

**EFFECT OF A RHEOLOGY MODIFIER ON SETTLEMENT CRACKING
OF CONCRETE**

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ABSTRACT

Thirty-one test specimens containing concrete with a 27 percent cement paste content and a water-to-cement ratio of 0.45 were used to evaluate the effectiveness of a rheology modifier in the form of a dry viscosity modifying admixture (dosed at 0.05% of mixture material dry weight) on settlement cracking. The results show that settlement cracking increases as the slump of the mixture increases. The addition of the viscosity modifying admixture reduces settlement cracking compared to the mixtures without the addition.

Keywords: concrete, crack reduction technologies, settlement cracking, slump, viscosity modifying admixture.

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Chapter 1 INTRODUCTION

Cracking of reinforced concrete bridge decks represents a significant problem in terms of bridge integrity and maintenance costs. Such cracks significantly reduce the service life of bridge decks by accelerating freeze-thaw damage and exposing the steel reinforcement to corrosive salts. These cracks provide paths for water, oxygen, and deicing salts to penetrate through the bridge decks and reach reinforcing steel; these paths can extend partially or entirely through the bridge deck. After water penetrates into bridge decks, freeze-thaw damage occurs because of the expansion of frozen water in the cracks. Moreover, as deicing salts are added for the purpose of ice removal from the decks, corrosion of reinforcement is significantly increased in the presence of cracks. Sodium chloride and calcium chloride are the most common types of deicing salts and have been used for many decades for this purpose. When the concentration of chlorides from these chemicals reaches the critical chloride corrosion threshold, corrosion starts and expansive corrosion products cause delamination and spalling in the bridge deck. Chlorides can also degrade the epoxy coating protecting reinforcement against corrosion (Darwin et al. 2011). The National Bridge Inventory (NBI) states that bridge deck deterioration caused by concrete distress and reinforcement corrosion is the main reason for structural deficiency of bridges (Russell 2004).

Concrete has a high compressive strength but a low tensile strength; typically, concrete tensile strength is equal to one-tenth of its compressive strength. When tensile stresses in bridge decks exceed the concrete tensile strength, cracks start to develop. Several factors can lead to the development of tensile stresses in concrete in bridge decks, such as the settlement of plastic concrete over reinforcement, plastic shrinkage, drying shrinkage, thermal shrinkage, and traffic loading. These factors are mainly influenced by concrete properties, environmental conditions, construction methods, and structural design of bridges.

In 2005, the annual direct costs of bridge deck corrosion was estimated at \$8.3 billion (Yunovich et al. 2005). Therefore, eliminating or reducing bridge deck cracking is extremely important. Since the 1960s, many transportation agencies have been involved in research programs in order to produce a higher performance and more durable concrete. Prior research at the University of Kansas has identified typical causes and proposed solutions for different types of

cracks such as plastic shrinkage cracking, thermal shrinkage cracking, drying shrinkage cracking, and flexural cracking (Lindquist et al. 2008). The goal of this research has been to eliminate or reduce cracks by improving the materials and construction procedures used for bridge decks. New materials are being applied to improve the internal curing potential using lightweight aggregates. Mineral admixtures and shrinkage reducing admixtures (SRAs) are being applied to improve concrete durability and reduce cracking (Pendergrass and Darwin 2014). This report describes the uses of a mineral rheology modifying admixture to reduce settlement cracking in concrete.

1.1 Settlement/Subsidence Cracking

After placement and consolidation, plastic concrete continues to settle around fixed objects such as reinforcing bars. This settlement can result in the formation of cracks directly above and parallel to the reinforcing bars in bridge decks. Even though cracks may not be visible immediately after the concrete has hardened, weakened planes can develop above the reinforcing bars that can increase the probability of other types of cracking over time (Babaei and Purvis 1995). Inadequate consolidation during the construction of bridge decks can increase the probability of settlement cracking. The key factors affecting settlement cracking include concrete slump, concrete cover, and reinforcing bar size. Settlement cracking can be reduced by increasing concrete cover and reducing concrete slump and reinforcing bar size (Dakhil et al. 1975). The current study targets reducing settlement cracking in bridge decks.

1.2 Technologies to Minimize Settlement Cracking

As discussed in Section 1.1, settlement cracking occurs because of the settlement of plastic concrete above fixed objects, such as reinforcing bars. As plastic concrete settles, cracks that are directly above and parallel to the reinforcing bars start to form because of the extremely low concrete tensile strength at early ages. Researchers have found that the primary factors that affect the formation of settlement cracks are cover thickness, concrete slump, and reinforcing bar size (Dakhil et al. 1975, Babaei and Fouladgar 1997). Figure 1.1 illustrates an increase in the settlement cracking with decreased cover thickness, increased slump, and increased reinforcing bar size (Dakhil et al. 1975). These findings were confirmed by Darwin et al. (2004) and Lindquist et al.

(2005), who observed an increase in crack density on bridge decks as slump increased from 1.5 to 3 in. (40 to 75 mm).

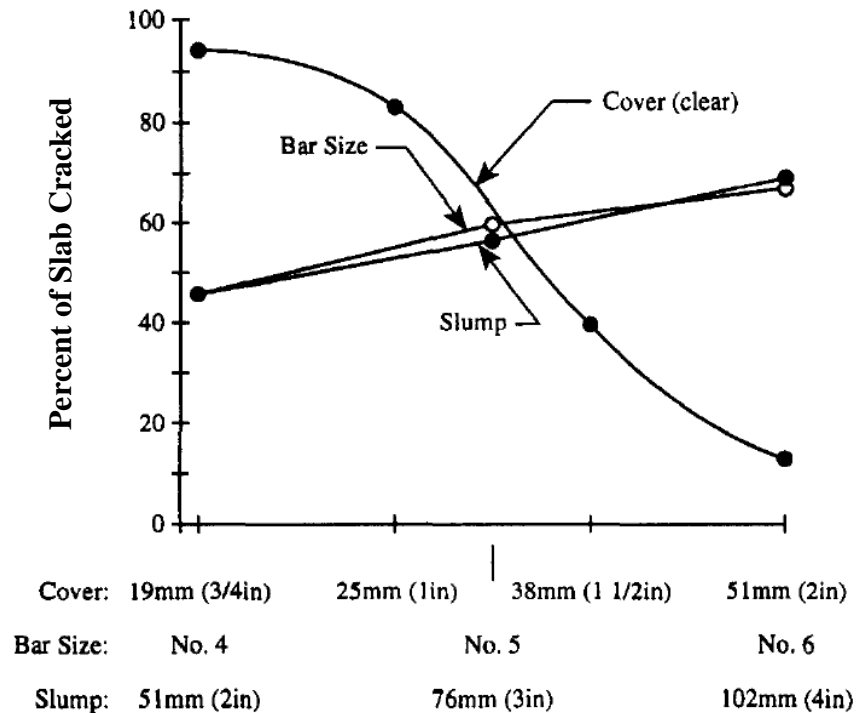


Figure 1.1: The effect of cover depth, concrete slump, and reinforcing bar size on settlement cracking (Dakhil, Cady, and Carrier 1975).

Some evidence exists that indicates that the use of synthetic polymer fibers may reduce settlement cracking. Although they provided no evidence, Suprenant and Malisch (1999) suggested that fibers can reduce the settlement cracking by reducing the amount of bleed water. Certain admixtures, such as rheology modifiers, may reduce the potential for settlement cracking by increasing the cohesiveness or decreasing the bleed water within the plastic concrete.

1.3 Previous Work

Dakhil, Cady, and Carrier (1975) studied the effect of concrete slump, depth of cover, and reinforcing bar size on settlement cracking of plastic concrete. The study included three concrete slumps, three cover depths, and three reinforcing bar sizes. Three specimens were tested for each set of variables, resulting in a total of 108 specimens. Slumps of 2, 3, and 4 in. (50, 70, and 100

mm), concrete covers of 0.75, 1.5, and 2 in. (19, 25, 38, and 51 mm), and bar sizes of No. 4, No. 5, and No. 6 (13, 16, and 19 mm) were investigated to reflect the range of values typically found in bridge decks. 12×12×8 in. (305×305×203 mm) molds were used to cast concrete with a bar attached at each mold at the desired depth by fabricating holes on the mold sides. All specimens were vibrated using a 1 in. (25.4 mm) electrical vibrator, screeded parallel to the orientation of the reinforcing bar, and finished using a wet burlap drag. Decreasing the concrete cover, decreasing the bar size, and using a higher concrete slump led to increased settlement cracking.

In their study, Dakhil, Cady, and Carrier (1975) also investigated the effect of the presence of cracks on the corrosion of reinforcing bars. The corrosion study included specimens with No. 5 (No. 16) reinforcing bars and 0.75 and 1.5 in. (20 and 40 mm) slump. Specimens were moist-cured for a week and then air dried in the laboratory. After that, a five percent (by weight) sodium chloride (NaCl) solution was ponded on the surface of specimens. The researchers followed a method developed by Stratfull (1973) to determine of corrosion activity of the embedded steel bars, that is, steel is corroding when the half-cell potential with respect to a copper/copper sulfate electrode (CSE) is less than -0.35 volts, and not corroding when the potential is greater than -0.30 volts with respect to CSE. Cracked specimens experienced higher corrosion potentials than uncracked, illustrating that settlement cracking increases the corrosion potentials of embedded reinforcing bars.

Babaei and Fouladgar (1997) studied the types of cracking found in bridge deck – plastic shrinkage cracking, settlement cracking, thermal shrinkage cracking, drying shrinkage, and flexural cracking. Practical methods to minimize cracking in bridge decks were provided in this study. Similar to Dakhil et al. (1975), Babaei and Fouladgar considered concrete slump, cover thickness, and reinforcing bar size as the main factors affecting settlement cracking. The researchers linked settlement cracking increases with decreases in cover thickness, increases in slump, and increases in bar size. Babaei and Fouladgar felt that a relatively high cover, 2.5 in. (64 mm), coupled with a moderate slump, 4 in. (100 mm), might prevent settlement cracking in bridge decks as recommended in this study. They also stated that settlement of plastic concrete causes weakened planes above the upper reinforcing bars, and that cracking because of other factors, such as drying shrinkage, can later occur at these weakened planes. Babaei and Fouladgar suggested

that alignment of top and bottom transverse reinforcing bars should be avoided in bridge decks when the upper transverse reinforcement is perpendicular to traffic to minimize the formation of cracking above the bars. Limiting the size of top transverse reinforcing bar to No. 5 (16 mm) was also suggested.

Combrinck and Boshoff (2013) studied how settlement cracking develops in concrete and the effect of revibration on the formation of settlement cracks. Two L-shaped molds consisting of deep and shallow sections were used to ensure differential settlement of plastic concrete. Transparent sides were used to allow the observation of any cracking below the concrete surface. The surfaces of the specimens were kept wet and cured in an environmentally controlled laboratory to prevent plastic shrinkage cracking. Both L-shaped specimens consisting of deep and shallow sections experienced hairline cracking at the boundary between the shallow and deep sections. One of the specimens experienced cracking below the surface. Based on that observation, the researchers determined that the plastic cracks forms from the bottom and spreads upward. This observation was confirmed using numerical analysis.

Combrinck and Boshoff (2013) recommended the use of revibration before final setting to reduce the settlement of concrete around reinforcing bars. To observe the influence of revibration on the concrete strength, two sets of concrete cubes were tested. The first set was revibrated at initial setting while the second set was revibrated at final setting. The results showed that revibrating concrete cubes at initial setting increases the strength while revibrating at final setting decreases the strength.

1.4 Objective and Scope

Slump, concrete cover, and reinforcing bar size are key variables that affect the development of settlement cracks in bridge decks. The first objective of this study was to develop a consistent test procedure to prepare, cure, and test concrete mixtures for settlement cracking. The second objective was to study the effect a rheology modifier on settlement cracking. Settlement cracking was compared for mixtures with and without the rheology modifier. The effect of the rheology modifier on the fresh concrete slump was also analyzed by testing the fresh concrete slump in accordance with ASTM C143 before and after addition of the admixture.

Chapter 2 EXPERIMENTAL PROGRAM

2.1 General

This chapter describes the laboratory work performed in this study. Thirty one mixtures with 27 percent paste content and a water-to-cement ratio of 0.45 were tested. The temperature the plastic concrete ranged from 71 to 75° F (22 to 24° C). Fourteen mixtures in this series served as controls, designated as Control. The remaining 17 mixtures in this series were used to evaluate the effectiveness of a rheology modifier in the form of a viscosity modifying admixture VMA-1 (dosed at 0.05% of mixture material dry weight) on settlement cracking performance. The admixtures used in this study are listed in Table 2.1. A full description of material properties is given in Section 2.2.

Table 2.1: Summary of admixtures used in this study.

Type of Material	Designation	Type	Material
VMA	VMA-1	Viscosity Modifying Admixture	Hydrated Magnesium Aluminosilicate
AEA	AEA-1	Air-Entraining Admixture	Rosin-based
WRA	WRA-1	High-Range Water-Reducing Admixture	Propylene Oxide

* Values of specific gravity and tensile strength provided by manufacturers.

2.2 Materials

This section describes the properties of the materials used in this study.

2.2.1 Cement

Type I/II portland cement meeting the requirements of ASTM C150 was used in this study.

2.2.2 Fine Aggregate

Kansas River sand and pea gravel were used in this study as fine aggregate in all mixtures. The Kansas River sand had a specific gravity of 2.60, a fineness modulus of 2.94, and an absorption of 0.47%. The pea gravel had a specific gravity of 2.61, a fineness modulus of 4.79, and an absorption of 1.42%. The sieve analysis results of the sand and pea gravel are presented in Tables A.1 and A.2 in Appendix A.

2.2.3 Coarse Aggregate

Granite was used as the coarse aggregate in this study. Two gradations of granite, designated B and C, were used to obtain a better gradation and improve the workability of the plastic concrete; Granite B had a MSA of 0.75 in. (19 mm), and Granite C had a MSA of 0.5 in. (13 mm). Both had a specific gravity of 2.62 and an absorption of 0.58%. Granites B and C had fineness moduli of 7.01, and 6.62, respectively. The sieve analyses for Granite B and Granite C are presented in Tables A.3 and A.4 in Appendix A.

2.2.4 VMA-1

VMA-1 is a thixotropic anti-settling and rheology modifying agent consisting of a hydrous magnesium aluminum-silicate. VMA-1 may reduce settlement cracking by decreasing the amount of bleed water and increasing concrete stability and aggregate suspension in the fresh concrete matrix. Adding VMA-1 to concrete may reduce the plastic concrete slump. VMA-1, however, reduces the plastic concrete yield stress, which provides high flowability and pumpability, but maintains high stability for fresh concrete when the shear force is removed.

2.2.5 Concrete Mixture

A mix design program (KU Mix), developed at the University of Kansas, was used to optimize the aggregate gradations of the concrete mixtures. Five aggregates were used to improve the concrete workability using the optimization program. Further discussion and information about aggregate optimization and the KU Mix program is presented by Lindquist et al. (2008, 2015). The KU Mix program can be downloaded from <https://iri.drupal.ku.edu/node/43>. The mixture proportions for the Control series are presented in Table 2.2 on a cubic yard saturated-surface-dry (SSD) basis. Mixture proportions for concrete containing the viscosity modifying admixture were identical to the control mixtures with the exception of the addition of VMA-1 at 0.05% of total

mixture dry weight. Further discussion of concrete mixtures and results is presented in Chapter 3. The volume of the VMA, WRA, and AEA were not considered as materially altering the volume of the concrete.

Table 2.2: Mixture Proportions of Control mixtures, SSD cubic yard batch.

Material Type	Material	Quantity
Cement	Type I/II	593 lb
Water	---	267 lb
Aggregate 1	Granite B	636 lb
Aggregate 2	Granite C	762 lb
Aggregate 3	Pea Gravel	629 lb
Aggregate 4	Sand	837 lb
WRA	WRA-1 (mL)	420 mL
AEA	AEA-1 (mL)	61 mL

2.3 Experimental Methods

Test specimens, mixing and curing procedures, and test measurements are described in this section.

2.3.1 Specimen Molds

Settlement cracking specimens were 12 × 12 × 8 in. (305 × 305 × 203 mm) and cast using molds, shown in Figure 2.1. A 12-in. (305-mm) long No. 6 (No. 19) reinforcing bar was attached to the molds 1.5 in. (38 mm) from the top of the mold providing a nominal clear cover of 1¹/₈ in. (29 mm). The relatively low cover was selected to obtain consistently reproducible, observable settlement cracking over a wide range of slumps. The ends of the bar were threaded and attached through holes in the molds using machine screws. The molds were made of 0.75 in. (19-mm) thick plywood. The edges of the molds were sealed with a white latex caulk and the internal surfaces were oiled prior to each mixture.

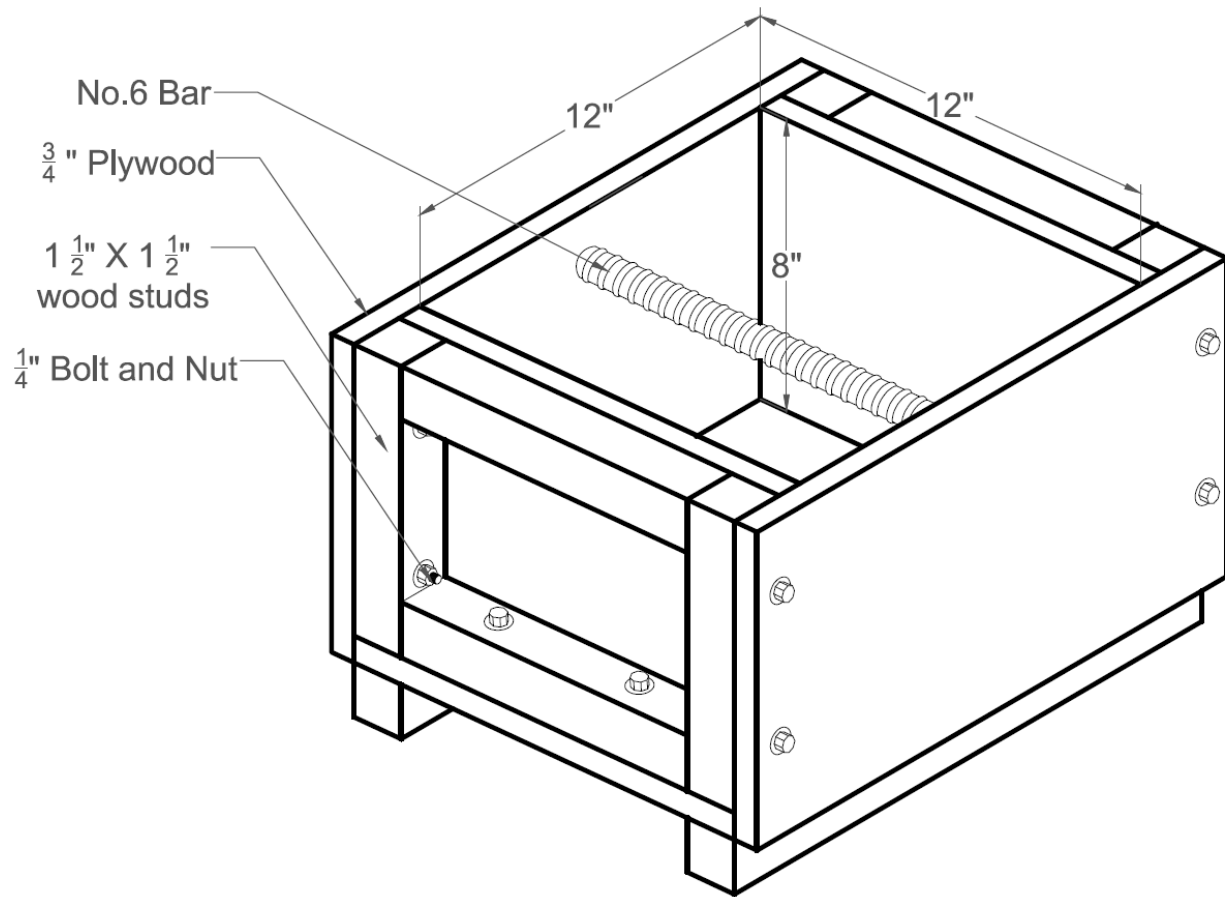


Figure 2.1: Settlement cracking mold.

2.3.2 Mixing Procedure

A counter-current pan mixer was used in this study. Prior to mixing, the interior surface of the pan and the mixer paddles were dampened. The coarse aggregate and 80 percent of the mixture water were first added to the pan. The concrete temperature was controlled using hot water or ice, as needed. Cement was then added and the combination mixed for one and a half minutes. Sand and pea gravel were then added and concrete was mixed for two minutes. Ten percent of the mixture water, with the desired dosage of the high-range water-reducing admixture (WRA-1), was added to the mixer pan and mixed for one minute. The dosage of WRA-1 was varied, as needed, to obtain the desired slump. The final 10 percent of the mixture water, with air-entraining agent (AEA-1), was then added and mixed for five minutes. The mixer was then turned off and the concrete was allowed to rest for five minutes. During the rest period, the concrete was covered

with wet towels to minimize evaporation from the fresh concrete surface. After the rest period, the concrete was uncovered and mixed for three minutes. The fresh concrete temperature and slump were then determined in accordance with ASTM C1064 and ASTM C143, respectively. Air content was determined in accordance with ASTM C173 at least twice for each series of test to confirm that the air content was within the desired range (7.0-9.0 percent). For non-control mixtures, the VMA was added at the desired dosage after taking the fresh concrete slump, and the concrete was mixed for 5 more minutes. After the five minutes of mixing, fresh concrete temperature and slump were measured again. The desired ranges of temperature and slump for each series of test were 65° F to 75° F (18° C to 24° C) and 2 in. to 8 in. (50 mm to 205 mm), respectively. Settlement cracking specimens were then cast and cured, as described in Sections 2.3.3 and 2.3.4, respectively.

2.3.3 Casting the Specimens

After measuring the fresh concrete temperature and slump, the concrete is transported to an environmentally controlled laboratory with a temperature of 73° ± 3° F (23° ± 1.5° C) and a relative humidity of 50 ± 4 percent. Specimens are filled in two layers of approximate equal depth (Figures 2.2a and 2.2b); each layer is vibrated using a 1¹/₈-in. diameter cordless spud vibrator (Figure 2.2c). The surface is then finished using a wood screed and metal hand float (Figure 2.2d).



(a)



(b)



(c)



(d)

Figure 2.2: Casting specimens: (a) half depth is filled and consolidated (b) second half is filled (c) consolidation of second layer (d) specimens after finishing.

2.3.4 Curing Procedure

The development of the test method used in this study is described by Brettmann, Darwin and O'Reilly (2015); the final curing procedure is described below.

Specimens were cured by covering them with a 15 degree sloped Plexiglas plate enclosed in a layer of plastic sheeting. Enclosing the specimens provided sufficient humidity to eliminate plastic shrinkage cracking while allowing the settlement cracks to form. Specimens were cured for 24 hours in an environmentally controlled laboratory with a temperature of $73^{\circ} \pm 3^{\circ}$ F ($23^{\circ} \pm 1.5^{\circ}$

C) and a relative humidity of 50 ± 4 percent. This procedure yielded consistent results without surface defects. Figure 2.3 shows the specimens during the curing period.



Figure 2.3: Settlement cracking specimens covered with sloped Plexiglas and plastic sheeting.

2.3.5 Settlement Cracking Reading

Settlement cracking readings were obtained after the specimens were cured for 24 hours in the environmentally controlled laboratory. Only cracks that were above and parallel to the reinforcing bar were considered settlement cracks. In few specimens, short cracks with a random orientation were observed around the perimeter of the upper surface of the specimen near the wooden form. These cracks had a width of less than 2 mils (0.002 in. [0.05 mm]) and were not counted as settlement cracks since they were remote from the reinforcing bar. Cracks were identified visually, without magnification; a flashlight was used to improve the visibility of narrow cracks. A black permanent marker was used to mark the settlement cracks. Marks were placed adjacent to the actual cracks to allow for subsequent measurement of the crack width, as shown in Figure 2.8. The intensity of cracking was then calculated by dividing the total length of cracks

Chapter 3 RESULTS AND EVALUATION

3.1 General

This chapter presents the results of the specimens designed to evaluate the effect of and the use of a rheology modifier in the form of a viscosity modifying admixture (VMA) on settlement cracking of plastic concrete. The mixtures had a 27 percent paste content and a water-to-cement ratio of 0.45. Three settlement cracking specimens were cast for each batch of specimens. The cracking intensity for a specimen was calculated by dividing the total length of settlement cracks observed on the surface of the specimen by the length of the reinforcing bar (12 in. [305 mm]); only cracks that are above and parallel to the reinforcing bar are counted as settlement cracks. In few specimens, short cracks with a random orientation were observed around the perimeter of the upper surface of the specimen near the wooden form. These cracks had a width of less than 2 mils (0.002 in. [0.05 mm]) and were not counted as settlement cracks since they were remote from the reinforcing bar. The average crack intensity of the three specimens used as the crack intensity for that batch.

3.2 Results

This series of specimens included 14 control mixtures, denoted as Control, and 17 mixtures containing VMA-1 (dosed at 0.05% of mixture material dry weight).

3.2.1 Control

Tests of the Control mixtures provided data on the effect of slump on settlement cracking and formed a basis of comparison (at the same water-to-cement ratio, paste content, and fresh concrete temperature range) for mixtures containing VMA.

Figure 3.1 shows settlement crack intensity versus slump for the Control mixture. The slump ranged from 2.25 to 7.75 in. (60 to 200 mm) and the crack intensity ranged from 0.32 to 0.88. As shown in the figure, crack intensity increased as slump increased, with the average crack intensity increasing from 0.45 at a slump of 3 in. to 0.86 at a slump of 8 in. Crack intensities for 11 of the 14 mixtures fell within 20% of the average trendline.

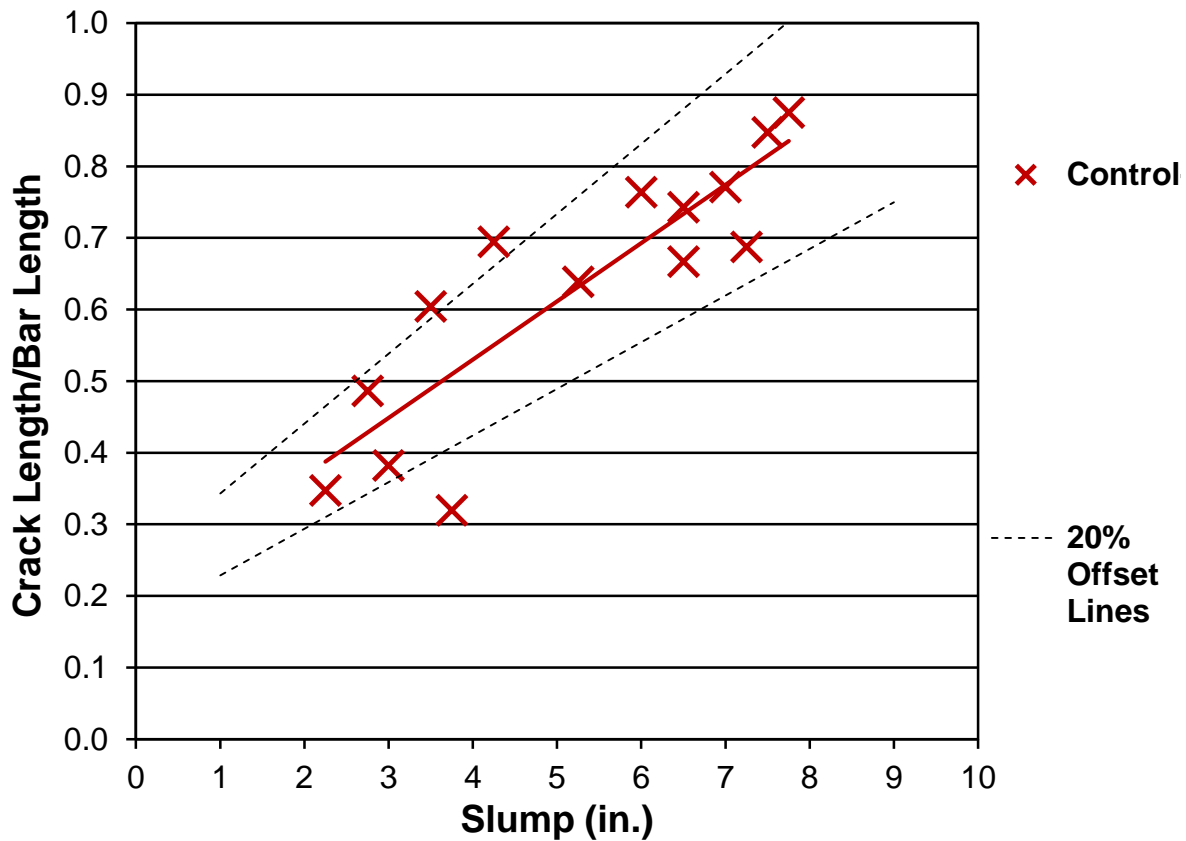


Figure 3.1: Settlement crack intensity versus slump for Control mixtures.

3.2.2 VMA-1

Figure 3.2 shows settlement crack intensity versus slump for the mixtures containing VMA-1. Seventeen mixtures containing VMA-1 dosed at 0.05% of total mixture dry weight were tested. The slump ranged from 1.75 to 7.75 in. (45 to 195 mm) and the crack intensity ranged from 0.22 to 0.64. Average crack intensity increased from 0.29 at a slump of 3 in. to 0.55 at a slump of 8 in. Fresh concrete slump was measured before and after adding the VMA-1 to determine its influence on the slump. The average reduction in slump after adding the VMA-1 was 2.0 in. (50 mm). The slump values presented here are those obtained after adding VMA-1; slump values before the addition of VMA-1 are presented in Appendix B.

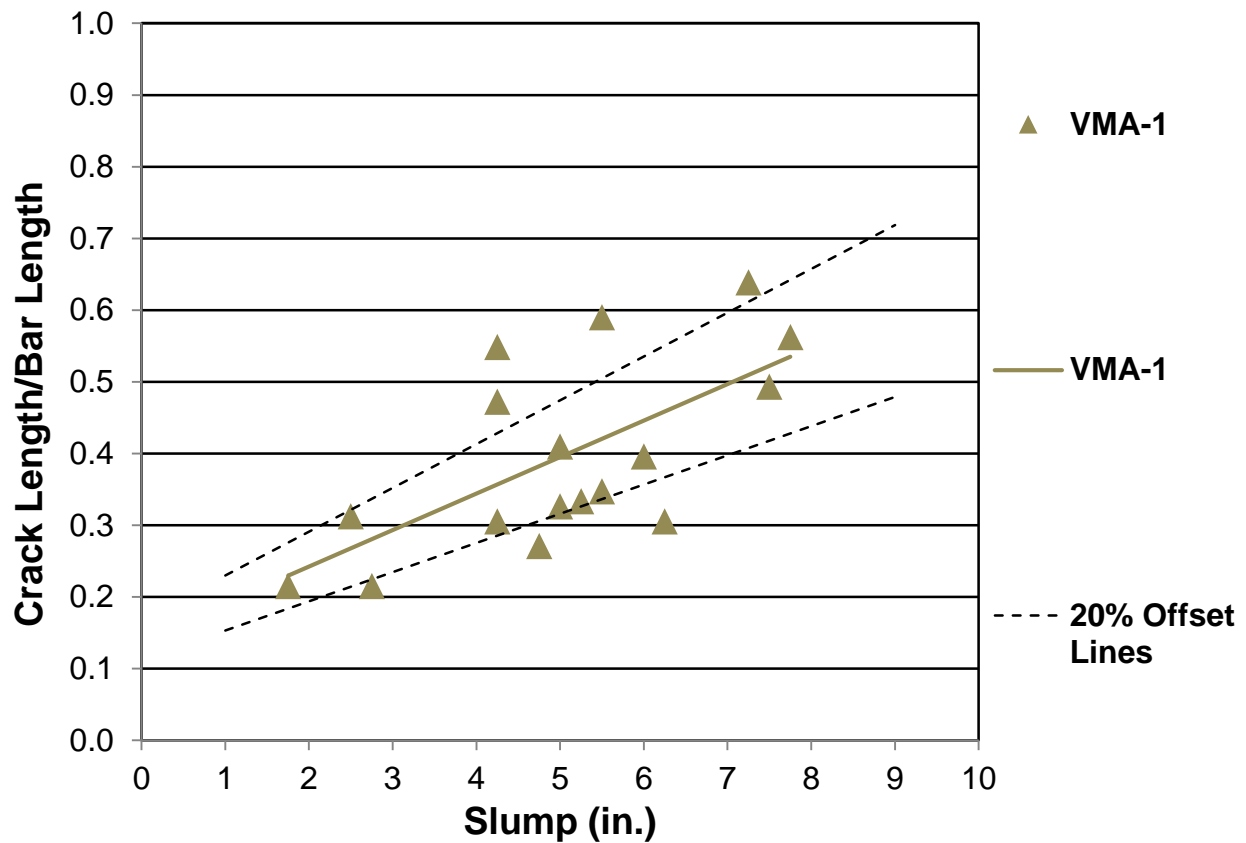


Figure 3.2: Settlement crack intensity versus slump for VMA-1 mixtures.

Figure 3.3 shows settlement crack intensity for the Control and VMA-1 mixtures. The addition of VMA-1 reduced cracking compared to control mixtures, with relatively better cracking performance for low slump than higher slump mixtures. The average reduction in the crack intensity between the Control and VMA-1 mixtures was 0.19 for a 4-in. (100-mm) slump. Student's t-test shows these differences are statistically significant (α ranged from 0.00756 to 2.81×10^{-10} over the slump range of 1 to 8 in. [25 to 205 mm]). VMA-1 tended to increase the cohesiveness of the plastic concrete and the stability of the concrete matrix, which resulted in less settlement around the reinforcing bar and led to an improvement in the settlement cracking performance.

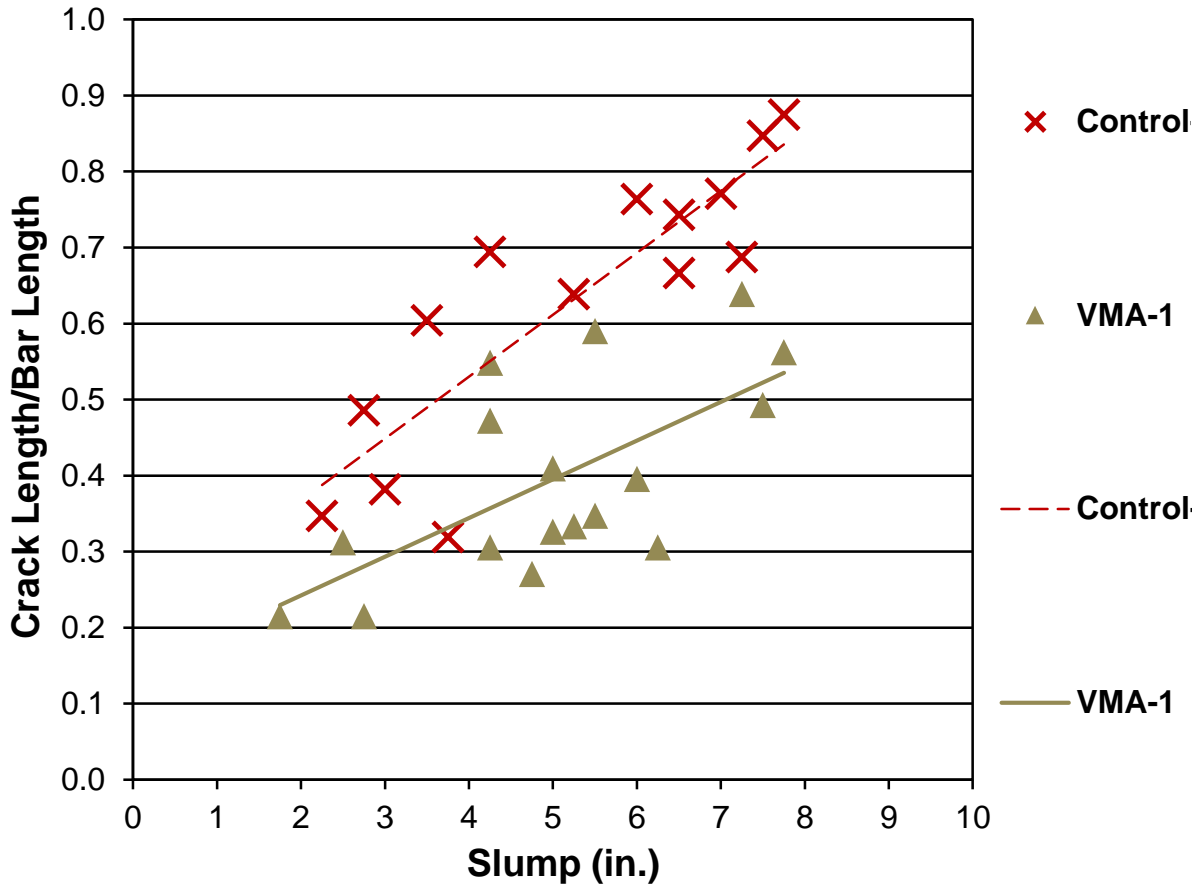


Figure 3.3: Settlement crack intensity versus slump for Control and VMA-1 mixtures.

3.3 Summary

The effect of the rheology modifying on the settlement crack behavior of concrete mixtures was investigated in this study. The results show that the addition of the rheology modifying significantly reduced the settlement cracking compared to a series of control mixtures that did not contain a crack reduction technology.

Chapter 4 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

4.1 Summary

Settlement cracking is a significant source of cracking in bridge decks. The presence of cracks in bridge decks provides a site for continued crack growth due to other causes, accelerates freeze-thaw damage, and exposes the reinforcement to corrosive salts. Many transportation agencies have acknowledged cracks as a serious problem that affects the durability of bridge decks.

Thirty-one mixtures were evaluated in this study; each mixture had a 27% paste content and a w/c ratio of 0.45. Fourteen mixtures in this series served as controls; the remaining 17 mixtures contained a rheology modifying in the form of a dry viscosity modifying admixture (dosed at 0.05% of mixture material dry weight).

4.2 Conclusions

Based on the results of this study, the following conclusions can be drawn:

- 1) The settlement cracking for a given mixture increases as the slump increases.
- 2) Adding the viscosity modifying admixture to the concrete significantly reduces the amount of settlement cracking.

4.3 Recommendations

In this study, the effects of a rheology modifier were tested to evaluate its influence on reducing settlement cracking; however, the addition of supplementary cementitious materials, such as silica fume or slag, was not tested. Since supplementary cementitious materials can reduce the bleed water in plastic concrete, further research is recommended to determine the effect of the addition of supplementary cementitious materials on settlement cracking performance of concrete mixtures containing a rheology modifier.

REFERENCES

- Al-Qassag, O., Darwin, D., and O'Reilly, M. (2015). "Effect of Synthetic Fibers and a Rheology Modifier on Settlement Cracking of Concrete," *SM Report* No. 136, University of Kansas Center for Research, Inc., Lawrence, KS, 113 pp.
- ASTM C1064-12 (2012). *Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete*, ASTM International, West Conshocken, PA, 3 pp.
- ASTM C143-15 (2015). *Standard Test Method for Slump of Hydraulic-Cement Concrete*, ASTM International, West Conshocken, PA, 4 pp.
- ASTM C150-15 (2015). *Standard Specification for Portland Cement*, ASTM International, West Conshocken, PA, 9 pp.
- ASTM C173-14 (2014). *Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method*, ASTM International, West Conshocken, PA, 9 pp.
- ASTM C31-15 (2015). *Standard Practice for Making and Curing Concrete Test Specimens in the Field*, ASTM International, West Conshocken, PA, 6 pp.
- Babaei, K. and Fouladgar, A. M. (1997). "Solutions to Concrete Bridge Deck Cracking," *Concrete International*, Vol. 19, No. 7, July, pp. 34-37.
- Babaei, K., and Purvis, R. L., (1995). "Prevention of Cracks in Concrete Bridge Decks: Report on Surveys of Existing Bridges," *Report PA-FHWA-95-001+89-01*, 100 pp.
- Brettmann, R., Darwin, D., and O'Reilly. (2015) "Developing A Test Procedure to Evaluate Settlement Cracking Performance," *SL Report* No. 15-2, University of Kansas Center for Research, Inc. Lawrence, KS, 43 pp.
- Combrinck, R. and Boshoff, W. P. (2013). "The Origin of Plastic Settlement Cracking and the Effect of Re-vibration," *Research and Applications in Structural Engineering, Mechanics and Computation*, Taylor and Francis Group, London, England, pp. 617-618.
- Dakhil, F. H., Cady, P. D., and Carrier, R. E., (1975). "Cracking of Fresh Concrete as Related to Reinforcement," *ACI Journal, Proceedings* Vol. 72, No. 8, pp. 421-428.
- Darwin, D., Browning, J., Lindquist, W. (2004). "Control of Cracking in Bridge Decks: Observations from the Field," *Cement, Concrete, and Aggregates*, Vol. 26, No. 2, December, pp. 148-154.
- Darwin, D., Browning, J., O'Reilly, M., Locke, C. E., and Virmani, Y. P. (2011). "Multiple Corrosion Protection Systems for Reinforced Concrete Bridge Components," *Publication No. FHWA-HRT-11-060*, Federal Highway Administration, also *SM Report* No. 101, University of Kansas Center for Research, Inc., Lawrence, KS, November, 255 pp.

Deshpande, S., Darwin, D., and Browning, J. (2007). "Evaluating Free Shrinkage of Concrete for Control of Cracking in Bridge Decks," *SM Report* No. 89, University of Kansas Center for Research, Inc. Lawrence, KS, 290 pp.

"KU Mix". <<https://iri.drupal.ku.edu/node/43>> (Nov. 20, 2015).

Lindquist, W. D., Darwin, D., and Browning, J., (2005). "Cracking and Chloride Contents in Reinforced Concrete Bridge Decks," *SM Report* No. 78, University of Kansas Center for Research, Inc., Lawrence, KS, 452 pp.

Lindquist, W. D., Darwin, D., and Browning, J., (2008). "Development and Construction of Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Free Shrinkage, Mixture Optimization, and Concrete Production," *SM Report* No. 92, University of Kansas Center for Research, Inc., Lawrence, KS, 540 pp

Lindquist, W., Darwin, D., Browning, J., McLeod, H. A. K., Yuan, J., and Reynolds, D. (2015). "Implementation of Concrete Aggregate Optimization," *Construction & Building Materials*, Vol. 74, pp. 49-56.

Pendergrass, B., Darwin, David (2014). "Low-Cracking High-Performance Concrete (LC-HPC) Bridge Decks: Shrinkage-Reducing Admixtures, Internal Curing, and Cracking Performance" *SM Report* No. 107, University of Kansas Center for Research, Lawrence, KS, 665 pp.

Russell, H. G., (2004). "Concrete Bridge Deck Performance," *National Cooperative Highway Research Program (NCHRP) Synthesis* 333, Transportation Research Board, Washington, D.C., 32 pp.

Suprenant, B. A. and Malisch, W. R. (1999). "The Fiber Factor – Lab Tests Show the Benefits of Using Synthetic Fibers to Limit Subsidence Cracking of Reinforced Concrete," *Concrete Construction*, Oct., 4 pp.

Yunovich, M., Thompson, N. G., and Virmani, Y. P. (2005). "Corrosion Protection System for Construction and Rehabilitation of Reinforced Concrete Bridges," *International Journal of Materials and Product Technology*, Vol. 23, Nos. 3-4, pp. 269-285.

APPENDIX A
SIEVE ANALYSIS OF AGGREGATE

Table A.1: Sieve Analysis of Fine Aggregate (Sand).

Sieve Number	Sieve Weight	Sieve + F.A. Weight	Weight of F.A. Retained	% Weight of F.A. Retained	Cumulative % Retained	% Passing
No. 4	750.3	760.3	10	1.82%	1.82%	98.18%
No. 8	475.4	549.4	74	13.50%	15.33%	84.67%
No. 16	446.1	572.7	126.6	23.10%	38.43%	61.57%
No. 30	386.2	513.3	127.1	23.19%	61.62%	38.38%
No. 50	382.5	495.2	112.7	20.57%	82.19%	17.81%
No. 100	328.8	398.9	70.1	12.79%	94.98%	5.02%
No. 200	322.4	341	18.6	3.39%	98.38%	1.62%
Pan	362.5	371.4	8.9	1.62%	100.00%	0.00%
Sum			548	100.00%		

Table A.2: Sieve Analysis of Fine Aggregate (Pea Gravel).

Sieve Number	Sieve Weight	Sieve + F.A. Weight	Weight of F.A. Retained	% Weight of F.A. Retained	Cumulative % Retained	% Passing
No. 4	750.8	853.3	102.5	11.25%	11.25%	88.75%
No. 8	475.9	1072.8	596.9	65.54%	76.79%	23.21%
No. 16	446.2	613.9	167.7	18.41%	95.20%	4.80%
No. 30	386.4	408.2	21.8	2.39%	97.60%	2.40%
No. 50	382.4	391.6	9.2	1.01%	98.61%	1.39%
No. 100	329.1	333.3	4.2	0.46%	99.07%	0.93%
No. 200	322.4	325.4	3	0.33%	99.40%	0.60%
Pan	362.5	368	5.5	0.60%	100.00%	0.00%
Sum	----	----	910.8	100.00%	----	----

Table A.3: Sieve Analysis of Coarse Aggregate (Granite B).

Sieve Number	Sieve Weight	Sieve + C.A. Weight	Weight of C.A. Retained	% Weight of C.A. Retained	Cumulative % Retained	% Passing
1 ½ in.	21.14	21.14	0	0.00%	0.00%	100.00%
1 in.	18.14	18.14	0	0.00%	0.00%	100.00%
¾ in.	20.85	21.54	0.69	4.84%	4.84%	95.16%
½ in.	19.18	31.84	12.66	88.84%	93.68%	6.32%
⅜ in.	22.18	22.9	0.72	5.05%	98.74%	1.26%
No. 4	19.36	19.36	0	0.00%	98.74%	1.26%
No. 8	18.45	18.45	0	0.00%	98.74%	1.26%
Pan	19.5	19.68	0.18	1.26%	100.00%	0.00%
Sum	----	----	14.25	100.00%	----	----

Table A.4: Sieve Analysis of Coarse Aggregate (Granite C).

Sieve Number	Sieve Weight	Sieve + C.A. Weight	Weight of C.A. Retained	% Weight of C.A. Retained	Cumulative % Retained	% Passing
1 ½ in.	21.14	21.14	0	0.00%	0.00%	100.00%
1 in.	18.14	18.14	0	0.00%	0.00%	100.00%
¾ in.	20.84	20.84	0	0.00%	0.00%	100.00%
½ in.	19.16	21.82	2.66	17.52%	17.52%	82.48%
⅜ in.	22.14	29.32	7.18	47.30%	64.82%	35.18%
No. 4	19.34	24.48	5.14	33.86%	98.68%	1.32%
No. 8	18.4	18.4	0	0.00%	98.68%	1.32%
Pan	19.68	19.88	0.2	1.32%	100.00%	0.00%
Sum	----	----	15.18	100.00%	----	----

APPENDIX B

TEMPERATURE, SLUMP BEFORE AND AFTER THE ADDITION OF VMA-1, AND SETTLEMENT CRACKING RESULTS

Table B.1: Settlement cracking results of Control series.

Mixture No.	Slump, in.	Concrete Temperature, ° F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S284	3	71	1	Yes	3 mils	6.5	0.382
			2	Yes	< 2 mils	2.75	
			3	Yes	< 2 mils	4.5	
S285	2.25	71	1	Yes	2 mils	5.5	0.347
			2	Yes	2 mils	2.5	
			3	Yes	3 mils	4.5	
S286	6	72	1	Yes	2 mils	10.5	0.764
			2	Yes	< 2 mils	6.75	
			3	Yes	3 mils	10.25	
S287	5.25	72	1	Yes	2 mils	11.5	0.639
			2	Yes	2 mils	6.75	
			3	Yes	3 mils	4.75	
S288	2.75	73	1	Yes	3 mils	3.75	0.486
			2	Yes	< 2 mils	5.25	
			3	Yes	2 mils	8.5	
S289	3.5	72	1	Yes	2 mils	8	0.604
			2	Yes	< 2 mils	5.75	
			3	Yes	< 2 mils	8	
S291	7.75	73	1	Yes	< 2 mils	10.5	0.875
			2	Yes	< 2 mils	9.75	
			3	Yes	2 mils	11.25	
S292	7.25	72	1	Yes	2 mils	7	0.688
			2	Yes	2 mils	7.75	
			3	Yes	3 mils	10	
S293	6.5	73	1	Yes	2 mils	8.5	0.743
			2	Yes	2 mils	8.75	
			3	Yes	2 mils	9.5	
S295	3.75	71	1	Yes	< 2 mils	2.75	0.319
			2	Yes	2 mils	5.5	
			3	Yes	2 mils	3.25	
S297	6.5	74	1	Yes	< 2 mils	9	0.667
			2	Yes	< 2 mils	3.75	
			3	Yes	2 mils	11.25	
S298	7	74	1	Yes	2 mils	10.25	0.771
			2	Yes	2 mils	7.5	
			3	Yes	3 mils	10	

Table B.1 (Continued): Settlement cracking results of Control series.

Mixture No.	Slump, in.	Concrete Temperature, °F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S299	4.25	75	1	Yes	2 mils	8	0.694
			2	Yes	2 mils	8.5	
			3	Yes	2 mils	8.5	
S300	7.5	73	1	Yes	2 mils	8.5	0.847
			2	Yes	2 mils	10.5	
			3	Yes	3 mils	11.5	

Table B.2: Settlement cracking results of VMA-1 series.

Mixture No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, °F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S180	4.75	2.75	74	1	Yes	< 2 mils	2.75	0.215
				2	Yes	< 2 mils	1.5	
				3	Yes	< 2 mils	3.5	
S181	7.5	4.25	75	1	Yes	< 2 mils	6.5	0.472
				2	Yes	< 2 mils	5	
				3	Yes	< 2 mils	5.5	
S182	3.25	1.75	74	1	Yes	< 2 mils	2.75	0.215
				2	Yes	< 2 mils	0.75	
				3	Yes	< 2 mils	4.25	
S183	7.25	5.5	72	1	Yes	< 2 mils	5.75	0.347
				2	Yes	< 2 mils	2.25	
				3	Yes	< 2 mils	4.5	
S188	8	5	74	1	Yes	< 2 mils	4	0.41
				2	Yes	< 2 mils	5.75	
				3	Yes	< 2 mils	5	
S191	7.5	4.25	74	1	Yes	2 mils	8.5	0.549
				2	Yes	< 2 mils	6.5	
				3	Yes	< 2 mils	4.75	
S192	8.5	5.5	74	1	Yes	< 2 mils	7.75	0.59
				2	Yes	2 mils	8.75	
				3	Yes	2 mils	4.75	
S202	7.5	4.75	74	1	Yes	2 mils	1.5	0.271
				2	Yes	< 2 mils	4.5	
				3	Yes	2 mils	3.75	
S203	9.5	7.75	74	1	Yes	2 mils	10.25	0.563
				2	Yes	< 2 mils	2.5	
				3	Yes	< 2 mils	7.5	
S205	8.5	7.5	75	1	Yes	2 mils	6.75	0.493
				2	Yes	< 2 mils	3.75	
				3	Yes	< 2 mils	7.25	

* Slump before the addition of the crack reduction technology.

** Slump after the addition of the crack reduction technology.

Table B.2 (Continued): Settlement cracking results of VMA-1 series.

Mixture No.	Initial Slump*, in.	Final Slump**, in.	Concrete Temperature, °F	Specimen Number	Settlement Cracks	Crack Width	Crack Length, in.	Crack Length/Bar Length
S209	8	5	74	1	Yes	< 2 mils	3.5	0.326
				2	Yes	< 2 mils	2.25	
				3	Yes	< 2 mils	6	
S210	8.5	6	74	1	Yes	< 2 mils	1	0.396
				2	Yes	< 2 mils	5	
				3	Yes	< 2 mils	8.25	
S211	8.5	6.25	74	1	Yes	2 mils	4.25	0.306
				2	Yes	< 2 mils	1.25	
				3	Yes	< 2 mils	5.5	
S212	9	7.25	74	1	Yes	2 mils	5	0.639
				2	Yes	2 mils	8.75	
				3	Yes	2 mils	9.25	
S213	7.25	4.25	73	1	Yes	< 2 mils	6.5	0.306
				2	Yes	< 2 mils	3	
				3	Yes	< 2 mils	1.5	
S214	4.5	2.5	72	1	Yes	2 mils	3.75	0.313
				2	Yes	< 2 mils	3.75	
				3	Yes	< 2 mils	3.75	
S216	8.5	5.25	75	1	Yes	3 mils	6	0.333
				2	Yes	< 2 mils	2.25	
				3	Yes	2 mils	3.75	

* Slump before the addition of the crack reduction technology.

** Slump after the addition of the crack reduction technology.

APPENDIX C

SLUMP BEFORE AND AFTER THE ADDITION OF VMA-1 (INITIAL AND FINAL SLUMP)

The influence of adding VMA-1 on concrete slump is illustrated in this Appendix. Slump was measured in accordance with ASTM C143 before and after the addition of the VMA. Figure D.1 shows the slump values before and after the addition of VMA-1 to the concrete. The average reduction in the slump after the addition of VMA-1 in 17 mixtures was 2.5 in. (65 mm). Figure D.1 illustrates that the decrease in the slump was nearly uniform across the range of slumps tested.

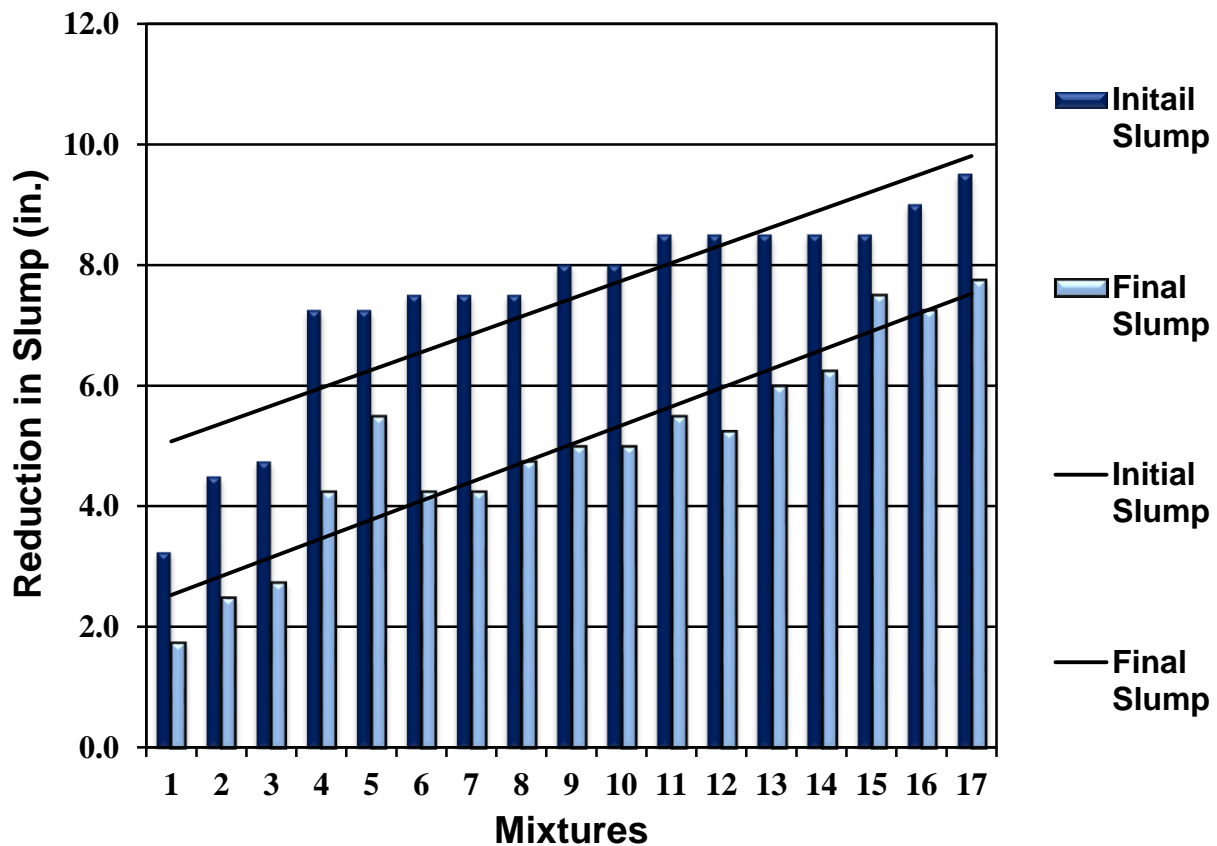


Figure D.1: Reduction in slump due to the addition of VMA-1 to the concrete.