AN ABSTRACT OF THE THESIS OF

Jiaming Chen for the degree of Master of Science in Civil Engineering presented on August 11, 2014

Title: Influence of Transport Parameters on the Fresh and Hardened Characteristics of Ready-mixed Concrete

Abstract approved:

David Trejo

Most specifications for ready-mix concrete (RMC) limit mixing time to 90 minutes and/or truck drum revolution counts (DRC) to 300 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, limited research has been performed to determine the validity of these limits. These limits could increase construction costs without increasing benefits. This is especially the case for concrete mixed for more than 300 truck DRCs and/or longer than 90 minutes that exhibits similar performance as those mixed for less than these limits. Because there have been significant changes in chemical admixtures and mixing equipment since these limits were first implemented in 1935, research is needed to assess whether these limits are still applicable. The objectives of this research program are to evaluate

whether existing specifications for mixing concrete are applicable for today's materials and equipment and if not, to identify key indicators that can be used for determining the acceptance of concrete mixtures. This study evaluated the influence of mixing time and truck DRC on fresh and hardened characteristics of concrete for several different concrete mixtures. Results from this research indicate that mixing time and truck DRC have no detrimental effects on the mechanical properties and durability characteristics when the mixtures exhibited good workability and castability. This research indicates that workability can be used as a key indicator for determining the acceptance of concrete and that time and truck DRC limits are not directly related to hardened concrete properties.

Influence of Transport Parameters on the Fresh and Hardened Characteristics of Ready-mix Concrete

by
Jiaming Chen

A THESIS

Submitted to

Oregon State University

In partial fulfillment of

the requirements for the

degree of

Master of Science

Presented August 11, 2014

Commencement June 2015

Master of Science thesis of Jiaming Chen presented on August 11, 2014.

APPROVED:

Major Professor, representing Civil Engineering

Interim Head of the School Civil, and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Jiaming Chen, Author

ACKNOWLEDGEMENTS

I would first like to thank my advisor Dr. David Trejo for taking me on as his graduate research assistant. Not only has he provided continuous guidance throughout my project, he has also provided me with career advice and taught me life lessons. I would like to thank Dr. Burkan Isgor, Dr. Chris Bell and Dr. Jack Higginbotham for being on my thesis committee.

I would also like to thank my parents, sister, and girlfriend for all of their love and support, without them I would not be in my current position and I would not be the person I am today.

Thank you to Washington State Department of Transportation (WSDOT) for providing this great research opportunity and funding this project.

As with all projects, the success of the project is dependent on many dedicated people. I would like to thank Tim Link, Manfred Dittrich, James Batti, Dana Ainsworth, Lapyote Prasittisopin, Chris Gaunt, Frank Porter, and Cody Tibbits. Special thanks to those that donated materials for this project. These companies include Lafarge, Wapenish Sand & Gravel, Cal Portland, Central Pre-Mix Concrete, Atlas Sand & Rock, Northwest Rock Inc., Miles Sand and Gravel, Van Boven Gravel Co., Maier's Enterprises, Spokane Rock Product, Cadman Inc., CEMEX, Knife River, WSDOT, Grace Construction products and BASF Construction Chemicals LLC. I am appreciative of their support. I sincerely thank all those that assisted with this project.

CONTRIBUTION OF AUTHORS

Dr. David Trejo is the principal investigator of this research project and is co-author of both manuscripts presented in this thesis.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

Figure Page

LIST OF FIGURES (Continued)

LIST OF TABLES

Chapter 1 INTRODUCTION

RMC is used for many infrastructure systems and the advantages of using RMC are significant. Historical and existing specifications place limits on the mixing time and truck drum revolution counts. However, these limits are based on general assumptions using materials seldom used in today's concrete (e.g., chemical admixtures) and were developed when less efficient mixing equipment was used to produce the concrete. Although significant improvements in equipment and admixture technology have occurred, the mixing time and the truck DRC limits still exist in many specifications. The value of these limits is unknown. The objectives of this study are to assess the influence of mixing time and truck DRC on concrete characteristics. The applicability of the current limits will be assessed. If it is determined that these limits are not applicable, the research will identify key indicators for determining the acceptance of RMC. If limits are applicable, the limits will be identified.

This thesis includes the results from a comprehensive study on the influence of mixing time and DRC (both experiences are tested with a laboratory mixer and truck mixer) on the fresh and hardened concrete characteristics. The first manuscript (Chapter 2) contains the evaluation for the influence of mixing time on the fresh and hardened concrete characteristics. The second manuscript evaluates the influence of DRC on the fresh and hardened concrete characteristics and these are presented in chapter 3.

Chapter 2 INFLUENCE OF MIXING TIME ON FRESH AND HARDENED CONCRETE CHARACTERISTICS

Submitted June 12, 2014

ACI Materials Journal

American Concrete Institute

38800 Country Club Dr.

Farmington Hills, MI 48331

2.1 ABSTRACT

Most specifications for RMC limit the time of mixing to 90 minutes 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, limited research has been performed to determine the validity of these limits. Because there have been significant changes in the concrete industry since these limits were first implemented by ASTM in 1935, research is needed to determine if these limits are still applicable. Approximately 1450 and 550 specimens were assessed for the various tests during the laboratory and field study, respectively. Results from this research indicate that extended mixing times (longer than current specification) have no detrimental effects on the mechanical properties and durability characteristics of concrete as long as the concrete exhibits adequate workability to be properly casted. Results also indicate that different mixtures exhibit a wide range of slump and slump loss values and the 90-minute discharge limit could not be validated in this research.

Keywords: mixing time; extended mixing; workability; compressive strength; tensile strength; modulus of elasticity; modulus of rupture; diffusivity; freeze-thaw

2.2 INTRODUCTION AND BACKGROUND

The American Society for Testing and Materials (ASTM) published the first ASTM C94, *Standard Specification for Ready Mixed Concrete*, in 1935. This standard specification required that RMC be discharged within 90 minutes after the introduction of water to the cement or after cement is introduced to moist aggregate.

Although significant improvements in mixing equipment, cement production, and admixture technology have occurred since this specification was first implemented, the justification of this time limit has not been recently assessed. Trejo and Prasittisopin (2014) reported that 50 SHA place limits on time to discharge. Even though many organizations and state highway agencies (SHA) use this limit from the first ASTM specification as a general baseline for limiting the time to discharge, there is a lack of data supporting the validity and value of this time limit. The objective of this study is to evaluate whether the 90-minute limit can be justified with research data, and if not, to identify variables or tests that can be used as indicators for acceptance of RMC.

RMC can be subjected to continuous mixing and/or agitation during its transport from the ready-mix plant to construction sites. Even though many specifications limit the time to discharge (referred to herein as mixing time) to no longer than 90 minutes, many construction projects require longer times. This can be a result of long transport distances, traffic, and delays in construction. Concrete workability is expected to decrease with time as a result of the cement hydration process. Low workability can result in difficult placements and may result in increased voids and honeycombing of the concrete. These conditions could reduce the mechanical and durability characteristics of the concrete. The effects of mixing time on concrete characteristics have been a topic of discussion and research for some time but only limited research are available on the influence of mixing time on concrete characteristics (Beaufait and Hoadle 1973, Ravina 1975, Beitzel 1981).

Beaufait and Hoadle (1973) studied mixtures that were agitated for up to 3.75 hours. The authors reported that extended periods of agitation do not adversely affect the compressive strength of concrete while the concrete is still placeable. Beitzel (1981) studied the influence of mixing time on the quality of the concrete and concluded that different concrete properties require different optimum mixing times. The author also reported that there should be an upper and lower limit on the mixing times for concrete to optimize properties.

Ravina (1975) reported that prolonged mixing can induce stiffening and slump loss, and slump loss can result in challenges with discharging, handling, and placing. The author also reported that ASTM Type A and D admixtures (from 1975) accelerated the slump loss. Since this publication, significant changes have occurred in admixture technology and newer generations of admixtures likely exhibit different results. Nehdi and Al-Martini (2009) investigated the coupled effect of prolonged agitation time and high temperature on mixtures containing three different types of water reducing admixtures (WRA). All three mixtures showed significantly lower slump losses with increased WRA dosages. High temperature was reported to accelerated slump loss.

Ravina (1996) evaluated the compressive strength of mixtures containing fly ash, WRA, and retarders when mixed up to 180 minutes. The author reported that for agitation times up to 135 minutes that compressive strength increased linearly for all three mixtures but at different rates. The author also reported minimal strength increases for concrete mixed between 135 to 180 minutes and reported some mixtures exhibited decreases in measured compressive strength (f'cm).

Kırca et al. (2002) also studied the effects of agitation time (up to 4 hours) on the compressive strength of concrete. The authors reported that concrete compressive strengths increased with increased mixing times. The authors hypothesized that the strength gain was a result of the loss of water due to evaporation, which led to a decrease in water to cement ratio (w/c). The authors also hypothesized that the increase in strength was a result of grinding of the cement particles which resulted in finer cement grains and more hydration.

The literature indicates that agitation and mixing concrete for longer mixing times can result in increased compressive strengths. Increased compressive strengths could result in improvements of other mechanical properties. However, research also shows that workability decreases with time. ACI 211.1 recommends minimum slump values for different types of construction and ACI 318 states that mixture proportions should “provide workability and consistency to permit concrete to be worked readily into forms and around reinforcement.” Clearly, some minimum workability is required for most concrete placements. However, placing limits on concrete mixing time can present challenges to users, especially when longer transport distances are required. According to Lobo and Gaynor (2006), time limits were established long ago when mixers had only one low mixing speed. Since the 90-minute time limit was established, significant changes have occurred in the concrete industry. The changes include the use of synthetic chemical admixtures, different cement production process, and more advanced mixing equipment. Yet specifications in many SHAs, as well as ASTM, the American Association of State Highway Transportation Officials (AASHTO), and the American Concrete Institute (ACI) still limit the time to discharge (ACI C09 Committee 2013-13b, AASHTO 2013, and ACI 304 Committee 2000). Current time to discharge limits may need to be modified based on current conditions and technology in the concrete industry. This research investigates the validity of discharge time limits.

2.3 RESEARCH SIGNIFICANCE

Despite many advances in the concrete industry, current specifications on mixing time limits for RMC have been in place without change since 1935. Limited research has been performed to assess how mixing time influences the performance of more modern concrete and research is needed to assess whether the original time limits in ASTM C94 and in many specifications are still applicable. This research investigates the influence of mixing time on the characteristics for laboratory- and field-mixed concrete. Specifications that impose restrictions without valid justification can decrease the economic viability of RMC.

2.4 MATERIALS AND EXPERIMENTAL PROGRAM

Eleven coarse aggregates (CA) were identified and selected for use in the concrete mixtures. These were selected to represent a wide range of concretes currently used and selection of these aggregates was based on the aggregate characteristics. All CA are from the State of Washington. The specific gravity (SG) of the aggregates ranged from 2.58 to 2.82 and the absorption values ranged from 0.6% to 3.3%. Of the 11 CA, one met #56 grading, seven met #57 grading, and three met #67 grading limits (ASTM C33). All aggregates are approved by the Washington State Department of Transportation (WSDOT) for use as aggregate in RMC. More details on the aggregates can be found in Trejo and Chen (2014). Type I/II ordinary portland cement, Class F fly ash, and slag were obtained from Lafarge North America (Centralia, WA). The chemical compositions of the materials are shown in Table 2.1. Three types of chemical admixtures (WRA, retarder, and air entraining agent [AEA]) were used in these mixtures. The WRA and retarders met ASTM C494, *Standard Specification for Chemical Admixtures for Concrete*, Type A, B, and D requirements and the AEA met ASTM C260, *Standard Specification for Air-Entraining Admixture for Concrete* requirements.

This research consisted of a laboratory study and a field study. The laboratory study assessed the fresh and hardened concrete characteristics of several different mixtures mixed for different times at different mixing speeds using a laboratory rotary concrete mixer (6 ft^3 [0.17 m^3]). The mixer is a tilting drum mixer with three blades fixed onto the inside wall of the drum. The mixer was modified with a variable speed motor such that the mixing speed could be changed and controlled. Fresh concrete characteristics were assessed and specimens were cast after predetermined mixing times until the concrete was no longer workable. The laboratory experimental program is shown in

Table 2.2. The mixture groups consisted of three general classifications: control, mixtures containing SCM (SCM_L), and mixtures containing chemical admixtures. The "L" subscript indicates laboratory-made specimens. The chemical admixture group consisted of a subgroup that contained recommended amounts of admixture ($AD_{R,L}$) and a subgroup that contained high amounts of chemical admixture ($AD_{H,L}$). The $AD_{R,L}$ group consists of mixtures containing WRA (W_L), AEA (A_L), and retarder ($R_{R,L}$). The subscripts "R" represent recommended dosage and the subscripts "H" represent high dosage. The $AD_{H,L}$ group consists of subgroups containing retarder ($RA_{H,L}$) and a combination of retarder and AEA ($RA_{H,L}$). In addition to the experimental plan shown in

Table 2.2, three mixtures (groups $R_{H,L}$ and $RA_{H,L}$ in

Table 2.2) were also evaluated for the modulus of elasticity (MOE), modulus of ruptures (MOR), and splitting tensile strength (STS). Also, the freeze thaw performance of two mixtures containing AEA and two mixtures without AEA were assessed (A_L and C_L subgroup).

The laboratory mixtures were proportioned using ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete*. The absolute volume method was used. The design strength (f'c) of the laboratory mixtures was 5200 psi (35.9 MPa) (w/c = 0.46) and the target slump was 4 inches (101 mm). Because the mixtures contained different constituent materials, the amount of the paste content was adjusted to target the 4-inch (101 mm) slump. General mixture proportions for the laboratory mixtures are shown in Table 3.3. These mixtures were mixed following the ASTM C192-13a, *Standard Practice for Making and Curing concrete Test Specimens in the Laboratory*. After the standard mixing process, the mixtures were further mixed at mixing speeds of 8 or 15 rpm up to the mixing times shown in

Table 2.2.

The field study evaluated two mixtures: a control concrete mixture (C_F) and a concrete with the same mixture proportions but containing a retarder (R_F). The "F" subscript indicates these are field-mixed mixtures. The target slump was 4 inches (101 mm) and the f'c was 4500 psi (31.0 MPa). Mixture proportions were provided by a RMC plant in the State of Washington. The proportions contain 3160 lb/cy (1875 kg/m^3) of aggregate (FA/CA = 0.71), 611 lb/cy (362 kg/m^3) of cement, and a w/c of 0.44.

Six mixtures were mixed and cast over a three day period. On the first day the C_F and R_F mixtures were mixed at 4 rpm. The C_F mixtures mixed at 8 and 15 rpm were cast on the second day and the R_F mixtures mixed at 8 and 15 rpm were cast on the third day. Each mixture was first mixed in a central mixer and then loaded onto a concrete truck mixer for longer mixing. These mixtures were mixed at 4 and 8 rpm for up to 120 minutes and at 15 rpm for up to 90 minutes in the truck mixer. Samples were taken at predetermined times and fresh and hardened concrete characteristics were samples and assessed. Due to space limitation and because similar results were observed with the 8 and 15 rpm mixtures from the field study, results from the mixtures mixed at 15 rpm will not be shown here. These results can be found in Trejo and Chen (2014). Table 2.4 shows the experimental plan for the field study.

2.5 TEST RESULTS AND ANALYSIS—LABORATORY STUDY

This section first provides results on the fresh concrete characteristics for the laboratory mixed concrete. Fresh concrete characteristics include the air content and slump. The analysis of fresh characteristics is followed by results on the mechanical properties and the durability performance of the concrete mixtures mixed for different times. The mechanical properties assessed include f'cm, MOE, MOR, and STS. The durability characteristics include the freeze-thaw performance and the apparent chloride diffusivity (D_a).

Concrete characteristics were compared using statistical measures. The student t-test and ANOVA test were used to compare the means of the concrete characteristics mixed for different times. The student t-test was used to compare the means of two groups and the ANOVA test was used to compare the mean values of three groups or more. The null hypotheses of both tests are that the mean values are equal. The alternative hypothesis for the t-test is that the means are not equal. The alternative hypothesis for the ANOVA test is that at least one of mean values is significantly different. The end result of these tests is a p-value. The p-value is a single number that summarizes the statistical test outcome and indicates how much evidence there is to accept or reject the hypothesis at a certain confidence level. For a 95 percent confidence level (As used in the assessments in this paper), the null hypothesis will be accepted if the p-value is greater than or equal to 0.05; otherwise the null hypothesis is rejected.

2.5.1 Fresh Concrete Characteristics of Laboratory Mixtures

Results for the air content of fresh concrete indicate that there is not a statistically significant difference in the means of the entrapped air content for the non-AEA mixtures mixed for 5, 15, and 60 minutes and mixed at 8 and 15 rpm. However, the mixtures mixed for 180 minutes at 8 rpm exhibited a small increase in entrapped air content. Also the air content of the mixtures mixed at 15 rpm for 180 minutes exhibited higher scatter than those mixed for shorter times. The increase in air content at longer mixing times and higher mixing speeds for mixtures without AEA seem to be related to the workability of these mixtures; stiff mixtures with lower workability exhibited higher entrapped air contents. Mixtures containing AEA exhibited a significant reduction in entrained air content when mixed at 8 and 15 rpm for 180 minutes.

Slump values decreased as a function of mixing time and mixing speed for all groups tested. Higher mixing speeds accelerated slump loss. The slump loss was different for the four groups. Models for the slump as a function of mixing time were first generated for each mixture group mixed at 8 and at 15 rpm. Models for the same group were then combined to become a function of mixing time and mixing speed. Because initial slump values varied, models are based on normalized slump values. Normalized slump is the measured slump at some time divided by the initial slump (initial slump is defined as the measured slump after 5 minutes of mixing). To distinguish between mixture groups, the normalized slump (*n-slump*) is followed by a subscript; these subscripts represent the mixture group (defined earlier).

Test results indicate that the *n-slump* for the $\text{Control}_{\text{L}}$, SCM_{L}, $\text{AD}_{\text{R,L}}$, and $\text{AD}_{\text{H,L}}$ mixture groups can be estimated as follows:

$$n\text{-}slump_{Control_L}(t,r) = -5.7\times10^{-6}\times(rt^2 + 6.7t^2 - 175,000) \quad (2\text{-}1)$$

$$n\text{-}slump_{SCM_L}(t,r) = -5.3\times10^{-6}(rt^2 - 14.7t^2 - 189,200) \quad (2\text{-}2)$$

$$n\text{-}slump_{AD_{R,L}}(t,r) = (2.4 - 0.09r)e^{(0\ 024 - 0\ 0039r)t} + 0.10r - 1.4 \quad (2\text{-}3)$$

$$n\text{-}slump_{AD_{H,L}}(t,r) = -2.0\times10^{-4}\times(rt + 18.2t - 5200) \quad (2\text{-}4)$$

where t is the time of mixing (minutes) and r is the laboratory mixer speed (rpm). Equation 2-1 is based on data from mixing times (t) between 5 and 90 minutes; equations 2-2 and 2-4 are based on data from mixing times between 5 and 60 minutes, and equation 2-3 is based on data from mixing times between 5 and 180 minutes. Mixing rates were 8 and 15 rpm. These equations can be used to estimate the slump at some time, t, as follows:

$$slump = n\text{-}slump(t,r)\times slump_{initial} \quad (2\text{-}5)$$

Figure 2.1 shows the n-slump models for the different groups. Note that at a mixing time of 90 minutes, the n-slump values varied from 0 to 0.65. Note also that if an n-slump value of 0.25 is required, the allowable mixing times vary from approximately 70 to 150 minutes. Although n-slump is a function of time and speed for the individual mixture group, n-slump does not seem to have a significant correlation amongst the different mixtures. The slump and slump loss exhibit significant variation between mixtures.

2.5.2 Harden Properties for Laboratory Mixtures

The laboratory mixed concrete was assessed for f'c, MOR, MOE, STS, D_a, and freeze-thaw performance. This section presents the results on the effects of mixing time on these characteristics. All mixtures were mixed at 8 and 15 rpm. At laboratory mixing speeds of 8 rpm, results indicate that mixing time has no negative influence on the measured 28-day compressive strength ($f'cm_{28}$) up to 180 minutes of mixing. However, at 15 rpm, the $f'cm_{28}$ exhibited large scatter when mixed for 120 minutes. This mixture also exhibited an 80 percent loss in $f'cm_{28}$ when mixed for 180 minutes. Figure 2.2 shows a box plot for the $f'cm_{28}$ at different mixing times and different mixing speeds. The large scatter and reduction in strength is a result of poor consolidation and honeycombing in the specimens. It should be noted that when mixtures exhibited good workability, all mixtures without SCM met the f'c at 28 days. When the SCM_L mixtures exhibited good workability, all mixtures met the f'c at 56 days. Delays in strength gain are common for mixtures containing SCMs (Bouzoubaâ et al. 2000; Barnett et al. 2006).

The MOE, MOR and STS were assessed for the $R_{H,L}$, and $RA_{H,L}$ subgroups. These two mixtures are analyzed separately. For each assessment, evaluation for the $R_{H,L}$

mixtures is shown first. Note that the w/c was not adjusted to for the mixtures containing AEA and as such, theses mixtures exhibited lower compressive strengths.

Figure 2.3 shows the MOE as a function of mixing time and mixing speed for the $R_{H,L}$ and $RA_{H,L}$ mixtures. An ANOVA analysis for the $R_{H,L}$ mixtures indicates that there is no statistically significant difference between the mean MOE values of the $R_{H,L}$ mixtures mixed for up to 180 minutes at 8 rpm (p-value = 0.122). However, at a mixing speed of 15 rpm the $R_{H,L}$ mixtures exhibited a significant reduction in mean MOE when mixed to 180 minutes (p-value < 0.001). The mixtures mixed for longer times at faster mixing speeds exhibited low slump values and low workability which resulted in honeycombing in the specimens. Specimens containing honeycombing exhibited lower MOE values. When mixtures exhibited sufficient workability, the MOE values were not significantly affected, even after prolonged mixing times.

For the $RA_{H,L}$ mixtures, ANOVA testing indicates that these mixtures mixed at different mixing times exhibited statistically significant differences in the mean MOE values when mixed at 8 rpm (p-value < 0.001). However, the MOE values for mixtures mixed for longer mixing times were higher than the mixtures mixed for shorter times. Data indicates that longer mixing times does not negatively impact concrete when mixed at 8 rpm. When mixed at 15 rpm, t-tests indicate that there is no statistically significant difference between the mean MOE of the $RA_{H,L}$ mixture mixed at 15 and 180 minutes (p-value = 0.919). The reason for the reduction in the MOE for the $R_{H,L}$ mixtures mixed at 15 rpm for 180 minutes is a result of the mixture exhibiting low slump (0 inch [0 mm]) and workability. Also, at a mixing time of 180 minutes, the measured slump of the $R_{H,L}$, $RA_{H,L}$ at 8 rpm, and the $RA_{H,L}$ at 15 rpm was 1.12, 0.25, and 1.0 inches (28, 6 and 25 mm). These provided sufficient workability for properly casting the test specimens.

The potential influence of mixing time on MOR was also assessed for the $R_{H,L}$ and $RA_{H,L}$ mixtures. The MOR values as a function of mixing time and speed for these mixtures are shown in Figure 2.4. An ANOVA analysis indicates mixing times up to 180 minutes at 8 rpm had no statistical influence on the mean MOR values of the $R_{H,L}$ mixtures (p-value = 0.839). However, when mixed at 15 rpm, the MOR values of the $R_{H,L}$ mixtures mixed for different time up to 180 exhibited a statistically significant difference in the mean MOR values (p-value = 0.001). These values were lower than the MOR values determined from ACI (ACI 318 9.5.2.3) based the f'c. Note that these mixtures mixed at 15 rpm for 180 minutes exhibited significantly lower workability (the slump value was zero) and exhibited significant honeycombing. The honeycombing likely resulted in lower MOR values. Similar findings were observed for the $RA_{H,L}$ mixtures (p-value = 0.178 and 0.018 for the mixtures mixed at 8 rpm and 15 rpm, respectively).

Figure 2.5 shows a box plot for the STS values of the $R_{H,L}$ and $RA_{H,L}$ mixtures. STS results from the laboratory study indicate that the $R_{R,L}$ mixtures mixed for 180 minutes at 8 rpm exhibited no statistically significant difference in the mean STS values (P-value = 0.468). However, the mean values were statistically significantly different when mixed to 180 minutes at 15 rpm (P-value = 0.001). This mixture exhibited low workability and castability which resulted in honeycombing in the specimens. Specimens containing honeycombing exhibited lower STS values than those exhibited no honeycombing. For the $RA_{H,L}$ mixtures, ANOVA testing indicates that there is also no statistically significant difference between the mean MOR values of the $RA_{H,L}$ mixtures mixed for different times up to 180 minutes and different speeds up to 8 and15 rpm (P-value = 0.504 and 0.645 respectively).

Figure 2.6 shows the D_a for the $Control_L$, $SCM_{L,}$ and $AD_{R,L}$ groups. The mean D_a coefficient values for these mixture groups mixed for 15 and 60 minutes at different mixing speeds were compared using t-tests. The test results indicate that for each group, there is no statistical difference between the mean D_a values of these mixtures mixed for different times at 8 rpm. P-values were 0.199, 0.689, and 0.720 for the $Control_L$, SCM_L, and $AD_{R,L}$ group, respectively. When these mixtures mixed at 15 rpm, there is no statistically significant difference between the mean D_a values of these mixtures mixed for different time (p-values = 0.514, 0.998, and 0.335 for the $Control_L$, SCM_L, and $AD_{R,L}$ group, respectively).

Two mixtures from the $Control_L$ and A_L groups were tested for freeze-thaw performance. For the A_L group mixtures, the relative dynamic modulus does not significantly differ up to 300 freeze thaw cycles for mixtures mixed for different mixing time up to 60 minutes. For mixtures without AEA, the relative dynamic modulus of the mixture mixed for 15 and 60 minutes decreased to 60 percent of the initial value (i.e., defined as failure by ASTM C666) before the 300 cycles. However, these specimens failed at approximately the same number of cycles regardless of mixing time (15 or 60 minutes). This indicates that mixing time likely does not influence freeze-thaw performance of laboratory mixed concrete.

2.6 TEST RESULTS AND ANALYSIS—FIELD STUDY

2.6.1 Fresh Concrete Characteristics for Field Mixtures

The entrapped air contents for the field concrete ranged from 1.6 to 3.1 percent. The results from the field study indicate that there is no significant difference between the mean entrapped air content of mixtures mixed at different mixing time up to 120 minutes. The maximum change in entrapped air content as a function of time in these mixtures was a 1.2 percent increase. These variations in entrapped air content are considered to be insignificant.

Similar to the laboratory study, slump values were significantly influenced by mixing time, as would be expected for the cement-based system. Models for the normalized slump values are generated for the C_F and R_F mixtures. These are shown in Figure 2.7.

The laboratory model for n-slump ($n\text{-}slump_{Control_L}(t)$) exhibited a low initial slump loss rate followed by a continuously increasing slump loss. However, the model for the field mixtures exhibited a high initial rate of slump loss followed by a continuous decrease in rate of slump loss. These differences are likely a function of mixing energy. American Petroleum Institute (2002), reported that rheology, thickening time, fluid loss, and compressive strength of cementitious systems are related to specific mixing energy. The smaller laboratory concrete mixer used in this research likely input less energy into the concrete mixtures when compared to the truck mixer. The slower initial slump loss rate in the laboratory model is likely a result of the lower energy input from the laboratory mixer. In addition, mixtures in the field were first mixed in a central mixer, where the input mixing energy is much greater than the mixing energy from a truck mixer. The high initial slump loss rate is likely a result of the higher mixing energy from both the central mixer and the truck mixer (when compared to the laboratory mixer). Also, the lower slump losses at the later mixing times could be a result of the truck mixer breaking the bonds of early hydration products. However, further research is needed to assess this.

Slump models as a function of mixing time were also generated for the field mixtures. The n-slump as a function of mixing time mixed at different mixing speeds for the C_F mixtures can be estimated as follows:

$$n\text{-}slump_{C_{F,4}}(t) = -44.5 + 45.5 \times e^{-0\ 000159t} \tag{2-6}$$

$$n\text{-}slump_{C_{F,8}}(t) = -0.46 + 1.54 \times e^{-0\ 010t} \tag{2-7}$$

$$n\text{-}slump_{C_{F,15}}(t) = -0.19 + 1.33 \times e^{-0\ 022t} \tag{2-8}$$

where t is the time of mixing (minutes). Equations 2-6 and 2-7 are based on data for mixing time between 5 and 120 minutes and equation 2-8 is based on data for mixing times between 5 and 90 minutes. The R^2 value for each of these three models is 99 percent.

The n-slump as a function of mixing time for field mixtures containing retarders mixed at different speeds can be estimated as the follows:

$$n\text{-}slump_{R_4}(t) = 0.053 + 1.10 \times e^{-0\ 021t} \tag{2-9}$$

$$n\text{-}slump_{R_8}(t) = 0.033 + 1.01 \times e^{-0\ 026t} \tag{2-10}$$

$$n\text{-}slump_{R_{15}}(t) = 0.0013 + 1.123 \times e^{-0.041t} \tag{2-11}$$

The R^2 values for the models are 99, 94, and 99 percent for the R_4, R_8, and R_{15} model, respectively. Equations 2-9 and 2-10 are based on data from mixing time between 5 and 120 minutes, and equation 2-11 is based on data from mixing times between 5 and 90 minutes.

2.6.2 Hardened Properties for Field Mixtures

Figure 2.8 shows the 28-day f'cm for the C_F and R_F mixtures. Results indicate that longer mixing time can significantly influence the f'cm of C_F mixtures, especially at higher mixing speeds. ANOVA testing indicates that there is no statistically significant difference between the mean f'cm$_{28}$ of the C_F mixtures mixed for difference mixing time and mixed 8 rpm (p-value = 0.683). However, when these mixtures were mixed at 15 rpm, ANOVA testing indicates that there is a statistically significant difference in the mean f'cm$_{28}$ of the C_F mixtures mixed for up to 120 minutes and mixed at 15 rpm (p-value < 0.001). For R_F mixtures, even though ANOVA testing indicate that there is a statistically significant difference between the mean f'cm$_{28}$ of the R_F mixtures mixed for different times at 8 rpm and 15 rpm (p-value = 0.020 and 0.061, respectively), the f'cm$_{28}$ values increased.

The research and resulting models show that workability is significantly influenced by mixing time and lack of workability can result in inadequate consolidation and honeycombing. This honeycombing resulted in low compressive strengths of the C_F mixtures. However, when a retarder is used, improved workability and slightly higher slump values were observed. Although small, this higher slump for the R_F mixtures provided sufficient workability up to a mixing time of 120 minutes when mixed at 4 and 8 rpm and the f'cm values were not significantly influenced. Results indicate that instead of time limits, workability and castability, which may be measured by slump, may be a better indicator of whether a concrete mixture is acceptable for discharge and placement. The 90-minute limit may be applicable for the C_F mixtures but results indicate that the 90-minute mixing limit is likely not applicable for the R_F mixtures.

Figure 2.9 shows the MOE results for the C_F and R_F mixtures. The analyses of the influence of mixing time on MOE indicates that mixing time significantly influences the MOE of C_F mixtures when mixed for longer mixing times and at higher mixing speeds (p-value < 0.036)). Larger scatter of the MOE values was also observed for the C_F mixtures mixed to 120 minutes at 8 rpm and for mixtures mixed for 90 and 120 minutes at 15 rpm. This is believed to be a result of the reduction in workability and castability of the mixtures. Even so, the R_F mixtures exhibited no statistically significant difference in MOE values for mixtures mixed up to 120 minutes at both 4 and 8 rpm (p-value = 0.956 and 0.336, respectively). This finding is similar to that of the compressive strength analyses. These findings indicate that acceptance of concrete mixtures may be based on workability and placability rather than time of mixing.

The MOR values were also assessed for the field mixtures. Figure 2.10 shows these results. Results indicate that the C_F and R_F mixtures exhibited no statistically significant difference in the mean MOR of mixtures mixed at different mixing times up to 120 minutes when mixed at 4 rpm (p-value 0.066 and 0.088, respectively). For the 8 rpm mixtures, even though a significant difference between the mean MOR values for the C_F mixtures mixed at different mixing times was identified (p-value = 0.040), results indicate that mixing times up to 120 minutes do not have detrimentally affect MOR values. And there is no statistical significant difference in the mean MOR values for the R_F mixtures mixed for difference times (p-value = 0.083).

Figure 2.11 shows a box plot for the STS values. The ANOVA analyses of the C_F mixture data indicates that mixing times up to 90 minutes do not influence the mean STS value when mixed at 4 and 8 rpm (p-value = 0.193 and 0.077, respectively). However, when mixed for 120 minutes, the mixture exhibited low workability and castability, resulting in honeycombing in the specimens and a significant decrease in mean STS. For R_F mixtures, when mixed at 4 rpm, ANOVA testing indicates that there is no statistically significant difference in the mean STS value of the R_F mixture mixed for difference time up to 120 minutes (p-value =0.179). However, when the R_F mixtures were mixed at 8 rpm, there is a statistically significant difference between the mean STS values of these mixtures when mixed for 120 minutes (p-value = 0.047).

The D_a values for the field mixtures mixed for different mixing times and speeds were assessed. Significant increase in D_a could result in increased rates of chloride transport and reduced service life of reinforced concrete structures. Results are shown in Figure 2.12. The ANOVA tests indicate that, for both C_F and R_F mixtures, there is no statistically significant difference in the mean D_a values for mixtures mixed for different mixing times and mixing speeds (p-value = 0.169 and 0.243 for the C_F and $R_{F,}$ respectively).

2.7 SUMMARY AND CONCLUSIONS

Limits on time of mixing have been in specifications since 1935. The original intent of these limits was to ensure that concrete was properly placed and consolidated. Nearly 80 years have passed since the first ASTM C94 limit on mixing time was published and this limit is now ubiquitous throughout specifications in our industry—50 SHAs still limit the time to concrete placement. Yet significant changes have occurred in the concrete industry; newer admixtures are being used, some specifically designed to extend workability. The validity and applicability of the 90-minute mixing limit needs to be assessed.

This research investigated the influence of mixing time and drum revolution speed on the fresh and hardened characteristics of laboratory- and field-produced concrete. Results show a wide variation in slump loss values for the different mixtures. For the laboratory control mixtures the slump ranged from approximately 0 to 30% of the original slump after 90 minutes of mixing. For the field control mixtures the slump ranged from approximately 0 to 40% of the original slump values. Laboratory mixtures containing chemical admixtures exhibited lower slump loss values at 60 minutes than the control mixtures and these mixtures exhibited higher slump and better workability than the control mixtures. The mixtures containing higher dosages of admixtures exhibited higher slump values and better workability than the mixtures containing recommended dosages after extended mixing times. Slump requirements are published to ensure placeability and these vary depending on type of construction. Many of the mixtures evaluated exhibited sufficient workability to properly place and consolidate for many construction applications. Based on these findings, the current 90-minute placement limit is likely not a reliable indicator for determining time-to-placement limits based on concrete workability.

In addition to the fresh characteristics, the hardened properties were assessed for laboratory- and field-mixed concrete mixed for different mixing times. Results indicate that the f'cm, MOE, MOR, STS, and chloride diffusivity for the laboratory-mixed concrete exhibited no significant reduction in characteristics 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 reduction in concrete characteristics was related to low workability and specimens containing honeycombing. In addition to the laboratory results, the field-mixed concrete exhibited significant reductions in f'cm, MOE, and STS after 120 minutes of mixing for the control mixtures. Field mixtures containing chemical admixtures exhibited no reduction in concrete characteristics after 120 minutes of mixing with the exception of the STS; the STS decreased with increased mixing time.

Results from laboratory and field studies indicate that mixtures containing newer generations of admixtures can exhibit good workability even after prolonged mixing times and at higher mixing speeds. Concrete performance seems to be directly related to workability or more importantly, related to the ability to properly place and cast the concrete. Results indicate that the time-to-placement limit, in this case 90 minutes, is not be reliable indicator for properly placing and consolidating concrete such that the concrete can provide safe and durable long-term performance.

2.8 REFERENCES

AASHTO. 2013. "AASHTO M 157-11 Standard Specification for Ready-Mixed Concrete". AASHTO.

ACI 304 Committee. 2000. "Guide for Measuring, Mixing, Transporting, and Placing Concrete." *ACI Materials Journal*, January.

American Petroleum Institute. 2002. "API SPEC 10A Specification for Cements and Materials for Well Cementing." *American Petroleum Institute*.

Barnett, S. J., M. N. Soutsos, S. G. Millard, and J. H. Bungey. 2006. "Strength Development of Mortars Containing Ground Granulated Blast-Furnace Slag: Effect of Curing Temperature and Determination of Apparent Activation Energies." *Cement and Concrete Research* 36 (3): 434–40. doi:10.1016/j.cemconres.2005.11.002.

Beaufait, F, and P Hoadle. 1973. "Mix Time and Retempering Studies on Ready-Mixed Concrete." *Journal Proceedings* 70 (12): 810–13.

Beitzel, H. 1981. "Effect of the Mixing Time on the Quality of the Mixing." *Precast Concrete* 12 (9): 403–8.

Bouzoubaâ, N, M. H Zhang, and V. M Malhotra. 2000. "Laboratory-Produced High-Volume Fly Ash Blended Cements: Compressive Strength and Resistance to the Chloride-Ion Penetration of Concrete." *Cement and Concrete Research* 30 (7): 1037–46.

C09 Committee. 2013. "ASTM C94/C94M - 13b Standard Specification for Ready-Mixed Concrete." *ASTM International* 04.02.

Kırca, Ö, L Turanli, and T Erdoğan. 2002. "Effects of Retempering on Consistency and Compressive Strength of Concrete Subjected to Prolonged Mixing." *Cement and Concrete Research* 32 (3): 441–45.

Lobo, Cl, and Rd Gaynor. 2006. “Chapter 45: Ready-Mixed Concrete.” In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, edited by Jf Lamond and Jh Pielert, 533–533–15. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International. http://www.astm.org/doiLink.cgi?STP37763S.

Nehdi, M, and S Al-Martini. 2009. “Coupled Effects of High Temperature, Prolonged Mixing Time, and Chemical Admixtures on Rheology of Fresh Concrete.” *Materials Journal* 106 (3): 231–40.

Ravina, D. 1975. “Retempering of Prolonged-Mixed Concrete with Admixtures in Hot Weather.” *ACI Journal Proceedings* 72 (6): 291–95.

———. 1996. “Effect of Prolonged Mixing on Compressive Strength of Concrete with and without Fly Ash And/or Chemical Admixtures.” *Materials Journal* 93 (5): 451–56.

Trejo, D, and J Chen. 2014. “Influence of Transport Parameter on Concrete Characteristics”. Washington State Department of Transportation.

Trejo, D, and L Prasittisopin. 2014. “Effects of Mixing Variables on Early-Age Characteristics of PC Systems.” *Accepted for Publication ACI Material Journals*.

Vickers Jr., Thomas M., Stephen A. Farrington, Jeffrey R. Bury, and Lynn E. Brower. 2005. “Influence of Dispersant Structure and Mixing Speed on Concrete Slump Retention.” *Cement and Concrete Research* 35 (10): 1882–90.

2.9 TABLES AND FIGURES

2.9.1 List of Tables

2.9.2 List of Figures:

Figure 2.2 Laboratory twenty-eight day f'cm of non-AEA mixture versus mixing time.

Figure 2.3 Box plot for MOE for $AD_{H,L}$ mixtures.

Figure 2.4 Box plot for the MOR of $AD_{H,L}$ mixtures.

Figure 2.5 Box plot for the STS of $AD_{H.L}$ mixtures.

Figure 2.6 Box plot for diffusion coefficient for $Control_L$, SCM_L and $AD_{R,L}$ mixtures.

Figure 2.7 N-slump model for the field-mixed concrete.

Figure 2.8 Box plot for $f'cm_{28}$ for field mixtures mixed at 4 and 8 rpm.

Figure 2.9 MOE for field-mixed mixtures mixed for different times at 4 and 8 rpm.

Figure 2.10 Box plot for MOR for the field mixtures.

Figure 2.11 Splitting tensile strength for field-mixed mixtures mixed for different times at 4 and 8 rpm.

Figure 2.12 Box plot for chloride diffusion coefficient for field-mixed Concrete mixed at different mixing speeds.

Table 2.1 Chemical Proportions for Cementitious Materials

Chemical Composition	Percent weight		
	Cement	Class F Fly Ash	Slag
SiO_2	20.3	49.4	31.0
Al_2O_3	4.8	16.4	12.2
Fe_2O_3	3.5	6.20	0.8
MgO	0.7	4.60	4.8
SO_3	2.8	1.00	1.9
CaO	63.9	13.9	43.2

Table 2.2 Experimental Plan for Laboratory Study

Groups	Sub-group	CA Source	Mixing Time (min.)		SCM or Chemical Admixture	Tests			
			@ 8 rpm	@ 15 rpm		Air Content	Slump	f'cm	Chloride Diffusion**
Control	C_L	1-11	5, 15, 60 & 90†	15, 60 & 90†	None	✓	✓	✓	✓
SCM_L	FA_L	1	5, 15 & 60	15 & 60	Fly Ash (20% & 30%)*	✓	✓	✓	✓
	SL_L	1	5, 15 & 60	15 & 60	Slag (20% & 40%)*	✓	✓	✓	✓
$AD_{R,L}$	W_L	1	5, 15 & 60	15 & 60	WRA A & B	✓	✓	✓	✓
	A_L	1	5, 15 & 60	15 & 60	AEA A & B	✓	✓	✓	✓
	$R_{R,L}$	1	5, 15 & 60	15 & 60	Retarder A & B	✓	✓	✓	✓
$AD_{H,L}$	$R_{H,L}$	1	5, 15, 60, 90 & 180	5, 15, 60, 90 & 180	Retarder B & C	✓	✓	✓	Not tested.
	$RA_{H,L}$	1	5, 15, 60, 90 & 180	5, 15, 60, 90 & 180	Retarder B & AEA B	✓	✓	✓	Not tested

A B & C: manufactures, * percent replacement by weight; ** only selected mixing time is assessed
†: only assessed for mixtures containing CA source 1.

Table 2.3 General Mixture Proportions for Laboratory Mixtures

Subgroups	CA lb/cy (kg/m^3)	FA lb/cy (kg/m^3)	Cement lb/cy (kg/m^3)	Water lb/cy (kg/m^3)	SCM lb/cy (kg/m^3)	Admixture
C_L	1542-1752 (915-1039)	1070-1297 (635-769)	647-739 (384-438)	298-340 (177-202)	0	0
W_L, $R_{R,L}$, $R_{H,L}$, $RA_{H,L}$	1730 (1026)	1200-1306 (712-775)	623-674 (370-400)	286-315 (170-186)	0	WRA & Retarder
FA_L, SL_L	1735 (1029)	1163-1307 (690-775)	396-539 (235-319)	260-313 (154-186)	117-202 (69-120)	0
A_L	1730 (1026)	1204-1324 (714-785)	609-674 (361-399)	280-314 (166-186)	0	AEA

Table 2.4 Experimental Plan for Field Study

Mixture ID	Test Parameters						
	Air Content	Slump	f'cm	STS	MOE	MOR	Chloride Diffusivity*
C_F	✓	✓	✓	✓	✓	✓	✓
R_F	✓	✓	✓	✓	✓	✓	✓

*only selected mixing time is assessed

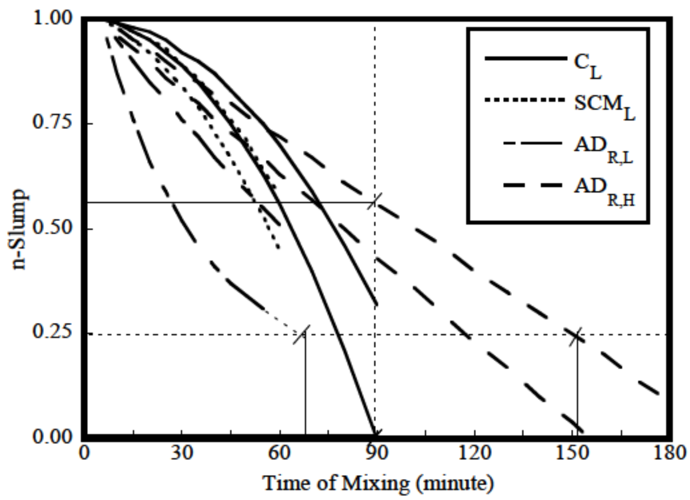

Figure 2.1 N-slump model for all laboratory concrete groups.

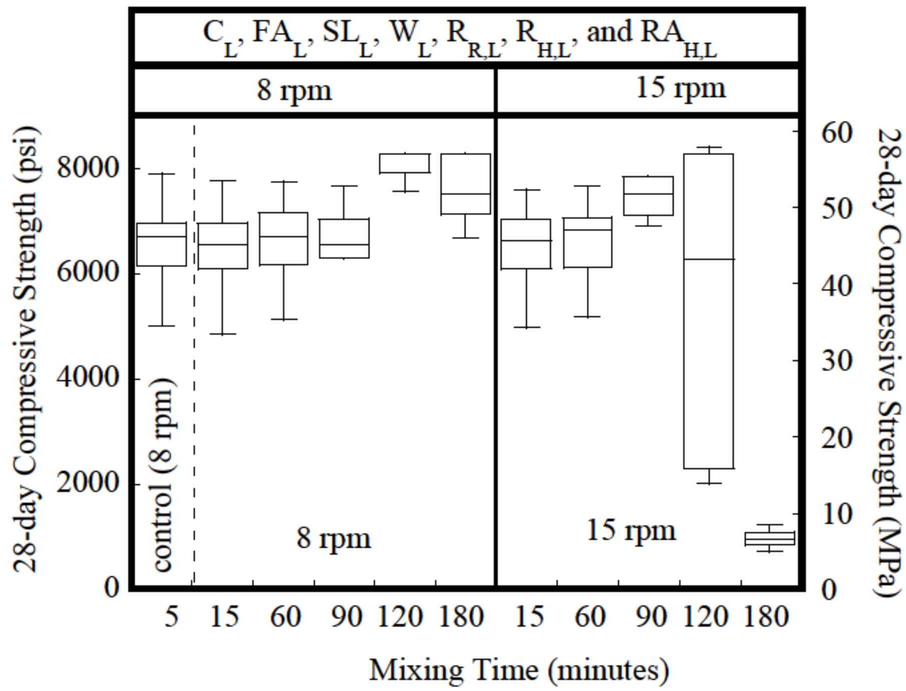

Figure 2.2 Laboratory twenty-eight day f'cm of non-AEA mixture versus mixing time.

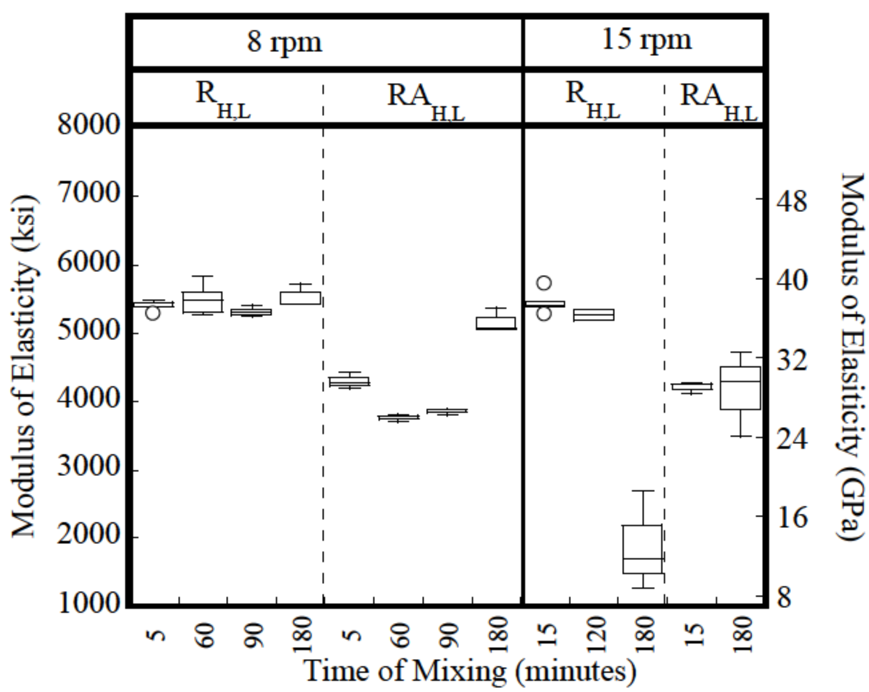

Figure 2.3 Box plot for MOE for $AD_{H,L}$ mixtures.

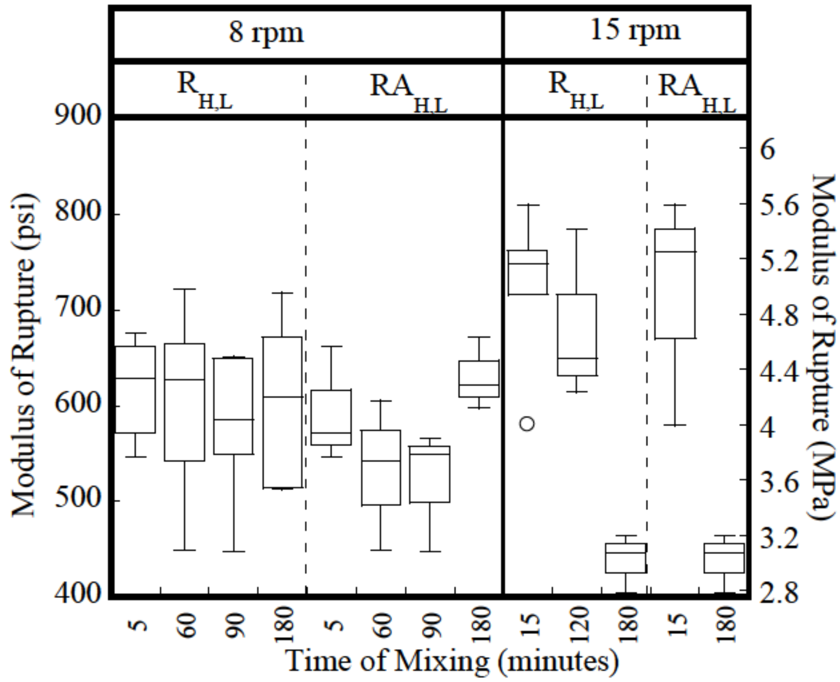

Figure 2.4 Box plot for the MOR of $AD_{H,L}$ mixtures.

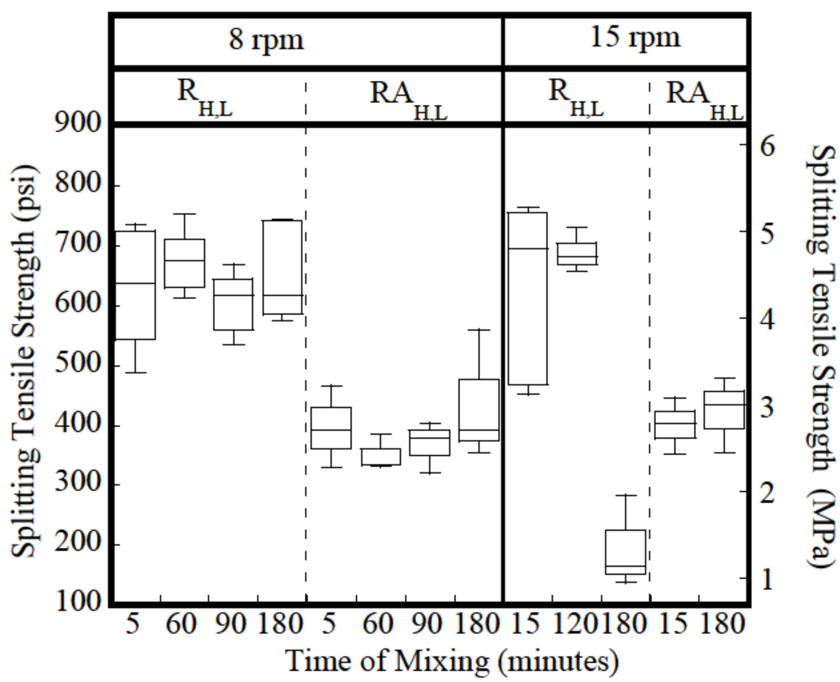

Figure 2.5 Box plot for the STS of $AD_{H.L}$ mixtures.

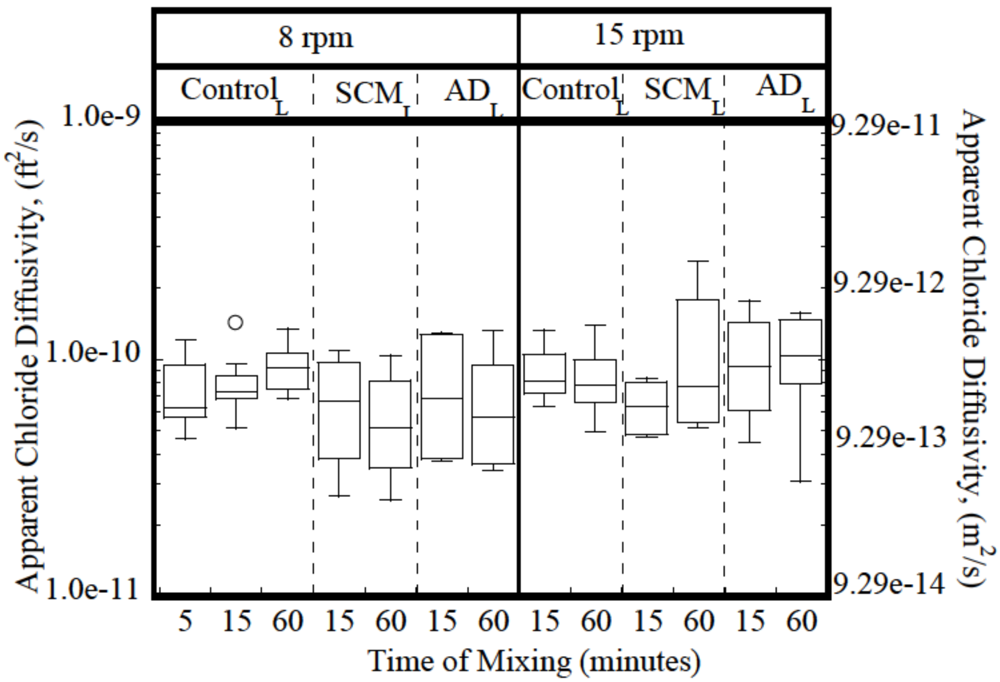

Figure 2.6 Box plot for diffusion coefficient for Control$_L$, SCM$_L$ and AD$_{R,L}$ mixtures.

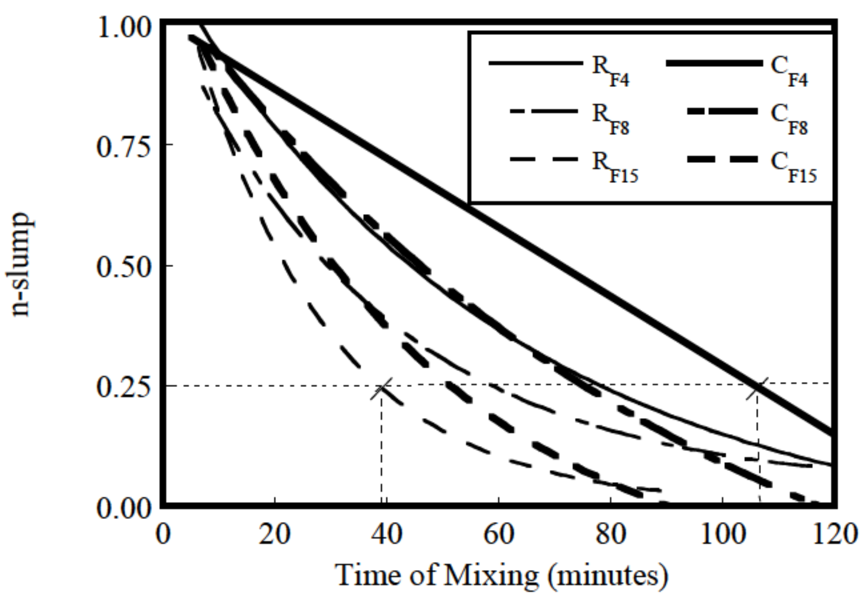

Figure 2.7 N-slump model for the field-mixed concrete.

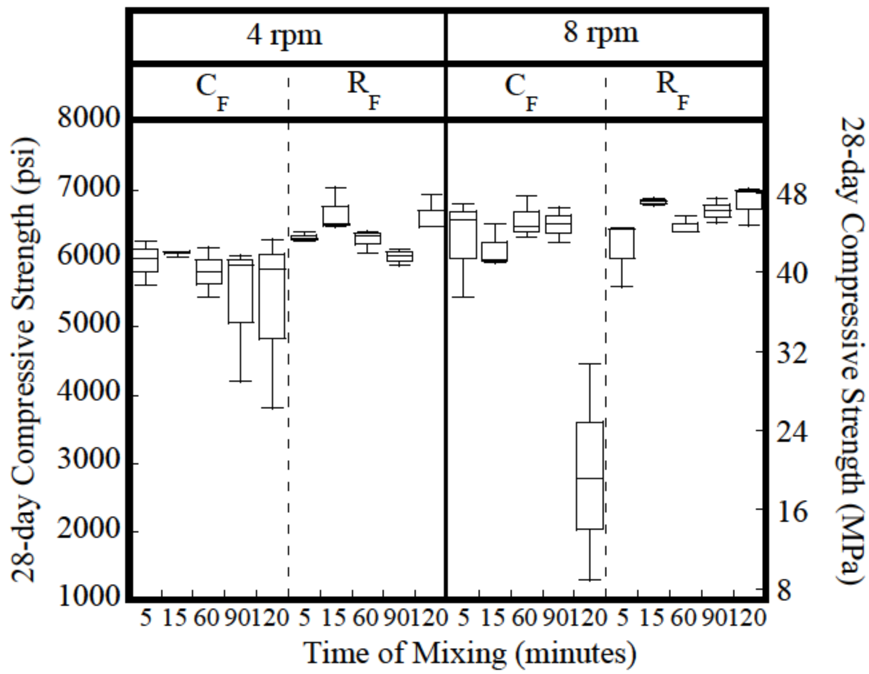

Figure 2.8 Box plot for f'cm$_{28}$ for field mixtures mixed at 4 and 8 rpm.

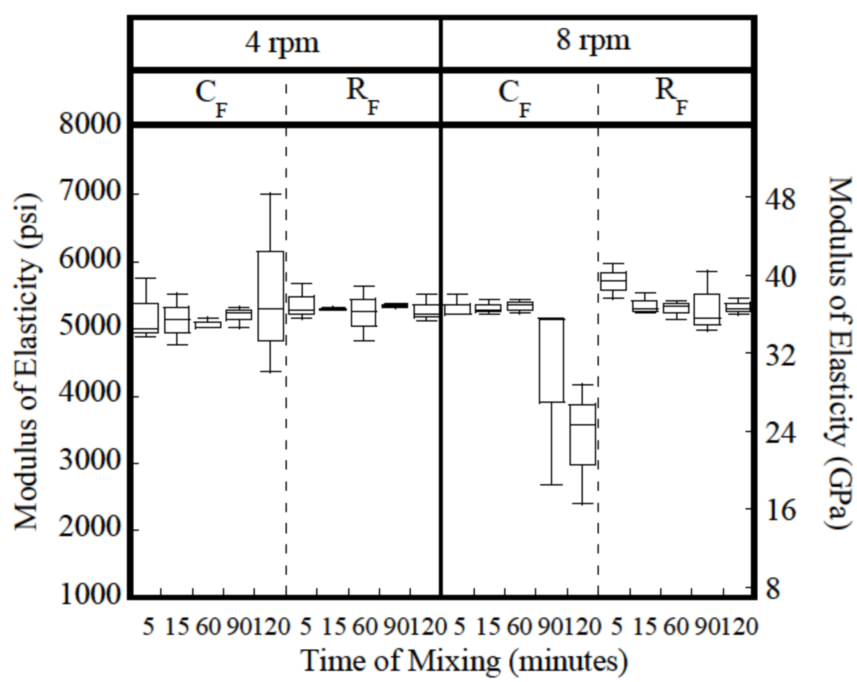

Figure 2.9 MOE for field-mixed mixtures mixed for different times at 4 and 8 rpm.

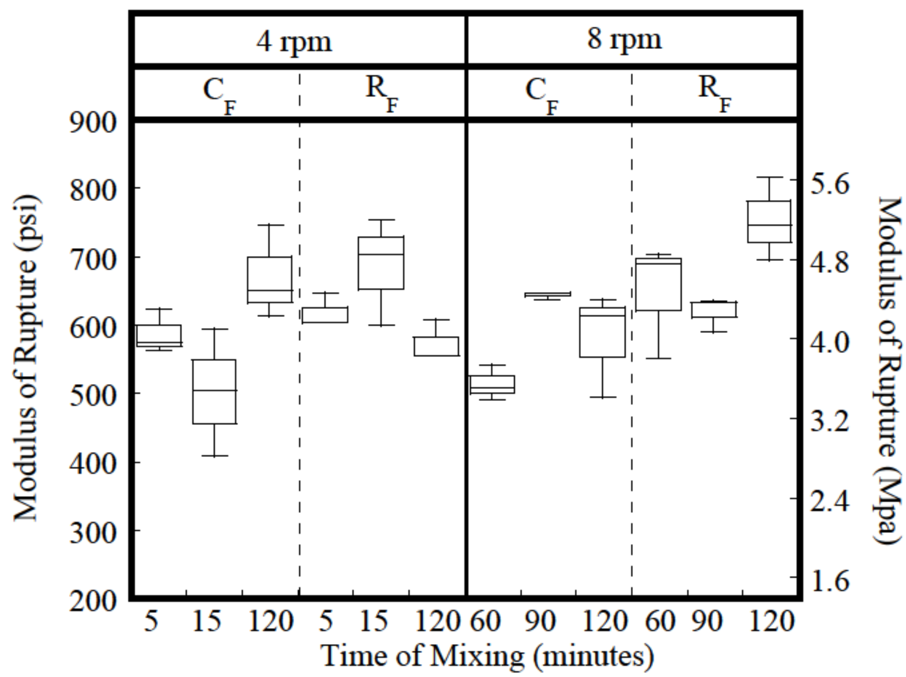

Figure 2.10 Box plot for MOR for the field mixtures.

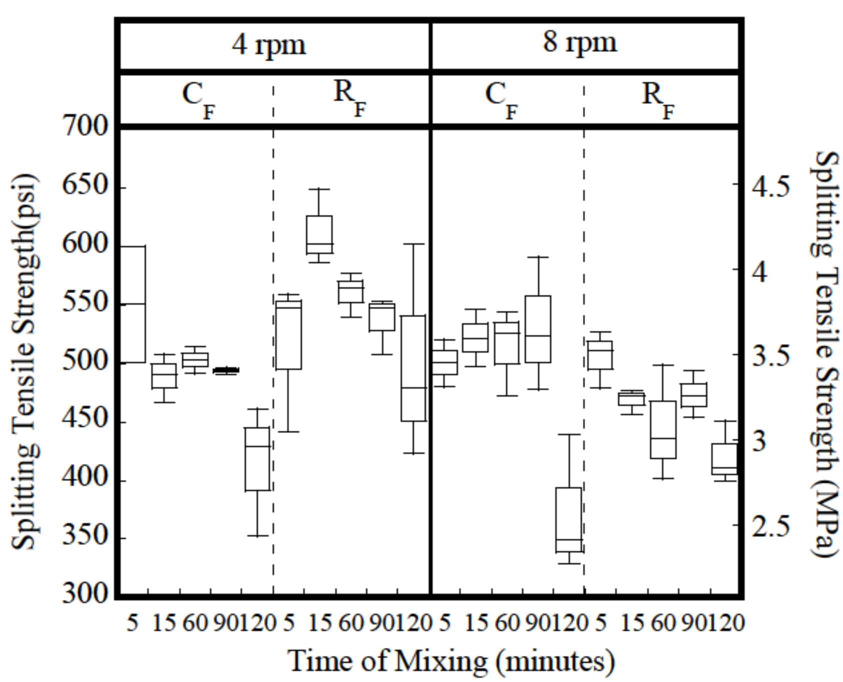

Figure 2.11 Splitting tensile strength for field-mixed mixtures mixed for different times at 4 and 8 rpm.

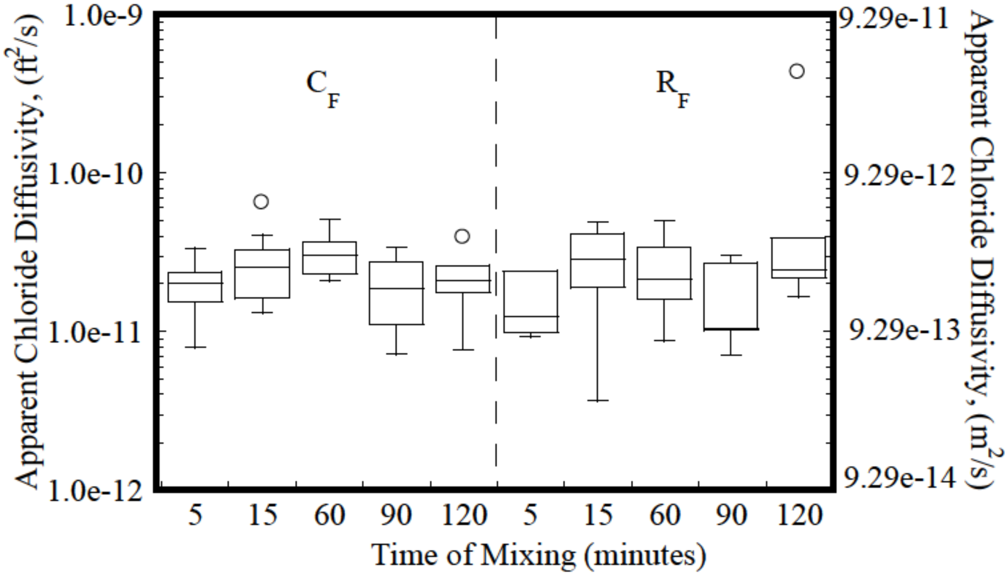

Figure 2.12 Box plot for chloride diffusion coefficient for field-mixed concrete mixed at different mixing speeds.

Chapter 3 INFLUENCE OF TRUCK DRUM REVOLUTION COUNT ON FRESH AND HARDENED CONCRETE CHARACTERISTICS

Will be Submitted to:

ACI Materials Journal

American Concrete Institute

38800 Country Club Dr

Farmington Hills, MI 48331

3.1 ABSTRACT

Ready-mix concrete (RMC) is limited to 300 truck drum revolution counts (DRCs) before discharge by most specifications. The objective of this specification is to ensure the quality and performance of the finished concrete product. However, the 300 truck DRC limit has been in place for many years and limited research has been performed to determine the validity of these limits. Since these limits were first implemented by the American Society for Testing and Materials (ASTM) in 1958, there have been significant changes in the concrete industry. Research is needed to determine if these limits are still applicable. Approximately 1450 and 550 specimens were assessed for the various tests during the laboratory and field study, respectively. Results from laboratory and field research indicate that, as long as the concrete exhibits adequate workability to be properly placed and casted, in most cases extended DRCs (longer than current specification) have no detrimental effects on the mechanical properties and durability characteristics. A wide range of slump and slump loss values were observed for the different mixtures and the 300 truck DRC could not be validated in this research.

Keywords: drum revolution count; extended mixing; workability; compressive strength; tensile strength; modulus of elasticity; modulus of rupture; diffusivity; freeze-thaw

3.2 INTRODUCTION AND BACKGROUND

The first ASTM C94, *Standard Specification for Ready Mixed Concrete,* was published in 1935. This standard specification required that RMC be discharged within 90 minutes after the introduction of water to the cement or after the cement was introduced to moist aggregate. A revision of the ASTM C94 specification was published in 1958. This revision limited the number of truck DRCs to no more than 300 revolutions before discharge and this limit has been used as a general based DRC limit for many state highway agencies (SHAs). However, the mixing equipment, cement production, and admixture technology have made significant changes since this limit was first implemented and the justification for the truck DRC limit has not been adequately assessed. ASTM C94 removed the 300 DRCs limit in the 2013 revision, and yet 30 SHAs still specify limits on truck DRCs (Trejo and Prasittisopin 2014). The lack of consistency between organizations and agencies is likely a result of the lack of data supporting the validity of this truck DRC limit. This indicates that research on the subject is needed. The objective of this study is to evaluate whether the truck DRC limit can be justified with research data. If the limit cannot be validated the objective is to identify variables or tests that can be used as indicators for acceptance of RMC.

When RMC is being transported from the ready-mix plant to construction sites, it can be subjected to continuous mixing and/or agitation during its transport. The time require to transport and discharge RMC varies as a result of long transport distances, traffic, and delays in construction. In many cases, longer time and DRCs may result in decreased workability and placeability because of the hydration of the cement. Low workability can cause difficult placements and may result in increased voids and honeycombing of the concrete. The mechanical properties and durability characteristics of the concrete could be reduced because of the voids and honeycombing. The truck DRC limits imply that that concrete mixed beyond these limits could exhibit inferior performance. The effects of truck DRCs on concrete characteristics have been a topic of much discussion but only limited data are available on the influence of truck DRCs on concrete characteristics. A brief review of the current literature follows.

Vickers Jr. et al. (2005) studied the effects of mixing speed on concrete slump retention. The authors reported a good correlation between slump and the number of DRCs and poor correlation between slump and mixing time. The authors also reported that slump decreases with an increasing DRC. Trejo and Chen (2014) observed similar results.

Ravina (1996) evaluated the compressive strength of mixtures containing fly ash, water reducing agent (WRA), and retarders when mixtures were mixed up to 180 minutes. The author only reported the effect of mixing time on the compressive strength of concrete. However, because the author reported mixing times and mixing speeds, the results from this study can also be assessed in terms of DRCs. The author reported that for mixing at 4 rpm (agitation speeds) up to 135 minutes (540 DRCs) the compressive strength increased linearly, but at different rates for the different mixtures. The author also reported minimal strength increases for concrete mixed between 135 to 180 minutes (540 to 720 DRCs) and reported some mixtures exhibited decreases in measured compressive strength (f'cm).

Kırca et al. (2002) reported that mixtures mixed at 4 rpm for 240 minutes (960 DRCs) exhibited significant slump loss. However, the 7-, and 28-day compressive strength increased. The authors hypothesized that the evaporation of water led to lower water to cement ratio (w/c) and resulted the increase in the compressive strength. The authors also hypothesized that the increase in strength could a result of grinding of the cement particles which resulted in finer cement grains and more hydration.

Other than these studies, limited work has been performed on the effects of DRCs on concrete characteristics. Some research indicates that agitation and mixing of concrete at high DRCs (and prolonged times) can result in increased compressive strengths (Ravina 1996). As a result of the increased compressive strengths, other mechanical properties could improve. However, the literature on the influence of DRCs also indicates increased DRCs result in decreased workability. ACI 211.1 recommends a minimum slump for different types of construction. and ACI 318 states that mixture proportions should "provide workability and consistency to permit concrete to be worked readily into forms and around reinforcement." It is recognized most concrete placement requires some minimum workability. However, placing limits on DRCs can present challenges to users, especially when higher DRCs to discharge are required.

Significant changes have occurred in the concrete industry since the 300 DRCs limit was established. Such as the use of synthetic chemical admixtures, the changes in the cement production process, and more advanced mixing equipment. Despite the changes, yet specifications in many SHAs, the American Association of State Highway Transportation Officials (AASHTO), and the American Concrete Institute (ACI) still place limits on the DRCs (ACI C09 Committee 2013-13b, AASHTO 2013, and ACI 304 Committee 2000). To ensure concrete construction remains an economically viable construction option, current DRC limits need to be justified based on current technology. This research investigates the validity of these DRC limits.

3.3 RESEARCH SIGNIFICANCE

Many specifications still specify 300 DRC limits for RMC and limited research has been performed to assess how DRCs influence the performance of the more modern concrete and research is needed to assess whether the DRC limits still in many specifications are applicable. This research investigates the influence of DRC on the characteristics for laboratory- and field-mixed concrete. Specifications that impose restrictions without valid justification can decrease the economic viability of RMC.

3.4 MATERIALS AND EXPERIMENTAL PROGRAM

This research included eleven coarse aggregates (CAs) were identified and selected for use in the concrete mixtures. These CAs were selected based on their specific gravity (SG) and absorption to represent a wide range of concretes currently used in practice in the state of Washington and all CAs are from the State of Washington. The SG of the aggregates ranged from 2.58 to 2.82 and the absorption values ranged from 0.6% to 3.3%. Of the 11 CA, one met #56, seven met #57, and three met #67 grading limits (ASTM C33). All aggregates have been approved by the Washington State Department of Transportation (WSDOT) for use as coarse aggregate in RMC. More details on the aggregates can be found in Trejo and Chen (2014). Type I/II ordinary portland cement, Class F fly ash, and slag were obtained from Lafarge North America (Centralia, WA). The chemical compositions of the materials are shown in Table 3.1. Three types of chemical admixtures (WRA, retarder, and air entraining agent [AEA]) were used in the research program. The WRA and retarders met ASTM C494—*Standard Specification for Chemical Admixtures for Concrete*, Type A, B, and D requirements and the AEA met ASTM C260, *Standard Specification for Air-Entraining Admixture for Concrete* requirements.

This research was conducted in two studies, a laboratory study and a field study. The laboratory study assessed the fresh and hardened concrete characteristics of several different mixtures mixed for different DRCs using a laboratory rotary concrete mixer (6 ft^3 [0.17 m^3]). The mixer is a tilting drum mixer with three blades fixed onto the inside wall of the drum. The mixer was modified with a variable speed motor such that the mixing speed could be changed and controlled. Fresh concrete characteristics were assessed and specimens were cast after predetermined DRCs until the concrete was no longer workable. The laboratory experimental program is shown in Table 3.2. The laboratory mixture groups consisted of four general classifications: control, mixtures containing SCM (SCM_L), mixtures containing recommended dosages of chemical admixtures ($AD_{R,L}$), and mixtures containing high dosages of chemical admixtures ($AD_{H,L}$). The "L" subscript indicates laboratory-made specimens. The $AD_{R,L}$ group consists of mixtures containing WRA (W_L), AEA (A_L), and retarder ($R_{R,L}$). The subscript "R" represents recommended dosages of admixtures. The $AD_{H,L}$ group consisted of subgroups containing a retarder ($R_{H,L}$) and a combination of retarder and AEA ($RA_{H,L}$). The subscript "H" represents mixtures containing high dosages of admixtures. In addition to the laboratory experimental plan shown in Table 3.2, three mixtures (subgroups $R_{H,L}$ and $RA_{H,L}$ in Table 3.2) were also evaluated for the modulus of elasticity (MOE), modulus of ruptures (MOR), and splitting tensile strength (STS). Also, the freeze-thaw performance of two mixtures containing AEA and two mixtures without AEA were assessed (subgroups A_L and C_L).

The laboratory mixtures were proportioned using ACI 211.1, *Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete*. The absolute volume method was used. The design strength (f'c) of the laboratory mixtures was 5200 psi (35.9 MPa) (w/c = 0.46) and the target slump was 4 inches (101 mm). Because the mixtures contained different constituent materials, the amount of the paste content was adjusted to target the 4-inch (101 mm) slump. General mixture proportions for the laboratory mixtures are shown in Table 3.3. These mixtures were mixed following the ASTM C192-13a, *Standard Practice for Making and Curing concrete Test Specimens in the Laboratory*. After the standard mixing process, the mixtures were further mixed to the number of DRCs shown in Table 3.2.

The field study evaluated two mixtures: a control concrete mixture (C_F) and a concrete with the same mixture proportions but containing a retarder (R_F). The "F" subscript indicates these are field-mixed mixtures. The target slump of the field-mixed concrete was 4 inches (101 mm) and the f'c was 4500 psi (31.0 MPa). Mixture proportions for the field-mixed concrete were 3160 lb/cy (1875 kg/m^3) of aggregate (FA/CA = 0.71), 611 lb/cy (362 kg/m^3) of cement, and the w/c was 0.44. The SG of the CA and FA for the field-mixed concrete was 2.68 and 2.62, respectively. The CA met the ASTM #57 aggregate gradation. The laboratory plan for the field study is shown in Table 3.4.

Six field mixtures were mixed and cast over a three day period. The mixtures were mixed at different drum speeds and times. On the first day the C_F and R_F mixtures were mixed at 4 rpm. The C_F mixtures mixed at 8 and 15 rpm were cast on the second day and the R_F mixtures mixed at 8 and 15 rpm were cast on the third day. Each mixture was first mixed in a central mixer and then loaded onto a concrete truck mixer for longer mixing. These mixtures were mixed up to1350 DRCs. Samples were fabricated at predetermined DRCs to assess the fresh and hardened concrete characteristics.

The testing in this study followed ASTM standards. The slump and air content of concrete mixtures were assessed following ASTM C143 and ASTM C231, respectively. The compressive strength values were assessed following ASTM C39. The MOE, MOR and STS were assessed following ASTM C469, ASTM C78, and ASTM C469, respectively. Select mixtures were assessed for freeze-thaw performance

(ASTM C666 Method A). The samples for the chloride transport were collected following ASTM 1556. These samples were analyzed for chloride concentration following WSDOT T414.

3.5 TEST RESULTS AND ANALYSIS—LABORATORY STUDY

Results on the fresh concrete characteristics for the laboratory-mixed concrete are presented first. The analysis of fresh characteristics is followed by results on the mechanical properties and the durability performance of the concrete mixtures mixed for different DRCs in the laboratory.

Statistical tests were used to compare the means of concrete characteristics. Specifically the student t-test and ANOVA test were used to compare the means of the values of concrete characteristics mixed for different DRCs. The student t-test was used to compare the means of two groups. The null hypothesis for the t-test is that there are no differences between the means of the samples. The alternative hypothesis for the t-test is that there is a difference between the means of the samples. For the ANOVA test, the null hypotheses is that there is no difference between the means of the sample groups. The alternative hypothesis for the ANOVA test is that at least one of the mean values is significantly different. Both t-test and ANOVA test result in a p-value. The p-value is a single number that summarizes the statistical test outcome and indicates how much evidence there is to accept or reject the hypothesis at a certain confidence level. For this research a 95 percent confidence level is used. The null hypothesis will be accepted if the p-value is greater than or equal to 0.05; otherwise the null hypothesis is rejected.

3.5.1 Fresh Concrete Characteristics of Laboratory Mixtures

Although variation in air content did exist, results indicate that there is not a statistically significant difference in the means of the entrapped and entrained air content for mixtures mixed for 40, 120, 225, 480, and 900 DRCs in the laboratory study. This indicates that the laboratory DRCs up to 900 revolutions does not significantly influence the entrapped and entrained air contents of concrete.

For all four laboratory groups tested (Control, SCM_L, $AD_{R,L}$, and $AD_{H,L}$), the slump values decreased as a function of DRCs. The slump loss was different for the four groups. Models for the slump as a function of laboratory DRC were generated for each mixture group. Because initial slump values varied, models are based on normalized slump values (*n-slump*). The normalized slump is defined as the measured slump at some DRC divided by the initial slump (initial slump is defined here as the measured slump after 40 DRC). To distinguish between mixture groups, the *n-slump* is followed by a subscript; the subscript represents the mixture group (defined earlier).

Test results indicate that the *n-slump* for the $Control_L$, SCM_L, $AD_{R,L}$, and $AD_{H,L}$ mixture groups can be estimated as follows:

$$n\text{-}slump_{Control_L}(n) = 1.06 - 0.000685n \tag{3-1}$$

$$n\text{-}slump_{SCM_L}(n) = 1.09e^{-0\ 00123n} \tag{3-2}$$

$$n\text{-}slump_{AD_{R,L}}(n) = 1.06e^{-0\ 00153n} \tag{3-3}$$

$$n\text{-}slump_{AD_{H,L}}(n) = 1.10e^{-0\ 0014n} \tag{3-4}$$

where *n* is the number of laboratory DRCs. Equation 2-1 is based on data from laboratory DRCs (*n*) between 40 and 1400; equations 2-2 and 2-3 are based on data between 40 and 900 laboratory DRCs, and equation 2-4 is based on data from laboratory DRCs between 40 and 2700. These equations can be used to estimate the slump at some number of laboratory DRCs, *n*, as follows:

$$slump = n\text{-}slump(n) \times slump_{initial} \tag{3-5}$$

Figure 3.1 shows the n-slump models for the different groups. Note that at a DRC of 300 for mixtures mixed in the laboratory, the n-slump values varied from approximately 0.68 to 0.85. Note also that if an n-slump value of 0.3 is required for the concrete to be placed (this is an arbitrarily selected value), the allowable DRCs for the laboratory-mixed concrete varies from approximately 780 to 1200 counts. Although n-slump is a function of the laboratory DRCs for the individual mixture groups, the n-slump does not have a significant correlation for all the different mixtures. The slump and slump loss exhibit significant variation between mixtures types.

3.5.2 Harden Properties for Laboratory Mixtures

The f'cm, MOR, MOE, STS, D_a, and freeze-thaw performance were assessed for the laboratory-mixed concrete. This section presents the results on the effects of laboratory-mixer DRCs on these characteristics. Figure 3.2 shows a box plot for the normalized $f'cm_{28}$ at different laboratory DRCs. The $f'cm_{28}$ is normalized to the average $f'cm_{28}$ of the specimen mixed for 40 laboratory DRCs. The results from the laboratory study indicate that DRCs have no negative influence on the $f'cm_{28}$ up to 1800 DRCs. However, at 2700 DRCs in the laboratory mixer, the $f'cm_{28}$ exhibited a significant reduction. The reduction in strength is a result of poor consolidation and honeycombing in the specimens. It should be noted here that when mixtures exhibited good workability all mixtures without SCM met the twenty-eight day f'c. When the SCM_L mixtures exhibited good workability all mixtures met the f'c by 56 days. Delays in strength gain have been reported for mixtures containing SCMs (Bouzoubaâ et al. 2000; Barnett et al. 2006) and the delay in strength gain for these mixtures is likely not a result of the extended DRCs but instead a result of the SCM replacement.

For the $R_{H,L}$ and $RA_{H,L}$ subgroups, the MOE, MOR, and STS were assessed. These two mixtures are analyzed separately. For each assessment, evaluation for the $R_{H,L}$ mixtures is shown first. Note that the w/c was not adjusted to for the mixtures containing AEA and as such, these mixtures exhibited higher initial slump values and lower compressive strengths.

Figure 3.3 shows the MOE as a function of laboratory DRCs for the $R_{H,L}$ and $RA_{H,L}$ mixtures. For the $R_{H,L}$ mixtures indicates that there is a statistically significant difference between the mean MOE values of the $R_{H,L}$ mixtures mixed for different laboratory DRCs up to 2700 DRCs (ANOVA, p-value < 0.001). A significant reduction in MOE is observed for the mixture mixed for 2700 laboratory DRCs (Figure 3.3). The mixture mixed for 2700 laboratory DRCs exhibited low slump values and low workability which resulted in honeycombing in the specimens.

ANOVA testing of the MOE data for the $RA_{H,L}$ mixtures indicates that mixtures mixed for different DRCs exhibited statistically significant differences in the mean MOE values (p-value < 0.001). Data indicates that there is a slight decrease in MOE value when mixtures were mixed for 480 and 720 laboratory DRCs. When mixtures were mixed for 1400 and 2700 laboratory DRCs, there was no negative impact on the MOE values for the $RA_{H,L}$. mixtures. Despite the MOE reduction for the specimens mixed for 480 and 720 laboratory DRCs, the mean MOE values still met the estimated MOE value (per ACI 318-08 8.5.1) based on a 4420 psi (30.5MPa) concrete (the f'c for this concrete was 5200 psi, 4420 psi is the f'c assuming 15% reduction in compressive strength due to the entrained air).

The MOR was also assessed for the $R_{H,L}$ and $RA_{H,L}$ mixtures. Figure 3.4 shows the normalized MOR values as a function of laboratory DRCs for these mixtures. The MOR for each mixture mixed at different laboratory DRCs are normalized by dividing the average MOR value from the same sub-group mixed for 40 laboratory DRCs. Results indicate laboratory DRCs up to 1800 have no detrimental effect on the mean MOR values of the $R_{H,L}$ mixtures. However, when mixed for 2700 DRCs in the laboratory mixer, the MOR values of the $R_{H,L}$ mixtures exhibited a statistically significant decrease in the mean MOR values (p-value <0.001). As with other mixtures, the specimens mixed for 2700 DRCs in the laboratory mixer exhibited significantly lower workability (the slump value was zero) and specimens contained significant honeycombing. The honeycombing likely resulted in lower MOR values. Similar findings were observed for the $RA_{H,L}$ mixtures mixed for 2700 DRCs in the laboratory. These mixtures exhibited low workability and lower MOR values when compared to those mixed for lower DRCs using the laboratory concrete mixer.

Box plot for the normalized STS of the $R_{H,L}$ and $RA_{H,L}$ mixtures is shown in Figure 3.5. The STS for each mixture mixed at different laboratory DRCs are normalized by dividing the average STS value from the same sub-group for mixtures mixed at 40 laboratory DRCs. STS results from the laboratory study indicate that the $R_{R,L}$ mixtures mixed for 1800 DRCs in the laboratory exhibited no statistically significant difference in the mean STS values (p-value = 0.586). However, the mean values were statistically significantly different when mixed to 2700 laboratory DRCs (p-value < 0.001). This mixture exhibited low workability and castability at 2700 DRC which resulted in honeycombing in the specimens. Specimens containing honeycombing exhibited lower STS values than those exhibited no honeycombing. For the $RA_{H,L}$ mixtures, ANOVA testing indicates that there is no statistically significant difference between the mean MOR values of the $RA_{H,L}$ mixtures mixed for different laboratory DRCs up to 2700 revolutions (p-value = 0.618).

Figure 3.6 shows the D_a for the $Control_L$, $SCM_{L,}$ and $AD_{R,L}$ groups. Significant increases in D_a could result in increased rates of chloride transport and reduced service life of reinforced concrete structures. The mean D_a values for these mixture groups mixed for different laboratory-mixer DRCs up to 900 revolutions exhibited no statistical significant difference. P-values were 0.505, 0.461, and 0.451 for the $Control_L$, SCM_L, and $AD_{R,L}$ group, respectively.

The freeze-thaw performance was also tested for four mixtures. These mixture include Two mixtures from each of the $Control_L$ and A_L groups For the A_L group mixtures, the relative dynamic modulus does not significantly differ up to 300 freeze-thaw cycles for mixtures mixed for different laboratory DRCs up to 900. For mixtures without AEA, the relative dynamic modulus of the mixtures mixed for 120, 225, 480 and 900 laboratory DRCs decreased to 60 percent of the initial value (i.e., defined as failure by ASTM C666) before the 300 cycles. However, these specimens failed at approximately the same number of cycles regardless of DRCs using the laboratory mixer. This indicates that laboratory-mixer DRCs likely do not influence freeze-thaw performance of laboratory-mixed concrete.

The results from the laboratory mixer DRC study indicates that the fresh and hardened characteristics of concrete can be influenced by DRC. However, results indicate that different characteristics are influenced at different DRCs. Table 3.5 shows a summary of the results. Results indicate that slump does vary significantly with DRCs. This would be expected for a material that requires chemical reactions (hydration) to achieve desired hardened characteristics. The MOE exhibited slight decreases between 300 and 900 DRCs in the laboratory and the f'c, MOE, MOR, and STS all exhibited significant reductions when mixed for 1800 or more DRCs in the laboratory. The freeze-thaw performance and chloride diffusivity of the laboratory-mixed specimens exhibited no significant reductions when mixed up to 900 DRCs in the laboratory mixer.

3.6 TEST RESULTS AND ANALYSIS—FIELD STUDY

3.6.1 Fresh Concrete Characteristics for Field Mixtures

The results from the field study indicate that there is no statistically significant difference between the mean entrapped air content for mixtures mixed at different truck DRCs up to 1350 revolutions. The maximum increase in entrapped air content as a function of increasing truck DRCs within one mixtures was a 1.2 percent. The entrapped air contents for the field-mixed concrete ranged from 1.6 to 3.1 percent. These variations in entrapped air content are considered to be insignificant.

Similar to the laboratory study, slump values were significantly influenced by truck DRCs, as would be expected for a cement-based system. Models for the normalized slump values are generated for the C_F and R_F mixtures. These are shown in Figure 3.7. The n-slump as a function of truck DRCs mixed at different mixing speeds for the C_F mixtures can be estimated as follows:

$$n - slump_{C_F}(n) = -0.095 + 1.12 \times e^{-0\ 0022n} \qquad (3\text{-}6)$$

$$n - slump_{R_F}(n) = 0.045 + 1.12 \times e^{-0\ 0039n} \qquad (3\text{-}7)$$

where *n* is the number of truck DRCs. Equations 2-6 and 2-7 are based on data for truck DRCs between 20 and 1350. The R^2 value for each of these two models is 94 percent.

This research and the resulting models indicate that slump is significantly influenced by truck DRCs. Low slump values indicate less workable concrete mixtures. The lack of workability can result in inadequate consolidation and honeycombing and lower mechanical properties. Workability is a key characteristic that must be adequate for proper concrete placement. Required workability is also associated with the type of construction and methods of consolidation. For example, concretes that are perceived as workable for a large foundation structure may be entirely unworkable for a thin structural member. A concrete mixture that cannot be adequately consolidated is not likely to yield the expected strength and durability characteristics.

3.6.2 Hardened Properties for Field Mixtures

The 28-day compressive strength is show in Figure 3.8 and results indicate that high number of truck DRCs significantly reduced the $f'cm_{28}$. The mixtures that exhibited lower compressive strengths also exhibited significant amounts of honeycombing and voids. However, the $f'cm_{28}$ for the R_F mixtures mixed up to 1350 truck DRCs was not significantly influenced by DRCs. No honeycombing and voids were observed for the R_F mixtures mixed up to 1350 truck DRCs. The results indicate that honeycombing resulted in low compressive strengths of the C_F mixtures but not the R_F mixtures. When a retarder is used, improved workability and slightly higher slump values were observed. Although small, this higher slump for the R_F mixtures provided sufficient workability up to a truck DRCs of 1350 revolutions and the f'cm values were not significantly influenced.

Figure 3.9 shows the MOE results for the C_F and R_F mixtures. The results indicate that truck DRCs significantly influences the MOE of the C_F mixtures when mixed for longer than 480 truck DRCs. Larger scatter of MOE values and lower MOE values were also observed for the C_F mixtures mixed for more than 480 truck DRCs. This is believed to be a result of the reduction in workability and castability of the mixtures. Even so, the R_F mixtures exhibited no statistically significant difference in MOE values for mixtures mixed up to 1350 truck DRCs. This finding is similar to that of the compressive strength analyses and indicates that acceptance of concrete mixtures may be based on workability, placeability, or castability rather than truck DRCs.

Figure 3.10 shows the MOR values for the field mixtures. Results indicate that the mean MOR of the C_F and R_F mixtures exhibited no statistically significant difference when mixed at different truck DRCs up to 1350 truck DRCs. Note that larger scatter in MOR values were observed at higher DRCs.

Figure 3.11 shows results for the STS values as a function of truck DRCs. The results from the C_F and R_F data indicate that the STS decreased slightly as the truck DRCs increase. Large scatter in the STS values is observed.

The D_a values for the field mixtures mixed for different truck DRC were also assessed. Results are shown in Figure 3.12. The ANOVA tests indicate that, for both C_F and R_F mixtures, there is no statistically significant difference in the mean D_a values for mixtures mixed for different DRCs (p-value is 0.169 and 0.243 for the C_F and $R_{F,}$ respectively).

Results from the field investigation indicate that truck DRCs can influence the fresh and hardened characteristics of concrete. Table 3.6 shows a general summary of the influence of DRCs on the fresh and hardened characteristics. Results indicate that a reduction in slump occurs at low truck DRCs and this is expected. What is critical here is at what slump can the concrete not be properly placed and consolidated? This is dependent on the type of construction. Results from the assessment of the mechanical properties indicate that MOE may decrease slightly after 300 truck DRCs. Other mechanical properties are not negatively impacted until 900 or more truck DRCs. The chloride diffusivity of the field mixtures was not negatively impacted for mixtures mixed to 1350 truck DRCs.

3.7 SUMMARY AND CONCLUSIONS

Limits on truck DRC have been in specifications since 1958. The original intent of these limits was likely to ensure that concrete could be properly placed and consolidated. Nearly 60 years have passed since the first limit on truck DRC was published and this limit is now ubiquitous throughout specifications in our industry—30 SHAs still limit the truck DRC for concrete placement. Yet significant changes have occurred in the concrete industry; newer admixtures are being used, some specifically designed to extend workability. The validity and applicability of the truck DRC limit needs to be assessed.

This research investigated the influence of DRCs on the fresh and hardened characteristics of laboratory- and field-produced concrete. For the laboratory mixtures the slump ranged from approximately 70 to 85% of the original slump after 300 laboratory DRCs. For the field mixtures the slump ranged from approximately 40 to

50% of the original slump values after 300 truck DRCs. The mixtures containing higher dosages of admixtures exhibited higher slump values and better workability than the mixtures containing recommended dosages after extended mixing. Slump requirements are commonly specified to ensure placeability and these vary depending on type of construction. Many of the mixtures evaluated in this research exhibited sufficient workability to properly place and consolidate the laboratory specimens. In many cases workability was sufficient for field placement. Although the different laboratory mixtures exhibited large scatter in the slump results, the field study, with limited mixture types, exhibited relatively better correlation between slump and DRC. The field study indicates that DRCs and slump is likely be correlated. DRC limits could be specified if slump were correlated to placeability, castability, or workability. The results from this study indicate that different mixtures exhibiting low but similar slump values exhibited very different placeability (or castability) characteristics. One mixture with a low slump value exhibited significant honeycombing while another mixture with the same slump exhibited little honeycombing. This indicates that the slump test is likely not a good measure for concrete placeability and resulting concrete performance. Even so, the slump test is likely a better conservative indicator of placeability than a single DRC limit.

In addition to the fresh characteristics, the hardened properties were assessed for laboratory- and field-mixed concrete mixed for different DRCs. Results indicate that the f'cm, MOE, MOR, STS, and chloride diffusivity for the laboratory-mixed concrete exhibited no significant reduction in characteristics when mixed up to 900 DRCs.

Laboratory mixtures mixed for 2700 DRC exhibited reduced f'cm, MOE, MOR, and STS values. In all cases the reduction in concrete characteristics was related to low workability and specimens containing honeycombing. In addition to the laboratory results, the field-mixed concrete exhibited significant reductions in f'cm, MOE, and STS after 1350 DRC of mixing for the control mixtures. Field mixtures containing chemical admixtures exhibited no significant reduction in concrete characteristics even when mixed up to 1350 truck DRCs. Results from laboratory and field studies indicate that mixtures containing newer generations of admixtures can exhibit good workability even after experiencing high DRCs. Concrete performance seems to be directly related to the ability to properly place and cast the concrete, which may or may not be measured with slump. Correlation was identified between slump and laboratory- and field-mixed DRCs for the different mixtures assessed in this research. However, the correlations are different for different mixture types. Results indicate that the DRC limit, in this case 300 counts, may provide a lower limit for some applications but in general is not a reliable indicator for ensuring proper placement and/or consolidation of concrete. Results indicate that some mixtures can experience much higher DRCs and still provide adequate workability, which can result in sufficient mechanical properties and durability characteristics. Although slump provides some indication of workability, concrete may be placeable at very low slump values. A methodology or test that can assess the placeability for different construction types is needed. This test could likely provide for castable concrete that can provide safe and durable long-term-performance. Further research is needed to develop this test.

3.8 REFERENCES

AASHTO. 2013. "AASHTO M 157-11 Standard Specification for Ready-Mixed Concrete". AASHTO.

ACI 304 Committee. 2000. "Guide for Measuring, Mixing, Transporting, and Placing Concrete." *ACI Materials Journal*, January.

American Petroleum Institute. 2002. "API SPEC 10A Specification for Cements and Materials for Well Cementing." *American Petroleum Institute*.

Barnett, S. J., M. N. Soutsos, S. G. Millard, and J. H. Bungey. 2006. "Strength Development of Mortars Containing Ground Granulated Blast-Furnace Slag: Effect of Curing Temperature and Determination of Apparent Activation Energies." *Cement and Concrete Research* 36 (3): 434–40. doi:10.1016/j.cemconres.2005.11.002.

Beaufait, F, and P Hoadle. 1973. "Mix Time and Retempering Studies on Ready-Mixed Concrete." *Journal Proceedings* 70 (12): 810–13.

Beitzel, H. 1981. "Effect of the Mixing Time on the Quality of the Mixing." *Precast Concrete* 12 (9): 403–8.

Bouzoubaâ, N, M. H Zhang, and V. M Malhotra. 2000. "Laboratory-Produced High-Volume Fly Ash Blended Cements: Compressive Strength and Resistance to the Chloride-Ion Penetration of Concrete." *Cement and Concrete Research* 30 (7): 1037–46. doi:10.1016/S0008-8846(00)00299-4.

C09 Committee. 2013. "ASTM C94/C94M - 13b Standard Specification for Ready-Mixed Concrete." *ASTM International* 04.02.

Kırca, Ö, L Turanli, and T Erdoğan. 2002. "Effects of Retempering on Consistency and Compressive Strength of Concrete Subjected to Prolonged Mixing." *Cement and Concrete Research* 32 (3): 441–45. doi:10.1016/S0008-8846(01)00699-8.

Lobo, Cl, and Rd Gaynor. 2006. "Chapter 45: Ready-Mixed Concrete." In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, edited by Jf Lamond and Jh Pielert, 533–533–15. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International. http://www.astm.org/doiLink.cgi?STP37763S.

Nehdi, M, and S Al-Martini. 2009. “Coupled Effects of High Temperature, Prolonged Mixing Time, and Chemical Admixtures on Rheology of Fresh Concrete.” *Materials Journal* 106 (3): 231–40.

Ravina, D. 1975. “Retempering of Prolonged-Mixed Concrete with Admixtures in Hot Weather.” *ACI Journal Proceedings* 72 (6): 291–95.

———. 1996. “Effect of Prolonged Mixing on Compressive Strength of Concrete with and without Fly Ash And/or Chemical Admixtures.” *Materials Journal* 93 (5): 451–56.

Trejo, D, and J Chen. 2014. “Influence of Transport Parameter on Concrete Characteristics”. Washington State Department of Transportation.

Trejo, D, and L Prasittisopin. 2014. “Effects of Mixing Variables on Early-Age Characteristics of PC Systems.” *Accepted for Publication ACI Material Journals*.

Vickers Jr., Thomas M., Stephen A. Farrington, Jeffrey R. Bury, and Lynn E. Brower. 2005. “Influence of Dispersant Structure and Mixing Speed on Concrete Slump Retention.” *Cement and Concrete Research* 35 (10): 1882–90. doi:10.1016/j.cemconres.2005.04.013.

3.9 TABLES AND FIGURES

3.9.1 List of Tables

3.9.2 List of Figures:

Table 3.1 Chemical Proportions for Cementitious Materials

Chemical Composition	Percent weight		
	Cement	Class F Fly Ash	Slag
SiO_2	20.3	49.4	31.0
Al_2O_3	4.8	16.4	12.2
Fe_2O_3	3.5	6.20	0.8
MgO	0.7	4.60	4.8
SO_3	2.8	1.00	1.9
CaO	63.9	13.9	43.2

Table 3.2 Experimental Plan for Laboratory Study

Group	Sub-group	CA Type	DRC	SCM or Chemical Admixture	Tests			
					Air Content	Slump	f'cm	Chloride Diffusivity**
Control	C_L	1-11	40, 120, 225, 480, 900, 1800†	None	✓	✓	✓	✓
SCM_L	FA_L	1	40, 120, 225, 480, 900	Fly Ash (20% & 30%)*	✓	✓	✓	✓
	SL_L	1	40, 120, 225, 480, 900	Slag (20% & 40%)*	✓	✓	✓	✓
$AD_{R,L}$	W_L	1	40, 120, 225, 480, 900	WRA A & B	✓	✓	✓	✓
	A_L	1	40, 120, 225, 480, 900	AEA A & B	✓	✓	✓	✓
	$R_{R,L}$	1	40, 120, 225, 480, 900	Retarder A & B	✓	✓	✓	✓
$AD_{H,L}$	$R_{H,L}$	1	40, 120, 225, 480, 720, 900, 1350, 1440, 2700	Retarder B & C	✓	✓	✓	Not tested
	$RA_{H,L}$	1	40, 120, 225, 480, 720, 900, 1350, 1440, 2700	Retarder B & AEA B	✓	✓	✓	Not tested

A B & C indicate manufactures, * percent replacement by weight; ** only selected DRCs are assessed

†: only assessed for mixtures containing CA source 1.

Table 3.3 General Mixture Proportions for Laboratory Mixtures

Subgroup	CA lb/cy (kg/m^3)	FA lb/cy (kg/m^3)	Cement lb/cy (kg/m^3)	Water lb/cy (kg/m^3)	SCM lb/cy (kg/m^3)	Admixture
C_L	1542-1752 (915-1039)	1070-1297 (635-769)	647-739 (384-438)	298-340 (177-202)	0	0
W_L, $R_{R,L}$, $R_{H,L}$, $RA_{H,L}$	1730 (1026)	1200-1306 (712-775)	623-674 (370-400)	286-315 (170-186)	0	WRA & Retarder
FA_L, SL_L	1735 (1029)	1163-1307 (690-775)	396-539 (235-319)	260-313 (154-186)	117-202 (69-120)	0
A_L	1730 (1026)	1204-1324 (714-785)	609-674 (361-399)	280-314 (166-186)	0	AEA

Table 3.4 Experimental Plan for Field Study

Mixture ID	Test Parameters						
	Air Content	Slump	f'cm	STS	MOE	MOR	Chloride Diffusivity*
C_F	✓	✓	✓	✓	✓	✓	✓
R_F	✓	✓	✓	✓	✓	✓	✓

*only selected mixing DRC is assessed

Table 3.5 Summary Table for the Laboratory Study

Concrete Characteristics	Laboratory Drum Revolution Counts				
	40	40-300	300-900	900-1800	>1800
Entrapped Air Content	↔	↔	↔	N.A.	N.A.
Entrained Air Content	↔	↔	↔	N.A.	N.A.
Slump	↔	↓	↓	↓	↓
f'cm	↔	↔	↔	↔	↓
MOE	↔	↔	↔↓	↔↑	↓
MOR	↔	↔↑	↔	↔	↓
STS	↔	↔	↔	↔	↓
Freeze-thaw performance	↔	↔	↔	N.A.	N.A.
Chloride Diffusivity	↔	↔	↔	N.A.	N.A.

↔ indicates no significant change
↑ indicates value increased
↓ indicates values decreased

Table 3.6 Summary Table for the Field Study

Concrete Characteristics	Field Drum Revolution Counts			
	20	21-300	301-900	901-1350
Entrapped Air Content	↔	↔	↔	↔
Entrained Air Content	N.A.	N.A.	N.A.	N.A.
Slump	↔	↓	↓	↔↓
f'cm	↔	↔	↔	↔↓
MOE	↔	↔	↔↓	↔↓
MOR	↔	↔	↔	↔
STS	↔	↔	↔	↔↓
Freeze-thaw performance	N.A.	N.A.	N.A.	N.A.
Chloride Diffusivity	↔	↔	↔	↔

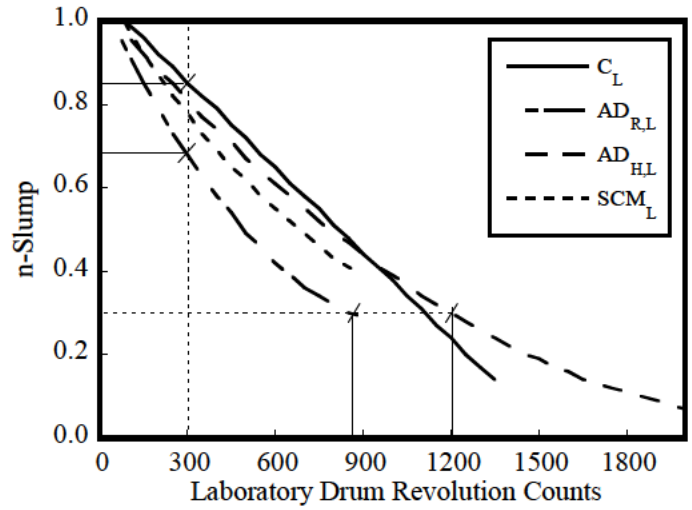

Figure 3.1 N-slump model for all laboratory concrete groups.

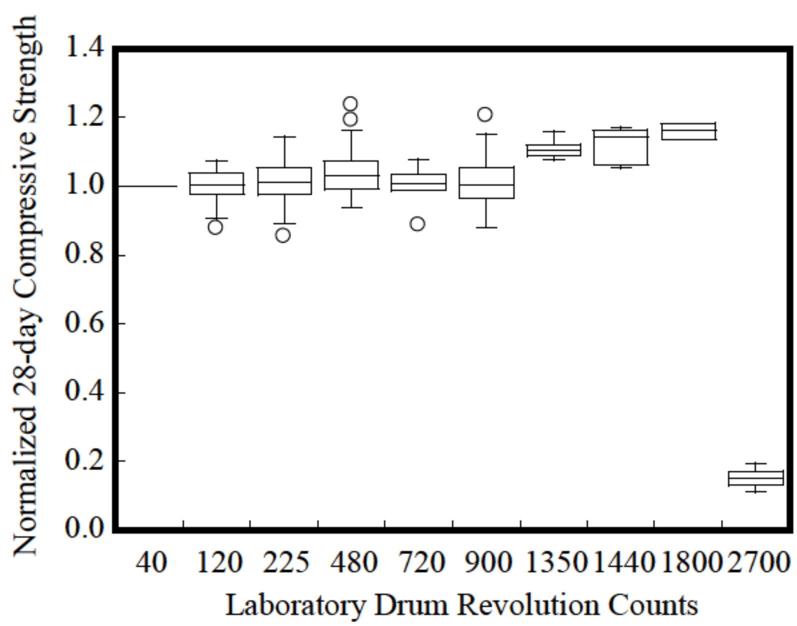

Figure 3.2 Laboratory twenty-eight day f'cm of non-AEA mixture versus mixing DRC.

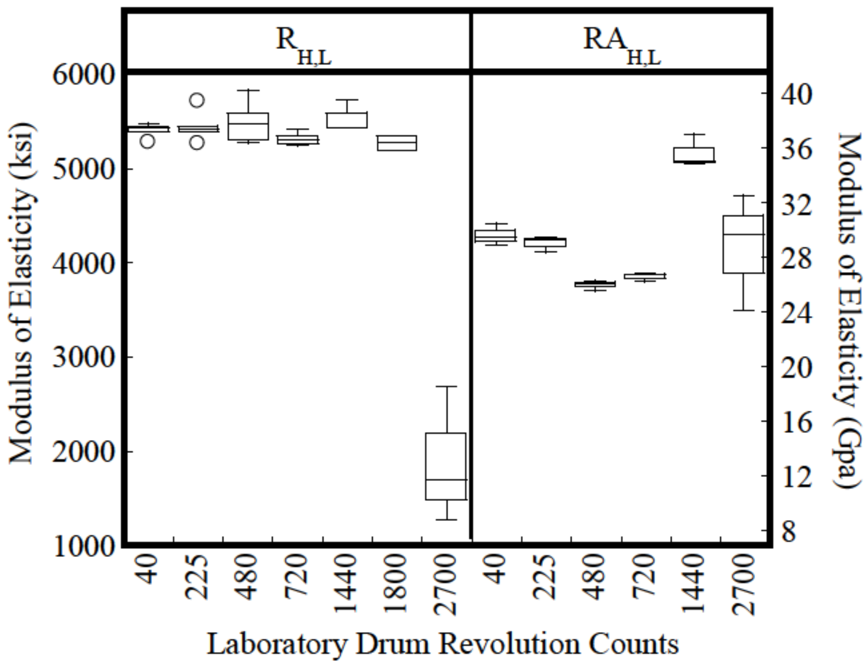

Figure 3.3 Box plot for MOE for $AD_{H,L}$ mixtures.

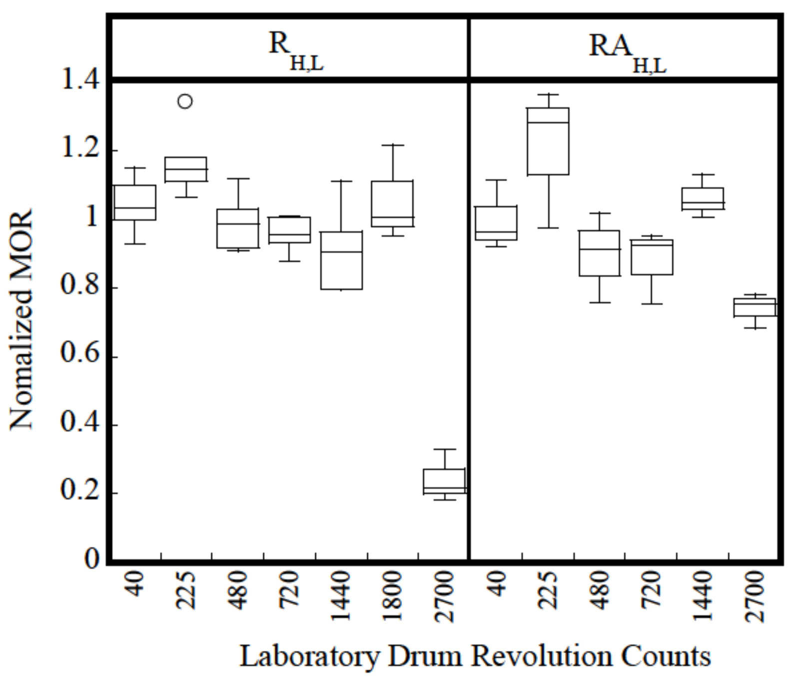

Figure 3.4 Box plot for the MOR of $AD_{H,L}$ mixtures.

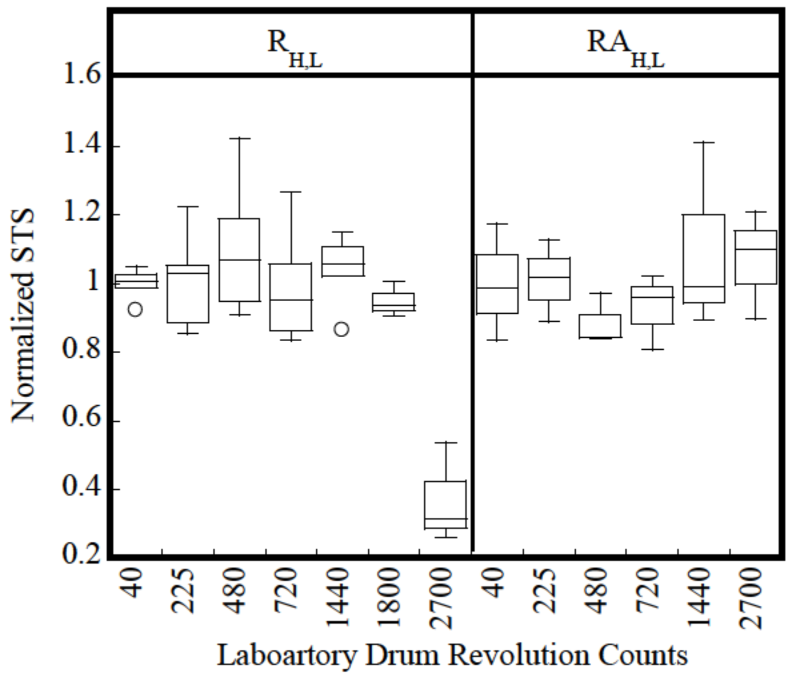

Figure 3.5 Box plot for the STS of $AD_{H.L}$ mixtures.

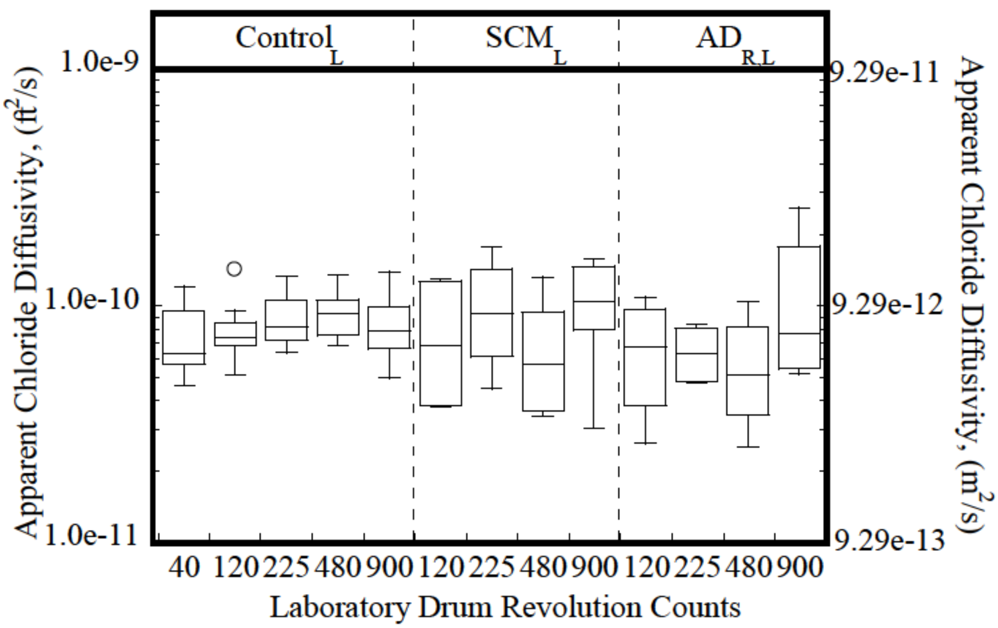

Figure 3.6 Box plot for diffusion coefficient for $Control_{L}$, SCM_{L} and $AD_{R,L}$ mixtures.

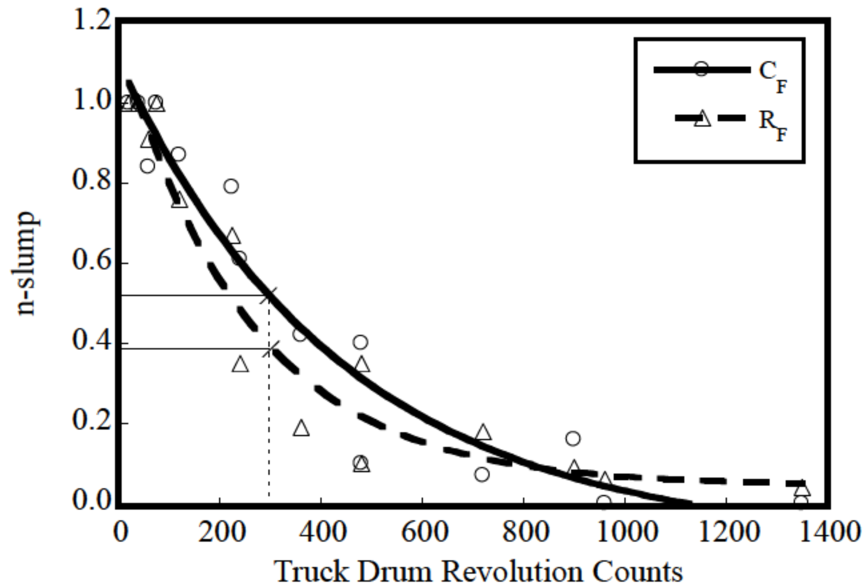

Figure 3.7 N-slump model for the field-mixed concrete.

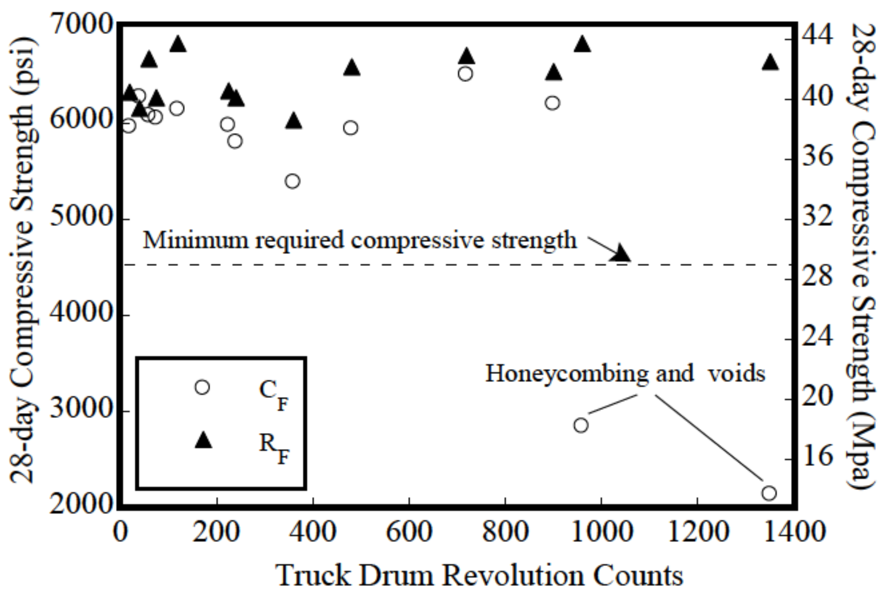

Figure 3.8 Box plot for f'cm$_{28}$ for field mixtures mixed at 4 and 8 rpm.

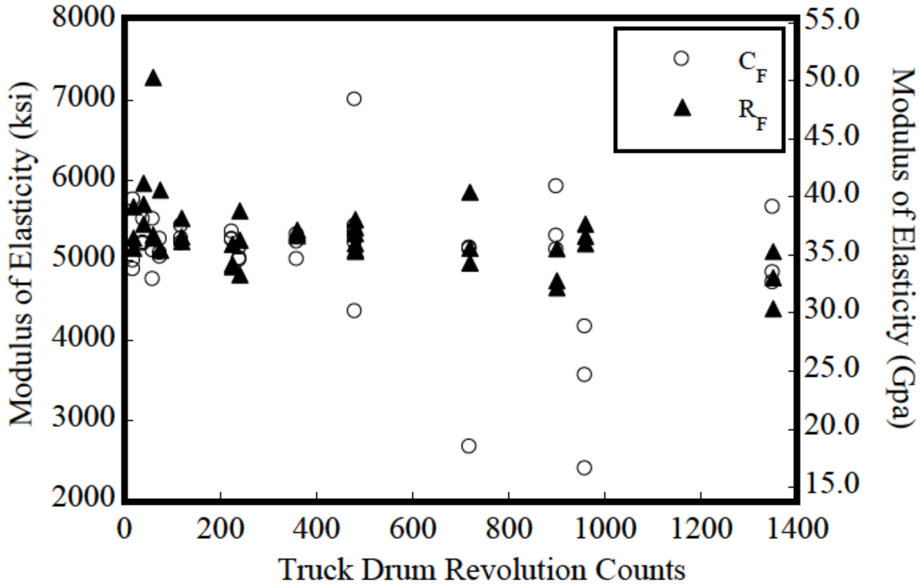

Figure 3.9 MOE for field-mixed mixtures Mixed for different DRC

.

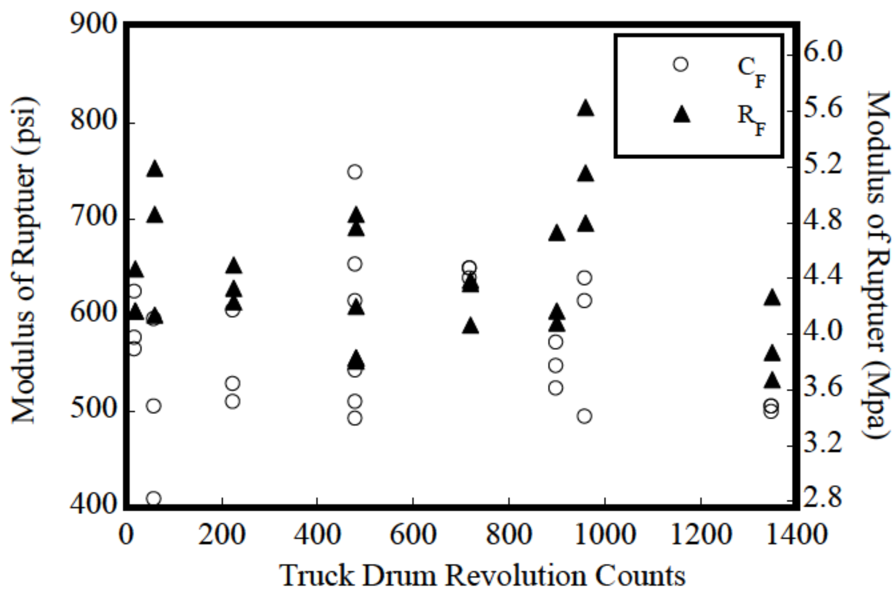

Figure 3.10 Box plot for MOR for the field mixtures.

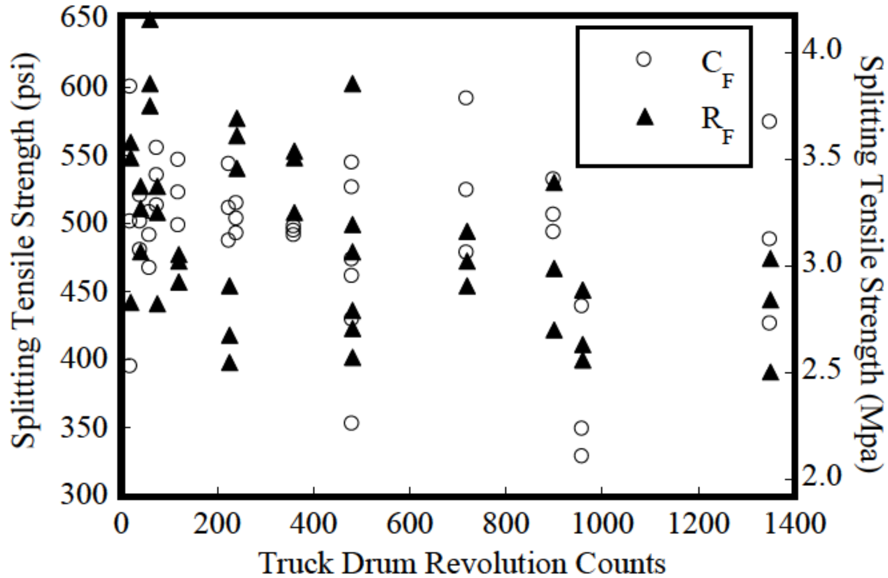

Figure 3.11 Splitting tensile strength for field-mixed mixtures mixed for different DRC.

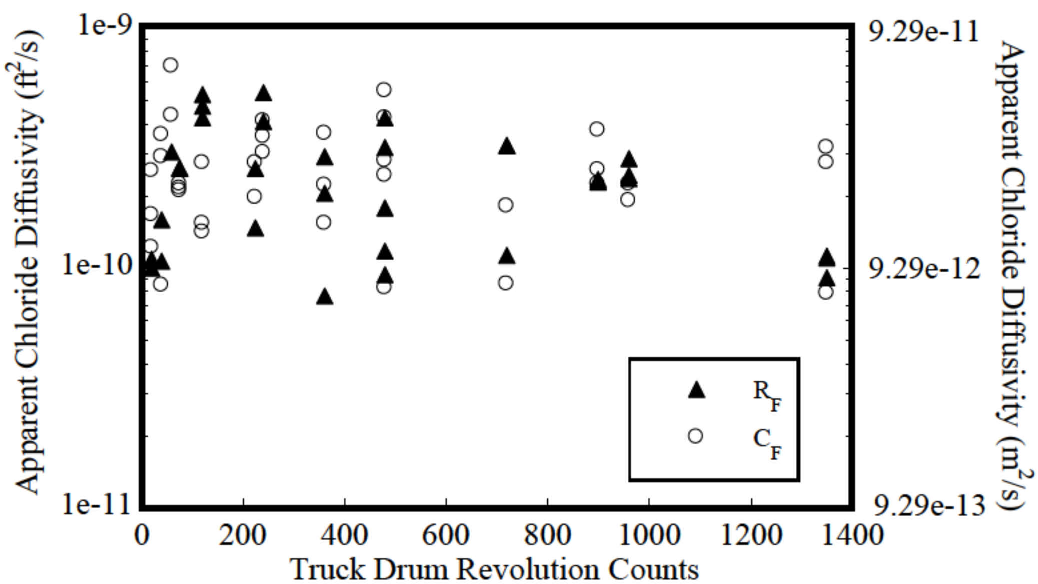

Figure 3.12 Box plot for chloride diffusion coefficient for field-mixed Concrete mixed at different mixing speeds.

Chapter 4 SUMMARY

The objectives of this research are to determine if existing limits in ASTM, WSDOT and other SHA specifications on 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 time of mixing, 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 mixture 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.

4.1 CONCLUSIONS

This section is divided in two sub-sections. The first sub-section contains the influence of mixing time and DRC on the characteristics of laboratory-mixed concrete. The second sub-section summarized the findings on the influence of mixing time and DRC on the characteristics of field-mixed concrete.

4.1.1 Influence of Mixing Time and Mixer Speeds for Laboratory-mixed Concrete

1) Mixing time has no significant influence on the entrapped and entrained air content for the all mixtures mixed up to 60 minutes at 8 and 15 rpm. However, when mixed to 180 minutes, the mixture containing AEA exhibited a significant decrease in entrained air content and the mixtures without AEA exhibited a slight increase in air content.

2) 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 loss and the mixtures containing high dosage of retarders exhibited lower rates of slump loss. Also, higher mixing speeds accelerated the slump loss for all mixtures.

3) The apparent chloride diffusivity and the freeze-thaw performance of the concrete mixtures mixed in the laboratory was not significantly influenced by mixing time up to 60 minutes and at mixing speeds up to 15 rpm.

4) Results indicate that the f'cm, MOE, MOR, and STS for the laboratory-mixed concrete exhibits no significant reduction in characteristics 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 reduction in concrete characteristics was related to low workability, which resulted in specimens containing honeycombing.

4.1.2 Influence of Drum Revolution Counts for Laboratory-mixed Concrete

1) Mixtures with no AEA exhibited no statistically significantly difference in mean entrapped air content for mixtures mixed up to 900 laboratory DRCs. Similar result was observed for the mixtures containing AEA.

2) The slump decreases as a function of the laboratory DRCs for all the mixture types but decreases at different rate. The slump values decrease as a function of laboratory DRCs. Models for slump as a function of laboratory DRCs were developed for the difference mixtures types. Results show that there is significant scatter in slump loss values for the difference mixtures.

3) The hardened characteristics of concrete (f'cm, MOE, MOR and STS) showed no significant reduction when mixed for up to 2700 laboratory DRCs for mixtures that maintained sufficient workability and castability. However, for mixtures mixed for 2700 laboratory DRCs that exhibited low workability and castability (which resulted

honeycombing in the specimens), a detrimental reduction in f'cm, MOE, MOR, and STS was observed.

4) Results indicate that laboratory DRCs up to 900 do not significantly influence the apparent chloride diffusivity and freeze-thaw performance of the concrete mixtures mixed in the laboratory.

4.1.3 Influence of Mixing Time and Mixer Speed for Field-mixed Concrete

1) Mixing times up to 120 minutes do not significantly influence the entrapped air content of 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 accelerate the slump loss of field-mixed mixtures.

3) Field-mixed mixtures mixed at faster mixing speeds and longer mixing times exhibited lower compressive strengths. This is due to loss of slump and lack of workability, which resulted in 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 do 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 chemical admixtures exhibited no reduction in concrete characteristics after 120 minutes of mixing. The STS decreased with increased mixing time.

4.1.4 Influence of truck DRCs for Field-mixed Concrete

1) Entrapped air for the field-mixed concrete does not correlate with truck DRCs.

2) The slump of field-mixed concrete decreases with increasing number of truck DRCs. However, the rates of slump loss are significantly different for mixtures with retarders and mixtures without retarders.

3) The compressive strength does not correlate with truck DRCs. However, very high truck DRCs can result in poor workability and honeycombing in the specimens. Low workability and castability resulted in lower compressive strengths for mixtures without retarders. In addition, mixtures containing retarders exhibited better workability even at higher truck DRCs. The compressive strength of mixture containing retarders was not significantly influenced when mixed up to 1350 truck DRCs.

4) Results indicate that the MOE, MOR, and STS do not correlate with the truck DRCs. Mixtures mixed for high truck DRCs that exhibited low workability and castability exhibited significant reductions in MOE, MOR, and STS. However, when mixtures retained sufficient workability for proper consolidation, no significant reduction in the MOE, MOR, and STS was observed at truck DRCs up to 1350.

5) The results indicate that truck DRCs does not significantly influence the apparent chloride diffusivity of field-mixed concrete for truck DRCs up to 1350.

The results from this research indicate that time and drum revolutions are correlated with the fresh characteristics of concrete. However, mechanical characteristics do not correlate with time and drum revolution. Although these existing limits are easily assessed, they could require that concrete of sufficient quality be discarded. An alternative approach for concrete acceptance could include slump and/or some other test that assesses castability.

Bibliography

AASHTO. 2013. “AASHTO M 157-11 Standard Specification for Ready-Mixed Concrete”. AASHTO.

ACI 304 Committee. 2000. “Guide for Measuring, Mixing, Transporting, and Placing Concrete.” *ACI Materials Journal*, January.

American Petroleum Institute. 2002. “API SPEC 10A Specification for Cements and Materials for Well Cementing.” *American Petroleum Institute*.

Barnett, S. J., M. N. Soutsos, S. G. Millard, and J. H. Bungey. 2006. “Strength Development of Mortars Containing Ground Granulated Blast-Furnace Slag: Effect of Curing Temperature and Determination of Apparent Activation Energies.” *Cement and Concrete Research* 36 (3): 434–40.

Beaufait, F, and P Hoadle. 1973. “Mix Time and Retempering Studies on Ready-Mixed Concrete.” *Journal Proceedings* 70 (12): 810–13.

Beitzel, H. 1981. “Effect of the Mixing Time on the Quality of the Mixing.” *Precast Concrete* 12 (9): 403–8.

Bouzoubaâ, N, M. H Zhang, and V. M Malhotra. 2000. “Laboratory-Produced High-Volume Fly Ash Blended Cements: Compressive Strength and Resistance to the Chloride-Ion Penetration of Concrete.” *Cement and Concrete Research* 30 (7): 1037–46.

C09 Committee. 2013. “ASTM C94/C94M - 13b Standard Specification for Ready-Mixed Concrete.” *ASTM International* 04.02.

Kırca, Ö, L Turanli, and T Erdoğan. 2002. “Effects of Retempering on Consistency and Compressive Strength of Concrete Subjected to Prolonged Mixing.” *Cement and Concrete Research* 32 (3): 441–45.

Lobo, Cl, and Rd Gaynor. 2006. “Chapter 45: Ready-Mixed Concrete.” In *Significance of Tests and Properties of Concrete and Concrete-Making Materials*, edited by Jf Lamond and Jh Pielert, 533–533–15. 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International. http://www.astm.org/doiLink.cgi?STP37763S.

Nehdi, M, and S Al-Martini. 2009. “Coupled Effects of High Temperature, Prolonged Mixing Time, and Chemical Admixtures on Rheology of Fresh Concrete.” *Materials Journal* 106 (3): 231–40.

Ravina, D. 1975. “Retempering of Prolonged-Mixed Concrete with Admixtures in Hot Weather.” *ACI Journal Proceedings* 72 (6): 291–95.

———. 1996. “Effect of Prolonged Mixing on Compressive Strength of Concrete with and without Fly Ash And/or Chemical Admixtures.” *Materials Journal* 93 (5): 451–56.

Trejo, D, and J Chen. 2014. “Influence of Transport Parameter on Concrete Characteristics”. Washington State Department of Transportation.

Trejo, D, and L Prasittisopin. 2014. “Effects of Mixing Variables on Early-Age Characteristics of PC Systems.” *Accepted for Publication ACI Material Journals*.

Vickers Jr., Thomas M., Stephen A. Farrington, Jeffrey R. Bury, and Lynn E. Brower. 2005. “Influence of Dispersant Structure and Mixing Speed on Concrete Slump Retention.” *Cement and Concrete Research* 35 (10): 1882–90.