Report No. CDOT-2010- 9
Final Report

DTD Applied Research and Innovation Branch

Where Ideas Become Reality

STUDY ON THE USE OF SELF-CONSOLIDATING CONCRETE ON THE INTERSTATE 25 BRIDGE REPLACEMENT IN TRINIDAD, CO

Panos D. Kiousis
Brent L. Whitcomb

December 2010

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

1. Report No.
CDOT-2010-9

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
STUDY ON THE USE OF SELF-CONSOLIDATING CONCRETE ON THE INTERSTATE 25 BRIDGE REPLACEMENT IN TRINIDAD, CO

5. Report Date
December 2010

6. Performing Organization Code

7. Author(s)
Panos D. Kiousis and Brent L. Whitcomb

8. Performing Organization Report No.
CDOT-2010-9

9. Performing Organization Name and Address
Colorado School of Mines
1600 Illinois Street
Golden, CO 80401

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
87.40

12. Sponsoring Agency Name and Address
Colorado Department of Transportation - Research
4201 E. Arkansas Ave.
Denver, CO 80222

13. Type of Report and Period Covered

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the US Department of Transportation, Federal Highway Administration

16. Abstract

As part of a national experiment sponsored by the FHWA under the Innovative Bridge Research and Construction (IBRC) program, CDOT used self-consolidating concrete (SCC) to construct abutments, piers, and retaining walls on a bridge replacement project. The purpose of this study was to determine the procedures and possible benefits associated with flowing concrete. Based on the study presented in this report, it was determined that SCC was used successfully in the I-25 bridge replacement project in Trinidad. Unfortunately, the all-around lack of construction experience with SCC resulted in numerous aesthetic problems that are atypical of the material. However, despite numerous visual defects that required patching and repair, it is believed that each component has the required structural integrity necessary for safe highway transportation projects.

Implementation:

The use of SCC can benefit bridge construction throughout Colorado by allowing contractors the option of using a flowable concrete that reduces placement labor costs as well as noise pollution at construction sites. In addition, the expected surface finish of SCC can eliminate repair work after the forms have been removed.

Construction specifications should include clauses that require contractors with reasonable experience with SCC to submit mix designs as well as perform a demonstration placement to show that the proposed construction methods will produce an acceptable product.

17. Keywords
SCC, retaining walls, bridge abutments, bridge piers, slump flow, air content, consolidation, bonding, flowable concrete, high-range water-reducing admixtures (HRWRA)

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service www.ntis.gov or CDOT's Research Report website http://www.coloradodot.info/programs/research/pdfs

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
31

22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

STUDY ON THE USE OF SELF-CONSOLIDATING CONCRETE ON INTERSTATE 25 BRIDGE REPLACEMENT IN TRINIDAD, CO

By
Panos D. Kiousis
Brent L. Whitcomb

Colorado School of Mines
1600 Illinois St.
Golden, CO 80401

Report No. CDOT-2010-9
Final Report

Sponsored by the
Colorado Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

December 2010

Colorado Department of Transportation
DTD Applied Research and Innovation Branch
4201 E. Arkansas Ave.
Denver, CO 80222

ACKNOWLEDGEMENTS

The authors of this report would like to express their utmost gratitude to the Colorado Department of Transportation for the opportunity to contribute to improved construction in Colorado. Special appreciation must be given to Aziz Khan, Roberto de Dios, Richard Griffin, Ahmad Ardani, and Jake Kononov for their thoughts and dedication towards this research project. We wish to thank the project panel members – Richard Osmun, Eric Prieve, Glenn Frieler, Joe Garcia, Lowell Lester, John Deland, and Matt Greer. Also, our appreciation must be expressed towards Lawrence Construction and Leone Concrete for their willingness to provide an environment that allowed the study to determine the benefits of SCC in modern construction.

EXECUTIVE SUMMARY

The Colorado Department of Transportation (CDOT) and the Colorado School of Mines (CSM) are interested in the benefits of using self-consolidating concrete (SCC) in modern bridge construction. As part of a national experiment sponsored by the FHWA under the Innovative Bridge Research and Construction (IBRC) program, a study on the use of cast-in-place SCC in retaining walls, abutments, and piers was conducted during the construction of a northbound bridge structure on Interstate 25 in Trinidad. The study comprises a review of mix design performance with regard to stability, flowability and finished product, a comparison of SCC and normal concrete in bond strength to reinforcement, and evaluation of placement procedures in retaining walls, abutments, and piers.

The authors proposed the use of an SCC mix that was developed at CSM, with the proper flowability, and stability characteristics for this project. The contractor selected a different mix with leaner characteristics, which was tested by the authors, and was found to meet the requirements of strength, flowability, air content, and mix stability. Proper mixture proportioning of sand and 3/8 inch aggregate, as well as high amounts of cementitious materials are paramount to the success of SCC. Most importantly, the use of high-range water-reducing admixtures (HRWRA) created a mix design capable of reaching the required strength and flow characteristics desired for this project.

In order to compare the bond capabilities of SCC and normal concrete, several concrete blocks were cast with standard No. 4 reinforcing bars protruding from the side of the blocks. After 7 days of curing, the reinforcing bars were pulled with a hydraulic jack to verify the pullout capacity of the SCC compared to the normal concrete. It was found that steel reinforcing bars cast into both the SCC and normal concrete blocks yielded before rupturing the concrete, concluding that SCC has at least the bond capabilities of normal concrete. The blocks were sawed perpendicular to the main reinforcement and were inspected visually for proper encapsulation of the reinforcement.

In addition, placement techniques in a retaining wall, two abutments and eight piers were evaluated. Each of these structural elements was cast with SCC by means of a boom pump truck in a manner that kept the end of the hose imbedded within the top 12 inches of the fresh concrete and allowed the SCC to flow without the use of mechanical vibration. Despite complications in

the delivery of the SCC during a few of these operations, acceptable structural elements were achieved.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Technological advances in chemical admixtures have contributed in the development of high performance concretes (HPC). Self-consolidating concrete (SCC) is an important HPC, with great potential for use in the design and construction of bridge components. SCC is a highly flowable, yet stable concrete that is able to flow around reinforcement and into complex forms under its own weight without the need for external vibration. The high flowability of SCC is achieved with relatively low water to cementitious (w/cm) ratio with the help of polycarboxylate-based high-range water-reducing admixtures (HRWRA), which provide cement dispersion through electrostatic repulsion and steric hindrance [1-3]. SCC mix designs typically include higher than usual amounts of cement and fly ash to create a heavier and more viscous paste that provides sufficient buoyancy to the aggregates and avoids segregation that can be caused by the high fluidity of the mix. Towards this goal of improved mix stability, viscosity modifying agents (VMA) may also be used, although they are often avoided due to higher costs. The ability of SCC to flow without the need for external vibration is of interest to CDOT and other state DOTs because of the potential savings in labor costs as well as reducing the cost of repairing poorly consolidated concrete.

In order to demonstrate the performance of SCC, CDOT awarded the Colorado School of Mines (CSM) a research contract to study the use of SCC during the construction of northbound bridge components on Interstate 25 in Trinidad, CO. A retaining wall, two abutments, and eight pier columns were scheduled to be cast with an approved SCC mix design. As will be discussed in this report, a number of difficulties in the production and delivery of the SCC were encountered. However the final product of its application is considered satisfactory. The tasks of CSM in this project included the evaluation of the SCC mix design performance, the bond strength of SCC to reinforcement, and an evaluation of the placement practices of the SCC.

2. MIX DESIGN

In the course of this study, the authors developed a mix design that was tested extensively for aggregate stability, low shrinkage, compressive strength, flowability, and pumpability. The mix proportions proposed by CSM for use in this project are presented in Table 1.

Table 1: Colorado School of Mines SCC Mix Proportions (per cu. yd)

Cement (Type I/II)	Fly Ash (Class F)	Sand	Coarse Agg.	Water	BASF Glenium 3400 (1)	BASF UW 450 (2)	Slump Flow	w/cm
lbs	**lbs**	**lbs**	**lbs**	**lbs**	**fl. oz**	**mL**	**mm**	
667	169	1594.	1306	288	131	12.6	29	0.345

1) HRWR 2) VMA

The contractor instead elected to use a different mix design, probably due to familiarity, which is listed in Table 2.

Table 2: Mix Proportions of SCC Used in the Project (per cu. yd)

Cement (Type I/II)	Fly Ash (Class F)	Sand	Coarse Agg.	Water	Master Builders PS 1466 (1)	Master Builders Rheomac UW 450 (2)	Master Builders MBVR (3)	Slump Flow	w/cm
lbs	**lbs**	**lbs**	**lbs**	**lbs**	**oz**	**Oz.**	**oz**	**mm**	
620	135	1250.	1400	321	131	12.6	3.8	29	0.345

1)HRWR 2)VMA 3)Air Entrainment

The contractor’s mix was evaluated by CSM in the field for flowability, stability, and compressive strength as described in the next chapter.

3. EVALUATION OF PROPOSED SCC MIX DESIGN

CDOT requirements for SCC, also known as *Class D Special Concrete*, state that the mix must achieve a compressive strength of 4500 psi at 56 days, maintain an air content range of 5% to 8%, have a maximum water to cementitious ratio of 0.44, and finally contain a minimum of 600 lbs of cement per cubic yard. Up to 40% of cement by weight may be replaced with an approved Class F fly ash. The construction specifications also state that the SCC must have a slump flow between 18 and 24 inches. However, during field slump flow testing, mixes were required to have a minimum slump flow of 24 inches after a CSM recommendation.

To evaluate the flowability and stability of SCC, slump flow tests combined with a J-Ring are used. The slump flow test is a modification of the standard Abrams Slump test for normal concrete. In this test, the concrete is placed in the cone in a single lift without tamping. The cone is then lifted and the "spread" of the concrete is measured. Given the fluidity of the SCC, it is often preferable to perform the slump flow test by placing the cone inverted. This approach provides the convenience of downward pressures of the concrete to the walls of the cone which helps the stability of the test. The J-Ring is often added to the slump flow test to add an obstacle to the outward flow of the mix when the cone is lifted. Figure 1 and 2 demonstrate the slump flow test as performed at the Trinidad project using an inverted Abrams cone and J-Ring.

The slump flow test through the J-Ring demonstrates the ability of the SCC to pass through reinforcement under its own weight without segregating. Although the minimum slump flow of 24 inches does not require the additional obstruction of a J-Ring, all slump flow tests for the Trinidad project met this requirement with a J-Ring.

The Trinidad project specifications stipulated that the SCC mix design would only be accepted by the approving engineer after the Contractor "*demonstrates the ability of Concrete Class D (Special) to bond to the reinforcement, take the shape of the form and flow through heavily congested reinforcement under its own weight without vibration or segregation of the aggregates*."[4] To meet this criterion, a specification was created requiring the contractor to build four prismatic specimens, 8 inches wide by 48 inches long by 24 inches high. Two of these specimens had a split level top, where half the length had an additional 11 inches of differential height. Both types of specimen forms are demonstrated in Figure 3.

Figure 1: Abrams Cone and J-Ring for Slump Flow Test

Two of the specimens were cast with normal Class D concrete using conventional consolidation techniques, while the other two specimens were cast with the approved SCC mix. A total of 15 cylinders were cast for the compressive strength testing of 3 cylinders each at 3, 7, 12, 28 and 56 days. A #4 reinforcing bar extended out from the side of the forms (although this is not apparent in Figure 3) to be pulled with a hydraulic ram and gripping wedges in order to determine the bond strength of the respective concretes. Figure 4 shows the testing apparatus for loading the #4 bars in an attempt to break the concrete bond and pull the bars out of the specimens.

Figure 2: Slump Flow Through J-Ring

Figure 3: Forms for Pullout Specimens

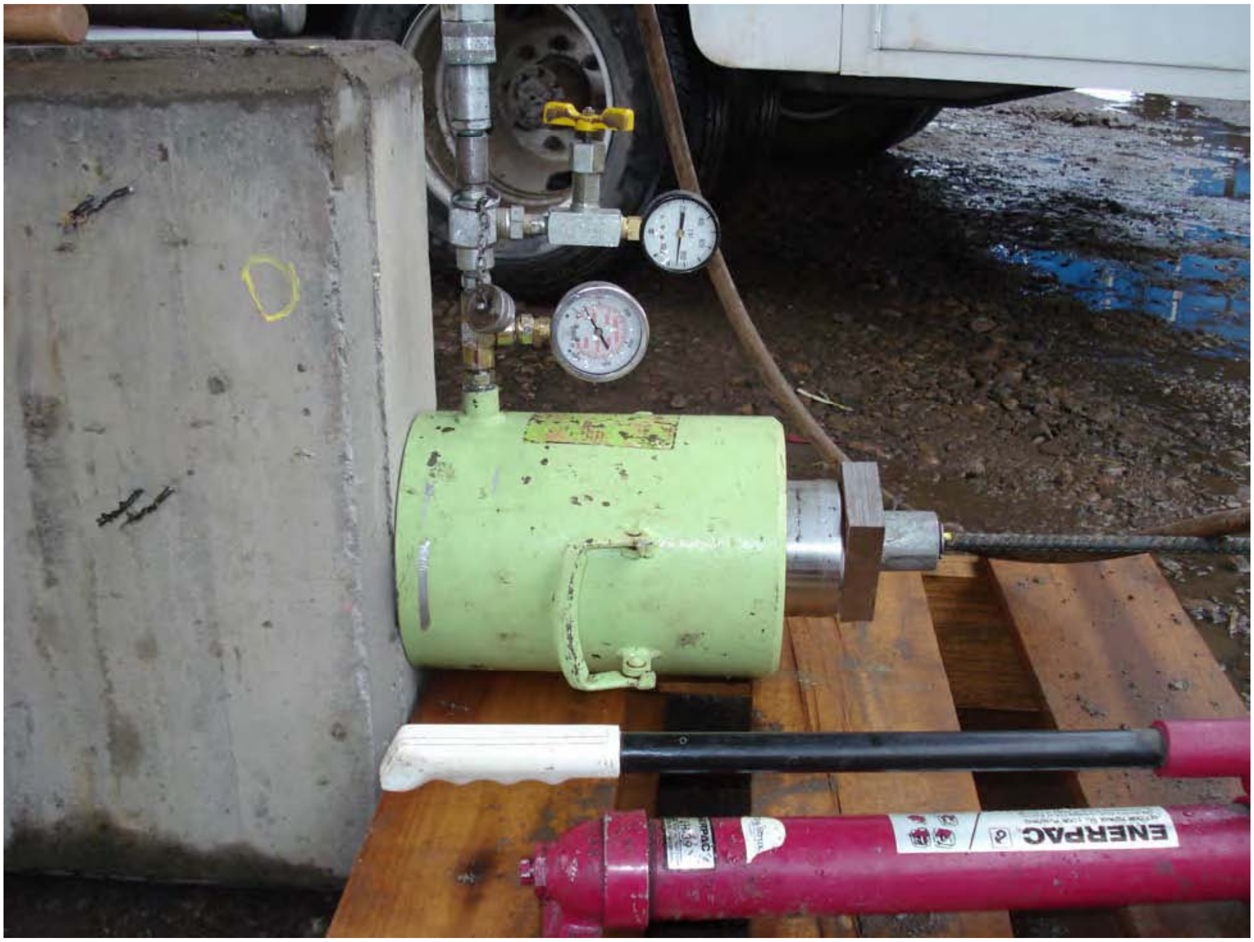

Figure 4: Pullout Test Apparatus

The pullout test was performed after 7 days of curing. Each of the specimens of both normal Class D concrete and SCC demonstrated its ability to bond with the reinforcement bars. The hydraulic jack reached an average force of 13.3 kips corresponding to a steel tensile stress of 66.9 ksi, which is greater than the stated 60 ksi yield strength of the reinforcement. At that time, a continuous deformation at constant force was observed, without any indication that the steel was being pulled out of the specimens.

To detect any potential pullout movement of the protruding steel bar, a yellow-colored ring was painted on the bar at the point of interface with the concrete block (Figures 5 and 6).

Figure 5: Worst Case Test

Figure 6: Typical Result

The yellow ring in each case remained in its original relative position next to the concrete, indicating that the bar had not slipped during the test. Figure 5 shows the one exception where a concrete ring around the bar broke off during the pullout tests. Figure 6 demonstrates the typical result of all other tests, where no movement was observed between the concrete and steel reinforcement.

Figure 7: Saw Cutting of Specimens

Upon completion of the pullout tests, the specimens were cut with a diamond saw (Figure 7) in order to provide a visual inspection of the bond of the concrete and steel within the specimen. It is clearly demonstrated in Figure 8 and 9 that both normal concrete and SCC samples completely encapsulated the reinforcement without segregation. It is also interesting to see from these figures the different aggregate sizes and their distributions. After this successful demonstration of bond strength and bar encapsulation, the submitted SCC mix design was approved for use in the Trinidad I-25 bridge.

Figure 8: Normal Concrete Bonding

Figure 9: SCC Bonding

4. EVALUATION OF PLACEMENT TECHNIQUES AND FINISHED PRODUCT

SCC was used in a retaining wall, two abutments, and seven of the eight columns at the four piers in the replacement of the I-25 bridge in Trinidad, CO. The retaining wall, 12 inches thick and approximately 290 ft long, was placed in two separate pours on a normal concrete footing. This retaining wall has an average height of 9 ft, with a constant 3.2% slope at the base. The individual abutments were placed in a single pour, and the steel forms on the exposed face had an architectural pattern to represent randomly placed quarry stone. The piers, also placed in a single pour, are approximately 30 ft tall, with a simple architectural pattern in the center.

4.1. Retaining Wall

At the start of the SCC operations at the retaining wall, the contractor decided to place the SCC while leaving the pump truck boom at two stationary quarter point positions along a portion of the wall, and allowing the SCC to flow to either side and consolidate with the previously placed SCC. After each truckload, the boom was relocated to the opposite location. This technique was designed to place the concrete in a way that the maximum flow distance of the SCC was approximately 40 feet. Longer flow distances are known to have the potential of segregation due to the rolling action of the course aggregates. In all cases, the end of the boom was submerged into the discharged SCC approximately 6 to 12 inches.

The placement of the first half of the wall was not observed by a Colorado School of Mines researcher. During the placement of the second half of the wall, it was noted that each accepted truck delivered concrete that had a slump flow of at least 24 inches, with a maximum slump flow of 27 inches. However, a few trucks (in one case, 5 trucks in a row) were rejected due to air contents above 8%. The initial truck loads delivered concrete with air content below 5%. Adjustments were made on site. This prompted the contractor to increase the air additives at the batching plant, which unfortunately resulted in unacceptably high air contents in the following trucks. Visual observation during the second wall placement revealed that the top two to three inches of the concrete did not contain a sufficient amount of aggregate indicating mix instability. Also, in this top layer, the SCC that traveled the longest distances developed a “soapy” texture as shown in Figure 10. This was initially attributed to a reaction or mixing with the form release agents. It is more likely that the observed texture was the result of segregation that resulted in a mortar of higher air content flowing on the top layer of placement.

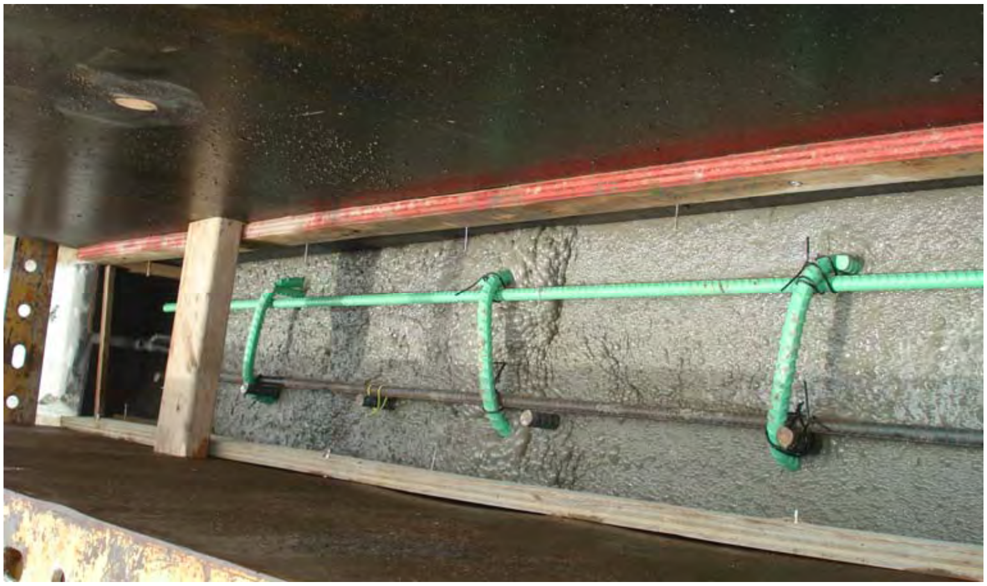

Figure 10: Bubbles in SCC

After removing the forms from the first section of the retaining wall, there were discolorations at the locations of the vertical reinforcement, as shown in Figure 11, indicating potential problems associated with segregation and instabilities of the SCC flowing through the tight spaces between the reinforcement and the formwork. There was also vertical cracking at chamfer locations as well as in the field of the wall.

The second wall placement produced noticeably better results as shown in Figure 12. The second portion of the wall had both vertical and horizontal cracking. Whereas the vertical walls cracks are easily attributed to drying and/or autogenous shrinkage, the horizontal cracks are not as easy to explain. Typically horizontal cracks in walls are due to loading. However, in this case, the horizontal crack is on the compressive side of the backfill load, suggesting a potential placement defect. The vertical reinforcement of the wall counters the structural threat. The vertical and horizontal cracks are shown in Figure 13 and Figure 14, respectively.

Despite cracking at a few sections along the entire wall, there were not any locations along the wall that required surface rehabilitation due to poor consolidation or spalling.

Figure 11: Discolorations on Retaining Wall

Figure 12: Second Retaining Wall Placement

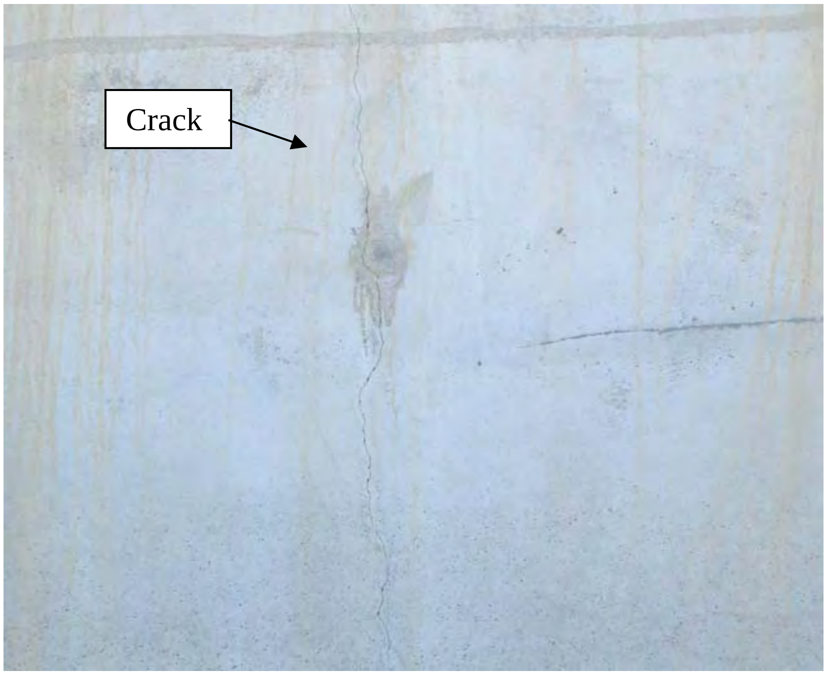

Figure 13: Vertical Crack in Second Placement

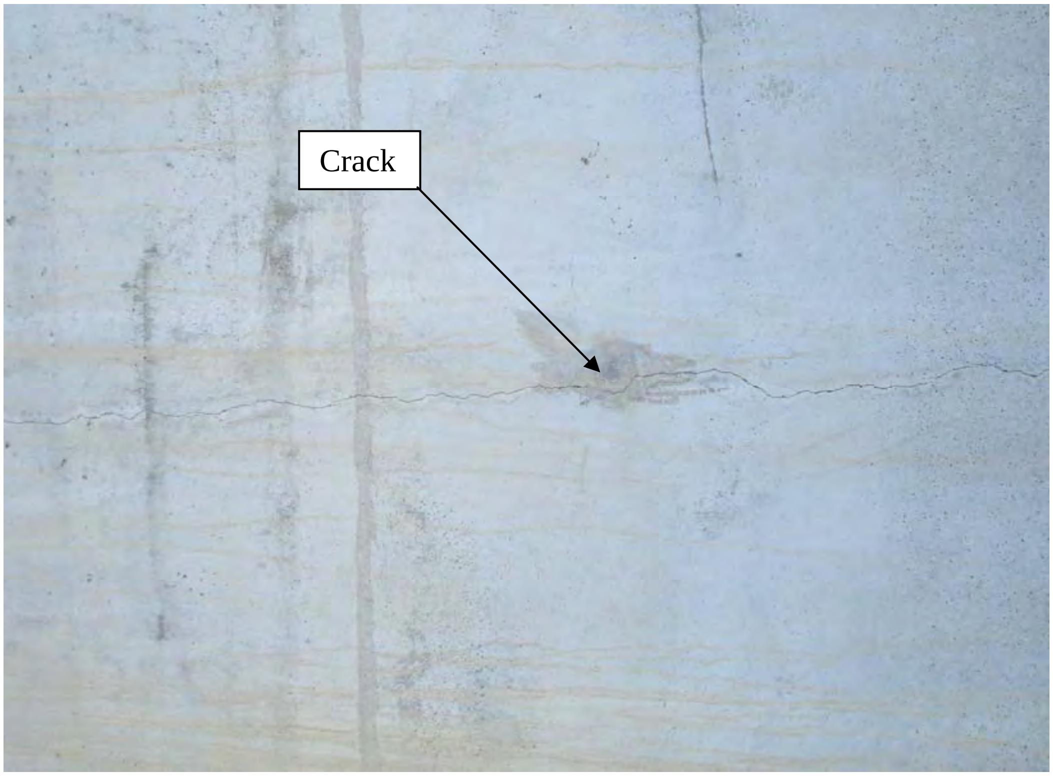

Figure 14: Horizontal Crack in Second Placement

4.2. Abutments with Architectural Stone Finish

Two abutments at the Main Street Bridge were placed using SCC with varying results. The placement of SCC in southern abutment encountered many difficulties. Concrete delivery delays, as long as 30 minutes between truck-loads, resulted in distinct joints between placements of concrete layers. Whereas such problem can be easily rectified in SCC with intermittent vibration that re-liquefies the mix, no such action was taken. In addition, it appears that the SCC did not have the same flow capabilities of the mix used in the retaining wall. Although slump flow tests were performed for each delivery and only mixes passing the minimum slump were accepted, the apparent lack of "self-leveling" that the SCC exhibited during placement indicates that some fluidity may have been lost during pumping, indicating problems of dynamic stability of the mix. Figure 15 demonstrates the stratification of the SCC that resulted from the reduced flowability and the delivery time-gaps between trucks.

Figure 15: Stratification of SCC

Although the strength of the SCC and the overall structural integrity of the southern abutment are acceptable, the exposed face with the architectural quarry stone finish required repairs in various regions. CDOT inspectors estimated that approximately 60 ft^2 of the exposed face was removed and repaired. Figure 16 through 18 demonstrate the resulting surface finish of the southern abutment SCC. Clear examples of reduced flow, instabilities, and bleeding can be seen in these figures.

Figure 16: Exposed Face Southern Abutment

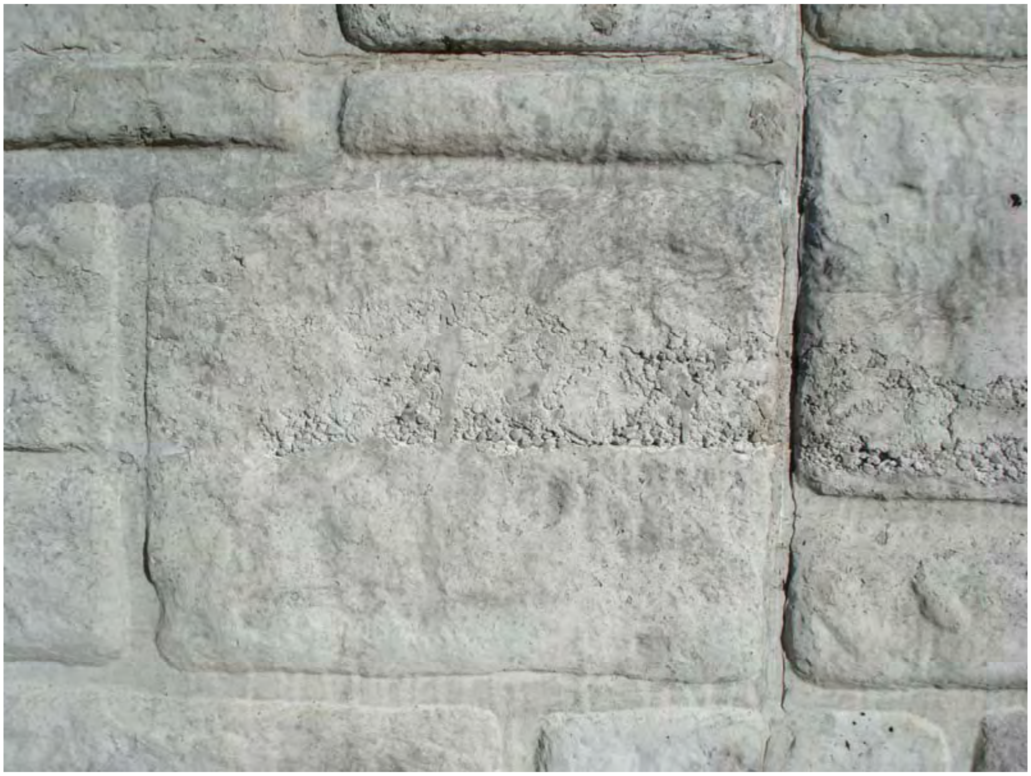

Figure 17: Southern Abutment Finish 1

Figure 18: Southern Abutment Finish 2

After re-evaluation of the contractor production and delivery techniques, adjustments were made that resulted in significant improvement in the consolidation and surface finish at the Northern abutment, where only minor areas required patching or repair. Figure 19 shows the back face of the northern abutment, where there is minimal stratification and improved surface finish at the form liners on the front face of the abutment.

Figure 19: Northern Abutment

Nevertheless, despite the improvements in the placement techniques, there are regions on the exposed face of the northern abutment that have less than perfect results. Figure 20 shows an area where instability and bleeding are apparent. As a result, the surface finish of the exposed face has areas that do not exhibit the high surface quality expected from SCC.

In general, the results of the two abutment finishes did not produce the appearance expected from SCC. Although the structural integrity of these elements is sufficient, the aesthetic results were far below the typical products seen in numerous other SCC structures. These shortcomings can be mainly attributed to an inconsistent batching and placement of the SCC.

Figure 20: Northern Abutment Exposed Face

4.3. Bridge Piers

Finally, seven piers for the northbound bridge were cast with SCC. The first three piers cast had significantly better results than the retaining wall or abutments. The piers have a high quality finish over their entire height, without apparent disruptions in the placement, nor joint formations between truck deliveries. However, during the placement of the fourth pier, the contractor could not produce a mix that would qualify as an acceptable SCC due to high air contents. As a result, the CDOT inspectors and contractor agreed to use normal Class D concrete to cast this pier. The final four piers were successfully cast with the approved SCC, which produced surface finishes expected from typical SCC placement.

It should be noted that the contractor adamantly attributes the high air content of the SCC during the pier placements to admixture sensitivity to increases in temperature. It was reported by Frank Leone (Leone Ready Mix, LLC, supplier of SCC for the project) that the air content increased significantly and uncontrollably with internal SCC temperatures above 75^0 Fahrenheit. The admixtures used were a combination of HRWR and accelerator, which required scheduled agitation to prevent the two admixtures from separating. This detail was learned from the chemical supplier after the unsuccessful batching.

In all, the eight piers, seven of which were cast using SCC, have the desired appearance and structural integrity. Figure 21 shows all but one of the piers cast, where the missing pier was cast with SCC and is located outside the left edge of the picture. Note the text in the figure indicating the normal Class D concrete pier.

Figure 21: Northbound Bridge Piers

Despite the more successful casting of the SCC columns, closer inspection reveals some slight surface problems. These appear to be a combination of minor aggregate segregation and delays between truck deliveries. Considering that the SCC in the pier columns was placed using a tremmy pipe and no external consolidation, the overall surface finish is satisfactory. However, each column has small areas where the SCC was unable to obtain the desired surface finish, as shown in Figure 22 and 23.

It has been concluded that most of the problems with the SCC surfaces in this project are associated with the concrete supplier's inexperience with batching SCC. The concrete supplier claimed that the superplasticizer, a BASF product, was not properly delivered or maintained. BASF recommends that the superplasticizer, which is a combination of high-range water-reducing admixture (HRWRA) and accelerator, be kept thoroughly mixed with an internal agitator to prevent separation. However, this information did not reach the concrete supplier until after several obvious problems arose.

Figure 22: Pier Column Surface Defect

In addition to the complaints about required mixing of the superplasticizer, the concrete supplier was adamant about the effects of ambient temperature on the amount of entrained air in the mix. In the eyes of the SCC supplier (Leone Ready Mix), the air content increases significantly with increases of temperature above 75^0 Fahrenheit. This dispute was rooted to the numerous rejections of delivery trucks. Although the slump flow was not influenced significantly, the increases in air content were highly inconsistent, and the specified air content difficult to obtain. The increases in air content, possibly with time, may have contributed to mix segregation and the resulting problems with surface finishes.

Despite the rejection of concrete batches, the contractor stated that the use of SCC has reduced the amount of labor required to cast the structural elements. The placement and finishing times were significantly reduced, with minimal increases in forming practices that would seal all form joints. The contractor used an expansive foam insulator to seal the forms at the joints.

Figure 23: Visible Placement Separations

5. CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to evaluate an SCC demonstration project on structural components of the northbound bridge on Interstate 25 at Trinidad, CO. The mix design performance has been evaluated with regard to stability, flowability, and finished product used to construct retaining walls, abutments, and piers.

Overall, it was determined that the use of SCC in this project was reasonably successful in the construction of bridge infrastructure components such as piers, retaining walls and abutments. Unfortunately, the all-around lack of construction experience with SCC resulted in numerous aesthetic problems that are rather atypical of the specific material. However, despite numerous visual defects that required patching and repair, it is believed that each component has the required structural integrity necessary for safe highway transportation projects.

SCC is proportioned in ways that are uncommon to normal concrete. In addition, it uses admixtures in quantities, combinations, and interactions that are also uncommon. An inexperienced contractor can easily make mistakes that may result in unstable concrete that segregates easily, loses its flowability in an untimely manner, and results in unexpected amounts of entrained air. After careful evaluation of the SCC components during and after construction, it was concluded that all the problems described above were encountered to some extent in this project. It is clear that a contractor’s knowledge of SCC, delivery capabilities, and placement techniques must be scrutinized before allowing construction to proceed.

Nevertheless, despite the apparent lack of experience with batching and casting SCC by the contractor that was awarded this project, this recommendation arises based on the overall results being acceptable even with a lower finish quality expected from SCC. Clearly, as the project progressed, the experience of the contractor in placement and batching developed accordingly and resulted in better construction and less need for repair.

Based on the experiences and observations of this study, it is recommended that similar SCC projects with more expanded scope be considered in the future. It will be preferable however, that in the early stages such projects be pursued closer to bigger urban centers, which will make it possible to find contractors with greater SCC experience to participate and help enrich CDOT’s related experience.

REFERENCES

1. Whitcomb, B. L., and Kiousis, P. D., “Development of Self-Consolidating Concrete for Thin Wall Applications Including Validation” ASCE Journal of Materials in Civil Engineering, Vol. 21, No 10, pp587-593, 2009.
2. Björnström, J. and Chandra, S. (2003). “Effect of superplasticizers on the rheological properties of cements.” J. Materials and Structures, 36(264), 685 – 692.
3. Yoshioka, K., Sakai, E., Daimon, M., and Kitahara, A. (1997). “Role of Steric Hindrance in the Performance of Superplasticizers for Concrete.” J. Am. Ceramic Society, V. 80 (10), 2667-2671.
4. Colorado Department of Transportation (2006), *Revision of Sections 601Structural Concrete,* October 19, 2006.