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Influence of Truck Drum Revolution Count on Fresh and Hardened Concrete Characteristics

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Most specifications for ready mixed concrete limit the truck drum revolution counts (DRCs) to 300 revolutions 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 International in 1958, research is needed to determine if these limits are still applicable. Results from laboratory and field research indicate that, in most cases, extended DRCs (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 placed and cast. Results also indicate that different mixtures exhibit a wide range of slump and slump-loss values, and correlation of fresh performance; the 300 truck DRC could not be validated in this research.

Keywords: compressive strength; diffusivity; drum revolution count; extended mixing; freezing and thawing; modulus of elasticity; modulus of rupture; tensile strength; workability.

INTRODUCTION AND BACKGROUND

ASTM International first published ASTM C94, "Standard Specification for Ready Mixed Concrete," in 1935. This standard specification required that ready mixed concrete 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 drum revolution counts (DRCs) to no more than 300 revolutions before discharge. Many state highway agencies specify DRC limits for ready mixed concrete based on this ASTM standard. However, significant improvements in mixing equipment, cement production, and admixture technology have occurred since this specification 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, yet 30 state highway agencies still specify limits on truck DRCs (Prasittisopin 2013). 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 ready mixed concrete.

Ready mixed concrete can be subjected to continuous mixing and/or agitation during transport from the concrete plant to construction sites. Even though many specifications limit the truck DRC to no more than 300 DRCs, many construction projects require longer times to transport the concrete, requiring higher DRCs. This can be a result of long transport distances, traffic, and delays in construction, and may result in decreased workability and placeability. Low workability can result in difficult placements and may result in increased voids and honeycombing of the concrete. These conditions could reduce the mechanical properties and durability characteristics of the concrete. DRC limits imply 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. A more comprehensive review is included in Trejo and Chen (2015).

Vickers 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 increasing DRCs. Trejo and Chen (2015) observed similar results.

Ravina (1996) evaluated the compressive strength of mixtures containing fly ash, water-reducing admixture, 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) also studied the influence of retempering after prolonged mixing. The authors reported that mixtures mixed at 4 rpm for 240 minutes (960 DRCs) exhib-

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ited significant slump loss. However, the 7- and 28-day compressive strengths increased. The authors hypothesized that the increase in strength was a result of the loss of water due to evaporation, which led to a decrease in the water-cement ratio (*w*/*c*). The authors also hypothesized that the increase in strength was possibly 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). Increased compressive strengths could result in improvements of other mechanical properties. However, research on the influence of DRCs also shows that workability decreases with increased DRCs. 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." Clearly, some minimum workability is required for most concrete placements. However, placing limits on DRCs can present challenges to users, especially when extended times to discharge are required. Since the DRC limit was established, significant changes have occurred in the concrete industry. The changes include the use of newer chemical admixtures, changes in the cement production process (for example, fuel type, grind), and more advanced mixing equipment. Yet specifications in many state highway agencies, the American Association of State Highway Transportation Officials (AASHTO), and the American Concrete Institute (ACI) still place limits on the DRCs (ASTM C94/C94M-13b; AASHTO 2013; ACI Committee 304 2000). Current DRC limits need to be justified based on current technology to ensure concrete construction remains an economically viable construction option. This research investigates the validity of these DRC limits.

RESEARCH SIGNIFICANCE

Despite many advances in the concrete industry, current specifications on DRC limits for ready mixed concrete have been in place without change since 1958. Limited research has been performed to assess how DRCs influence the performance of more modern concrete and research is needed to assess whether the original DRC limits, which are 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 ready mixed concrete.

MATERIALS AND EXPERIMENTAL PROGRAM

Eleven coarse aggregates were identified and selected for use in the concrete mixtures. These were selected to represent a wide range of concretes currently used in practice, and selection of these aggregates was based on the coarse aggregate characteristics. All coarse aggregates are from the State of Washington and considered to be hard and durable (LA Abrasion < 20). The specific gravity of the aggregates ranged from 2.58 to 2.82 and the absorption values ranged from 0.6% to 3.3%. Of the 11 coarse aggregates, one met No. 56, seven met No. 57, and three met No. 67 grading limits (ASTM C33/C33M). All aggregates have been approved by the Washington State Department of Transportation (WSDOT) for use as coarse aggregate in ready mixed concrete. More details on the aggregates can be found in Trejo and Chen (2015). Type I/II ordinary portland cement (specific gravity = 3.15), Class F fly ash, and slag were obtained from Centralia, WA. The chemical compositions of the materials are shown in Table 1. Initial setting time of the cement paste at normal consistency (*w*/*c* = 0.3) was 135 minutes and final setting time was 165 minutes. In addition, the setting time of cement mortar was investigated using Ottawa graded standard sand following ASTM C807. Results indicate that the setting time of the mortar is approximately 140 minutes.

Table 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

Three types of chemical admixtures (water-reducing admixture, retarder, and air-entraining agent) were used in the research program. The water-reducing admixture and retarders met ASTM C494 Type A, B, and D requirements, and the air-entraining agent met ASTM C260 requirements.

This research consisted of a laboratory study and a field study. The laboratory study assessed the fresh and hardened concrete characteristics of several mixtures mixed for different DRCs using a laboratory rotary concrete mixer (3.5 ft^3 [0.01 m^3]). 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 2. The laboratory mixture groups consisted of four general classifications: control; mixtures containing supplementary cementitious materials (SCM_L); mixtures containing recommended dosages of chemical admixtures ($AD_{R,L}$); and mixtures containing high dosages of chemical admixtures ($AD_{H,L}$). Note that "recommended dosages" are dosages recommended by the manufacturer of the chemical admixture. The "L" subscript indicates laboratory-made specimens. The $AD_{R,L}$ group consists of mixtures containing water-reducing admixture (W_L), air-entraining agent (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 air-entraining agent ($RA_{H,L}$). The subscript "H" represents mixtures containing

Table 2—Experimental plan for laboratory study

Group	Subgroup	Coarse aggregate type	DRC	Supplementary cementitious materials 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% and 30%)‡	✓	✓	✓	✓
	SL_L	1	40, 120, 225, 480, 900	Slag (20% and 40%)‡	✓	✓	✓	✓
$AD_{R,L}$	W_L	1	40, 120, 225, 480, 900	Water-reducing admixture A and B	✓	✓	✓	✓
	A_L	1	40, 120, 225, 480, 900	Air-entraining agent A and B	✓	✓	✓	✓
	$R_{R,L}$	1	40, 120, 225, 480, 900	Retarder A and B	✓	✓	✓	✓
$AD_{H,L}$	$R_{H,L}$	1	40, 120, 225, 480, 720, 900, 1350, 1440, 2700	Retarder B and C	✓	✓	✓	Not tested
	$RA_{H,L}$	1	40, 120, 225, 480, 720, 900, 1350, 1440, 2700	Retarder B and air-entraining agent B	✓	✓	✓	Not tested

*Only select DRCs are assessed.

†Percent replacement by weight.

‡Only assessed for mixtures containing coarse aggregate source 1.

Note: A, B, and C indicate manufacturers.

Table 3—General mixture proportions for laboratory mixtures

Subgroup	Coarse aggregate, lb/yd^3 (kg/m^3)	Fly ash, lb/yd^3 (kg/m^3)	Cement, lb/yd^3 (kg/m^3)	Water, lb/yd^3 (kg/m^3)	Supplementary cementitious materials, lb/yd^3 (kg/m^3)	Admixture
C_L	1542 to 1752 (915 to 1039)	1070 to 1297 (635 to 769)	647 to 739 (384 to 438)	298to 340 (177 to 202)	0	0
W_L, $R_{R,L}$, $R_{H,L}$, $RA_{H,L}$	1730 (1026)	1200 to 1306 (712 to 775)	623 to 674 (370 to 400)	286 to 315 (170 to 186)	0	Water-reducing admixture and retarder
FA_L, SL_L	1735 (1029)	1163 to 1307 (690 to 775)	396 to 539 (235 to 319)	260 to 313 (154 to 186)	117 to 202 (69 to 120)	0
A_L	1730 (1026)	1204 to 1324 (714 to 785)	609 to 674 (361 to 399)	280 to 314 (166 to 186)	0	Air-entraining agent

high dosages of admixtures. In addition to the laboratory experimental plan shown in Table 2, three mixtures (subgroups $R_{H,L}$ and $RA_{H,L}$ in Table 2) were also evaluated for the modulus of elasticity (MOE), modulus of rupture (MOR), and splitting tensile strength (STS). Also, the freezing-and-thawing performance of two mixtures containing air-entraining agent and two mixtures without air-entraining agent were assessed (subgroups A_L and C_L).

The laboratory mixtures were proportioned using ACI 211.1. 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 in. (101 mm). Because the mixtures contained different constituent materials, the amount of the paste content was adjusted to target the 4 in. (101 mm) slump. General mixture proportions for the laboratory mixtures are shown in Table 3. These mixtures were mixed following ASTM C192-13a. After the standard mixing process, the mixtures were further mixed to the number of DRCs shown in Table 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 in. (101 mm) and the f_c' was 4500 psi (31.0 MPa). Mixture proportions for the field-mixed concrete were 3160 lb/yd^3 (1875 kg/m^3) of aggregate (fine aggregate/coarse aggregate [FA/CA] = 0.71), 611 lb/yd^3 (362 kg/m^3) of cement, and the w/c was 0.44. The specific gravity of the coarse aggregate and fine aggregate for the field-mixed concrete was 2.68 and 2.62, respectively. The coarse aggregate met the ASTM No. 57 aggregate gradation. The temperature during field mixing averaged approximately 80°F (26.5°C) over the 3 days. Specimens were maintained in the field for 1 day and then transported to the lab and placed at a standard curing regime until testing (72°F [22°C]) and > 90% RH). The laboratory plan for the field study is shown in Table 4.

Six field mixtures (three each of two mixture proportions) were mixed and cast over a 3-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 to 1350 DRCs. Samples

Table 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.

were fabricated at predetermined DRCs to assess the fresh and hardened concrete characteristics. Although this paper focuses on the influence of DRCs, it should be noted that these mixtures also exhibited different mixing times. Mixing times varied from 90 to 338 minutes for the field mixtures and 5 to 180 minutes for the laboratory mixtures (Trejo and Chen 2015).

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. In addition, a select number of mixtures were assessed for freezing-and-thawing 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.

TEST RESULTS AND ANALYSIS—LABORATORY STUDY

Results on the fresh concrete characteristics for the laboratory-mixed concrete are presented first. Fresh concrete characteristics assessed 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 in the laboratory for different DRCs. The mechanical properties assessed include f'_{cm}, MOE, MOR, and STS. The durability characteristics include the freezing-and-thawing 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 values of concrete characteristics mixed for different DRCs. The student t-test was used to compare the means of two groups and the ANOVA test was used to compare the means of three or more groups. The null hypotheses of both tests are 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. The alternative hypothesis for the ANOVA test is that at least one of the 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 this research, a 95% 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.

Fresh concrete characteristics of laboratory mixtures

Due to space limitations, the results of the testing of air content is not shown; this information and additional information on slump and slump loss can be found in Trejo and Chen (2015). However, 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.

Slump values decreased as a function of DRCs for all four laboratory groups tested (Control, SCM_L, $AD_{R,L}$, and $AD_{H,L}$). 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 herein 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

$$n\text{-}slump_{\mathrm{Control_L}}(n) = 1.06 - 0.000685n \quad (1)$$

$$n\text{-}slump_{\mathrm{SCM_L}}(n) = 1.09e^{-0.00123n} \quad (2)$$

$$n\text{-}slump_{\mathrm{AD_{R,L}}}(n) = 1.06e^{-0.00153n} \quad (3)$$

$$n\text{-}slump_{\mathrm{AD_{H,L}}}(n) = 1.10e^{-0.0014n} \quad (4)$$

where *n* is the number of laboratory DRCs. Equation (1) is based on data from laboratory DRCs (*n*) between 40 and 1400; Eq. (2) and (3) are based on data between 40 and 900 laboratory DRCs, and Eq. (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

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

Figure 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 mixtures. The slump and slump loss exhibit significant variation between mixtures types.

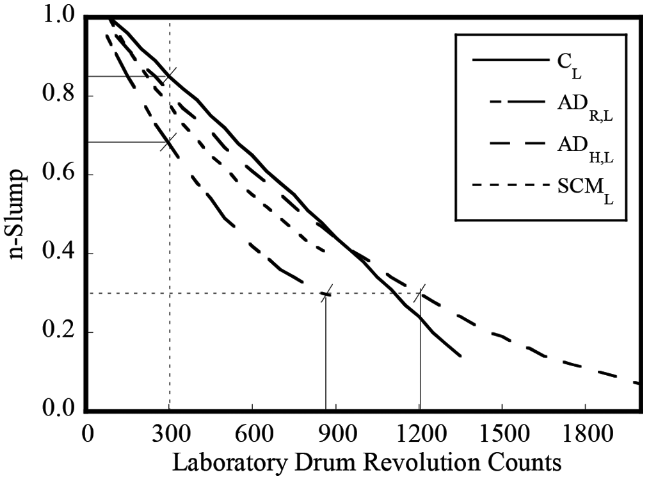

*Fig. 1—*n-slump *model for all laboratory concrete groups.*

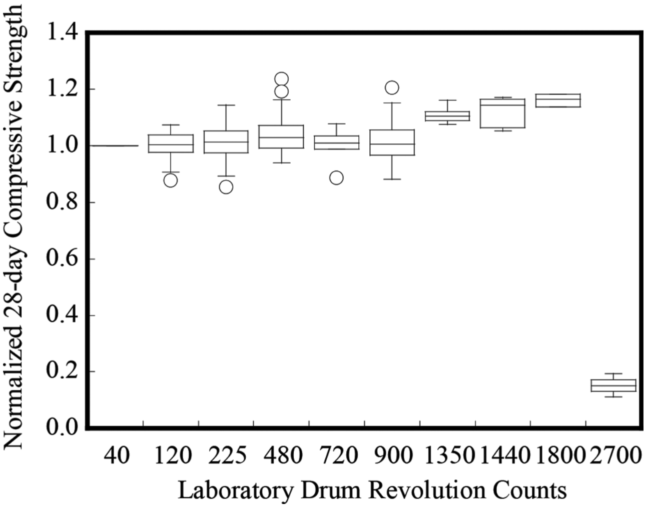

Fig. 2—Laboratory 28-day f'_{cm} *of non-air-entraining agent mixture versus mixing DRC.*

Hardened properties for laboratory mixtures

The laboratory-mixed concrete was assessed for f'_{cm}, MOR, MOE, STS, D_a, and freezing-and-thawing performance. This section presents the results on the effects of laboratory-mixer DRCs on these characteristics. Figure 2 shows a box plot for the normalized f'_{cm28} at different laboratory DRCs. The f'_{cm28} is normalized to the average f'_{cm28} of the specimen mixed for 40 laboratory DRCs. The results from the laboratory study indicate that DRCs have no negative influence on the f'_{cm28} up to 1800 DRCs. However, at 2700 DRCs in the laboratory mixer, the f'_{cm28} 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 supplementary cementitious materials met the 28-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 supplementary cementitious materials (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 supplementary cementitious materials replacement.

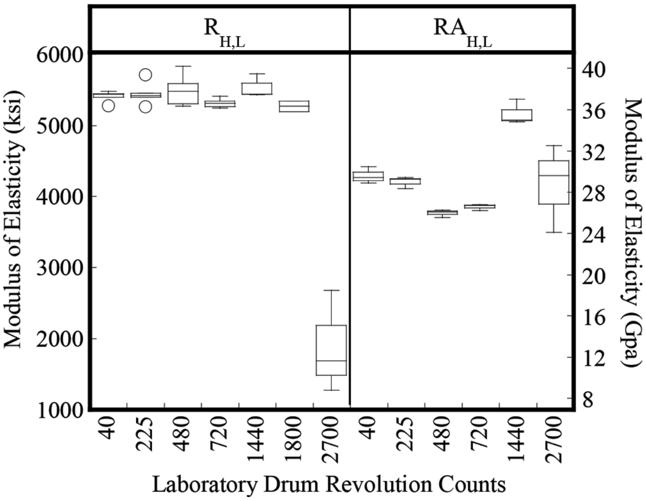

Fig. 3—Box plot for MOE for $AD_{H,L}$ *mixtures.*

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 air-entraining agent and, as such, these mixtures exhibited higher initial slump values and lower compressive strengths.

Figure 3 shows the MOE as a function of laboratory DRCs for the $R_{H,L}$ and $RA_{H,L}$ mixtures. An ANOVA analysis 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 (p-value < 0.001). The results show that only the MOE of the mixture mixed for 2700 laboratory DRCs exhibited a significant reduction. The mixture mixed for 2700 laboratory DRCs exhibited low slump values and low workability, which resulted in honeycombing in the specimens. Specimens containing honeycombing exhibited lower MOE values. ANOVA testing of the MOE data for the $RA_{H,L}$ indicates that mixtures mixed for different DRCs exhibited statistically significant differences in the mean MOE values (p-value < 0.001). Data indicate 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 Section 8.5.1) based on a 4420 psi (30.5MPa) concrete (the f_c' for this concrete was 5200 psi [35.9 MPa]; 4420 psi [30.5 MPa] is the f_c' assuming 15% reduction in compressive strength due to the entrained air).

The potential influence of laboratory DRCs on MOR was also assessed for the $R_{H,L}$ and $RA_{H,L}$ mixtures. The normalized MOR values as a function of laboratory DRCs for these mixtures are shown in Fig. 4. The MOR for each mixture mixed at different laboratory DRCs are normalized by dividing the average MOR value from the same subgroup 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

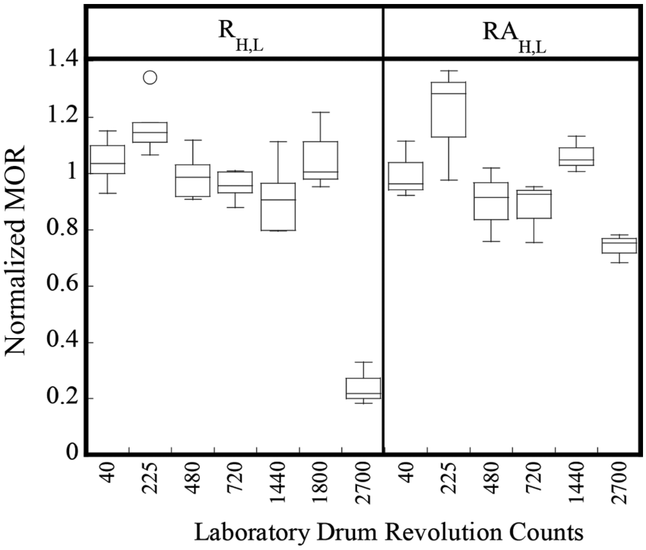

Fig. 4—Box plot for MOR of $AD_{H,L}$ mixtures.

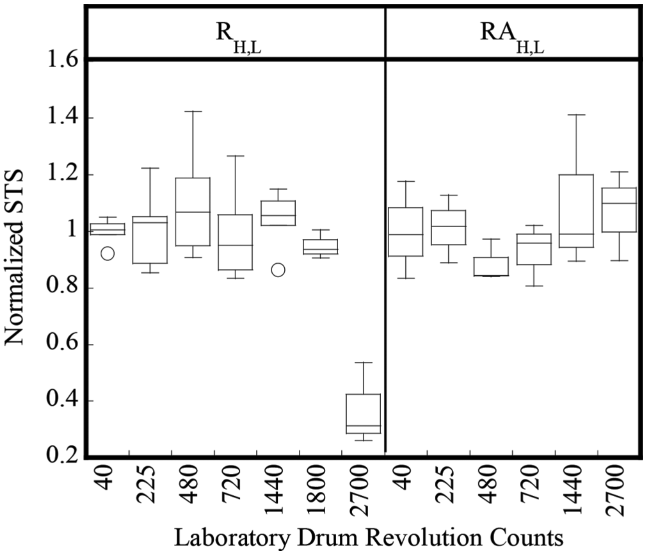

Fig. 5—Box plot for STS of $AD_{H,L}$ mixtures.

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.

Figure 5 shows a box plot for the normalized STS of the $R_{H,L}$ and $RA_{H,L}$ mixtures. The STS for each mixture mixed at different laboratory DRCs are normalized by dividing the average STS value from the same subgroup 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).

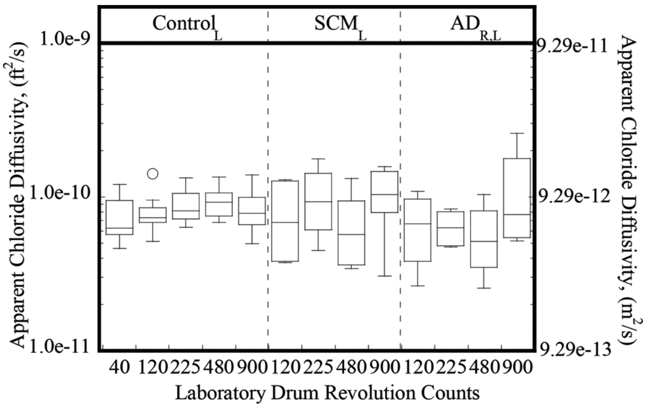

Fig. 6—Box plot for diffusion coefficient for $Control_L$, SCM_L, and $AD_{R,L}$ mixtures.

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 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.

Two mixtures from each of the $Control_L$ and A_L groups were tested for freezing-and-thawing performance. For the A_L group mixtures, the relative dynamic modulus does not significantly differ up to 300 freezing-and-thawing cycles for mixtures mixed for different laboratory DRCs up to 900. For mixtures without air-entraining agent, the relative dynamic modulus of the mixtures mixed for 120, 225, 480, and 900 laboratory DRCs decreased to 60% of the initial value (that is, 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 freezing-and-thawing 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 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

Table 5—Summary table for laboratory study

Concrete characteristics	Laboratory drum revolution counts				
	40	40 to 300	300 to 900	900 to 1800	>1800
Entrapped air content	↔	↔	↔	NA	NA
Entrained air content	↔	↔	↔	NA	NA
Slump	↔	↓	↓	↓	↓
f'_{cm}	↔	↔	↔	↔	↓
MOE	↔	↔	↔↓	↔↑	↓
MOR	↔	↔↑	↔	↔	↓
STS	↔	↔	↔	↔	↓
Freezing-and-thawing performance	↔	↔	↔	NA	NA
Chloride diffusivity	↔	↔	↔	NA	NA

Notes: ↔ indicates no significant change; ↑ indicates value increased; and ↓ indicates values decreased.

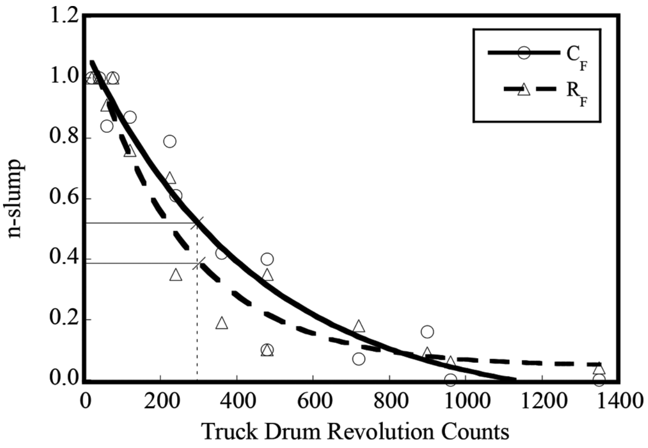

Fig. 7—n-slump *model for field-mixed concrete.*

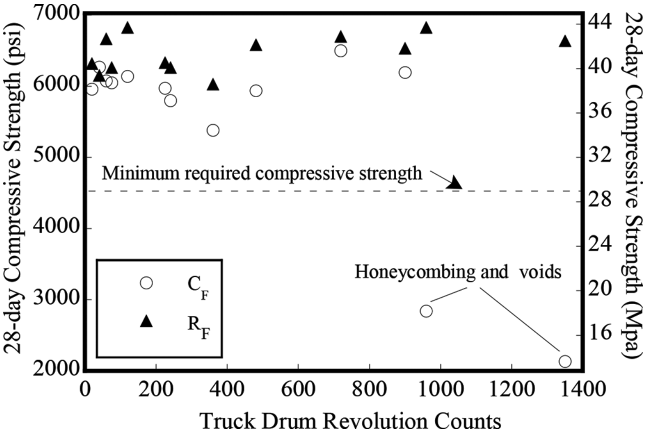

Fig. 8—Box plot for f'_{cm28} *for field mixtures mixed at 4 and 8 rpm.*

DRCs in the laboratory. The freezing-and-thawing performance and chloride diffusivity of the laboratory-mixed specimens exhibited no significant reductions when mixed up to 900 DRCs in the laboratory mixer.

TEST RESULTS AND ANALYSIS—FIELD STUDY

Fresh concrete characteristics for field mixtures

The entrapped air contents for the field-mixed concrete ranged from 1.6 to 3.1%. 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 change in entrapped air content as a function of truck DRCs in these mixtures was a 1.2% increase. These variations in entrapped air content are considered 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 Fig. 7. Data for actual slump values can be found in Trejo and Chen (2015). The *n-slump* as a function of truck DRCs mixed at different mixing speeds for the C_F mixtures can be estimated as follows

$$n\text{-}slump_{C_F}(n) = -0.095 + 1.12 \times e^{-0.0022n} \tag{6}$$

$$n\text{-}slump_{R_F}(n) = 0.045 + 1.12 \times e^{-0.0039n} \tag{7}$$

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

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 as well as 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.

Hardened properties for field mixtures

Figure 8 shows the 28-day f'_{cm} for the C_F and R_F mixtures. Results indicate that a high number of truck DRCs significantly reduced the f'_{cm28}. The mixtures that exhibited lower compressive strengths also exhibited significant amounts of honeycombing and voids. However, the f'_{cm28} 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 (~1/2 in. [12 mm]) 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. Results indicate that instead of a truck DRCs limit, workability, placeability, and/or castability, which may

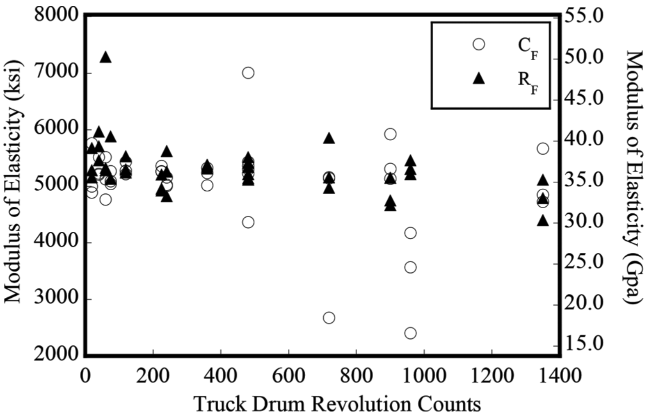

Fig. 9—MOE for field-mixed mixtures mixed for different DRC.

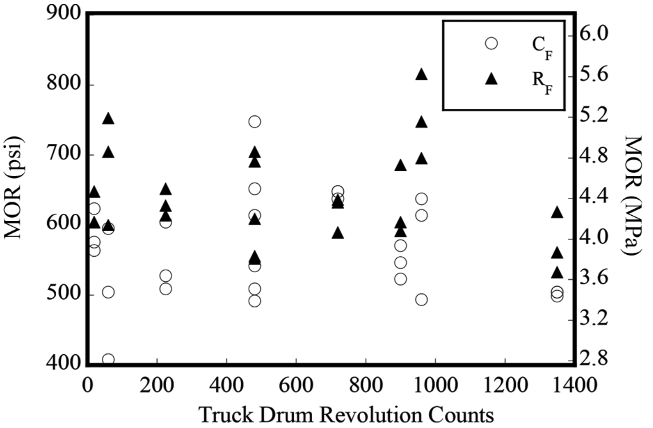

Fig. 10—Box plot for MOR for field mixtures.

be measured by slump, may be a better indicator of whether a concrete mixture is acceptable for discharge and placement. Further research is needed in these areas. The truck DRCs limit may be applicable for the C_F mixtures, but results indicate that the truck DRCs limit is likely not applicable for the R_F mixtures.

Figure 9 shows the MOE results for the C_F and R_F mixtures. The analyses of the influence of truck DRCs on MOE 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.

The MOR values were also assessed for the field mixtures. Figure 10 shows these results. Results indicate that the C_F and R_F mixtures exhibited no statistically significant difference in the mean MOR for mixtures mixed at different truck DRCs up to 1350 truck DRCs. Note that larger scatter in MOR values were observed at higher DRCs.

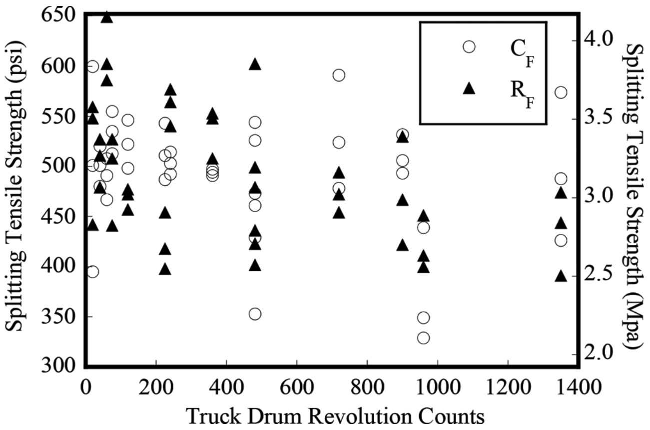

Fig. 11—Splitting tensile strength for field-mixed mixtures mixed for different DRC.

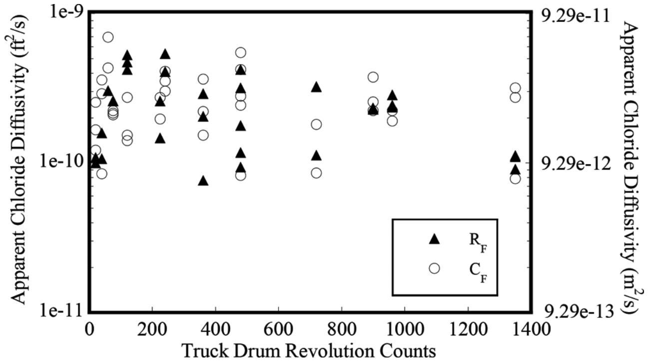

Fig. 12—Box plot for chloride diffusion coefficient for field-mixed concrete mixed at different mixing speeds.

Figure 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 Fig. 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 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 the concrete can no longer 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.

SUMMARY AND CONCLUSIONS

Limits on truck DRCs have been in specifications since 1958. The original intent of these limits was likely to ensure

Table 6—Summary table for field study

Concrete characteristics	Field drum revolution counts			
	20	21 to 300	301 to 900	901 to 1350
Entrapped air content	↔	↔	↔	↔
Entrained air content	NA	NA	NA	NA
Slump	↔	↓	↓	↔↓
f'_{cm}	↔	↔	↔	↔↓
MOE	↔	↔	↔↓	↔↓
MOR	↔	↔	↔	↔
STS	↔	↔	↔	↔↓
Freezing-and-thawing performance	NA	NA	NA	NA
Chloride diffusivity	↔	↔	↔	↔

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 the industry—30 state highway agencies 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 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 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 are likely correlated. This research indicates that DRC limits could be specified if slump were correlated to placeability, castability, or workability.

The results from this study indicate that 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.

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 poor castability, and specimens that exhibited honeycombing exhibited the reduced properties. 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 admixtures can exhibit good workability even after experiencing DRCs much greater than the current limit of 300.

The results show that concrete performance is 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 mixtures assessed in this research. However, the correlations are different for mixture types. Results indicate that the DRC limit, in this case 300 counts, may provide a conservative 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 and placeability, which can result in sufficient mechanical properties and durability characteristics. Although slump provides some indication of workability, concrete may be placeable even at very low slump values. Slump may be a better indicator than DRC for acceptance of concrete mixtures, but this was not determined to be the case for low-slump concrete. For low-slump concrete, a methodology or test that can assess the placeability for different construction types is needed. This test could likely provide for placeable concrete that can provide safe and durable long-term-performance. Further research is needed to develop this test.

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