysis because there is only one data point (minimum of three are needed). However, Figure 5-13 clearly shows that the entrained air content decreases when mixed to 90 and 180 minutes (for the single mixture). This indicates that longer mixing time can cause entrained air contents to decrease for mixture containing AEA. For concrete construction projects consisting of air-entrained concrete care must be taken to achieve target air contents.

Table 5-6 shows the air contents for the mixtures containing AEA and mixed at 15 rpm and Figure 5-18 shows the box plot for the same mixtures.

Table 5-6. Air Content of Fresh Concrete for Mixture Containing AEA Mixed at 15 rpm.

Admixtures	Air Content of Fresh Concrete, %				
	Time of mix, minute				
	5	15	60	90	180
MBAE 90	N.A.	8.7	6.5	N.A.	N.A.
Daravair	N.A.	6.0	4.5	N.A.	N.A.
Delvo and MBAE 90	N.A.	8.0	8.9	7.0	3.5

N.A. = not available.

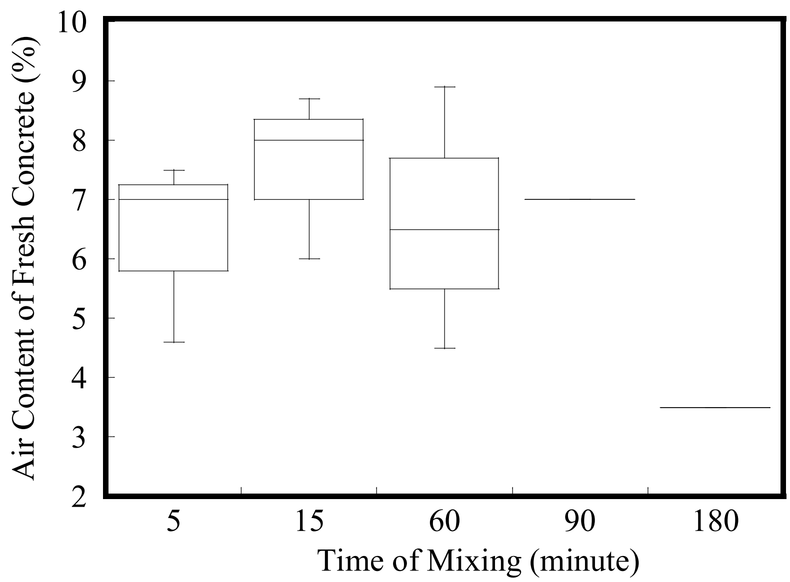


Figure 5-18. Box Plot for Sub-group with no AEA Mixed at 15 rpm.

For mixture containing AEA mixed at 15 rpm, the ANOVA test indicates that there is no significant difference in the means of air content of fresh concrete mixed at 5, 15, and 60 minutes at the 95 percent confidence level (ANOVA, p-value = 0.695). However, Figure 5-14 shows that air content decreases between mixing times of 90 and 180 minutes. This indicates that prolonged mixing times leads to decreases in air content for mixture containing AEA.

The reduction in air content was not observed for mixture with WRAs and retarders. Results indicate that the entrapped air content is not significantly influence by mixing time. However, care must be taken after longer mixing times to ensure larger quantities of air are not entrapped as a result of concrete stiffening. The analyses for the influence of mixing time on entrained air content indicates that prolonged mix time (up to 180 minutes) can lead to decreases in air content at both mixing speed (8 and 15 rpm).

SCM Group

Table 5-7 shows the air content of fresh concrete mixtures for the SCM group. Figure 5-19 shows a box plot for the air contents of the fresh concrete for both mixing speeds. Air contents ranged from 1.0 to 2.0 percent.

Table 5-7. Effect of Mixing Time on Fresh Concrete Air Content for SCM Group.

Mixtures	Air Content of Fresh Concrete, %				
	Time of mix, minute (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
20% slag	1.5	1.2	1.1	1.1	1.3
40% slag	1.5	1.5	1.5	1.6	1.6
20% FA	2.1	1.6	1.0	1.7	2.0
30% FA	1.5	1.9	1.6	1.5	1.8

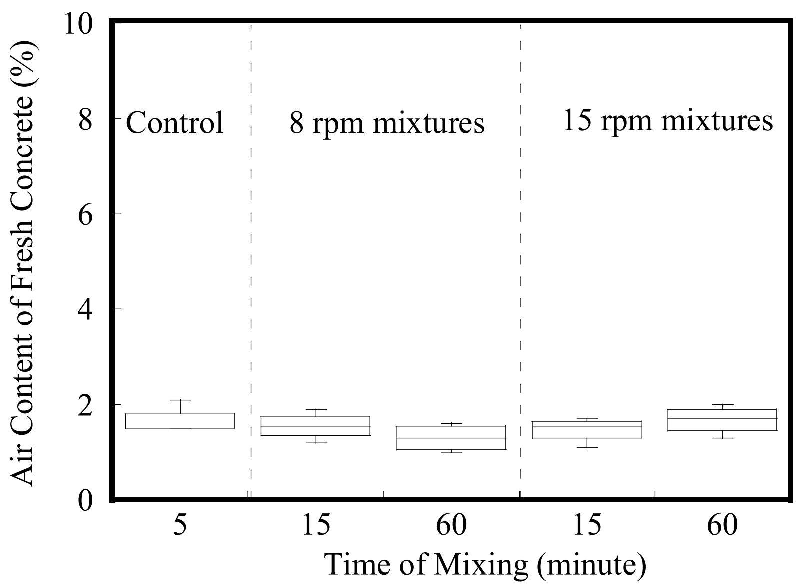


Figure 5-19. Box Plot of Air Content of Fresh Concrete for SCM Group.

For mixing at 8 rpm, statistical analysis indicates that there is not a statistically significant difference in the means of the air content for mixtures mixed for 5, 15 and 60 minutes (ANOVA, p-value = 0.274, 95 percent confidence level). ANOVA tests were used to compare the control (5 minute), 15 and 60 minutes mixtures mixed at 15 rpm. The test indicates no significant difference between the mean air contents for these mixtures (p-value = 0.066, 95 percent confidence level).

5.2.3.2 Potential Influence of Mixing Time on RMC Temperature

Table 5-8 shows the concrete temperature at the time of discharge from the mixer. Figure 5-20 shows the box plot for RMC temperature. The maximum recorded concrete temperature was 82 °F (28 °C) for both mixing speeds. The temperatures at time zero are the weighted average temperatures of all constituent materials prior to mixing (by weight). The largest changes in concrete temperature during the 60 minutes of mixing were 7 and 8 °F (3 and 4 °C) for the 8 and 15 rpm mixtures, respectively.

Table 5-8. Effect of Mixing Time on Concrete Temperature

Aggregate Source	Concrete Temperature, °F (°C)					
	Time of mixing, minute (8 rpm)				Time of mixing, minutes (15 rpm)	
	0	5	15	60	15	60
Dulin	65 (18)	71 (22)	72 (22)	75 (24)	73 (23)	80 (27)
Central	67 (19)	72 (22)	72 (22)	77 (25)	73 (23)	79 (26)
Spokane	67 (19)	72 (22)	72 (22)	76 (24)	75 (24)	85 (29)
WSDOT	72 (22)	75 (24)	76 (24)	82 (28)	77 (25)	82 (28)
Miles	69 (21)	72 (22)	73 (23)	78 (26)	73 (23)	79 (26)
Cadman	65 (18)	71 (22)	73 (23)	80 (27)	74 (23)	79 (26)
Glacier NW	69 (21)	73 (23)	74 (23)	77 (25)	76 (24)	81 (27)
Whatcom	68 (20)	73 (23)	73 (23)	78 (26)	75 (24)	82 (28)
Pinkham	68 (20)	72 (22)	75 (24)	76 (24)	74 (23)	80 (27)
Atlas	68 (20)	71 (22)	73 (23)	77 (25)	73 (23)	81 (27)
Maier	69 (21)	72 (22)	74 (23)	78 (26)	72 (22)	80 (27)

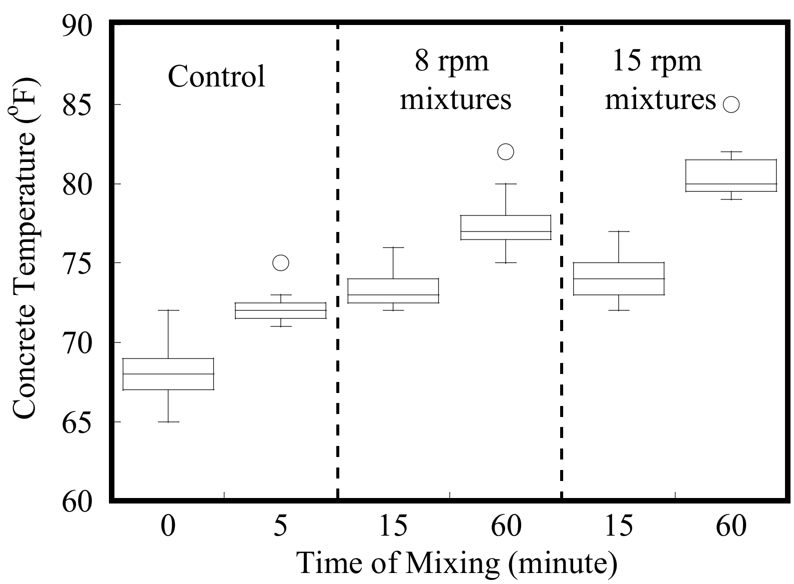


Figure 5-20. Box Plot for Concrete Temperature at the Time of Discharge.

Note that the temperatures were recorded at pre-mix, and 5, 15, and 60 minutes of mixing. To better assess the potential influence of mixing time on concrete temerature change, the changes in temperature per unit time will be assessed. ANOVA testing indicates that there is a statistically significant difference between the mean concrete temperatures for the control temperatures (0 and 5 minutes) and the 8 rpm mixtures (15 and 60 minutes) (p-value = 0.000). In addition, the ANOVA test also indicates that there is a statistically significant difference between the mean concrete temperatures for the control temperatures (0 and 5 minutes) and the 8 rpm mixtures (15 and 60 minutes), (p-value = 0.000). Because of this, the rate of change in temperature will be further assessed.

For the 8 rpm mixtures, the average concrete temperature increase is 0.12 °F/minute (0.07 °C/minutes) when mixed from 5 to 15 minutes and 0.10 °F/minute (0.05 °C/minute) when mixed from 15 to 60 minutes. For the mixtures mixed at 15 rpm, the average concrete temperature rise is 0.19 °F/minute (0.11 °C/minutes) when mixed from 5 to 15 minutes of mixing and 0.15 °F/minute (0.08 °C/minute) when mixed from 15 to 60 minutes of mixing.

Figure 5-21 shows a box plot for the rate of change for concrete temperature for the different mixing times. Because the data distributions do not exhibit equal variance, the median values are compared instead of the mean values. The Kruskal-Wallis Test is used to compare the median rate of change for the different mixing times. The test shows that there is a significant difference in the median value of all concrete temperature rates for the different mixing periods (p-value = 0.000).

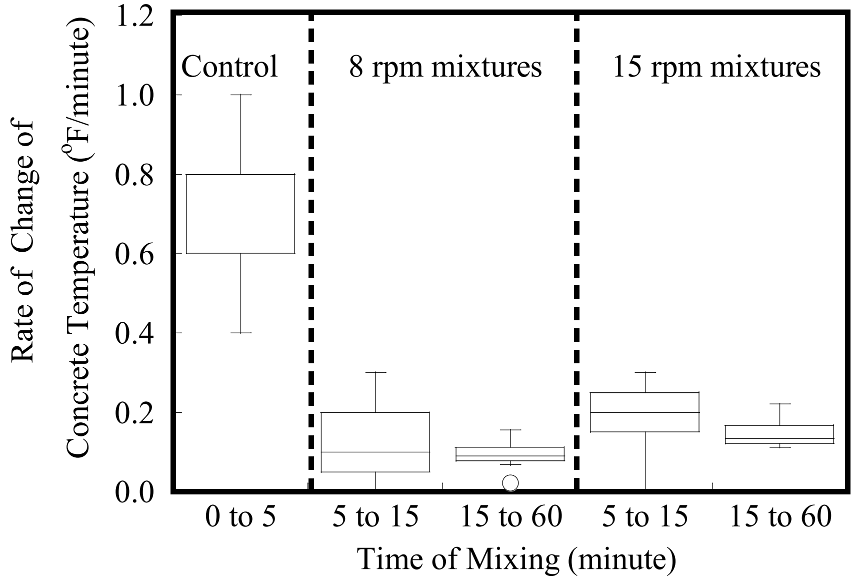


Figure 5-21. Rate of Change for RMC Temperature during Mixing.

Figure 5-21 clearly shows that there is a significantly higher temperature rate from 0 to 5 minutes. This is because of the significant chemical reactions that occur when water is introduced to cement. Because all mixtures were mixed at 8 rpm for the first five minutes, a comparison is needed for the rates between the increments of 5 to 15 minutes and 15 to 60 minute for both speeds (8 and 15 rpm). A t-test assessment indicates that there is no significant difference in the temperature rates between 5 to 15 minutes and 15 to 60 minutes at the 95 percent confidence level for both mixing speeds (p-value = 0.521 and 0.194 for 8 and 15 rpm, respectively). This indicates the rate of temperature change is not significantly influenced by mixing time up to 60 minutes. Figure 5-22 shows a box plot for the rate of concrete temperature for the two mixing speeds (8 and 15 rpm).

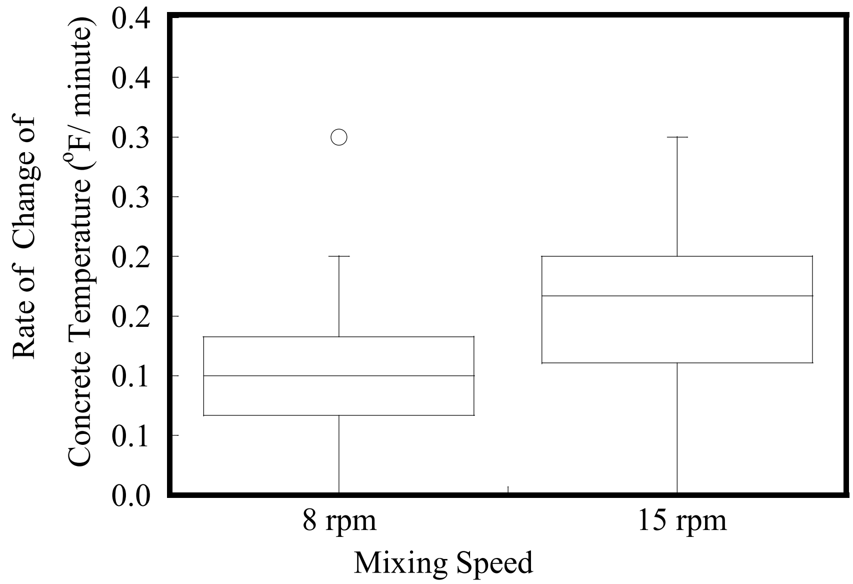


Figure 5-22. Box Plot for Rate of Temperature for Different Mixing Speed.

A t-test assessment indicates that there is a statistical significant difference in the mean rate of temperature between the 8 and 15 rpm mixtures (p-value = 0.007).

5.2.3.3 Potential Influence of Mixing Time on Slump

The concrete mixtures mixed in this research can be classified into three groups: 1) plain concrete (CA group), 2) concrete with chemical admixtures (AD group), and 3) concrete with SCMs (SCM group). Because the quantities of the chemical admixtures can significantly influence the fresh characteristics of the concrete, the AD group is further divided into subgroups: concrete with recommended dosages of admixtures (AD_{rd} subgroup) and concrete with high dosages of admixtures (AD_{hd} subgroup). The slump data for all groups of mixtures are shown in Tables 5-9 through 5-12. All but the AD_{hd} group is designed with a target slump of 4 inches (102 mm). Because of the higher dosages of admixtures used in the AD_{hd} group, the initial average slump values (after mixing for 5 minutes at 8 rpm) are higher than the other two groups.

Table 5-9. Slump Values for CA Group.

CA Sources	Slump, inch (mm)				
	Time of mixing, minutes (8 rpm)			Time of mixing, minutes (15 rpm)	
	5	15	60	15	60
Dulin	6.50 (165)	6.25 (159)	5.50 (140)	5.50 (140)	2.50 (64)
Central	4.25 (108)	4.00 (102)	3.00 (76)	4.00 (102)	2.25 (57)
Spokane	5.75 (146)	6.00 (152)	3.25 (83)	5.50 (140)	2.75 (70)
WSDOT	3.50 (89)	3.25 (83)	2.50 (64)	3.00 (76)	2.00 (51)
Miles	4.00 (102)	4.00 (102)	2.25 (57)	3.25 (83)	1.75 (44)
Cadman	3.50 (89)	3.25 (83)	2.75 (70)	2.75 (70)	1.25 (32)
Glacier NW	4.25 (108)	4.00 (102)	3.25 (83)	3.50 (89)	2.25 (57)
Whatcom	4.25 (108)	6.00 (152)	3.75 (95)	4.50 (114)	2.75(70)
Pinkham	4.50 (114)	5.25 (133)	3.50 (89)	4.25 (108)	2.25 (57)
Atlas	4.50 (114)	4.25 (108)	3.00 (76)	3.75 (95)	1.75 (44)
Maier	4.00 (102)	4.25 (108)	3.00 (76)	4.00 (102)	2.00 (51)

Table 5-10. Slump Values for the Mixtures Containing AD_{rd}.

Mixtures with recommended dosage		Slump, inch (mm)				
		Time of mixing, minutes (8 rpm)	Time of mixing, minutes (8 rpm)		Time of mixing, minutes (15 rpm)	
		5	15	60	15	60
WRA	WRDA 64	4.50 (114)	5.00 (127)	1.75 (44)	1.25 (32)	1.00 (25)
	Pozzolith 200N	3.25 (83)	2.50 (64)	1.00 (25)	2.50 (64)	0.75 (19)
Retarder	Delvo	3.00 (76)	2.75 (70)	1.50 (38)	2.25 (57)	1.00 (25)
	Daratard 17	4.75 (121)	3.75 (95)	1.75 (44)	3.25 (83)	1.00 (25)
AEA	MBAE 90	4.00 (102)	4.00 (102)	4.00 (102)	3.75 (95)	1.75 (44)
	Daravair	4.50 (114)	4.00 (102)	2.25 (57)	3.25 (83)	1.25 (32)

Table 5-11. Slump Values for the Mixture Containing AD_{hd}.

Retarders	Slump, inch (mm)								
	Time of mixing, minutes (8 rpm)					Time of mixing, minutes (15 rpm)			
	5	15	60	90	180	15	60	90	180 or max
Recover	8.25 (210)	9.50 (241)	7.75 (197)	7.50 (191)	2.00 (51)	8.75 (222)	4.25 (108)	0.75 (19)	1.00 (25)*
Delvo	8.00 (203)	8.00 (203)	2.25 (57)	1.50 (38)	0.25 (6)	7.00 (178)	2.00 (51)	1.25 (32)	0.00 (0)
Delvo and MBAE 90	8.50 (216)	6.00 (152)	7.75 (197)	4.25 (108)	0.25 (6)	5.00 (127)	6.50 (165)	5.00 (127)	1.00 (25)

*Mixture mixed to 120 minutes.
N.A.: not available

Table 5-12. Slump Value for the SCM Group Mixtures.

SCM	Slump, inch (mm)				
	Time of Mixing, minutes (8 rpm)			Time of Mixing, minutes (15 rpm)	
	5	15	60	15	60
20% slag	4.25 (108)	5.00 (127)	3.25 (83)	4.25 (108)	2.50 (64)
40% slag	3.75 (114)	4.50 (114)	3.50 (89)	4.00 (102)	2.50 (64)
20% FA	3.25 (83)	3.25 (83)	1.75 (44)	2.75 (70)	1.00 (25)
30% FA	4.50 (121)	4.75 (121)	1.50 (38)	4.00 (102)	1.00 (25)

To assess the slump of the different mixtures, statistical analyses are used. Specifically, the ANOVA test is used to compare slump values of mixtures mixed for the same mixing times. Because the initial slump values of the concretes varied, the slump values are normalized and assessed. The normalized values are referred to as n-slump. The n-slump represents the fraction of the original slump at the time of sampling. If it is determined that the mean slump values for the different mixture groups are not statistically significantly different when mixed under the same conditions (mixing speed and time), data can then be combined and governed by one model. However, if the ANOVA analysis indicates that the means are statistically different, separate models will be developed for each group. Other factors could also lead to not combining data. Table 5-13 and Table 5-14 show the n-slump values for the different groups mixed at 8 and 15 rpm, respectively.

Table 5-13. Normalized Slump for Different Groups of Mixture Mixed at 8 rpm for Different Mixing Times.

Normalized Slump (8 rpm)							
15 minutes				60 minutes			
CA	SCM	AD_{rd}	AD_{hd}	CA	SCM	AD_{rd}	AD_{hd}
1.00	1.18	1.11	1.15	0.56	0.76	0.39	0.94
0.94	1.20	0.77	1.00	0.71	0.93	0.31	0.28
1.04	1.00	0.92	0.71	0.57	0.54	0.50	0.91
0.94	1.06	0.79		0.67	0.33	0.37	
1.41		1.00		0.88		1.00	
0.96		0.89		0.85		0.50	
0.93				0.79			
0.93				0.71			
1.17				0.78			
1.06				0.75			
0.94				0.77			

Table 5-14. Normalized Slump for Different Groups of Mixture Mixed at 15 rpm for Different Mixing Times.

Normalized Slump (15 rpm)							
15 minutes				60 minutes			
CA	SCM	AD_{rd}	AD_{hd}	CA	SCM	AD_{rd}	AD_{hd}
0.813	1.00	0.28	1.061	0.438	0.59	0.22	0.515
0.941	1.07	0.77	0.875	0.529	0.67	0.23	0.250
0.957	0.85	0.75	0.588	0.478	0.31	0.33	0.765
0.833	0.89	0.68		0.389	0.22	0.21	
1.059		0.94		0.647		0.44	
0.846		0.72		0.385		0.28	
0.786				0.357			
0.857				0.571			
0.944				0.500			
1.000				0.500			
0.824				0.529			

Table 5-15 and Table 5-16 show the statistical parameters for the data sets. The tables include the average, standard deviation, and number of samples.

Table 5-15. Statistical Parameters for Data of the Mixtures Mixed at 8 rpm.

Statistical Parameters	8 rpm mixtures							
	15 minutes				60 minutes			
	CA	SCM	AD	RET	CA	SCM	AD	RET
Average	1.03	1.11	0.91	0.95	0.73	0.64	0.51	0.71
Standard Deviation	0.15	0.10	0.13	0.23	0.10	0.26	0.25	0.37
Number of Samples	11	4	6	3	11	4	6	3

Table 5-16. Statistical Parameters for the Data of the Mixtures Mixed at 15 rpm.

Statistical Parameters	15 rpm mixtures							
	15 minutes				60 minutes			
	CA	SCM	AD_{rd}	AD_{hd}	CA	SCM	AD_{rd}	AD_{hd}
Average	0.90	0.95	0.69	0.84	0.48	0.45	0.29	0.51
Standard Deviation	0.09	0.10	0.22	0.24	0.09	0.22	0.09	0.26
Number of Samples	11	4	6	3	11	4	6	3

Table 5-17 through Table 5-20 show ANOVA tables for these groups. Note that Table 5-17 is a comparison of the median values because the CA group data set is not normally distributed. Table 5-18 through Table 5-20 are comparison of means. Each table shows a resulting p-value. P-values of less than 0.05 indicate that there is a statistically significant difference in the mean (or median) of the data sets at the 95 percent confidence level. The results indicate that there is not a statistical difference in the median of the mixtures mixed for 15 minutes at 8 rpm at the 95 percent confidence level (p-value = 0.089). This indicates that the different groups of mixtures (CA, SCM, and AD) mixed for 15 minutes at 8 rpm could be pooled. However, the distribution for the n-slump of the CA group is different than the n-slump values of the SCM and AD groups and these data should not be merged. Also, the other ANOVA tables indicate there is a significant difference between the means of the groups mixed for 15 minutes at 15 rpm (p-value = 0.0126). The means of the groups mixed for 60 minutes at 15 rpm also exhibit a statistically significant difference at the 95 percent confidence level (p-value = 0.0125). Figure 5-23 shows a box plot for all mixtures mixed at 8 and 15 rpm. Because of the different distribution and different mean or median values, separate models will be developed for each group.

Table 5-17. ANOVA Test Comparison Between the Group Mixed for 15 minutes at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.100	2	0.0500	2.77	0.0895
Within groups	0.325	18	0.0180		
Total	0.425	20			

Sum of squares: the sum of the squares of the difference between the group mean and the measured values
Df: degrees of freedom
Mean square: sum of squares/Df
F-ratio: ratio of the mean squares (between groups/within groups)

Table 5-18. ANOVA Test Comparison Between the Group Mixed for 60 minutes at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.187	2	0.0936	2.71	0.0939
Within groups	0.622	18	0.0345		
Total	0.809	20			

Table 5-19. ANOVA Test Comparison Between the Group Mixed for 15 minutes at 15 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.219	2	0.109	5.64	0.0126
Within groups	0.349	18	0.0194		
Total	0.569	20			

Table 5-20. ANOVA Test Comparison Between the Group Mixed for 60 minutes at 15 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.159483	2	0.0797	5.65	0.0125
Within groups	0.254098	18	0.0141		
Total	0.413581	20			

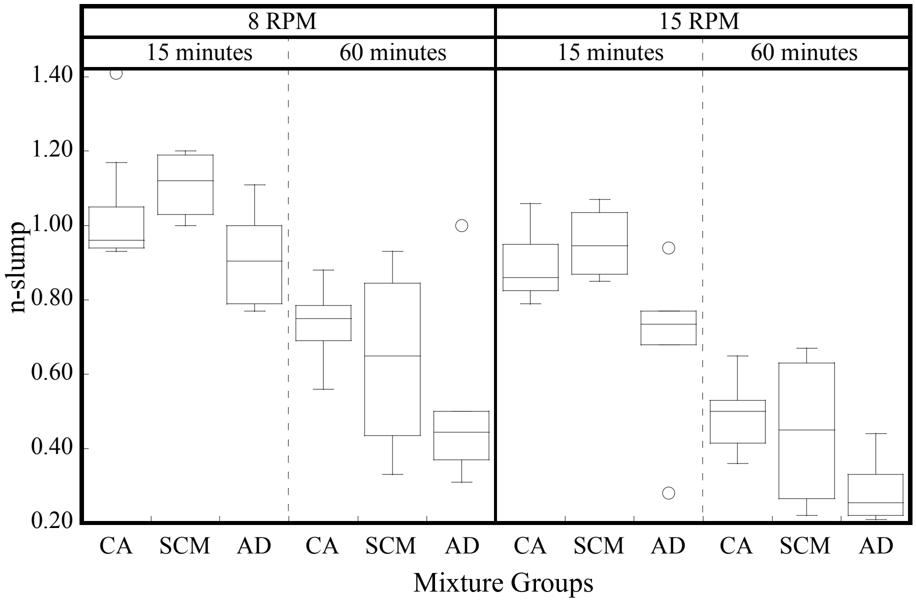


Figure 5-23. Box Plot for the 8 and 15 rpm Mixtures Mixed for 15 and 60 Minutes.

Model Development for CA Group Mixtures

Figure 5-24 and Figure 5-25 show the slump values as a function of mixing time for the CA group mixtures when mixed at 8 and 15 rpm, respectively.

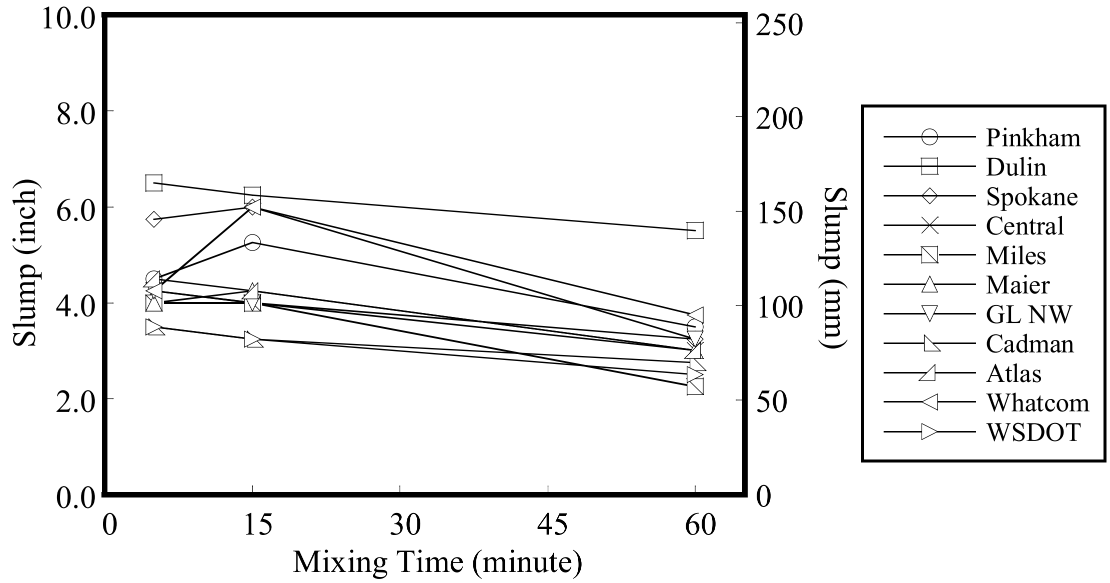


Figure 5-24. Mixing Time Versus Slump for the CA Group Mixtures (8 rpm).

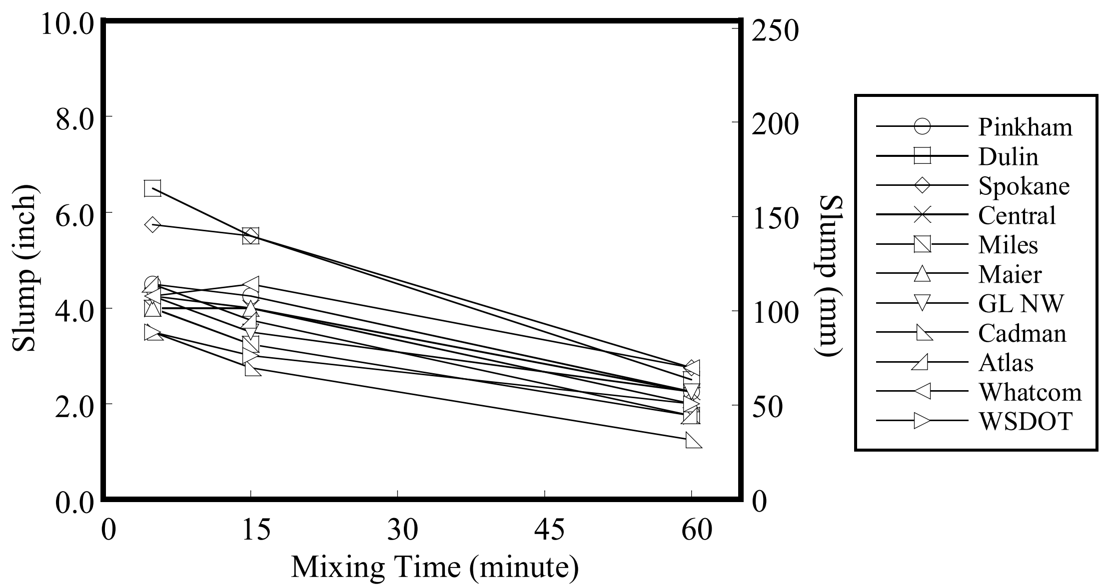


Figure 5-25. Mixing Time Versus Slump for the CA Group Mixtures (15 rpm).

As expected, all mixtures in the CA group showed a decrease in slump when mixed for up to 60 minutes. However, when mixed at 8 rpm between 5 and 15 minutes, mixtures containing Pinkham, Spokane, Whatcom, and Maier coarse aggregates exhibited an increase in slump. As already discussed, it is believed that this increase in slump is a result of insufficient mixing energy necessary to produce a homogeneous mixture when mixed for just 5 minutes.

Figure 5-26 and Figure 5-27 show the normalized slump values as a function of mixing time for the CA group mixtures mixed at 8 and 15 rpm, respectively. The slump values were normalized by the initial slump value. At a mixing speed of 8 rpm, the average slump between 5 and 15 minutes of mixing increased by 3 percent and between 15 and 60 minutes of mixing the slump decreased by 30 percent. At 15 rpm, the average slump decreased by 10 percent between 5 and 15 minutes of mixing and decreased by 42 percent for mixtures mixed between 15 and 60 minutes.

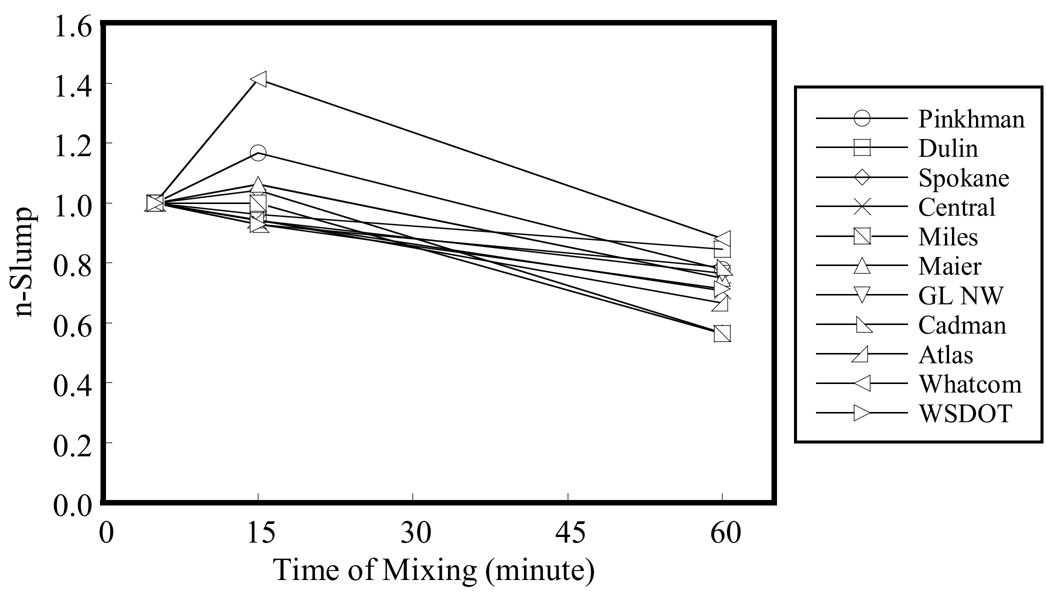


Figure 5-26. Normalized Slump for CA Group Mixtures (8 rpm).

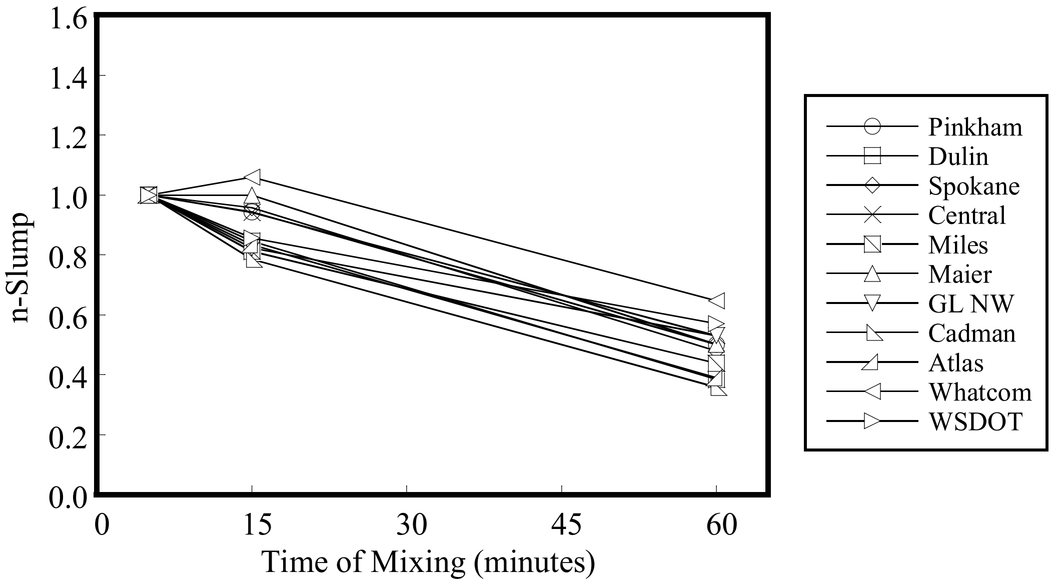


Figure 5-27. Normalized Slump Value for CA Group Mixtures (15 rpm).

Non-linear regression analyses models were developed to assess the effect of the mixing time on normalized slump for mixtures mixed at 8 and 15 rpm. These models and the 95 percent prediction interval (PI) are shown in Figure 5-28 and Figure 5-29.

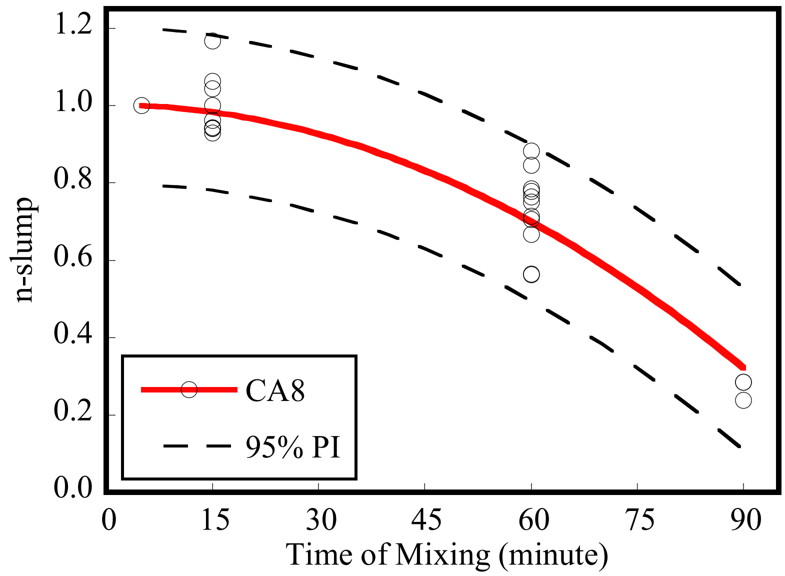


Figure 5-28. Regression Analysis Model for Slump as a Function of Mixing Time (8 rpm).

For mixtures from the CA group mixed at 8 rpm (*n-slump*$_{CA8}$), the n-slump as a function of time can be estimated as follows:

$$n - slump_{CA8} = 1 - 8.40 \times 10^{-5} \times t^2 \qquad (5\text{-}2)$$

where t is the time of mixing (minutes). The R^2 for the model is 87 percent. This equation is valid for mixing times between 5 and 90 minutes. As already noted, the n-slump is simply a measure of the percent of the original slump value (slump value at 5 minutes).

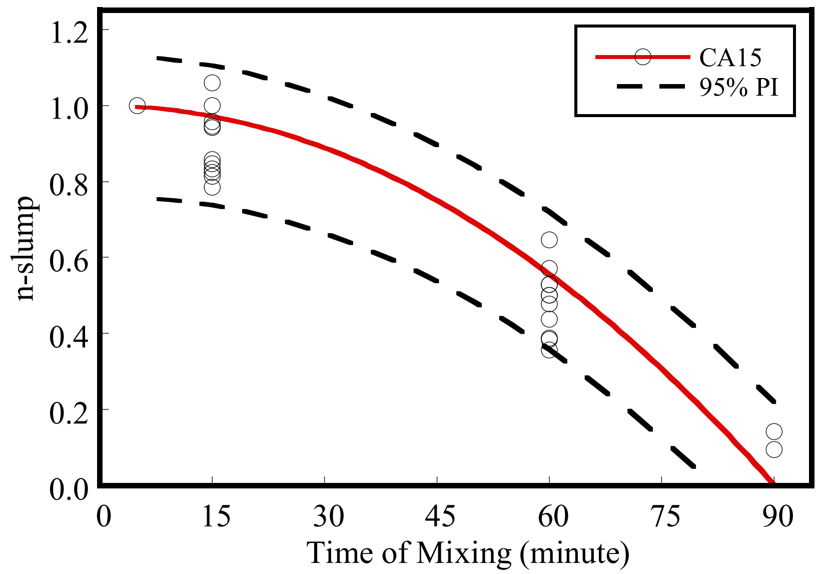


Figure 5-29. Regression Analysis Model for Slump as a Function of Mixing Time (15 rpm).

For the CA group mixtures mixed at 15 rpm ($n\text{-}slump_{CA15}$), the n-slump as a function of time can be estimated as follows:

$$n\text{-}slump_{CA15} = 0.99\text{-}1.21\times10^{-4}\times t^2 \qquad (5\text{-}3)$$

The R^2 for the 15 rpm model is 94 percent. Equation 5-3 is valid for mixing times between 5 to 90 minutes.

Figure 5-30 shows the n-slump models for CA group mixtures mixed at 8 and 15 rpm. The figure indicates that concrete mixed at 15 rpm exhibited a faster reduction rate in slump values than the mixtures mixed at 8 rpm. Figure 5-31 shows the n-slump models for the 8 and 15 rpm mixtures.

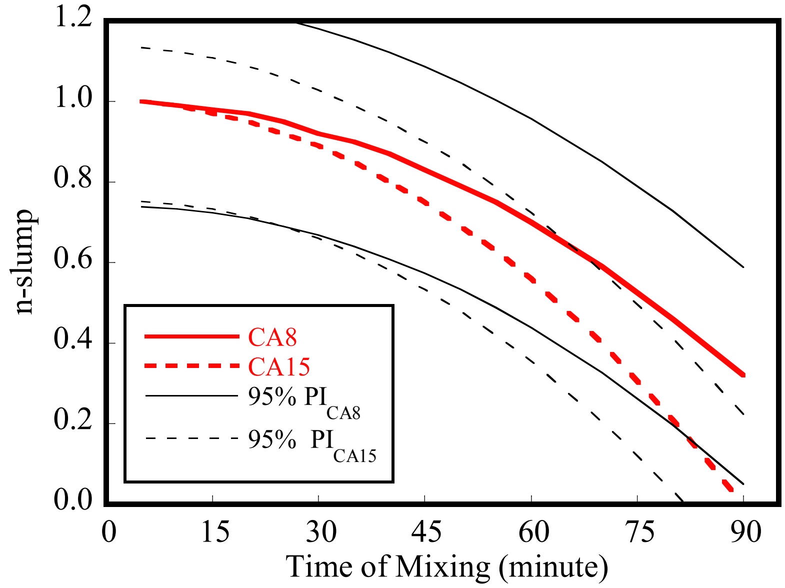


Figure 5-30. n-slump Model for Both 8 and 15 rpm mixtures for the CA Group.

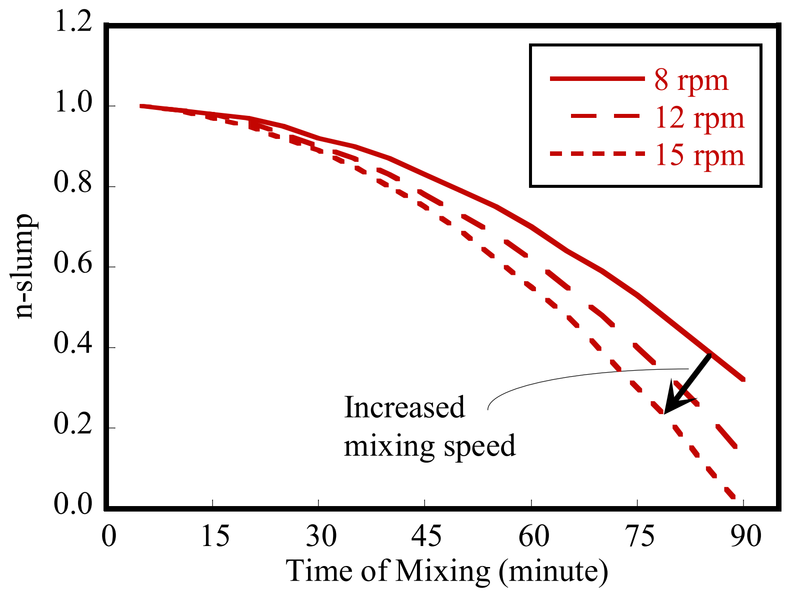


Figure 5-31. n-slump Models for the CA Group Mixtures (8, 12, and 15 rpm)

The models for the CA group with different mixing speed can be combined. For all of the CA group mixtures, the n-slump as a function of time and mixing speed can be estimated as follows:

$$n - slump_{CA} = -5.71 \times 10^{-6} \times (rt^2 + 6.72t^2 - 175{,}131) \qquad (5\text{-}4)$$

where r is the rate of the mixer (rpm) between 8 and 15 rpm.

Model Development for Admixture Group Mixtures

This section includes the modeling process for n-slump value as a function of mixing time and mixer speed for the AD_{rd} groups. Note that only 1 aggregate source was used for these mixtures. Figure 5-32 and Figure 5-33 show the relationships between slump and mixing time for the admixture group mixtures mixed at 8 and 15 rpm, respectively. The normalized slump values for the admixture group are shown in Figure 5-34 and Figure 5-35.

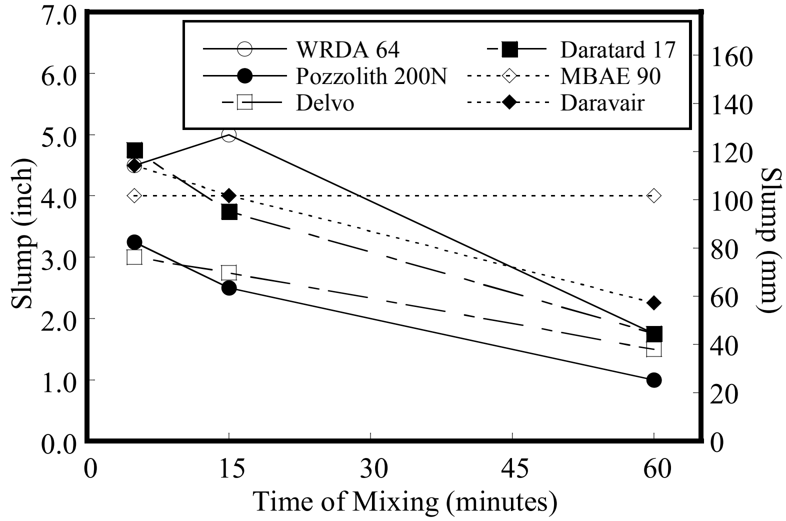


Figure 5-32. Mixing Time versus Slump for the AD_{rd} Group Mixtures (8 rpm).

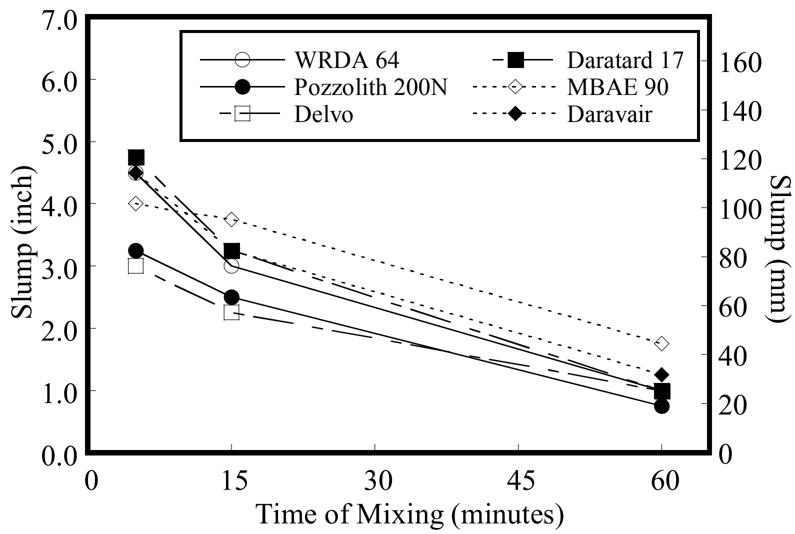


Figure 5-33. Mixing Time Versus Slump for the AD_{rd} Group Mixture (15 rpm).

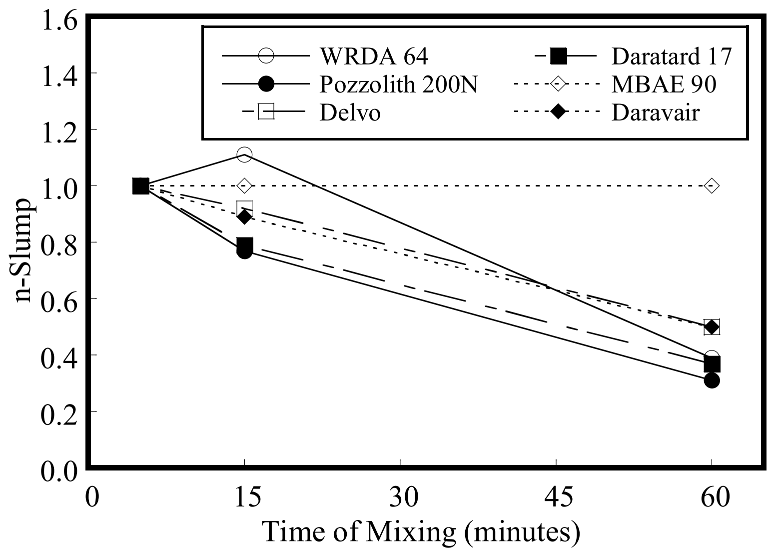


Figure 5-34. Mixing Time versus n-Slump for the AD_{rd} Mixtures (8 rpm).

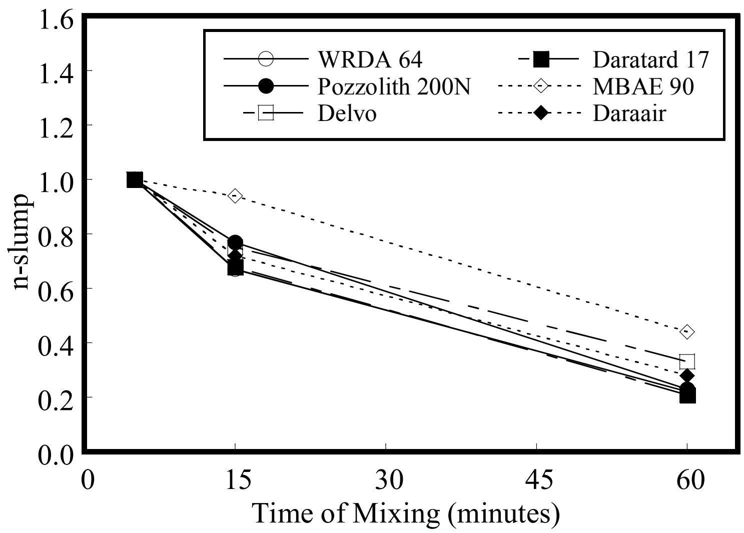


Figure 5-35. Mixing Time versus n-Slump for the AD_{rd} Mixtures (15 rpm).

For mixtures mixed at 8 rpm, the average slump decreased by 9 percent between 5 and 15 minutes of mixing and decreased by 40 percent between 15 and 60 minutes of mixing. At 15 rpm, the average slump of the AD_{rd} group decreased by 31 percent between 5 and 15 minutes of mixing and decreased by 40 percent between 15 and 60 minutes of mixing.

Figure 5-36 and Figure 5-37 show the n-slump models for mixtures containing recommended dosage of admixtures mixed at 8 and 15 rpm, respectively. AD_{rd8} represents the 8 rpm mixtures and AD_{rd15} represents the 15 rpm mixtures.

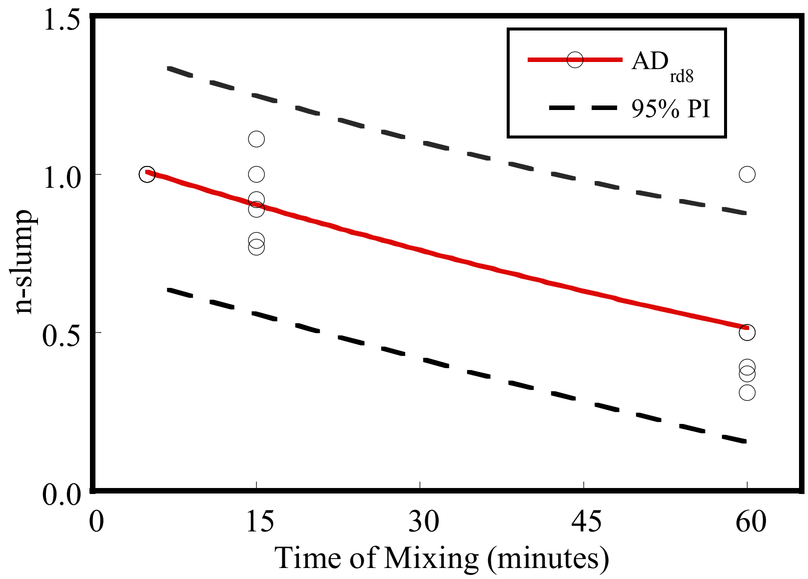


Figure 5-36. Estimated n-slump Values for the AD_{rd} Mixtures Mixed at 8 rpm.

For the AD_{rd8} mixtures, the $n\text{-}slump_{ADrd8}$ as function of time can be estimated as follows:

$$n - slump_{ADrd8} = -0.569 + 1.63 \times e^{-0.0068t} \qquad (5\text{-}5)$$

The R^2 for this model is 67 percent. Equation 5-5 is valid for mixing times between 5 to 60 minutes.

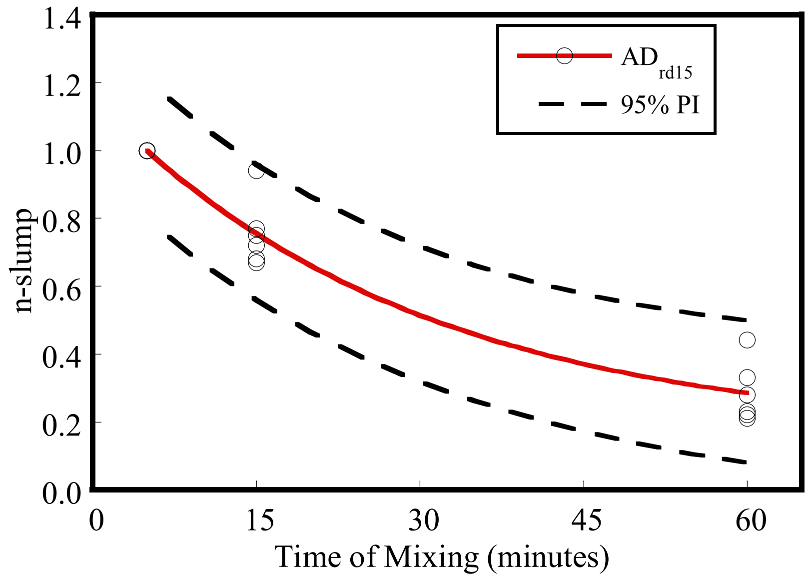


Figure 5-37. Estimated n-slump values for the ADrd Mixtures Mixed at 15 rpm.

For the AD_{rd} mixtures mixed at 15 rpm, the $n\text{-}slump_{ADrd15}$ as function of time can be estimated as follows:

$$n - slump_{ADrd15} = 0.157 + e^{-0.0344t} \tag{5-6}$$

Equation 5-5 is valid for mixing times between 5 to 60 minutes. The R^2 for the 15 rpm model is 88 percent.

Figure 5-38 shows the n-slump model for mixtures containing recommended dosages of admixtures and mixed at 8 and 15 rpm. The figure shows that mixtures mixed at higher speeds exhibit faster slump loss. Similarly to the mixture for the CA group, these two models can be combined to include speed and time as variables.

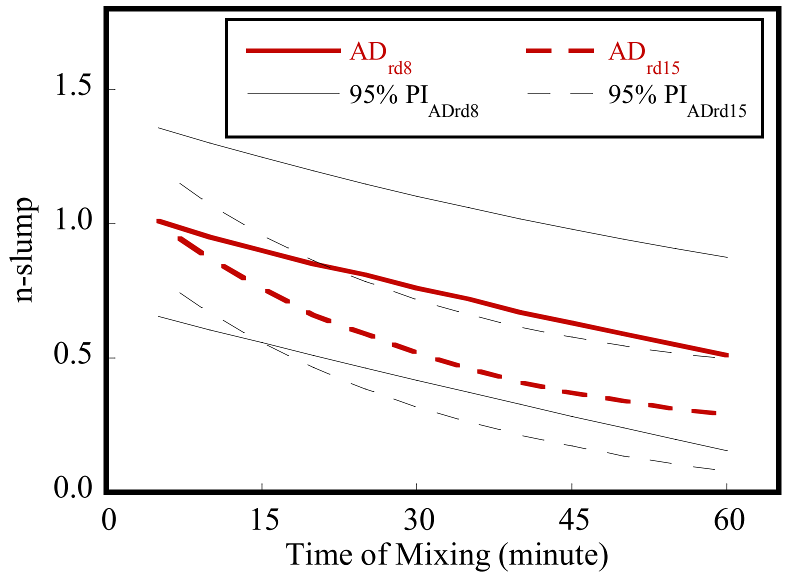


Figure 5-38. Estimated n-slump for AD_{rd} group Mixtures Mixed at 8 and 15 rpm.

Figure 5-39 shows the n-slump models for concrete containing recommended dosages of admixtures mixed at different mixing speeds.

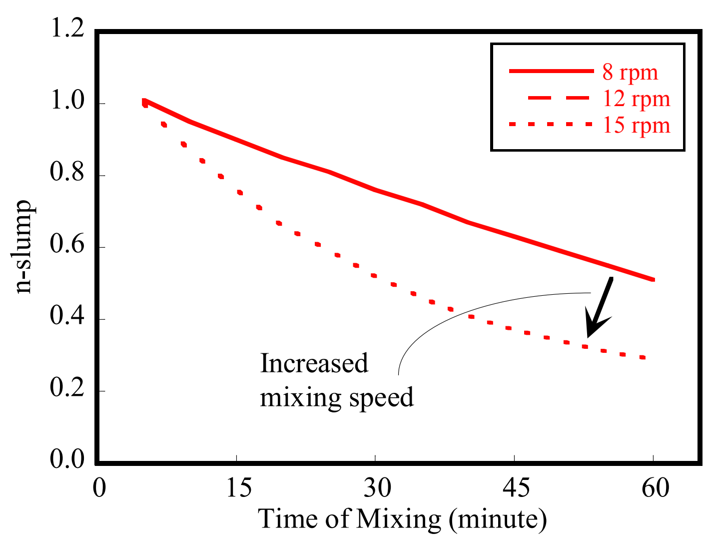


Figure 5-39. Estimated n-slump for the Mixtures Containing Recommended Dosages of Admixtures (8 and 15 rpm)

For mixtures containing recommend dosages of admixtures the $n\text{-}slump_{ADrd}$ as a function of time and mixing speed can be estimated as follows:

$$n - slump_{ADrd} = (2.35 - 0.09r)e^{(0.024-0.0039r)t} + 0.104r - 1.4 \qquad (5\text{-}7)$$

where r is the rate (rpm) of the mixer between 8 and 15 rpm and t is mixing time valid between 5 to 60 minutes.

The assessment of the influence of admixtures on concrete fresh characteristics indicates that some of these mixtures may be able to retain slump for longer mixing times. Because of this, additional testing was performed on specimens containing higher dosages of retarders. These mixtures were mixed up the 180 minutes and assessed for slump. Figure 5-40 and Figure 5-41 show the slump values for the mixtures containing retarders for the 8 rpm and 15 rpm mixing speeds, respectively. Figure 5-42 and Figure 5-43 show the normalized slump values as a function of mixing time for the mixtures mixed at 8 rpm and 15 rpm, respectively.

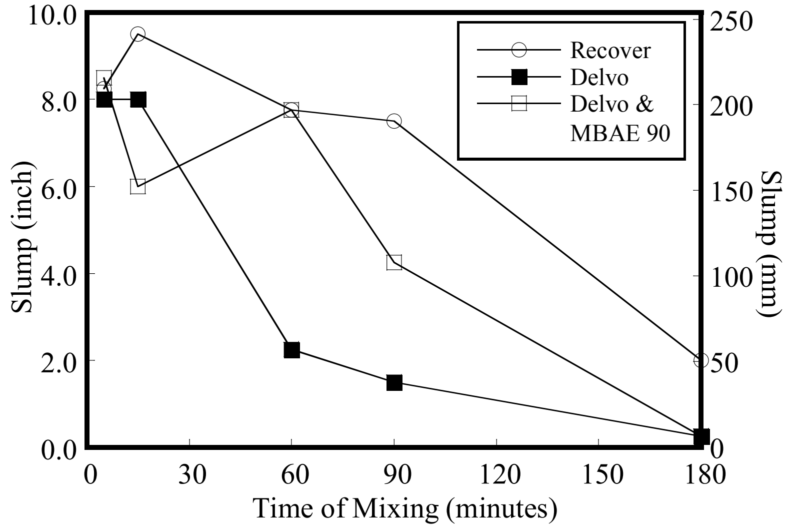


Figure 5-40. Mixing Time versus Slump for the AD_{hd} Group (8 rpm) for Extended Mixing Times.

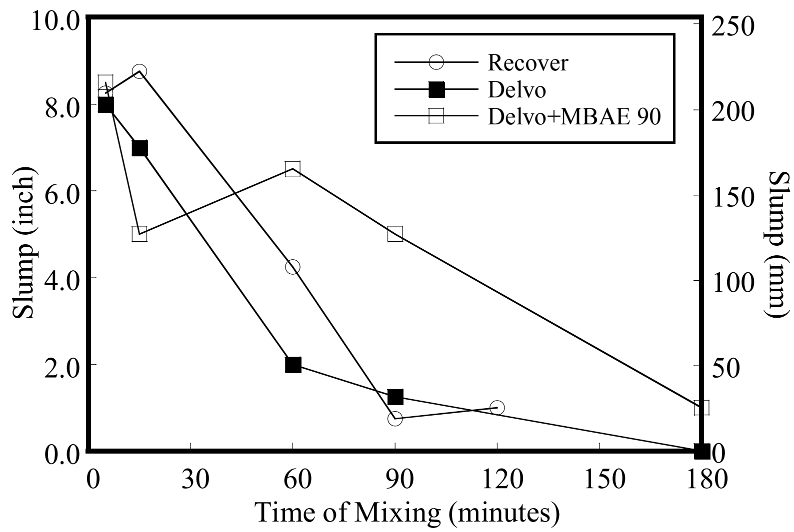


Figure 5-41. Mixing Time versus Slump for the AD_{hd} Group (15 rpm) for Extended Mixing Times.

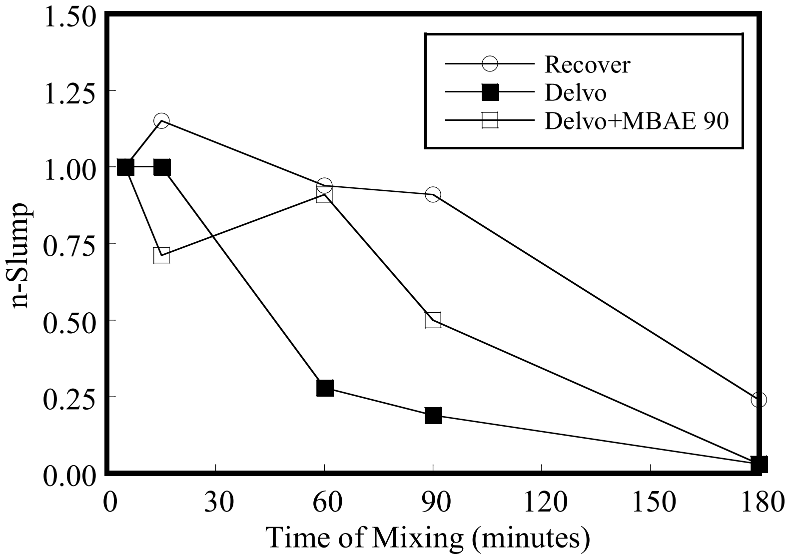


Figure 5-42. Mixing Time versus n-Slump for AD_{hd} Group Mixed at 8 rpm for Extended Mixing Times.

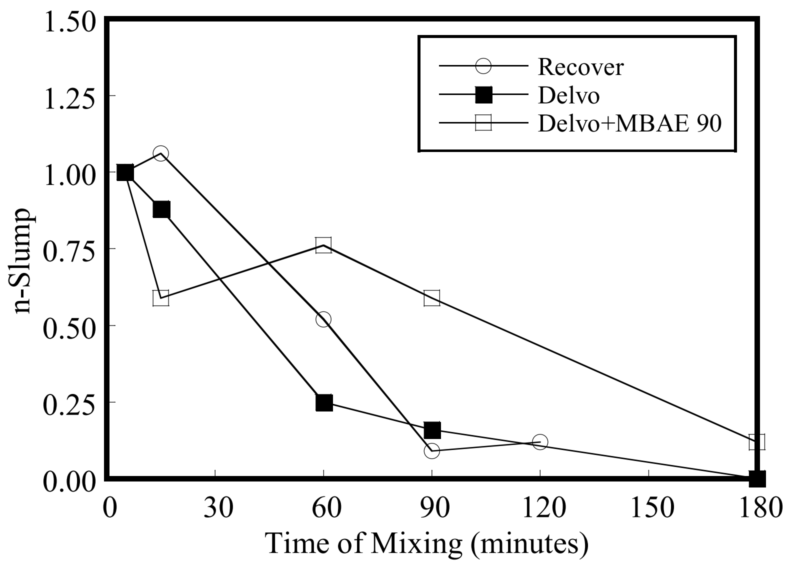


Figure 5-43. Mixing Time versus n-Slump for AD_{hd} Group Mixed at 15 rpm for Extended Mixing Times.

For the mixtures mixed at 8 rpm, the average slump of these mixtures decreased by 5 percent between 5 and 15 minutes of mixing, decreased by 24 percent between 15 and 60 minutes of mixing, decreased by 18 percent between 60 to 90 minutes of mixing and decreased by 43 percent between 90 and 180 minutes of mixing.

At 15 rpm, the average slump decreased by 16 percent between 5 and 15 minutes of mixing, decreased by 33 percent between 15 and 60 minutes of mixing, decreased by 23 percent between 60 and 90 minutes of mixing, and decreased by 22 percent between 90 and 180 minutes (excluding mixtures containing the Recover admixture because these mixtures were only mixed to 120 minutes).

Figure 5-44 and Figure 5-45 show the n-slump models as a function of mixing time for the AD_{hd} mixtures mixed at 8 and 15 rpm, respectively. The models for the mixtures mixed at 8 and 15 rpm are referred to here as $n\text{-}slump_{ADhd8}$ and $n\text{-}slump_{ADhd15}$, respectively. Note the large scatter in these figures.

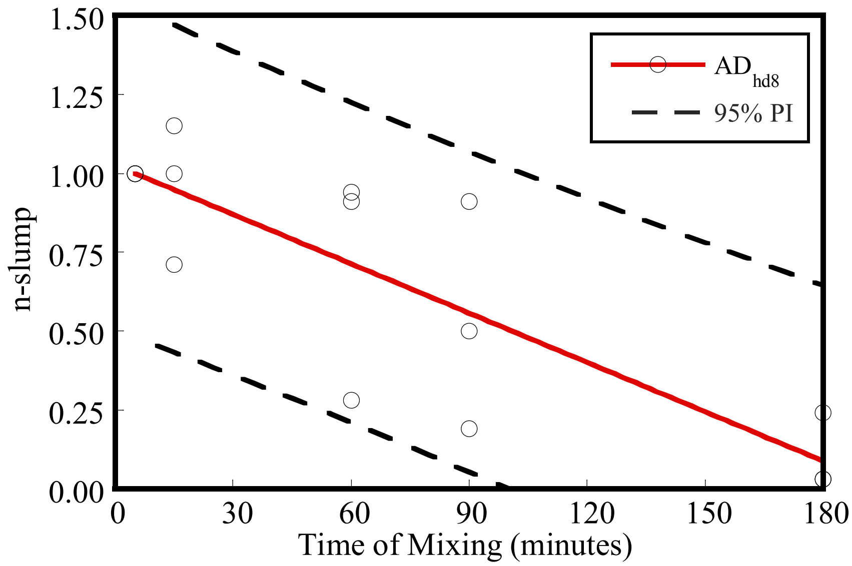


Figure 5-44. Normalized Slump for AD_{hd} Group Mixtures Mixed at 8 rpm.

The n-slump of the mixtures containing high dosages of retarders mixed at 8 rpm can be estimated as follows:

$$n-slump_{ADhd8} = 1.03 - 0.00521t \qquad (5\text{-}8)$$

for $5 \leq t \leq 180$ minutes. The R^2 for the model is 83 percent.

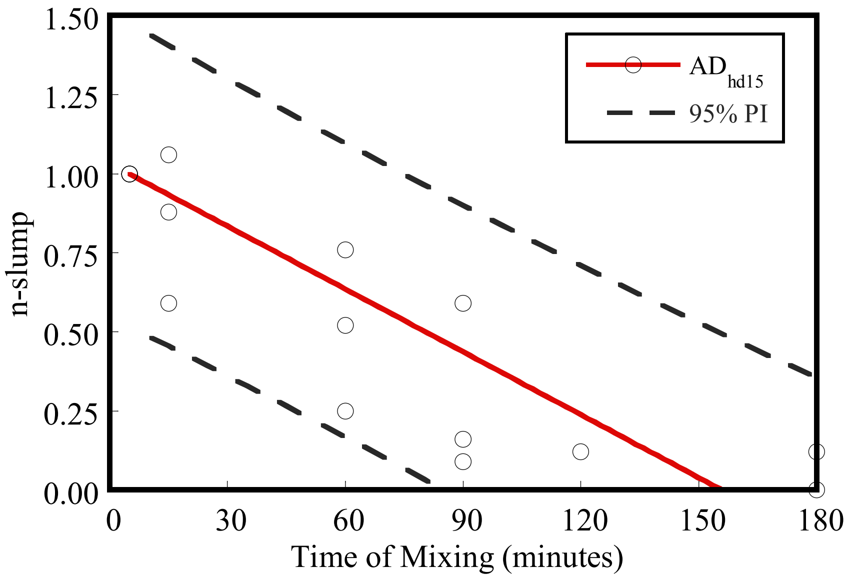


Figure 5-45. Normalized Slump and Model for Mixtures Containing High Dosage of Retarders and Model (15 rpm).

For the mixtures containing high dosages of retarders mixed at 15 rpm, the n-slump can be estimated as:

$$n - slump_{ADhd15} = 1.03 - 0.0066t \qquad (5\text{-}9)$$

for $5 \leq t \leq 180$ minutes. The R^2 for the model is 87 percent.

Figure 5-46 shows the models for mixtures containing high dosages of retarders mixed at 8 and 15 rpm and Figure 5-47 shows the combined model.

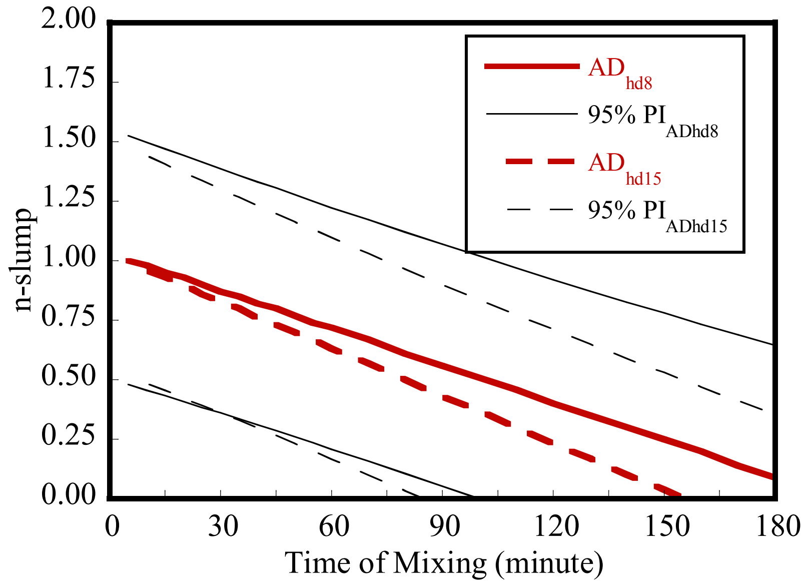


Figure 5-46. Models for Mixtures in the AD_{hd} Group Mixed at 8 and 15 rpm.

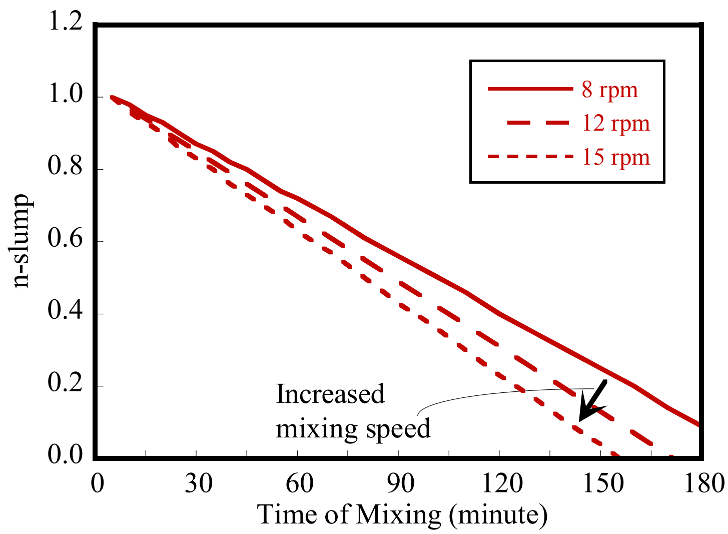


Figure 5-47. n-slump Models for AD_{hd} Mixtures.

These models can be combined to be a function of mixing speed and time. The $n\text{-}slump_{ADhd}$ as a function of time and mixing speed can be estimated as follows:

$$n - slump_{ADhd} = -1.99 \times 10^{-4} \times (rt + 18.2t - 5187) \tag{5-10}$$

where mixing time *t* is between 5 to 180 minutes.

Model Development for SCM Group Mixtures

Figure 5-48 and Figure 5-49 show the relationships between slump and the mixing time for the SCM group mixtures mixed at mixing speed of 8 and 15 rpm, respectively.

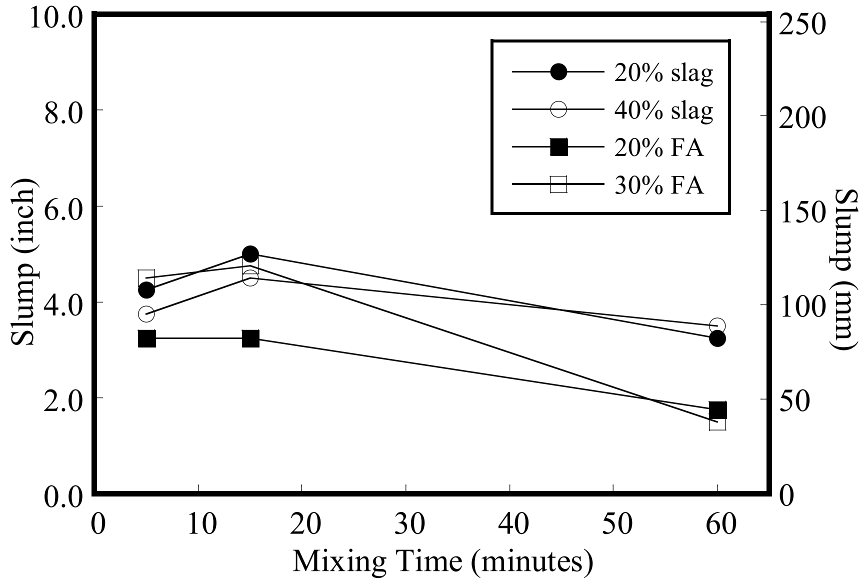


Figure 5-48. Mixing Time Versus Slump for the SCM Group Mixtures (8 rpm).

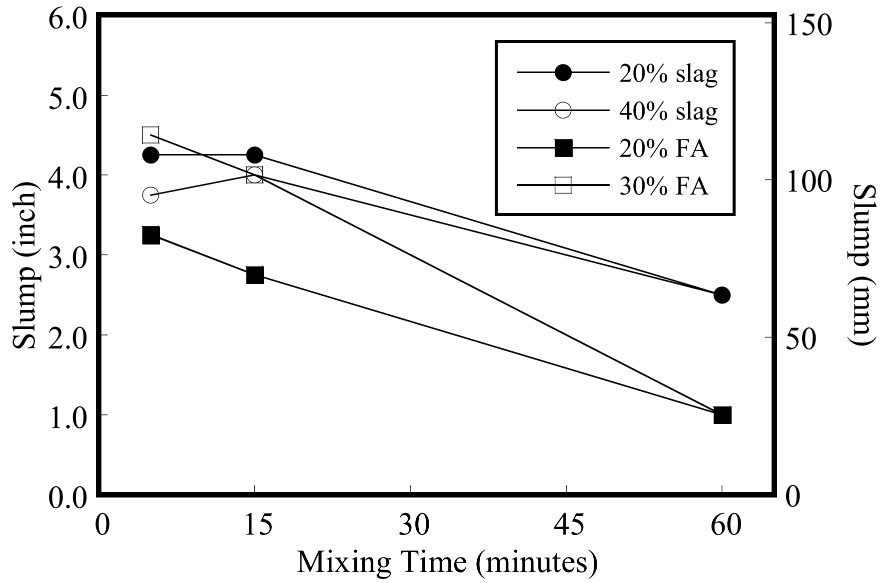


Figure 5-49. Mixing Time Versus Slump for the SCM Group Mixtures (15 rpm).

Figure 5-50 and Figure 5-51 show the n-slump values for the SCM group mixtures. Note that the slag mixtures mixed at 8 rpm were normalized to slump values at 15 minutes instead of 5 minutes. All slump values for the slag mixtures increased from 5 to 15 minute, indicating insufficient mixing energy at 5 minutes. For mixtures mixed at 8 rpm, the average slump increased by 11 percent between 5 and 15 minutes of mixing and decreased by 36 percent between 15 and 60 minutes of mixing. At 15 rpm mixing speed, the average slump value of the SCM group decreased by 5 percent between 5 and 15 minutes of mixing and decreased by 55 percent between 15 and 60 minutes of mixing.

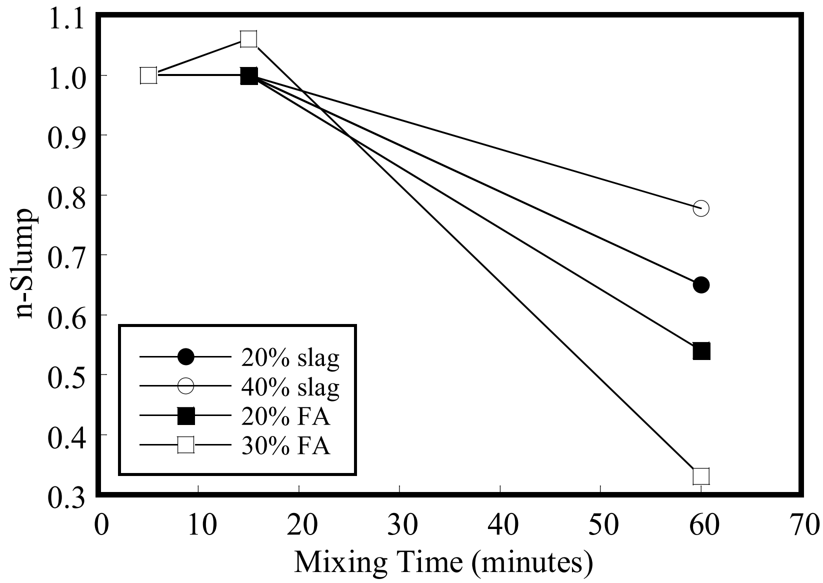


Figure 5-50. Normalized Slump for SCM Group Mixtures (8 rpm).

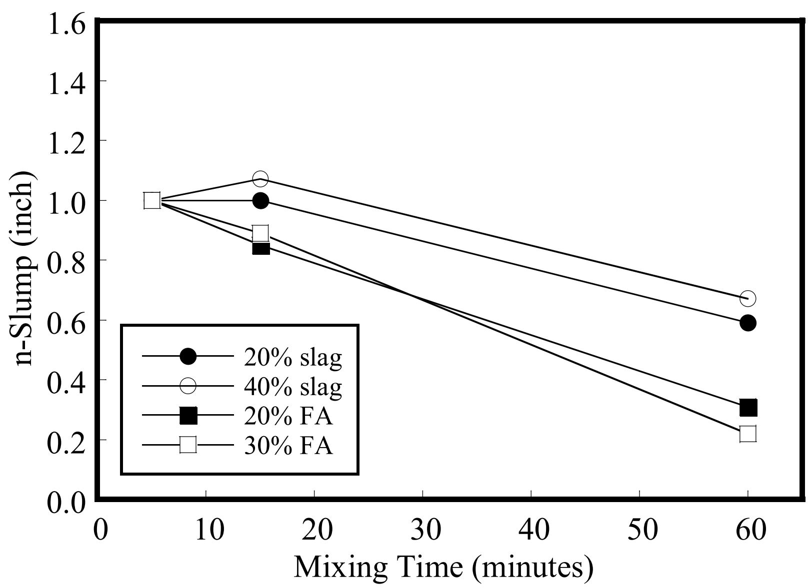


Figure 5-51. Normalized Slump for SCM Group Mixtures (15 rpm).

Models for the normalized slump as a function of mixing time are developed for the 8 and 15 rpm mixing speeds and are shown in Figure 5-52 and Figure 5-53, respectively. The n-slump values for these mixtures are referred to as $n\text{-}slump_{SCM8}$ and $n\text{-}slump_{SCM15}$.

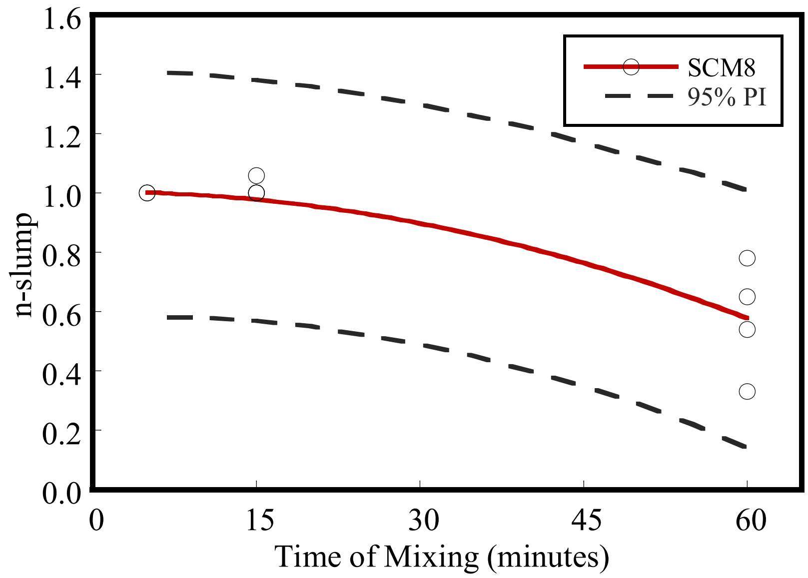


Figure 5-52.Model for n-slump for SCM Group Mixtures Mixed at 8 rpm.

For mixtures containing SCMs mixed at 8 rpm the n-slump can be estimated as follows:

$$n - slump_{SCM8} = 1 - 0.00012t^2 \qquad (5\text{-}11)$$

for $5 \leq t \leq 60$. The R^2 for the model is 85 percent.

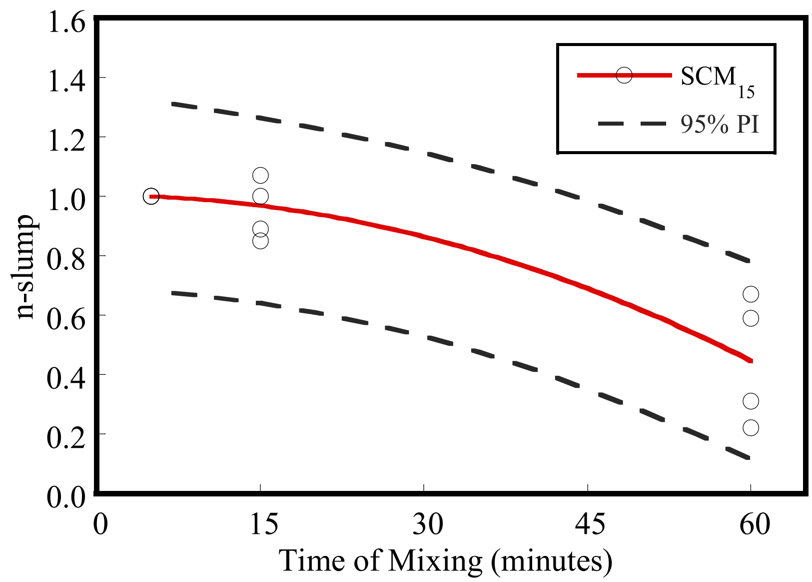


Figure 5-53. Model for n-slump for SCM Group Mixtures Mixed at 15 rpm.

For mixtures containing SCMs and mixed at 15 rpm the n-slump can be estimated as follows:

$$n - slump_{SCM15} = 1 - 0.000155t^2 \qquad (5\text{-}12)$$

for $5 \leq t \leq 60$. The R^2 for the model is 87 percent.

Figure 5-54 shows the combined n-slump models for mixtures mixed at mixing speeds of both 8 and 15 rpm mixtures. The figure indicates that the mixtures mixed at 15 rpm exhibited faster slump loss than mixtures mixed at 8 rpm. The two models are combined to include mixing speed and time as variables.

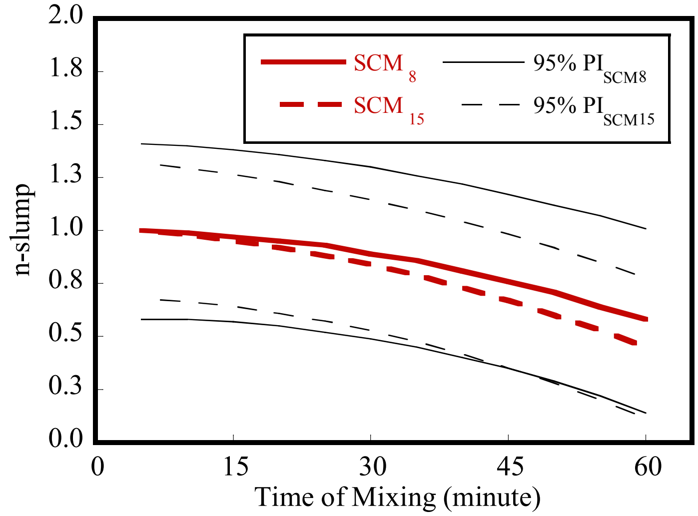


Figure 5-54. Mixing Time versus n-slump for Mixture Mixed at 8 and 15 rpm for the SCM Group.

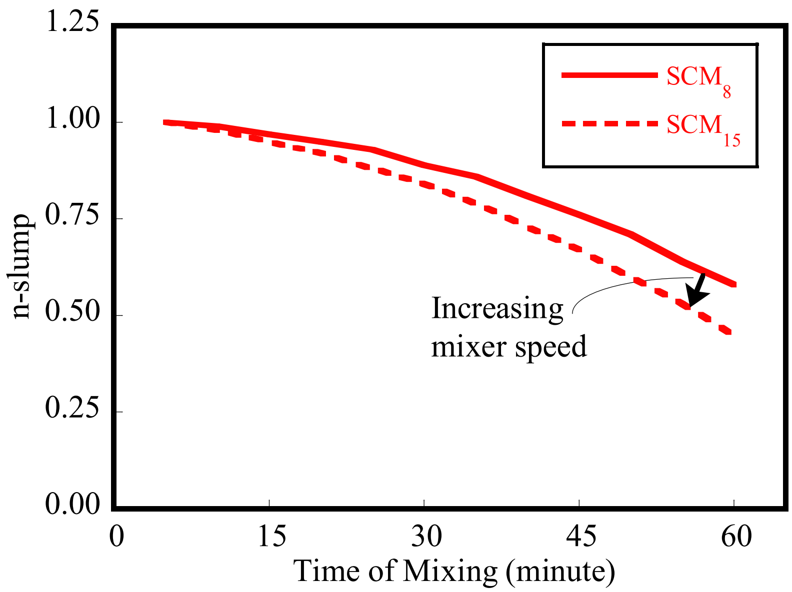


Figure 5-55. n-slump Models for the SCM Group Mixtures.

For the SCM group mixtures, the n-slump as a function of time and mixing speed can be estimated as follows:

$$n\text{-}slump_{SCM} = -5.29\times10^{-6}(rt^2 - 14.7t^2 - 189{,}189) \quad (5\text{-}13)$$

Figure 5-55 shows the combined n-slump models for different mixing speeds.

To estimate the slump value at time *t*, the following equation can be used:

$$slump = n\text{-}slump \times slump_{initial} \quad (5\text{-}14)$$

where s$lump_{CA}$ is in inches, and *slump* is the initial slump value (inches).

5.2.3.4 Comparison of Slump Values for Different Groups

Models assessing slump as a function of time were developed for the different groups. Figure 5-56 shows the models for conventional concrete mixtures (CA group), concrete containing admixtures (AD_{rd} and AD_{hd}), and concrete containing SCMs. Results indicate that concrete mixtures containing recommended dosages of chemical admixtures exhibited accelerated slump loss, whereas mixtures containing higher dosages of retarders exhibited lower slump loss rates. If it is assumed that 30 percent of the original slump is necessary to place the concrete (an arbitrary number), allowable mixing times could range from approximately 50 minutes to 150 minutes. Results indicate that placeability is likely a function of minimum slump requirement.

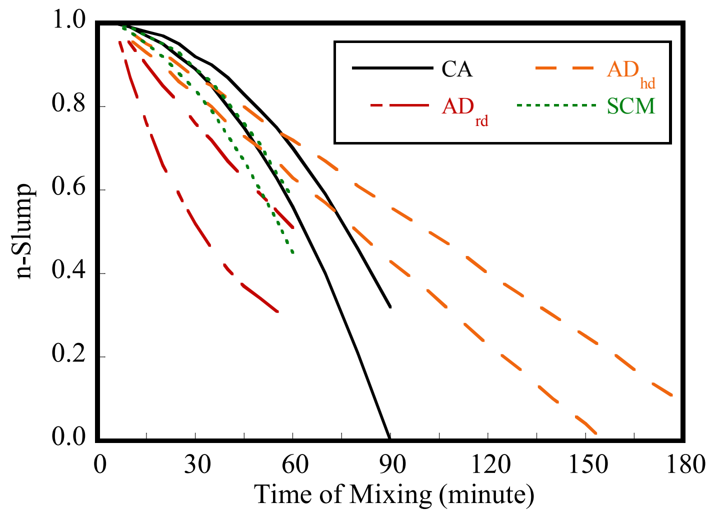


Figure 5-56. n-slump Model for All Concrete Groups.

5.3 INFLUENCE OF MIXING TIME ON HARDENED CHARACTERISTICS OF CONCRETE

The hardened characteristics of concrete mixtures assessed include 28- and 56-day compressive strength, freeze-thaw performance, and chloride diffusivity. The following sections first present data and analyses for assessing the influence of aggregate characteristics on these hardened concrete properties. Statistical tests are then performed to compare the mean values of these concrete characteristics when mixed for different length of times. If the statistical test results indicate statistically significant difference in means between the different mixtures containing the 11 aggregates, each of the aggregate characteristics will be assessed for potential influence on the hardened concrete characteristics. Models will then be developed as a function of these characteristics if correlations are found. The influence of mixing time on hardened concrete characteristics is then assessed.

5.3.1 Potential Influence of Constituent Material Characteristics on Compressive Strength

The potential influences of CA characteristics and cement content on compressive strength are analyzed here. The specified concrete compressive strength (f'c) for these mixtures is 4000 psi (27 MPa). These mixtures are proportioned following ACI 211.1 and have a required average compressive strength used for proportioning (f'cr) of 5200 psi (36 MPa). Figure 5-57 and Figure 5-58 show the box plots for the 28-day and 56-day measured compressive strength (f'cm) for these mixtures, respectively. These mixtures contain mixtures with the 11 different coarse aggregates mixed for 5 minutes at 8 rpm. The average f'cm for these mixtures is 6907 psi (47.6 MPa) and 7541 psi (52.0 MPa) for the 28- and 56-day strengths, respectively.

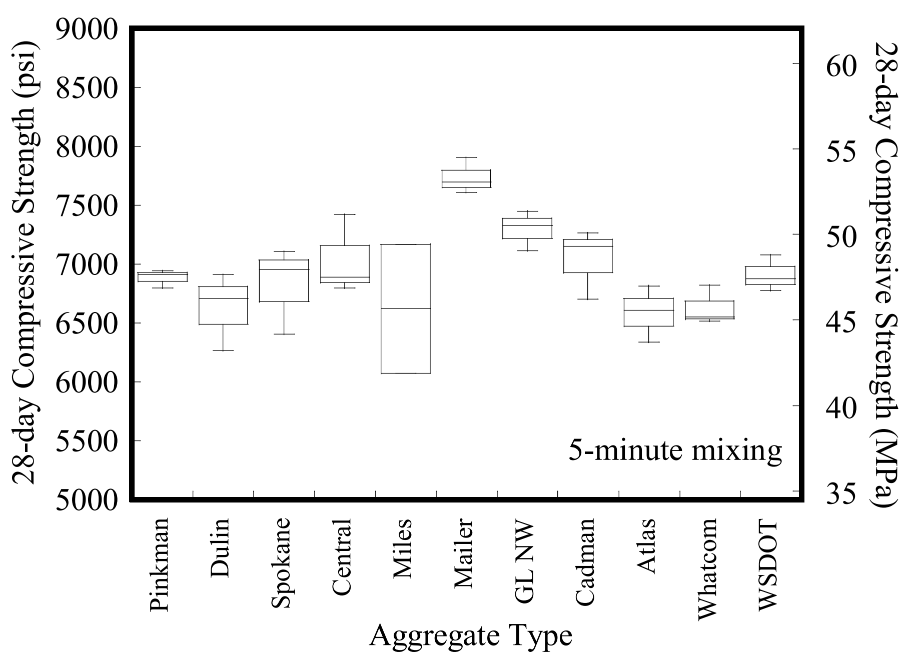


Figure 5-57. 28-Day f'cm for the CA Group Mixtures.

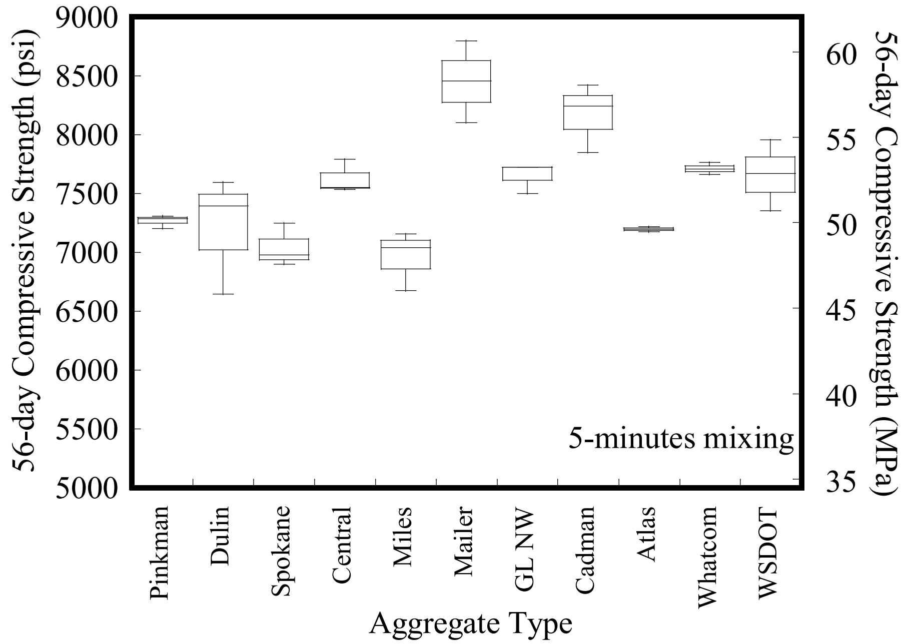


Figure 5-58. 56-Day f'cm for the CA Group Mixtures.

Statistical analyses were performed to assess whether the CA source significantly influences the 28-day and 56-day f'cm of these concretes. ANOVA tests indicate that there is a statistically significant difference in the 28-day f'cm within the mixtures containing the 11 different CA at the 95 percent confidence level (p-value = 0.003). Similar statistical test result were observed for the 56-day f'cm for the same 11 mixtures (p-vale =0.000).

5.3.1.1 Potential Influence of CA Characteristics on Compressive Strength

Because statistical tests indicate a difference in the mean f'cm between the mixtures with different aggregates, analyses will be performed to determine if aggregate characteristic and mixture proportion influence f'cm. The effect of the different aggregate characteristics on compressive strength is shown in Figure 5-59 through Figure 5-66. The

CA characteristics assessed include SG_{CA}, $absorption_{CA}$, PI_{CA}, and FM_{CA}. As shown in Figure 5-59 and Figure 5-60, SG_{CA} is not significantly correlated with the 28-day or 56-day f'cm for mixtures mixed for 5 minutes at 8 rpm.

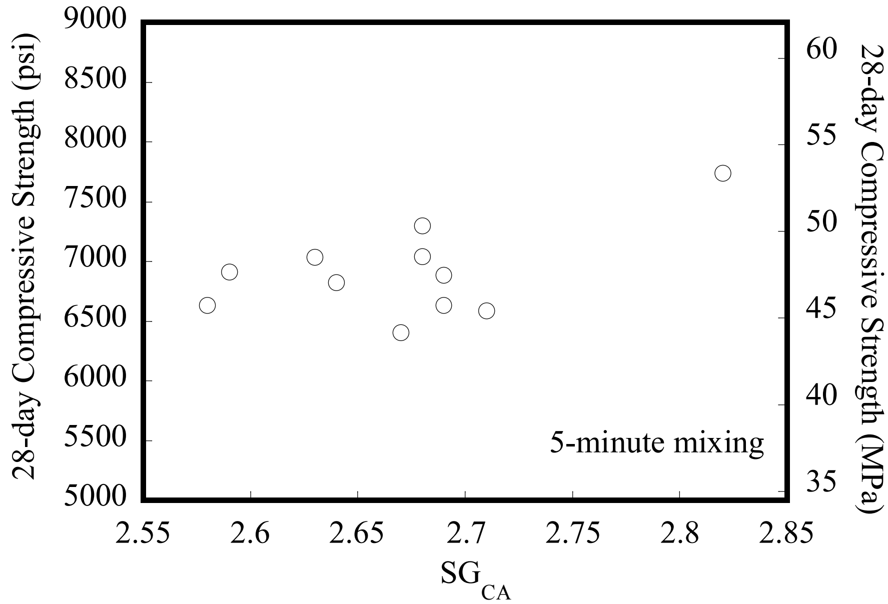


Figure 5-59. SG_{CA} versus 28-day f'cm for CA Group Mixtures Mixed at 8 rpm.

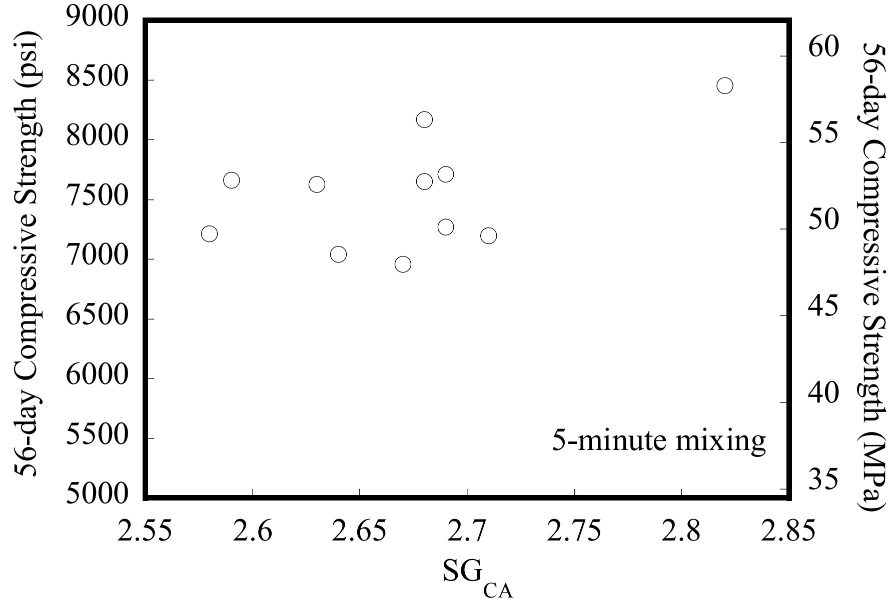


Figure 5-60. SG_{CA} versus 56-day f'cm for CA Group Mixtures Mixed at 8 rpm.

Figure 5-61 and Figure 5-62 show the 28- and 56-day f'cm as a function of CA absorption, respectively. The figures show that the 28- and 56-day f'cm decreases with CA absorption values from 0.5 to 1.5 percent and then slightly increases.

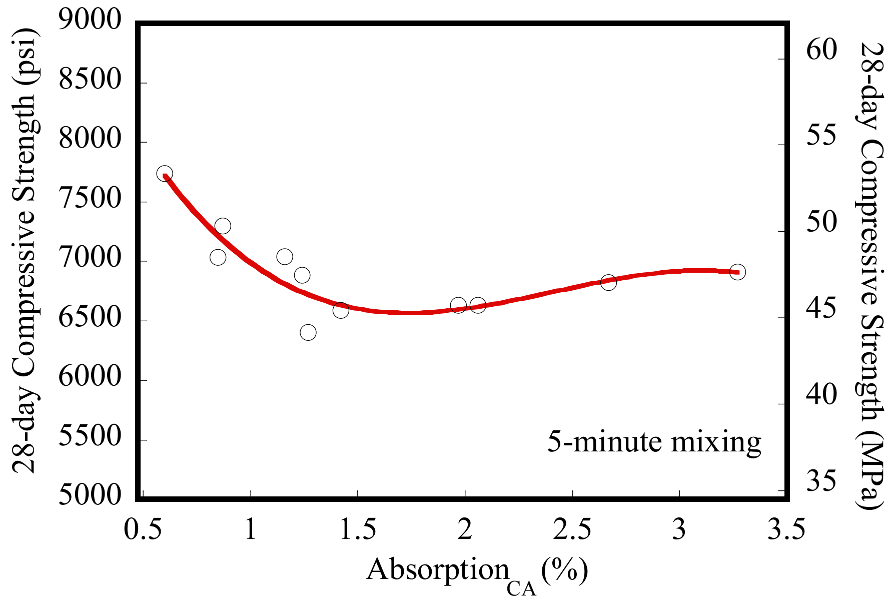


Figure 5-61. Absorption$_{CA}$ versus n-f'cm$_{28}$ for CA Group Mixtures Mixed at 8 rpm.

The normalized 28-day f'cm as a function of absorption of CA for concrete with design strength of 5200 psi can be estimated as follows:

$$n - f'cm_{CA,abs} = 1.88 - 0.88x + 0.40x^2 \tag{5-15}$$

where n-$f'cm_{CA,abs}$ is the normalized 28-day f'cm and x is the coarse aggregate absorption (%). The R^2 is 84 percent.

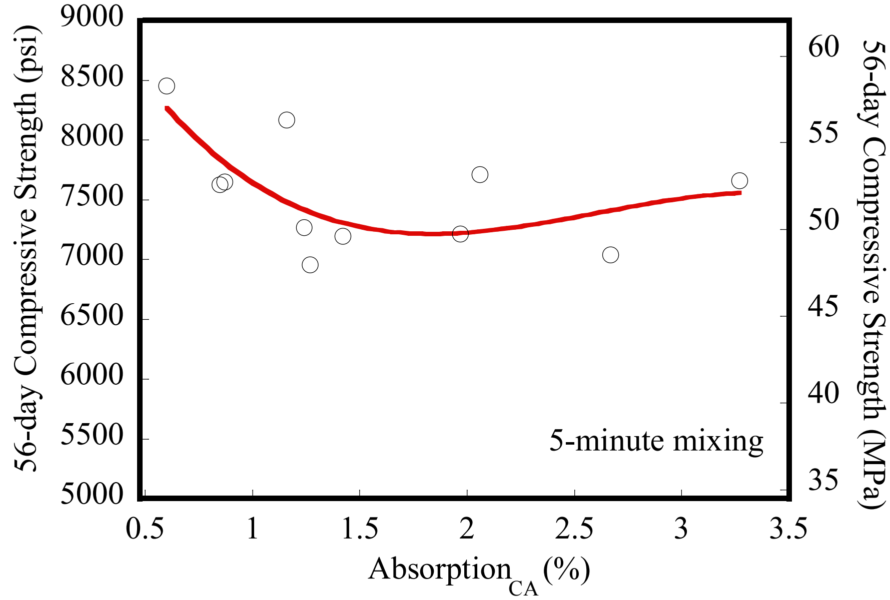


Figure 5-62. Absorption$_{CA}$ versus n-f'cm$_{56}$ for CA Group Mixtures Mixed at 8 rpm.

The normalized 56-day f'cm as a function of absorption of the CA for concrete with design strength of 5200 psi can be estimated as follows:

$$n - f'cm_{CA,abs} = 1.91 - 0.69x + 0.29x^2 \qquad (5\text{-}16)$$

where n-$f'cm_{CA,abs}$ is the 56-day f'cm as a function of coarse aggregate absorption and x is the absorption (%). The R^2 is 46 percent.

The models for f'cm as a function of absorption$_{CA}$ for the normalized 28- and 56-day can be combined. Figure 5-63 show both 28- and 56-day f'cm as a function of absorption$_{CA.}$ The figure shows that the 28- and 56-day models are nearly parallel. That indicates absorption$_{CA}$ has a similar influence on strength as a function of concrete age.

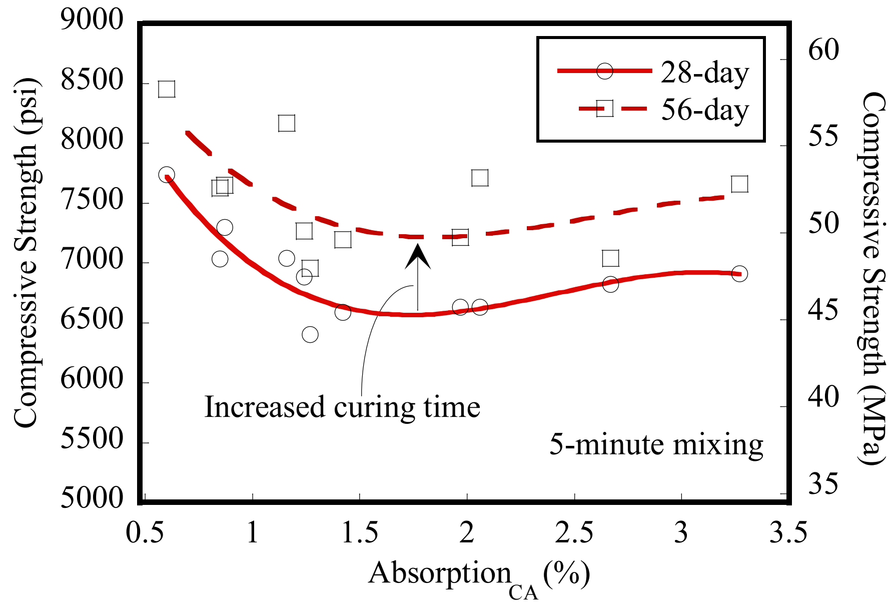


Figure 5-63. CA Absorption versus 28- and 56-day f'cm.

The n-f'cm can be estimated as a function of absorption of CA and concrete age as follows:

$$n - f'cm_{CA,abs} = (1.88 - 0.88x + 0.40x^2) \times (0.038 \times T_{cure}) \tag{5-17}$$

where T_{cure} is the age after 28 day of curing.

Figure 5-64 and Figure 5-65 show the PI_{CA} versus the 28- and 56-day f'cm, respectively. Lower PI values indicate smooth and less angular coarse aggregates. The figure indicates that PI_{CA} is not significantly correlated with the 28- and 56-day f'cm. Therefore, PI_{CA} will not be included in a strength model.

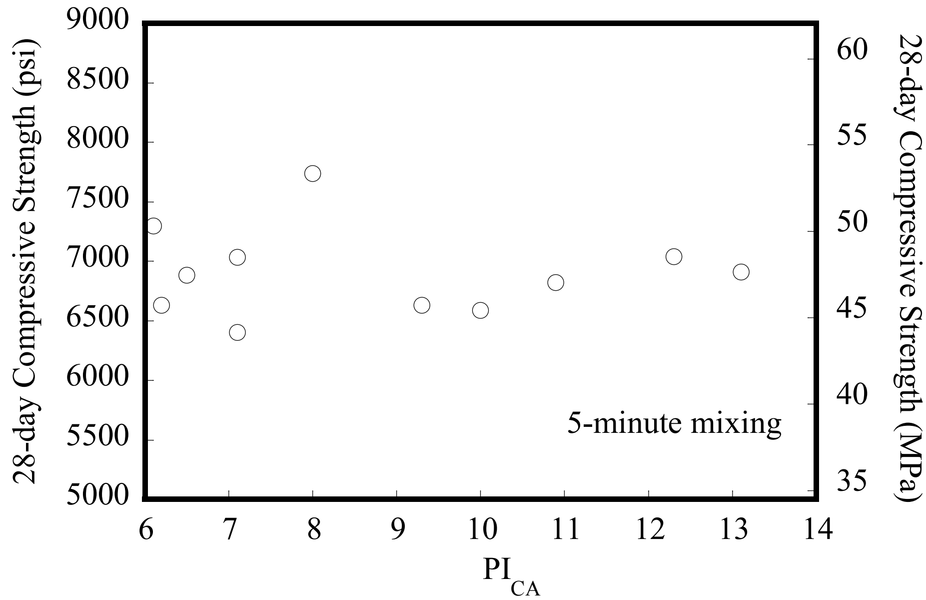


Figure 5-64. PI_{CA} versus 28-day f'cm for CA Group Mixtures mixed at 8 rpm.

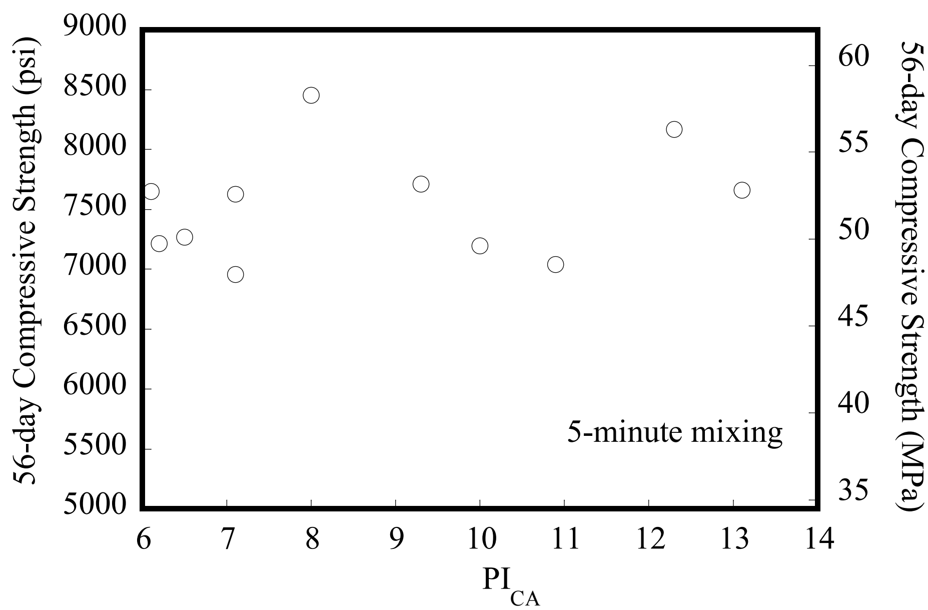


Figure 5-65. PI_{CA} versus 56-day f'cm for CA Group Mixtures mixed at 8 rpm.

Although the fineness modulus (FM) is not commonly used for CAs, this value can provide a measure of the coarseness of the CA. Figure 5-66 and Figure 5-67 show the

FM of the CA versus the 28- and 56-day f'cm, respectively. The figure shows a weak correlation between FM_{CA} with the 28-and 56-day f'cm (R^2 is 26 percent and 16 percent, respectively). Because of the weak correlation, FM_{CA} will not be included in the strength models.

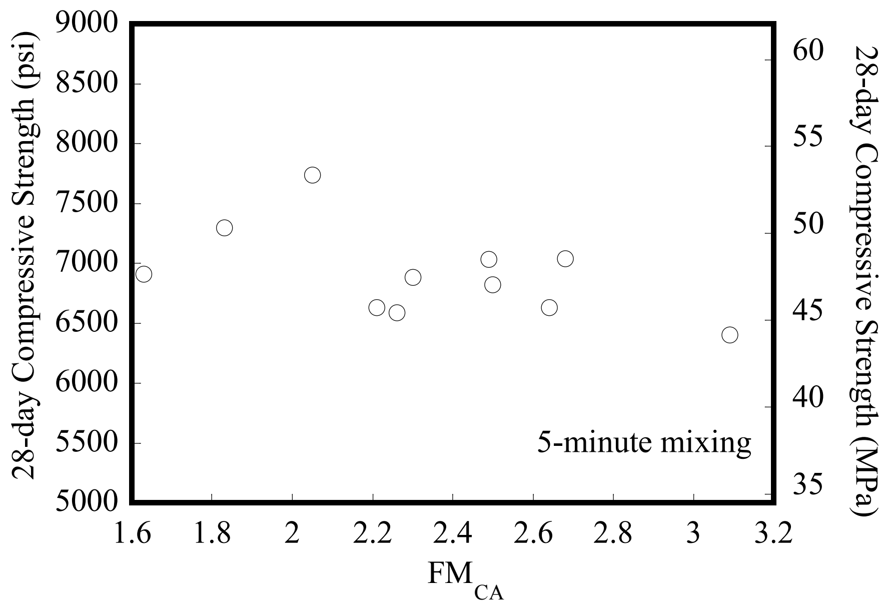


Figure 5-66. CA FM versus 28-day f'cm for CA Group Mixtures Mixed at 8 rpm.

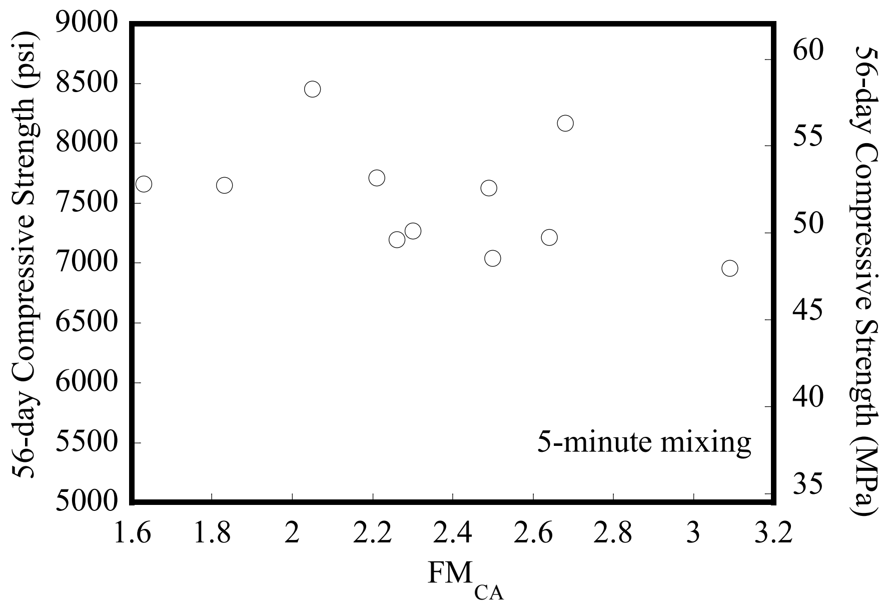


Figure 5-67. FM_{CA} versus 56-day f'cm for CA Group Mixtures Mixed at 8 rpm.

The the influence of coarse aggregate characteristics on the 28- and 56-day f'cm indicate that SG_{CA} PI_{CA}, FM_{CA} are not significantly correlated with the 28- and 56-day f'cm. However, $absorption_{CA}$ does correlates with the 28-day compressive strength, thus is included in a strength model.

5.3.1.2 Potential Influence of Cement Content

This section assesses the potential influence of cement content on the 28- and 56-day f'cm. Cement contents ranged between 645 and 755 lb/yd^3 (383 and 448 kg/m^3). Figure 5-68 and Figure 5-69 show cement content versus the 28-day and the 56-day f'cm, respectively. These figures indicate no correlation between the f'cm and cement content and therefore, cement content will not be included in the strength model.

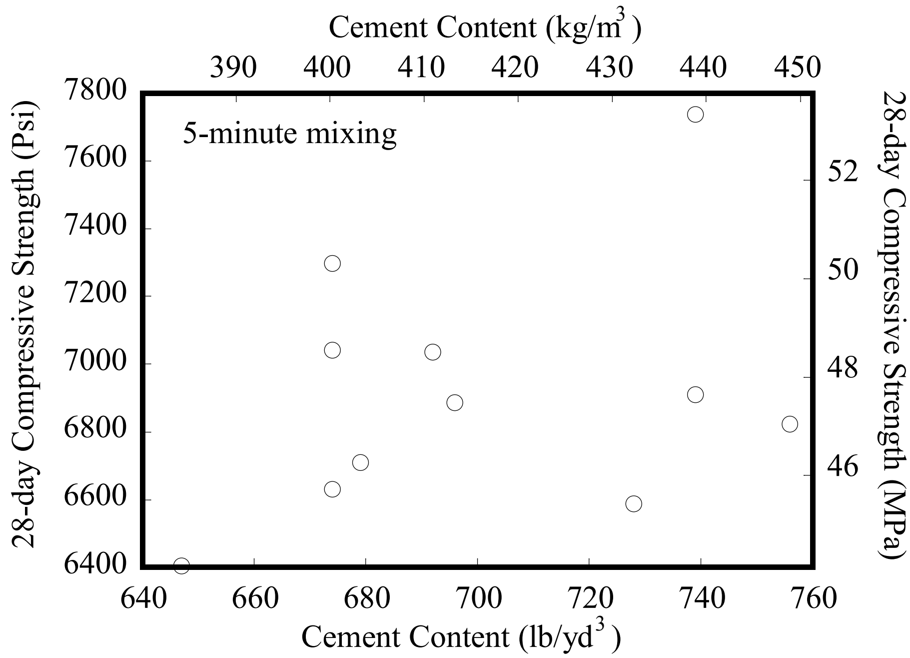


Figure 5-68. Cement Content versus 28-day Compressive Strength.

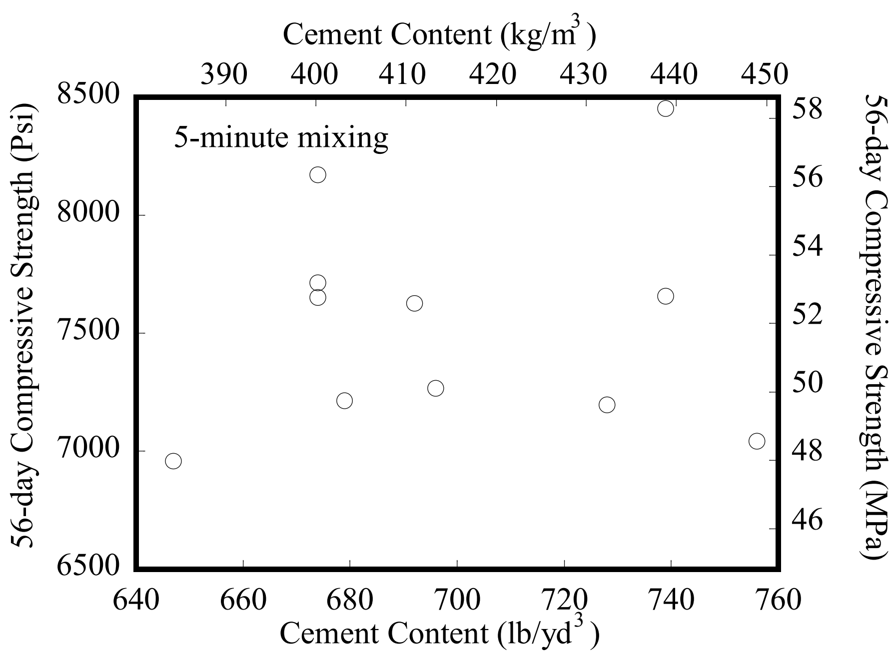


Figure 5-69. Cement Content versus 56-day Compressive Strength.

The analyses on the potential influence of constituent materials characteristic on the compressive strength indicates that coarse aggregate absorption correlates with the 28- and 56-day compressive strength. Equation 5-15 can be used to predict the compressive strength as a function of CA absorption.

5.3.1.3 Potential Influence of Initial Temperature of the Constituent Materials

Two concrete mixtures were mixed with constituent materials at different temperatures. The temperatures of the constituent materials were at 71 °F (22 °C) and 79 °F (25 °C) prior to mixing. Compressive cylinders were cast to assess the compressive strength of these mixtures. These mixtures were mixed for up to 60 minutes at 8 and 15 rpm. Compressive cylinders were cast after 5, 15, and 60 minutes of mixing. Table 5-22 shows the f'cm values for these mixtures. Figure 5-70 and Figure 5-71 shows mixing time versus 28-day f'cm values and normalized 28-day f'cm, respectively.

Table 5-21. Slump Values for Mixture with Different Initial Temperatures.

Time	Initial Temperature °F (°C)			
	8 rpm		15 rpm	
	71 (22)	79 (26)	71 (22)	79 (26)
	28-day Compressive Strength			
5	6817 (47.0)	6530 (45.0)	N/A	N/A
15	6830 (47.1)	6207 (42.8)	6527 (45.0)	7119 (49.1)
60	6516 (44.9)	6625 (45.7)	6660 (45.9)	6309 (43.5)

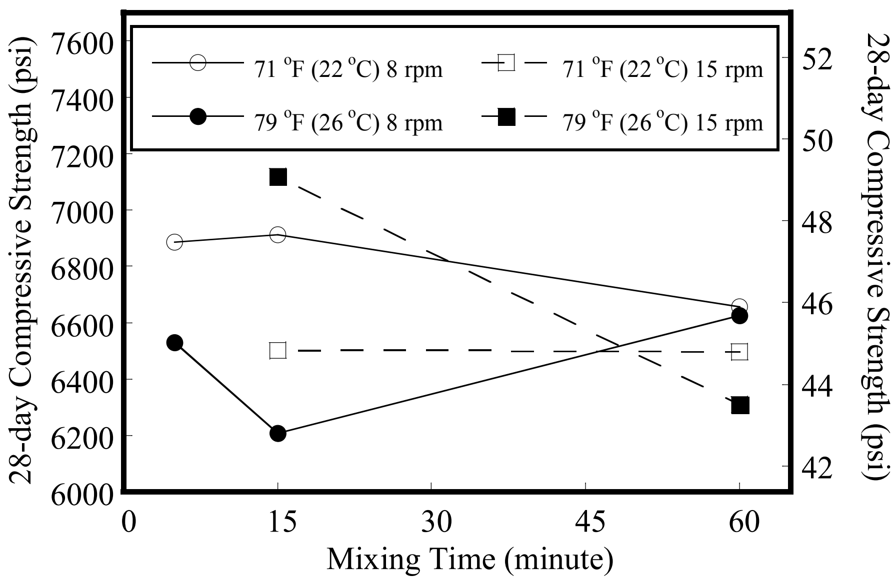


Figure 5-70. f'cm_{28} for Mixtures with Different Initial Constituent Material Temperatures.

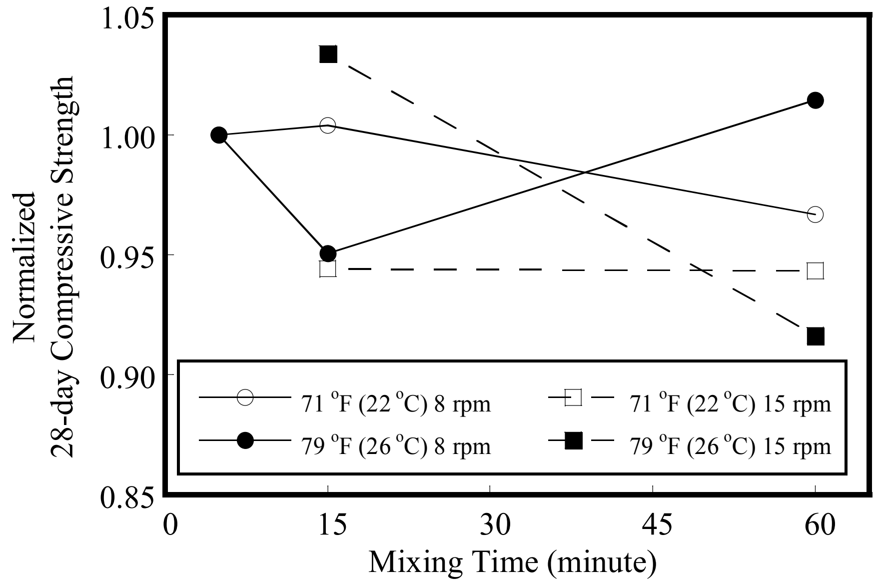


Figure 5-71. Normalized f'cm$_{28}$ for Mixtures with Different Initial Constituent Material Temperatures.

For the mixture mixed at an initial temperature of 71 °F (22 °C), the 28-day f'cm decreased approximately 4 and 6 percent from 5 to 60 minutes of mixing when mixed at 8 rpm and 15 rpm, respectively. For the mixture mixed with initial temperature at 79 °F (25 °C), the 28-day f'cm increased approximately 1 percent when mixed from 5 to 60 minutes of mixing at 8 rpm, and decrease approximately 9 percent when mixed from 5 to 60 minutes at 15 rpm. No clear relationship with strength and initial temperature was observed.

5.3.2 Potential Influence of Mixing Time on Compressive Strength

Similar to the analyses on the fresh concrete characteristics, these mixtures are separated into five groups: 1) plain concrete (the CA group); 2) concrete with regular dosages of chemical admixtures (the AD_{rd} group); 3) concrete with high dosages of chemical admixtures (AD_{hd}); 4) concrete with AEA; and 5) concrete with SCMs (the SCM group). Table 5-22 through Table 5-31 shows the 28- and 56-day f'cm for these groups for each aggregate type.

Table 5-22. Compressive Strength (28-day) for Different Mixing Times and Mixing Speeds for the CA Group.

Aggregate Source	28-day Compressive Strength, psi (MPa)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
Dulin	6710 (46.3)	6396 (44.0)	6806 (46.9)	6891 (47.5)	6801 (46.9)
Central	7036 (48.5)	7336 (50.6)	7214 (49.7)	6826 (47.1)	7201 (49.6)
Spokane	6823 (47.0)	6991 (48.2)	7515 (51.8)	6838 (47.1)	7307 (50.4)
WSDOT	6910 (47.6)	6889 (47.5)	7340 (50.6)	6926 (47.8)	7208 (49.7)
Miles	6624 (45.7)	6294 (43.4)	6612 (45.6)	6153 (45.6)	5667 (39.1)
Cadman	7041 (48.5)	7029 (48.5)	7448 (51.4)	7188 (49.6)	7403 (51.0)
GL NW	7297 (50.3)	7148 (49.3)	7221 (49.8)	7030 (48.5)	7254 (50.0)
Whatcom	6631 (45.7)	6613 (45.6)	6771 (46.7)	6877 (47.4)	6730 (46.4)
Pinkham	6886 (47.5)	6913 (47.7)	6657 (45.9)	6502 (44.8)	6572 (45.3)
Atlas	6587 (45.4)	6952 (47.9)	7183 (49.5)	6625 (45.7)	6669 (46.0)
Maier	7737 (53.3)	7660 (52.8)	7684 (53.0)	7093 (48.9)	7280 (50.2)

Table 5-23. Compressive Strength (56-day) for Different Mixing Times and Mixing Speeds for the CA Group.

Aggregate Source	56-day Compressive Strength, psi (MPa)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
Dulin	7233 (49.9)	7466 (51.5)	7578 (52.2)	7281 (50.2)	6951 (47.9)
Central	7267 (50.1)	7830 (54.0)	7918 (54.6)	7371 (50.8)	7924 (54.6)
Spokane	7043 (48.6)	7203 (49.7)	7712 (53.2)	7572 (52.2)	7770 (53.6)
WSDOT	7659 (52.8)	7485 (51.6)	8213 (56.6)	7798 (53.8)	8199 (56.5)
Miles	6959 (48.0)	7304 (50.4)	7169 (49.4)	7023 (48.4)	7147 (49.3)
Cadman	7627 (52.6)	7830 (54.0)	7918 (54.6)	7371 (50.8)	7924 (54.6)
GL NW	7651 (52.8)	8304 (57.3)	7771 (53.6)	8328 (57.4)	8315 (57.3)
Whatcom	7713 (53.2)	7547 (52.0)	7981 (55.0)	7595 (52.4)	7754 (53.5)
Pinkham	7210 (49.7)	7380 (50.9)	7125 (49.1)	7006 (48.3)	7047 (48.6)
Atlas	7206 (49.7)	7226 (49.8)	7599 (52.4)	7508 (51.8)	7596 (52.4)
Maier	8453 (58.3)	8626 (59.5)	8384 (57.8)	7907 (54.5)	8112 (55.9)

Table 5-24. Compressive Strength (28-day) for Different Mixing Times and Mixing Speeds for the AD_{rd} Subgroup.

Mixtures with recommended admixture dosage		28-day Compressive Strength, psi (MPa)				
		Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
		5	15	60	15	60
WRA	WRDA 64	6810 (47.0)	6653 (45.9)	6052 (41.7)	6009 (45.9)	6762 (46.6)
	Pozzolith 200N	6165 (42.5)	5917 (40.8)	6080 (41.9)	5902 (40.7)	6620 (45.6)
Retarder	Delvo	6368 (43.9)	6504 (44.8	6732 (46.4)	6569 (45.3)	6919 (47.7)
	Daratard 17	6899 (47.6)	7148 (49.3)	6887 (47.5)	7371 (50.8)	7145 (49.3)

Table 5-25. Compressive Strength (56-day) for Different Mixing Times and Mixing Speeds for the AD_{rd} Subgroup.

Mixtures with recommended admixture dosage		56-day Compressive Strength, psi (MPa)				
		Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
		5	15	60	15	60
WRA	WRDA 64	7157 (49.3)	6949 (47.9)	6853 (47.3)	6983 (48.1)	7115 (49.1
	Pozzolith 200N	6730 (46.4)	6602 (45.5)	6874 (47.4)	6767 (46.7)	7130 (49.2)
Retarder	Delvo	6668 (46.0)	7069 (48.7)	7223 (49.8)	7384 (50.9)	7256 (50.0)
	Daratard 17	7569 (52.2)	7693 (53.0)	7422 (51.2)	7946 (54.8)	7908 (54.5)

Table 5-26. Compressive Strength (28-day) for Different Mixing Times and Mixing Speeds for the AEA group.

Mixtures with AEA	28-day Compressive Strength, psi (MPa)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
MBAE 90	3650 (25.2)	3575 (24.6)	3336 (23.0)	3175 (21.9)	4020 (27.7)
Daravair	4404 (30.4)	3900 (26.9)	4339 (29.9)	3949 (27.2)	4507 (31.1)

Table 5-27. Compressive Strength (56-day) for Different Mixing Times and Mixing Speeds for the AD_{rd} Subgroup.

Mixtures with AEA	56-day Compressive Strength, psi (MPa)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
MBAE 90	3716 (25.6)	3865 (26.6)	3722 (25.7)	3593 (24.8)	4205 (29.0)
Daravair	3222 (22.2)	4536 (31.3)	4745 (32.7)	4221 (29.1)	4944 (34.1)

Table 5-28. Compressive Strength (28-day) for Different Mixing Times and Mixing Speeds for the AD_{hd} Subgroup.

Retarders	28-day Compressive Strength, psi (MPa)								
	Time of mixing, minutes (8 rpm)					Time of mixing, minutes (15 rpm)			
	5	15	60	90	180	15	60	90	180 or max
Recover	7108 (49.0)	6738 (46.5)	7550 (52.0)	7006 (48.3)	8039 (55.4)	7445 (51.3)	6805 (46.9)	7779 (53.6)	8256 (56.9)*
Delvo	6353 (43.8)	6351 (43.8)	7607 (52.4)	6463 (44.6)	7087 (48.8)	6924 (47.7)	7291 (50.3)	7140 (49.2)	964 (6.6)

*Mixture mixed to 120 minutes.
N.A.: not available

Table 5-29. Compressive Strength (56-day) for Different Mixing Times and Mixing Speeds for the AD_{hd} Subgroup.

Retarders	56-day Compressive Strength, psi (MPa)								
	Time of mixing, minutes (8 rpm)					Time of mixing, minutes (15 rpm)			
	5	15	60	90	180	15	60	90	180 or max
Recover	7108 (49.0)	6738 (46.5)	7550 (52.1)	7006 (48.3)	8039 (55.4)	7455 (51.4)	6805 (46.9)	7779 (53.6)	8256 (56.9)*
Delvo	6353 (43.8)	6351 (43.8)	7607 (52.5)	6463 (44.6)	7087 (48.9)	6924 (47.7)	7291 (50.3)	7140 (49.2)	964 (6.6)

*Mixture mixed to 120 minutes.
N.A.: not available

Table 5-30. Compressive Strength (28-day) for Different Mixing Times and Mixing Speeds for the SCM Group

Mixtures	28-day Compressive Strength, psi (MPa)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
20% slag	6013 (41)	5955 (41)	6059 (42)	6021 (42)	5786 (40)
40% slag	5269 (36)	5279 (36)	5451 (38)	5629 (39)	5457 (38)
20% FA	6016 (41)	5849 (40)	6184 (43)	6199 (43)	6073 (42)
30% FA	5006 (36)	5387 (36)	5316 (37)	5177 (35)	5356 (38)

Table 5-31. Compressive Strength (56-day) for Different Mixing Times and Mixing Speeds for the SCM Group

Mixtures	56-day Compressive Strength, psi (MPa)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
20% slag	6572 (45.3)	6865 (47.3)	6671 (40.6)	6682 (46.1)	4560 (31.4)
40% slag	6106 (42.1)	5893 (40.6)	6195 (42.7)	6243 (43.0)	6235 (43.0)
20% FA	6470 (44.6)	6389 (44.0)	6747 (46.5)	7062 (48.7)	6857 (47.3)
30% FA	5340 (44.0)	5898 (46.5)	6076 (41.9)	6042 (41.7)	6374 (43.9)

Statistical analyses are used to assess the difference in means of the different concrete groups as a function of mixing time and speed for the 28- and 56-day compressive strength of the different mixtures. Because the initial compressive strengths of the concrete varied, these values are first normalized and then assessed. The normalized 28-day and normalized 56-day compressive strength values are referred to as n-$f'cm_{28}$ and $f'cm_{56}$. Table 5-32 and Table 5-33 show the n-$f'cm_{28}$ for the different mixtures mixed for different times and speeds. Each value in Table 5-31 and Table 5-32 are the average of three specimens unless noted otherwise.

Table 5-32. Normalized Compressive Strength (28 day) for Different Groups of Mixture mixed at 8 rpm for Different Mixing Times.

Normalized 28-day Compressive Strength									
15 minutes					60 minutes				
CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
1.00	0.99	0.98	0.95	0.89	0.97	1.01	0.96	1.06	0.99
1.02	1.00	0.96	1.00	1.04	1.03	1.03	0.99	1.20	0.97
1.02	1.01	1.02			1.10	1.04	1.06		
1.04	0.97	1.04			1.03	1.03	1.00		
1.05					1.10				
0.99					0.99				
0.98					0.99				
1.00					1.06				
1.06					1.09				
1.00					1.02				
1.00					1.06				

Table 5-33. Normalized Compressive Strength (28 day) for Different Groups of Mixture mixed at 15 rpm for Different Mixing Times.

Normalized 28-day Compressive Strength									
15 minutes					60 minutes				
CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
0.94	1.00	0.98	1.05	0.90	0.94	0.96	0.99	0.96	1.02
1.04	1.07	0.96	1.09	0.93	1.02	1.04	1.07	1.15	1.17
1.00	1.02	1.03			1.07	1.06	1.09		
0.97	1.03	1.07			1.02	1.01	1.04		
1.02					0.94				
0.92					0.94				
0.98					0.99				
1.02					1.05				
1.01					1.01				
1.04					1.01				
1.00					1.04				

Table 5-34 and Table 5-35 show the statistical parameters for the 28-day f'cm at different mixing speeds. Average, standard deviations, and number of samples are shown.

Table 5-34. Statistical Parameters for the f'cm$_{28}$ of the Mixtures Mixed at 8 rpm.

Statistical Parameters	8 rpm mixtures									
	15 minutes					60 minutes				
	CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
Average	1.01	0.99	1.00	0.97	0.96	1.04	1.03	1.00	1.13	0.98
Standard Deviation	0.04	0.04	0.04	0.07	0.10	0.05	0.04	0.04	0.09	0.02
Number of Samples	33	12	12	6	6	33	12	12	6	6

Table 5-35. Statistical Parameters for the f'cm$_{28}$ of the Mixtures Mixed at 15 rpm.

Statistical Parameters	15 rpm mixtures									
	15 minutes					60 minutes				
	CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
Average	0.99	1.03	1.01	1.07	0.91	1.00	1.02	1.05	1.05	1.10
Standard Deviation	0.05	0.04	0.05	0.06	0.03	0.05	0.05	0.05	0.11	0.09
Number of Samples	32	12	12	6	6	33	12	12	6	6

Table 5-36 through Table 5-39 show the ANOVA tables for these groups. The calculated values were defined earlier. The ANOVA test indicates that there is no statistically significant difference between the means of the n-f'cm$_{28}$ for the CA, SCM, and AD_{rd} groups mixed for 15 minutes at 8 rpm at the 95 percent confidence level (p-value = 0.266). For the 60 minutes of mixing at 8 rpm, there is also no statistically significant difference between the mean n-f'cm of the same three groups at the 95 percent confidence level (p-value = 0.067). Similarly, these groups are also tested for difference in means when mixed at 15 rpm. The results indicate there is no statistical difference in the mean n-f'cm$_{28}$ between 15 and 60 minutes of mixing for the three groups (p-value = 0.099 and 0.068, respectively).

Table 5-36. ANOVA Test for the Groups Mixed for 15 minutes at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.00425	2	0.00212	1.36	0.266
Within groups	0.0846	54	0.00156		
Total (Corr.)	0.0889	56			

Table 5-37. ANOVA Test for the Groups Mixed for 60 minutes at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0126	2	0.00634	2.85	0.066
Within groups	0.120	54	0.00222		
Total (Corr.)	0.133	56			

Table 5-38. ANOVA Test for the Groups Mixed for 15 minutes at 15 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0112	2	0.00560	2.42	0.098
Within groups	0.122	53	0.00231		
Total (Corr.)	0.134	55			

Table 5-39. ANOVA Test for the Groups Mixed for 60 minutes at 15 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0158	2	0.00792	2.84	0.067
Within groups	0.150	54	0.00279		
Total (Corr.)	0.166	56			

Because there is no statistically significant difference between the means of the three groups mixed for the same times and speeds, the data from the three groups (CA, SCM, AD_{rd}) that share the same mixing times and speeds will be pooled together. This combined data will be referred to as the conventional mixtures. To assess the influence of mixing speed, the mixtures mixed at different speeds are compared. The conventional mixtures mixed at different speeds but at the same time are compared (i.e., conventional mixtures mixed for 15 minutes at 8 rpm versus conventional mixtures mixed for 15 minutes at 15 rpm). The t-test analysis indicates that there is no statistically significant difference between the mean n-$f'cm_{28}$ for conventional mixtures mixed for 15 minutes at

8 and 15 rpm (p-value = 0.839). Similarly for the mixtures mixed for 60 minutes at different speeds, there is no statistically significant difference between the n-$f'cm_{28}$ of mixtures mixed at 8 and 15 rpm (p-value = 0.192). This indicates that mixing speed likely does not influence the $f'cm_{28}$ for the conventional mixtures.

The data from 8 and 15 rpm are also pooled together to assess the influence of mixing time. The data from conventional mixtures mixed for 15 minutes at 8 and 15 rpm are combined and the mixtures mixed for 60 minutes at 8 and 15 rpm are combined. The t-test indicates that there is no statistically significance difference between the mean n-$f'cm_{28}$ for the conventional mixtures mixed for 15 and 60 minutes (p-value = 0.445). This indicates that mixing time does not influence the $f'cm_{28}$ for the conventional mixtures. Therefore, no model is needed to predict the 28-day f'cm as function of time and speed. This concludes the statistical analyses for the conventional mixtures. This statistical analysis process is repeated for the AD_{hd} and AEA group and the 56-day f'cm for all the groups.

For the AD_{hd} group, it was found that there is a statistically significant difference in the f'cm between the mixtures containing admixtures from different manufacturers. For admixtures from both manufacturers, the statistical analysis indicates there is statistically significant difference in the mean n-$f'cm_{28}$ for the AD_{hd} mixtures mixed for different mixing times up to 180 minutes (p-value = 0.000 for mixture containing “Recover” and 0.002 for mixtures containing “Delvo”). For the AEA group, it was also found that the two admixtures from the different manufacturers exhibited statistically significant differences in mean n-f'cm_{28} at the 95 percent confidence level (p-value = 0.012). It was determined that mixing speed does not significantly influence the n-f'cm_{28} but mixing time does significantly influence the n-f'cm_{28} for the mixtures containing AEA. Although significantly different, chemical admixtures are proprietary and can vary significantly between different manufacturers. Therefore, general trends will be shown but no model will be developed.

Figure 5-72 and Figure 5-73 show the f'cm_{28} as a function of mixing time for the 8 and 15 rpm conventional mixtures, respectively. Figure 5-74 and Figure 5-75 show the n-f'cm_{28} versus mixing time for these same mixtures. For the 8 rpm mixture, the average 28-compressive strength exhibited no significant change when mixed for 15 minutes, and increased 2 percent when mixed for 60 minutes. For the 15 rpm, the average 28-day compressive strength exhibited no significant change when mixed to 15 minutes and 60 minutes.

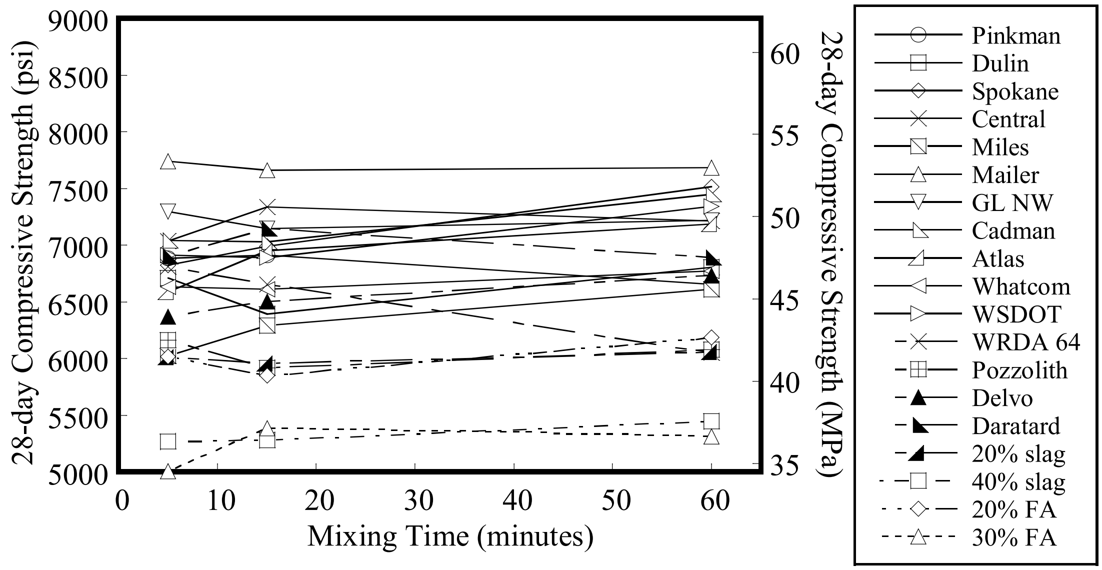


Figure 5-72. Mixing Time Versus 28-day f'cm for Conventional Mixtures (8 rpm).

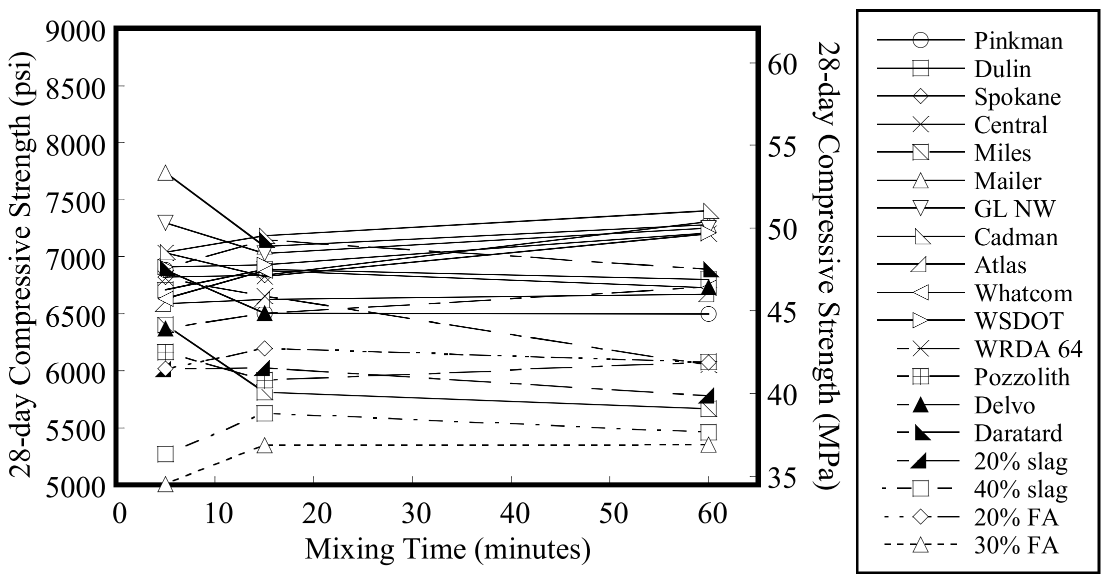


Figure 5-73. Mixing Time Versus 28-day f'cm for Conventional Mixtures (15 rpm).

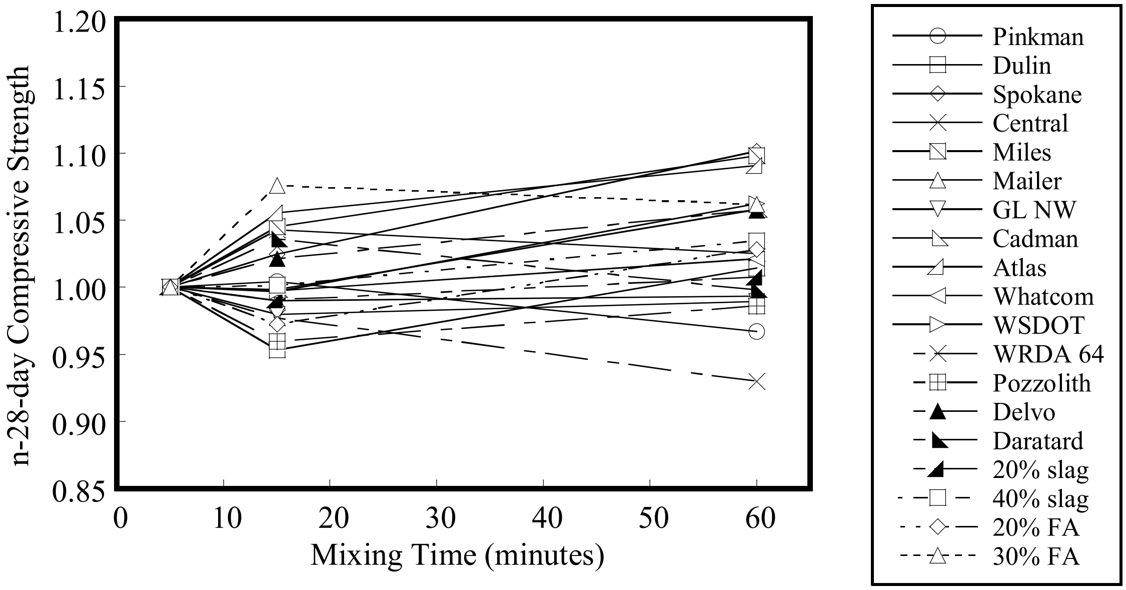


Figure 5-74. Normalized 28-day f'cm for Conventional Mixtures (8 rpm).

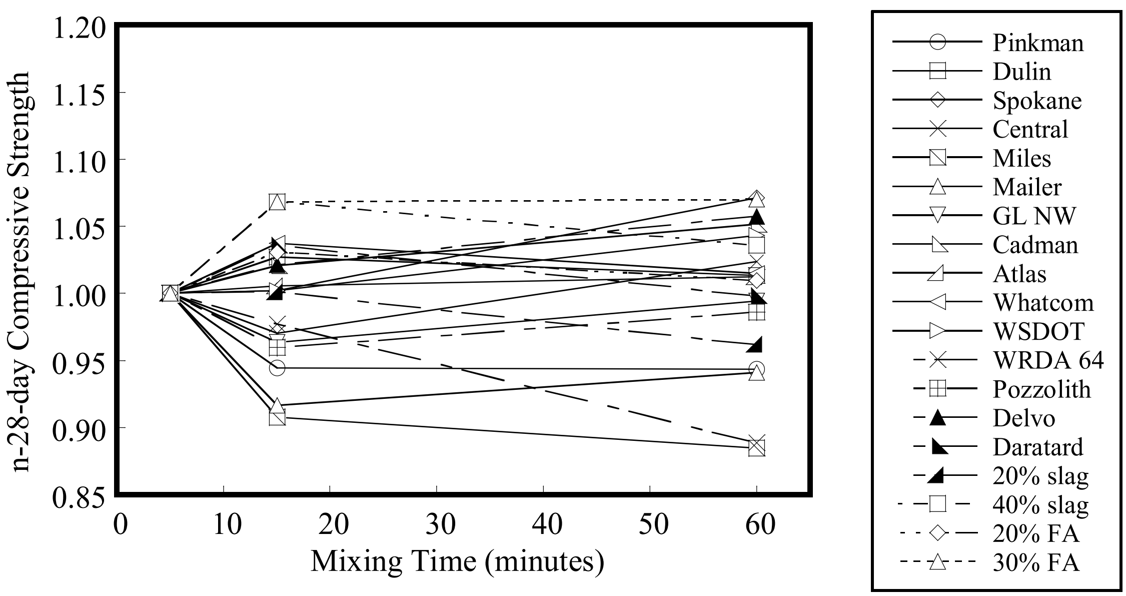


Figure 5-75. Normalized 28-day f'cm for Conventional Mixtures (15 rpm).

The AD_{hd} mixtures were mixed for up to 180 minutes because of their high dosage of retarders. Figure 5-76 and Figure 5-77 show the $f'cm_{28}$ and n-$f'cm_{28}$ for the mixtures containing high dosage of admixtures, respectively.

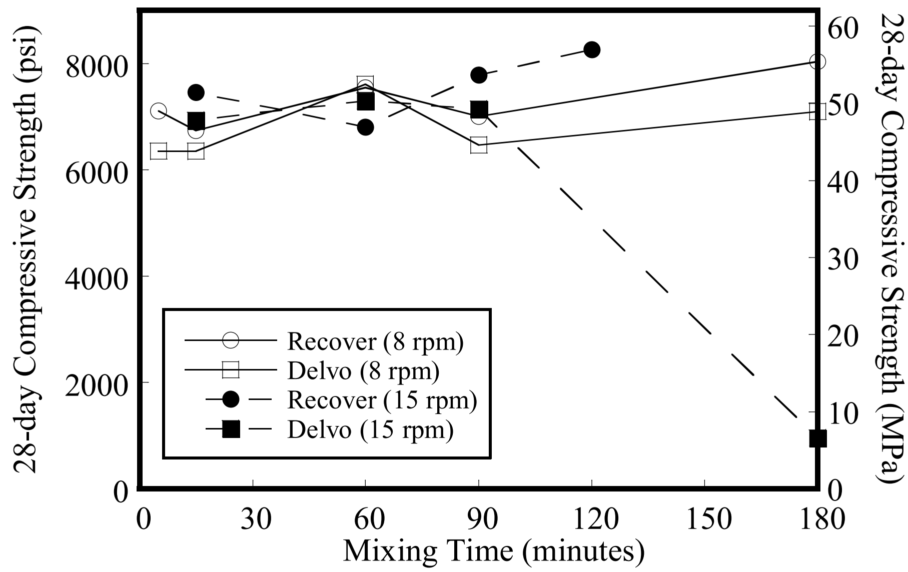


Figure 5-76. Mixing Time versus f'cm$_{28}$ for the AD$_{hd}$ Group Mixtures.

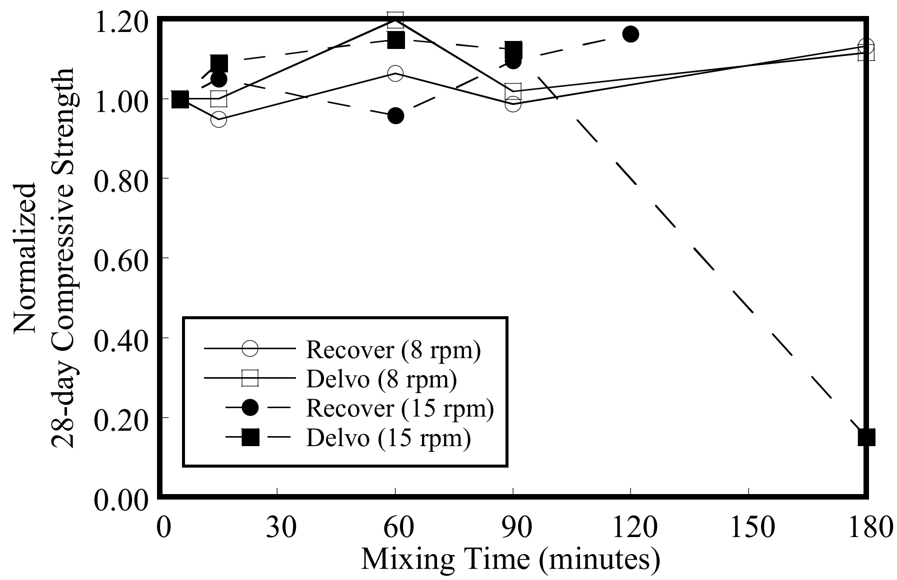


Figure 5-77. Mixing Time versus n-f'cm$_{28}$ for the AD$_{hd}$ Group Mixtures.

For the 8 rpm mixtures, a small increase in f'cm$_{28}$ occurs with increasing mixing times. The f'cm$_{28}$ increased 13 percent when mixing for 180 minutes at 8 rpm. No negative impact was observed for the f'cm$_{28}$ with increasing mixing times up to 180 minutes.

However, at 15 rpm, the mixtures containing Delvo exhibited an 80 percent loss in compressive strength when mixed for 180 minutes. This reduction in strength was a result of poor consolidation of the specimens. This mixture had a slump of zero when sampled from the mixer. Large air voids and honeycombing in the specimen caused the decrease in compressive strength.

Figure 5-78 and Figure 5-79 show the f'cm_{28} and n-f'cm_{28} for the mixtures containing AEA, respectively.

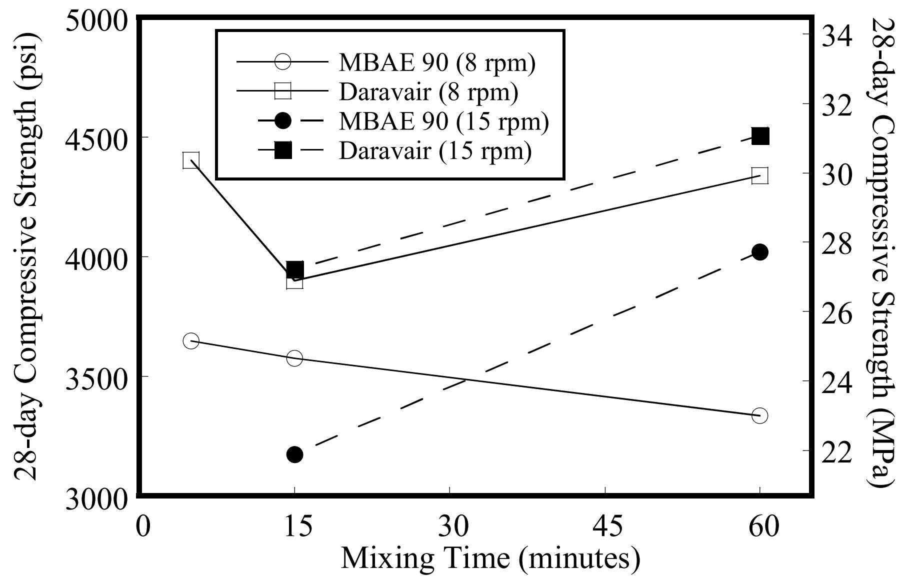


Figure 5-78. Mixing Time versus f'cm_{28} for the AEA Group Mixtures.

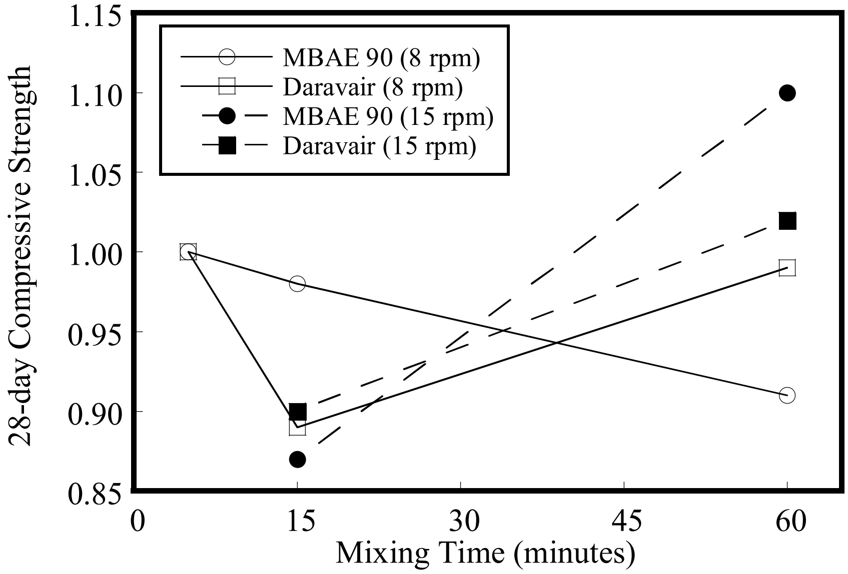


Figure 5-79. Mixing Time versus n-f'cm$_{28}$ for the AEA Group Mixtures.

Because these mixtures exhibited no statistically significant difference in mean f'cm$_{28}$ values for mixing times from 5 to 60 minutes, the f'cm$_{28}$ values are assumed to be similar. Therefore, no model is needed. This completes the analyses on the influence on of mixing time on f'cm$_{28}$.

A similar analysis process for the 56-day compressive strength follows. Figures 5-80 through 5-83 show the 56-day and normalized 56-day compressive strengths. Table 5-40 and Table 5-41 show the normalized 56-day f'cm values for the different groups mixed at different speeds. Note that f'cm$_{56}$ for mixtures containing high dosage of admixtures were not assessed for this group.

Table 5-40. Normalized Compressive Strength (56 day) for Different Groups of Mixture mixed at 8 rpm for Different Mixing Times.

Normalized 56-day Compressive Strength							
15 minutes				60 minutes			
CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
1.02	1.04	0.97	0.94	0.97	1.02	0.96	0.98
1.03	1.97	0.98	1.04	1.05	1.01	1.02	1.00
1.02	1.10	1.06		1.10	1.14	1.08	
1.03	0.99	1.02		1.04	1.04	0.98	
1.05				1.03			
1.02				0.98			
1.09				1.02			
0.96				0.97			
1.00				1.06			
0.98				1.05			
0.98				1.07			

Table 5-41. Normalized Compressive Strength (56 day) for Different Groups of Mixture mixed at 15 rpm for Different Mixing Times.

Normalized 56-day Compressive Strength							
15 minutes				60 minutes			
CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
0.96	1.02	0.98	0.87	0.97	1.00	0.99	1.02
1.01	1.02	1.01	0.97	0.97	1.02	1.06	1.13
1.08	1.12	1.11		1.10	1.19	1.19	
0.97	1.09	1.05		1.04	1.06	0.94	
1.01				1.03			
0.94				0.96			
1.09				1.09			
0.99				0.97			
1.04				1.06			
0.98				1.01			
1.02				1.07			

Table 5-42 and Table 5-43 show the statistical parameters for the 56-day f'cm for different mixing speeds. The tables include the average, standard deviation, and number of samples.

Table 5-42. Statistical Parameters for the $f'cm_{28}$ of the Mixtures Mixed at 8 rpm.

Statistical Parameters	8 rpm mixtures							
	15 minutes				60 minutes			
	CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
Average	1.02	1.03	1.01	0.99	1.03	1.05	1.01	0.99
Standard Deviation	0.05	0.06	0.05	0.06	0.05	0.07	0.06	0.03
Number of Samples	32	12	12	6	32	12	12	6

Table 5-43. Statistical Parameters for the $f'cm_{28}$ of the Mixtures Mixed at 15 rpm.

Statistical Parameters	15 rpm mixtures							
	15 minutes				60 minutes			
	CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
Average	1.01	1.06	1.03	0.92	1.02	1.07	1.05	1.08
Standard Deviation	0.06	0.06	0.06	0.06	0.06	0.08	0.10	0.06
Number of Samples	32	12	12	6	33	12	12	6

Table 5-44 through Table 5-47 show the ANOVA tables for these groups. The calculated values were defined earlier. The ANOVA test indicates that there is no statistically significant difference between the means of the n-$f'cm_{28}$ for the CA, SCM, and AD_{rd} groups mixed for 15 minutes at 8 rpm at the 95 percent confidence level (p-value = 0.534). For the 60 minutes of mixing at 8 rpm, there is also no statistically significant difference between the mean n-f'cm of the same three groups at the 95 percent confidence level (p-value = 0.107). Similarly, these groups are also tested for difference in means between the groups when mixed at 15 rpm. The results indicate there is no statistical difference between the mean n-f'cm_{56} of the group when mixed for 60 minutes (p-value = 0.163, 95 percent confidence level). However, when mixtures were mixed for 15 minutes at 15 rpm, ANOVA test indicates that there is a statistically significant difference between the 56-day n-f'cm of the four groups at the 95 percent confidence level (p-value = 0.0001).

Table 5-44. ANOVA Test for the Groups Mixed for 15 minutes at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.00586	3	0.00195	0.74	0.534
Within groups	0.153	58	0.00264		
Total (Corr.)	0.159	61			

Table 5-45. ANOVA Test for the Groups Mixed for 60 minutes at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0184	3	0.00615	2.13	0.107
Within groups	0.167	58	0.00289		
Total (Corr.)	0.18	61			

Table 5-46. ANOVA Test for the Groups Mixed for 15 minutes at 15 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0886	3	0.0295	8.81	0.0001
Within groups	0.194	58	0.0034		
Total (Corr.)	0.283	61			

Table 5-47. ANOVA Test for the Groups Mixed for 60 minutes at 15 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0271	3	0.00904	1.77	0.163
Within groups	0.301	59	0.00511		
Total (Corr.)	0.328	62			

Because there is a statistically significant difference between the meas f'cm_{56} values of the four groups it is best to analyze these group individually. ANOVA testing is used to compare the mean n-f'cm_{56} values of the individual groups at different mixing times and speeds. Statistical testing indicates that for the CA group mixed for 15 minutes at 8 rpm, 60 minutes at 8 rpm, 15 minutes at 15 rpm, and 60 minutes at 15 rpm; there is no statistically significant difference between the mean n-f'cm_{56} of these mixtures (ANOVA p-value = 0.395). ANOVA testing also indicates similar result for the SCM and admixture groups (p-value = 0.452 and 0.462, respectively). Therefore, no model for the 56-day compressive strength as a function of mixing time or mixing speed will be developed for the CA, SCM, and AD_{rd} groups.

Similar to the n-f'cm_{28}, statistical analyses also indicate that there is a statistically significant difference in the n-f'cm_{56} of the AEA group mixed at different speeds. As noted earlier, although significantly different, chemical admixtures are proprietary and can vary significantly between different manufacturers. Therefore, general trends will be shown but no model will be developed.

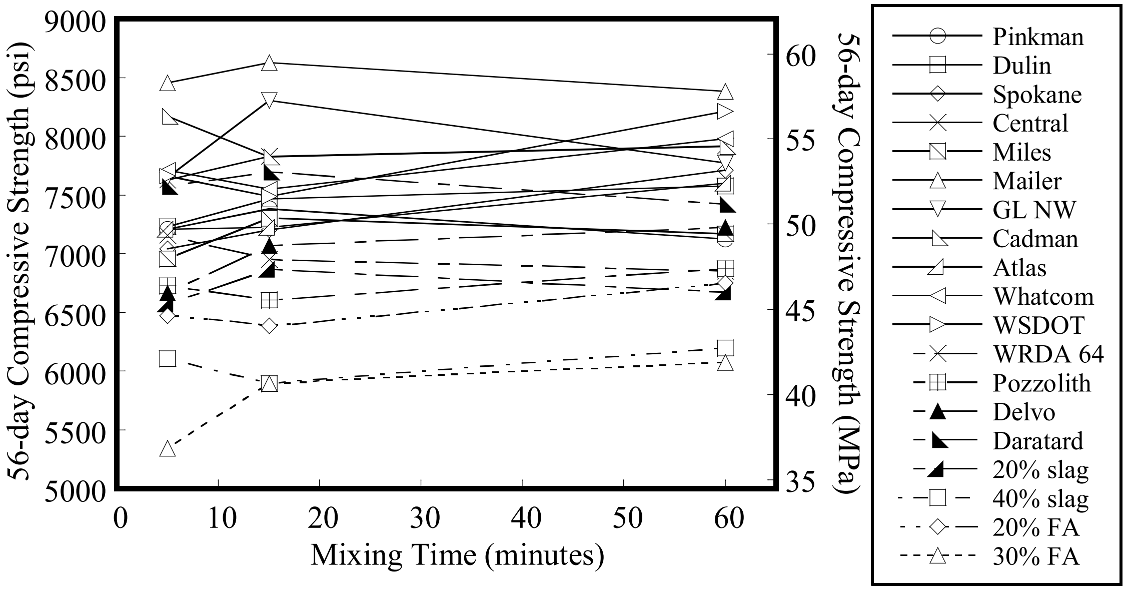


Figure 5-80. Mixing Time versus f'cm$_{56}$ for Conventional Mixtures (8 rpm).

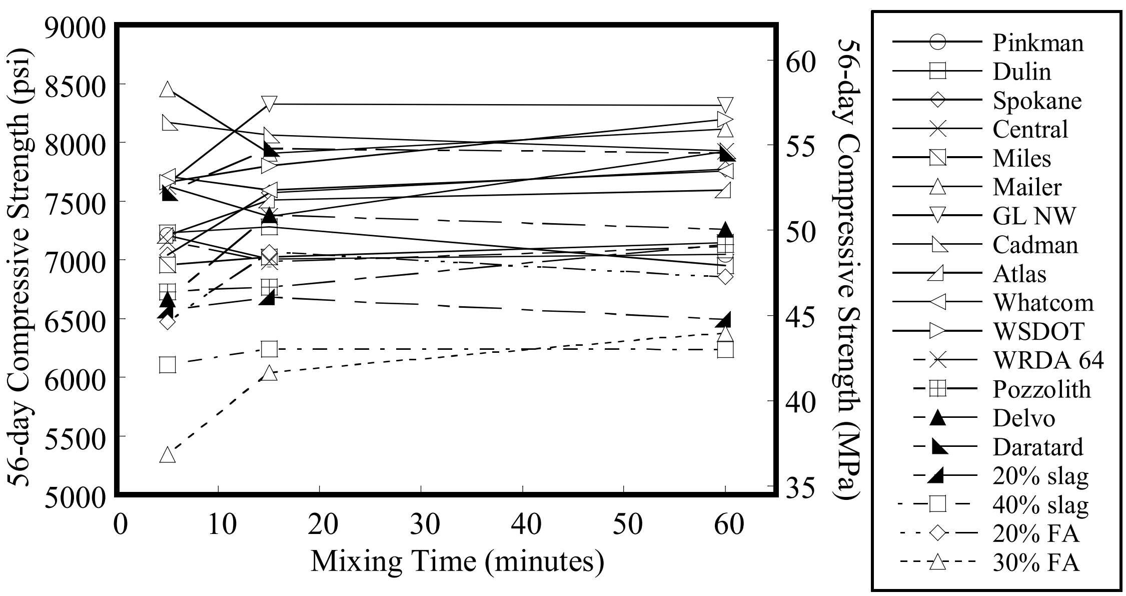


Figure 5-81. Mixing Time versus f'cm$_{56}$ for Conventional Mixtures (15 rpm).

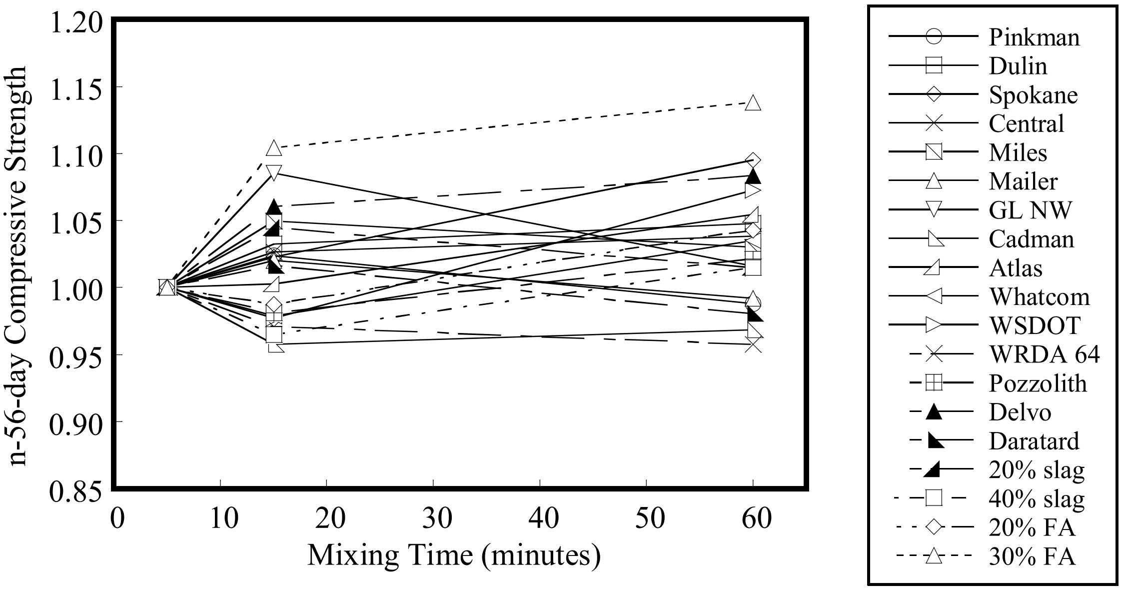


Figure 5-82. Normalized f'cm$_{56}$ for Conventional Mixtures (8 rpm).

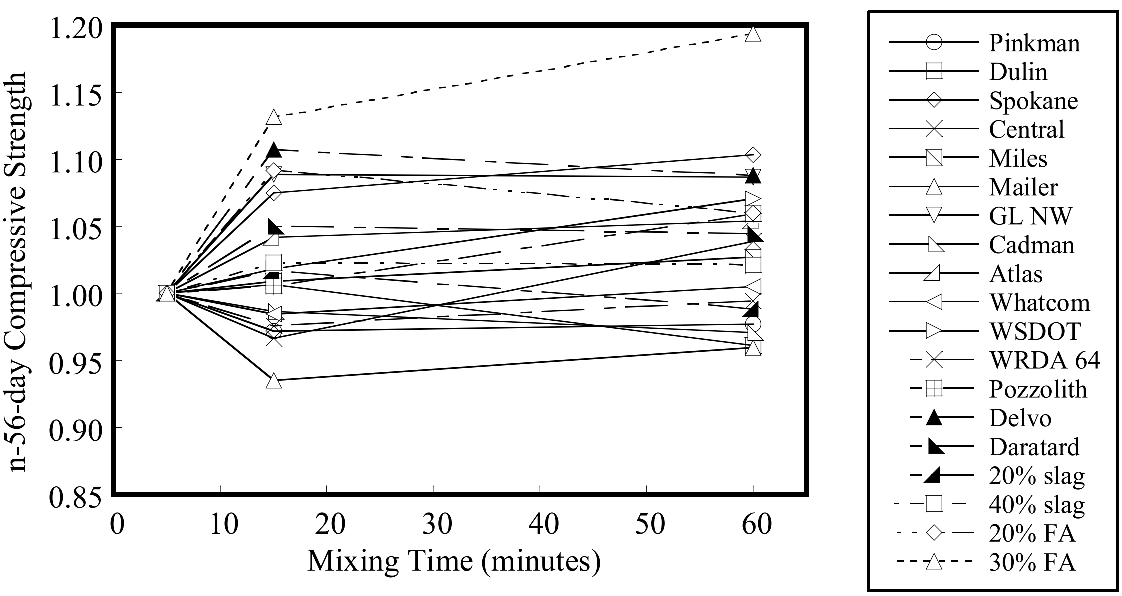


Figure 5-83. Normalized f'cm$_{56}$ for Conventional Mixtures (15 rpm).

Figure 5-84 and Figure 5-85 show the f'cm$_{28}$ and n-f'cm$_{28}$ for the mixtures containing AEA, respectively.

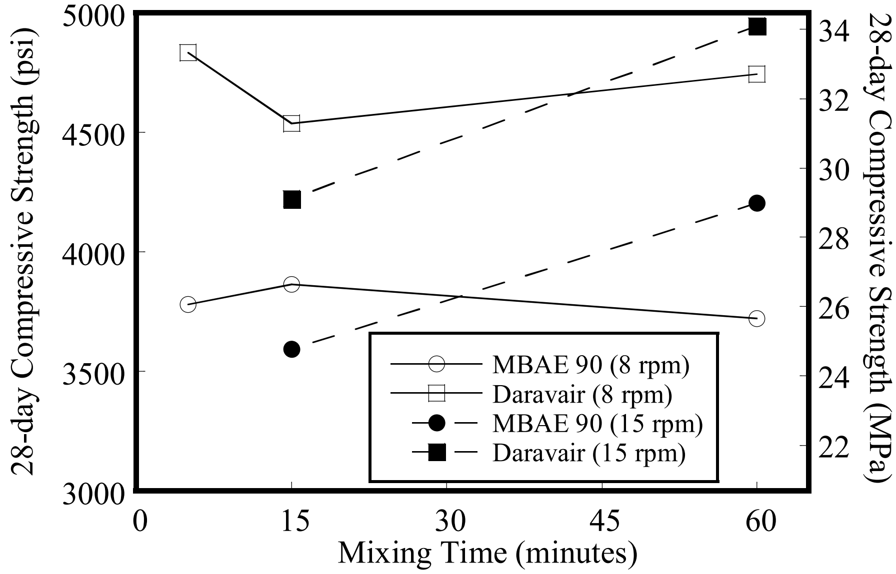


Figure 5-84. Mixing Time versus f'cm$_{56}$ for the AEA Group Mixtures.

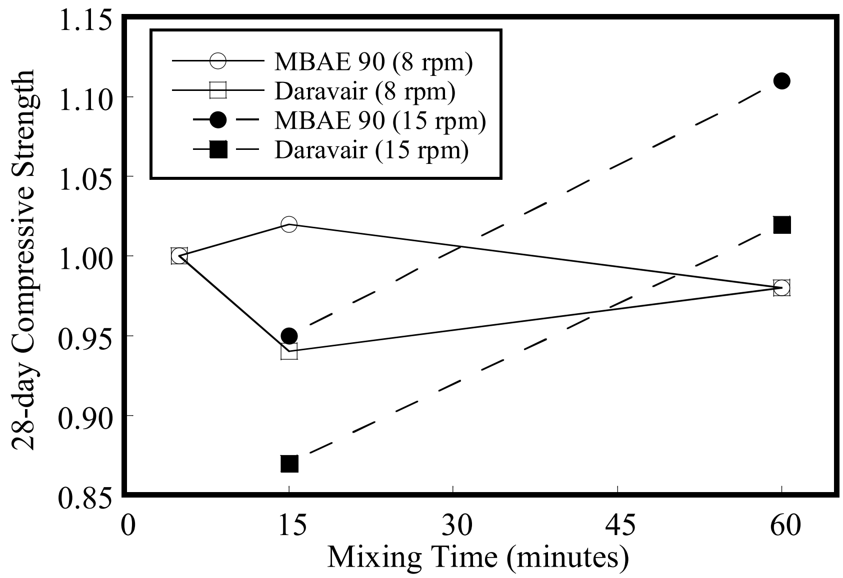


Figure 5-85. Mixing Time versus n-f'cm$_{56}$ for the AEA Group Mixtures.

5.3.3 Potential Influence of Mixing Time on Apparent Chloride Diffusivity

5.3.3.1 CA Group Mixtures

Apparent chloride diffusivity was another variable investigated during this research. Table 5-48 shows the apparent chloride diffusion coefficients for the concrete produced with the 11 coarse aggregates. These coefficients are the average from triplicate samples.

Table 5-48. Effect of Mixing Time on Chloride Diffusion Coefficient

Aggregate Source	Apparent Chloride Diffusion Coefficient D_a, in^2/s (m^2/s)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
Dulin	9.22E-9 (5.95E-12)	1.21E-8 (7.80E-12)	1.16E-8 (7.51E-12)	1.09E-8 (7.01E-12)	7.41E-9 (4.78E-12)
Central	8.48E-9 (5.47E-12)	1.02E-8 (6.58E-12)	9.22E-9 (7.00E-12)	1.13E-8 (7.27E-12)	1.17E-8 (7.54E-12)
Spokane	6.91E-9 (4.46E-12)	1.01E-8 (6.52E-12)	1.39E-8 (8.96E-12)	1.05E-8 (6.77E-12)	9.32E-9 (6.01E-12)
WSDOT	N.A.	7.63E-9 (4.92E-12)	1.13E-8 (7.32E-12)	9.46E-9 (6.10E-12)	7.44E-9 (4.80E-12)
Miles	1.80E-8 (1.16E-11)	2.11E-8 (1.36E-11)	1.92E-8 (1.24E-11)	1.91E-8 (1.23E-11)	2.06E-8 (1.33E-11)
Cadman	N.A.	1.09E-8 (7.05E-12)	1.1E-8 (7.12E-12)	1.43E-8 (9.25E-12)	1.04E-8 (6.70E-12)
Glacier NW	N.A.	1.21E-8 (7.82E-12)	2.0E-8 (1.29E-11)	1.69E-8 (1.09E-11)	1.67E-8 (1.08E-11)
Whatcom	N.A.	1.03E-8 (6.63E-12)	1.37E-8 (8.86E-12)	1.0E-8 (6.48E-12)	1.17E-8 (7.52E-12)
Pinkham	1.40E-8 (9.10E-12)	1.43E-8 (9.20E-12)	1.40E-8 (9.01E-12)	1.41E-8 (9.12E-12)	1.28E-8 (8.28E-12)
Atlas	N.A.	9.47E-9 (6.11E-12)	1.01E-8 (6.54E-12)	1.21E-8 (7.83E-12)	1.11E-8 (7.18E-12)
Maier	9.44E-9 (6.09E-12)	1.32E-8 (8.54E-12)	1.75E-8 (1.13E-11)	1.98E-8 (1.28E-11)	1.69E-8 (1.09E-11)

N.A.: not available

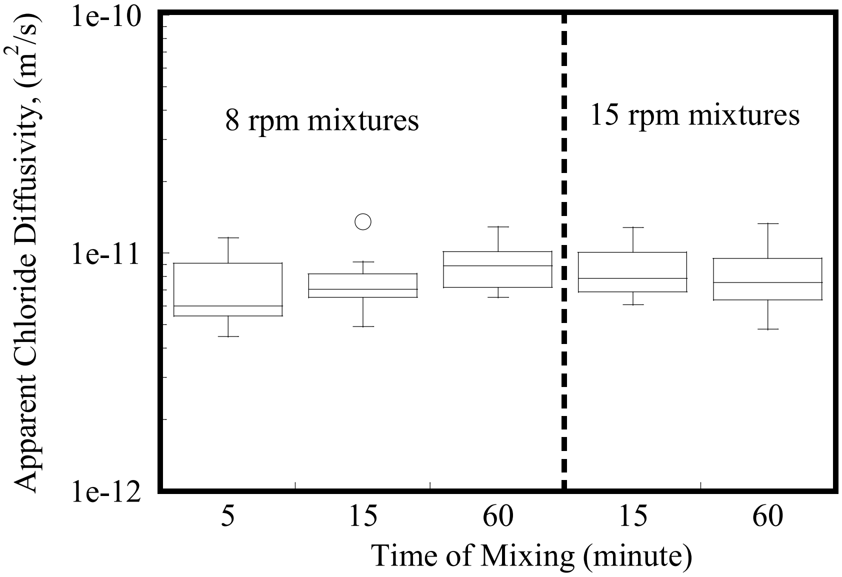


Figure 5-86. Box Plot for Apparent Chloride Diffusivity for the CA Group.

ANOVA analysis indicates there is not a statistically difference in the mean apparent chloride diffusivity for the CA group mixture at the 95 percent confidence level (p-value = 0.503).

5.3.3.2 Admixture Group Mixtures

Table 5-49 shows the diffusion data for the mixtures containing admixtures. ANOVA analyses indicates there is not a statistically significant difference in the mean apparent chloride diffusivity for the admixture group at the 95 percent confidence level (p-value = 0.464).

Table 5-49. Apparent Chloride Diffusivity for the Mixtures Containing Admixtures.

Mixtures	Apparent Chloride Diffusivity D_a, in^2/s (m^2/s)			
	Time of mix, minutes (8 rpm)		Time of mix, minutes (15 rpm)	
	15	60	15	60
WRDA 64	5.57E-9 (3.60E-12)	5.1E-9 (3.29E-12)	N.A.	1.49E-8 (9.63E-12)
Pozzolith 200N	5.69E-9 (3.67E-12)	1.15E-8 (7.44E-12)	6.67E-9 (4.30E-12)	2.18E-8 (1.41E-11)
Delvo	1.04E-8 (6.70E-12)	5.39E-9 (3.48E-12)	9.11E-9 (5.88E-12)	1.61E-8 (1.04E-11)
Daratard 17	1.89E-8 (1.22E-11)	1.97E-8 (1.27E-11)	2.63E-8 (1.70E-11)	2.34E-8 (1.51E-11)
MBAE 90	1.94E-8 (1.25E-11)	5.39E-9 (3.48E-12)	2.13E-8 (1.37E-11)	4.56E-9 (2.94E-12)
Daravair	9.92E-9 (6.40E-12)	1.41E-8 (9.08E-12)	1.38E-8 (8.93E-12)	1.18E-8 (7.60E-12)

N.A.: not available

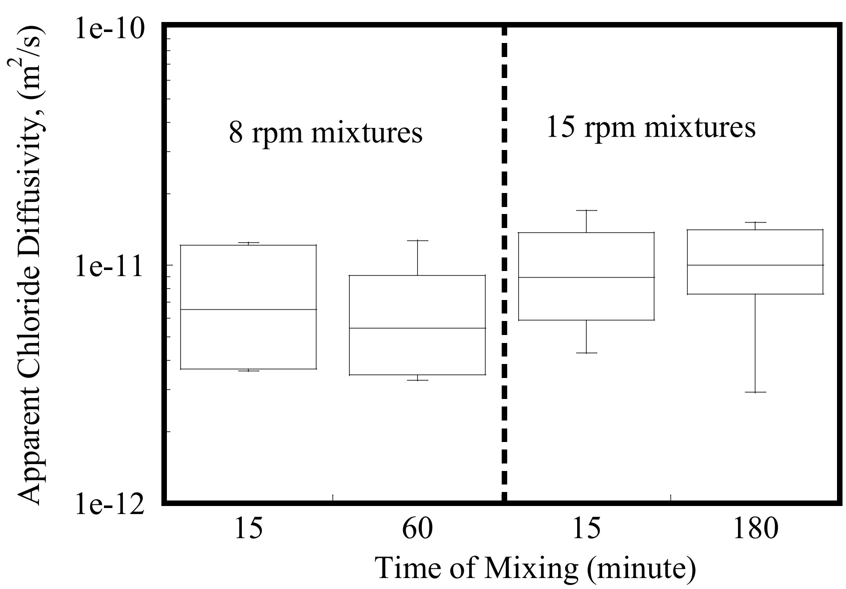


Figure 5-87. Box Plot of Apparent Chloride Diffusivity for Admixture Group.

ANOVA analyses indicate there is not a statistically significant difference in the mean apparent chloride diffusivity for the SCMs group mixture at the 95 percent confidence level (p-value = 0.251).

5.3.3.3 SCMs Group Mixtures

Table 5-50 shows the D_a for the SCM mixtures and Figure 5-88 shows the box plot for these mixtures. ANOVA analysis indicates there is not a statistically difference in the mean apparent chloride diffusivity for the SCM group mixture at the 95 percent confidence level (p-value = 0.454). As such, no model will be developed.

Table 5-50. Apparent Chloride Diffusivity for the SCMs Mixtures.

Mixtures	Apparent Chloride Diffusivity D_a, in^2/s (m^2/s)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
20% slag	N.A.	1.25E-8 (8.09E-12)	8.76E-9 (5.65E-12)	1.14E-8 (7.38E-12)	7.72E-9 (4.98E-12)
40% slag	N.A.	3.93E-9 (2.54E-12)	3.80E-9 (2.45E-12)	7.32E-9 (4.72E-12)	8.49E-9 (5.48E-12)
20% FA	N.A.	7.41E-9 (4.78E-12)	6.54E-9 (4.22E-12)	7.05E-9 (4.55E-12)	3.84E-8 (2.48E-11)
30% FA	N.A.	1.62E-8 (1.04E-11)	1.55E-8 (9.98E-12)	1.24E-8 (8.01E-12)	1.44E-8 (9.29E-12)

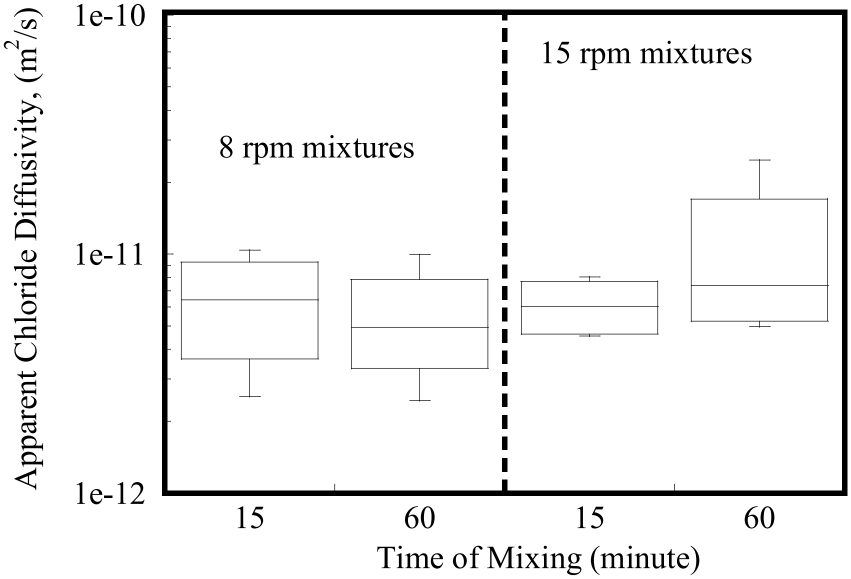


Figure 5-88. Box Plot of Concrete Apparent Chloride Diffusivity for SCM Group.

The mean apparent chloride diffusivity for the individual mixture groups (CA, SCM, AD) mixed at different times and speeds were compared using ANOVA testing. The results indicate that there is no significant difference in the mean apparent chloride diffusion coefficients of mixtures mixed at different mixing times and at different mixing speeds.

5.3.4 Potential Influence of Mixing Time on Freeze-thaw Performance

Selective mixtures were assessed for the influence of mixing time on freeze-thaw performance of the concrete. Two mixtures with different coarse aggregates (non-AEA) and two mixtures containing AEA were tested. These specimens were subjected up to 300 freeze-thaw cycles or until the relative dynamic modulus was reduced to 60 percent of the original dynamic modulus, whichever came first. Specimens were assumed to fail when the relative dynamic modulus falls below 60 percent of the initial dynamic modulus. Table 5-51 and Table 5-52 show the values for the mixtures containing AEA and for the mixtures without AEA, respectively.

Table 5-51. Relative Dynamic Modulus for Mixtures Containing AEA.

Mixtures	Relative Dynamic Modulus, % (cycles)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
MBAE 90	N.A.	100 (296)	100 (296)	99 (296)	99 (296)
Daravair	N.A.	101 (296)	100 (296)	101 (296)	97 (296)

Table 5-52. Relative Dynamic Modulus for Non-AEA Mixtures.

Mixtures	Relative Dynamic Modulus, % (cycles)				
	Time of mix, minutes (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
Mile	N.A.	60 (17)	60 (19)	60 (19)	60 (17)
Maier	N.A.	60 (38)	60 (38)	60 (45)	60 (46)

For the mixture containing AEA, the relative dynamic modulus does not change significantly after the 300 cycles specified by ASTM C666. In addition, mixtures mixed at different speeds or times do not seem to be significantly different from each other. For mixtures without AEA mixed at different mixing times and mixing speeds the relative dynamic modulus of these mixtures reached 60 percent before the 300 cycles. However, for the same mixtures mixed for 15 minutes and 60 minutes, their relative dynamic modulus reached 60 percent after approximately the same number of cycles (17 cycles for concrete with Miles coarse aggregare and 38 cycles for concrete containing the Maier coarse aggregate). This indicates that mixing time likely does not influence the freeze-thaw performance of laboratory mixed concrete.

5.3.5 Potential Influence of Mixing Time on Modulus of Elasticity

This section presents the analysis on the potential influence of mixing time on the modulus of elasticity (MOE) for the laboratory-mixed concrete. The MOE was evaluated at 28 days after casting. Table 5-32 shows the MOE values for mixtures mixed for different mixing times and speeds. Due to limited data, only trends are shown for the mixtures containing retarder A. Figure 5-89 and Figure 5-90 show the MOE values of this mixture as a function of mixing times mixed at 8 and 15 rpm, respectively.

Table 5-53. Modulus of Elasticity for Concrete Mixed in the Laboratory.

Modulus of Elasticity, ksi (Gpa)						
Mixing Speed (rpm)	8 rpm				15 rpm	
Mixing Time (minutes)	5	60	90	180	15	180
Retarder A	5441 (37.5)	5480 (37.8)	5264 (36.3)	5731 (39.5)	5452 (37.6)	5343 (36.8)
	5481 (37.8)	5308 (36.6)	5244 (36.2)	5594 (38.6)	5717 (39.4)	5193 (35.8)
Retarder B	5449 (37.6)	5834 (40.2)	5413 (37.3)	5440 (37.5)	5397 (37.2)	1690 (11.7)
	5277 (36.4)	5589 (38.5)	5342 (36.8)	5438 (37.5)	5267 (36.3)	2681 (18.5)
	5399 (37.2)	5274 (36.4)	5316 (36.6)	5432 (37.4)	5417 (37.3)	1278 (8.8)
Retarder B & AEA	4264 (29.4)	3783 (26.1)	3876 (26.7)	5073 (35)	4111 (28.3)	3494 (24.1)
	4421 (30.5)	3810 (26.3)	3804 (26.2)	5370 (37)	4246 (29.3)	4293 (29.6)
	4191 (28.9)	3708 (25.6)	3887 (26.8)	5056 (34.9)	4266 (29.4)	4720 (32.5)

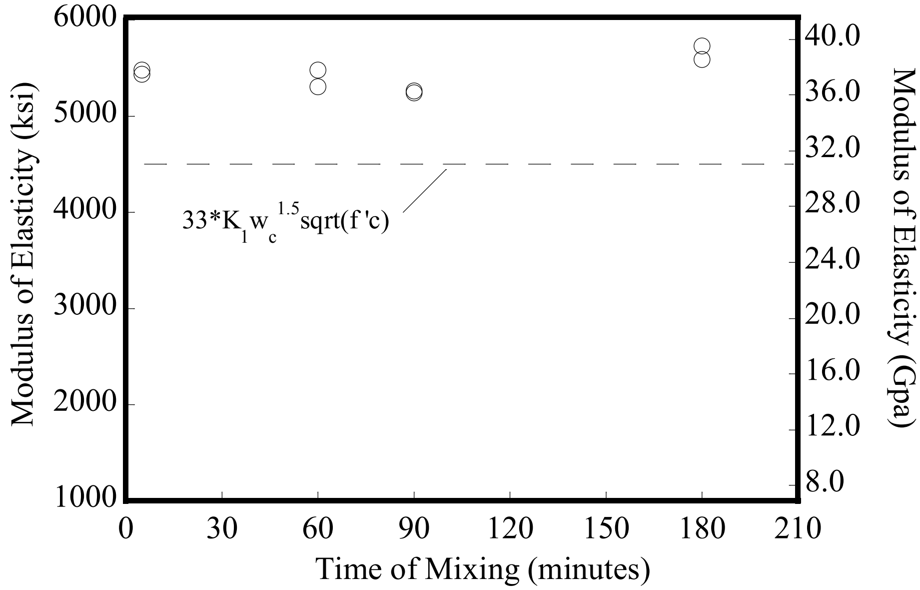


Figure 5-89. MOE versus Time of Mixing for the Mixtures Containing Retarder A (8 rpm).

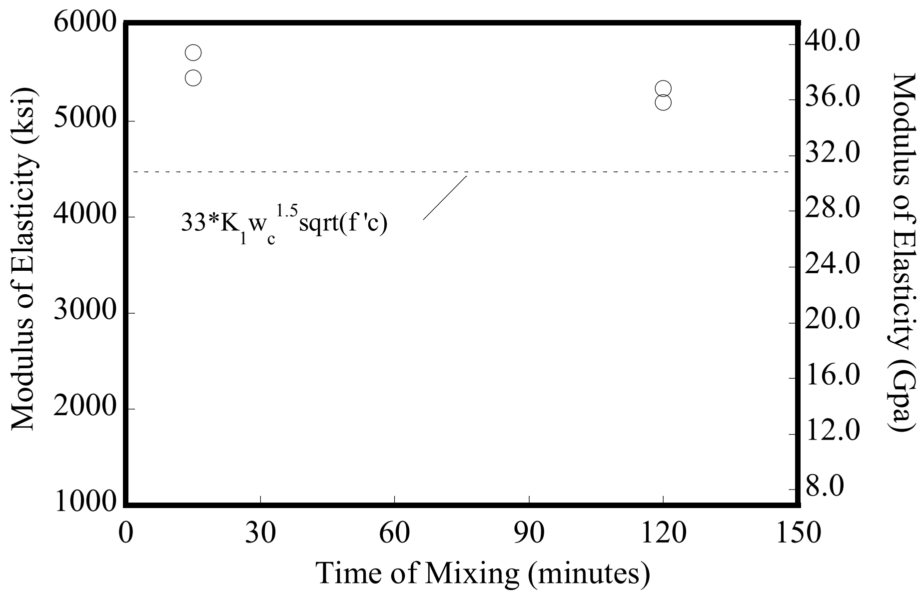


Figure 5-90. MOE versus Time of Mixing for the Mixtures Containing Retarder A (15 rpm).

Figure 5-89 and Figure 5-90 show that the MOE values of the mixtures containing retarder A can be mixed up to 180 minutes at 8 rpm and up to 120 minutes at 15 rpm without detrimentally affecting the MOE values. The MOE values of these mixtures are well above the estimated MOE value (AASHTO) for a 5200 psi (35.9 MPa) concrete.

For mixtures containing retarder B, ANOVA analysis indicates that there is no statistically significant difference between the mean MOE of mixtures mixed for up to 180 minutes at 8 rpm. However, at a speed of 15 rpm, the mixtures mixed for 180 minutes exhibited a significant reduction in MOE values. This reduction is a result of the low workability of the mixtures, which resulted in honeycombing and voids in specimens. Note that when these mixtures maintained sufficient workability, the MOE values are well above the estimated MOE value for a 5200 psi concrete per AASHTO as shown in Figure 5-91.

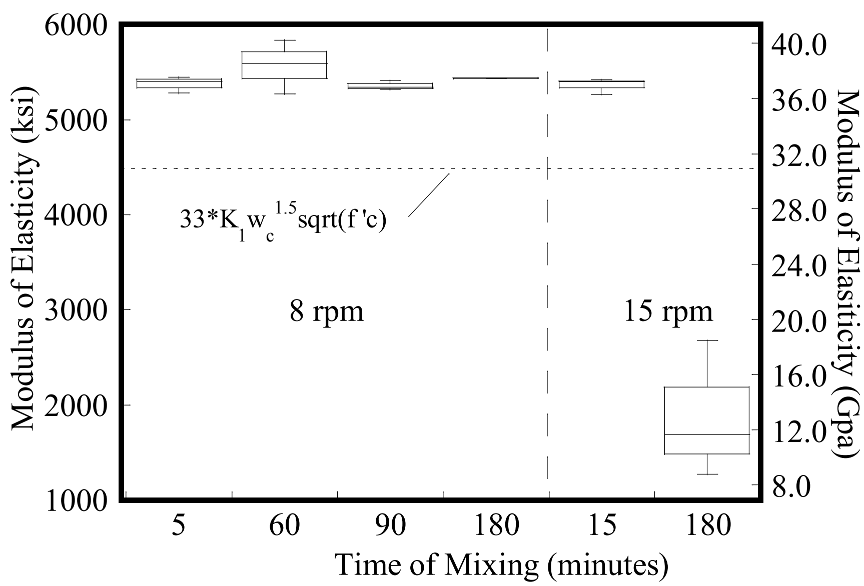


Figure 5-91. Box Plot for MOE of the Mixtures Containing Retarder B.

For the mixtures containing both retarder B and AEA, even though the ANOVA test indicates that the mean MOE values for mixtures mixed at different mixing times exhibited statistically significant differences for both mixing speeds, the mean MOE values are all above the estimated MOE value for a 3200 psi (22 MPa) concrete per AASHTO prediction equations.

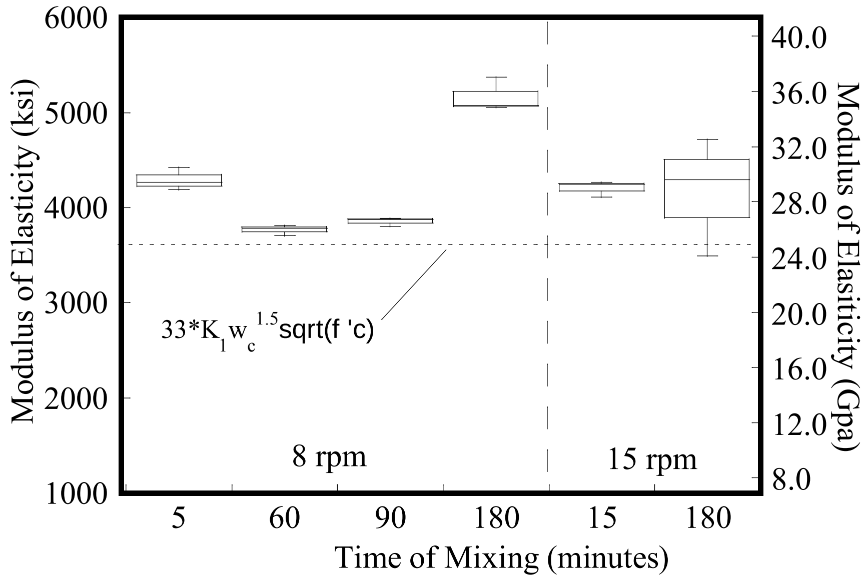


Figure 5-92. Box Plot for MOE of the Mixtures Containing Retarder B and AEA

5.3.6 Potential Influence of Mixing Time on Modulus of Rupture

The potential influence of mixing time on MOR is assessed in this section. Statistical analyses are used to compare the mean MOR values of mixtures mixed for different times and speeds. Table 5-54 shows MOR values for these mixtures. Figure 5-93 and Figure 5-94 show these values plotted as a function of mixing time for the 8 and 15 rpm, respectively.

Table 5-54. Modulus of Rupture for Mixtures Mixed for Different Times.

Modulus of Rupture, psi (Mpa)						
Mixing Speed (rpm)	8 rpm				15 rpm	
Mixing Time (minutes)	5	60	90	180	15	180
Retarder A	676 (4.7)	650 (4.5)	607 (4.2)	513 (3.5)	736 (5.1)	785 (5.4)
	659 (4.5)	721 (5.0)	652 (4.5)	514 (3.5)	716 (4.9)	649 (4.5)
	600 (4.1)	664 (4.6)	649 (4.5)	718 (5.0)	762 (5.3)	615 (4.2)
Retarder B	749 (5.2)	694 (4.8)	699 (4.8)	648 (4.5)	963 (6.6)	236 (1.6)
	752 (5.2)	652 (4.5)	631 (4.4)	653 (4.5)	825 (5.7)	132 (0.9)
	653 (4.5)	659 (4.5)	669 (4.6)	693 (4.8)	765 (5.3)	157 (1.1)
Retarder B & AEA	662 (4.6)	543 (3.7)	448 (3.1)	672 (4.6)	580 (4)	464 (3.2)
	547 (3.8)	450 (3.1)	566 (3.9)	623 (4.3)	810 (5.6)	405 (2.8)
	571 (3.9)	605 (4.2)	549 (3.8)	597 (4.1)	761 (5.2)	447 (3.1)

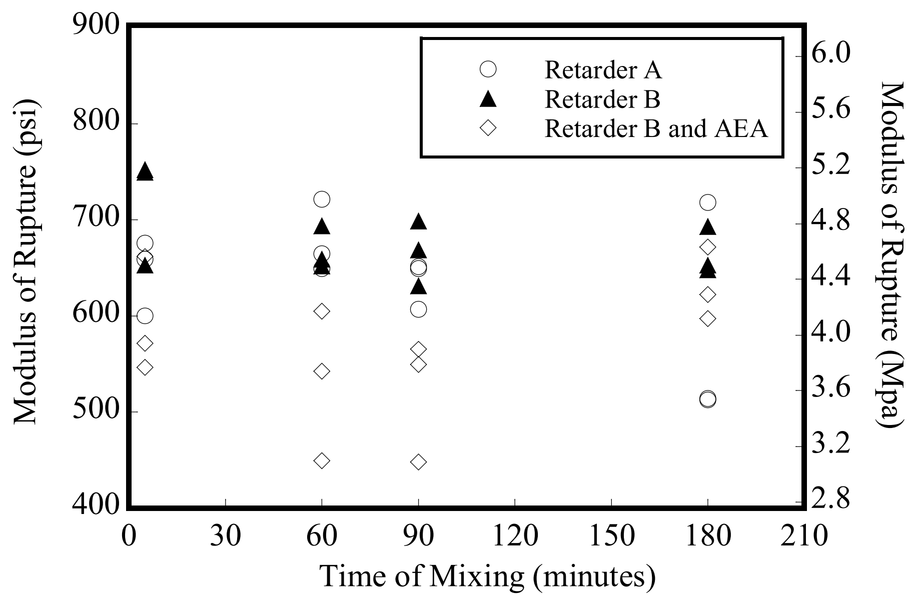


Figure 5-93. MOR versus Time of Mixing (8 rpm)

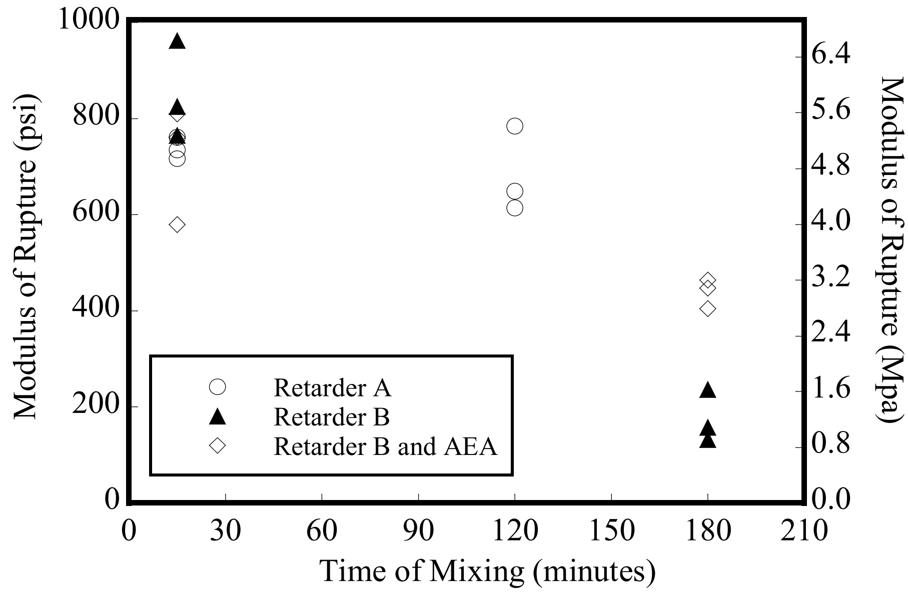


Figure 5-94. MOR versus Time of Mixing (15 rpm)

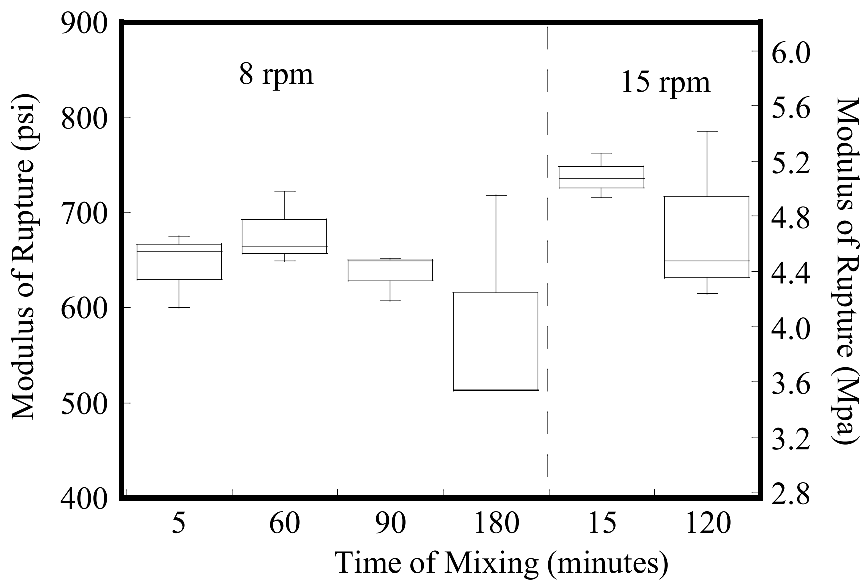


Figure 5-95. Box Plot for Mixtures Containing Retarder A.

For mixtures containing retarder A (figure 5-95), ANOVA testing indicates mixing time up to 90 minutes exhibited no statistical significant difference in mean MOR values at the 95 percent confidence level (p-value = 0.353). In addition, mixing time of 180 minutes at 8 rpm and 120 minutes at 15 rpm, the MOR exhibited significant reduction.

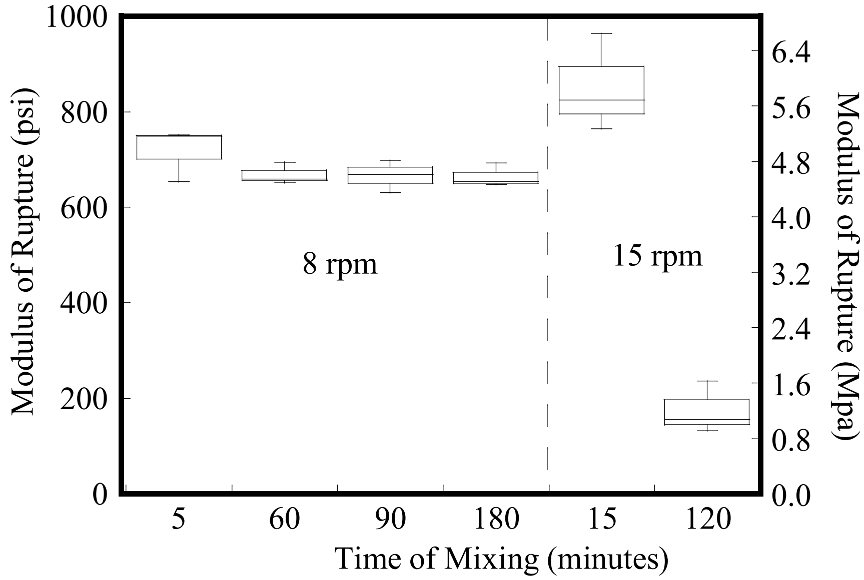


Figure 5-96. Box Plot for Mixtures Containing Retarder B.

For mixtures containing retarder B (Figure 5-96), when mixing at 8 rpm, ANOVA testing indicates mixing time up to 180 minutes exhibited no statistically significant difference in mean MOR values at the 95 percent confidence level (p-value = 0.293). However, when mixing at faster speeds, the MOR exhibited significant reduction when mixed for 120 minutes. This is likely a result of the honeycombing due to low workability and castability.

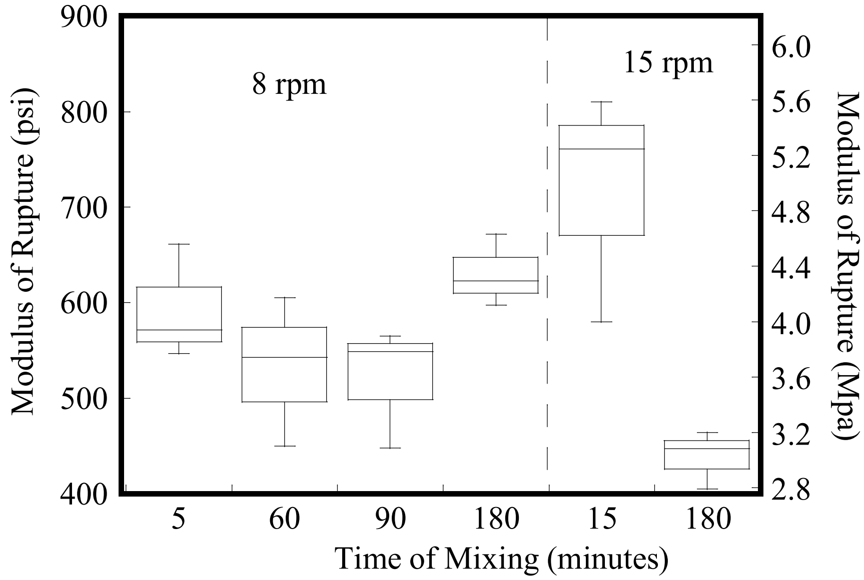


Figure 5-97. Box Plot for Mixtures Containing Retarder B and AEA.

For mixtures containing both retarder B and AEA (Figure 5-97), no statistically significant difference is observed for these mixtures mixed up to 180 minutes at 8 rpm. However, at higher mixing speeds mixtures mixed for 180 minutes exhibited low workability and honeycombing. This likely resulted in the significant reduction in the MOR as shown in Figure 5-97 for the mixture mixed for 180 minutes.

5.3.7 Potential Influence of Mixing Time on the Splitting Tensile Strength

The analysis of the influence of mixing time on the splitting tensile strength (STS) is presented in this section. The STS of concrete mixtures containing a high dosage of retarder was assessed at different mixing times and different speeds. Triplicate samples were tested for different mixing times up to 180 minutes. Statistical analyses are used to compare the mean STS values of mixtures mixed for different mixing times at 8 rpm and similarly for the mixtures mixed at 15 rpm. Table 5-55 shows the STS data.

Table 5-55. Splitting Tensile Strength for Mixture Mixed for Different Time.

Splitting Tensile Strength, psi (Mpa)						
Mixing Speed (rpm)	8 rpm				15 rpm	
Mixing Time (minutes)	5	60	90	180	15	180 or max
Retarder A	719 (4.96)	711 (4.90)	646 (4.46)	745 (5.14)	743 (5.12)	731 (5.04)*
	737 (5.08)	660 (4.55)	606 (4.18)	742 (5.12)	756 (5.21)	659 (4.54)*
	726 (5.00)	691 (4.76)	628 (4.33)	629 (4.33)	765 (5.27)	681 (4.69)*
Retarder B	544 (3.75)	614 (4.23)	560 (3.86)	609 (4.20)	469 (3.23)	166 (1.14)
	489 (3.37)	630 (4.34)	670 (4.62)	586 (4.04)	452 (3.12)	138 (0.95)
	556 (3.83)	754 (5.20)	536 (3.69)	576 (3.97)	647 (4.46)	284 (1.96)
Retarder B and AEA	392 (2.70)	352 (2.43)	333 (2.30)	405 (2.79)	560 (3.86)	436 (3.00)
	331 (2.28)	403 (2.78)	335 (2.31)	380 (2.62)	393 (2.71)	479 (3.30)
	467 (3.22)	447 (3.08)	386 (2.66)	320 (2.21)	355 (2.45)	355 (2.45)

*mixture only mixed for 120 minutes

The STS values of mixtures containing Retarder A mixed for 5, 60, 90, and 180 minutes at 8 rpm are compared. The Welch ANOVA test is used because the different groups exhibited significantly different variance. The test indicates that the mean values of the STS values are statistically significantly different for the groups mixed at different mixing times up to 180 minutes (p-value = 0.012). Also, comparison of the mixtures containing Retarder A mixed at 15 rpm and mixed for 5 and 120 minutes indicate that the two groups exhibited statistically significant differences in means (t-test, p-value = 0.044). Figure 5-98 shows the splitting tensile data in a box plot for the different mixing times.

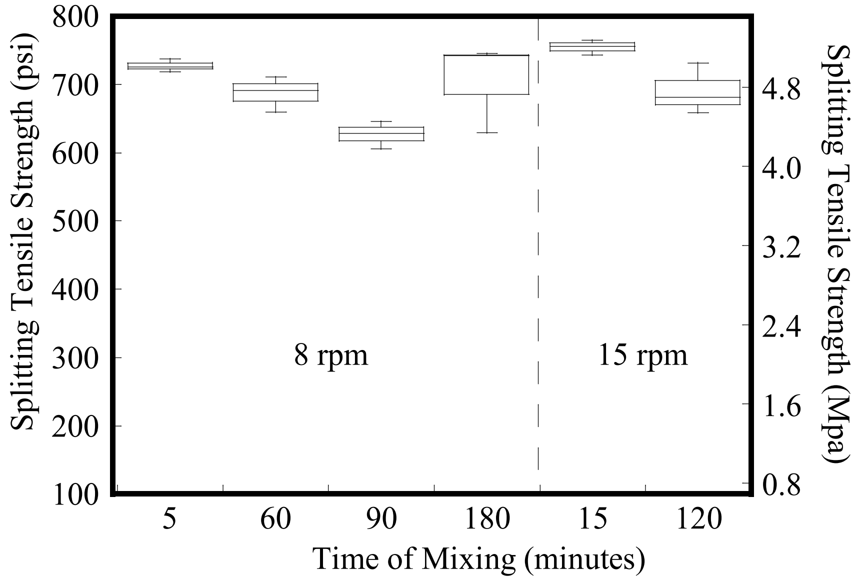


Figure 5-98. Box Plot for the Splitting Tensile Strength of Mixture Containing Retarder A Mixed for Different Time.

Similar comparisons of means are performed for the mixtures containing Retarder B. At a mixing speed of 8 rpm, unlike the mixtures containing Retarder A, these mixtures mixed for 5, 60, 90 and 180 minutes exhibited no statistically significant difference in the STS (ANOVA test, p-value = 0.096). At a mixing speed of 15 rpm, the mean STS value for mixtures containing Retarder B and mixed for 15 minutes is compared to that of the mixtures mixed for 180 minutes using a t-test. The test indicates that there is a statistically significant difference between the means of the two groups (p-value = 0.013). A box plot for this comparison is show in Figure 5-99. Note that the mixture mixed for 180 minutes exhibited poor workability and a high degree of honeycombing. This likely resulted in the reduction in the STS for the longer mixing time.

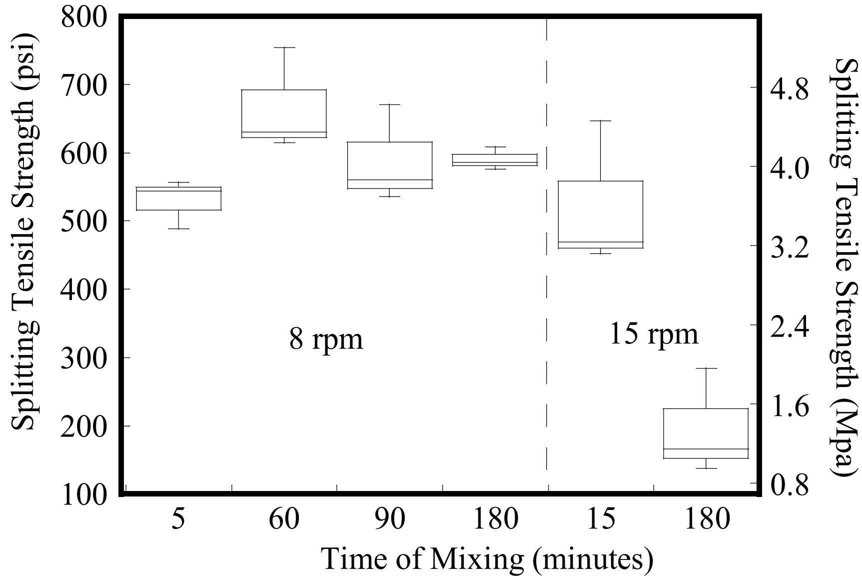


Figure 5-99. Box Plot for the Splitting Tensile Strength of Mixture Containing Retarder B Mixed for Different Time.

For the mixtures containing both Retarder B and AEA (Figure 5-100), ANOVA testing indicates the STS exhibited no statistically significant difference between the mixtures mixed for 5, 60, 90, and 180 minutes at 8 rpm. When mixing at 15 rpm, comparisons of means are performed for specimens mixed for 15 and 180 minutes. The t-test results indicate that there is no statistically significant difference in the mean values between the two groups (p-value = 0.645).

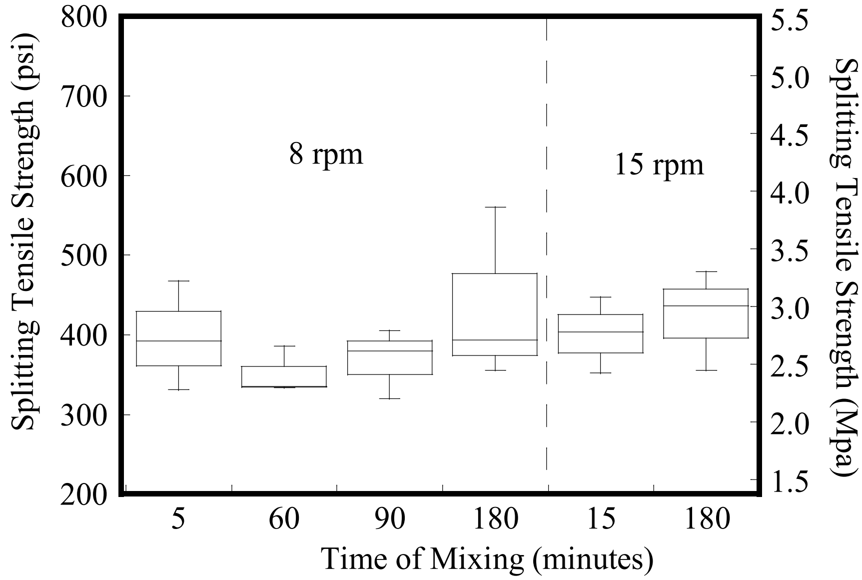


Figure 5-100. Box Plot for the Splitting Tensile Strength of Mixture Containing Retarder B and AEA Mixed for Different Time.

The analyses of the influence of mixing time on STS indicates that mixtures can be mixed for up to 180 minutes and the STS exhibits no statistically significant difference than those mixed for 15, 60 or 90 minutes. However, one mixture exhibited a statistically significant difference when mixed for 120 minutes. This mixture exhibited low workability and castability which resulted in honeycombing within the hardened specimen. This resulted in lower STS values than those exhibiting no honeycombing. The findings from these analyses indicate that mixtures with good workability and castability show no statistically significant difference in STS when mixed for up to 180 minutes. Mixtures with low workability exhibited a statistically significant difference when mixed for 120 minutes. This indicates that mixing time may not be a good indicator of workability, castability, or placeability of concrete mixtures.

6. LABORATORY RESULTS AND ANALYSIS: EFFECT OF LABORATORY DRUM REVOLUTION COUNTS ON CONCRETE CHARACTERISTICS

6.1 INFLUENCE OF LABORATORY DRUM REVOLUTION COUNTS ON FRESH CHARACTERISTICS

The following sections assess the influence of laboratory drum revolution counts (LDRCs) on the fresh concrete characteristics. The fresh characteristics assessed include air content, concrete temperature, and slump. These sections will be followed by a section containing analyses on the influence of LDRCs on hardened concrete properties. Similar to Chapter 5 the same grouping scheme is used in this chapter: CA, AD, and SCM groups.

6.1.1 Potential Influence of Laboratory Drum Revolution Counts on Air Content of Fresh Concrete

Entrapped air content of fresh concrete was assessed at different LDRCs for each of the different mixture group. The following section shows the analysis on the air content for these groups. For each group, the measured air contents of fresh concretes are shown in tabulated form. These data are then shown in box plots. Statistical analyses are used to compare the difference in the air content of fresh concrete for mixtures mixed at different LDRCs. In addition, the air content of mixtures mixed for less than and greater than 250 LDRCs are compared to determine whether current specifications are justified.

6.1.1.1 CA Group

The entrapped air content of fresh concrete was measured and recorded for the mixtures mixed at different LDRCs. Figure 6-1 shows a box plot for the entrapped air contents of the fresh concrete from the CA group. The entrapped air contents range from 1.1 to 1.9 percent for these mixtures. ANOVA tests indicate that there is no statistically significant difference in the mean entrapped air content of mixtures mixed at different LDRCs at the 95 percent confidence level (p-value = 0.672). Also, entrapped air content values for mixtures mixed for less than 250 LDRCs are pooled together to compare with those that are mixed for greater than 250 LDRCs (because the specification limits mixing to 250 LDRCs). T-tests indicate that there is no statistically significant difference in the mean entrapped air content between mixtures mixed for less than 250 LDRCs and greater than 250 LDRCs at the 95 percent confidence level (p-value = 0.268). Figure 6-2 shows a box plot for this comparison.

Table 6-1. Entrapped Air Content of Fresh Concrete for CA Group Mixed for Different LDRCs.

Aggregate Source	Entrapped Air Content of Fresh Concrete, %				
	Drum Revolution Counts				
	40	120	225	480	900
Dulin	1.3	1.2	1.2	1.4	1.4
Central	1.6	1.7	1.5	1.6	1.6
Spokane	1.3	1.2	1.2	1.5	1.3
WSDOT	1.0	1.5	1.5	1.5	1.7
Miles	1.4	1.1	1.1	1.5	1.4
Cadman	1.5	1.5	1.4	1.4	1.0
Glacier NW	1.4	1.1	1.3	1.6	1.2
Whatcom	1.1	1.2	1.0	1.2	1.3
Pinkham	1.3	1.9	1.4	1.4	1.7
Atlas	1.4	1.4	1.4	1.3	1.2
Maier	1.7	1.5	1.5	1.5	1.5

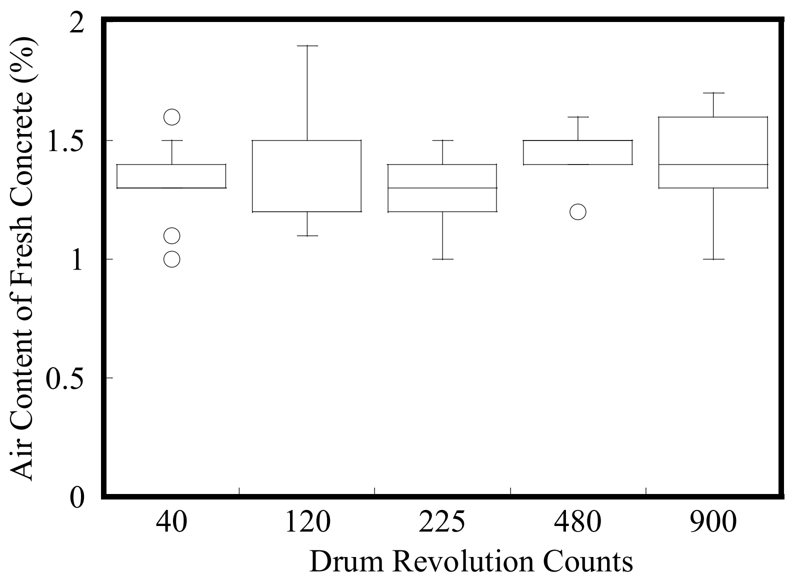


Figure 6-1. Box Plot for Entrapped Air Content of Fresh Concrete for CA Group Mixed for Different Revolution Counts.

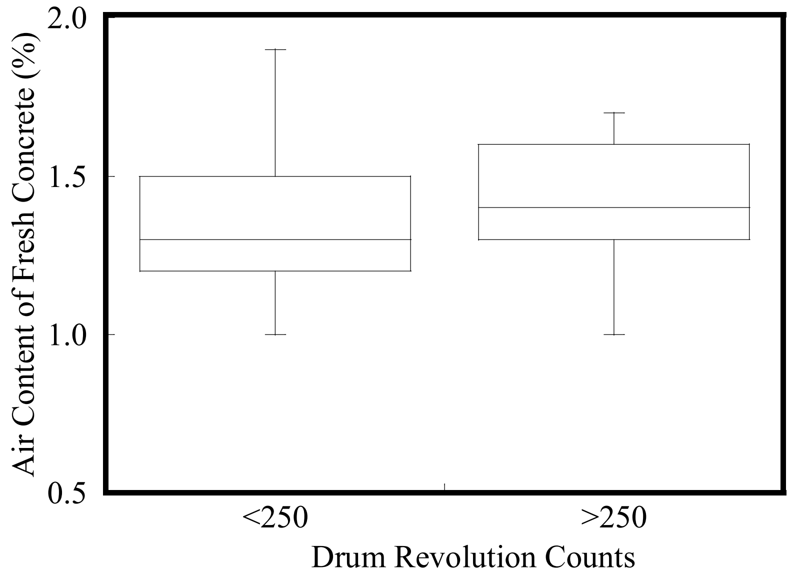


Figure 6-2. Entrapped Air Content of CA Group Mixture Mixed for Lesser and Greater than 250 LDRCs.

6.1.1.2 Admixture Group

The admixture group contains mixtures with WRAs, retarders, and AEAs. For the purposes of assessing air content of fresh concrete, the admixture group is separated into two sub-groups: mixtures with no AEAs and mixtures with AEA. The entrapped air contents ranged from 0.9 to 2.9 percent for the non-AEA mixtures and 4.6 to 9.0 percent for the AEA mixtures.

Table 6-2 shows the entrapped air content values of the fresh concrete for the sub-group with no AEAs. These mixtures were mixed for up to 900 LDRCs. Figure 6-3 shows a box plot for the entrapped air content values of these mixtures.

Table 6-2. Entrapped Air Content of Fresh Concrete for Non-AEA Subgroup at Different LDRCs.

Admixtures	Air Content of Fresh Concrete, %				
	Drum Revolution Counts				
	40	120	225	480	900
WRDA 64	0.9	1.8	1.5	1.9	1.7
Pozzolith 200N	1.8	1.7	1.7	1.7	1.8
Delvo	1.6	1.7	1.6	1.9	2.0
Daratard 17	1.9	2.0	2.2	2.0	2.0
Recover	1.3	1.0	1.3	1.3	1.3
Delvo (high dosage)	2.9	1.80	2.1	0.7	2.0

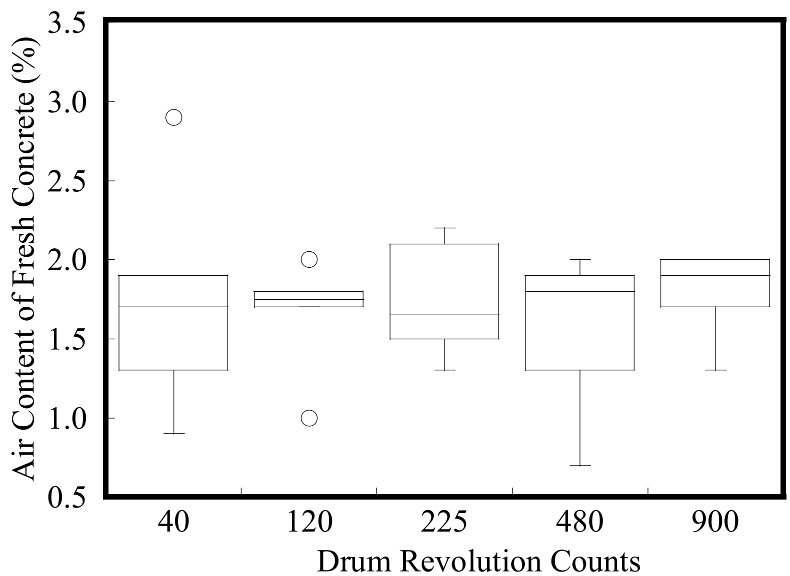


Figure 6-3. Box Plot for Entrapped Air Content of Fresh Concrete for Sub-group Mixtures without AEA Mixed at Different LDRCs.

ANOVA analysis indicates that there is no statistically significant difference between the mean entrapped air content of these mixtures mixed for up to 900 LDRCs (ANOVA, p-value = 0.938). A comparison between the mixtures mixed for less than 250 LDRCs and greater than 250 LDRCs indicate that there is no statistically significant difference between the mean entrapped air contents of these two groups at the 95 percent confidence level (t-test, p-value = 0.905). Figure 6-4 shows a box plot for these two groups.

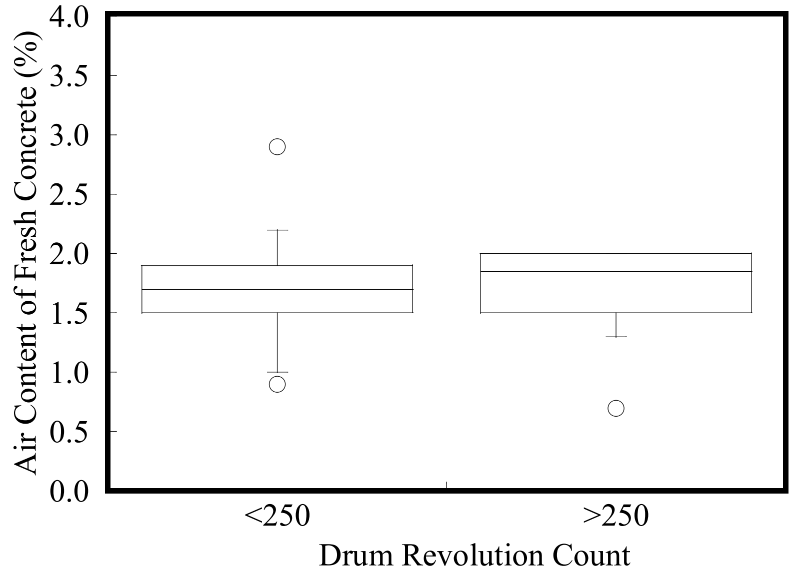


Figure 6-4. Entrapped Air Content of Fresh Concrete for Non-AEA Mixtures Mixed for Less than and Greater than 250 LDRCs.

Table 6-3 shows the entrained air content values of fresh concrete for the sub-group with AEA mixed up to 900 LDRCs. Figure 6-5 shows a box plot for these mixtures.

Table 6-3. Air Content of Fresh Concrete for Mixture Containing AEA Mixed at Different LDRCs.

Admixtures	Air Content of Fresh Concrete, %				
	Drum Revolution Counts				
	40	120	225	480	900
MBAE 90	7.5	8.0	8.7	7.9	6.5
Daravair	4.6	5.6	6.0	5.2	4.5
Delvo and MBAE 90	7.0	9.0	8.0	8.9	8.9

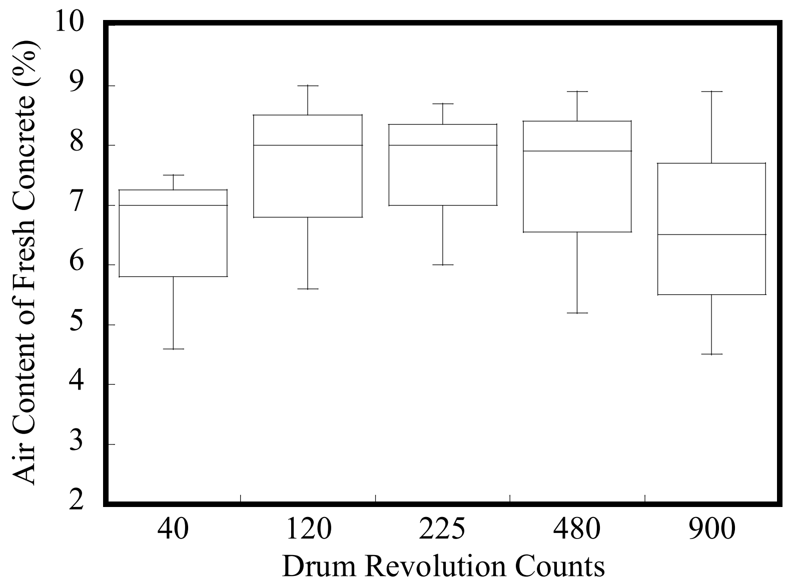


Figure 6-5. Box Plot for the Entrained Air Contents for Sub-group Mixtures Containing AEA Mixed at Different LDRCs.

ANOVA testing indicates that there is no statistically significant difference between the mean entrained air content of the mixtures containing AEA mixed at different LDRCs (p-value = 0.881, 95 percent confidence level). As with the other groups, a comparison of the mixtures mixed for less than and greater than 250 LDRCs indicates there is no statistically significant difference between these air contents (p-value = 0.846, 95 percent confidence level). A box plot showing these results is shown in Figure 6-6.

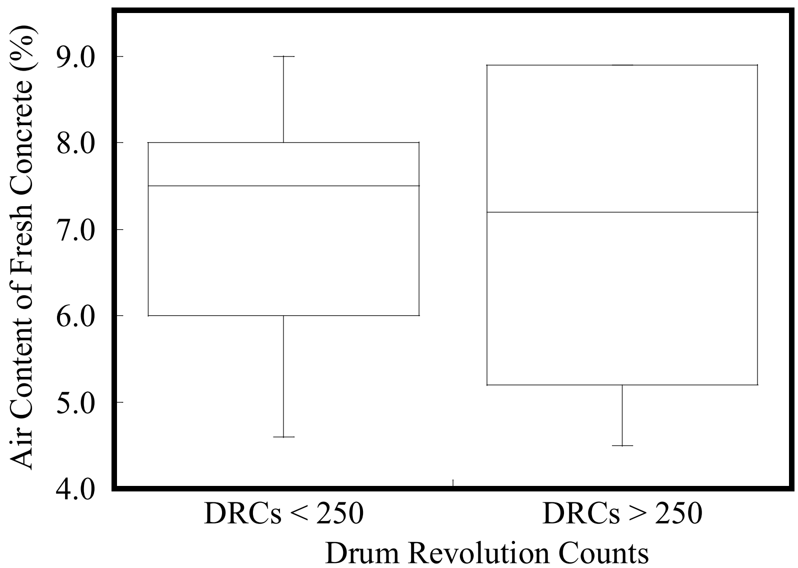


Figure 6-6. Air Content of AEA Mixtures Mixed for Lesser and Greater than 250 LDRCs.

6.1.1.3 SCM Group

The SCM group contains mixtures mixed with slag and Class F fly ash. Table 6-4 shows the air contents of the fresh concrete mixtures for the SCM group. Figure 6-7 shows a box plot for the air contents of the fresh concrete for these mixtures. Air contents ranged from 1.0 to 2.1 percent.

Table 6-4. Effect of Mixing Time on Fresh Concrete Air Content for SCM Group.

Mixtures	Air Content of Fresh Concrete, %				
	Time of mix, minute (8 rpm)			Time of mix, minutes (15 rpm)	
	5	15	60	15	60
20% slag	1.5	1.2	1.1	1.1	1.3
40% slag	1.5	1.5	1.5	1.6	1.6
20% FA	2.1	1.6	1.0	1.7	2.0
30% FA	1.5	1.9	1.6	1.5	1.8

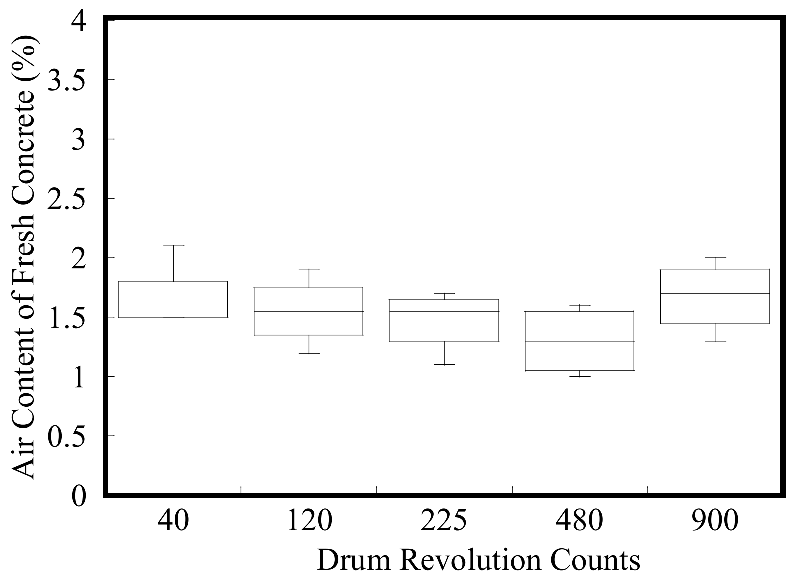


Figure 6-7. Box Plot of Entrapped Air Content of Fresh Concrete for SCM Group.

A statistical analysis shows that there is no statistically significant difference in the mean entrapped air contents of the fresh concrete mixtures for mixtures mixed for 40, 120, 225, 480, and 900 LDRCs at the 95 percent confidence level (ANOVA, p-value = 0.394). Statistical tests were also used to compare the entrapped air content of mixtures mixed for less than 250 and greater than 250 LDRCs. The test results indicate there is no statistically significant difference between the mean values of the entrapped air contents for these mixtures (95 percent confidence level, p-value = 0.609).

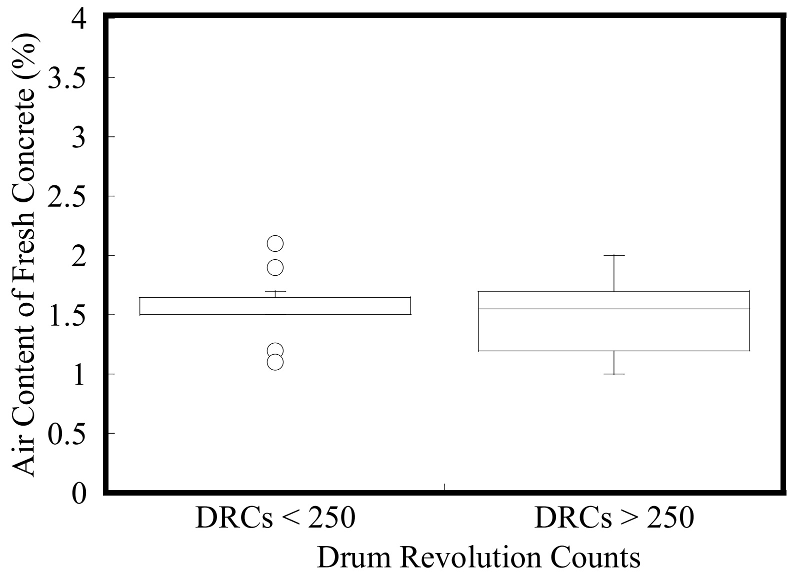


Figure 6-8. Entrapped Air Content of SCM Mixtures Mixed for Less and Greater than 250 LDRCs.

The results of the assessment for the influence of LDRCs on air content for the different mixtures groups are similar to those from the time study. The statistical tests indicate that there is no statistically significant difference in the mean air content between mixtures mixed for different LDRCs. Additionally, results indicate that there is no statistically significant difference in the mean air content between mixtures mixed for less and greater than 250 LDRCs.

6.1.2 Potential Influence of Laboratory Drum Revolution Counts on RMC Temperature

Table 6-5 shows the concrete temperature at the time of discharge from the mixer. Figure 6-9 shows the box plot for RMC temperature. The average temperature of the constituent materials prior to mixing (zero LDRCs) was 68 °F (20 °C). The maximum recorded concrete temperature after mixing was 85 °F (29 °C). The temperatures prior to mixing are the weighted average temperatures of all constituent materials (by weight). The largest change in concrete temperature during mixing was 8 °F (4 °C) for these mixtures. Statistical analyses for these values are shown next.

Table 6-5. Concrete Temperature for Mixtures Mixed for Different LDRCs

Aggregate Source	Concrete Temperature, °F (°C)					
	Drum Revolution Counts					
	0	40	120	225	480	900
Dulin	65 (18)	71 (22)	72 (22)	73 (23)	75 (24)	80 (27)
Central	67 (19)	72 (22)	72 (22)	73 (23)	77 (25)	79 (26)
Spokane	67 (19)	72 (22)	72 (22)	75 (24)	76 (24)	85 (29)
WSDOT	72 (22)	75 (24)	76 (24)	77 (25)	82 (28)	82 (28)
Miles	69 (21)	72 (22)	73 (23)	73 (23)	78 (26)	79 (26)
Cadman	65 (18)	71 (22)	73 (23)	74 (23)	80 (27)	79 (26)
GL NW	69 (21)	73 (23)	74 (23)	76 (24)	77 (25)	81 (27)
Whatcom	68 (20)	73 (23)	73 (23)	75 (24)	78 (26)	82 (28)
Pinkham	68 (20)	72 (22)	75 (24)	74 (23)	76 (24)	80 (27)
Atlas	68 (20)	71 (22)	73 (23)	73 (23)	77 (25)	81 (27)
Maier	69 (21)	72 (22)	74 (23)	72 (22)	78 (26)	80 (27)

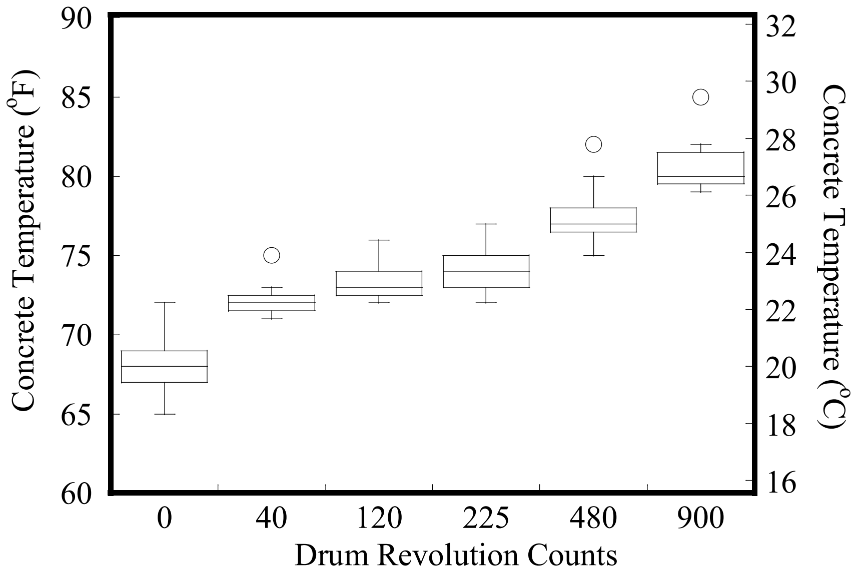


Figure 6-9. Box Plot for Concrete Temperature at Discharge.

Note that the temperatures were recorded prior to mixing and at 40, 120, 225, 480 and 900 LDRCs. Because of the exothermic reaction between cement and water, temperature increases are expected. ANOVA analysis indicates that there is a statistically significant difference in the mean temperatures of concrete for mixtures mixed for different LDRCs (p-value = 0.000, 95 percent confidence level). However, what is more important here is the rate of concrete temperature. Because of this, the rate of change in temperature will be further assessed. Figure 6-10 shows the concrete temperature as a function of drum revolution.

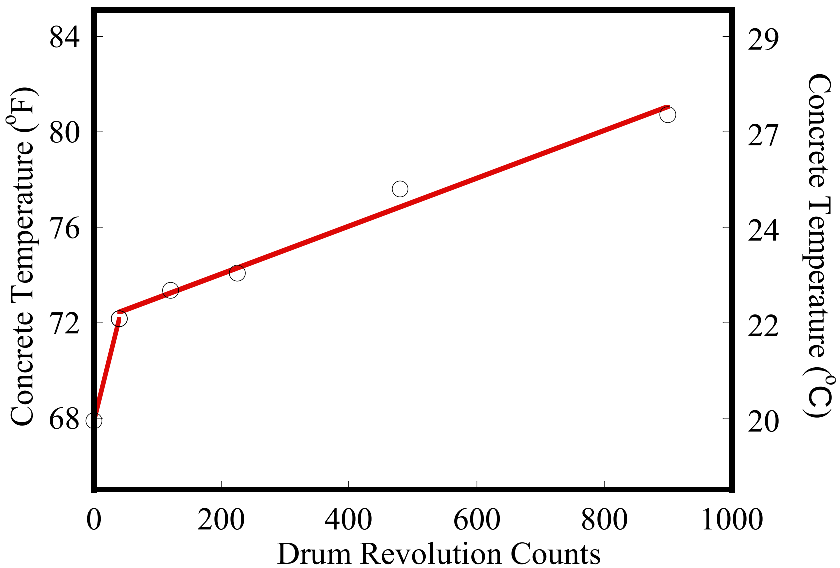


Figure 6-10. Concrete Temperature versus LDRCs.

The figure shows that the concrete temperature increases rapidly initially when water is introduced to the cement (DRCs 0 to 40). However, from 40 to 900 LDRCs, the rate of temperature increase is much slower and relatively constant. This indicates that after the initial heat increase, the LDRCs do not significantly influence the rate of concrete temperature increase during mixing. For the initial 40 revolution counts, the rate of the average concrete temperature increase is 0.11 °F/revolution count (0.56 °C/revolution count). Figure 6-11 shows a box plot for temperature rate increase of mixtures mixed for less than 40 LDRCs, between 40 and 250 LDRCs, and greater than 250 LDRCs.

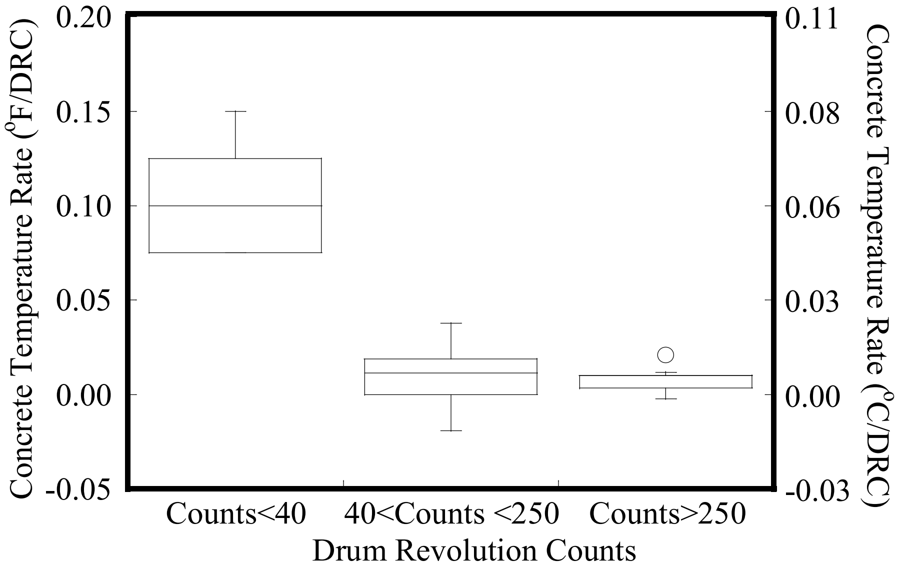


Figure 6-11. Box Plot for Rate of Concrete Temperature Change per LDRCs.

T-test results indicate that there is no statistically significant difference between the mean rate of change of the concrete temperature for mixtures mixed for 40 to 250 LDRCs and mixtures mixed for greater than 250 LDRCs (p-value = 0.318). Figure 6-11 shows that the rate of concrete temperature increase is higher initially.

6.1.3 Potential Influence of Laboratory Drum Revolution Counts on Concrete Slump

This section contains the analyses for the influence of LDRCs on concrete slump. Similar to the analysis of the influence of mixing time on slump, mixtures are assessed by separating into three groups: 1) plain concrete (CA group), 2) concrete with chemical admixtures (AD group), and 3) concrete with SCMs (SCM group). The AD group is further divided into subgroups: concrete with regular dosages of admixtures (AD_{rd} subgroup) and concrete with high dosages of admixtures (AD_{hd} subgroup). The slump data for all groups of mixtures are shown in Table 6-6 through Table 6-9. All but the AD_{hd} group is designed with a target slump of 4 inches (102 mm). Because of the higher dosages of admixtures used in the AD_{hd} group, the initial average slump (after 40 LDRCs) is higher than the other groups.

Table 6-6. Slump Values for CA Group Mixed for Different LDRCs.

CA Sources	Slump, inch (mm)				
	Drum Revolution Counts				
	40	120	225	480	900
Dulin	6.50 (165)	6.25 (159)	5.50 (140)	5.50 (140)	2.50 (64)
Central	4.25 (108)	4.00 (102)	4.00 (102)	3.00 (76)	2.25 (57)
Spokane	5.75 (146)	6.00 (152)	5.50 (140)	3.25 (83)	2.75 (70)
WSDOT	3.50 (89)	3.25 (83)	3.00 (76)	2.50 (64)	2.00 (51)
Miles	4.00 (102)	4.00 (102)	3.25 (83)	2.25 (57)	1.75 (44)
Cadman	3.50 (89)	3.25 (83)	2.75 (70)	2.75 (70)	1.25 (32)
Glacier NW	4.25 (108)	4.00 (102)	3.50 (89)	3.25 (83)	2.25 (57)
Whatcom	4.25 (108)	6.00 (152)	4.50 (114)	3.75 (95)	2.75(70)
Pinkham	4.50 (114)	5.25 (133)	4.25 (108)	3.50 (89)	2.25 (57)
Atlas	4.50 (114)	4.25 (108)	3.75 (95)	3.00 (76)	1.75 (44)
Maier	4.00 (102)	4.25 (108)	4.00 (102)	3.00 (76)	2.00 (51)

Table 6-7. Slump Values for the Mixtures Containing AD_{rd} Mixed for Different LDRCs.

Mixtures with recommended dosage		Slump, inch (mm)				
		Drum Revolution Counts				
		40	120	225	480	900
WRA	WRDA 64	4.50 (114)	5.00 (127)	1.25 (32)	1.75 (44)	1.00 (25)
	Pozzolith 200N	3.25 (83)	2.50 (64)	2.50 (64)	1.00 (25)	0.75 (19)
Retarder	Delvo	3.00 (76)	2.75 (70)	2.25 (57)	1.50 (38)	1.00 (25)
	Daratard 17	4.75 (121)	3.75 (95)	3.25 (83)	1.75 (44)	1.00 (25)
AEA	MBAE 90	4.00 (102)	4.00 (102)	3.75 (95)	4.00 (102)	1.75 (44)
	Daravair	4.50 (114)	4.00 (102)	3.25 (83)	2.25 (57)	1.25 (32)

Table 6-8. Slump Values for the Mixture Containing AD_{hd} Mixed for Different LDRCs.

Retarders	Slump, inch (mm)								
	Drum Revolution Counts								
	40	120	225	480	720	900	1350	1440	2700
Recover	8.25 (210)	9.50 (241)	8.75 (222)	7.75 (197)	7.50 (191)	4.25 (108)	0.75 (19)	2.00 (51)	1.00 (25)*
Delvo	8.00 (203)	8.00 (203)	7.00 (178)	2.25 (57)	1.50 (38)	2.00 (51)	1.25 (32)	0.25 (6)	0.00 (0)
Delvo and MBAE 90	8.50 (216)	6.00 (152)	5.00 (127)	7.75 (197)	4.25 (108)	6.50 (165)	5.00 (127)	0.25 (6)	1.00 (25)

*Mixture mixed to 1800 LDRCs.
N.A.: not available

Table 6-9. Slump Value for the SCM Group Mixtures Mixed for Different LDRCs.

SCM	Slump, inch (mm)				
	Drum Revolution Counts				
	40	120	225	480	900
20% slag	4.25 (108)	5.00 (127)	4.25 (108)	3.25 (83)	2.50 (64)
40% slag	3.75 (114)	4.50 (114)	4.00 (102)	3.50 (89)	2.50 (64)
20% FA	3.25 (83)	3.25 (83)	2.75 (70)	1.75 (44)	1.00 (25)
30% FA	4.50 (121)	4.75 (121)	4.00 (102)	1.50 (38)	1.00 (25)

To assess the slump of the different mixtures, statistical analyses are used to compare slump values of the same mixtures at different LDRCs. Because the initial slump value of the concrete was not the same for all mixtures, the slump values are normalized and assessed. The n-slump represents the fraction of the original slump at the different LDRCs. Table 6-10 through Table 6-13 show the n-slump values for the different groups mixed at different LDRCs.

Table 6-10. Normalized Slump for CA Groups Mixed for Different LDRCs.

CA Group Mixtures				
Drum Revolution Counts				
40	120	225	480	900
1.00	1.00	0.81	0.56	0.44
1.00	0.94	0.94	0.71	0.53
1.00	1.04	0.96	0.57	0.48
1.00	0.94	0.83	0.67	0.39
1.00	1.41	1.06	0.88	0.65
1.00	0.96	0.85	0.85	0.39
1.00	0.93	0.79	0.79	0.36
1.00	0.93	0.86	0.71	0.57
1.00	1.17	0.94	0.78	0.50
1.00	1.06	1.00	0.75	0.50
1.00	0.94	0.82	0.77	0.53

Table 6-11. Normalized Slump for SCM Groups Mixed for Different LDRCs.

SCM Group Mixtures				
Drum Revolution Counts				
40	120	225	480	900
1.00	1.18	1.00	0.76	0.59
1.00	1.20	1.07	0.93	0.67
1.00	1.00	0.85	0.54	0.31
1.00	1.06	0.89	0.33	0.22

Table 6-12. Normalized Slump for AD_{rd} Groups Mixed for Different LDRCs.

AD_{rd} Group Mixtures				
Drum Revolution Counts				
40	120	225	480	900
1.00	1.11	0.28	0.39	0.22
1.00	0.77	0.77	0.31	0.23
1.00	0.92	0.75	0.50	0.33
1.00	0.79	0.68	0.37	0.21
1.00	1.00	0.94	1.00	0.44
1.00	0.89	0.72	0.50	0.28

Table 6-13. Normalized Slump for AD_{hd} Groups at Different Revolution Counts.

AD_{hd} Group Mixtures				
Drum Revolution Counts				
40	120	225	480	900
1.00	1.15	1.06	0.94	0.52
1.00	1.00	0.88	0.28	0.25
1.00	0.71	0.59	0.91	0.77

Table 6-14 and Table 6-15 show the statistical parameters for the data sets. The tables include the average, standard deviation, and number of samples.

Table 6-14. Statistical Parameters for Data of the CA and SCM Groups Mixed for Different LDRCs.

Statistical Parameters	CA Group Mixtures				SCM Group Mixtures			
	120	225	480	900	120	225	480	900
Average	1.03	0.90	0.73	0.48	1.11	0.95	0.64	0.45
Standard Deviation	0.15	0.09	0.10	0.09	0.10	0.10	0.26	0.22
Number of Samples	11	11	11	11	4	4	4	4

Table 6-15. Statistical Parameters for the Data of the AD_{rd} and AD_{hd} Mixed for Different LDRCs.

Statistical Parameters	AD_{rd} Group Mixtures				AD_{hd} Group Mixtures			
	120	225	480	900	120	225	480	900
Average	0.91	0.69	0.51	0.29	0.95	0.84	0.71	0.51
Standard Deviation	0.13	0.22	0.25	0.09	0.22	0.24	0.37	0.26
Number of Samples	6	6	6	6	3	3	3	3

Table 6-16 through Table 6-19 show the ANOVA test results for the four mixture groups mixed at different LDRCs. The results indicate that there is a statistically significant difference in the mean n-slump values of mixtures mixed at different LDRCs within each of the CA, SCM and AD_{rd} group (p-value = 0.000, 0.001 and 0.000 at the 95 percent level, respectively).

The ANOVA test indicates that there is no statistically significant difference in the mean normalized slump value for the AD_{hd} group (p-value = 0.318). Figure 6-12 shows the slump values for the different LDRCs and groups. The figure shows that all four groups, including the AD_{hd} group, exhibited decreases in the n-slump values with increasing LDRCs. In addition, large scatter was observed for the AD_{hd} group. Even though ANOVA test results indicate no statistically significant difference in the n-slump for the AD_{hd} mixtures mixed at different LDRCs, large scatter in the AD_{hd} mixtures can affect the ANOVA result. Therefore, a slump model as function of LDRCs will be developed for each group.

Table 6-16. ANOVA Test for the CA Group Mixed for Different LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	1.81	3	0.603	51.2	0.0000
Within groups	0.471	40	0.0117		
Total (Corr.)	2.28	43			

Table 6-17. ANOVA Test for the SCM Group Mixed for Different LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	1.07	3	0.358	10.6	0.001
Within groups	0.403	12	0.0335		
Total (Corr.)	1.47	15			

Table 6-18. ANOVA Test for the AD_{rd} Group Mixed for Different LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	1.27	3	0.426	12.6	0.0001
Within groups	0.677	20	0.0338		
Total (Corr.)	1.95	23			

Table 6-19. ANOVA Test for the AD_{hd} Group Mixed for Different LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.322	3	0.107	1.38	0.3184
Within groups	0.625	8	0.078		
Total (Corr.)	0.948	11			

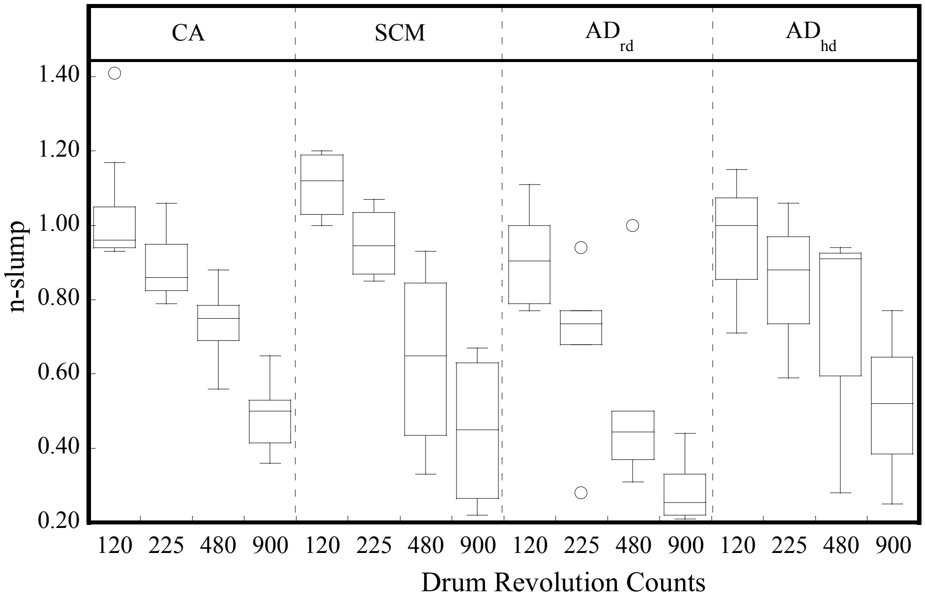


Figure 6-12. Box Plot for the Mixtures Groups Mixed for Different LDRCs.

Model Development for CA Group Mixtures

It was determined that constituent material characteristics do not significantly influence the concrete (Chapter 5), therefore constituent material parameters will not be included in these models. Figure 6-13 and Figure 6-14 show the slump values and n-slump values as a function of LDRCs for the CA group, respectively.

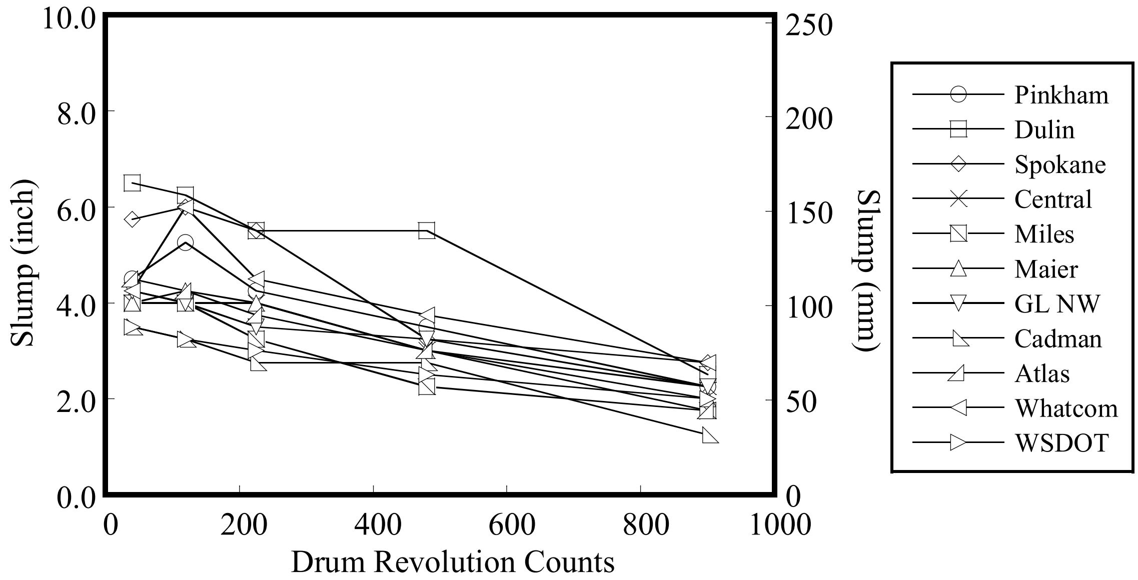


Figure 6-13. Slump versus LDRCs for the CA Group Mixtures.

As expected, all mixtures in the CA group showed a decrease in slump and n-slump when mixed for up to 900 LDRCs.

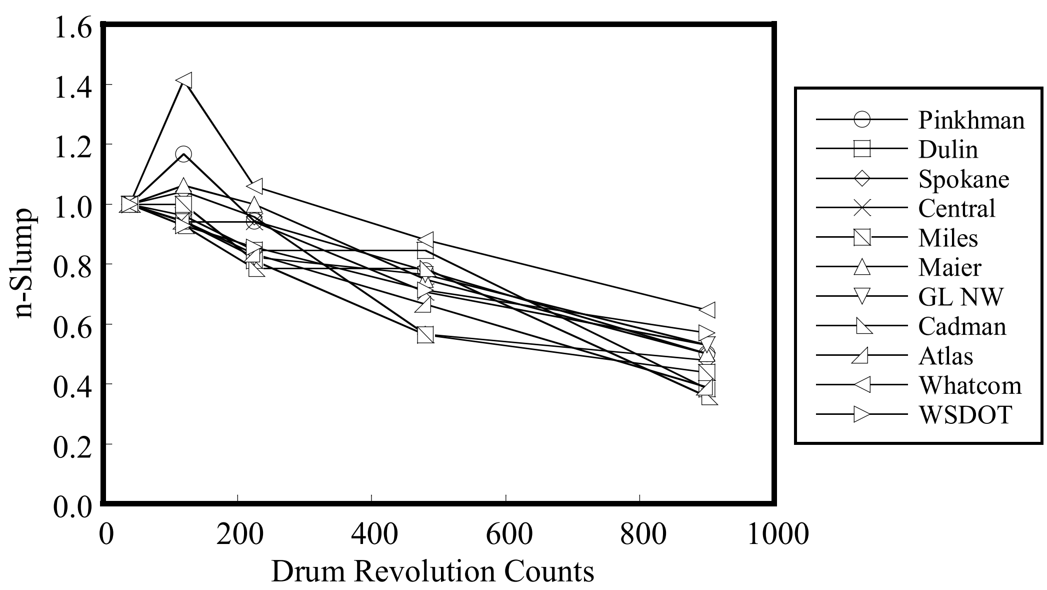


Figure 6-14. n-slump versus LDRCs for CA Group Mixtures at Different LDRCs.

A linear regression model was developed to assess the effect of the LDRCs on normalized slump for the CA group mixtures mixed up to 900 LDRCs. The model and the 95 percent prediction interval (PI) are shown in Figure 6-15.

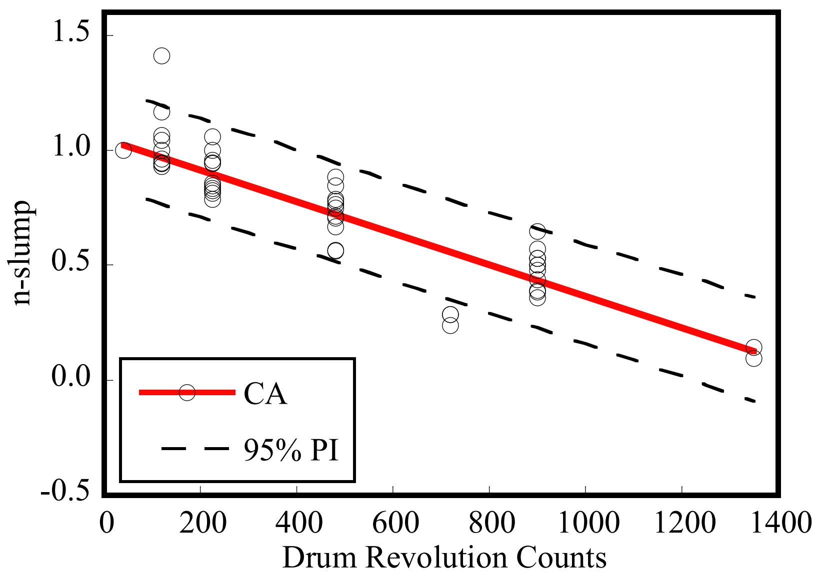


Figure 6-15. N-Slump as a Function of LDRCs for the CA Group.

For the CA group mixtures, the n-slump as a function of LDRCs can be estimated as follows:

$$n - slump_{CA}(n) = 1.06 - 0.000685n \qquad (6\text{-}1)$$

where n is the number of LDRCs. The R^2 for the model is 85 percent. This equation is valid for LDRCs between 40 and 1350 counts.

Model Development for Admixture Group Mixtures

This section includes the modeling process for n-slump values as a function of LDRCs for the AD_{rd} groups. Note that only 1 aggregate source was used for these mixtures. Figure 6-16 shows the relationships between slump and LDRCs for the AD_{rd} group mixtures. The normalized slump values for the AD_{rd} group are shown in Figure 6-17.

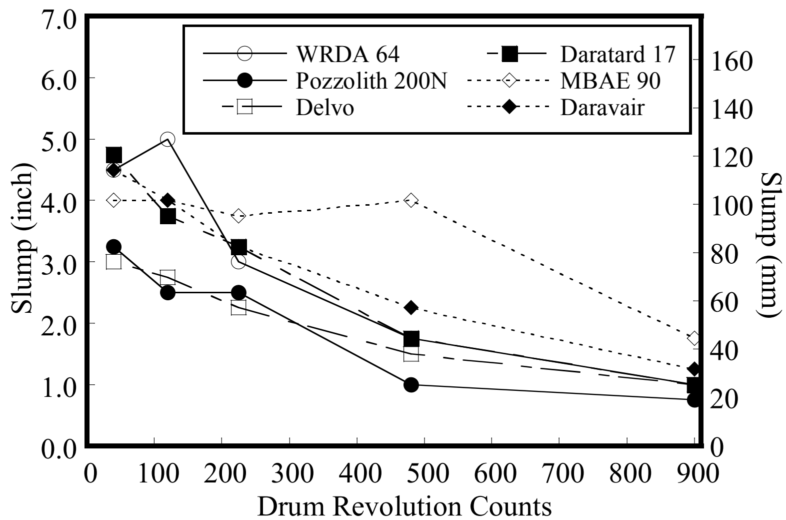


Figure 6-16. Slump versus LDRCs for the AD_{rd} Group Mixtures.

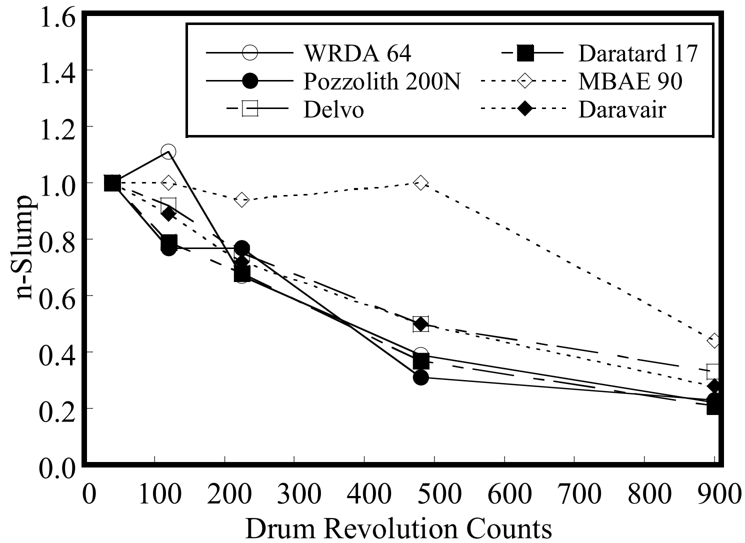


Figure 6-17. N-Slump versus LDRCs for the AD_{rd} Mixtures.

Figure 6-18 shows the n-slump model for mixtures containing recommended dosages of admixtures. For mixtures mixed up to 900 LDRCs, the average slump decreased from 4 inches (102 mm) to 1.13 inches (29 mm), a 72 percent decrease from its original value.

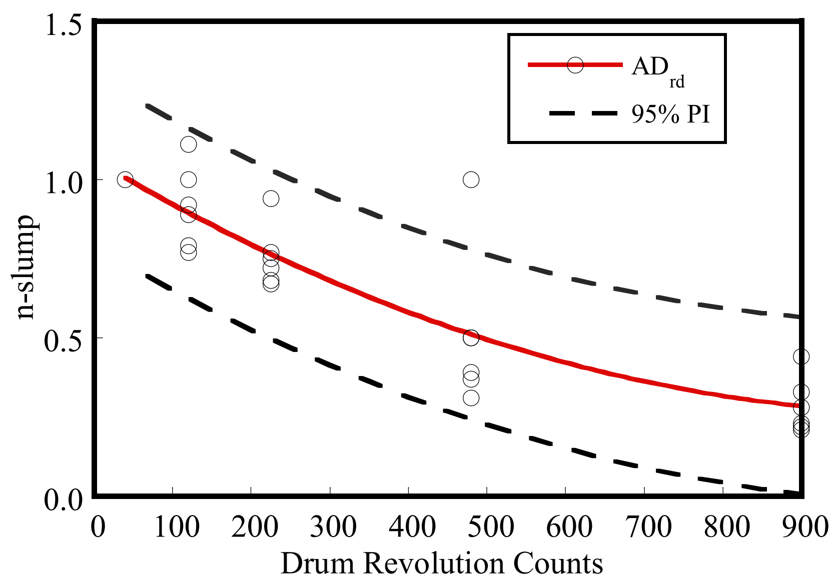


Figure 6-18. N-slump as a Function of LDRCs for the AD_{rd} Mixtures.

For the AD_{rd} mixtures, the $n\text{-}slump_{ADrd}(n)$ as a function of LDRCs can be estimated as follows:

$$n - slump_{ADrd}(n) = 1.06 - 0.00147n \times 6.77 \times 10^{-7} \times n^2 \qquad (6\text{-}2)$$

where n has already been defined. The R^2 for this model is 84 percent. Equation 6-2 is valid for LDRCs between 40 to 900 counts.

Unlike the CA, AD_{rd} and SCM groups, the AD_{hd} mixtures were mixed up to 2700 LDRCs. Figure 6-19 shows the slump values for the mixtures containing high dosages of admixtures (AD_{hd} group). Figure 6-20 shows the normalized slump values as a function of LDRCs for these mixtures.

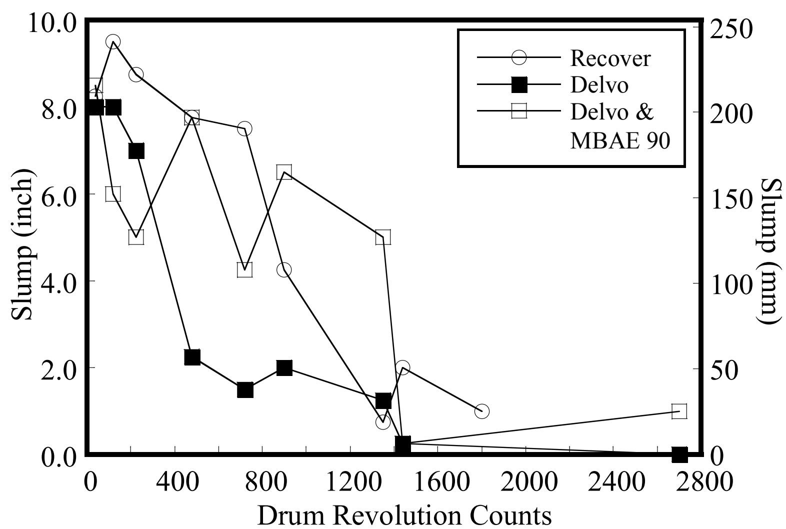


Figure 6-19. Slump versus LDRCs for the AD_{hd} Group.

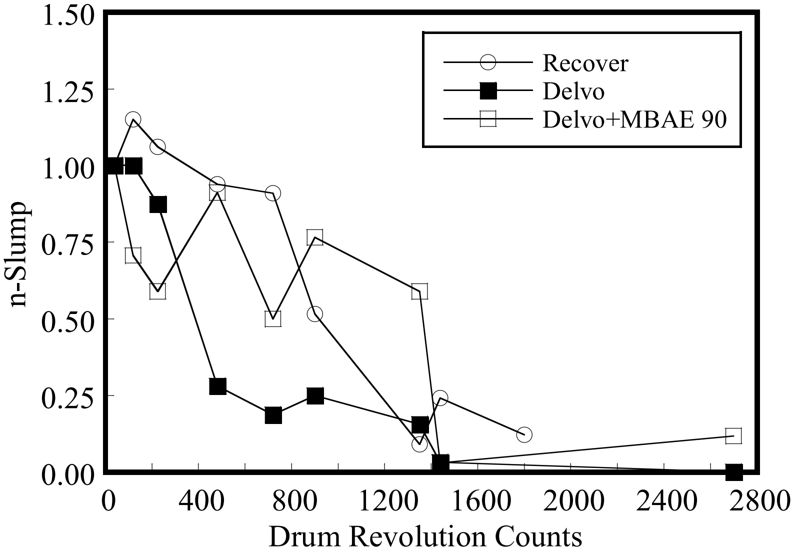


Figure 6-20. N-Slump versus LDRCs for AD_{hd} Group.

For the mixtures containing high dosages of admixtures, the average slump decreased from 8.25 to 0.67 inches (210 to 17 mm), or to 8 percent of its initial slump values. Figure 6-21 shows the n-slump model as a function of LDRCs for the AD_{hd} mixtures. The model for these mixtures is referred to as $n\text{-}slump_{ADhd}(n)$. Note the large scatter in these figures.

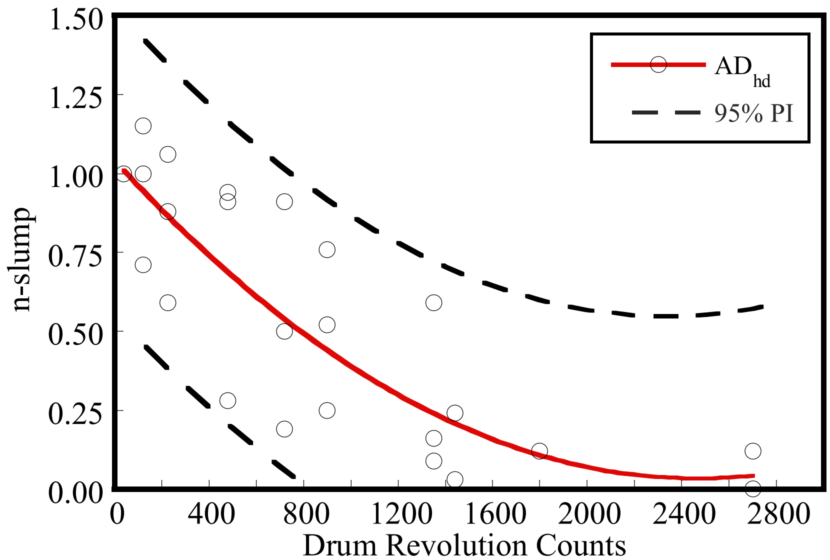


Figure 6-21. N-Slump versus LDRCs for AD_{hd} Group Mixtures.

The n-slump of the mixtures containing high dosages of admixtures as a function of LDRCs can be estimated as follows:

$$n - slump_{ADhd}(n) = 1.04 - 0.000817n + 1.66 \times 10^{7} \times n^{2} \qquad (6\text{-}3)$$

for $40 \leq n \leq 2700$ counts. The R^2 for the model is 75 percent.

Model Development for SCM Group Mixtures

Figure 6-22 and Figure 6-23 show the slump and n-slump values for the SCM group mixtures.

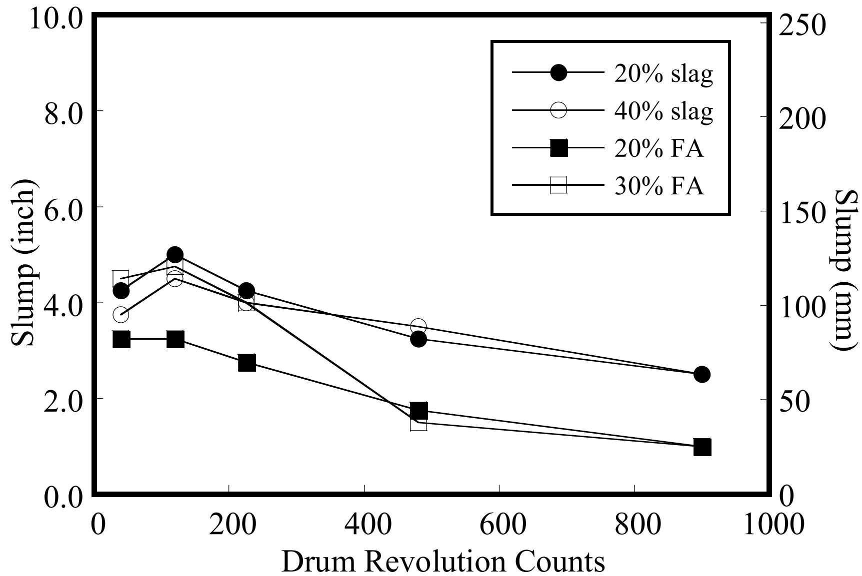


Figure 6-22. Slump versus LDRCs for the SCM Group Mixtures.

Note that the mixtures containing slag is normalized to the slump value of the mixtures mixed for 120 LDRCs. This is because the slump value of the mixtures containing slag increased from 40 to 120 LDRCs. This indicates that insufficient mixing energy during the first 40 LDRCs was applied to the mixture and the mixture was likely not homogenious at this number of mixer revolutions.

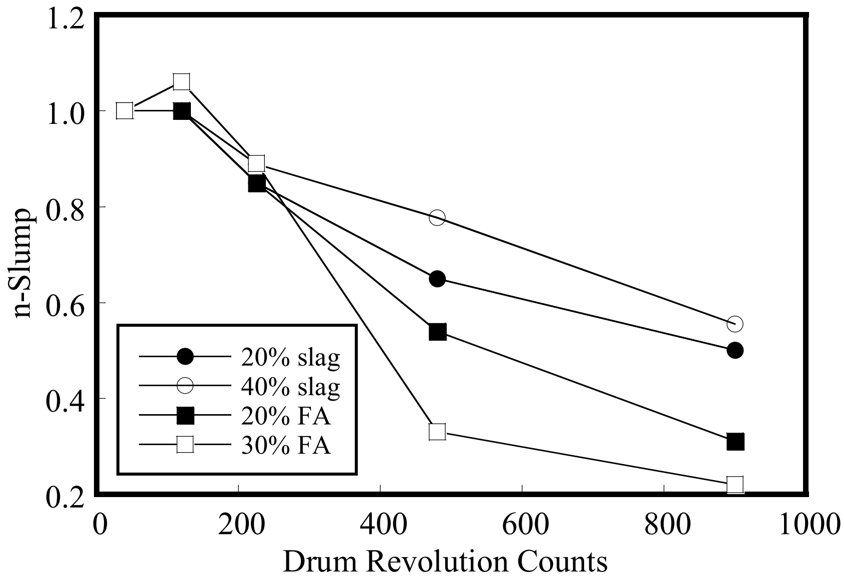


Figure 6-23. n-Slump for SCM Group Mixtures at Different LDRCs.

A model for the n-slump as a function of LDRCs is developed for these mixtures and this is shown in Figure 6-24. The n-slump for the SCM group mixture will be referred to as $n\text{-}slump_{SCM}$.

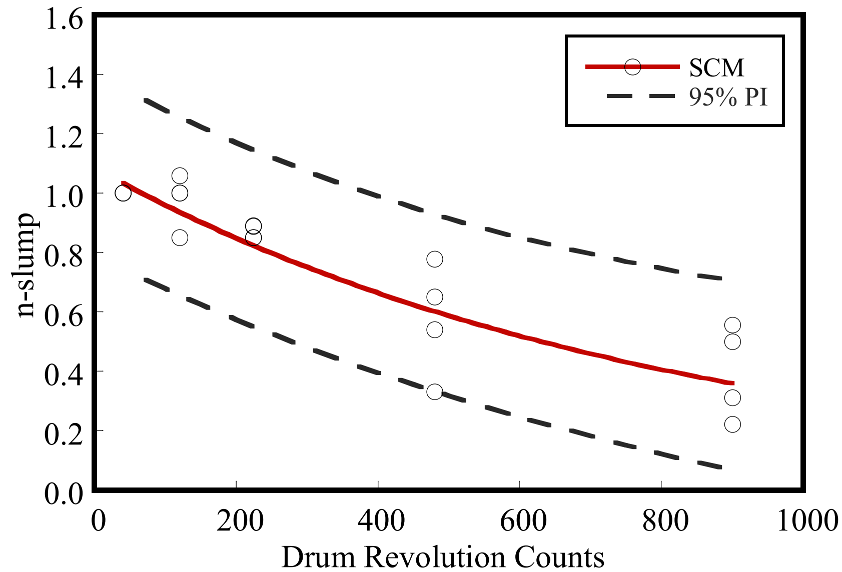


Figure 6-24. Model for n-slump for SCM Group Mixtures Mixed at 8 rpm.

The $n\text{-}slump_{SCM}$ as a function of LDRCs can be estimated as follows:

$$n - slump_{SCM}(n) = 1.09e^{(-0.00123n)} \tag{6-4}$$

for $40 \leq n \leq 900$. The R^2 for the model is 83 percent.

6.1.4 Comparison of Slump Values for Different Groups

Models assessing slump as a function of LDRCs were developed for the different groups. Figure 6-25 shows the models for conventional concrete mixtures (CA group), concrete containing admixtures (AD_{rd} and AD_{hd}), and concrete containing SCMs. Results indicate that concrete mixtures containing recommended dosages of chemical admixtures exhibited accelerated slump loss, whereas mixtures containing higher dosages of retarders exhibited lower slump loss rates. Note that concrete has a wide range of applications and different applications may have different specifications and/or requirements for slump and/or slump loss. Thus minimum slump or slump loss values are dependent on the application or construction type. If it is assumed that 30 percent of the original slump is necessary to place the concrete (an arbitrary number), allowable LDRCs could range from approximately 900 LDRCs to 1100 LDRCs. Results indicate that placeability is likely a function of some minimum slump requirement.

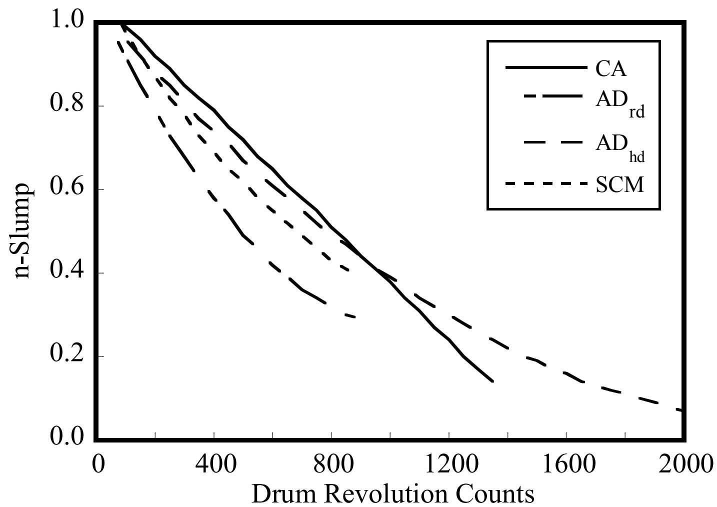


Figure 6-25. n-slump Model as a function of LDRCs for All Concrete Groups.

6.2 INFLUENCE OF LABORATORY DRUM REVOLUTION COUNTS ON HARDENED CONCRETE CHARACTERISTICS

6.2.1 Potential Influence of Laboratory Drum Revolution Counts on Compressive Strength

Similar to the previous analyses, these mixtures are separated into three groups for analyses: 1) plain concrete (the CA group); 2) concrete with chemical admixtures (the AD group); and 3) concrete with SCMs (the SCM group). The AD group is further divided into subgroups: concrete with regular dosages of admixtures (the AD_{rd}

subgroup), concrete with higher dosages of admixtures (the AD_{hd} subgroup), and concrete containing AEA (the AEA group). Table 6-20 through Table 6-24 show the 28- and 56-day f'cm for these groups. Note that the $f'cm_{56}$ for the AD_{hd} group was not assessed.

Table 6-20. Concrete f'cm as a Function of LDRCs for the CA Group.

Concrete With Different CA	Drum Revolution Counts									
	28-day f'cm, psi (MPa)					56-day f'cm, psi (MPa)				
	40	120	225	480	900	40	120	225	480	900
Dulin	6710 (46)	6396 (44)	6891 (47)	6806 (46)	6801 (46.9)	7233 (50)	7466 (52)	7281 (50)	7578 (52)	6951 (48)
Central	7036 (4)	7336 (50)	6826 (47)	7214 (49)	7201 (49.6)	7267 (50)	7830 (54)	7371 (51)	7918 (55)	7924 (55)
Spokane	6823 (47)	6991 (48)	6838 (47)	7515 (51)	7307 (50.4)	7043 (49)	7203 (50)	7572 (52)	7712 (53)	7770 (54)
WSDOT	6910 (47)	6889 (47)	6926 (47)	7340 (50)	7208 (49.7)	7659 (53)	7485 (52)	7798 (54)	8213 (57)	8199 (57)
Miles	6624 (45)	6294 (43)	6153 (45)	6612 (45)	5667 (39.1)	6959 (48)	7304 (50)	7023 (48)	7169 (49)	7147 (49)
Cadman	7041 (48)	7029 (48)	7188 (49)	7448 (51)	7403 (51.0)	7627 (53)	7830 (54)	7371 (51)	7918 (55)	7924 (55)
GL NW	7297 (50)	7148 (49)	7030 (48)	7221 (50)	7254 (50.0)	7651 (53)	8304 (57)	8328 (57)	7771 (54)	8315 (57)
Whatcom	6631 (45)	6613 (45)	6877 (47)	6771 (47)	6730 (46.4)	7713 (53)	7547 (52)	7595 (52)	7981 (55)	7754 (54)
Pinkham	6886 (47)	6913 (47)	6502 (44)	6657 (46)	6572 (45.3)	7210 (50)	7380 (51)	7006 (48)	7125 (49)	7047 (49)
Atlas	6587 (45)	6952 (47)	6625 (45)	7183 (50)	6669 (46.0)	7206 (50)	7226 (50)	7508 (52)	7599 (52)	7596 (52)
Maier	7737 (53)	7660 (52)	7093 (48)	7684 (53)	7280 (50.2)	8453 (58)	8626 (60)	7907 (55)	8384 (58)	8112 (56)

Table 6-21. Concrete f'cm as a Function of LDRCs for the AD_{rd} Subgroup.

Mixtures with Recommended Admixture Dosage		Drum Revolution Counts									
		28-day f'cm, psi (MPa)					56-day f'cm, psi (MPa)				
		40	120	225	480	900	40	120	225	480	900
WRA	WRDA 64	6810 (47)	6653 (45)	6009 (45)	6052 (41)	6762 (46)	7157 (49)	6949 (47)	6983 (48)	6853 (47)	7115 (49)
	Pozzolith 200N	6165 (42)	5917 (40)	5902 (40)	6080 (41)	6620 (45)	6730 (46)	6602 (45)	6767 (46)	6874 (47)	7130 (49)
Retarder	Delvo	6368 (43)	6504 (44)	6569 (45)	6732 (46)	6919 (47)	6668 (46)	7069 (48)	7384 (50)	7223 (49)	7256 (50)
	Daratard 17	6899 (47)	7148 (49)	7371 (50)	6887 (47)	7145 (49)	7569 (52)	7693 (53)	7946 (54)	7422 (51)	7908 (54)

Table 6-22. Concrete f'cm as a Function of LDRCs for the AEA Subgroup.

Mixtures with AEA	Drum Revolution Counts									
	28-day f'cm, psi (MPa)					56-day f'cm, psi (MPa)				
	40	120	225	480	900	40	120	225	480	900
MBAE 90	3650 (25)	3575 (24)	3175 (21)	3336 (23)	4020 (27)	3716 (25)	3865 (26)	3593 (24)	3722 (25)	4205 (29)
Daravair	4404 (30)	3900 (26)	3949 (27)	4339 (29)	4507 (31)	3222 (22)	4536 (31)	4221 (29)	4745 (32)	4944 (34)

Table 6-23. Concrete $f'cm_{28}$ as a Function of LDRCs for the AD_{hd} Subgroup.

High Dosage Retarders	Drum Revolution Counts								
	28-day f'cm, psi (MPa)								
	40	120	225	480	720	900	1350	1440	2700
Recover	7108 (42)	6738 (46)	7550 (52)	7006 (48)	8039 (55)	7445 (51)	6805 (47)	7779 (54)	8256 (57)*
Delvo	6353 (44)	6351 (44)	7607 (52)	6463 (45)	7087 (49)	6924 (48)	7291 (50	7140 (49)	964 (7)

*Mixture mixed to 1800 LDRCs.

Table 6-24. Concrete f'cm as a Function of LDRCs for the SCM Group

SCM Mixtures	Drum Revolution Counts									
	28-day f'cm, psi (MPa)					56-day f'cm, psi (MPa)				
	40	120	225	480	900	40	120	225	480	900
20% slag	6013 (41)	5955 (41)	6021 (42)	6059 (42)	5786 (40)	6572 (45.3)	6865 (47.3)	6682 (46.1)	6671 (40.6)	4560 (31.4)
40% slag	5269 (36)	5279 (36)	5629 (39)	5451 (38)	5457 (38)	6106 (42.1)	5893 (40.6)	6243 (43.0)	6195 (42.7)	6235 (43.0)
20% FA	6016 (41)	5849 (40)	6199 (43)	6184 (43)	6073 (42)	6470 (44.6)	6389 (44.0)	7062 (48.7)	6747 (46.5)	6857 (47.3)
30% FA	5006 (36)	5387 (36)	5177 (35)	5316 (37)	5356 (38)	5340 (44.0)	5898 (46.5)	6042 (41.7)	6076 (41.9)	6374 (43.9)

Statistical analyses are used here to assess the potential differences in means of the f'cm of the different concrete groups as a function of LDRCs. Because the initial compressive strengths of the concrete varied, values are first normalized and then assessed. The compressive strength values were normalized with the average strength of the same mixture mixed at 40 LDRCs. The normalized 28-day and normalized 56-day compressive strength values will be referred to as n-$f'cm_{28}$ and $f'cm_{56}$. Table 6-25 shows the n-$f'cm_{28}$ for the different mixtures mixed for different LDRCs. Each value in Table 6-25 is the average of three specimens unless noted otherwise.

Table 6-25. Normalized Compressive Strength (28 day) for Different Groups of Mixture mixed for Different LDRCs.

Normalized 28-day Compressive Strength									
120 Drum Revolution Counts					225 Drum Revolution Counts				
CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
1.00	0.99	0.98	0.95	0.89	0.94	1.00	0.98	1.05	0.90
1.02	1.00	0.96	1.00	1.04	1.04	1.07	0.96	1.09	0.93
1.02	1.01	1.02			1.00	1.02	1.03		
1.04	0.97	1.04			0.97	1.03	1.07		
1.05					1.02				
0.99					0.92				
0.98					0.98				
1.00					1.02				
1.06					1.01				
1.00					1.04				
1.00					1.00				
480 Drum Revolution Counts					900 Drum Revolution Counts				
CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
0.97	1.01	0.96	1.06	0.99	0.94	0.96	0.99	0.96	1.02
1.03	1.03	0.99	1.20	0.97	1.02	1.04	1.07	1.15	1.17
1.10	1.04	1.06			1.07	1.06	1.09		
1.03	1.03	1.00			1.02	1.01	1.04		
1.10					0.94				
0.99					0.94				
0.99					0.99				
1.06					1.05				
1.09					1.01				
1.02					1.01				
1.06					1.04				

Table 6-26 shows the statistical parameters for the 28-day f'cm for mixtures mixed with different LDRCs. The tables include the average, standard deviation, and number of samples.

Table 6-26. Statistical Parameters for the f'cm$_{28}$ of the Mixtures Mixed at Different LDRCs.

Statistical Parameters	Drum Revolution Counts									
	120 Drum Revolution Counts					225 Drum Revolution Counts				
	CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
Average	1.01	0.99	1.00	0.97	0.96	0.99	1.03	1.01	1.07	0.91
Standard Deviation	0.04	0.04	0.04	0.07	0.10	0.05	0.04	0.05	0.06	0.03
Number of Samples	33	12	12	6	6	32	12	12	6	6
Statistical Parameters	480 Drum Revolution Counts					900 Drum Revolution Counts				
	CA	SCM	AD_{rd}	AD_{hd}	AEA	CA	SCM	AD_{rd}	AD_{hd}	AEA
Average	1.04	1.03	1.00	1.13	0.98	1.00	1.02	1.05	1.05	1.10
Standard Deviation	0.05	0.04	0.04	0.09	0.02	0.05	0.05	0.05	0.11	0.09
Number of Samples	33	12	12	6	6	33	12	12	6	6

Table 5-36 through Table 5-39 show the ANOVA tables for these groups. The calculated values were defined earlier. The ANOVA testing indicates that there is no statistically significant difference between the means of the n-f'cm$_{28}$ for the CA, SCM, and AD_{rd} groups mixed for 120 LDRCs at the 95 percent confidence level (p-value = 0.266). Similarly, for the mixtures mixed for 225 LDRC, there is also no statistically significant difference between the mean n-f'cm of the same three groups at the 95 percent confidence level (ANOVA, p-value =0.098). Analysis on the mixtures mixed for 480 and 900 LDRCs also indicated no statistically significant difference at the 95 percent confidence level (p-value = 0.066 and 0.067, respectively).

Table 6-27. ANOVA Test for the Groups Mixed for 120 LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.00425	2	0.00212	1.36	0.266
Within groups	0.0846	54	0.00156		
Total (Corr.)	0.0889	56			

Table 6-28. ANOVA Test for the Groups Mixed for 225 LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0112	2	0.00560	2.42	0.098
Within groups	0.122	53	0.00231		
Total	0.134	55			

Table 6-29. ANOVA Test for the Groups Mixed for 480 LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0126	2	0.00634	2.85	0.066
Within groups	0.120	54	0.00222		
Total	0.133	56			

Table 6-30. ANOVA Test for the Groups Mixed for 900 LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0158	2	0.00792	2.84	0.067
Within groups	0.150	54	0.00279		
Total	0.166	56			

Because there is no statistically significant difference between the means of the three groups mixed at different LDRCs, the data from the three groups (CA, SCM, AD_{rd}) that share the same LDRCs will be pooled together. This combined group will be referred to hare as the "conventional mixtures." To assess the influence of LDRCs, the mixtures mixed at the different LDRCs are then compared. The conventional mixtures mixed at 120, 225, 480, and 900 are compared using the AVOVA test. The results are shown in Table 6-31.

Table 6-31. ANOVA Test for the Conventional Groups Mixed at Different LDRCs.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.021	3	0.00708	3.02	0.031
Within groups	0.523	223	0.00234		
Total	0.544	226			

The ANOVA analysis indicates that there is a statistically significant difference between the mean n-f'cm_{28} value of the conventional concrete mixture mixed at different LDRCs. The Tukey test was used to determine which "number of LDRCs" is significantly different than the other. It was determined that the n-f'cm_{28} of mixtures mixed at 480 LDRCs is significantly different than the mixtures mixed at 120, 225 and 900 LDRCs. Figure 6-26 shows a box plot for the n-f'cm_{28} for these mixtures mixed at different LDRCs. The figure shows that the mean n-f'cm_{28} of the mixtures mixed for 480 LDRCs is slightly higher than that of the mixtures mixed at 120, 225, and 900 LDRCs. The mean f'cm_{28} of mixtures mixed at 480 LDRCs is approximately 2 percent higher than the other mixtures. Because this research is concerned with the potential detrimental effects of LDRCs on concrete properties, a small increase in strength, even though statistically significant, is of limited concern. Because of this, modeling for the n-f'c_{28} as a function of LDRCs is not needed.

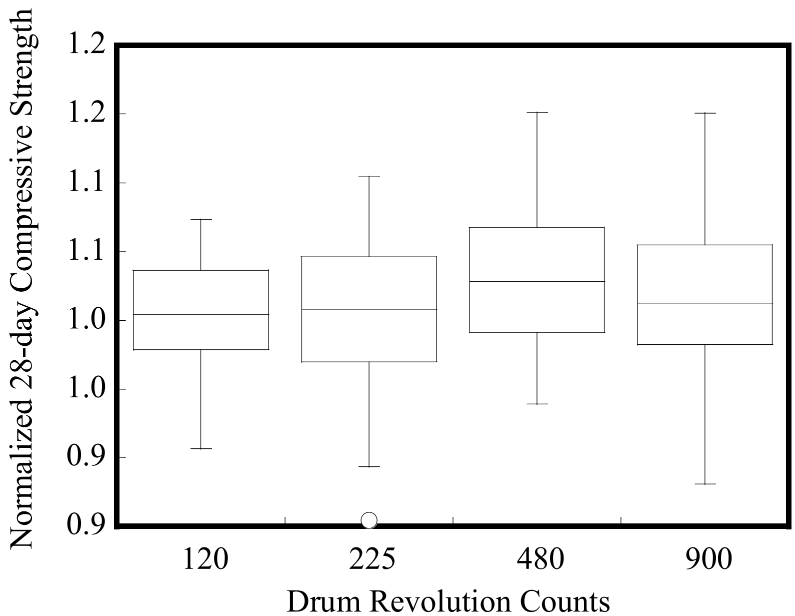


Figure 6-26. Box Plot for Conventional Mixtures Mixed for Different LDRCs.

This concludes the statistical analyses for the conventional mixtures group. The analyses of the AD_{hd} and AEA groups follow.

For the AD_{hd} and AEA groups, it was determined that there is a statistically significant difference in the $f'cm_{28}$ between the mixtures containing admixtures from the different manufacturers. Although significantly different, chemical admixtures are proprietary and can vary significantly between different manufacturers. Therefore, general trends will be shown but no model will be developed.

Figure 6-27 shows the $f'cm_{28}$ as a function of LDRCs. Figure 6-28 shows the n-$f'cm_{28}$ versus LDRCs for these same mixtures.

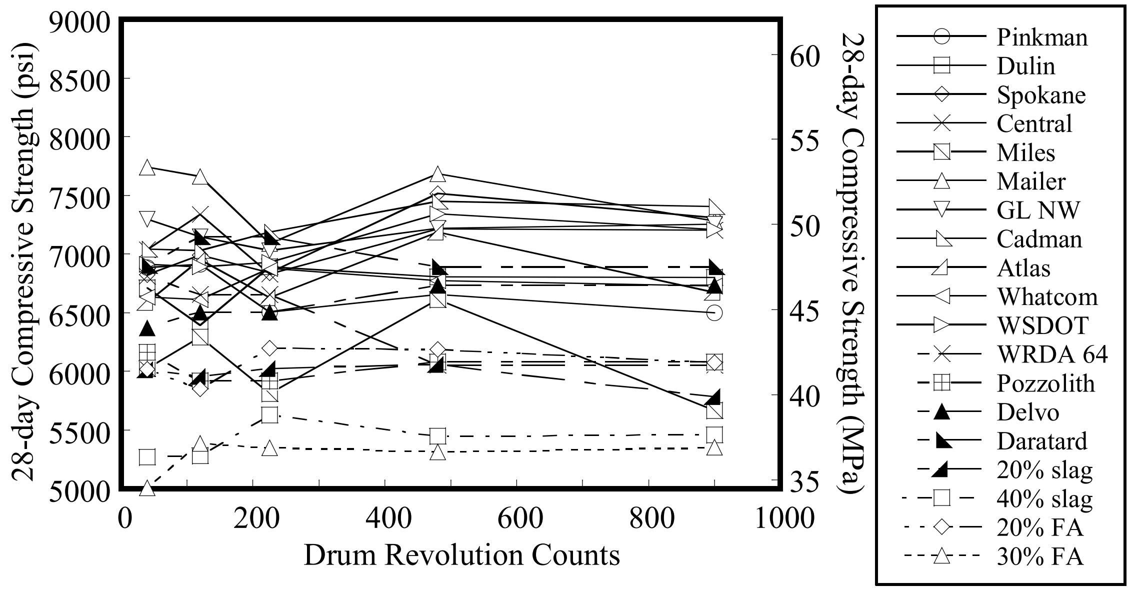


Figure 6-27. The f'cm$_{28}$ versus LDRCs for Conventional Mixtures.

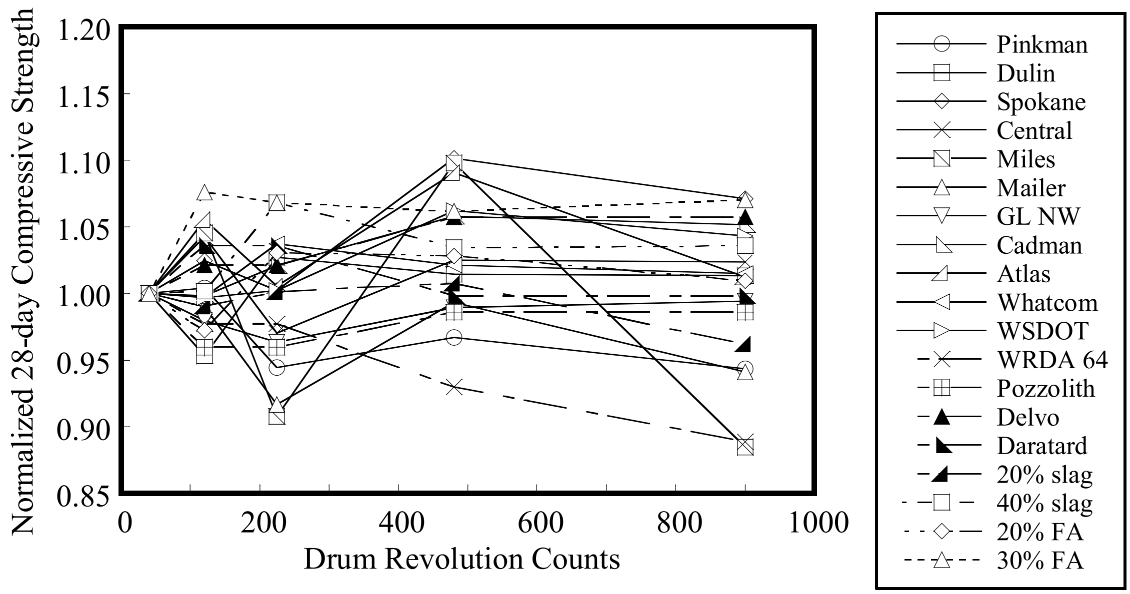


Figure 6-28. The n-f'cm$_{28}$ versus LDRCs for Conventional Mixtures.

The AD_{hd} mixtures were mixed for up to 2700 LDRCs. Figure 6-29 and Figure 6-30 show the f'cm$_{28}$ and n-f'cm$_{28}$ for these mixtures, respectively.

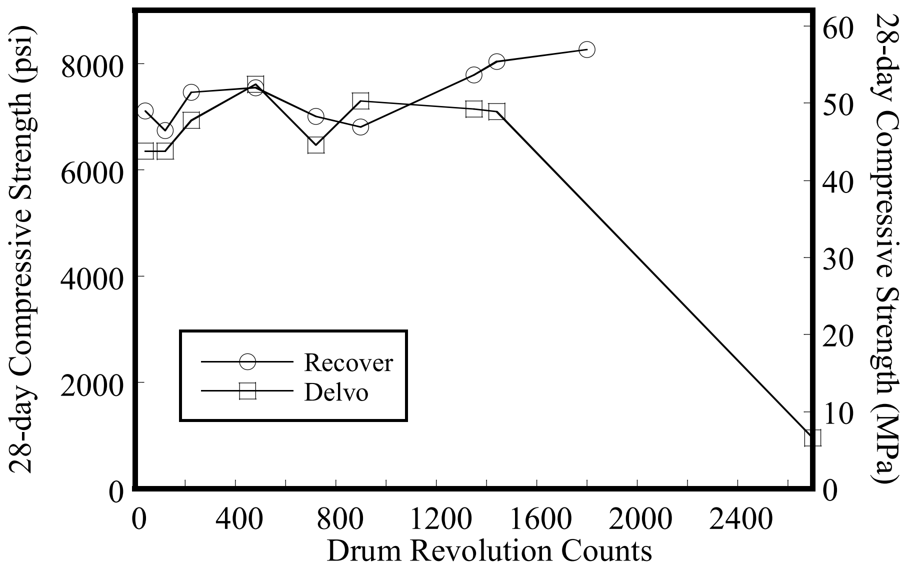


Figure 6-29. The f'cm_{28} versus LDRCs for the AD_{hd} Group Mixtures.

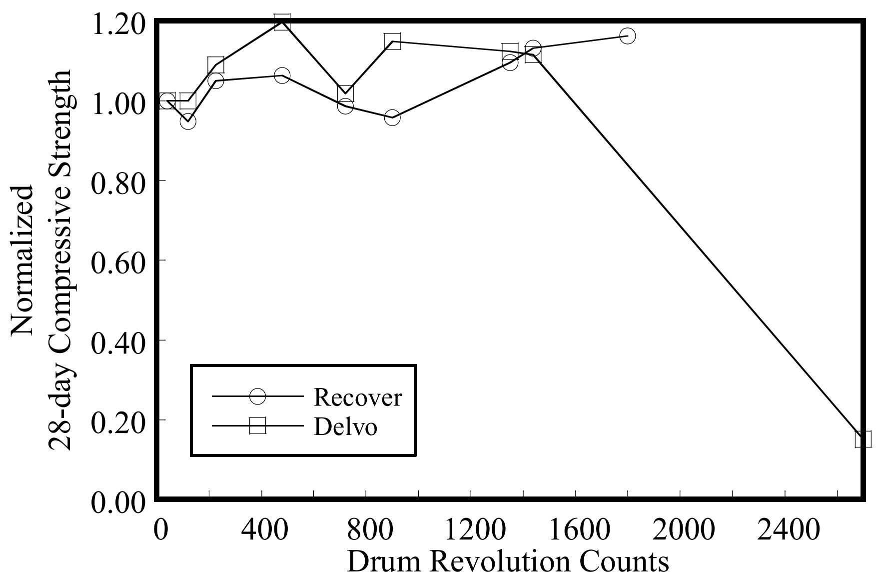


Figure 6-30. The n-f'cm_{28} versus LDRCs for the AD_{hd} Group Mixtures.

Figure 6-30 shows the AD_{hd} mixtures exhibited some variation in f'cm_{28} as LDRCs increase up to 1440 LDRCs. However, the f'cm_{28} did not decrease by more than 6 percent. This indicates that there is no significant negative impact on the f'cm_{28} with increasing LDRCs up 2700. However, the mixtures containing Delvo exhibited an 80 percent loss in compressive strength when mixed to 2700 LDRCs. This reduction in strength is caused by poor workability and poor consolidation at these high mixer revolution counts. This mixture had a slump of zero when sampled from the mixer. Large air voids were present in the hardened specimens. These voids were present because the mixture exhibited low workability and the researchers were unable to properly consolidate the specimens after mixing. This resulted in a significant decrease in compressive strength.

Figure 6-31 and Figure 6-32 show the $f'cm_{28}$ and n-$f'cm_{28}$ as a function of LDRCs for the mixtures containing AEA, respectively.

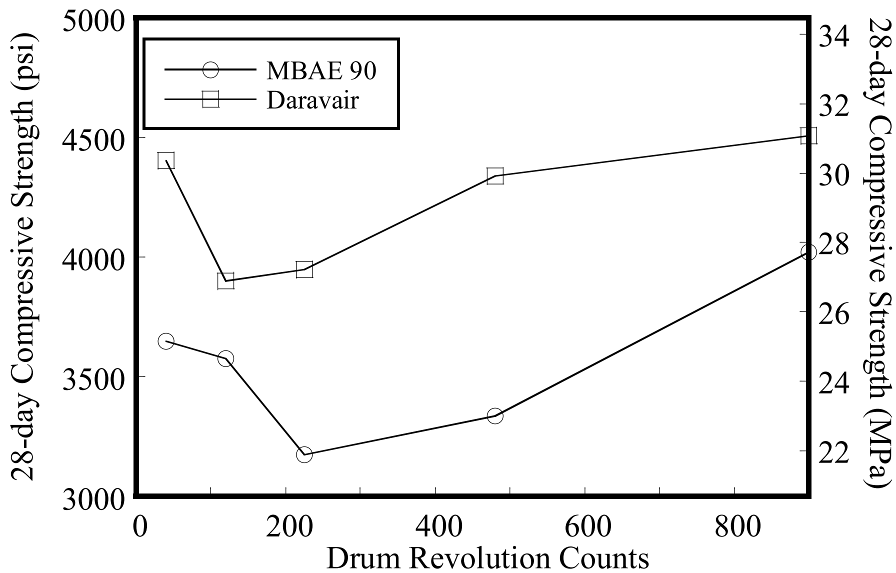


Figure 6-31. LDRCs versus $f'cm_{28}$ for the AEA Group Mixtures.

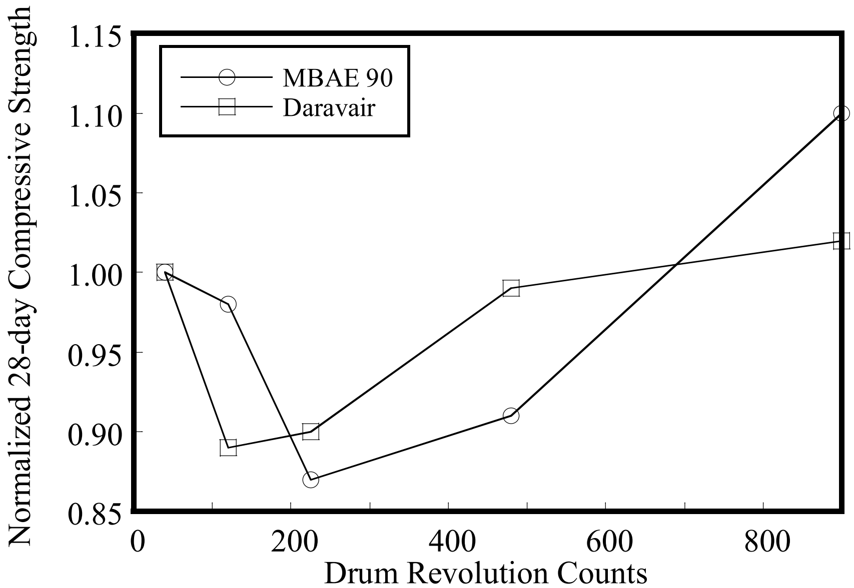


Figure 6-32. LDRCs versus n-f'cm_{28} for the AEA Group Mixtures.

The n-f'cm_{28} for the AEA group shows that the f'cm_{28} decreased for mixtures mixed for 40 to 225 LDRCs, then increased. It is thought that increases in the LDRCs resulted in the AEA admixture generating higher air contents for LDRCs from 40 to approximately 200. However, after 200 LDRCs the air was forced from the concrete mixture, thereby decreasing the air content and increasing the strength.

Results indicate that the LDRCs has limited influence on the f'cm_{28} of the conventional mixtures. However, results also indicate that very large LDRCs resulted in a decrease in f'cm_{28}. This was a result of lack of workability of the mixture. Results also indicate that LDRCs can affect the f'cm_{28} of mixtures containing AEA, with large LDRCs likely decreasing air content and increasing f'cm_{28}. The f'cm_{56} as a function of LDRCs will be assessed next.

Table 6-32 shows the normalized f'cm$_{56}$ for the different groups mixed at different LDRCs. Note that the f'cm$_{56}$ for mixtures containing high dosages of admixture was not assessed.

Table 6-32. Normalized Compressive Strength for Different Groups of Mixture mixed for Different LDRCs.

Normalized 56-day Compressive Strength							
120 Drum Revolution Counts				225 Drum Revolution Counts			
CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
1.02	1.04	0.97	0.94	0.96	1.02	0.98	0.87
1.03	1.97	0.98	1.04	1.01	1.02	1.01	0.97
1.02	1.10	1.06		1.08	1.12	1.11	
1.03	0.99	1.02		0.97	1.09	1.05	
1.05				1.01			
1.02				0.94			
1.09				1.90			
0.96				0.99			
1.00				1.04			
0.98				0.98			
0.98				1.02			
480 Drum Revolution Counts				900 Drum Revolution Counts			
CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
0.97	1.02	0.96	0.98	0.97	1.00	0.99	1.02
1.05	1.01	1.02	1.00	0.97	1.02	1.06	1.13
1.10	1.14	1.08		1.10	1.19	1.19	
1.04	1.04	0.98		1.04	1.06	0.94	
1.03				1.03			
0.98				0.96			
1.02				1.09			
0.97				0.97			
1.06				1.06			
1.05				1.01			
1.07				1.07			

Table 6-33 show the statistical parameters for the $f'cm_{56}$ for the different LDRCs. The tables include the average, standard deviation, and number of samples for the analyses.

Table 6-33. Statistical Parameters for the $f'cm_{56}$ of the Mixtures Mixed for Different LDRCs.

Statistical Parameters	Drum Revolution Counts							
	120 Drum Revolution Counts				480 Drum Revolution Counts			
	CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
Average	1.02	1.03	1.01	0.99	1.01	1.06	1.03	0.92
Standard Deviation	0.05	0.06	0.05	0.06	0.06	0.06	0.06	0.06
Number of Samples	32	12	12	6	32	12	12	6
Statistical Parameters	225 Drum Revolution Counts				900 Drum Revolution Counts			
	CA	SCM	AD_{rd}	AEA	CA	SCM	AD_{rd}	AEA
Average	1.03	1.05	1.01	0.99	1.02	1.07	1.05	1.08
Standard Deviation	0.05	0.07	0.06	0.03	0.06	0.08	0.10	0.06
Number of Samples	32	12	12	6	33	12	12	6

Table 6-34 through Table 6-37 show the ANOVA tables for these groups. The ANOVA testing indicates that there is no statistically significant difference between the means of the n-$f'cm_{56}$ for the CA, SCM, AD_{rd} and AEA groups mixed for 120 LDRCs at the 95 percent confidence level (p-value = 0.534). For the mixtures mixed for 225 LDRCs, there is also no statistically significant difference between the mean n-f'cm of the same three groups at the 95 percent confidence level (p-value = 0.163). Also, these groups are also tested for difference in means between the groups when mixed for 480 and 900 LDRCs. The results indicate there is no statistical difference between the mean n-$f'cm_{56}$ of the group when mixed for 900 (p-value = 0.107, 95 percent confidence level). However, when mixtures were mixed for 225, ANOVA test indicates that there is a statistically significant difference between the 56-day n-f'cm of the four groups at the 95 percent confidence level (p-vale = 0.000).

Table 6-34. ANOVA Test for the Groups Mixed for 120 revolutions at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.00586	3	0.00195	0.74	0.534
Within groups	0.153	58	0.00264		
Total	0.159	61			

Table 6-35. ANOVA Test for the Groups Mixed for 225 revolutions at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0184	3	0.00615	2.13	0.107
Within groups	0.167	58	0.00289		
Total	0.18	61			

Table 6-36. ANOVA Test for the Groups Mixed for 480 revolutions at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0886	3	0.0295	8.81	0.0001
Within groups	0.194	58	0.0034		
Total	0.283	61			

Table 6-37. ANOVA Test for the Groups Mixed for 900 revlutions at 8 rpm.

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.0271	3	0.00904	1.77	0.163
Within groups	0.301	59	0.00511		
Total	0.328	62			

Because there is a statistically significant difference between the mean $f'cm_{56}$ of the four groups, groups will be analyzed individually. ANOVA tests are used to compare the mean $n\text{-}f'cm_{56}$ of the individual groups mixed for different LDRCs. For the CA group mixed for 120, 225, 480, 900 LDRCs, the ANOVA test results indicate that there is no statistically significant difference between the mean $n\text{-}f'cm_{56}$ (p-value = 0.395). ANOVA test results also indicate similar results for the SCM and AD_{rd} groups (p-value = 0.452 and 0.462, respectively). This indicates that LDRCs does not significantly influence $f'cm_{56}$. Therefore, no 56-day compressive strength model as a function of LDRCs will be developed for the CA, SCM, and AD_{rd} groups. Figure 6-33 through Figure 6-35 show the general trends of the $f'cm_{56}$ for the CA, SCM, and AD_{rd} group mixtures.

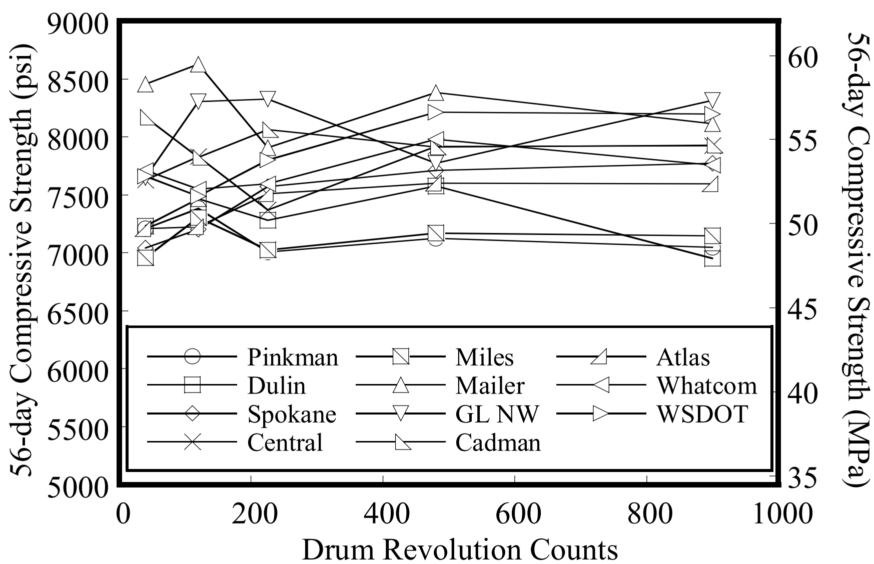


Figure 6-33. $f'cm_{56}$ versus LDRCs for CA Group.

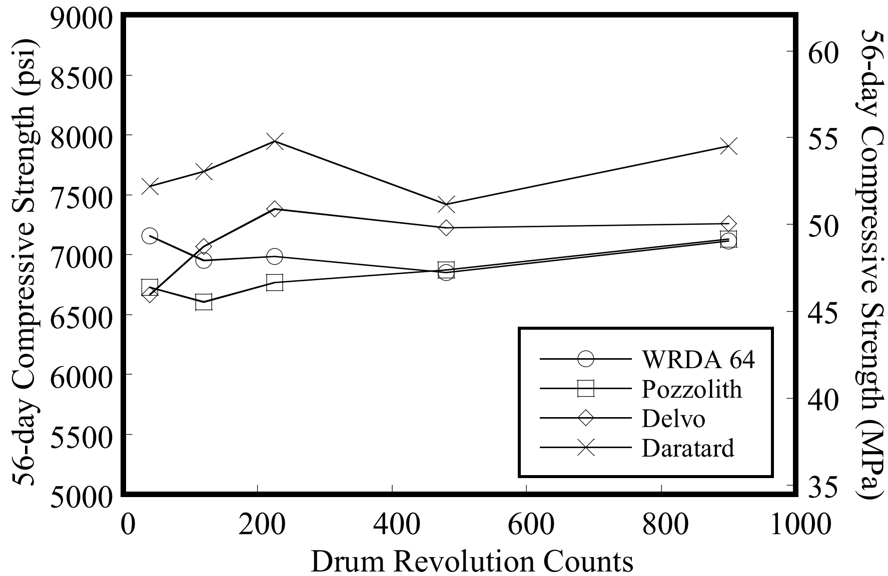


Figure 6-34. f'cm$_{56}$ versus LDRCs for Mixtures for AD$_{RD}$ Group.

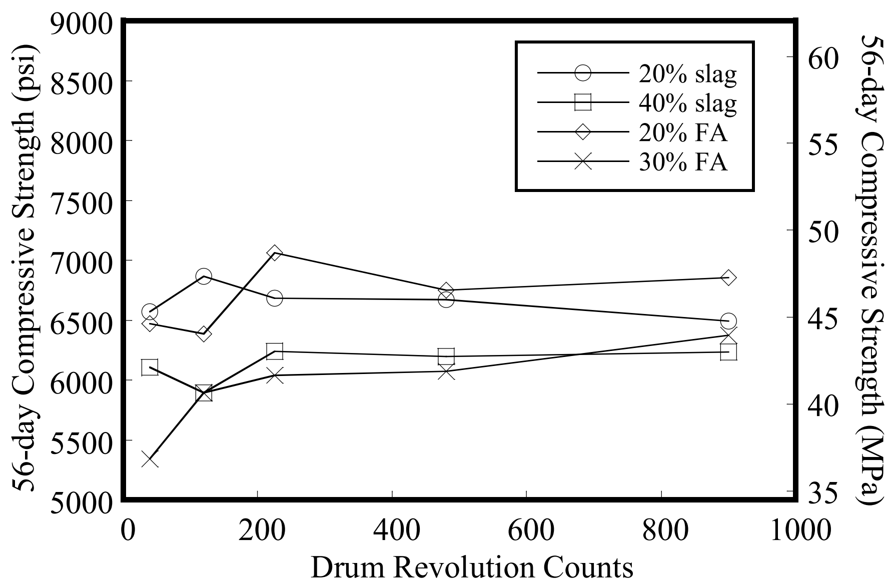


Figure 6-35. LDRCs versus f'cm$_{56}$ for Mixture Containing SCMs.

Similar to the n-f'cm$_{28}$, an analysis also indicates that there is a statistically significant difference in the n-f'cm$_{56}$ of the AEA group mixed at different LDRCs. As stated earlier, although significantly different, chemical admixtures are proprietary and can vary significantly between different manufacturers. Therefore, general trends will be shown but no model will be developed. Figure 6-36 shows the 56-day compressive strength for the mixtures containing AEA.

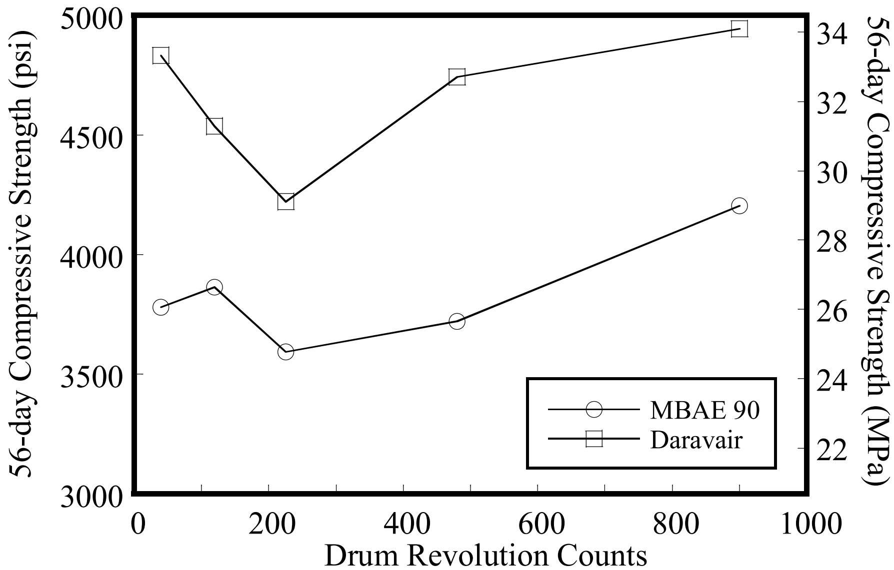


Figure 6-36. LDRCs versus f'cm$_{56}$ for the AEA Group Mixtures.

6.2.2 Potential Influence of Laboratory Drum Revolution Counts on Apparent Chloride Diffusivity

The apparent chloride diffusion coefficient were assess for mixtures mixed for different LDRCs. The following section provides the analyses.

6.2.2.1 CA Group Mixtures

The CA group mixtures contain mixtures proportioned with 11 different CAs. Table 6-38 shows the apparent chloride diffusion coefficient values for the CA group. These coefficients are the average from triplicate samples.

Table 6-38. Chloride Diffusion Coefficient for CA Group Mixed at Different LDRCs.

Aggregate Source	Apparent Chloride Diffusion Coefficient Da, ft^2/s (m^2/s)				
	Drum Revolution Counts				
	40	120	480	225	900
Dulin	6.40E-11 (5.95E-12)	8.40E-11 (7.80E-12)	7.55E-11 (7.01E-12)	8.08E-11 (7.51E-12)	5.15E-11 (4.78E-12)
Central	5.89E-11 (5.47E-12)	7.08E-11 (6.58E-12)	7.83E-11 (7.27E-12)	7.53E-11 (7.00E-12)	8.12E-11 (7.54E-12)
Spokane	4.80E-11 (4.46E-12)	7.02E-11 (6.52E-12)	7.29E-11 (6.77E-12)	9.64E-11 (8.96E-12)	6.47E-11 (6.01E-12)
WSDOT	N.A.	5.30E-11 (4.92E-12)	6.57E-11 (6.10E-12)	7.88E-11 (7.32E-12)	5.17E-11 (4.80E-12)
Miles	1.25E-10 (1.16E-11)	1.46E-10 (1.36E-11)	1.32E-10 (1.23E-11)	1.33E-10 (1.24E-11)	1.43E-10 (1.33E-11)
Cadman	N.A.	7.59E-11 (7.05E-12	9.96E-11 (9.25E-12)	7.66E-11 (7.12E-12)	7.21E-11 (6.70E-12)
Glacier NW	N.A.	8.42E-11 (7.82E-12)	1.17E-10 (1.09E-11)	1.39E-10 (1.29E-11)	1.16E-10 (1.08E-11)
Whatcom	N.A.	7.14E-11 (6.63E-12)	6.98E-11 (6.48E-12)	9.54E-11 (8.86E-12)	8.09E-11 (7.52E-12)
Pinkham	9.80E-11 (9.10E-12)	9.90E-11 (9.20E-12)	9.82E-11 (9.12E-12)	9.70E-11 (9.01E-12)	8.91E-11 (8.28E-12)
Atlas	N.A.	6.58E-11 (6.11E-12)	8.43E-11 (7.83E-12)	7.04E-11 (6.54E-12)	7.73E-11 (7.18E-12)
Maier	6.56E-11 (6.09E-12)	9.19E-11 (8.54E-12	1.83E-10 (1.28E-11)	1.22E-10 (1.13E-11)	1.17E-10 (1.09E-11)

N.A.: not available

Figure 6-37 shows a box plot of apparent chloride diffusion coefficient values for the mixtures mixed for different LDRCs. ANOVA analysis indicates there is no statistically difference in the mean apparent chloride diffusivity for the CA group mixtures mixed at different LDRCs at the 95 percent confidence level (p-value = 0.503).

To assess whether current LDRCs limits are justified (i.e., 250 LDRCs), the apparent chloride coefficient of mixtures mixed for less than 250 LDRCs are compared to those of mixtures that were mixed for greater than 250 LDRCs. Figure 6-38 shows a box plot comparing these two groups. T-test indicates that there is no statistically significant difference in the mean apparent chloride diffusion coefficient between mixtures mixed for less than 250 LDRCs and mixtures mixed for greater than 250 LDRCs (p-value = 0.462, 95 percent confidence level).

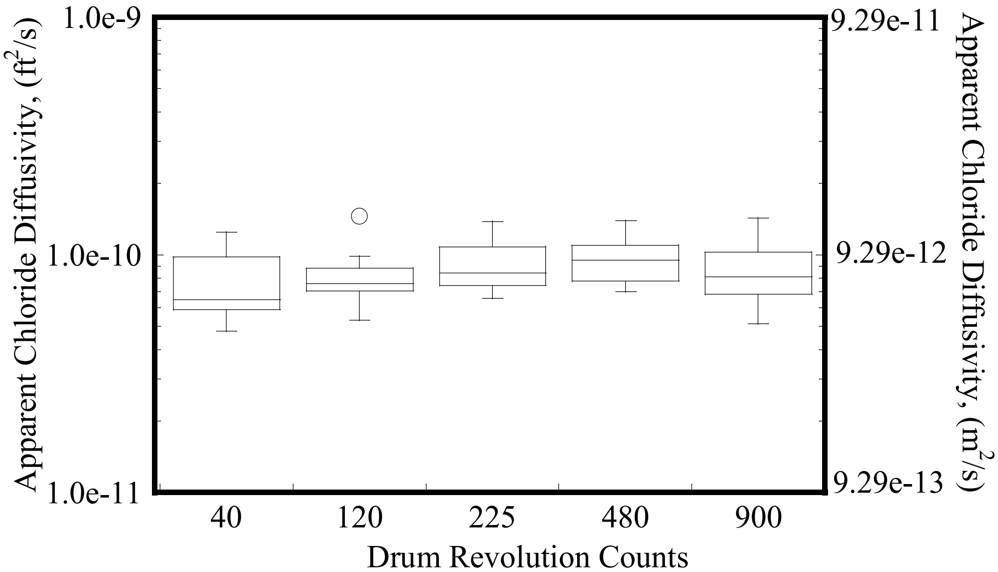


Figure 6-37. Box Plot for Apparent Chloride Diffusivity for the CA Group Mixed at Different LDRCs.

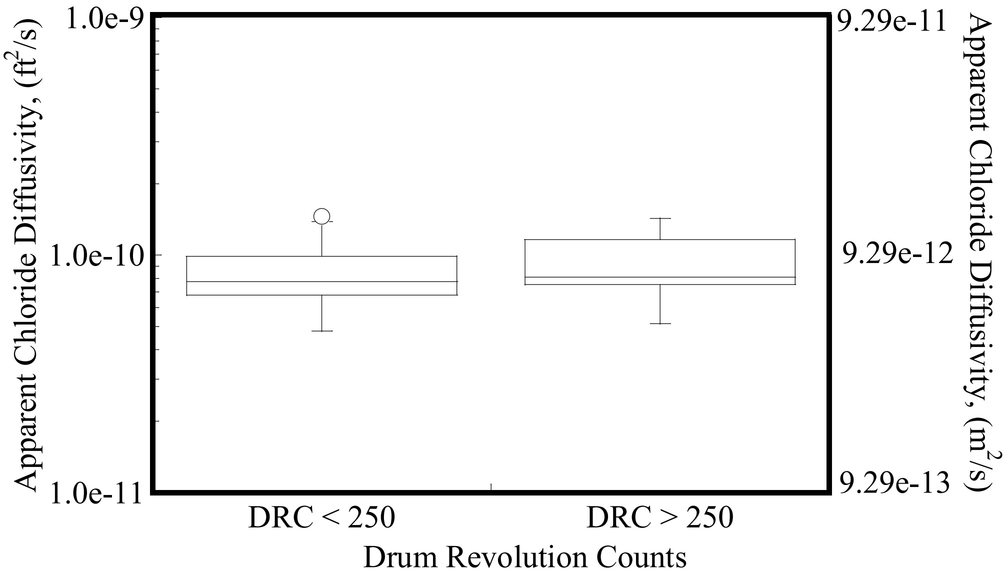


Figure 6-38. Box Plot for Apparent Chloride Diffusion Coefficient for CA Mixtures Mixed for Lesser than and Greater than 250 LDRCs.

6.2.2.2 Admixture Group Mixtures

The admixture group includes mixtures that contain WRAs, retarders, and AEA. ANOVA analysis indicates there is no statistically significant difference in the mean apparent chloride diffusivity for the admixture group mixtures mixed at different LDRCs at the 95 percent confidence level (p-value = 0.464). Table 6-39 shows a box plot for the apparent chloride diffusion coefficient values for the AD_{rd} group. A comparison of the mixtures mixed for less than and greater than 250 LDRCs is shown in Figure 6-40. Statistical analyses indicate that there is no statistically significant difference in the mean apparent chloride diffusion coefficient for mixtures mixed for less than and mixtures mixed for more than 250 LDRCs (t-test, p-value = 0.850 at 95 percent confidence level).

Table 6-39. Apparent Chloride Diffusivity for the Mixtures Containing Admixtures.

Mixtures	Apparent Chloride Diffusion Coefficient Da, in^2/s (m^2/s)			
	Drum Revolution Counts			
	120	225	480	900
WRDA 64	3.87E-11 (3.60E-12)	N.A.	(3.290E-12)	1.04E-10 (9.63E-12)
Pozzolith 200N	3.95E-11 (3.67E-12)	4.63E-11 (4.30E-12)	3.54E-11 (7.44E-12)	1.52E-10 (1.41E-11)
Delvo	7.21E-11 (6.70E-12)	6.32E-11 (5.88E-12)	8.01E-11 (3.48E-12)	1.12E-10 (1.04E-11)
Daratard 17	1.31E-10 (1.22E-11)	1.83E-10 (1.70E-11)	3.74E-11 (1.27E-11)	1.63E-10 (1.51E-11)
MBAE 90	1.35E-10 (1.25E-11)	1.48E-10 (1.37E-11)	1.37E-10 (3.48E-12)	3.16E-11 (2.94E-12)
Daravair	6.89E-11 (6.40E-12)	9.61E-11 (8.930E-12)	3.74E-11 (9.08E-12)	8.18E-11 (7.60E-12)

N.A.: not available

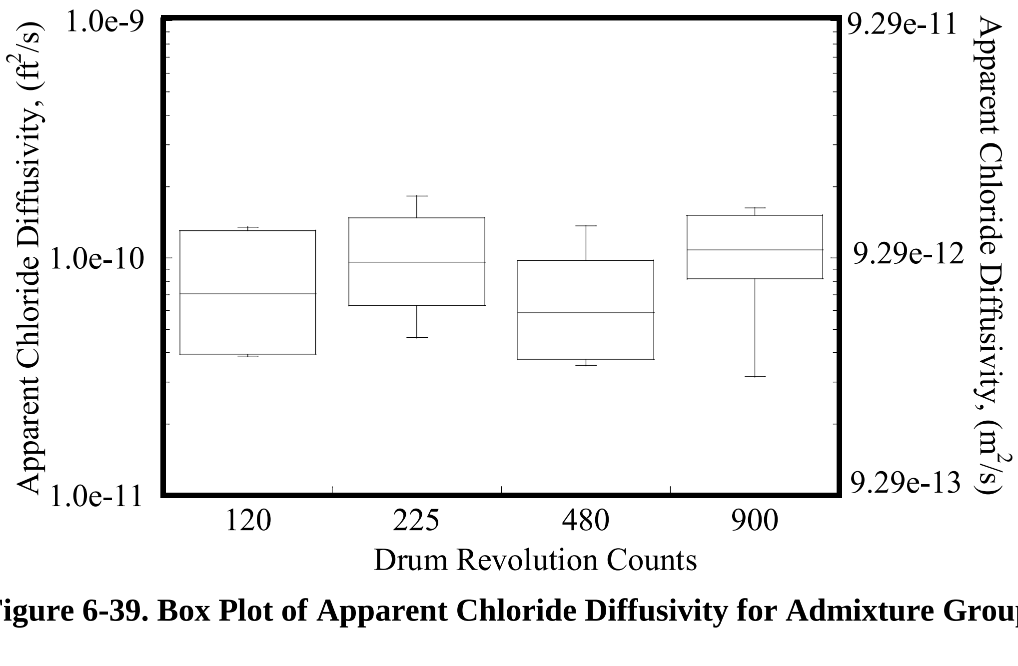


Figure 6-39. Box Plot of Apparent Chloride Diffusivity for Admixture Group.

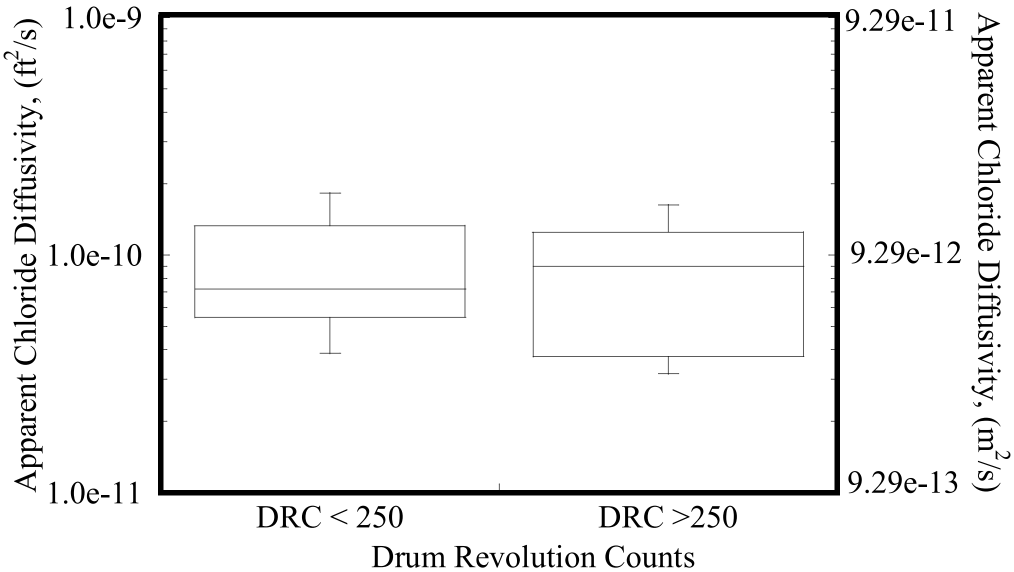


Figure 6-40. Box Plot for Apparent Chloride Diffusion Coefficient for AD_{rd} Mixtures Mixed for Lesser than and Greater than 250 LDRCs.

6.2.2.3 SCMs Group Mixtures

The SCM group mixtures include mixtures mixed with slag and Class F fly ash. ANOVA analysis indicates there is not a statistical difference in the mean apparent chloride diffusivity for the SCM group mixtures at the 95 percent confidence level (p-value = 0.251). Table 6-40 shows the apparent chloride diffusion coefficient for the SCM mixtures mixed at different LDRCs. Figure 6-41 shows a box plot for these values. Similar to other groups, t-test comparisons indicate no statistically significant difference in the mean apparent chloride diffusion coefficient between mixtures mixed for less than and greater than 250 LDRCs. Figure 6-42 shows this comparison.

Table 6-40. Apparent Chloride Diffusivity for the SCMs Mixtures.

Mixtures	Apparent Chloride Diffusion Coefficient Da, ft^2_{ft}/s (m^2/s)			
	Drum Revolution Counts			
	120	225	480	900
20% slag	8.71E-11 (8.09E-12)	6.08E-11 (7.38E-12)	7.94E-11 (5.65E-12)	5.36E-11 (4.98E-12)
40% slag	2.72E-11 (2.54E-12)	2.64E-11 (4.724E-12)	5.08E-11 (2.45E-12)	5.90E-11 (5.48E-12)
20% FA	5.15E-11 (4.78E-12)	4.54E-11 (4.55E-12)	4.90E-11 (4.22E-12)	2.67E-10 (2.48E-11)
30% FA	1.12E-10 (1.04E-11)	1.07E-10 (8.01E-12)	8.63E-11 (9.98E-12)	1.00E-10 (9.29E-12)

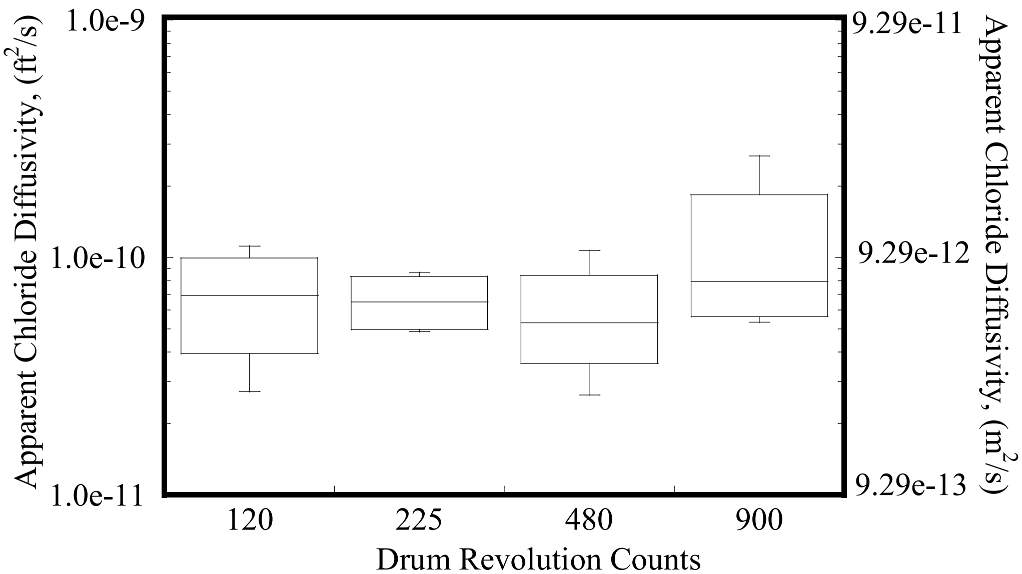


Figure 6-41. Box Plot of Concrete Apparent Chloride Diffusivity for SCM Group.

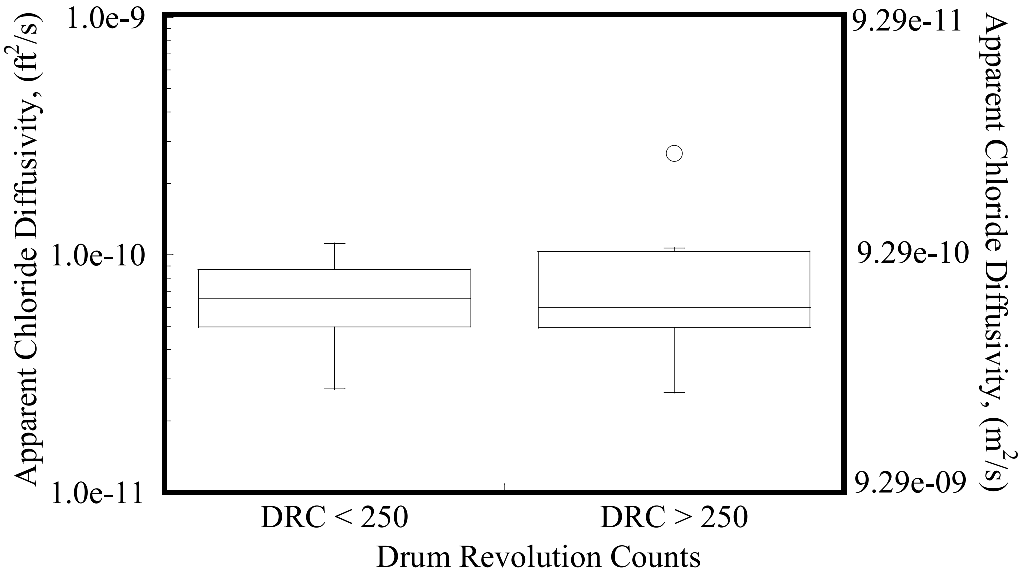


Figure 6-42. Box Plot for Apparent Chloride Diffusion Coefficient for SCM Group Mixtures Mixed for Lesser and Greater than 250 LDRCs.

6.2.3 Potential Influence of Laboratory Drum Revolution Counts on Freeze-thaw Performance

The freeze-thaw performance of the concrete mixtures was also assessed as a function of LDRCs. These specimens were subjected to freeze-thaw cycle for up to 296 cycles or until the relative dynamic modulus decrease to 60 percent, whichever came first. Table 6-41 and Table 6-42 show these relative dynamic modulus values for the mixtures containing AEA and mixtures without AEA, respectively. These values are the average value from triplicate samples.

Table 6-41. Relative Dynamic Modulus for Mixtures Containing AEA.

Mixtures Containing AEAs	Relative Dynamic Modulus, % (cycles)				
	Drum Revolution Counts				
	40	120	225	480	900
MBAE 90	N.A.	100 (296)	100 (296)	100 (296)	99 (296)
Daravair	N.A.	101 (296)	101 (296)	100 (296)	97 (296)

Table 6-42. Relative Dynamic Modulus for Non-AEA Mixtures

Mixtures With Different CAs	Relative Dynamic Modulus, % (cycles)				
	Drum Revolution Counts				
	40	120	225	480	900
Mile	N.A.	60 (16.2)	60 (18.3)	60 (18.6)	60 (16.8)
Maier	N.A.	60 (26.2)	60 (21.9)	60 (15.8)	60 (25.7)

For mixtures containing AEA, comparison of the relative dynamic modulus values at 296 cycles were assessed. ANOVA analysis indicates that there is a statistically significant difference between the mean relative dynamic modulus of these mixtures mixed at different LDRCs (p-value = 0.037, 95 percent confidence level). Even though there is a statistical significant difference, the relative dynamic modulus of mixtures mixed for 900 LDRCs is approximately 98 percent. This is significantly higher than the specified 60 percent indicating that freeze-thaw performance of concrete mixture containing AEA is likely not detrimentally impacted by mixing up to 900 LDRCs in the laboratory. It should be noted that testing of strength for mixtures containing AEA indicated that air content likely decreased with increasing mixing, which could result in reduced freeze-thaw performance. However, results from the freeze-thaw testing indicates that although the air-content could decrease there is likely sufficient entrained air to ensure good freeze-thaw performance.

The mixtures mixed without AEA failed without reaching the 300 cycle limit. That is, the relative dynamic modulus drops below 60 percent. Instead of comparing the relative dynamic modulus at this maximum number of cycles, as was with the mixtures containing AEA, the numbers of cycles at failure (60 percent relative dynamic modulus) will be compared. ANOVA test results indicate that there is no statistically significant difference between the mean number of cycle to failure of the mixtures mixed at different drum revolutions at the 95 percent confidence level (p-value = 0.906). This indicates that LDRCs does not significantly influence the freeze-thaw performance of concrete mixed without AEA.

The results from analyses on the influence of LDRCs on freeze-thaw performance indicate that there is a statistically significant difference in the mean relative dynamic modulus of mixtures containing AEA mixed for different LDRCs. However, the difference in mean values is small and the mean relative dynamic modulus of the mixtures mixed for 900 LDRCs is still well above the failure limit. This indicates that mixing up to 900 LDRCs in the laboratory likely does not detrimentally affect the freeze-thaw performance of concrete mixtures containing AEA. For mixtures without AEA, the statistical results indicate that LDRCs does not significantly influence the freeze-thaw performance of concrete mixtures.

6.2.4 Potential Influence of Laboratory Drum Revolution Counts on Modulus of Elasticity

Unlike the previous hardened concrete characteristics, the MOE was only evaluated for the mixtures containing high dosages of retarders. Table 6-43 shows the MOE values for these mixtures mixed for different LDRCs. Statistical analyses were performed to compare the mean MOE of these mixtures.

Table 6-43. Modulus of Elasticity for the Concrete Mixed at Different LDRCs.

DRC	Modulus of Elasticity, ksi (Gpa)							
	With Retarder A		With Retarder B			With Retarder B and AEA		
40	5441 (37.5)	5481 (37.8)	5449 (37.6)	5277 (36.4)	5399 (37.2)	4264 (29.4)	4421 (30.5)	4191 (28.9)
225	5452 (37.6)	5717 (39.4)	5397 (37.2)	5267 (36.3)	5417 (37.3)	4111 (28.3)	4246 (29.3)	4266 (29.4)
480	5480 (37.8)	5308 (36.6)	5834 (40.2)	5589 (38.5)	5274 (36.4)	3783 (26.1)	3810 (26.3)	3708 (25.6)
720	5264 (36.3)	5244 (36.2)	5413 (37.3)	5342 (36.8)	5316 (36.6)	3876 (26.7)	3804 (26.2)	3887 (26.8)
1440	5731 (39.5)	5594 (38.6)	5440 (37.5)	5438 (37.5)	5432 (37.4)	5073 (35.0)	5370 (37)	5056 (34.9)
1800	5343 (36.8)	5193 (35.8)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2700	N.A.	N.A.	1690 (11.7)	2681 (18.5)	1278 (8.8)	3494 (24.1)	4293 (29.6)	4720 (32.5)

ANOVA testing was used to compare the mean MOE values of the mixtures mixed for different LDRCs. The comparisons were only performed for the mixtures containing Retarder B and mixtures containing Retarder B and AEA. ANOVA testing was not performed for the mixtures containing Retarder A due to limited data. However, general trends for these data will be shown.

Figure 6-43 shows the general trend of the MOE for the mixtures containing Retarder A. Even though statistical analyses cannot be performed, the figure shows that mixtures containing Retarder A show no significant reduction in MOE with LDRCs up to 1800.

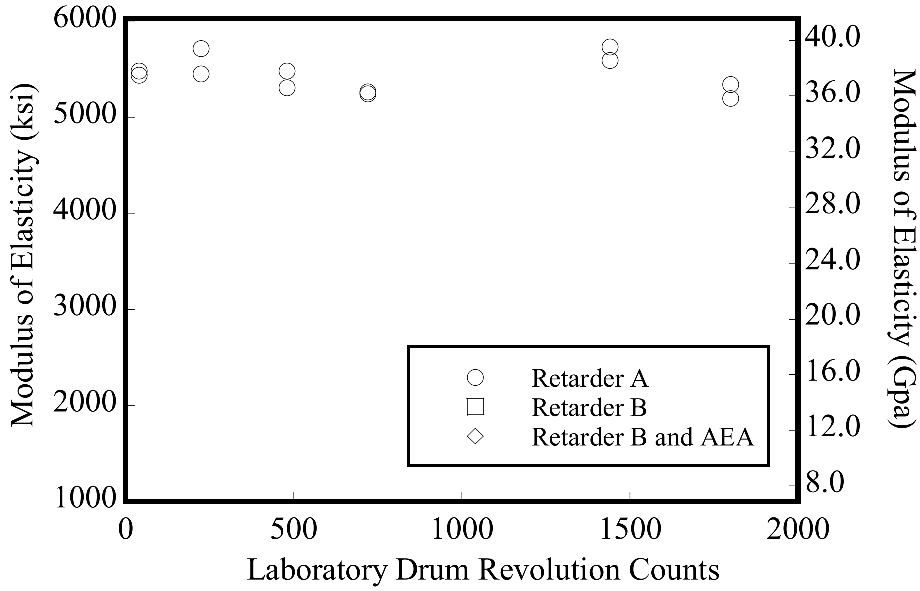


Figure 6-43. MOE of Mixtures Containing Retarder A versus LDRCs.

For the mixtures containing only Retarder B, ANOVA testing indicates that there is a statistically significant difference between the mean MOE of these mixtures mixed at different LDRCs up to 2700 (p-value = 0.000). However, no significant difference was observed between the MOE of mixtures mixed up to 1440 LDRCs. Figure 6-44 shows a box plot for this comparison. The MOE of the mixture mixed at 2700 LDRCs is significantly lower when compared to the MOE values of mixtures mixed at lower LDRCs. The reduction in MOE is a result of poor consolidation for these specimens due to lack of workability. These specimens exhibited high degrees of honeycombing and voids. In addition, the comparison of the MOE values for mixtures mixed for less than 250 and greater 250 is shown in Figure 6-45. Note that the MOE values of the mixtures mixed for 2700 LDRCs is not included because it was determined that the MOE is significantly lower due to low workability. A t-test comparison indicates that there is no statistically significant difference between the means of these two group (p-value = 0.271).

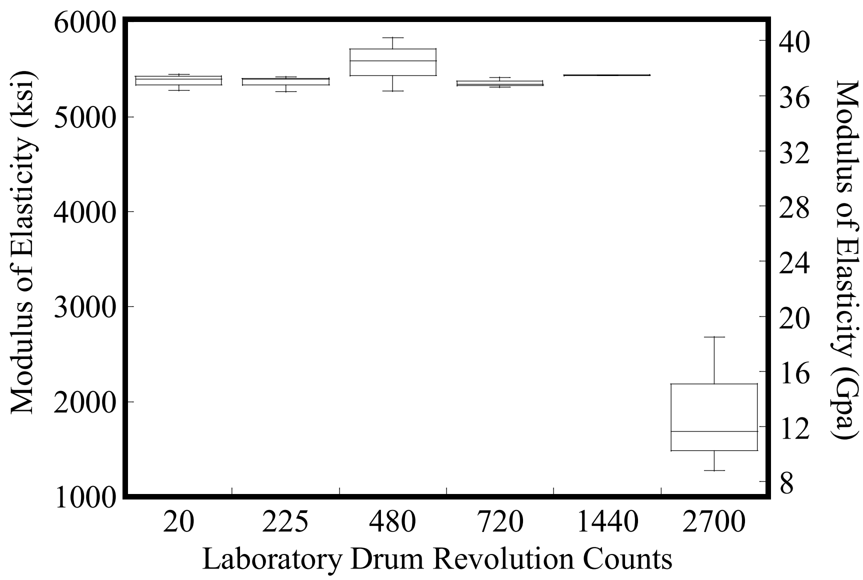


Figure 6-44. Box Plot for the MOE Laboratory Mixtures Containing Retarder B.

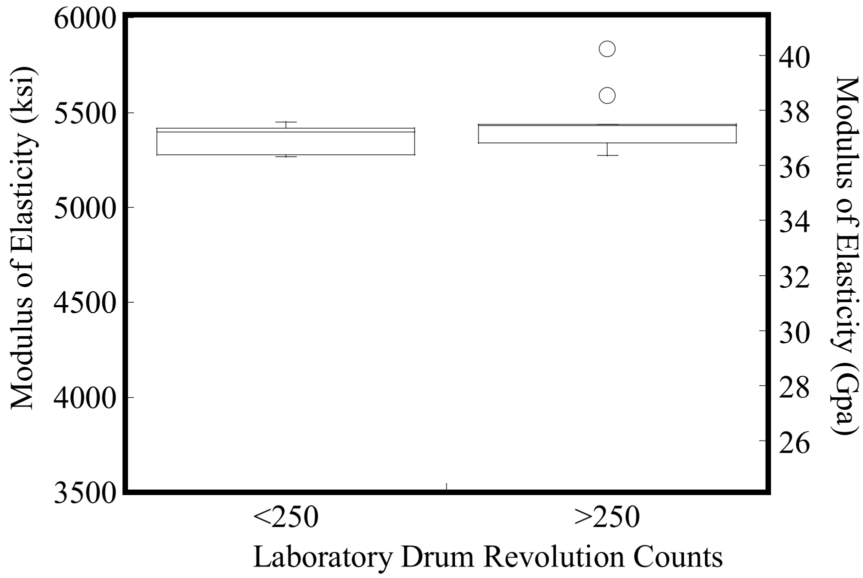


Figure 6-45. Box Plot for MOE of Mixture Containing Retarder B Mixed for Less and Greater than 250 LDRCs.

Figure 6-46 shows the MOE values for the mixtures containing both Retarder B and AEA. ANOVA testing indicates that there is a statistically significant difference in means for these mixtures mixed at different LDRCs up to 2700 (p-value = 0.000). Post ANOVA testing indicates the MOE exhibited significant difference between mixtures mixed for 40 to 225 and 480 to 720. Figure 6-47 shows a box plot for these MOE values. The low workability and castability exhibited in the mixture with higher LDRCs, likely resulted in inconsistent consolidation of the specimens which likely resulted in larger scatter of the MOE values.

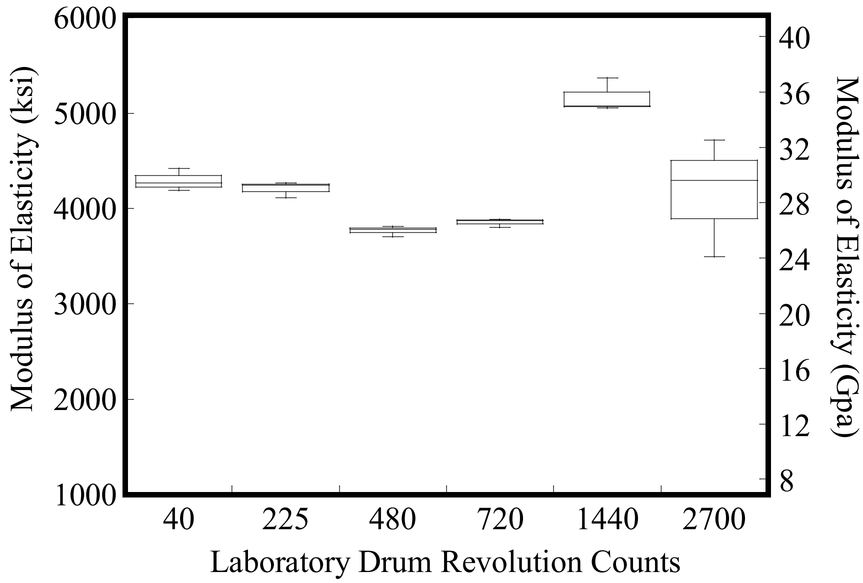


Figure 6-46. Box Plot for the MOE of Laboratory Mixtures Containing Retarder B and AEA Mixed for Different LDRCs.

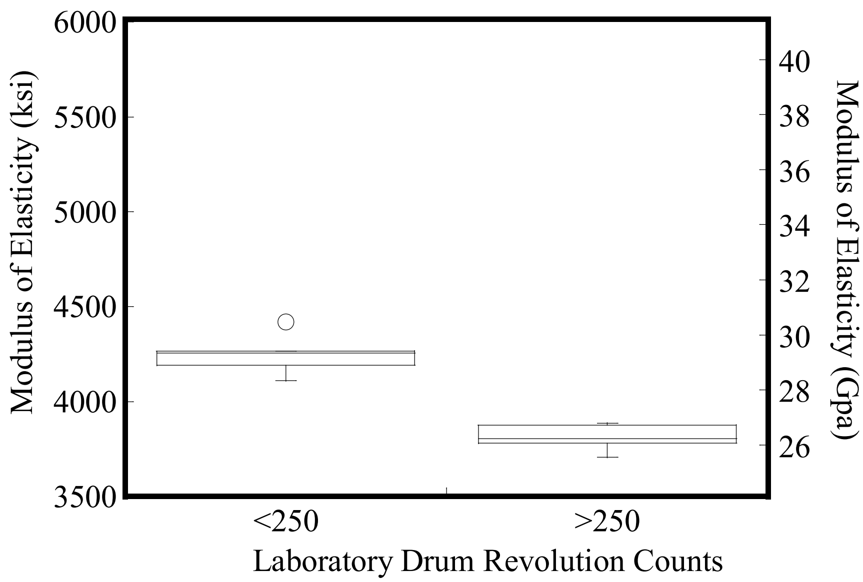


Figure 6-47. Box Plot for MOE of Mixture Containing Retarder B Mixed for Less and Greater than 250 LDRCs.

6.2.5 Potential Influence of Laboratory Drum Revolution Counts on Modulus of Rupture

The influence of LDRCs on the MOR is assessed in this section. Table 6-44 shows the MOR values for these mixtures. Statistical comparisons to assess the potential difference in the means of MOR values of mixtures mixed for different LDRCs was performed. The limits of current mixing specifications is then assessed by comparing the mean values of mixtures mixed for less than and greater than 250 LDRCs. Attempts to correlate MOR and LDRCs are then made.

Table 6-44. Modulus of Rupture for Field Concrete Mixed at Different LDRCs.

TDRC	Modulus of Rupture, psi (Mpa)								
	Retarder A			Retarder B			Retarder B and AEA		
40	676 (4.7)	659 (4.5)	600 (4.1)	749 (5.2)	752 (5.2)	653 (4.5)	662 (4.6)	547 (3.8)	571 (3.9)
225	736 (5.1)	716 (4.9)	762 (5.3)	963 (6.6)	825 (5.7)	765 (5.3)	580 (4)	810 (5.6)	761 (5.2)
480	650 (4.5)	721 (5.0)	664 (4.6)	694 (4.8)	652 (4.5)	659 (4.5)	543 (3.7)	450 (3.1)	605 (4.2)
720	607 (4.2)	652 (4.5)	649 (4.5)	699 (4.8)	631 (4.4)	669 (4.6)	448 (3.1)	566 (3.9)	549 (3.8)
1440	513 (3.5)	514 (3.5)	718 (5.0)	648 (4.5)	653 (4.5)	693 (4.8)	672 (4.6)	623 (4.3)	597 (4.1)
1800	785 (5.4)	649 (4.5)	615 (4.2)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
2700	N.A.	N.A.	N.A.	236 (1.6)	132 (0.9)	157 (1.1)	464 (3.2)	405 (2.8)	447 (3.1)

N.A.: not available

For the mixtures containing Retarder A (see Figure 6-48), ANOVA analysis indicates that there is no statistically significant difference in the MOR of mixtures mixed at different LDRCs up to 1800 (p-value = 0.166). T-test comparisons indicate there is no statistically significant difference between the mean MOR of mixtures mixed for less than and greater than 250 LDRCs (p-value = 0.220). Figure 6-49 shows a box plot for this comparison.

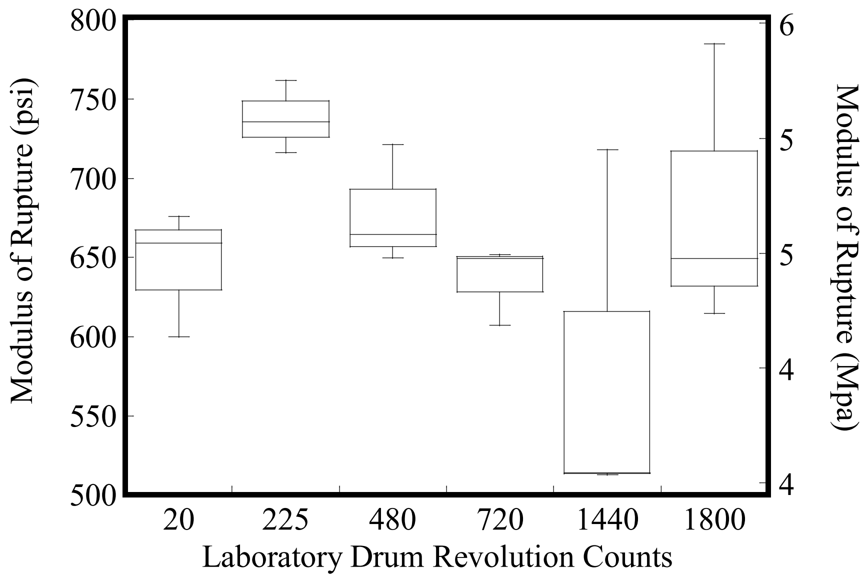


Figure 6-48. Box Plot for the MOR of Mixtures Containing Retarder A Mixed for Different LDRCs.

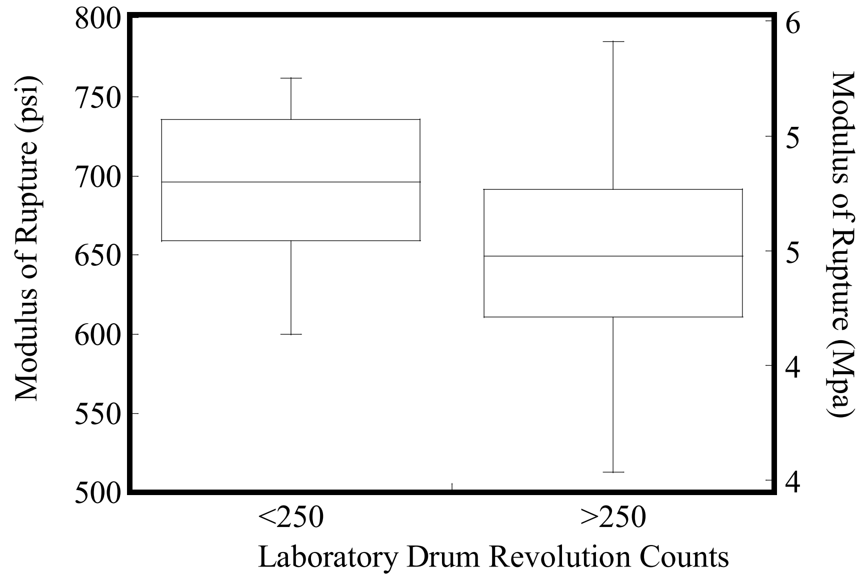


Figure 6-49. Box Plot for MOR of Mixtures Containing Retarder A Mixed for Less and Greater than 250 LDRCs.

Figure 6-50 shows the box plot for the mixtures containing Retarder B mixed at different LDRCs. Statistical analyses indicate that the mean value of MOR for the mixtures mixed for 225 and 2700 LDRCs exhibited a significant difference (p-value = 0.000). When excluding these groups, ANOVA testing indicates there is not significant difference in the mean MOR values between the mixture mixed for 20, 280, 720 and 1440 LDRCs. The mixture mixed for 225 LDRCs exhibited an increase in MOR values and the mixtures mixed for 2700 LDRCs exhibited significantly lower MOR values. The low values are a result of low workability and honeycombing of the specimen. Figure 6-51 shows that the MOR of the mixtures mixed for more than 250 LDRCs is lower than the MOR values of mixtures mixed less than 250 LDRCs.

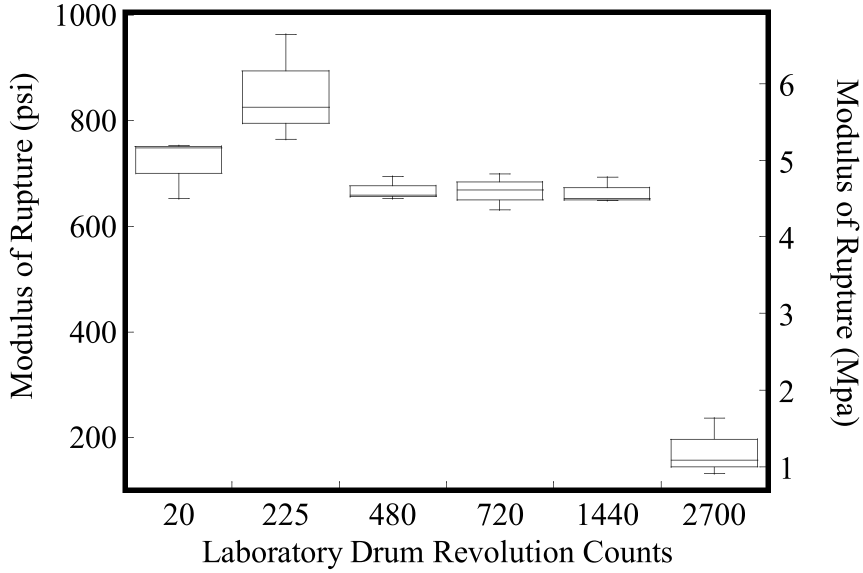


Figure 6-50. Box Plot for the MOR of Mixtures Containing Retarder B Mixed for Different LDRCs.

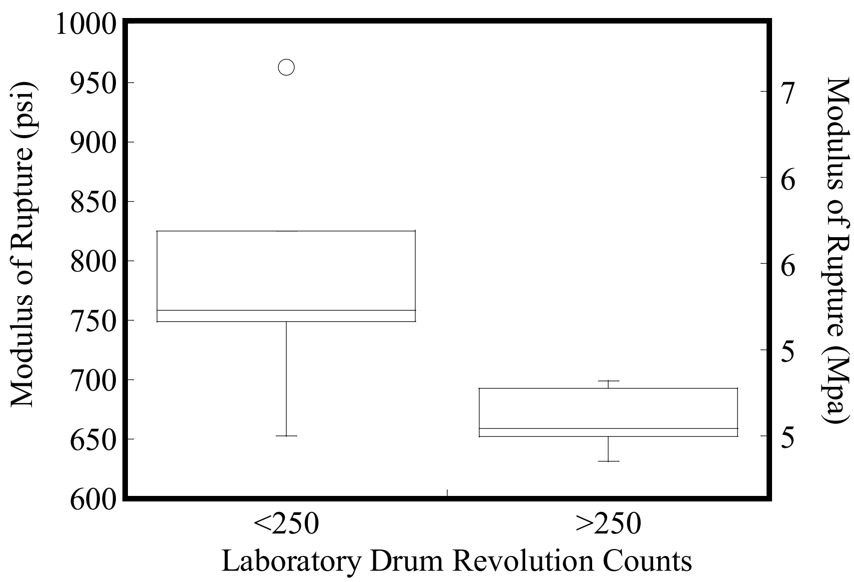


Figure 6-51. Box Plot for MOR of Mixtures Containing Retarder B Mixed for less and greater than 250 LDRCs.

Figure 6-50 shows the box plot for the mixtures containing Retarder B and AEA mixed for different LDRCs. The figure shows that there is a slight decrease in MOR with

LDRCs but this decrease is statistically insignificant. Figure 6-53 shows that the MOR values of the Ratarder B + AEA mixtures mixed for less than and more than 250 LDRCs. The figure indicates that although the MOR is lower for the mixtures mixed for more than 250 LDRCs, the difference is insignificant.

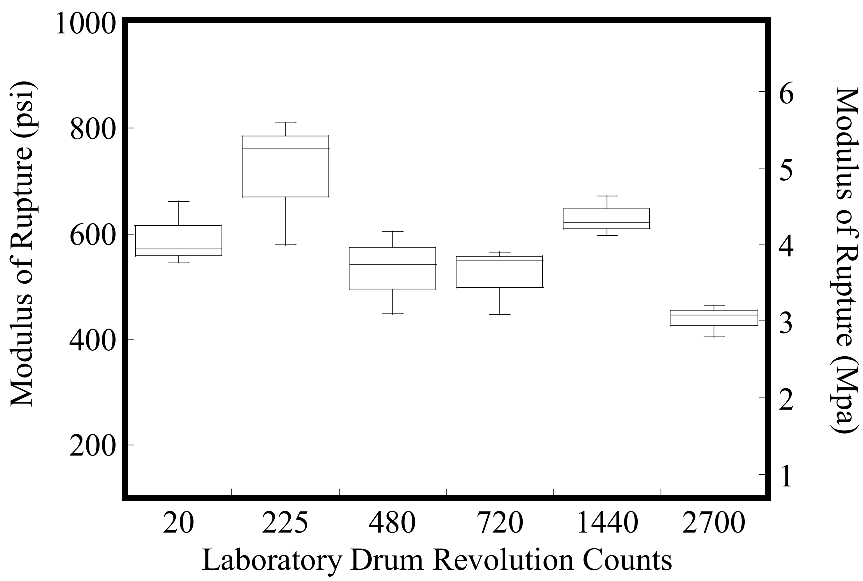


Figure 6-52. Box Plot for the MOR of Mixtures Containing Retarder B and AEA Mixed for Different LDRCs.

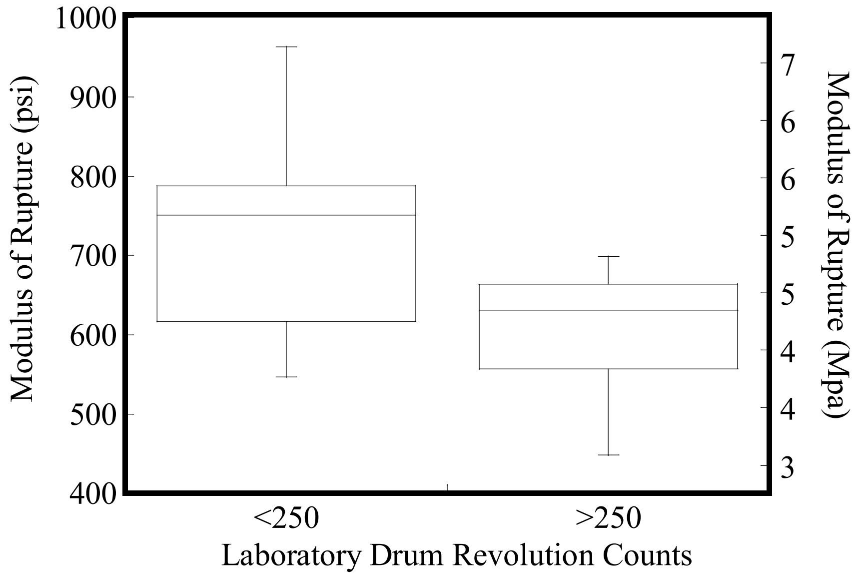


Figure 6-53. Box Plot for MOR of Mixtures Containing Retarder B and AEA Mixed for less and greater than 250 LDRCs.

6.2.6 Potential Influence of Laboratory Drum Revolution Counts on the Splitting Tensile Strength

The analyses of the influence of LDRCs on the STS are presented in this section. The STS of mixtures containing high dosages of retarders were assessed at different LDRCs. Triplicate samples were tested for each mixture. Statistical analyses are used to compare the mean STS values of mixtures mixed for different LDRCs. Table 6-45 shows the STS values.

Table 6-45. Splitting Tensile Strength for Mixture Mixed for Different LDRCs.

Splitting Tensile Strength, psi (Mpa)						
LDRC	40	225	480	720	1440	2700 or max
Retarder A	719 (4.96)	743 (5.12)	711 (4.90)	646 (4.46)	745 (5.14)	731 (5.04)*
	737 (5.08)	756 (5.21)	660 (4.55)	606 (4.18)	742 (5.12)	659 (4.54)*
	726 (5.00)	765 (5.27)	691 (4.76)	628 (4.33)	629 (4.33)	681 (4.69)*
Retarder B	544 (3.75)	469 (3.23)	614 (4.23)	560 (3.86)	609 (4.20)	166 (1.14)
	489 (3.37)	452 (3.12)	630 (4.34)	670 (4.62)	586 (4.04)	138 (0.95)
	556 (3.83)	647 (4.46)	754 (5.20)	536 (3.69)	576 (3.97)	284 (1.96)
Retarder B & AEA	392 (2.70)	560 (3.86)	352 (2.43)	333 (2.30)	405 (2.79)	436 (3.00)
	331 (2.28)	393 (2.71)	403 (2.78)	335 (2.31)	380 (2.62)	479 (3.30)
	467 (3.22)	355 (2.45)	447 (3.08)	386 (2.66)	320 (2.21)	355 (2.45)

*mixture only mixed for 1800 LDRCs.

The STS of mixtures containing Retarder A mixed for different LDRCs is compared. Because the data sets exhibited significant differences in variance, the Welch ANOVA test is used. The test indicates that the mean values of STSs are statistically significantly different between the groups mixed for different LDRCs up to 1800 (p-value = 0.005). Figure 6-54 shows the STS as a function of LDRCs.

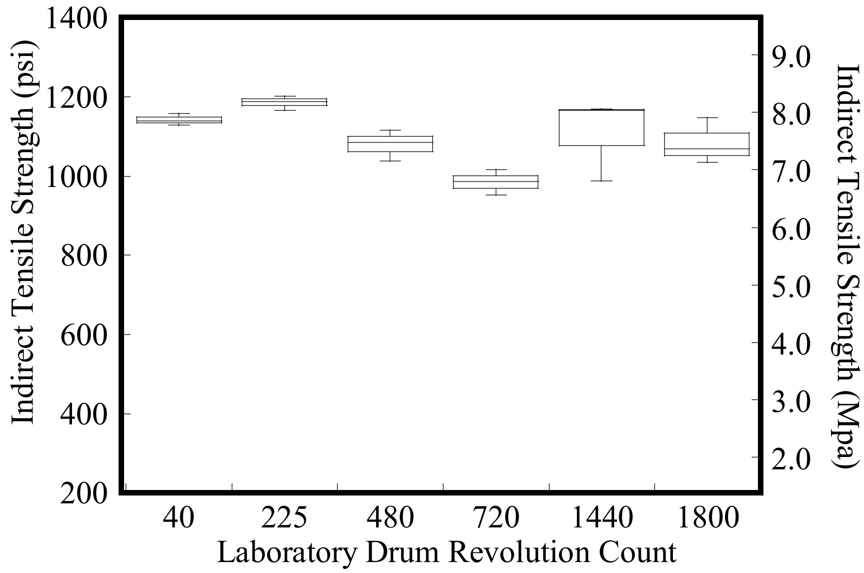


Figure 6-54. Box Plot for the Splitting Tensile Strength of Mixture Containing Retarder A Mixed for Different LDRCs.

For the mixtures containing Retarder B and mixed for different LDRCs, the ANOVA test indicates that there is a statistically significant difference in the mean STS when mixed up to 2700 LDRCs (p-value = 0.000). A box plot for the values used in these comparisons is shown in Figure 6-55. The figure shows that the mean STS of mixtures mixed for 2700 LDRCs are significantly lower than the other mixtures mixed at lower LDRCs. As with the other mixtures, the mixture mixed for 2700 minutes exhibited poor workability and high degrees of honeycombing and voids. This likely resulted in the reduction in the STS. When excluding the mixture that exhibited high degrees of honeycombing in the mean comparison, no statistically significant difference was detected in the mean STS for the other mixtures (Welch ANOVA test, p-value = 0.162).

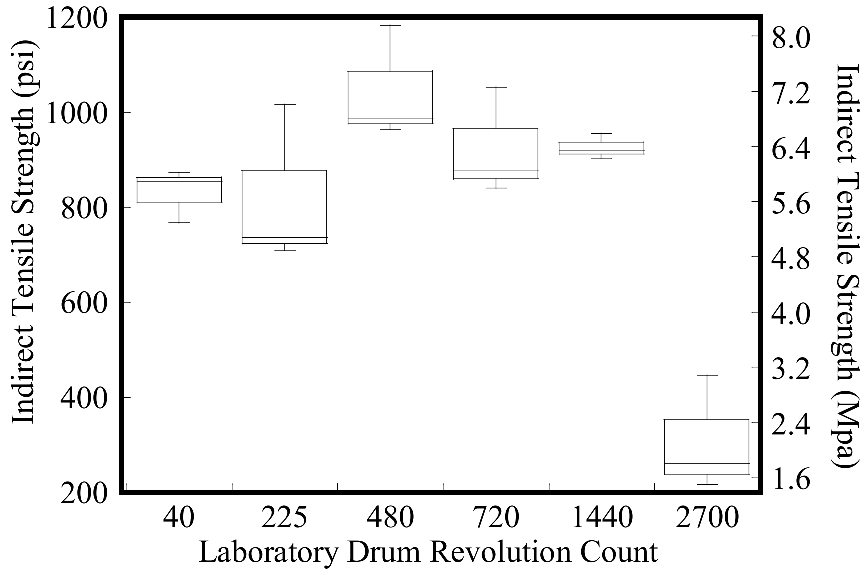


Figure 6-55. Box Plot for the Splitting Tensile Strength of Mixture Containing Retarder B Mixed for Different LDRCs.

For the mixtures containing both Retarder B and AEA, ANOVA testing indicates the mean STS exhibited no statistically significant difference for mixture mixed up to 2700 LDRCs (p-value = 0.618). Figure 6-56 shows a box plot for the STS values of these specimens.

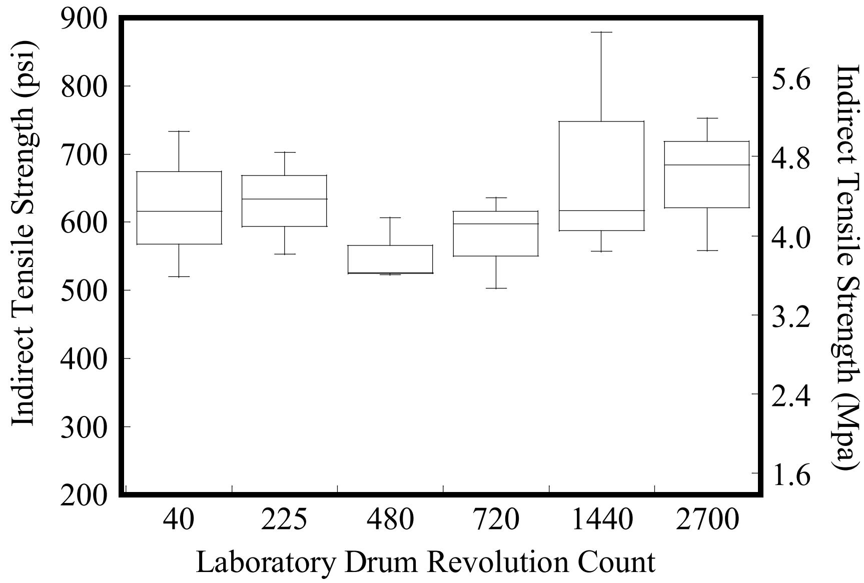


Figure 6-56. Box Plot for the Splitting Tensile Strength of Mixture Containing Retarder B and AEA Mixed for Different LDRCs.

The analysis of the influence of LDRCs on STS indicates that workable mixtures exhibit no statistically significant difference in STS when mixed up to 2700 LDRCs. Specimens that exhibited honeycombing due to low workability did exhibit low STS values. However, no correlation between LDRCs and STS was determined for this study.

7. FIELD RESULTS AND ANALYSIS: EFFECTS OF MIXING TIME AND TRUCK DRUM REVOLUTION COUNTS ON FIELD-MIXED CONCRETE

A study on the influence of the mixing time and truck drum revolution counts (TDRCs) on the field-mixed concrete was conducted. The purpose of this field study is to determine whether existing specification limits on mixing time and number of TDRCs are valid. Validity here is assessed by variables that significantly influence the fresh and/or hardened characteristic. Attempts will be made to correlate laboratory resuts with field results. Researchers worked with a WSDOT approved ready-mix concrete plant (Vancouver, WA) to produce field-mixed concrete. Concrete mixture proportions met Class 4000 concrete requirements and the concrete was initially mixed in the central mixer. The concrete was then loaded onto a concrete truck mixer and mixed to predetermined times or TDRCs. Concrete specimens were cast and cured for 3 days in the molds. After de-molding at day 3, specimens were cured in a lime bath for 25 days.

Laboratory results indicated that retarders may extend the workability of fresh concrete. As such, two different mixtures were assessed: one with retarder and one without retarder. Each mixture was assessed at three mixing speeds: agitation speed (4 rpm), slow mixing speed (8 rpm), and fast mixing speed (15 rpm). For each mixing speed, samples were taken from the truck after different mixing times and different TDRCs. Table 7-1 and Table 7-2 show the experimental programs for the field study. The nomenclature used in this chapter includes identifying the mixtures first (N for no retarder and R for retarder) followed by a subscript that indicates mixing speed (e.g., N_4

is a mixture with no retarder mixed at 4 rpm). The entrapped air content of the field concrete and slump were assessed for each sampling. Specimens were also cast to assess the compressive strength, chloride diffusivity, MOE, MOR and STS.

Table 7-1. Experimental Program for the Field Study—Mixing Time

Mixture	Time of Mixing (minutes)													
	4 rpm					8 rpm					15 rpm			
	5	15	60	90	120	5	15	60	90	120	5	15	60	90
N	x	x	x	x	x	x	x	x	x	x	x	x	x	x
R	x	x	x	x	x	x	x	x	x	x	x	x	x	x

R: mixture with no retarder
N: mixture containing retarder

Table 7-2. Experimental Program for the Field Study—TDRC

Mixture	Truck Drum Revolution Counts												
	20	40	60	75	120	225	240	360	480	720	900	960	1350
N	x	x	x	x	x	x	x	x	x	x	x	x	x
R	x	x	x	x	x	x	x	x	x	x	x	x	x

R: mixture with no retarder
N: mixture containing retarder

This chapter presents data from the field study and assesses the influence of mixing time and TDRCs on the characteristics of field-mixed concrete. The methodology for the analyses will be similar to the analyses performed in the laboratory study. That is, comparison of mean values followed by modeling if the comparison of means indicate there is a statistically significant difference and correlation. In addition, comparisons of the results from the laboratory and the field studies will be made. The following sections assess the influence of mixing time on field concrete characteristics. These sections are followed by analyses on the effects of TDRCs on characteristics of the field concrete.

7.1 POTENTIAL INFLUENCE OF MIXING TIME ON FIELD CONCRETE CHARACTERISTICS

The analyses on the potential influence of mixing time on fresh field concrete characteristics are shown first. The analyses on the hardened concrete characteristics follow. Entrapped air content of fresh concrete and slump values were assessed as a function of time. The hardened concrete characteristics assessed as a function of mixing time include compressive strength, chloride diffusivity, MOE, MOR, and STS.

7.1.1 Potential Influence of Mixing Time on Fresh Field Concrete Characteristics

The fresh characteristics of concrete mixtures mixed in the field are assessed at different mixing times. Analyses on the air content of field concrete are shown first. This is followed by analyses of the slump of the field concrete.

7.1.1.1 Potential Influence of Mixing Time on Entrapped Air Content of Fresh Concrete Mixed in the Field

Table 7-3 shows the entrapped air content values of field concrete mixed at different speeds. Figure 7-1 shows the box plot for these entrapped air content values.

Table 7-3. Entrapped Air Content of Fresh Concrete for Field-mixed Concrete.

Mixtures	Entrapped Air Content of Fresh Field Concrete, %				
	Time of Mixing, minute				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	2.5	2.5	2.8	2.8	3.0
R	2.7	2.6	2.5	2.2	1.5
	Mixtures Mixed at 8 rpm				
N	2.5	2.5	2.8	2.8	3.0
R	2.7	2.6	2.5	2.2	1.5
	Mixtures Mixed at 15 rpm				
N	2.8	1.8	1.7	2.3	N.A.
R	1.7	1.8	2.1	2.5	N.A.

R: mixture with no retarder
N: mixture containing retarder
N.A. = not available.

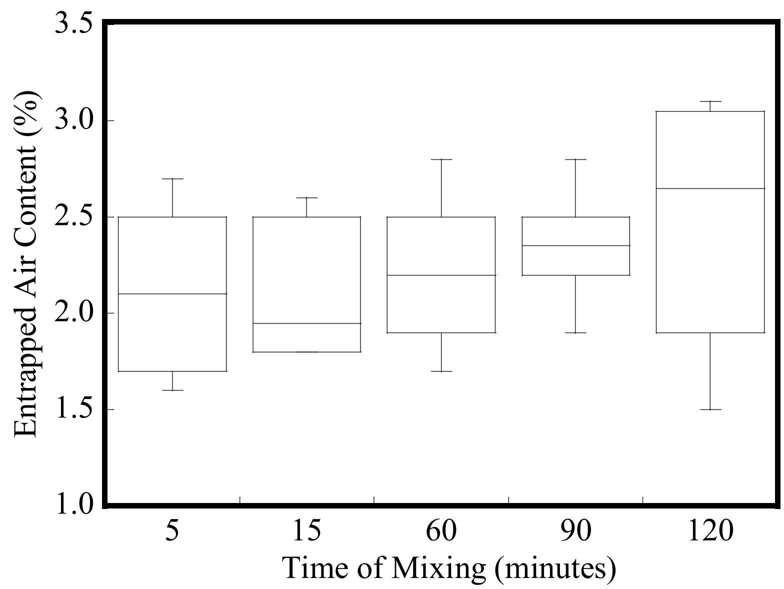


Figure 7-1. Box Plot of Entrapped Air Content of Fresh Concrete Mixed in the Field.

ANOVA testing indicates that there is no statistically significant difference between the mean entrapped air content of mixtures mixed at different mixing times at the 95 percent confidence level (p-value = 0.912). The range of these entrapped air contents for the field concrete is from 1.6 to 3.1 percent. The maximum change in entrapped air content in these mixtures is 1.2 percent. These variations in entrapped air content are considered to be relatively small.

7.1.1.2 Potential Influence of Mixing Time on the Slump of Field-mixed Concrete

The slump data for the field mixtures are shown in Table 7-4. These mixtures are proportioned for a target slump of 4 inches (102 mm). Note that the values in the table are the average value of two slump tests. Because the initial slump value varied for different mixtures, the slump values are normalized by the slump value of the initial mixtures (after 5 minutes of mixing). The normalized slump versus time of mixing is shown in Figure 7-2.

Table 7-4. Slump Values for Field Study Mixtures.

Mixtures	Slump, inch (mm)				
	Time of Mix, minute				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	3.88 (98)	3.25 (83)	2.38 (60)	1.63 (41)	0.38 (10)
R	4.00 (102)	3.63 (92)	1.38 (35)	0.75 (19)	0.38 (10)
	Mixtures Mixed at 8 rpm				
N	3.75 (95)	3.25 (83)	1.50 (38)	0.25 (10)	0.00 (0)
R	4.25 (121)	3.25 (70)	1.50 (41)	0.75 (16)	0.25 (6)
	Mixtures Mixed at 15 rpm				
N	5.38 (137)	4.25 (108)	0.88 (22)	0.00 (0)	N.A.
R	5.75 (146)	3.88 (98)	0.50 (13)	0.25 (6)	N.A.

N: mixture with no retarder R: mixture containing retarder
N.A. = not available

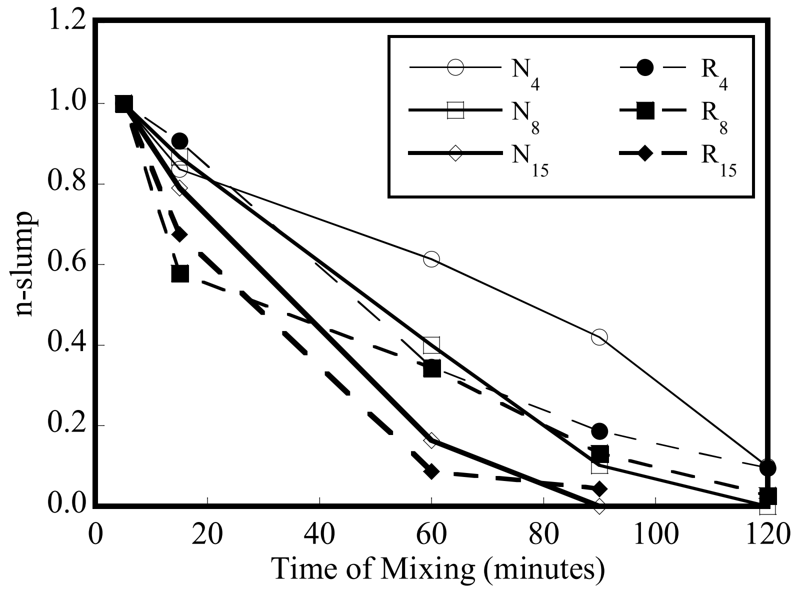


Figure 7-2. N-slump Values versus Time of Mixing for Field Concrete.

Figure 7-2 shows that faster mixing speeds could result in faster slump loss values for both mixtures. In addition, mixtures containing a retarder exhibited faster initial slump loss rates than the mixtures without retarders. Figure 7-3 shows models for the n-slump as a function of time for the field mixtures without retarders mixed at 4, 8 and 15 rpm.

In addition, Figure 7-2 shows the laboratory models for n-slump as a function of mixing time. Note that mixtures mixed at a mixing speed of 4 rpm were not assessed in the laboratory study. Figure 7-3 shows that the n-slump values from both the laboratory and field studies deceased to zero at approximately 90 minutes of mixing at 15 rpm. For the mixtures mixed at 8 rpm, the n-slump values from the field mixture decreased to zero after approximately 110 minutes of mixing. For the 4 rpm, the n-slump value will likely reach zero at approximately 140 minutes of mixing.

The n-slump as a function of mixing time for the field mixtures can be estimated as follows:

$$n-slump_{CA4} = -44.5 + 45.5 \times e^{-0.000159t} \quad (7\text{-}1)$$

$$n-slump_{CA8} = -0.46 + 1.54 \times e^{-0.010t} \quad (7\text{-}2)$$

$$n-slump_{CA15} = -0.19 + 1.33 \times e^{-0.022t} \quad (7\text{-}3)$$

where t is the time of mixing (minutes). Equation 7-1 and 7-2 are valid for times of mixing between 5 and 120 minutes, and equation 7-3 is valid for time of mixing between 5 and 90 minutes. The R^2 value for each of these three models is 99 percent.

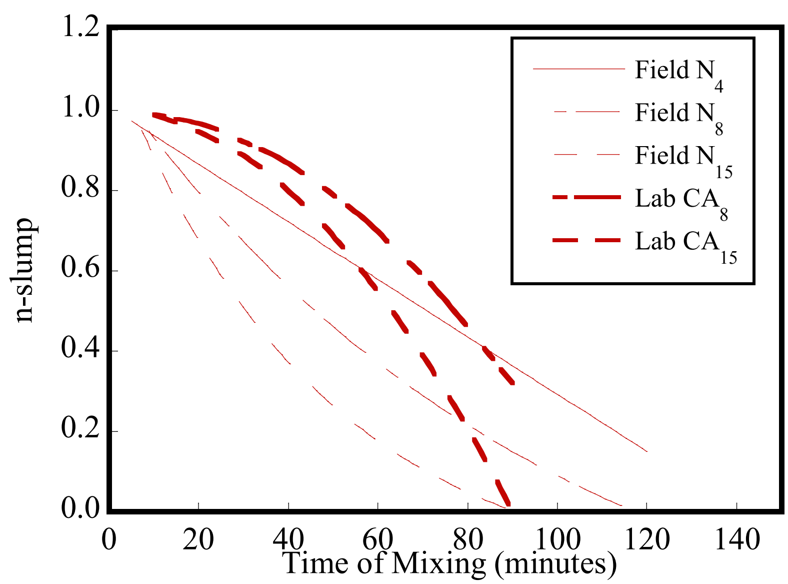


Figure 7-3. Regression Model for Slump as a Function of Mixing Time for Field and Laboratory Mixtures Mixed at Different Speeds.

Also note that the n-slump values of mixtures from the laboratory and field studies decrease at different rates. Figure 7-3 shows that the laboratory models have a concave down shape; which indicates that the slump loss rate is initially low and then increases. However, the model for the field mixtures exhibit a concave up shape, which indicates that slump loss is initially high and then decreases. These differences may be explained by mixture temperature and mixing energy. It was determined in the laboratory study that an increase of initial mixture temperature could result in accelerated slump loss. In addition, mixing energy could also influence the slump value. The smaller concrete mixer in the laboratory input less energy when compared to the truck mixer. The slower initial slump loss rate in the laboratory model may be a result of the smaller energy input from the laboratory mixer. In addition, mixtures in the field were first mixed in a central mixer when mixing energy could be much greater than the energy from a truck mixer. The high slump loss rate initially may be a result of the higher mixing energy from the truck mixer and the central mixture. The decreased slump loss at later mixing times may be because the truck mixer was able to produce enough energy to slow solids from forming in the hydration process. Further research is needed to assess this.

Figure 7-4 shows the regression model for n-slump as a function of mixing time for the field mixtures containing retarders and mixed at 4, 8 and 15 rpm. The model for the n-slump values from the laboratory study is also shown. Models from both studies exhibit concave up shapes. Note that the AD_{rd8} and AD_{rd15} models were developed using retarders and water reducers. The models indicate that the n-slump of the field mixtures decrease at a faster rate than those of the laboratory mixtures. This is likely due to the higher temperatures during the field mixing and due to the higher mixing energies from the field equipment.

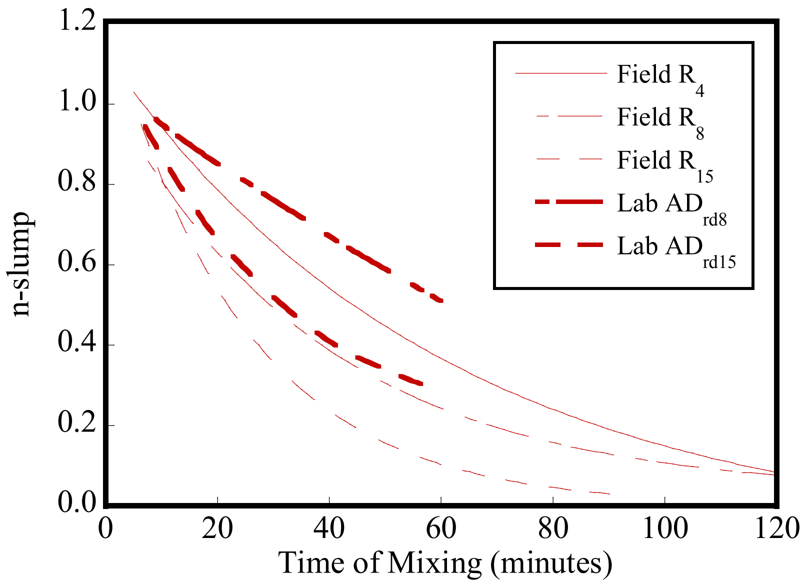


Figure 7-4. Regression Model for n-slump as a Function of Mixing Time for Field and Laboratory Mixtures Containing Retarders and Mixed at Different Speeds.

For field mixtures containing retarders and mixed at 4, 8 and 15 rpm (*n-slump*$_{AD4}$, *n-slump*$_{AD8}$, *n-slump*$_{AD15}$), the n-slump as a function of time can be estimated as follows:

$$n - slump_{AD4} = 0.053 + 1.10 \times e^{-0.021t} \qquad (7\text{-}3)$$

$$n - slump_{AD8} = 0.033 + 1.01 \times e^{-0.026t} \qquad (7\text{-}4)$$

$$n - slump_{AD15} = 0.0013 + 1.123 \times e^{-0.041t} \qquad (7\text{-}5)$$

The R^2 values for the models are 99, 94, and 99 percent for the R_4, R_8, and R_{15}, respectively. Equation 7-3 and 7-4 are valid for time between 5 and 120 minutes and equation 7-5 is valid for mixing times between 5 and 90 minutes.

Models assessing slump as a function of time were developed for the field mixtures. Figure 7-5 shows the n-slump models for field mixtures without a retarder and for a concrete containing a retarder. Results indicate that concrete mixtures containing a retarder exhibited accelerated slump loss. This correlates with the findings in the laboratory study. In addition, the models developed in the field study indicate a faster initial rate of slump loss than those developed in the laboratory. The faster initial rate of slump loss may be a result of the higher temperature and higher mixing energy input when mixed in the field.

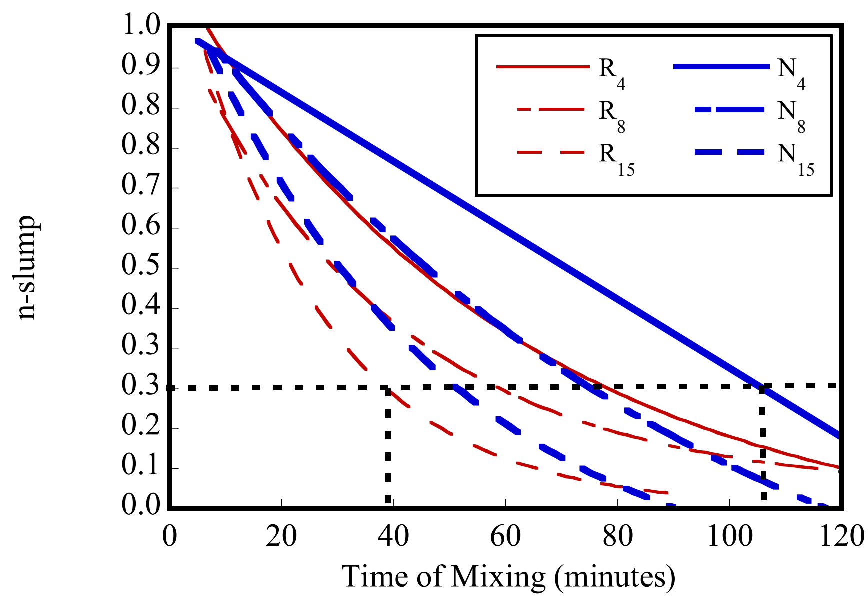


Figure 7-5. n-slump Model for the Two Field-mixed Concrete.

7.1.2 Potential Influence of Mixing Time on Hardened Characteristics of Field-mixed Concrete

Specimens were cast to assess the compressive strength, chloride diffusivity, MOE, MOR and STS as a function of mixing time for the field-mixed concrete. The effect of mixing time on compressive strength will be analyzed first. This is then followed the analyses on the effect of mixing time on chloride diffusivity, MOE, MOR and STS.

7.1.2.1 Potential Influence of Mixing Time on Compressive Strength of Concrete

For the field study, the concrete mixtures were assessed for 3-, 7- and 28-day f'cm. Statistical tests were performed to compare the mean f'cm values of these concrete mixtures. The statistical tests were used to determine whether a statistically significant difference in the means of compressive strengths exist between mixtures mixed for different times. Table 7-5 through Table 7-7 show the 3-, 7- and 28-day f'cm values for these mixtures. The 3-day f'cm is analyzed first.

Table 7-5. Three-day f'cm of Field Mixtures Mixed for Different Mixing Times and Speeds.

Mixtures	Compressive Strength, psi (Mpa)				
	Time of Mixing, minutes				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	4307 (29.7)	4857 (33.5)	4655 (32.1)	4666 (32.2)	2239 (15.4)
R	5145 (35.5)	5284 (36.4)	5010 (34.5)	5559 (38.3)	5276 (36.4)
	Mixtures Mixed at 8 rpm				
N	3883 (26.8)	3704 (25.5)	3730 (25.7)	4087 (28.2)	1733 (11.9)
R	4374 (30.2)	4628 (31.9)	4630 (31.9)	4475 (30.9)	4786 (30.0)
	Mixtures Mixed at 15 rpm				
N	3280 (22.6)	3054 (21.1)	3537 (24.4)	3761 (25.9)	N.A.
R	3987 (27.5)	4367 (30.1)	4117 (28.4)	4546 (31.3)	N.A.

N: mixture with no retarder
R: mixture containing retarder
N.A. = not available

Table 7-6. Seven-day f'cm of Field Mixtures Mixed for Different Mixing Times and Speeds.

Mixtures	Compressive Strength, psi (Mpa)				
	Time of Mixing, minutes				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	4134 (28.5)	4235 (29.2)	4298 (29.6)	4021 (27.7)	4198 (28.9)
R	4136 (28.5)	4131 (28.5)	4180 (28.8)	4516 (31.1)	4448 (30.7)
	Mixtures Mixed at 8 rpm				
N	4783 (33.0)	4462 (30.8)	3859 (26.6)	5269 (36.3)	2479 (17.1)
R	5104 (35.2)	4915 (33.9)	5136 (35.4)	5330 (36.7)	4776 (32.9)
	Mixtures Mixed at 15 rpm				
N	4125 (28.4)	4333 (29.9)	4991 (34.4)	2745 (18.9)	N.A.
R	4479 (30.9)	5022 (34.6)	5226 (36.0)	3209 (22.1)	N.A.

N: mixture with no retarder
R: mixture containing retarder
N.A. = not available

Table 7-7. Twenty-eight day f'cm of Field Mixtures Mixed for Different Mixing Times and Speeds.

Mixtures	Compressive Strength, psi (Mpa)				
	Time of Mixing, minutes				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	5959 (41.1)	6078 (41.9)	5800 (40.0)	5385 (37.1)	5309 (36.6)
R	6318 (43.6)	6669 (46.0)	6269 (43.2)	6028 (41.6)	6625 (45.7)
	Mixtures Mixed at 8 rpm				
N	6273 (43.2)	6144 (42.4)	6568 (45.3)	6503 (44.8)	2841 (19.6)
R	6153 (42.4)	6831 (47.1)	6472 (44.6)	6704 (46.2)	6825 (47.1)
	Mixtures Mixed at 15 rpm				
N	6053 (41.7)	5974 (41.2)	6196 (42.7)	2136 (14.7)	N.A.
R	6267 (43.2)	6333 (43.7)	6535 (45.1)	6644 (45.8)	N.A.

N: mixture with no retarder
R: mixture containing retarder
N.A. = not available

For mixtures without a retarder (N mixtures) mixed at a mixing speed of 4 rpm, the ANOVA test indicates that there is a statistically significant difference between the means of the $f'cm_3$ for mixtures mixed for different times up to 120 minutes (p-value = 0.000). There is a significant decrease in the $f'cm_3$ for the mixture mixed for 120 minutes. The mixture mixed for 120 minutes exhibited limited workability and the average of two slump values was 0.38 inch (10 mm). The specimens could not be adequately consolidated due to lack of workability and exhibited high degrees of honeycombing (void pockets). This likely resulted in the decrease in compressive strength.

Alternatively, the ANOVA test indicates that there is no statistically significant difference between the mean $f'cm_3$ of the R mixtures mixed for different mixing times up to 120 minutes. (p-value = 0.536, 95 percent confidence level). Figure 7-6 shows a box plot of the $f'cm_3$ for the field mixtures containing a retarder mixed for different mixing times at 4 rpm. It should be noted that the slump of the R mixtures after 120 minutes of mixing also exhibited low slump values. However, these specimens exhibited less honeycombing and higher compressive strengths. Figure 7-7 shows a photograph of specimens from mixtures with and without a retarder. The photograph shows typical degrees of honeycombing for these mixtures mixed for 120 minutes.

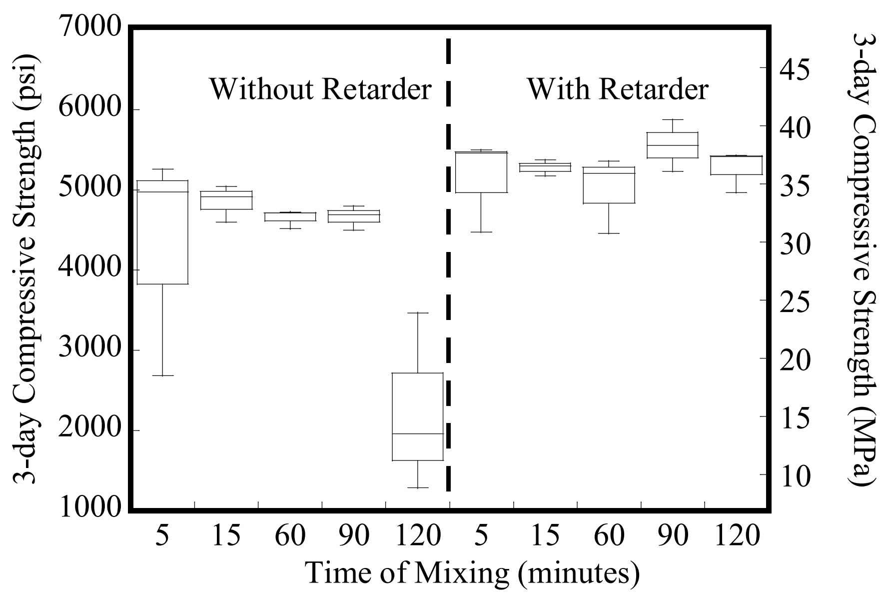


Figure 7-6. Box Plot for $f'cm_3$ for Field Mixtures Mixed at 4 rpm.

Figure 7-7. Specimens for Compressive Strength Test (4X8 cylinder) for N (left) and R (right) Mixtures Mixed for 120 Minutes at 4 rpm.

The mixtures mixed at 8 rpm exhibited similar results as the mixtures mixed at 4 rpm. That is, the $f'cm_3$ of mixtures without retarder mixed for 120 minutes at 8 rpm exhibited a significant decrease in $f'cm_3$ due to poor workability and honeycombing of the concrete (ANOVA, p-value = 0.000). The slump value was zero for the N mixture mixed for 120 minutes at 8 rpm. The ANOVA test of the $f'cm_3$ for mixtures containing retarders indicates that there is no statistically significant difference in the mean $f'cm_3$ for mixtures mixed for different mixing times up to 120 minutes (p-value = 0.080, 95 percent confidence level). The average slump for the R mixtures was 0.13 inch (3.3 mm) after 120 minutes of mixing. Although low, the specimens exhibited significantly lower degrees of honeycombing than the N mixtures. Figure 7-8 shows a box plot of these mixtures mixed at 8 rpm.

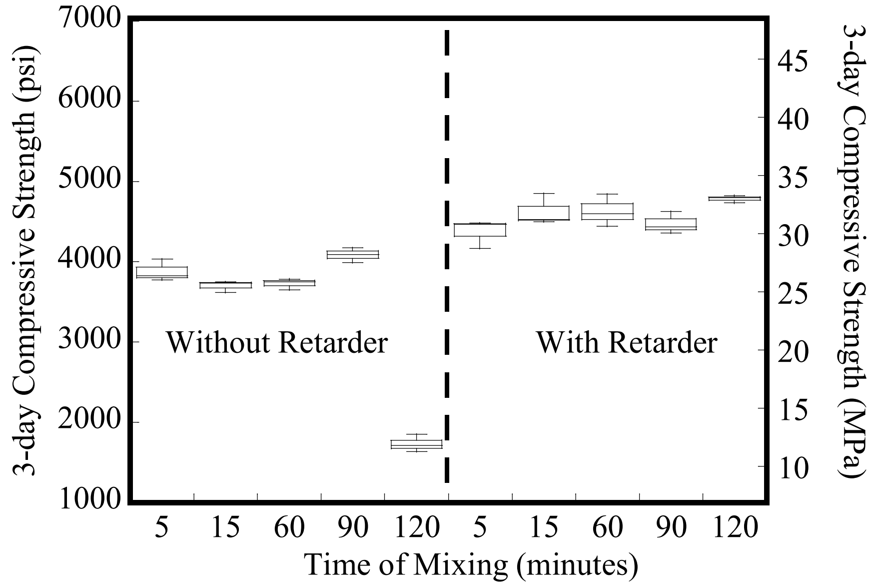


Figure 7-8. Box Plot of f'cm$_3$ for Field Mixtures Mixed at 8 rpm.

The mixtures mixed at 15 rpm were only mixed up to 90 minutes due to stiffening of the mixtures. ANOVA testing indicates that there is a statistically significant difference between the mean f'cm$_3$ of the N mixtures mixed for different mixing times at the 95 percent confidence levels. However, instead of a significant decrease in f'cm$_3$, the f'cm$_3$ of the mixture mixed for 90 minutes exhibited an increase in strength. For the R mixture, no statistically significant difference in f'cm$_3$ was identified for mixing times up to 90 minutes. Figure 7-9 shows a box plot of the mixtures mixed at 15 rpm.

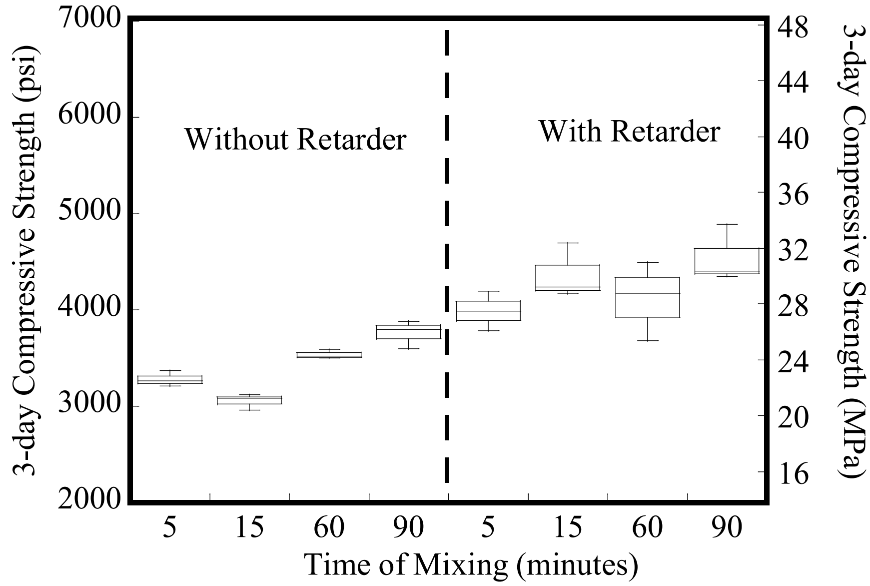


Figure 7-9. Box Plot for f'cm$_3$ for Field Mixtures Mixed at 15 rpm.

The influence of mixing time on 3-day compressive strength was assessed and statistical analyses indicate that mixing times of 120 minutes significantly reduce the 3-day f'cm of mixtures without retarder (N mixtures). The reduction in compressive strength is a result of poor consolidation and honeycombing of the specimens due to poor workability and stiffening of the mixture. For mixtures containing a retarder, results indicate that mixing up to 120 minutes has no significant influence on the 3-day compressive strength. Although mixtures with and without retarders exhibited similar slump values, the workability and degrees of honeycombing between the R and N mixtures are significantly different. This indicates that although slump may be a common measure of workability it likely does not fully represent the workability and placeability of concrete. Even so, a conservative concrete slump value (e.g., 30 percent of original slump) may be an appropriate indicator for placeability and resulting strength. The 7-day compressive strength is analyzed next.

The ANOVA analyses for the N mixtures mixed at 4 rpm, shows that there is no statistically significant difference in the mean f'cm$_7$ for N mixtures mixed for different times up to 120 minutes at the 95 percent confidence level. For the R mixtures mixed at 4 rpm, ANOVA testing also indicates no statistical difference in mean f'cm$_7$ for mixtures mixed for different times when mixed at different mixing time up to 120 minutes. Figure 7-10 shows a box plot for these two mixtures.

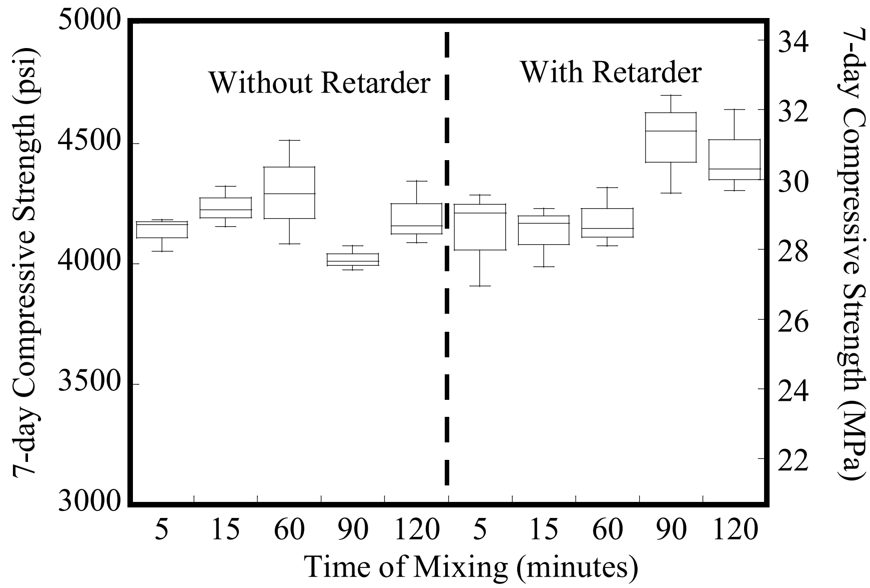


Figure 7-10. Box Plot for f'cm$_7$ for Field Mixtures Mixed at 4 rpm.

For the N mixtures mixed at 8 rpm the mean f'cm$_7$ exhibited a statistically significant difference for the mixtures mixed for different times up to 120 minutes (95 percent confidence level). The N mixtures mixed for 120 minutes at 8 rpm showed a significant decrease in f'cm_7. However, the mixtures containing a retarder do not exhibit a significant difference in mean f'cm_7 when mixed for different times at 8 rpm. Figure 7-11 shows a box plot for these mixtures.

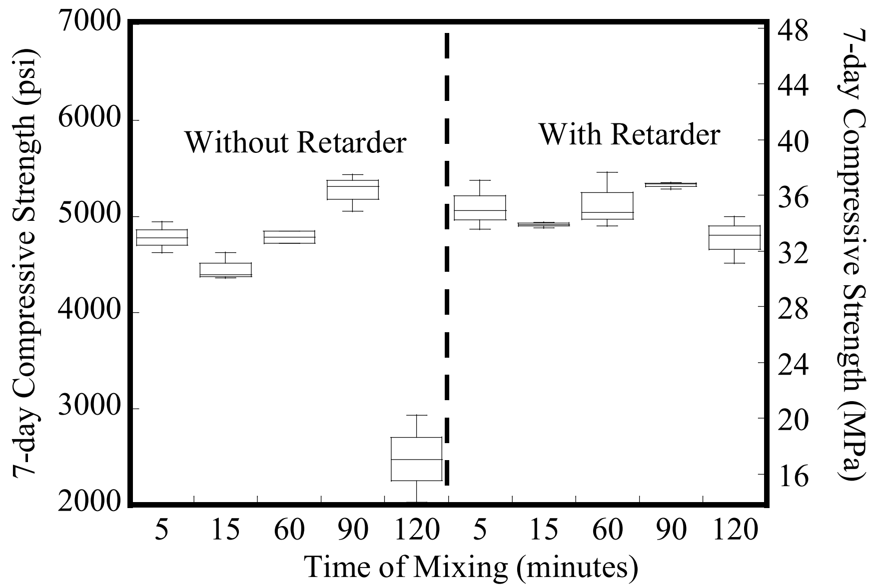


Figure 7-11. Box Plot for f'cm_7 for Field Mixtures Mixed at 8 rpm.

For the mixtures mixed for 90 minutes at 15 rpm a significant decrease in f'cm_7 was observed for both the "N" and "R" mixtures. The slump values for these mixtures were 0 and 0.25 inch (0 and 6 mm) for the N and R mixtures, respectively. These strength reductions are likely caused by poor workability, poor consolidation, and high honeycombing of the specimens due to stiffening of the mixtures. Figure 7-12 shows the box plots for these mixtures.

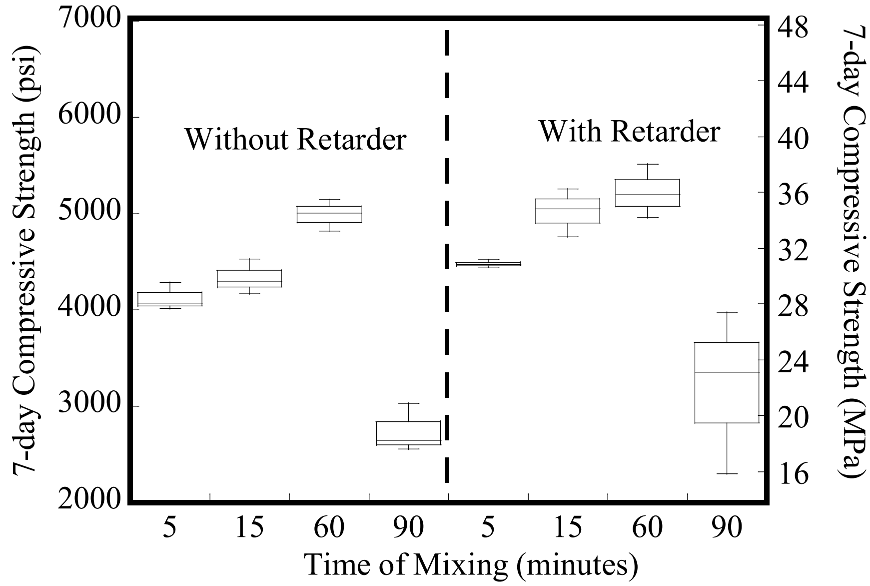


Figure 7-12. Box Plot for f'cm_7 for Field Mixtures Mixed at 15 rpm.

The study on the influence of mixing time on the 7-day f'cm shows similar results as the influence of mixing time on the 3-day f'cm. That is, mixing time can significantly reduce the 7-day f'cm when workability is significantly reduced to a point where proper consolidation of the specimen is not achievable. The 28-day f'cm will be assessed next.

The ANOVA analysis indicates that there is no statistically significant difference in the mean f'cm_{28} for mixtures mixed for different mixing times when mixed at 4 rpm. Even though ANOVA testing indicates no significant difference in mean f'cm_{28} the data shows that when mixing time increased to 90 and 120 minutes the f'cm_{28} values exhibit larger scatter. For the R mixtures mixed at 4 rpm statistical analyses also indicate there is a significant difference in the mean f'cm_{28} of mixtures mixed for different mixing times (p-value = 0.020). Even though a significant difference was identified, the f'cm_{28} is more than the required specified strength (4000 psi [27.6 Mpa]) for mixtures with mixing times up to 120 minutes for the R mixtures. Figure 7-13 shows the box plot for f'cm_{28} for mixtures mixed for different mixing times.

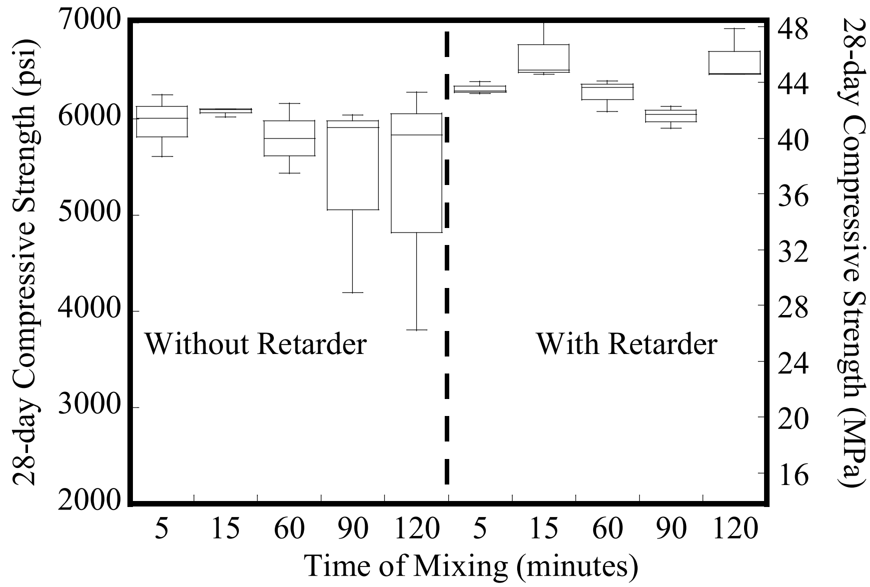


Figure 7-13. Box Plot for f'cm_{28} for Field Mixtures Mixed at 4 rpm.

For the N mixtures mixed at 8 rpm (Figure 7-14), the f'cm_{28} exhibited a significant reduction in compressive strength when mixed for 120 minutes. This reduction is a result of poor consolidation due to low workability. The slump was 0 for the mixtures mixed for 120 minutes. For the mixtures containing a retarder, ANOVA testing indicates that there is no statistically significant difference between the mean f'cm_{28} for R the mixtures mixed for different times. This is similar to earlier findings.

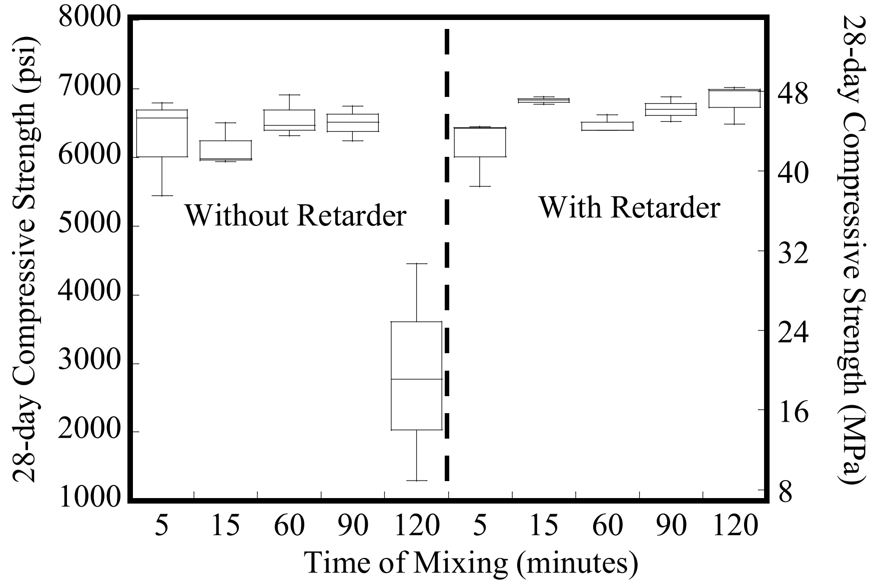


Figure 7-14. Box Plot for f'cm$_{28}$ for Field Mixtures Mixed at 8 rpm.

The f'cm$_{28}$ of the N mixtures mixed at 15 rpm (Figure 7-15) also exhibited a significant decrease in compressive strength when mixed up to 90 minutes. As already noted, the reduction in f'cm$_{28}$ is also due to poor consolidation resulting from low workability. The slump was 0 for the N mixture mixed for 90 minutes. For the mixture containing retarder, ANOVA testing indicates that there is no statistically significant difference between the mean f'cm$_{28}$ for mixtures mixed for different mixing times (p-value = 0.428).

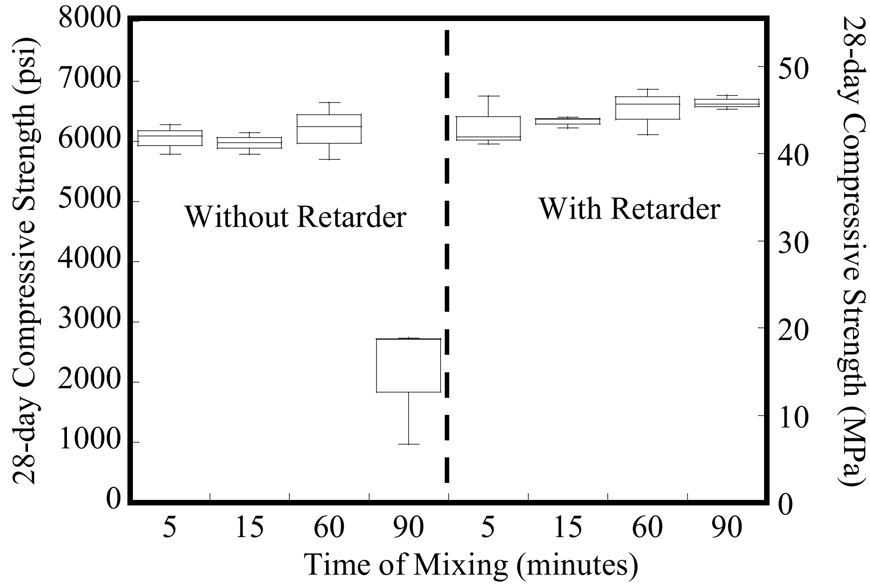


Figure 7-15. Box Plot for f'cm$_{28}$ for Field Study Mixtures Mixed at 15 rpm.

The results on the influence of mixing time on compressive strength indicate that prolonged mixing times can significantly influence the workability of a concrete mixture. Low workability can result in inadequate consolidation and low compressive strengths for concrete mixed in the field. However, when a retarder is used, slightly higher slump values and improved workability were observed. Although small, this higher slump provided sufficient workability up to 120 minutes for the 4 and 8 rpm mixtures and up to 90 minutes for the 15 rpm mixtures to adequately consolidate the specimens.

Results indicate that mixing times up to 60 minutes and mixing speeds up to 15 rpm have no significant decrease on compressive strength. A mixture that exhibited sufficient workability and placeability also exhibited no significant reduction in compressive strength up to 120 minutes of mixing at mixing speed up to 15 rpm. Therefore, instead of time limits, slump or a placeability test, may be a better indication of whether a concrete mixture is acceptable.

7.1.2.2 Potential Influence of Mixing Time on Chloride Diffusivity

This section includes the analysis of the influence of mixing times on apparent chloride diffusivity. Table 7-8 and Table 7-9 show the apparent chloride diffusion coefficients for the N and R mixtures, respectively. Figure 7-16 shows a box plot for these values.

Table 7-8. Apparent Chloride Diffusion Coefficient for the N Mixtures Mixed for Different Time and Speeds.

N Mixtures	Apparent Chloride Diffusion Coefficient, in^2/s (m^2/s)				
	Time of Mixing, minute				
	5	15	60	90	120
4 rpm	1.75E-8 (1.13E-11)	6.25E-8 (4.03E-11)	4.36E-8 (2.81E-11)	3.19E-8 (2.06E-11)	4.03E-8 (2.60E-11)
	3.66E-8 (2.36E-11)	1.00E-7 (6.48E-11)	5.08E-8 (3.28E-11)	2.22E-8 (1.43E-11)	6.08E-8 (3.92E-11)
	2.40E-8 (1.55E-11)	N.A.	5.94E-8 (3.83E-11)	5.24E-8 (3.38E-11)	1.19E-8 (7.67E-12)
8 rpm	1.22E-8 (7.90E-12)	3.95E-8 (2.55E-11)	N.A.	2.62E-8 (1.69E-11)	2.74E-8 (1.77E-11)
	4.19E-8 (2.70E-11)	2.22E-8 (1.43E-11)	7.94E-8 (5.12E-11)	1.24E-8 (7.98E-12)	3.22E-8 (2.08E-11)
	5.19E-8 (3.35E-11)	2.03E-8 (1.31E-11)	3.50E-8 (2.26E-11)	N.A.	N.A.
15 rpm	3.02E-8 (1.95E-11)	N.A.	3.70E-8 (2.39E-11)	1.13E-8 (7.28E-12)	N.A.
	3.12E-8 (2.01E-11)	3.97E-8 (2.56E-11)	5.43E-8 (3.50E-11)	4.57E-8 (2.95E-11)	N.A.
	3.22E-8 (2.08E-11)	2.84E-8 (1.83E-11)	3.24E-8 (2.09E-11)	3.95E-8 (2.55E-11)	N.A.

N.A.: not available

Table 7-9. Apparent Chloride Diffusion Coefficient for the R Mixture Mix for Different Time and Speeds.

R Mixtures	Apparent Chloride Diffusion Coefficient, in^2/s (m^2/s)				
	Time of Mixing, minute				
	5	15	60	90	120
4 rpm	1.44E-8 (9.31E-12)	4.40E-8 (2.84E-11)	N.A.	1.10E-8 (7.11E-12)	2.56E-8 (1.65E-11)
	1.57E-8 (1.01E-11)	N.A.	7.75E-8 (5.00E-11)	4.20E-8 (2.71E-11)	6.08E-8 (3.92E-11)
	N.A.	N.A.	5.89E-8 (3.80E-11)	2.95E-8 (1.90E-11)	6.67E-8 (4.30E-10)
8 rpm	2.28E-8 (1.47E-11)	6.09E-8 (3.93E-11)	4.59E-8 (2.96E-11)	4.63E-8 (2.99E-11)	3.50E-8 (2.26E-11)
	N.A.	7.61E-8 (4.91E-11)	1.35E-8 (8.71E-12)	4.68E-8 (3.02E-11)	3.39E-8 (2.19E-11)
	1.54E-8 (9.93E-12)	6.84E-8 (4.41E-11)	1.69E-8 (1.09E-11)	1.63E-8 (1.05E-11)	4.12E-8 (2.66E-11)
15 rpm	3.75E-8 (2.42E-11)	2.12E-8 (1.37E-11)	3.38E-8 (2.18E-11)	1.63E-8 (1.05E-11)	N.A.
	3.74E-8 (2.41E-11)	3.75E-8 (2.42E-11)	3.29E-8 (2.12E-11)	1.31E-8 (8.43E-12)	N.A.
	N.A.	5.72E-8 (3.69E-12)	3.32E-8 (2.14E-11)	1.58E-8 (1.02E-11)	N.A.

N.A.: not available

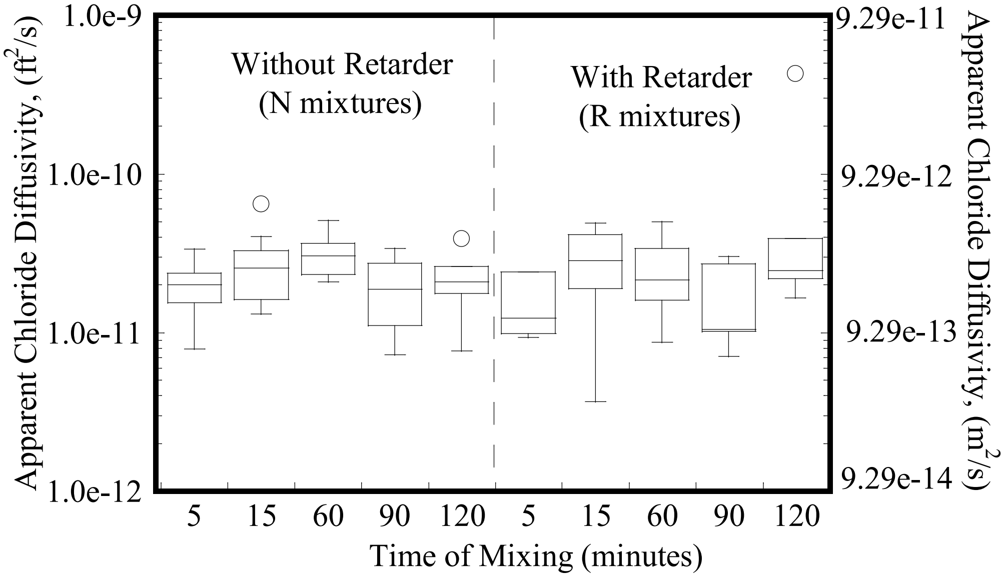


Figure 7-16. Box Plot for Chloride Diffusion Coefficient for Field-mixed Concrete.

ANOVA tests were used to compare the apparent chloride diffusion coefficients of mixtures mixed for different times. The tests indicate that for both the N and R mixtures there is no statistically significant difference in the mean diffusion coefficients for mixtures mixed for different mixing times. The p-value is 0.169 and 0.491 for the N and R mixtures, respectively.

7.1.2.3 Potential Influence of Mixing time On Modulus of Elasticity

This section presents the analysis on the potential influence of mixing time on the MOE for field-mixed concrete. The MOE of field-mixed concrete was evaluated at 28 days after casting. Table 7-10 shows the MOE values for mixtures mixed for different mixing times. Each value in Table 7-10 is the average of three tests.

Table 7-10. Modulus of Elasticity for Field-Mixed Concrete.

Mixtures	Modulus of Elasticity, ksi (Mpa)				
	Time of Mixing, minutes				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	4894 (33737)	5130 (35364)	5030 (34675)	5329 (36735)	4368 (30114)
	5759 (39703)	5519 (38048)	5013 (34559)	5021 (34612)	7012 (48338)
	5002 (34486)	4768 (32872)	5161 (35578)	5239 (36117)	5300 (36540)
R	5159 (35564)	5330 (36747)	5259 (36256)	5382 (37103)	5216 (35962)
	5285 (36434)	5286 (36443)	4828 (33285)	5317 (36653)	5122 (35309)
	5680 (39160)	7296 (50298)	5628 (38802)	5350 (36882)	5516 (38025)
	Mixtures Mixed at 8 rpm				
N	5517 (38035)	5280 (36401)	5357 (36931)	5141 (35444)	2399 (16538)
	5208 (35904)	5221 (35994)	5437 (37481)	2680 (18475)	4173 (28767)
	5225 (36022)	5434 (37461)	5229 (36050)	5159 (35563)	3565 (24574)
R	5972 (41170)	5534 (38153)	5146 (35473)	4980 (34330)	5459 (37632)
	5707 (39343)	5302 (36550)	5419 (37357)	5863 (40419)	5307 (36588)
	5458 (37630)	5243 (36145)	5343 (36836)	5162 (35587)	5216 (35961)
	Mixtures Mixed at 15 rpm				
N	5046 (34784)	5262 (36279)	5310 (36608)	4727 (32585)	N.A.
	5266 (36302)	5265 (36296)	5138 (35425)	4848 (33419)	N.A.
	5092 (35104)	5359 (36946)	5930 (40879)	5672 (39101)	N.A.
R	5133 (35386)	4961 (34199)	4749 (32736)	5122 (35310)	N.A.
	5888 (40589)	4929 (33978)	4665 (32164)	4791 (33027)	N.A.
	5134 (35395)	5207 (35895)	5151 (35510)	4406 (30374)	N.A.

N.A.: not available

For the N mixtures mixed at 4 rpm, ANOVA testing indicates that there is no statistically significant difference in the mean MOE for the N mixtures mixed for different mixing times (p-value = 0.905, 95 percent confidence level). However, larger scatter was observed for the N mixture mixed at 120 minutes. These mixtures also had larger amount of voids and honeycombs when compared with the other specimens mixed for shorter durations. This may be a result of the decreased workability, which resulted in decreased placeability (or castability). For the R mixtures mixed 4 rpm, there is also no statistically significant difference in the mean MOE between the R mixtures mixed for different time up to 120 minutes (ANOVA, p-value = 0.963). Figure 7-17 shows a box plot for these comparisons.

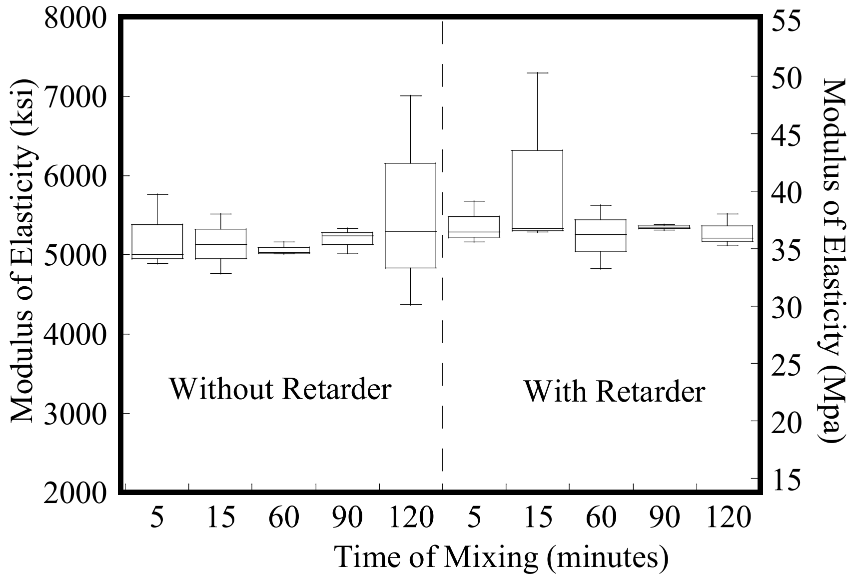


Figure 7-17. MOE for Field-mixed Mixtures Mixed for Different Times at 4 rpm.

Figure 7-18 shows a box plot for the MOE of mixtures mixed at the 8 rpm. ANOVA testing indicates that the N mixtures exhibited significant reduction in MOE when mixed to 90 and 120 minutes (p-value = 0.036 at the 95 percent confidence level). It was also observed that specimens mixed for longer durations contained voids and honeycombing. However, mixtures containing retarders exhibited no statistically significant difference in the mean MOE for the different mixing times (ANOVA, p-value = 0.337 at the 95 percent confidence level).

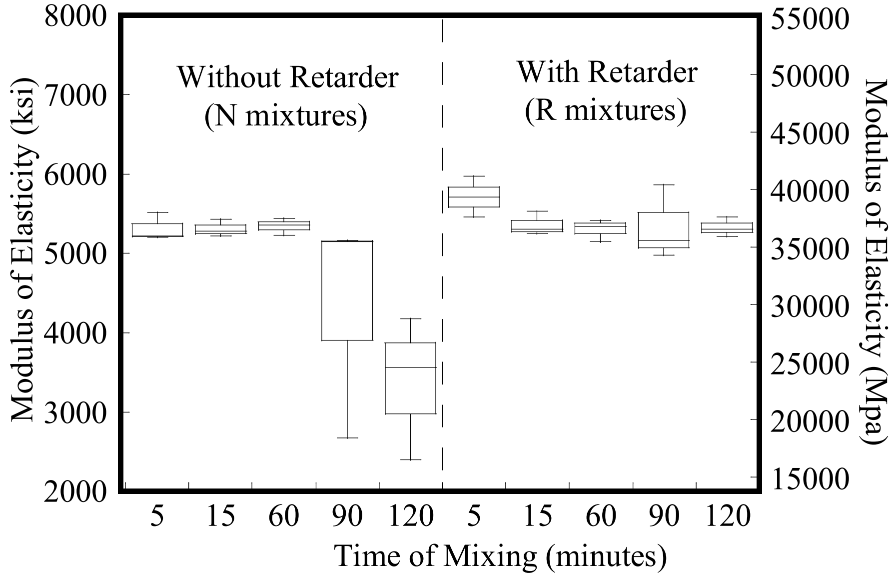


Figure 7-18. MOE for Field-mixed Mixtures Mixed for Different Times at 8 rpm.

For field mixtures mixed at 15 rpm, these mixtures were only mixed to 90 minutes due to concerns regrading the potential setting of the concrete in the ready-mix truck. ANOVA testing for the N mixtures indicates that there is no statistically significant difference between the mean MOE of mixtures mixed at different times up 90 minutes (p-value = 0.593 at the 95 percent confidence level). However, mixtures mixed for 60 and 90 minutes exhibited larger scatter. For the R mixtures, there is also no statistically significant difference in the mean MOE of mixtures mixed up to 90 minutes (p-value = 0.593). Figure 7-19 shows a box plot for these comparisons.

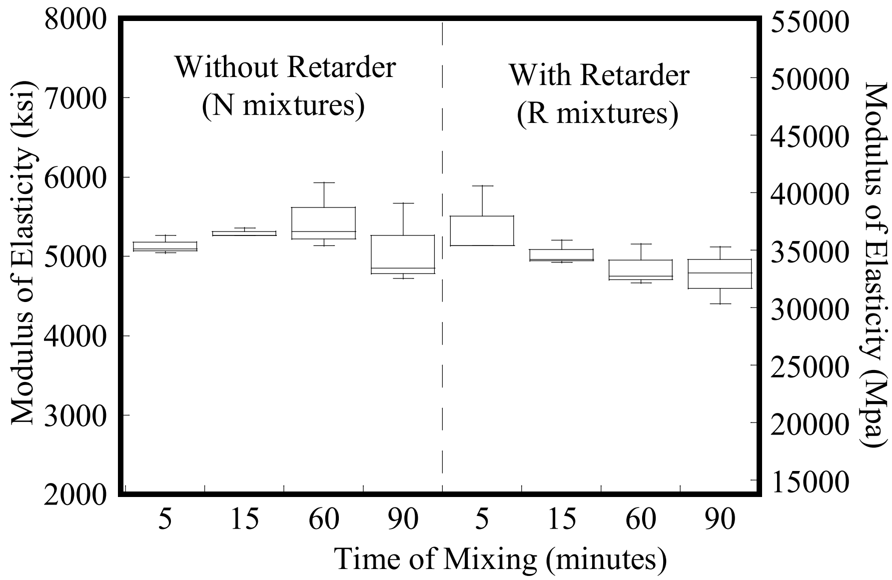


Figure 7-19. MOE for Field-mixed Mixtures Mixed for Different Times at 15 rpm.

The analyses of the influence of mixing time indicate that longer mixing times can significantly influence the MOE of mixtures containing no retarder. Larger scatter of the MOE values was observed for mixtures mixed for 60 minutes or longer and this is believed to be a result of reduction in workability and castability of the concrete mixture when mixed for prolonged times. The lack of workability led to honeycombing and poor consolidation of the specimens that resulted in larger scatter and lower MOE values. However, mixtures containing retarders exhibited no statistically significant difference in MOE values for mixtures mixed up to 120 minutes at 4 and 8 rpm and for mixtures mixed up to 90 minutes for 15 rpm. This finding is similar to that of the compressive strength analyses and acceptance of a concrete mixture may be based on workability and placeability of a mixture rather than mixing time.

7.1.2.4 Potential Influence of Mixing Time on Modulus of Rupture

The potential influence of mixing time on MOR is assessed in this section. Unlike other characteristics, the MOR is only assessed for a subset of the mixtures. Table 7-11 shows MOR of mixtures mixed for different times and speeds.

Table 7-11. Modulus of Rupture for Mixtures Mixed for Different Times.

Modulus of Rupture, psi (Mpa)									
Mixing Speed	4 rpm			8 rpm			15 rpm		
Time of Mixing (minutes)	5	15	120	60	90	120	15	60	90
N	576 (3.97)	408 (2.81)	652 (4.49)	542 (3.74)	648 (4.47)	494 (3.41)	604 (4.16)	571 (3.94)	499 (3.44)
	624 (4.3)	595 (4.1)	748 (5.16)	509 (3.51)	648 (4.47)	614 (4.23)	528 (3.64)	523 (3.61)	504 (3.47)
	564 (3.89)	504 (3.47)	614 (4.23)	492 (3.39)	638 (4.4)	638 (4.4)	509 (3.51)	547 (3.77)	504 (3.47)
R	604 (4.16)	753 (5.19)	609 (4.2)	691 (4.76)	590 (4.07)	816 (5.63)	628 (4.33)	686 (4.73)	561 (3.87)
	648 (4.47)	600 (4.14)	556 (3.83)	552 (3.81)	636 (4.38)	748 (5.16)	614 (4.23)	604 (4.16)	533 (3.67)
	604 (4.16)	705 (4.86)	556 (3.83)	705 (4.86)	633 (4.36)	696 (4.8)	652 (4.49)	592 (4.08)	619 (4.27)

For the 4 rpm mixtures, ANOVA testing indicates there is no statistically significant difference in the mean MOR for the N mixtures mixed at different times up to 120 minutes (p-value = 0.066). Similar results are obtained for the R mixtures (ANOVA, p-value = 0.088).

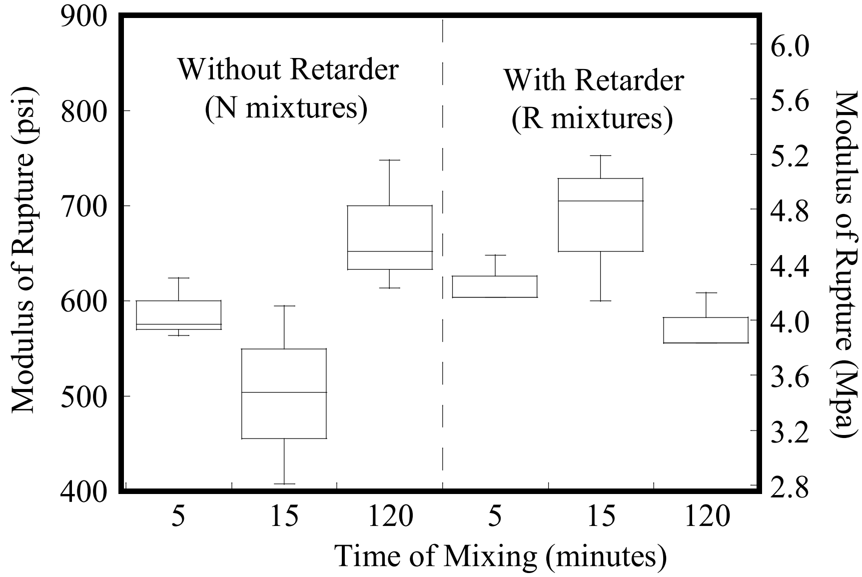


Figure 7-20. Box Plot for Field-mixed Mixtures (4 rpm).

For the N mixtures mixed at 8 rpm (Figure 7-21) there is a statistically significant difference in the mean MOR values for mixtures mixed between 60 and 120 minutes (ANOVA, p-value = 0.040). However, note that the MOR for mixtures mixed for longer durations exhibited values higher than that of the mixture mixed for 60 minutes and there seems to be limited detrimental influence of longer mixing times for these mixtures. For the R mixtures mixed at 8 rpm (Figure 7-21) there is no statistically significant difference in the mean MOR values for mixtures mixed between 60 and 120 minutes (p-value = 0.083).

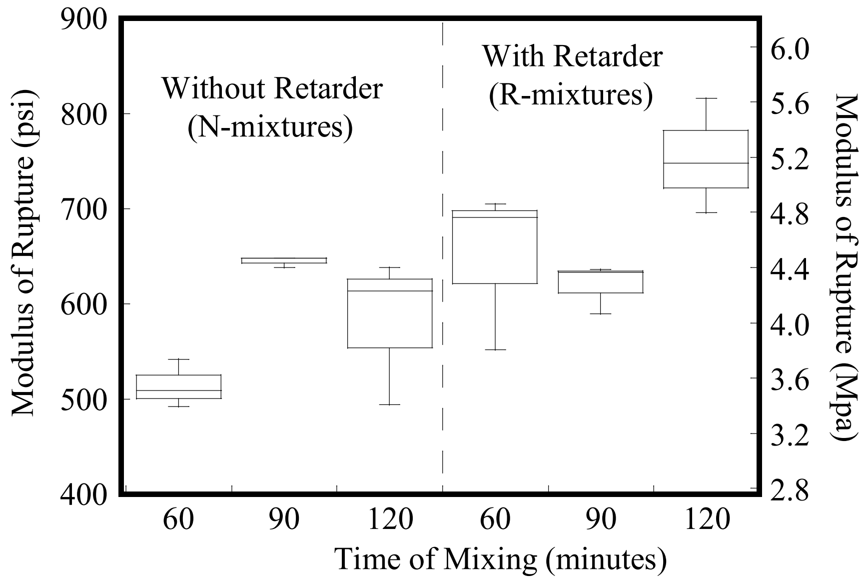


Figure 7-21. Box Plot for Field-mixed Mixtures (8 rpm).

For mixtures mixed at 15 rpm ANOVA testing indicates that both the R and the N mixtures (Figure 7-22) mixed up to 90 minutes exhibited no statistical significant difference in mean MOR values at the 95 percent confidence level (p-value = 0.187 and 0.205). Note that data for the N mixture were transformed (inversed) to meet the ANOVA testing assumptions.

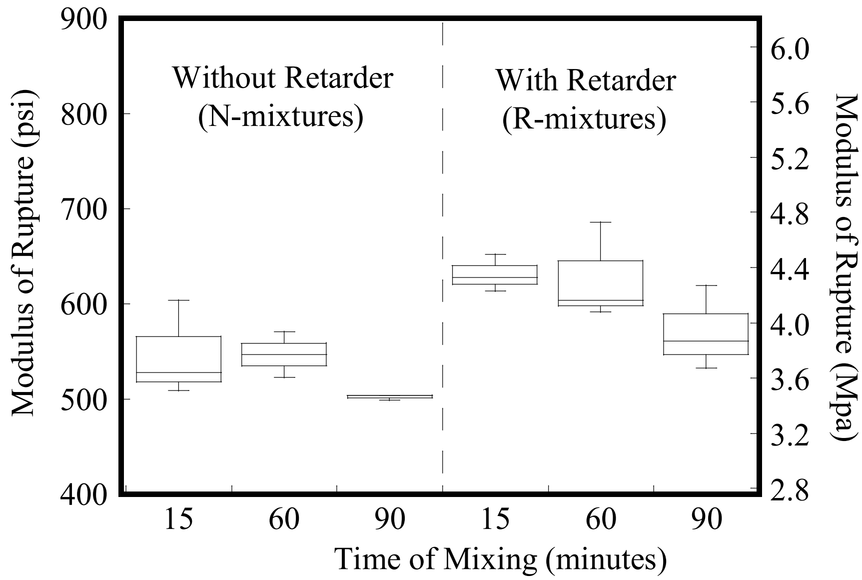


Figure 7-22. Box Plot for Field-mixed Mixtures (15 rpm).

Results indicate that when mixed at 4 rpm both the N and R mixtures exhibited no statistically significant difference in the mean MOR when mixed up to 120 minutes. For the 8 rpm mixtures there does not seem to be a detrimental influence of longer mixing times on MOR, assuming specimens can be cast properly. No significant influence of mixing time on MOR was observed for the R mixtures mixed at 8 rpm. For both the N and R mixtures mixed at 15 rpm no significant difference in mean MOR values was observed for mixing times up to 90 minutes. Results indicate that mixing time has no detrimental influence on MOR for mixing times up to 90 minutes. However, limited data were assessed and further research may be needed.

7.1.2.5 Potential Influence of Mixing Time on Splitting Tensile Strength

The STS for the field mixtures mixed for different mixing times is presented in this section. Statistical analyses are performed to compare the mean STS values for mixtures mixed for different times and speeds. Table 7-12 presents the STS values as a function of mixing time and speeds for the different mixtures.

Table 7-12. Splitting Tensile Strength for Field-Mixed Concrete.

Mixtures	Splitting Tensile Strength, psi (Mpa)				
	Time of Mixing, minutes				
	5	15	60	90	120
	Mixtures Mixed at 4 rpm				
N	395 (2.72)	467 (3.22)	503 (3.47)	494 (3.41)	353 (2.43)
	501 (3.45)	491 (3.38)	492 (3.39)	491 (3.38)	429 (2.95)
	600 (4.13)	508 (3.50)	514 (3.55)	497 (3.43)	461 (3.18)
R	548 (3.78)	602 (4.15)	577 (3.98)	548 (3.78)	423 (2.92)
	442 (3.05)	649 (4.48)	540 (3.72)	553 (3.82)	479 (3.30)
	559 (3.85)	586 (4.04)	564 (3.89)	508 (3.50)	602 (4.15)
	Mixtures Mixed at 8 rpm				
N	520 (3.59)	546 (3.76)	544 (3.75)	524 (3.61)	439 (3.03)
	480 (3.31)	498 (3.43)	526 (3.63)	478 (3.30)	329 (2.27)
	501 (3.45)	522 (3.60)	473 (3.26)	591 (4.08)	349 (2.4)
R	479 (3.30)	457 (3.15)	402 (2.77)	494 (3.40)	400 (2.76)
	511 (3.52)	472 (3.25)	499 (3.44)	472 (3.25)	411 (2.83)
	527 (3.63)	477 (3.29)	436 (3.01)	454 (3.13)	451 (3.11)
	Mixtures Mixed at 15 rpm				
N	555 (3.83)	511 (3.53)	493 (3.40)	574 (3.96)	N.A.
	513 (3.54)	543 (3.74)	532 (3.67)	488 (3.36)	N.A.
	535 (3.69)	487 (3.36)	506 (3.49)	426 (2.94)	N.A.
R	508 (3.5)	454 (3.13)	422 (2.91)	391 (2.70)	N.A.
	527 (3.64)	418 (2.88)	530 (3.66)	444 (3.06)	N.A.
	441 (3.04)	398 (2.74)	467 (3.22)	474 (3.27)	N.A.

N.A.: not available

For both the N and the R mixtures mixed at 4 rpm, ANOVA tests indicate that there is no statistically significant difference in the mean STS for these mixtures mixed for different mixing times up to 120 minutes. The p-values are 0.289 and 0.179 for the N and the R mixtures, respectively. Figure 7-23 shows a box plot for these for these STS for mixtures mixed at 4 rpm. Figure 7-23 shows the STS as a function of mixing time for both the N and R mixtures. Note that significant reductions in the STS occurred for the N mixture mixed for 120 minutes. As with other mixtures, the mixtures exhibited lower STS values contained significant voids and honeycombs due to lack of workability and castability.

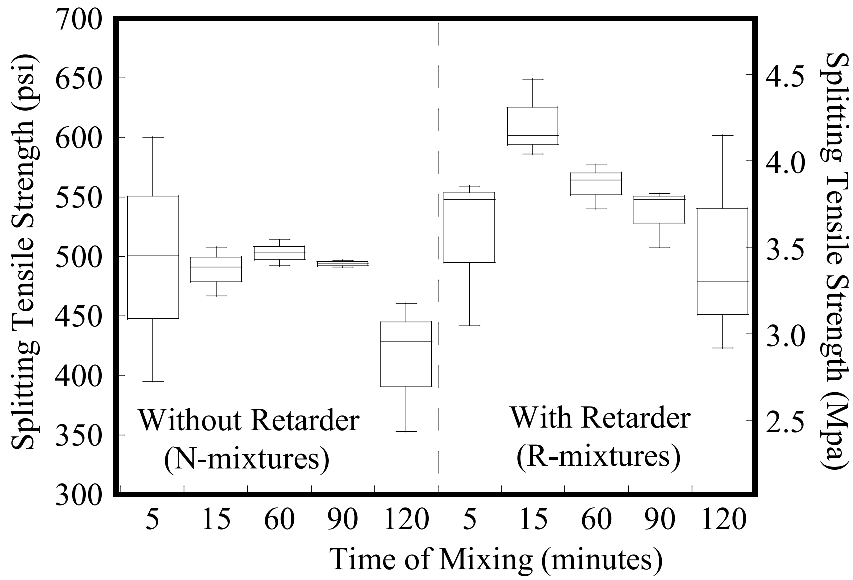


Figure 7-23. Splitting Tensile Strength for Field-mixed Mixtures Mixed for Different Times at 4 rpm.

Figure 7-24 shows a box plot for the STS of the N and R mixtures mixed at the 8 rpm. ANOVA testing indicates that these mixtures exhibited significant reduction in the mean STS values when mixed for 120 minutes (p-value = 0.005 and 0.047, respectively). The STS for the N and the R mixtures mixed at 120 minutes are statistically significantly lower than those of the respective mixtures mixed for less than 120 minutes. Note that N-mixtures mixed for 120 minutes exhibited significantly higher degrees of honeycombing when compared to the mixtures containing retarder and mixed at 120 minutes.

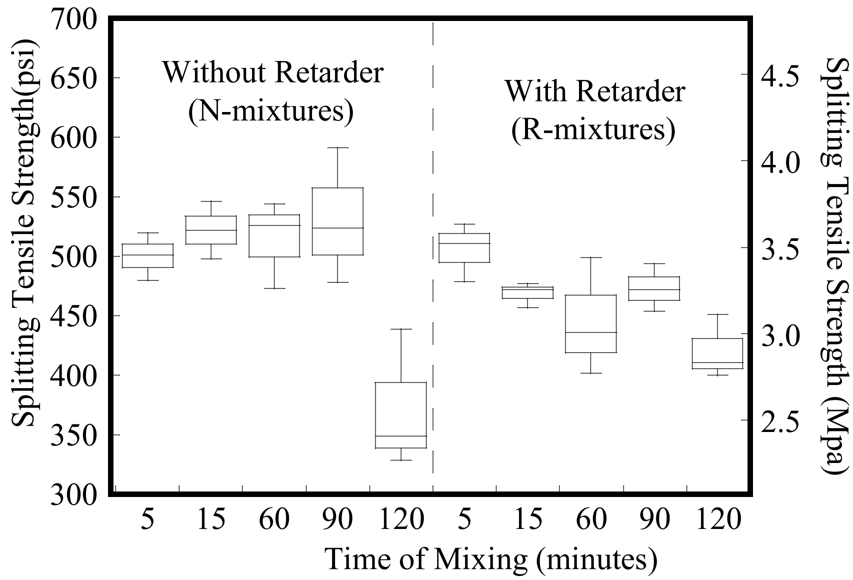


Figure 7-24. Splitting Tensile Strength for Field-mixed Mixtures Mixed for Different Times at 8 rpm.

Field mixtures mixed at 15 rpm were only mixed to 90 minutes due to concerns with setting of the concrete in the ready-mix truck. ANOVA testing for the N mixtures indicates that there is no statistically significant difference between the mean STS of mixtures mixed at different times up 90 minutes (p-value = 0.744). Similar results were observed for the R mixtures mixed up to 90 minutes (p-value = 0.262). Figure 7-19 shows a box plot for STS values used for these comparisons.

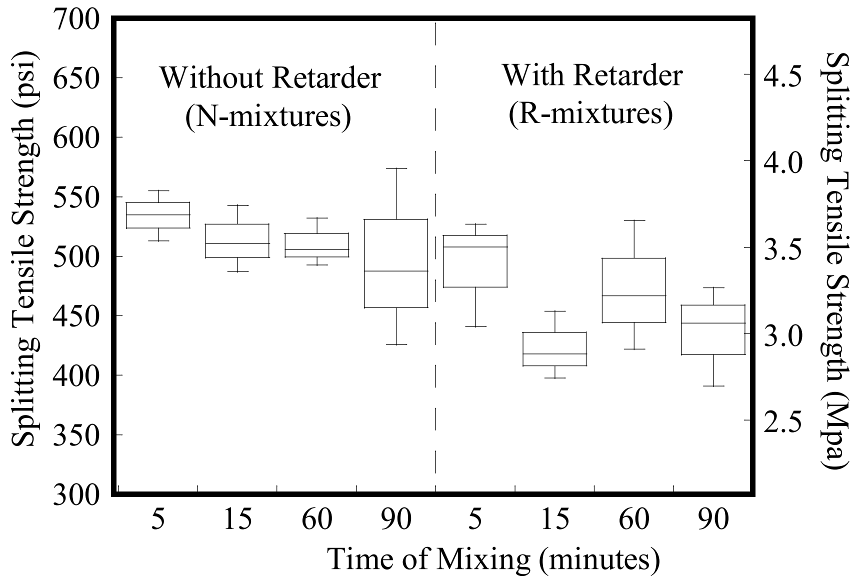


Figure 7-25. Splitting Tensile Strength for Field-mixed Mixtures Mixed for Different Times at 15 rpm.

The analyses of the influence of mixing time indicates that mixing times up to 120 minutes do not significantly influence the STS when mixed at lower speeds. However, when mixing at higher speeds the mixtures mixed for 120 minutes exhibited low workability and castability, resulting in honeycombing in the specimens and a decrease in STS. These findings indicate that when mixtures can be properly placed, concrete may be mixed for longer periods than currently allowed in existing specifications without detrimentally affecting the STS. In addition, the workability and castability of mixtures may be a better indicator for the acceptance of concrete mixtures than mixing time.

7.2 INFLUENCE OF TRUCK DRUM REVOLUTION COUNTS ON FIELD CONCRETE CHARACTERISTICS

The following section includes analyses for the influence of TDRCs on both the fresh and hardened characteristics of concrete mixed in the field. The analyses for the fresh characteristics will be presented first.

7.2.1 Potential Influence of Truck Drum Revolution Counts on Fresh Field Concrete Characteristics

The fresh characteristics of concrete mixed in the field are assessed at different TDRCs. The fresh concrete characteristics assessed include entrapped air content and slump. The analysis on the potential influence of TDRCs on entrapped air content of field concrete is presented first.

7.2.1.1 Potential Influence of Truck Drum Revolution Counts on Entrapped Air Content of Fresh Field Concrete

Table 7-13 shows the entrapped air content of mixtures mixed for different TDRCs. Because of the limited data, statistical comparisons will not be made. However, the general trend of entrapped air content as a function of TDRCs is shown in Figure 7-26. The figure shows that there is no correlation between entrapped air content of fresh field concrete and TDRCs.

Table 7-13. Entrapped Air Content of Fresh Field Concrete.

Mixtures	Entrapped Air Content of Fresh Field Concrete, %												
	Truck Drum Revolution Counts												
	20	40	60	75	120	225	240	360	480	720	900	960	1350
N	2.5	2.3	2.5	2.8	2.1	1.8	2.8	2.8	2.6	2.4	1.7	3.1	2.3
R	2.7	1.6	2.6	1.7	1.8	1.8	2.5	2.2	1.7	1.9	2.1	1.5	2.5

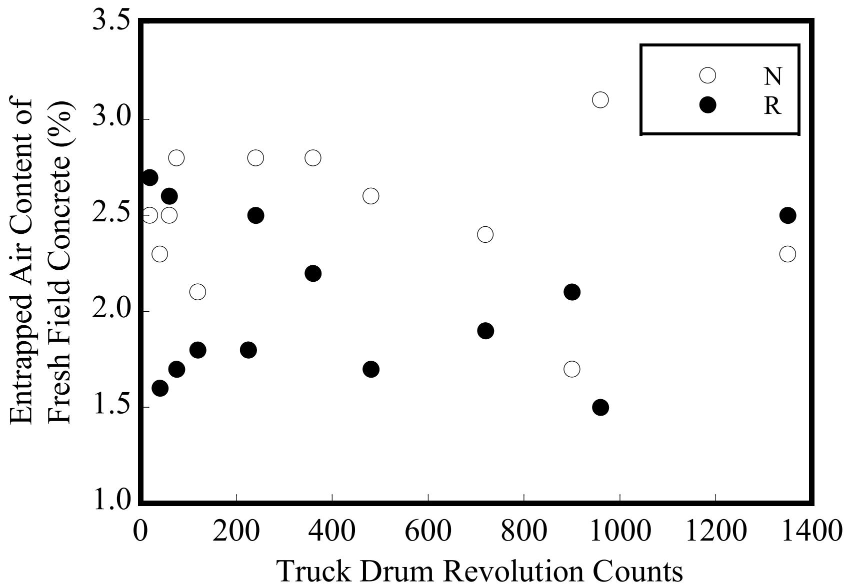


Figure 7-26. Entrapped Air Content of Field Concrete as a Function of TDRCs.

7.2.1.2 Potential Influence of Truck Drum Revolution Counts on Slump of Field Concrete

Table 7-14 shows the slump values of the field-mixed concrete for different TDRCs. Three mixtures were mixed up to 120 minutes at three different mixing speeds. Because the initial slump values of the three mixtures are different, the slump values are normalized. The normalized values are shown in Figure 7-27. Similar to the analysis for the air content of fresh field concrete, due to limited data, no statistical comparisons will be made.

Table 7-14. Slump Values of Field Concrete for Different TDRCs.

Mix I.D	Slump, inch (mm)												
	Truck Drum Revolution Counts												
	20	40	60	75	120	225	240	360	480	720	900	960	1350
N	3.88 (98)	3.75 (95)	3.25 (83)	5.38 (137)	3.25 (83)	4.25 (108)	2.38 (60)	1.63 (41)	0.38 (10)	0.25 (10)	0.88 (22)	0.00 (0)	0.00 (0)
R	4.00 (102)	4.25 (121)	3.63 (92)	5.75 (146)	3.25 (70)	3.88 (98)	1.38 (35)	0.75 (19)	0.38 (10)	0.75 (16)	0.50 (13)	0.25 (6)	0.25 (6)

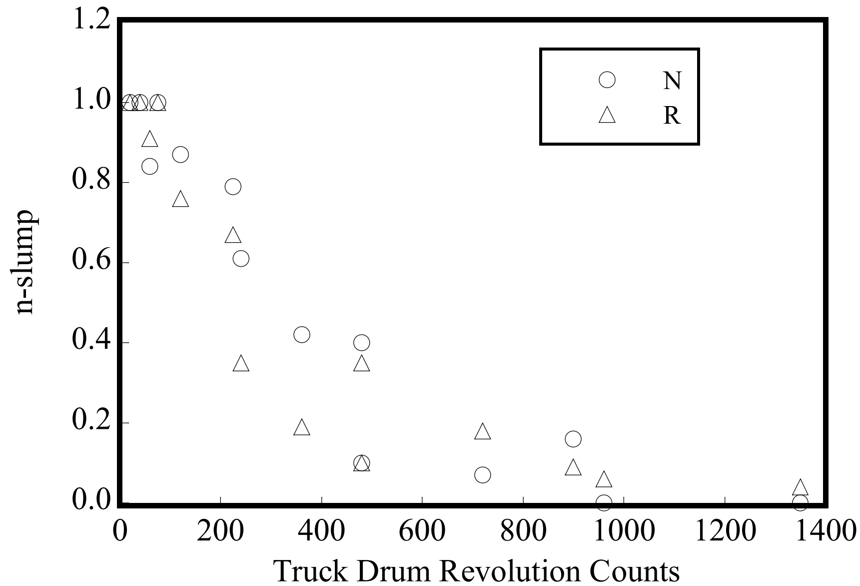


Figure 7-27. Slump Value as a function of TDRCs.

Regression models for n-slump value as a function of TDRCs for mixtures N and R can be developed. For the N and R ($n\text{-slump}_N$ and $n\text{-slump}_R$) mixtures, n-slump as a function of TDRCs can be estimated as follows:

$$n - slump_N(n) = -0.095 + 1.12 \times e^{-0.0022n} \qquad (7\text{-}6)$$

$$n - slump_R(n) = 0.045 + 1.12 \times e^{-0.0039n} \qquad (7\text{-}7)$$

where n is the numbers of TDRCs. The R^2 value for each of the models is 94 percent. Equation 7-6 and 7-7 are valid for TDRCs between 40 to 1350 counts and these are shown in Figure 7-28.

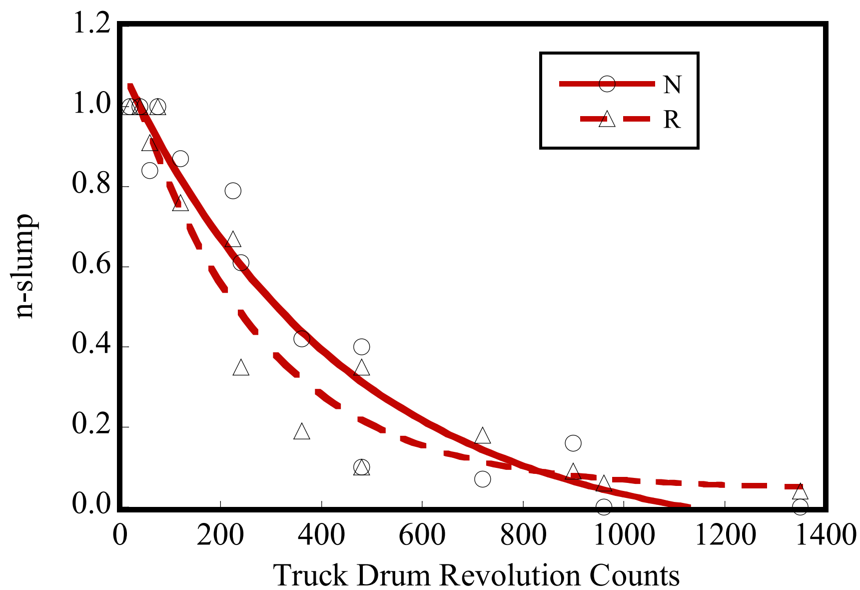


Figure 7-28. N-slump Models as Function of TDRCs for the N and R Mixtures.

Figure 7-29 shows the laboratory and field n-slump models for mixtures without retarders. The figure shows that the laboratory mixtures without chemical admixtures (Lab_{CA}) exhibited a constant slump loss and the field model exhibited an exponential decay in slump loss. The higher rate of initial slump loss in the field mixtures could be the results of the higher ambient temperature during field mixing. Higher temperatures could accelerate the chemical reactions, resulting in stiffrening of mixtures at earlier times. Also, mixing energy could influence the rate of slump loss. The larger drum mixer used in the field has greater energy input than the smaller drum mixer used in the laboratory studies. Even though both laboratory and field mixtures were mixed at similar angular speed, the tangential speed of the larger truck drum mixer is greater. In addition, mixtures mixed in the field were first mixed in a central mixer which was not done in the laboratory study.

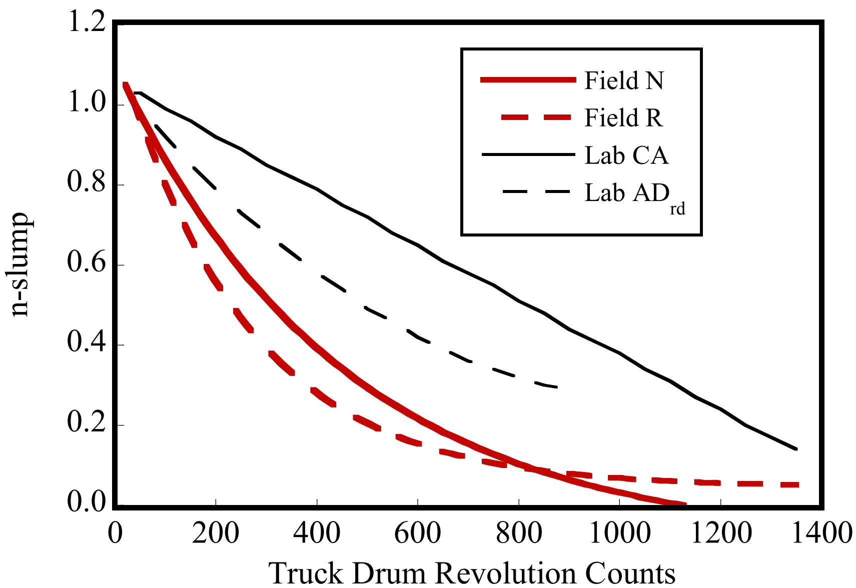


Figure 7-29. Laboratory and Field Models for Mixture without Retarders.

The lower slump loss values observed at the higher TDRCs for the field-mixed mixtures could be a result of the higher energy mixer. As the fresh concrete stiffens and forms solids, the higher energy mixing of the truck mixer is more likely to break the initial bonding between the hydrating particles when compared with laboratory mixers. Therefore, mixtures mixed in the field exhibited lower rates of slump loss at high TDRCs than mixtures mixed in the laboratory.

7.2.2 Potential Influence of Truck Drum Revolution Counts on Hardened Characteristics

7.2.2.1 Potential Influence of Truck Drum Revolution Counts on Compressive Strength

The potential influence of TDRCs on concrete compressive strength is assessed for TDRCs up to 1350. The compressive strength was assessed at 3, 7, and 28 days. The analysis for the 3-day f'cm is presented first. Table 7-15 shows the $f'cm_3$ for the field-mixed mixtures and Figure 7-30 shows the $f'cm_3$ versus TDRCs.

Table 7-15. Compressive Strength (3-day) for Field Mixtures Mixed for Different TDRCs.

TDRC	3-day Compressive Strength, psi (Mpa)	
	N mixtures	R mixtures
20	4307 (29.7)	5145 (35.5)
40	3883 (26.8)	4374 (30.2)
60	4857 (33.5)	5284 (36.4)
75	3280 (22.6)	3987 (27.5)
120	3704 (25.5)	4628 (31.9)
225	3054 (21.1)	4367 (30.1)
240	4655 (32.1)	5010 (34.5)
360	4666 (32.2)	5559 (38.3)
480	2984 (20.6)	4950 (34.2)
720	4087 (28.2)	4475 (30.9)
900	3537 (24.4)	4117 (28.4)
960	1733 (11.9)	4786 (30.0)
1350	3761 (25.9)	4546 (31.3)

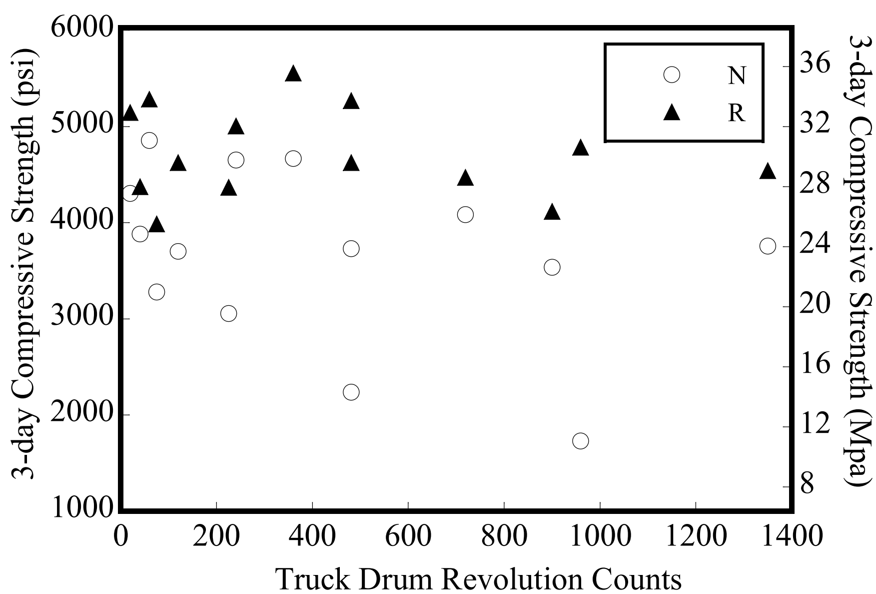


Figure 7-30. Compressive Strength (3-day) versus TDRCs.

Figure 7-30 shows that there is no correlation between the $f'cm_3$ and TDRCs. However, a slightly decreasing trend for the $f'cm_3$ is present for the mixtures without a retarder. To assess the validity of the current specification limit (250 TDRC), the $f'cm_3$ of mixtures mixed for less than and greater than 250 TDRCs are compared. This is shown in Figure 7-31. For both the N and R mixture, t-tests indicates that there is no statistically significant difference between the mean $f'cm_3$ of mixtures mixed for less than and greater than 250 TDRCs (p-value = 0.248 and 0.749 for the N and R mixtures, respectively). The 7-day compressive strength is assessed next.

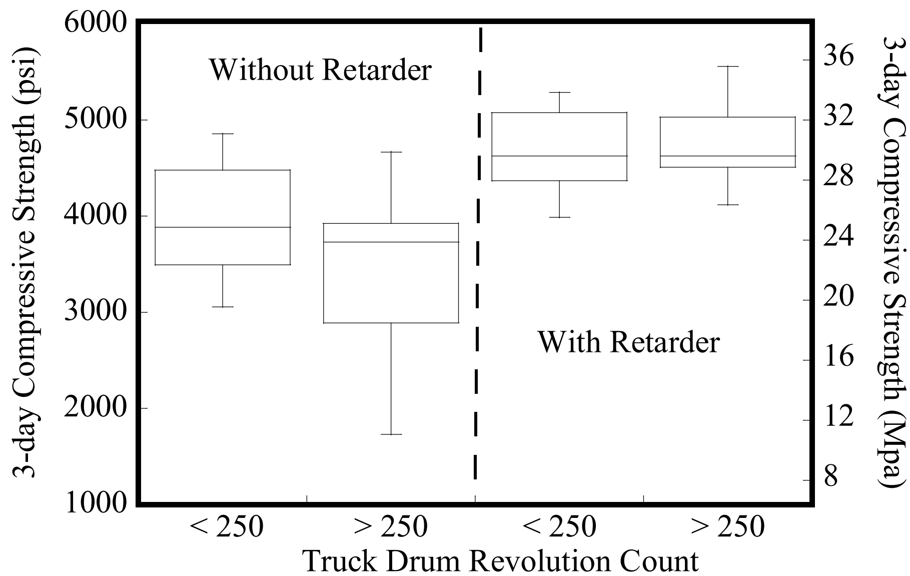


Figure 7-31. Compressive Strength (3-day) for Mixtures Mixed for Less and Greater than 250 TDRCs.

The $f'cm_7$ values for field-mixed concrete are shown in Table 7-16. Figure 7-32 shows the $f'cm_7$ versus TDRCs. The figure shows that there is no correlation between $f'cm_7$ and TDRCs. However, lower $f'cm_7$ is observed for mixtures mixed for higher TDRCs when slump and workability of the mixtures are low. The lower $f'cm_7$ values were observed from specimens containing higher degrees of voids and honeycombing.

Table 7-16. Compressive Strength (7-day) for Field Mixtures Mixed for Different TDRCs.

TDRC	7-day Compressive Strength, psi (Mpa)	
	N mixtures	R mixtures
20	4134 (28.5)	4136 (28.5)
40	4783 (33.0)	5104 (35.2)
60	4235 (29.2)	4131 (28.5)
75	4125 (28.4)	4479 (30.9)
120	4462 (30.8)	4915 (33.9)
225	4333 (29.9)	5022 (34.6)
240	4298 (29.6)	4180 (28.8)
360	4021 (27.7)	4516 (31.1)
480	4028 (32.6)	4792 (32.9)
720	5269 (36.3)	5330 (36.7)
900	4991 (34.4)	5226 (36.0)
960	2479 (17.1)	4776 (32.9)
1350	2745 (18.9)	3209 (22.1)

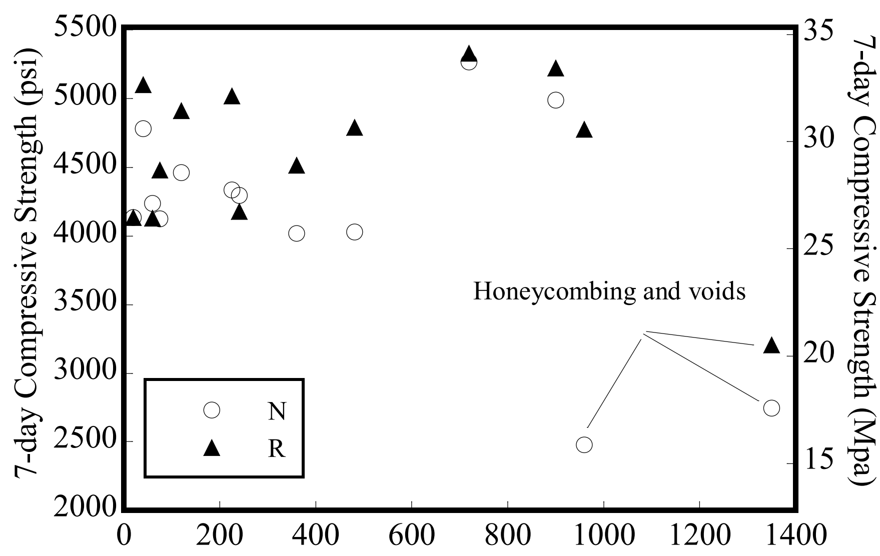


Figure 7-32. Compressive Strength (7-day) versus TDRCs.

Figure 7-32 shows the comparison between the $f'cm_7$ of mixtures mixed for less than and greater than 250 TDRCs. For both the N and R mixture, t-tests indicate that there is no statistically significant difference between the mean $f'cm_7$ of mixtures mixed for less than and greater than 250 TDRCs (p-value = 0.520 and 0.829 for the N and R mixtures, respectively). Even though mixtures exhibited no statistically significant difference, note that large variance was observed for the N mixtures mixed for greater than 250 TDRCs. The large variation in compressive strength is likely a result of inconsistent consolidation of the specimens. The 28-day compressive strength is assessed next.

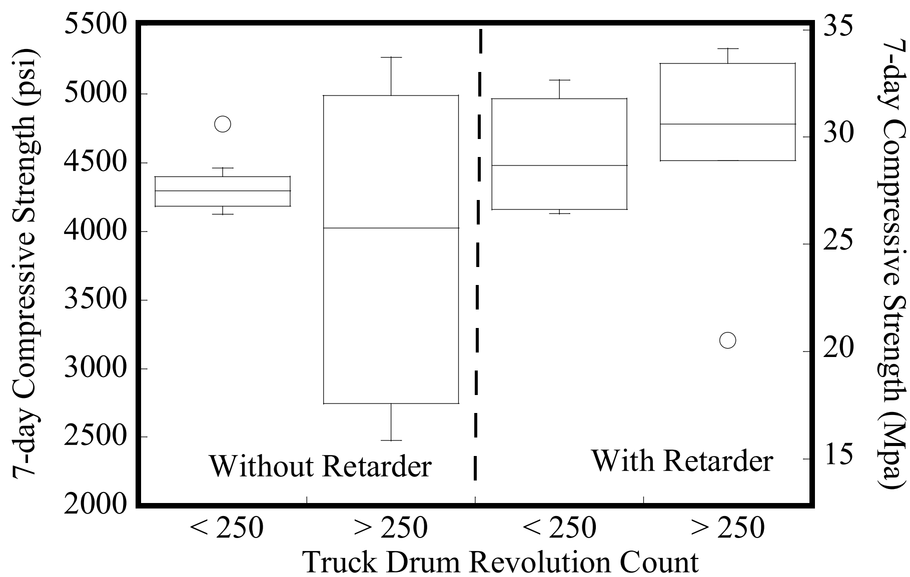


Figure 7-33. Compressive Strength (7-day) for Mixtures Mixed for Less and Greater than 250 TDRCs.

Table 7-17 shows the $f'cm_{28}$ for field-mixed mixtures and Figure 7-34 shows the $f'cm_{28}$ versus TDRCs. Similar to previous findings, there is no correlation between TDRCs and the 28-day compressive strength.

Table 7-17. Compressive Strength (28-day) for Field Mixtures Mixed for Different TDRCs.

TDRC	28-day Compressive Strength, psi (Mpa)	
	N mixtures	R mixtures
20	5959 (41.1)	6318 (43.6)
40	6273 (43.2)	6153 (42.4)
60	6078 (41.9)	6669 (46.0)
75	6053 (41.7)	6267 (43.2)
120	6144 (42.4)	6831 (47.1)
225	5974 (41.2)	6333 (43.7)
240	5800 (40.0)	6269 (43.2)
360	5385 (37.1)	6028 (41.6)
480	5938 (40.5)	65483 (45.2)
720	6503 (44.8)	6704 (46.2)
900	6196 (42.7)	6535 (45.1)
960	2841 (19.6)	6825 (47.1)
1350	2136 (14.7)	6644 (45.8)

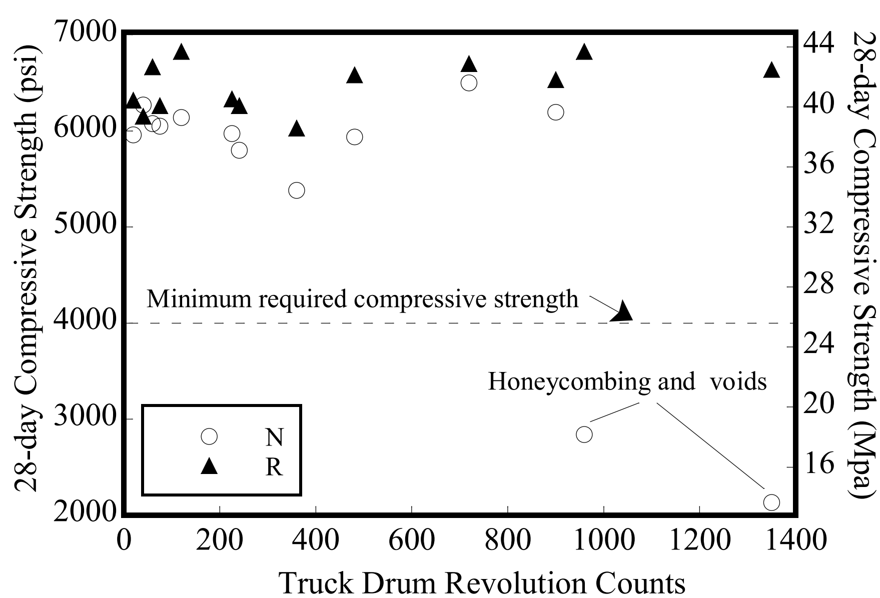


Figure 7-34. Compressive Strength (28-day) versus TDRCs.

Figure 7-34 shows the f'cm$_{28}$ of mixtures mixed up to approximately 900 TDRCs meets the design strength (4000 psi [27.6 Mpa]). However, the N mixtures mixed for 960 and 1350 TDRCs exhibited a significant decrease in $f'cm_{28}$. The decrease in $f'cm_{28}$ is a result of low workability and honeycombing of the mixtures. The low workability led to poor consolidation of the specimen resulting in significant reduction in compressive strength. Note that the R mixtures show no significant decrease in $f'cm_{28}$ when mixed for 1350 TDRCs. This is likely the retarder delaying stiffening of the mixture such that sufficient workability allowed for better placeability and consolidation of the specimens.

The $f'cm_{28}$ of mixtures mixed for less than and greater than 250 TDRCs are compared in Figure 7-35. T-tests indicates that, for both the N and R mixtures, there is no statistical significant difference in the mean $f'cm_{28}$ of mixtures mixed for less than and greater than 250 TDRCs. The p-values are 0.174 and 0.331 for the N and R mixtures, respectively.

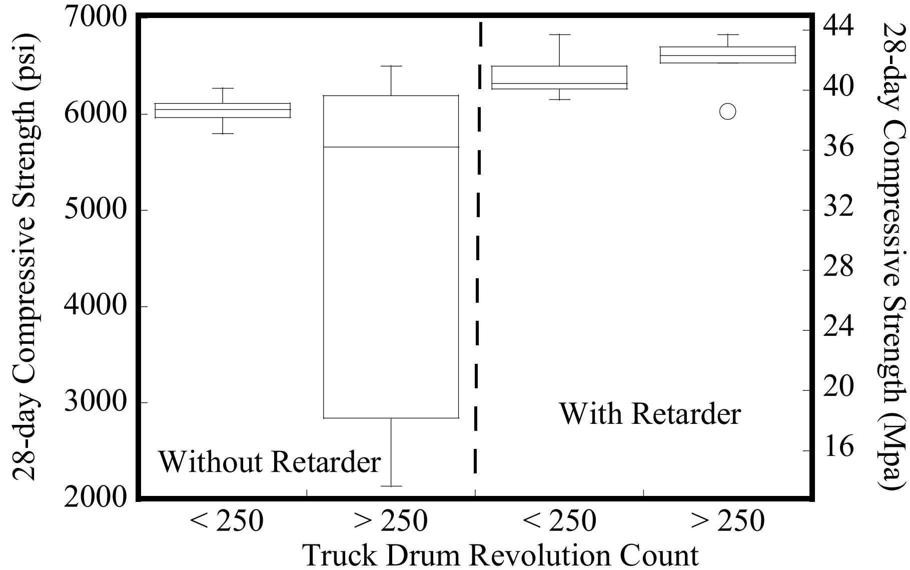


Figure 7-35. Compressive Strength (28-day) for Mixtures Mixed for Less and Greater than 250 TDRCs.

The analyses on the influence of TDRCs on compressive strength indicate that TDRCs does not correlate with compressive strength. However, when TDRC values are very high, the concrete mixtures without retarder can exhibit low workability and lower strength. In addition, the mixtures containing a retarder exhibited sufficient workability even after very high TDRCs and no significant reduction in compressive strength was observed. Statistical tests indicate that the f'cm of mixtures mixed for less than 250 and greater than 250 TDRCs exhibit no statistical significant difference. These findings contradict current specification that limits TDRCs for RMC mixtures for no more than 250 drum revolution counts.

7.2.2.2 Potential Influence of Truck Drum Revolution Counts on Apparent Chloride Diffusivity

This section includes the analyses of the influence of TDRCs on the apparent chloride diffusivity for two different mixtures: mixtures N and R. Table 7-18 shows the apparent chloride diffusion coefficients for the field-mixed concrete. These coefficients are plotted as a function of TDRCs in Figure 7-36. For both the N and R mixtures, t-tests were performed to compare the mean apparent chloride coefficient between mixtures mixed for less and greater than 250 TDRCs. The comparison indicates that there is no statistically significant difference between the two groups at the 95 percent confidence level (p-value = 0.205 and 0.637 for the N and R mixtures, respectively). Figure 7-37 show the box plots for these two tests.

Table 7-18. Apparent Chloride Diffusion Coefficients for the R Mixtures Mixed at Different TDRCs.

TDRC	Apparent Chloride Diffusion Coefficient, ft^2/s (m^2/s) x10^{11}					
	N Mixtures			R Mixtures		
20	12.2 (1.14)	25.4 (2.36)	16.7 (1.55)	10.0 (0.93)	10.9 (1.01)	N.A
40	8.51 (0.79)	29.1 (2.70)	36.04 (3.35)	15.8 (1.47)	10.7 (0.99)	N.A
60	43.4 (4.032)	69.76 (6.48)	N.A	30.5 (2.84)	N.A	N.A
75	21.0 (1.95)	21.6 (2.01)	22.4 (2.09)	26.1 (2.42)	26.0 (2.41)	N.A
120	27.5 (2.55)	15.4 (1.43)	14.1 (1.31)	42.3 (3.93)	52.8 (4.91)	47.5 (4.41)
225	27.6 (2.56)	19.67 (1.83)	N.A	14.7 (1.37)	26.0 (2.42)	4.00 (0.37)
240	30.3 (2.81)	35.4 (3.29)	41.2 (3.83)	53.8 (5.00)	40.9 (3.80)	N.A
360	22.1 (2.06)	15.4 (1.43)	36.4 (3.38)	7.70 (0.71)	29.2 (2.71)	20.4 (1.90)
480	28.0 (2.60)	42.2 (3.92)	8.26 (0.77)	17.8 (1.65)	42.1 (3.92)	N.A
	55.1 (5.12)	24.4 (2.26)	N.A	31.9 (2.96)	9.40 (0.87)	11.8 (1.09)
720	18.1 (1.69)	8.60 (0.80)	N.A	32.2 (2.99)	32.5 (3.02)	11.3 (1.05)
900	25.7 (2.39)	37.7 (3.50)	22.5 (2.09)	23.4 (2.18)	22.8 (2.12)	23.0 (2.14)
960	19.1 (1.77)	22.4 (2.08)	N.A	24.3 (2.26)	23.6 (2.19)	28.7 (2.66)
1350	7.80 (0.73)	31.8 (2.95)	27.5 (2.55)	11.3 (1.05)	9.10 (0.84)	11.0 (1.02)

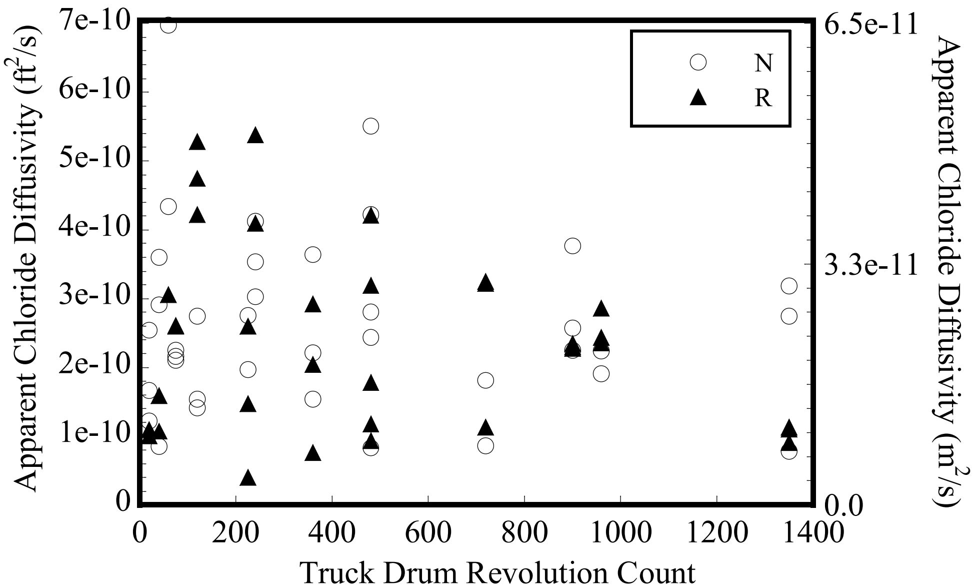


Figure 7-36. Apparent Chloride Diffusion Coefficient versus TDRCs for the N Mixtures.

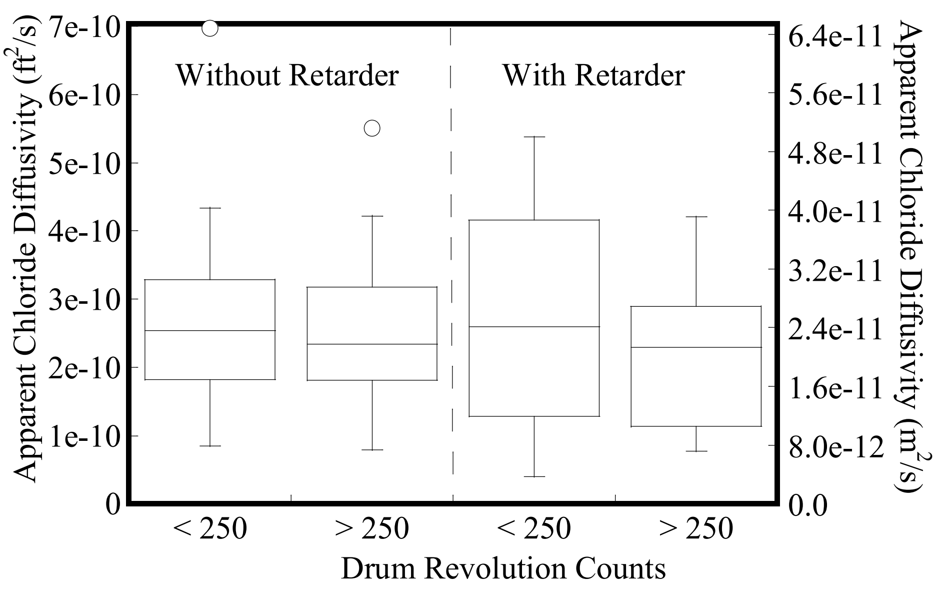


Figure 7-37 Box Plot for Apparent Chloride Diffusion Coefficient of the N and R Mixture Mixed for less than and greater than 250 TDRCs.

The results indicate that TDRCs do not significantly influence the apparent chloride diffusivity for mixtures experienceing up to 1350 TDRCs. In addition, statistical analyses indicate that the apparent chloride diffusivity of field mixtures mixed for less and greater than 250 TDRCs exhibited no significant difference. This finding conflicts with current WSDOT specification limits that do not allow RMC to be mixed for more than 250 TDRCs. However, caution should be taken as once inferior concrete is placed the time and costs associated with removing and replacing this concrete can be significant.

7.2.2.3 Potential Influence of Truck Drum Revolution Counts on Modulus of Elasticity

Table 7-19 show the MOE of mixtures mixed for different TDRCs. These values are plotted as a function of TDRCs in Figure 7-38. The figures show that there is no strong correlation between MOE and TDRCs. This indicates that TDRCs does not significantly influence the MOE. However, the N mixtures exhibited larger scatter at higher TDRCs. This is likely due the honeycombing and air void in the specimen from mixtures mixed at higher TDRCs.

Table 7-19. Modulus of Elasticity for the Field-mixed Concrete Mixed at Different TDRCs.

TDRC	Modulus of Elasticity, ksi (Gpa)					
	N Mixtures			R Mixtures		
20	4894 (33.7)	5759 (39.7)	5002 (34.5)	5159 (35.6)	5285 (36.4)	5680 (39.2)
40	5517 (38.0)	5208 (35.9)	5225 (36.0)	5972 (41.2)	5707 (39.3)	5458 (37.6)
60	5130 (35.4)	5519 (38.0)	4768 (32.9)	5330 (36.7)	5286 (36.4)	7296 (50.3)
75	5046 (34.8)	5266 (36.3)	5092 (35.1)	5133 (35.4)	5888 (40.6)	5134 (35.4)
120	5280 (36.4)	5221 (36.0)	5434 (37.5)	5534 (38.2)	5302 (36.6)	5243 (36.1)
225	5262 (36.3)	5265 (36.3)	5359 (36.9)	4961 (34.2)	4929 (34.0)	5207 (35.9)
240	5030 (34.7)	5013 (34.6)	5161 (35.6)	5259 (36.3)	4828 (33.3)	5628 (38.8)
360	5329 (36.7)	5021 (34.6)	5239 (36.1)	5382 (37.1)	5317 (36.7)	5350 (36.9)
480	5357 (36.9)	5437 (37.5)	5229 (36.0)	5146 (35.5)	5419 (37.4)	5343 (36.8)
	4368 (30.1)	7012 (48.3)	5300 (36.5)	5216 (36.0)	5122 (35.3)	5516 (38.0)
720	5141 (35.4)	2680 (18.5)	5159 (35.6)	4980 (34.3)	5863 (40.4)	5162 (35.6)
900	5310 (36.6)	5138 (35.4)	5930 (40.9)	4749 (32.7)	4665 (32.2)	5151 (35.5)
960	2399 (16.5)	4173 (28.8)	3565 (24.6)	5459 (37.6)	5307 (36.6)	5216 (36.0)
1350	4727 (32.6)	4848 (33.4)	5672 (39.1)	5122 (35.3)	4791 (33.0)	4406 (30.4)

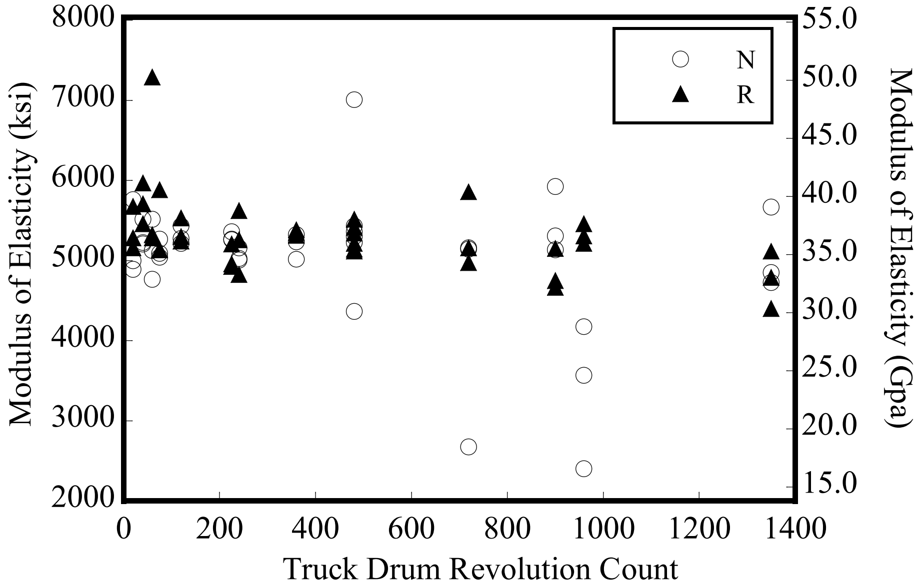


Figure 7-38. MOE versus TDRC.

The validity of current specification limits is assessed by comparing the median of MOE of mixtures mixed for less than and greater than 250 TDRCs. Note that these data are not normal; therefore the medians are compared instead of the mean values. For the N mixtures, t-tests indicate that there is no statistically significant difference between the two groups (p-value = 0.563). Similar results were obtained for the R mixtures (p-value = 0.138). Figure 7-39 shows a box plot for these comparisons.

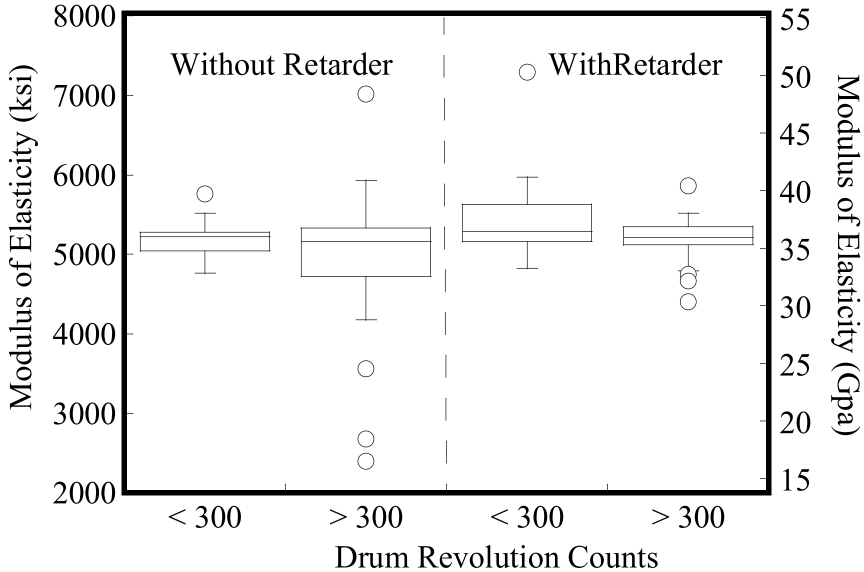


Figure 7-39. Box Plot for MOE of the N and R Mixtures Mixed for less than and greater than 250 TDRCs.

Results indicate that mixtures experienceing high TDRCs exhibited low workability and castability and this led to significant reductions in MOE values. However, when mixtures retained sufficient workability for a proper casting and consolidation, no significant reduction in MOE is observed for TDRCs up to 1350.

7.2.2.4 Potential Influence of Truck Drum Revolution Counts on Modulus of Rupture

The influence of TDRCs of the MOR is assessed in this section. Note that only a subset of the field-mixed mixtures is evaluated. Table 7-20 shows the MOR values for these mixtures. Like previous analyses, correlation between the MOR and TDRCs is first assessed.

Table 7-20. Modulus of Rupture for Field Concrete Mixed at Different TDRCs.

TDRC	Modulus of Rupture, psi (Mpa)					
	N Mixtures			R Mixtures		
20	576 (3.97)	624 (4.30)	564 (3.89)	604 (4.16)	648 (4.47)	604 (4.16)
60	408 (2.81)	595 (4.10)	504 (3.47)	753 (5.19)	600 (4.14)	705 (4.86)
225	604 (4.16)	528 (3.64)	509 (3.51)	628 (4.33)	614 (4.23)	652 (4.49)
480	652 (4.49)	748 (5.16)	614 (4.23)	609 (4.20)	556 (3.83)	556 (3.83)
	542 (3.74)	509 (3.51)	492 (3.39)	691 (4.76)	552 (3.81)	705 (4.86)
720	648 (4.47)	648 (4.47)	638 (4.40)	590 (4.07)	636 (4.38)	633 (4.36)
900	571 (3.94)	523 (3.61)	547 (3.77)	686 (4.73)	604 (4.16)	592 (4.08)
960	494 (3.41)	614 (4.23)	638 (4.40)	816 (5.63)	748 (5.16)	696 (4.80)
1350	499 (3.44)	504 (3.47)	504 (3.47)	561 (3.87)	533 (3.67)	619 (4.27)

Figure 7-40 shows the MOR of field-mixed concrete as a function of TDRCs. The figure indicates there is no strong correlation between TDRCs and MOR of field-mixed concrete. Thus, the TDRCs likely do not influence the MOR of field-mixed concrete. Because limited data available, the MOR of mixtures mixed for less than 225 TDRCs and greater than 480 TDRCs are compared. For the N mixtures, t-test results indicate that there is no statistically significant difference in the mean values of the two groups (p-value = 0.729 at the 95 percent confidence level). Similarly for the R mixtures no significant difference was observed (p-value = 0.688)

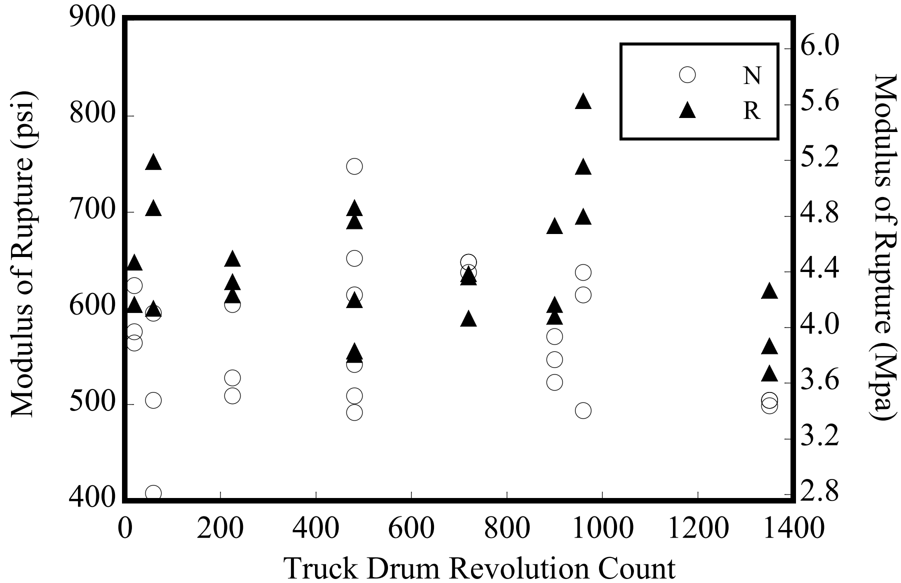


Figure 7-40. MOR of Field-mixed Concrete versus TDRCs.

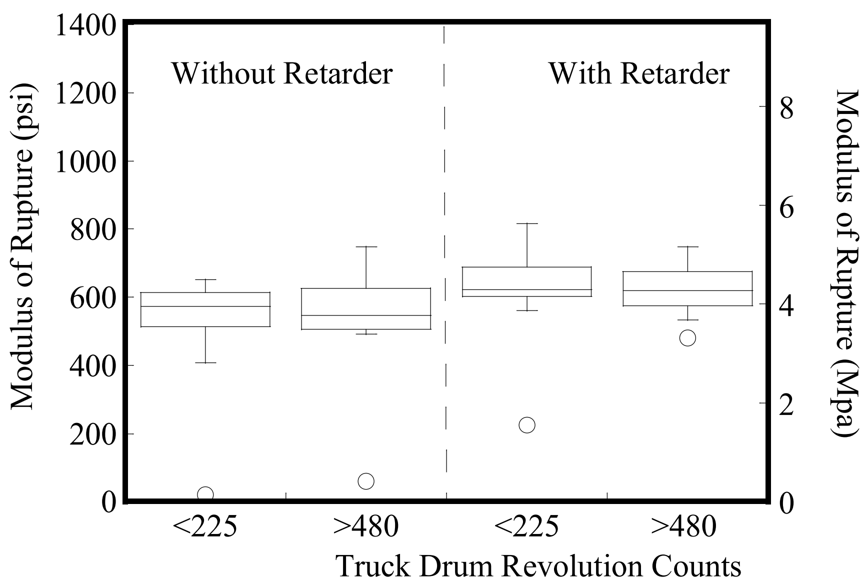


Figure 7-41. Box Plot for MOR of the N and R Mixtures Mixed for less than 225 and greater than 480 TDRCs.

The results for the analyses for MOR indicates the TDRCs likely do not significantly influence the MOR of mixtures for up to 1350 TDRCs. Note that limited data were assessed, even though results indicate no significant difference in MOR, further studies are needed.

7.2.2.5 Potential Influence of Truck Drum Revolution Counts on Splitting Tensile Strength

The STSs for the field mixtures assessed at different TDRCs up to 1350 are shown in Table 7-21. Statistical analyses were performed to compare the mean STS values from mixtures mixed for different TDRCs. Figure 7-42 shows that there is no correlation between STS and TDRCs.

Figure 7-43 shows a box plot for the STS of the N mixtures mixed at different TDRCs. ANOVA testing indicates that there is a statistically significant difference between the mean STS of mixture N when mixed at different TDRCs up to 1350 (p-value = 0.011). The mixtures mixed for 480 (4 rpm for 120 minutes) and 960 (8 rpm for 120 minutes) TDRCs exhibited a significant reduction in STS. The reduction is likely due to the low workability and castability of the mixtures, which resulted in honeycombing and voids in the specimens. When excluding these two mixtures, there is a strong evidence that there is no statistically significant difference in the mean STS for mixtures mixed up to 1350 TDRCs (p-value = 0.882).

Table 7-21. Splitting Tensile Strength for Field-Mixed Concrete.

TDRC	Splitting Tensile Strength, psi (Mpa)					
	N Mixtures			R Mixtures		
20	395 (2.72)	501 (3.45)	600 (4.13)	548 (3.78)	442 (3.05)	559 (3.85)
40	520 (3.59)	480 (3.31)	501 (3.45)	479 (3.30)	511 (3.52)	527 (3.63)
60	467 (3.22)	491 (3.38)	508 (3.50)	602 (4.15)	649 (4.48)	586 (4.04)
75	555 (3.83)	513 (3.54)	535 (3.69)	508 (3.50)	527 (3.64)	441 (3.04)
120	546 (3.76)	498 (3.43)	522 (3.60)	457 (3.15)	472 (3.25)	477 (3.29)
225	511 (3.53)	543 (3.74)	487 (3.36)	454 (3.13)	418 (2.88)	398 (2.74)
240	503 (3.47)	492 (3.39)	514 (3.55)	577 (3.98)	540 (3.72)	564 (3.89)
360	494 (3.41)	491 (3.38)	497 (3.43)	548 (3.78)	553 (3.82)	508 (3.50)
480	353 (2.43)	429 (2.95)	461 (3.18)	423 (2.92)	479 (3.30)	602 (4.15)
	544 (3.75)	526 (3.63)	473 (3.26)	402 (2.77)	499 (3.44)	436 (3.01)
720	524 (3.61)	478 (3.30)	591 (4.08)	494 (3.40)	472 (3.25)	454 (3.13)
900	493 (3.40)	532 (3.67)	506 (3.49)	422 (2.91)	530 (3.66)	467 (3.22)
960	439 (3.03)	329 (2.27)	349 (2.40)	400 (2.76)	411 (2.83)	451 (3.11)
1350	574 (3.96)	488 (3.36)	426 (2.94)	391 (2.70)	444 (3.06)	474 (3.27)

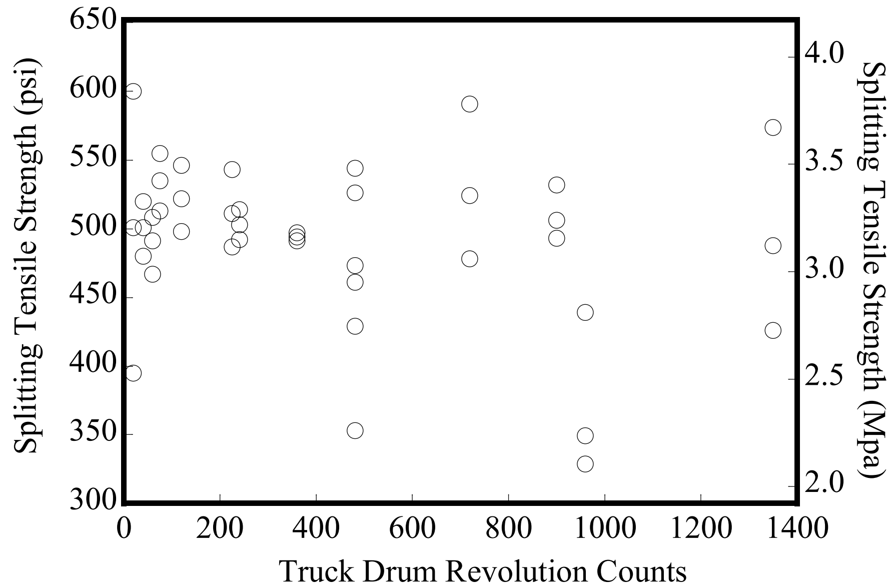


Figure 7-42. Splitting Tensile Strength versus TDRCs for the N Mixtures.

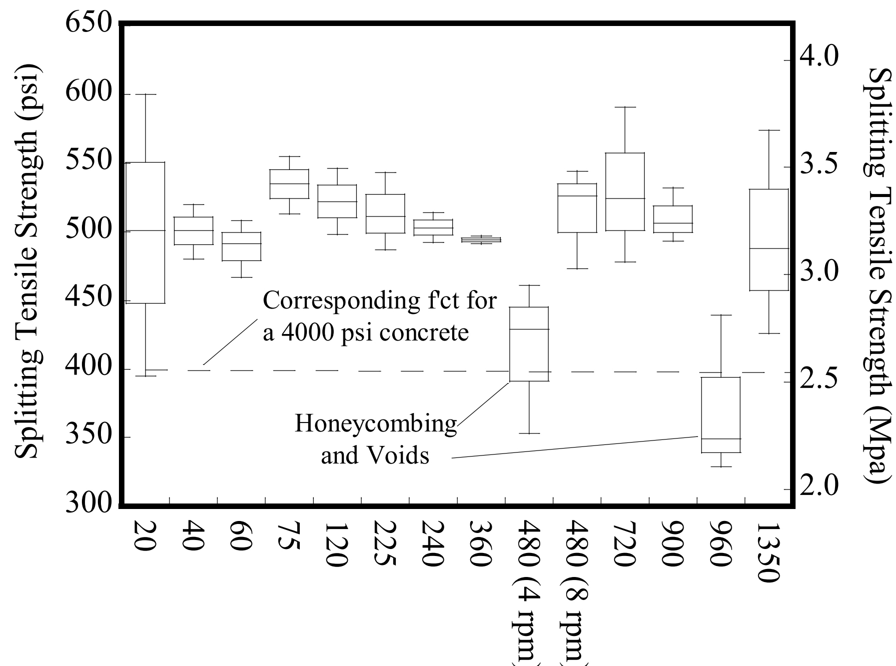


Figure 7-43. Box Plot for the N Mixtures Mixed for Different TDRCs.

To assess the validity of the current specification limit (250 TDRCs), the STS of mixtures mixed for less than and greater than 250 TDRCs are compared (excluding honeycombing mixtures). A box plot of these values is shown in Figure 7-44. The t-test indicates that there is no statistically significant difference in the mean STS for these two groups (p-values = 0.826).

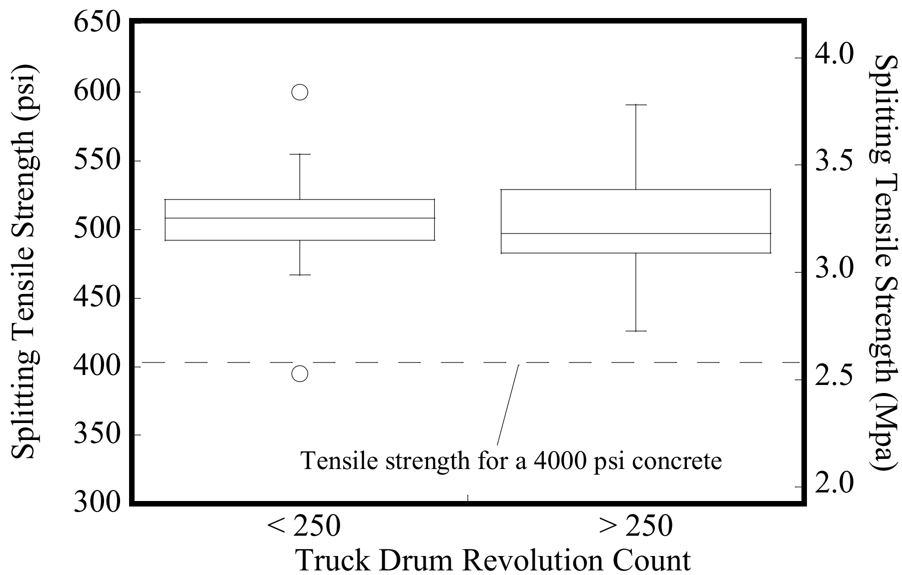


Figure 7-44. Splitting Tensile Strength for the N Mixtures Mixed for Less than and Greater than 250 TDRCs.

Figure 7-45 shows a plot for the STS versus TDRCs for the R mixtures. The figure shows that there is not a strong correlation between STS and TDRCs. Figure 7-43 includes the STS data of the R mixtures mixed at different TDRCs.

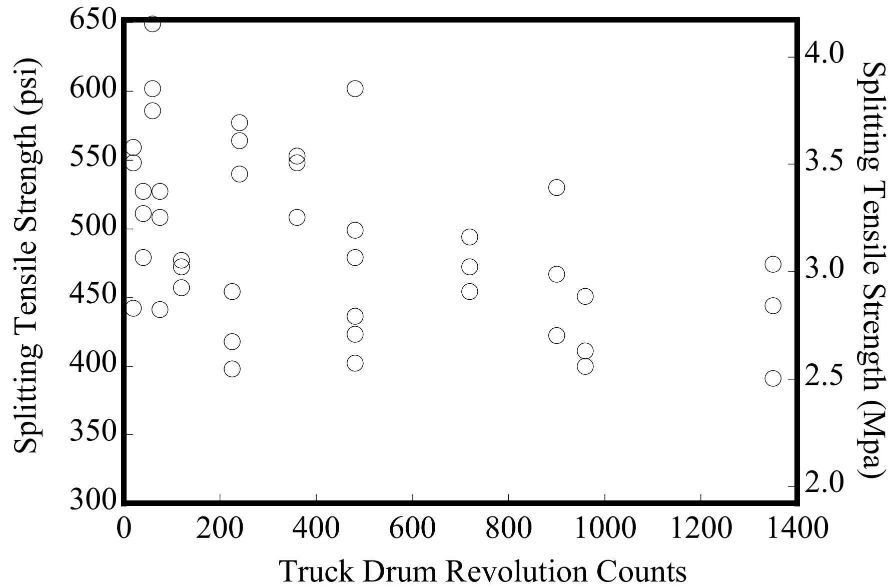


Figure 7-45. Splitting Tensile Strength for the R Mixtures versus TDRCs.

ANOVA testing indicates that there is a statistically significant difference between the mean STS of the mixtures mixed at different TDRCs up to 1350 (p-value = 0.000). Even though there is a statistically significant difference between the means, the mean STS value was not lower than the estimated tensile strength (based on AASHTO) for a 4000 psi (27.6 Mpa) concrete. This indicates that TDRCs has no significant detrimental effect on the splitting tensile. However, note that individual specimen from mixtures experiencing high TDRCs can fall below the estimated tensile strength for a 4000 psi (27.6 Mpa) concrete.

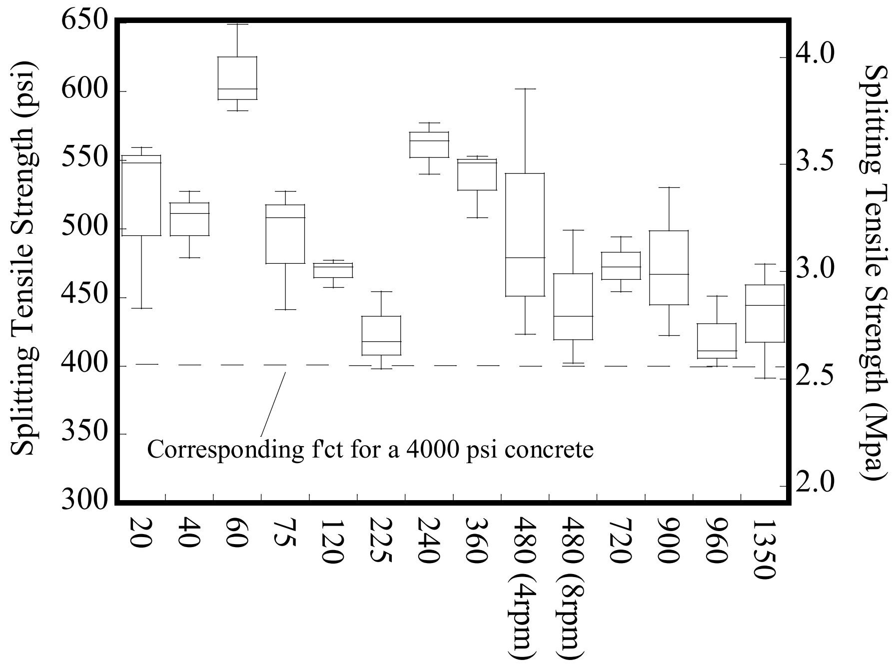


Figure 7-46. Box Plot for the R Mixtures Mixed for Different TDRCs.

The STS of the R mixtures mixed for less than and greater than 250 TDRCs are compared. A box plot for these values is shown in Figure 7-47. The t-test indicates that the mean STS of mixtures mixed for less than 250 TDRCs is higher than those mixed for greater than 250 TDRCs (p-values = 0.033). Even so, the large majority of the tensile strength is well above the AASHTO estimated STS value.

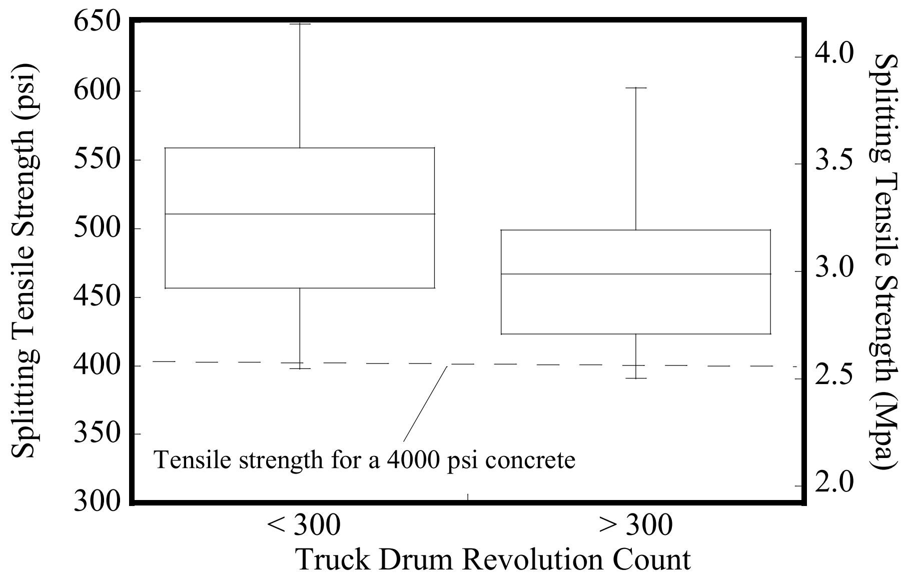


Figure 7-47. Splitting Tensile Strength for the R Mixtures Mixed for Less than and Greater than 250 TDRCs.

The analyses on the influence of TDRCs on the STS indicate that large TDRCs can significantly reduce the workability of mixtures without retarder. Low workability and castability can result in detrimental reductions in the STS. However, similar to previous findings, when mixtures maintained sufficient workability and castability and can be properly consolidated, larger TDRCs do not significantly influence the STS. In addition, the STS of mixtures mixed for greater than 250 TDRCs did exhibit lower mean STS values when compared to those that mixed for less than 250 TDRCs. However, the large majority of the STS values are well above the AASHTO estimated values.

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1 SUMMARY

The objectives of this research were to determine if existing limits in ASTM, WSDOT and other SHA specifications on mixing time and DRC limits for RMC are applicable to typical concrete mixtures. If not applicable, the objective of this research is to identify indicators that can be used for determining the acceptance of RMC. A comprehensive study was performed to investigate the influence of mixing time, mixer speeds, and DRC on the characteristics of concrete.

This research assessed laboratory- and field-mixed concrete mixtures. The laboratory-mixed concrete consisted of a wide variety of materials from the State of Washington. The field-mixed concrete focused on a control mixture and a mixtures containing a retarder. All materials for the field study were from the State of Washington. Data were collected and statistical analyses were performed to determine if concrete mixtures exhibit significant differences in fresh or hardened characteristics when mixed within specification limits and when mixed beyond specification limits. The conclusions and recommendations are based on these results.

8.2 CONCLUSIONS

This section is divided in two sub-sections. The first sub-section describes the influence of mixing time and LDRCs on the characteristics of laboratory-mixed concrete.

The second sub-section summarizes the findings on the influence of mixing time and TDRCs on the characteristics of field-mixed concrete.

8.2.1 Influence of Mixing Time and Mixer Speeds for Laboratory-mixed Concrete

1) The characteristics of the concrete aggregates (CA and FA) and the cement content do not significantly influence the slump loss for mixtures mixed in the laboratory.

2) With the exception of the absorption of CA, there is limited influence of the aggregate characteristics or cement content on compressive strength. Mixtures mixed with lower CA absorption values exhibited higher compressive strengths.

3) Results indicate that mixing time has no significant influence on the entrapped and entrained air contents of mixtures mixed up to 60 minutes at 8 and 15 rpm in this research. However, when mixed for 180 minutes, mixtures containing AEA exhibited a significant decrease in entrained air content and the mixtures without AEA exhibited a slight increase in air content.

4) Higher initial mixture temperatures lead to faster initial slump losses. A slump reduction factor can be computed using Equation 5-1. The initial temperature of the mixtures evaluated in the research does not seem to have a significant effect on the 28-day compressive strength. However, this temperature range was limited

and initial temperatures beyond this range could likely influence fresh properties.

5) The rate of mixture temperature increase is significantly higher during the first 5 minutes of mixing compared to the temperature rises at later times. Mixtures mixed at a higher speeds exhibited higher rates of temperature increase.

6) Slump values decreased as a function of mixing time for all mixtures but at different rates. The mixtures containing recommended dosages of retarder exhibited accelerated slump losses and the mixtures containing higher dosages of retarders (exceeding the manufacturer's recommended dosage) exhibited lower rates of slump loss. Also, higher mixing speeds accelerated the slump loss for all mixtures.

7) The apparent chloride diffusivity and the freeze-thaw performance of the concrete mixtures mixed in the laboratory were not significantly influenced by mixing times up to 60 minutes and mixing speeds up to 15 rpm.

8) Results indicate that the f'cm, MOE, MOR, and STS for the laboratory-mixed concrete exhibited no significant reduction in properties when mixed up to 180 minutes at 8 rpm or less. Laboratory mixtures mixed at a mixing speed of 15 rpm exhibited

reduced MOE, STS, and MOR values. In all cases the reductions in concrete properties were related to low workability and castability, which resulted in specimens containing voids and honeycombs.

8.2.2 Influence of Drum Revolution Counts for Laboratory-mixed Concrete

1) Mixtures without AEA exhibited no statistically significant difference in the mean entrapped air content when mixed for up to 900 LDRCs. Similar results were observed for the mixtures containing AEA.

2) During the first 40 LDRCs, the rate of temperature increase was significantly higher when compared to temperature increases after these initial LDRCs. The rates of increase in mixture temperature were nearly constant from 40 to 900 LDRCs.

3) The slump decreases as a function of the LDRCs for all the mixture types but decreases at different rates. Models for slump as a function of LDRCs were developed for the different mixture types. Results show that there is significant scatter in slump loss values for the different mixtures.

4) The hardened characteristics of concrete (f'cm, MOE, MOR and STS) showed no significant reduction when mixed for up to 2700 LDRCs for mixtures that maintained sufficient workability and castability. However, for mixtures mixed for 2700 LDRCs that

exhibited low workability and castability (which resulted in voids and honeycombing in the specimens), reductions in the values of f'cm, MOE, MOR, and STS were observed.

5) Results indicate that LDRCs up to 900 do not significantly influence the apparent chloride diffusivity and freeze-thaw performance of the concrete mixtures mixed in the laboratory.

8.2.3 Influence of Mixing Time and Mixer Speed for Field-mixed Concrete

1) Mixing times up to 120 minutes did not significantly influence the entrapped air content of the fresh concrete. Mixtures containing AEA were not evaluated in the field study.

2) The slump of field-mixed concrete decreases with mixing time. The field-mixed concrete exhibited different rates of slump loss. Higher mixing speeds accelerated the slump loss of the field-mixed mixtures.

3) Field-mixed mixtures mixed at faster mixing speeds and longer mixing times exhibited lower compressive strengths. This was due to loss of slump and lack of workability and castability, which resulted in the presence of high void contents and honeycombing in the specimens. However, even at faster mixing speeds and longer mixing times, the compressive strength was not significantly

reduced when mixtures maintained sufficient workability for proper placement of the specimens.

4) Mixing times up to 120 minutes at 4 and 8 rpm and mixing times up to 90 minutes at 15 rpm did not significantly influence the apparent chloride diffusivity of field-mixed concrete.

5) After 120 minutes of mixing of the control mixtures, the field-mixed concrete exhibited significant reductions in f'cm, MOE, and STS. This was a result of poor workability and honeycombing of the specimen. With the exception of STS, field-mixed mixtures containing recommended dosages of retarder exhibited no reduction in hardened concrete characteristics after 120 minutes of mixing. The STS did decrease with mixing times longer than 120 minutes.

8.2.4 Influence of TDRCs for Field-mixed Concrete

1) Entrapped air for the field-mixed concrete was not significantly influenced by TDRCs.

2) The slump of field-mixed concrete decreases with increasing TDRCs. However, the rates of slump loss were significantly different for mixtures with and without retarders.

3) The TDRCs did not significantly influence compressive strength at lower counts. Some mixtures did exhibit lower strengths when mixed for very high TDRCs. Very high TDRCs produced mixtures

with poor workability and castability which resulted in a high content of voids and honeycombing in the specimens. Low workability and castability resulted in lower compressive strengths for mixtures without retarders. Mixtures containing retarders exhibited sufficient workability at higher TDRCs and as a result the compressive strengths of these specimens were not significantly influenced when mixed up to 1350 TDRCs.

4) Results indicate that TDRCs have limited influence on the MOE, MOR, and STS unless the TDRCs are very high. Mixtures mixed for high TDRCs exhibited low workability and castability and these specimens exhibited significant reductions in MOE, MOR, and STS. When mixtures retained sufficient workability for proper casting and consolidation, no significant reduction in the MOE, MOR, and STS was observed at TDRCs values up to 1350 revolutions.

5) The results indicate that TDRCs do not significantly influence the apparent chloride diffusivity of field-mixed concrete for TDRCs up to 1350 revolutions.

8.3 RECOMMENDATIONS

Limits on time to discharge and TDRCs have been in specifications for many years. These limits were implemented when mixing equipment was relatively rudimentary and when chemical admixtures were not yet developed. Significant changes have occurred in the concrete industry since discharge times and drum revolution limits were first included in specifications. In 2013, ASTM C94 required that "discharge of concrete shall be completed within 1½ h, or before the drum has revolved 300 revolutions, whichever comes first, after the introduction of water." In 2014, the limit on drum revolutions was removed and C94 only requires that "discharge of concrete shall be completed within 1½ h after the introduction of water." Even so, forty-eight SHAs limit times to discharge and thirty SHAs still limit the number of drum revolutions. This research investigated the fresh and hardened characteristics of laboratory- and field-mixed concrete mixed for different times, different mixer speeds, and different drum revolutions using constituent materials from the State of Washington.

Results from the laboratory and field studies indicate that concrete mixtures exhibit a wide range of slump loss values. Because properly placing and consolidating concrete is dependent on the initial design target slump, the slump loss of the concrete mixture, the workability at time of placement (commonly measured with slump), and the type of construction, the results from this research indicate that specifying one limit on mixing time is likely not appropriate for conditions. In fact, results from this research indicate some mixtures exhibited low workability and were difficult to cast at mixing times less than 90 minutes while others exhibited sufficient workability and could be cast when mixed for 180 minutes. Although relationships between mixing time and slump were identified for specific groups of concrete, no single relationship between mixing time and slump could be identified for all the different mixtures assessed in this research. This indicates that one limit on discharge time is likely not appropriate for all cases and all mixtures. In addition to the results for the fresh characteristics, results indicate that time to discharge cannot be directly correlated with hardened properties. In fact, most hardened properties exhibited no reductions of properties after long mixing durations and after high TDRCs. The one key factor identified in the research is whether the concrete mixture can be properly placed, cast, and consolidated. Because no clear relationship was identified for slump (which is not always a good indicator of placeability and castability) and time to discharge, no relationship was identified for time to discharge and concrete performance. Because of this, the current time to discharge as specified by WSDOT was determined to be conservative for nearly all cases. However, this research did not identify 90 minutes of mixing as being lower limits for most of the mixtures assessed in this research.

In addition to time limits, varying relationships between DRC (both laboratory and field truck) and the fresh and hardened characteristics of concrete were identified for various mixtures assessed in this research. In general, TDRCs exhibited a better correlation than mixing time with slump. The 250 TDRCs limit was found to be conservative even though it was not determined to be the limiting TDRCs value for most mixtures (e.g., the limiting TDRCs value would be the value where the concrete fresh characteristics or hardened properties exhibited a significant change). No clear influence of TDRCs on concrete performance was identified in this research.

It should be noted that mixer speed can significantly influence the slump loss and slump of concrete at discharge. Although ASTM C94 states that central-mixed concrete that is mixed completely in a stationary mixer and transported to a point of delivery in a truck mixer operating at agitating speed (≤ 6 rpm per NRMCA) requires certain charging into the mixer and requires that mixing time be measured, no other requirements on drum speed are specified. When mixtures are not sufficiently mixed, faster mixing speeds can be used, which could alter the slump and workability. In addition to mixing speed, the characteristics of constituent materials may influence workability and hardened properties. This research included coarse and fine aggregates from the State of Washington. In locations where softer aggregates are used for concrete, different performance than identified in this research may be observed. Also, different admixtures could exhibit different results. As with all research, the results from this research are applicable to the materials, methods, and conditions used in this research. Although the results could be applicable to other materials, methods, and conditions, these will have to be assessed for those different materials, methods, and conditions.

The results from this research indicate that the current limits in time to discharge and drum revolutions are conservative. Because significant challenges can occur when concrete is placed and hardens and then does not meet specified properties, only SHAs can determine the appropriateness of these limit values. Environmental factors can influence the fresh characteristics of concrete mixtures, making these limit values less conservative. The current research found that limited correlations exist between time to discharge and hardened properties. This research also found limited correlations between drum revolution counts and hardened properties of concrete. Reductions in slump and workability were observed with extended mixing times and extended DRCs. Although these existing time and drum revolution limits currently in the specifications are easily measured, they could require that concrete of sufficient quality be rejected or discarded. An alternative approach for concrete acceptance could include slump and/or some other test that assesses castability. Although slump is an indicator of workability, it does not quantify all workability characteristics and may not always be a good indicator for castability. However, test methods to assess castability are not yet available and slump is the predominate measure of workability. Ultimately, the quality of the finished product will be the deciding factor of whether a concrete exhibited sufficient workability for the specific construction type. The current specifications are in place to proactively identify potential issues that could lead to an inferior or potentially unsafe product—determining that a concrete had insufficient workability and/or insufficient hardened properties after it has hardened in the structure provides limited, if any, value to the owner of the structure. Although conservative, the current limits should be used unless the contractor can clearly show that adequate workability and/or performance can be achieved with extended mixing times and/or high drum revolution counts.

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