Report No. CDOT-2012-11
Final Report

APPLICATION OF ROLLER COMPACTED CONCRETE IN COLORADO'S ROADWAYS

Nattapong Damrongwiriyanupap
Yu-Chang Liang
Yunping Xi

October 2012

COLORADO DEPARTMENT OF TRANSPORTATION
DTD APPLIED RESEARCH AND INNOVATION BRANCH

Technical Report Documentation Page

1. Report No. CDOT-2012-11	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle APPLICATION OF ROLLER COMPACTED CONCRETE IN COLORADO'S ROADWAYS		5. Report Date October 2012 6. Performing Organization Code
7. Author(s) Nattapong Damrongwiriyanupap, Yu-Chang Liang, Yunping Xi		8. Performing Organization Report No. CDOT-2012-11
9. Performing Organization Name and Address Department of Civil, Environmental and Architectural Engineering University of Colorado Boulder, Colorado 80309		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 25.00
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
Roller Compacted Concrete (RCC) is a no-slump concrete mixture that is transported, placed, and compacted with the same construction equipment as asphalt pavement. RCCs were used to construct three sections of pavement in Weld County Road 28 (WCR 28), eastbound of State Highway (EB 66), and westbound of State Highway (WB 66). Three sets of field inspections were conducted: 1) during construction; 2) nine months after construction; and 3) two years after construction. Strength and durability behaviors of the RCCs were tested right after construction, and some of the material properties of the RCCs were further tested nine months after construction. Field inspections showed that the diamond ground surface texture of EB 66 and WB 66 is better and smoother than the surface of WCR 28 where large cracks and chipping occurred along both longitudinal and transverse directions. The relatively poor quality of RCC samples at WCR 28C location may be due to the different quality of concrete mix, the degree of compaction used during construction, and the absence of saw cut joints. The concrete specimens were tested for rapid chloride permeability, drying shrinkage, freeze-thaw resistance, compressive strength, splitting tensile strength, and flexural strength. The test results obtained after the construction indicated that the chloride permeabilities are in the low to very low ranges, the drying shrinkages are in the normal range, and freeze-thaw resistance is fine. The compressive strength, splitting tensile strength, and flexural strength are also in the normal range similar to that of conventional concrete. The test results obtained nine months after the construction indicated that deteriorations occurred in the RCC concretes.

Implementation
After only nine months of service, the RCCs already showed noticeable changes in all of the selected properties tested. More tests and field inspections should be conducted in the future after a longer monitoring period to verify and validate the initial findings observed in the material properties and surface conditions of the RCC pavements.

17. Keywords RCC pavement, concrete compaction, concrete strength, concrete durability, concrete cracking, field inspections, cost/benefit analysis		18. Distribution Statement This document is available on CDOT's 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 60	22. Price

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CHAPTER 1 - OBSERVATION OF CONSTRUCTION PROCESSES

Roller Compacted Concrete (RCC) is a no-slump concrete mixture. It is defined by the American Concrete Institute (ACI) as the concrete compacted by vibrating roller compaction. The major advantages of using RCC compared to conventional concrete are lower consumption of cement, less form work, and reduced construction periods. Over the years, it has been widely used for construction of rigid pavements that require fast construction while maintaining low initial costs. RCC can save 15 to 30 % of the initial cost when compared with conventional concrete pavement. A detailed literature review on the various aspects of RCC is provided in Appendix A.

In this project, two concrete slabs were built using RCC on Weld County Road 28 and State Highway 66. The research team at the University of Colorado at Boulder visited the RCC pavement job sites on April 28, 2009. Photos (Figures 1.1 to 1.7) were taken during the visit and show the construction process for RCC pavement.

Fig. 1.1 The base course is prepared before placing RCC mix

Fig. 1.2 A water truck is used for providing moisture to the base course

Fig. 1.3 A grader is used to prepare the base course

Fig. 1.4 RCC mix is transported to a paver by a dump truck

Fig. 1.5 RCC mix is transferred to the paver using a GOMACO RTP-500

Fig. 1.6 RCC is placed using a Titan paver

The requirement on mix design of the RCC is discussed in Section A.3 of Appendix A. The RCC mix designs used in the present project are shown in Table A.7 of Appendix A. To verify conformance with the design density, the degree of compaction of RCC pavement was determined using a nuclear moisture/density gage as shown in Fig. 1.8.

Fig. 1.7 RCC pavement is compacted by a vibratory roller

Fig. 1.8 A Nuclear gauge for measuring the degree of compaction of RCC pavement

CHAPTER 2 - EXPERIMENTAL STUDY OF THE RCCs

Concrete samples taken from the RCC slabs are designated in this report as WB66 from westbound S.H. 66, EB66 from eastbound S.H. 66, and WCR28 from Weld County Road 28. These extracted samples were then tested for their mechanical and durability properties. Compressive strength, splitting tensile strength, and flexural strength of the RCC samples were determined by CDOT. Chloride permeability tests, rapid freezing and thawing tests, and drying shrinkage tests were conducted at the University of Colorado at Boulder.

2.1 Chloride Permeability Test

Testing Method

This test was conducted using ASTM C 1202. The testing method is a commonly used method for testing electric conductivity of the saturated concrete. The test result has been used as an indicator for chloride permeability of concrete. The specimens were prepared using a water-cooled diamond saw to cut the specimens into cylindrical discs of 50 mm thick and 100 mm diameter as shown in Fig. 2.1. To prevent fluid from leaking through the sidewalls of the disc and to create linear flow of electrical current, the cylinder walls of specimens were sealed with a coating of silicone and allowed to dry for 12 hours. The specimens were saturated and then placed into an apparatus as depicted in Fig. 2.2. Two different solutions were added to the two chambers: one was filled with a 3% solution of NaCl and the other 0.3 M NaOH. Once the set-up is complete, an electrical current generated by a 60-volt power supply is passed across the concrete specimens for six hours. The ability of chloride ions to move through a concrete specimen was measured in terms of the impedance in Coulombs over the total time of the test.

Fig. 2.1 RCC specimens for Rapid Chloride Permeability Test

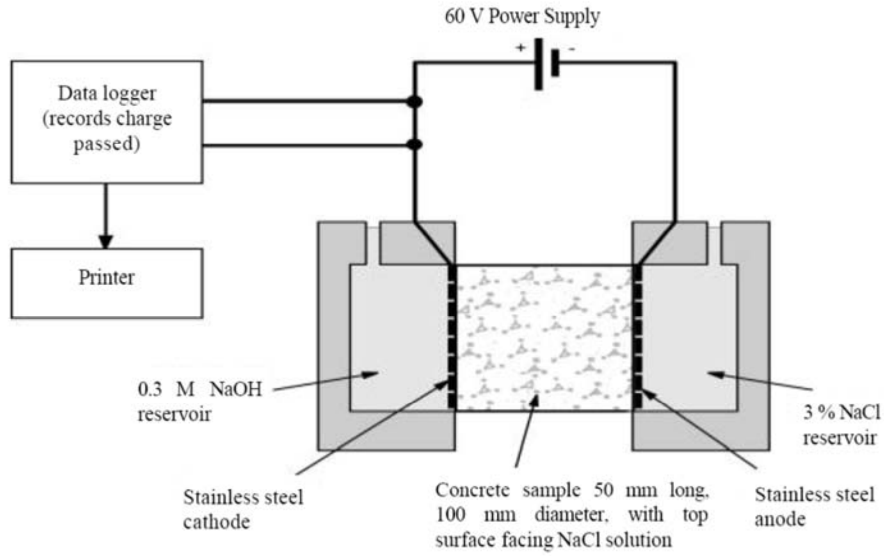

Fig. 2.2 Rapid Chloride Permeability Test Set Up (Stanish et al., 1997)

Test Results of Chloride Permeability

The results of the rapid chloride permeability test (RCPT) of RCC concrete samples taken from the three different locations are shown in Table 2.1. The categories of permeability specified by ASTM C 1202 are shown in Table 2.2. The total charges passing through the concrete specimens from the three different locations are in either the very low or low rate of chloride ion permeability when compared with the ASTM standard. Therefore, it can be concluded that the RCCs used in the project have very low to low chloride ion permeability. As a result, the RCCs can be considered to have high chloride ion resistance.

Table 2.1 RCPT test results

Location 1 (WB 66 #9)	Coulombs	Chloride ion penetrability
Sample# 1	1172	Low
Sample# 2	621	Very Low
Location 2 (EB 66 #2)	Coulombs	Chloride ion penetrability
Sample# 1	1017	Low
Sample# 2	608	Very Low
Location 3 (WCR 28 #1)	Coulombs	Chloride ion penetrability
Sample# 1	299	Very Low
Sample# 2	510	Very Low

Table 2.2 RCPT concrete permeability ratings (ASTM C 1202)

Charge Passed (Coulombs)	Chloride Ion Penetrability
> 4000	High
2000 – 4000	Moderate
1000 – 2000	Low
100 -1000	Very Low
< 100	Negligible

2.2 Drying Shrinkage Test

Testing Method

This test was conducted using ASTM C 157 to measure the longitudinal length change of concrete specimens taken from the three different locations. All specimens were cut in prisms with approximately a 3-in. square cross-section and 11.25-in. long. The specimens were drilled and then gage studs were installed at both ends as shown in Fig. 2.3. To measure the extent of drying shrinkage, specimens were soaked in water for two weeks to reach a saturated condition. After soaking, the specimens were placed in the lab at room temperature and allowed to dry and measure the magnitude of drying shrinkage. By using a comparator, shown in Fig. 2.4, the length change of specimens was measured every day in the first week, every three days in the second and third weeks, and every seven days in the following weeks.

Fig. 2.3 RCC specimens for Drying Shrinkage Test

Fig. 2.4 A comparator for measurement of length change

Results of Drying Shrinkage Test

Length change of concrete specimens can be calculated using Eq. (2.1). The results of the drying shrinkage test of the specimens from the three locations were plotted between length change (%) and time (days) in Figs. 2.5, 2.6, and 2.7. From these plots, one can see that the drying shrinkage occurred at a faster rate in the first few days and became slower in subsequent days.

$$L_c = \frac{(L_2 - L_1)}{L_1} \times 100 \qquad (2.1)$$

L_C = Length change of specimen (%) at x days
L_1 = Length comparator reading at 0 days
L_2 = Length comparator reading at x days

The drying shrinkage tests continued for more than 100 days. All drying shrinkages are in the range of 500 to 700 micro-strains. There is only one specimen with 800 micro-strains. Overall, the drying shrinkage of RCCs used in this project is comparable to the drying shrinkage of regular Portland cement concrete.

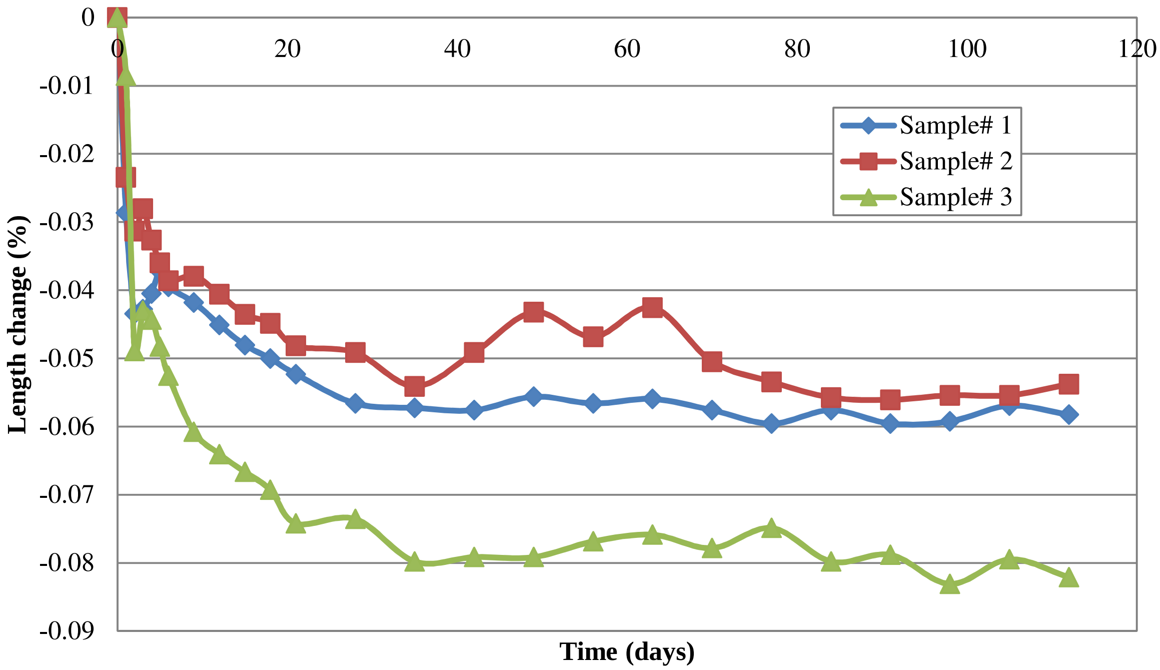

Fig. 2.5 The length change vs. time for the specimens from WCR 28

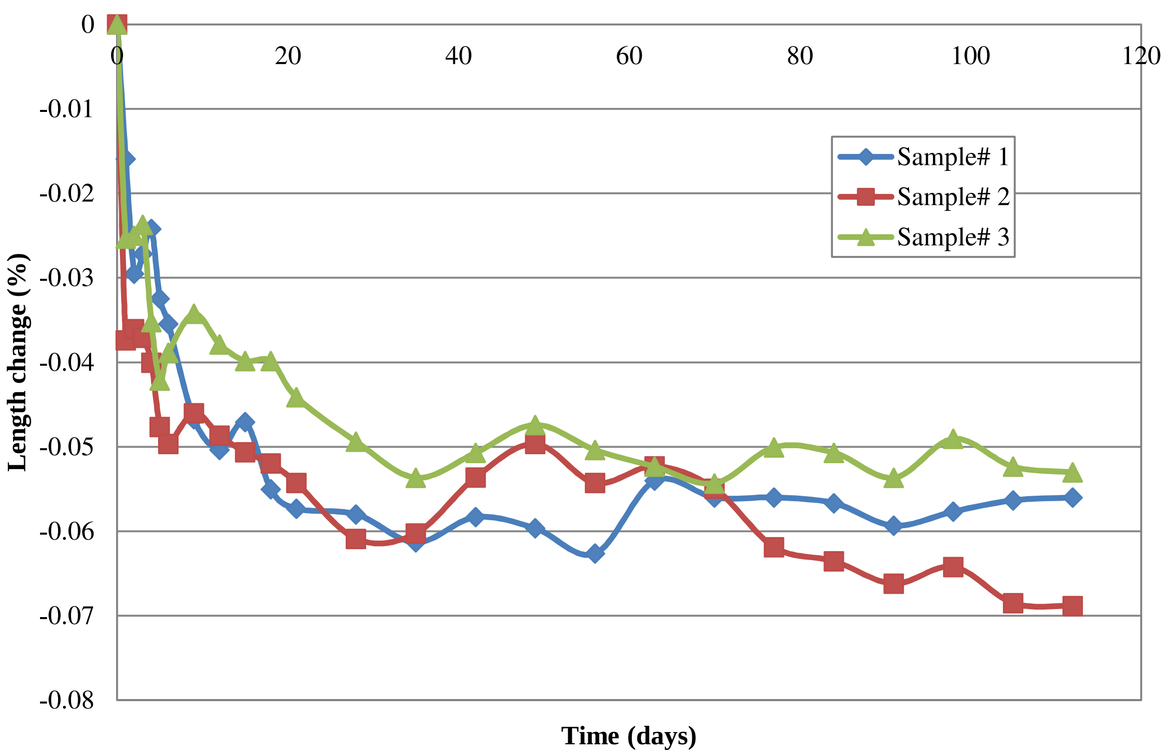

Fig. 2.6 The length change vs. time for the specimens from WB66

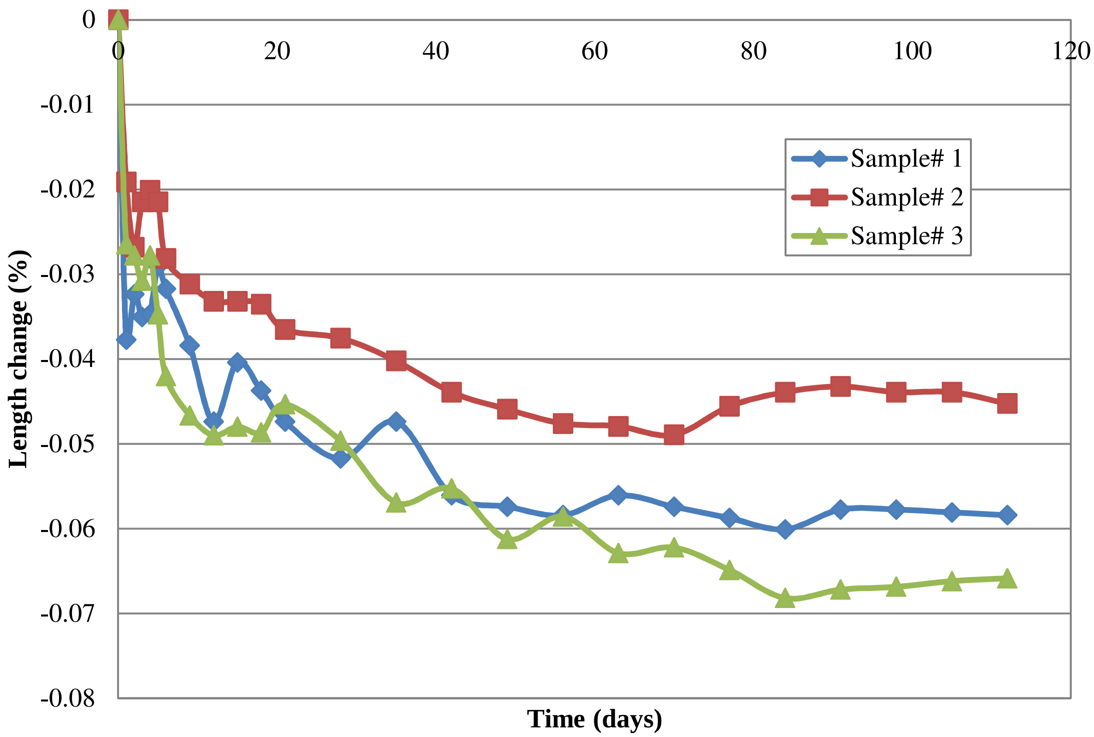

Fig. 2.7 The length change vs. time for the specimens from EB66

2.3 Rapid Freeze-Thaw Test

Testing Method

Concrete blocks were taken from the three different locations and cut into prisms with a cross-section dimension of approximately 3 inches by 3 inches and a length of 11.25 inches. The rapid freeze-thaw test was conducted using the Logan Rapid Freeze-Thaw Cabinet. This machine has a 6'x3' freezer-plate beneath its containers to cool the concrete specimens and electric heaters between each container to heat the specimens. The rapid freeze-thaw testing was conducted following ASTM C 666. The freeze-thaw cycles were specified by the ASTM standard to allow lowering the temperature from 40 °F to 0 °F and raising the temperature from 0 °F to 40 °F in a complete cycle, which should be accomplished in not less than 2 hours but not more than 5 hours. The testing also requires that the temperature at the center of the specimen should be 0 ± 3 °F at the end of the cooling period and 40 ± 3 °F at the end of the thawing period.

Before the test program started, the Logan cabinet was tested and calibrated. A thermal sensor was installed at the center of specimen as depicted in Fig. 2.8. The results of the temperature calibration are shown in Fig. 2.9. The freeze-thaw cycle was completed in approximately 3 hours and 26 minutes, which is within the time limit specified by the ASTM standard. The maximum temperature at the end of the thawing period is approximately 37.9 °F (0.65 °C), which is within the specified temperature limit. The temperature at the end of cooling period is 9.6 °F (-12.4 °C), which is slightly above the requirement (0 ± 3 °F). Prior to the start of the test cycle, each container was filled with water that did not cover more than 1/8" of the specimens' surface. The test program was repeated for 300 cycles. The cycles were divided into 10 intervals and each interval contained 30 cycles. Specimens were removed from the Logan cabinet at the end of each interval and then the length change, weight loss, and dynamic elastic modulus were measured. The length change measurement was conducted based on ASTM C 157 as mentioned in the previous section. The weight loss of the specimens was measured using a scale with accuracy of 0.5 g, which satisfies the ASTM standard. The dynamic elastic modulus was measured by ultrasonic pulse velocity.

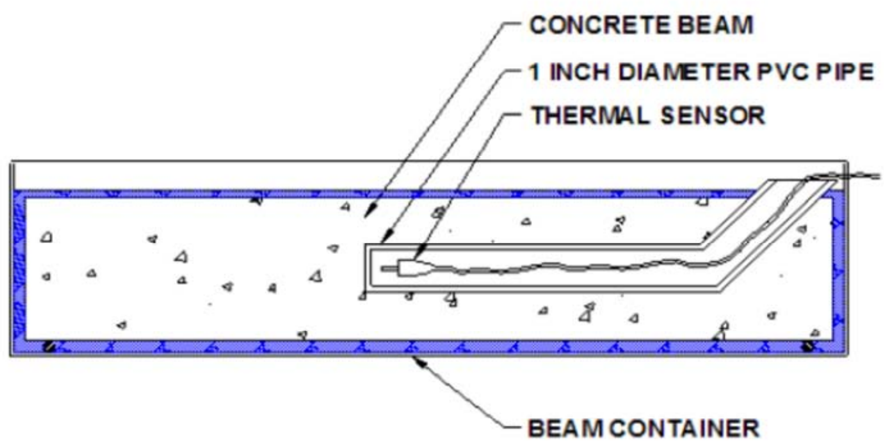

Fig. 2.8 The thermal sensor at the center of specimen (Hamel, 2005)

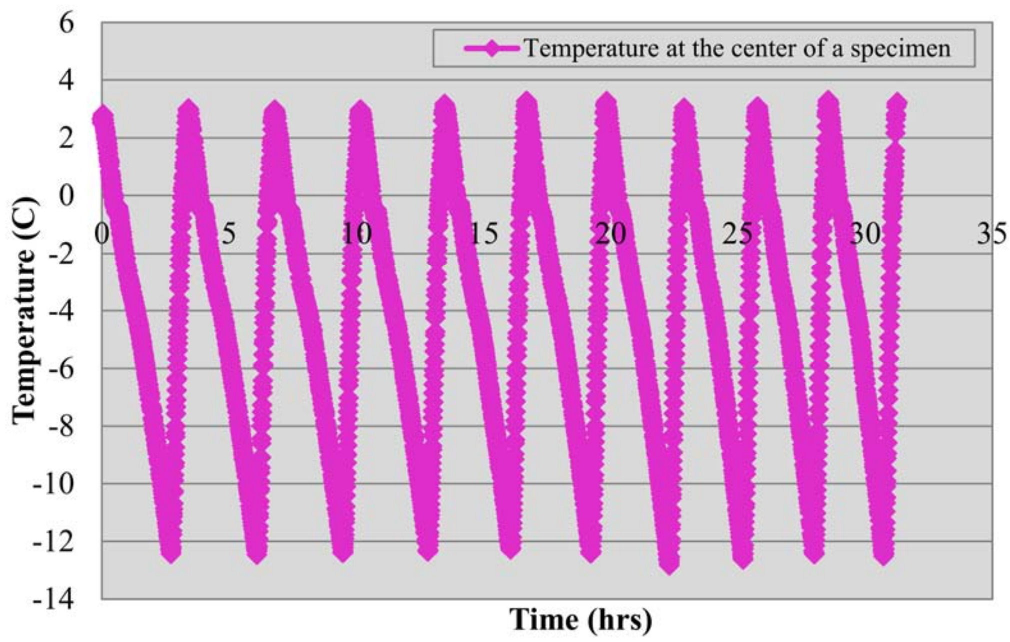

Fig. 2.9 Temperature measurement during freeze-thaw cycles

Results of Freeze-Thaw Test

Test results are categorized into three sections that focus on a particular type of test, namely Ultrasonic Pulse Velocity, Weight Loss, and Length Change.

- **Ultrasonic Pulse Velocity**

The ultrasonic pulse velocity measures the speed at which an ultrasonic signal travels through a concrete specimen. It is specified by ASTM C 597. The transit time for the ultrasonic signals can be determined by using two transducers mounted on the specimen at a fixed distance. The pulse velocity can be calculated by dividing the distance by the measured transit time. Then, the dynamic elastic modulus can be calculated by Eq. (2.2),

$$E_d = \rho V^2 \frac{(1+\mu)(1-2\mu)}{(1-\mu)} \tag{2.2}$$

in which E_d = The dynamic elastic modulus (Pa); μ = Poisson's ratio, and μ = 0.2 was used in Eq. (2.2); ρ = Density of specimen (kg/m^3); and V = Pulse velocity (m/s).

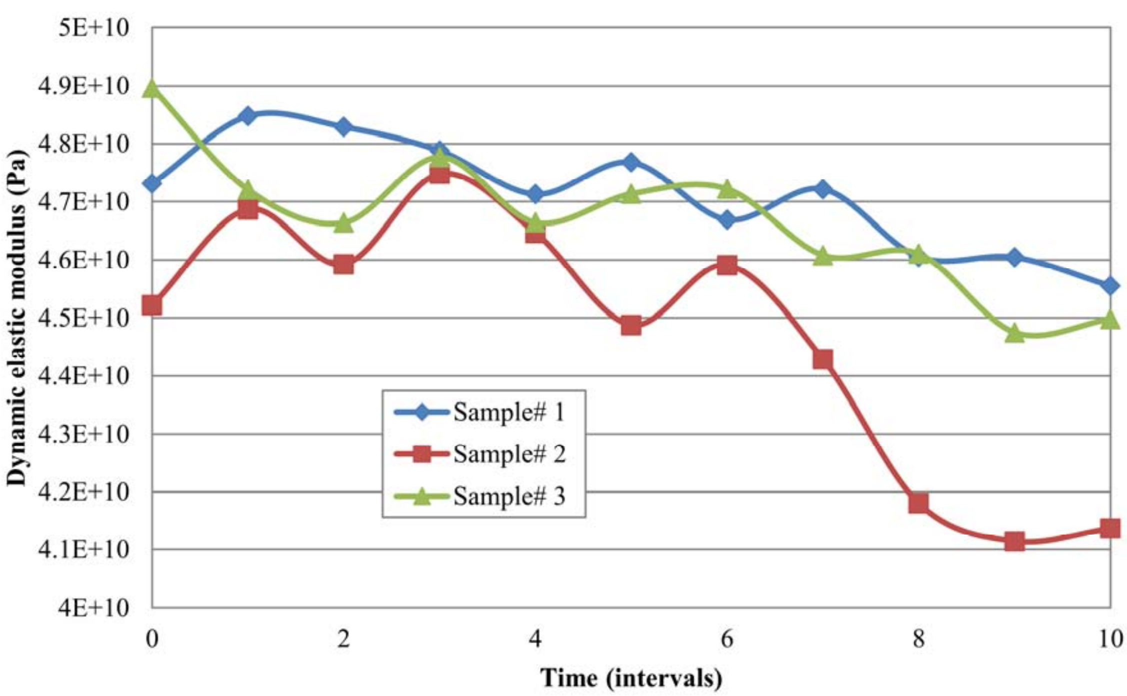

Fig. 2.10 Dynamic elastic modulus vs. freeze/thaw intervals for the RCC from EB66

Dynamic elastic modulus depends on the extent of damage in the concrete. Theoretically, concrete with increasing amounts of damage and cracking will require more time for the pulse to travel through it. A longer transit time results in a lower velocity and thus lower modulus. The plots between dynamic elastic modulus and freeze/thaw cycles of the specimens are shown in Figs. 2.10, 2.11, and 2.12. From these figures, it can be seen that the trend of dynamic elastic modulus is decreasing with increasing freeze/thaw intervals (cycles). For all specimens, the percentage change of the modulus is 5.9%, which is less than the specified failure values in ASTM C666.

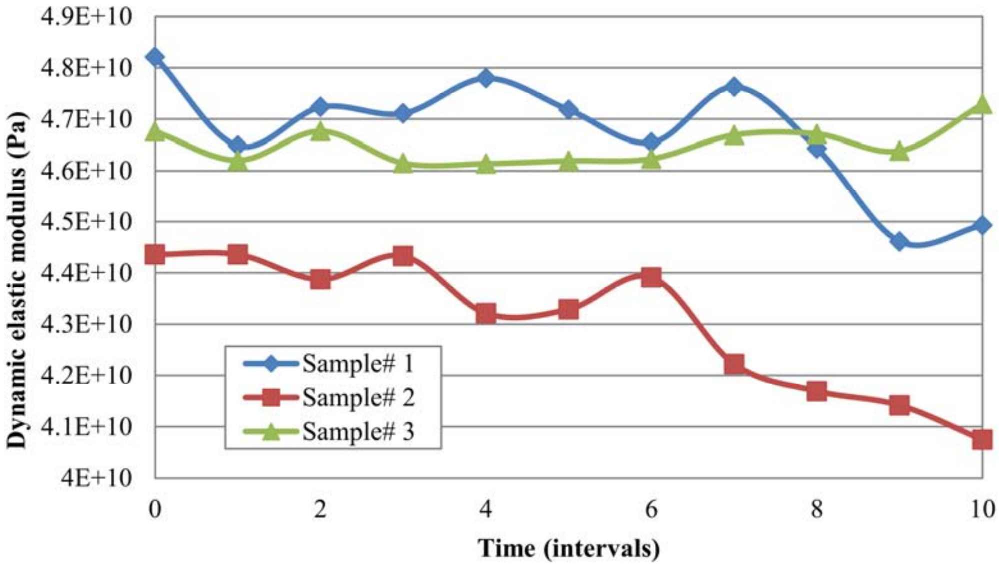

Fig. 2.11 Dynamic elastic modulus vs. freeze/thaw intervals for the RCC from WB66

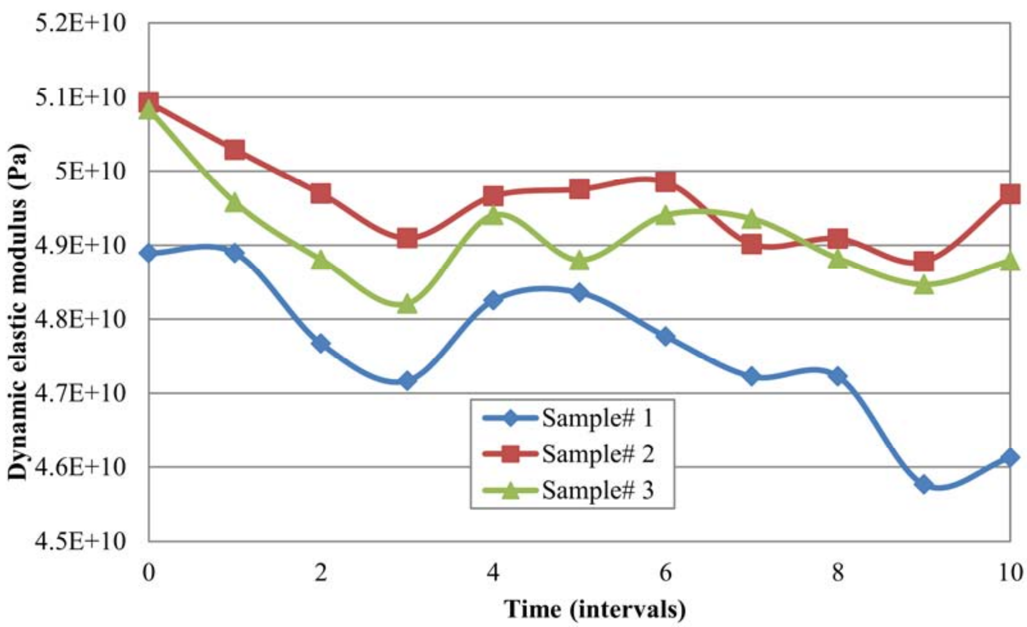

Fig. 2.12 Dynamic elastic modulus vs. freeze/thaw intervals for the RCC from WCR28

- **Weight Loss**

Weight loss of specimens is measured using a scale with an accuracy of 0.5 g, which can be calculated as:

$$W_c = \frac{(W_2 - W_1)}{W_1} \times 100 \qquad (2.3)$$

Where:

W_C = Weight loss of specimen (%) at x days
W_1 = Weight of specimen at 0 intervals
W_2 = Weight of specimen at x intervals.

The relationships between weight loss and time interval of specimens from the three different locations are shown as Figs. 2.13, 2.14, and 2.15. As the time increases, so does the spalling of concrete, which increases the weight loss of the specimens. For all specimens, the percentage change (loss) of weight was less than 0.5%.

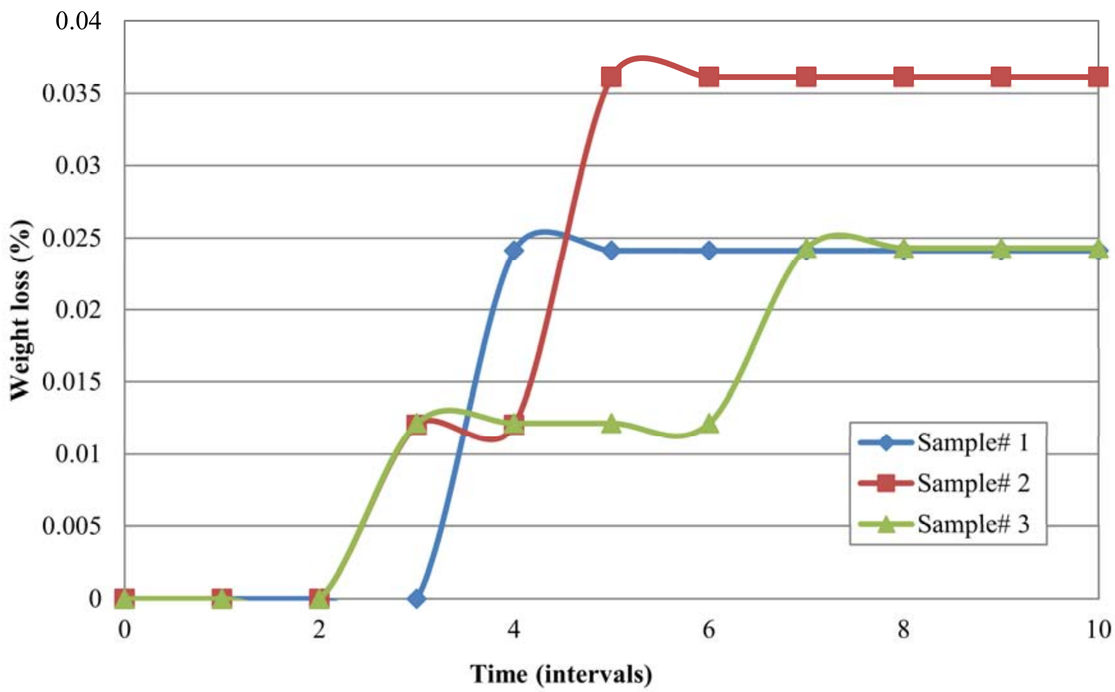

Fig. 2.13 Weight loss vs. freeze/thaw intervals for the RCC from EB66

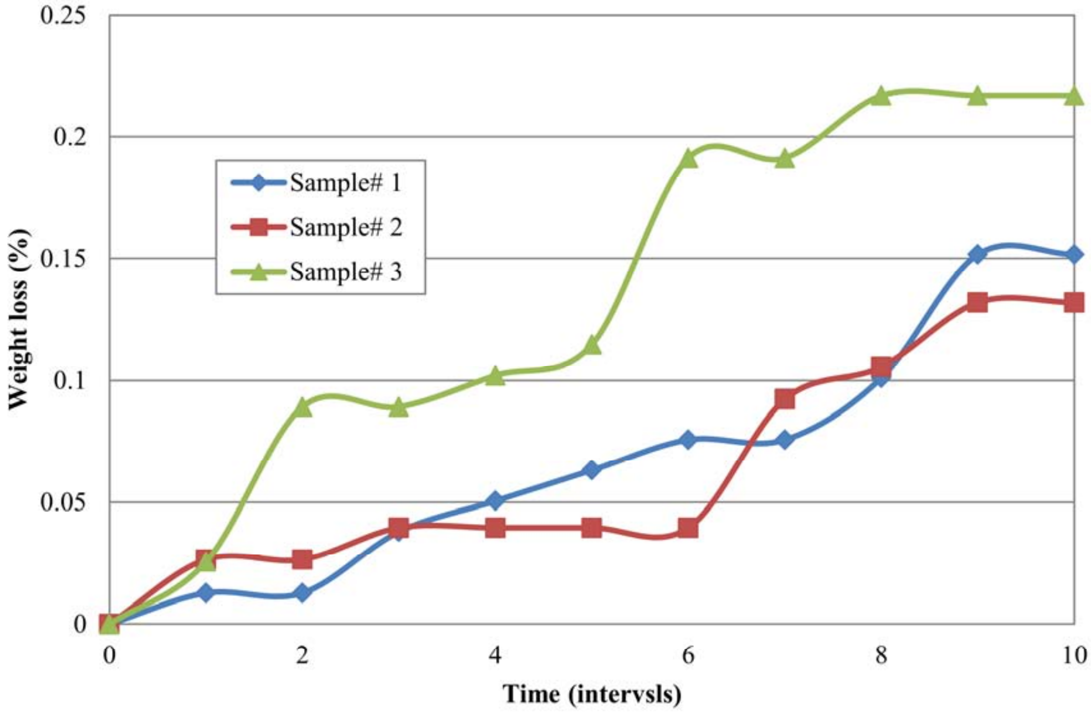

Fig. 2.14 Weight loss vs. freeze/thaw intervals for the RCC from WB66

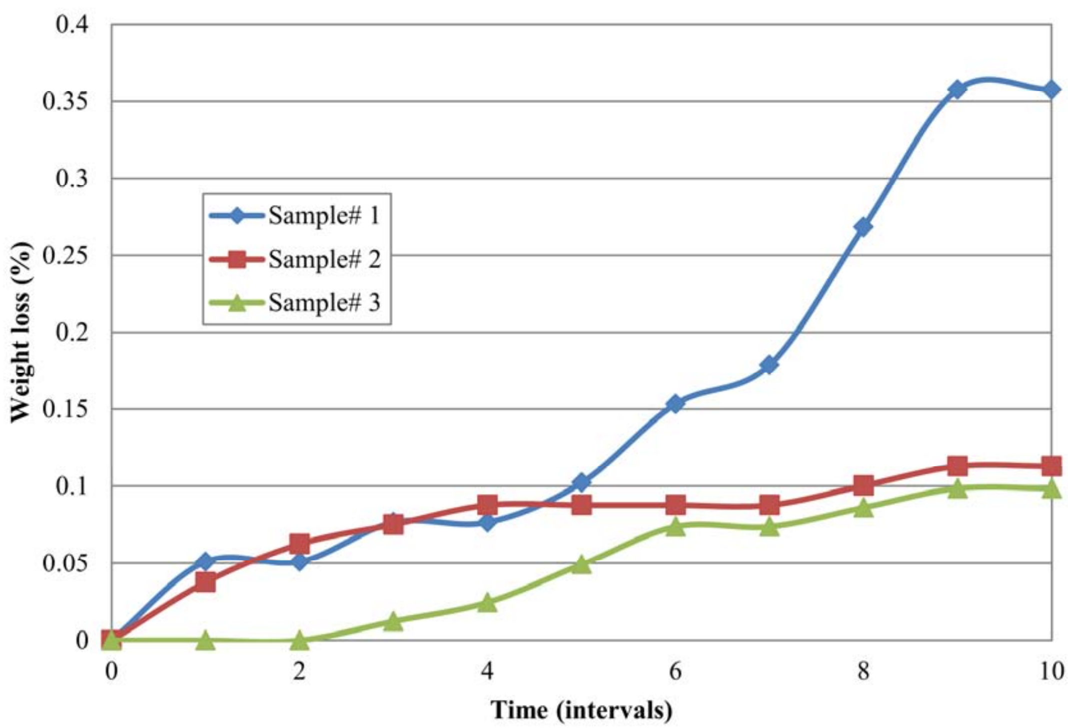

Fig. 2.15 Weight loss vs. freeze/thaw intervals for the RCC from WCR28

- **Length Changes**

Length change of specimens can be determined by the same method as for the drying shrinkage. The results were plotted in length change (%) vs. time (days) as shown in Figures 2.16, 2.17, and 2.18. From these plots, it is evident that the length change of the specimens decreases quickly at the beginning and becomes slower with increasing time. For all specimens, the percentage change in length was about 0.015%, which is less than the specified failure values in ASTM C666.

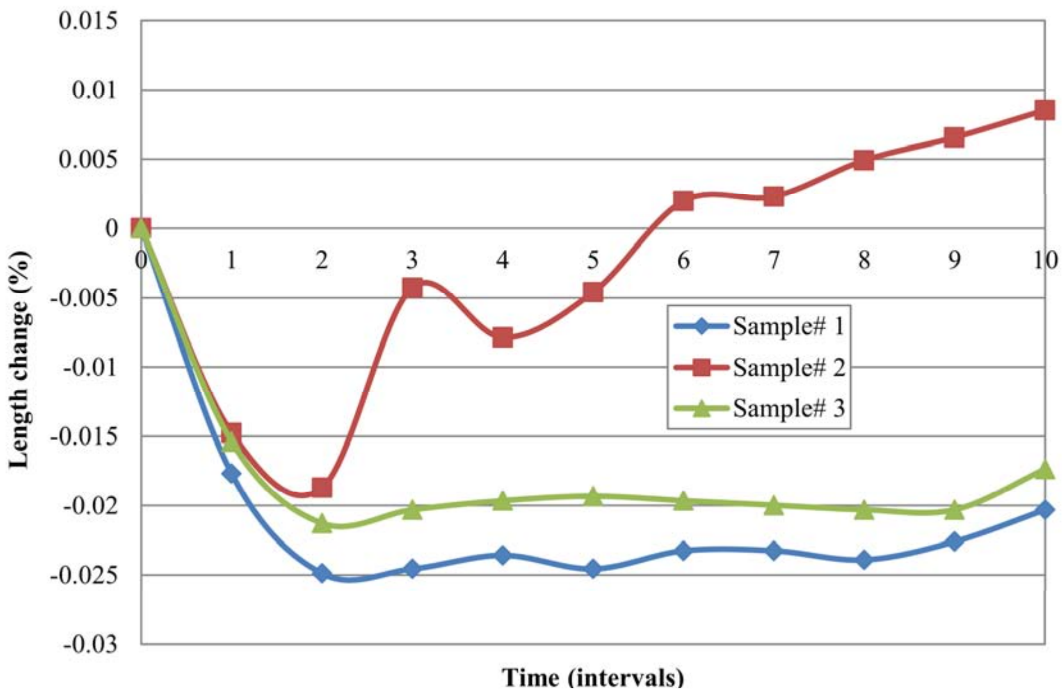

Fig. 2.16 Length changes vs. time for specimens from EB66

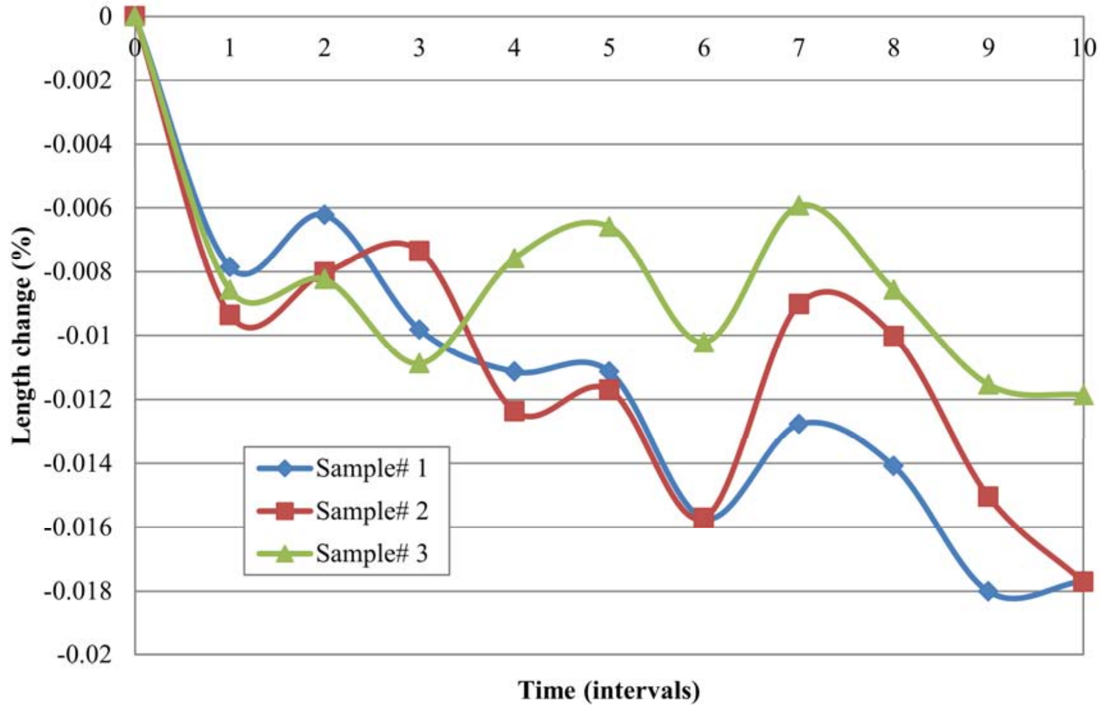

Fig. 2.17 Length changes vs. time for specimens from WB66

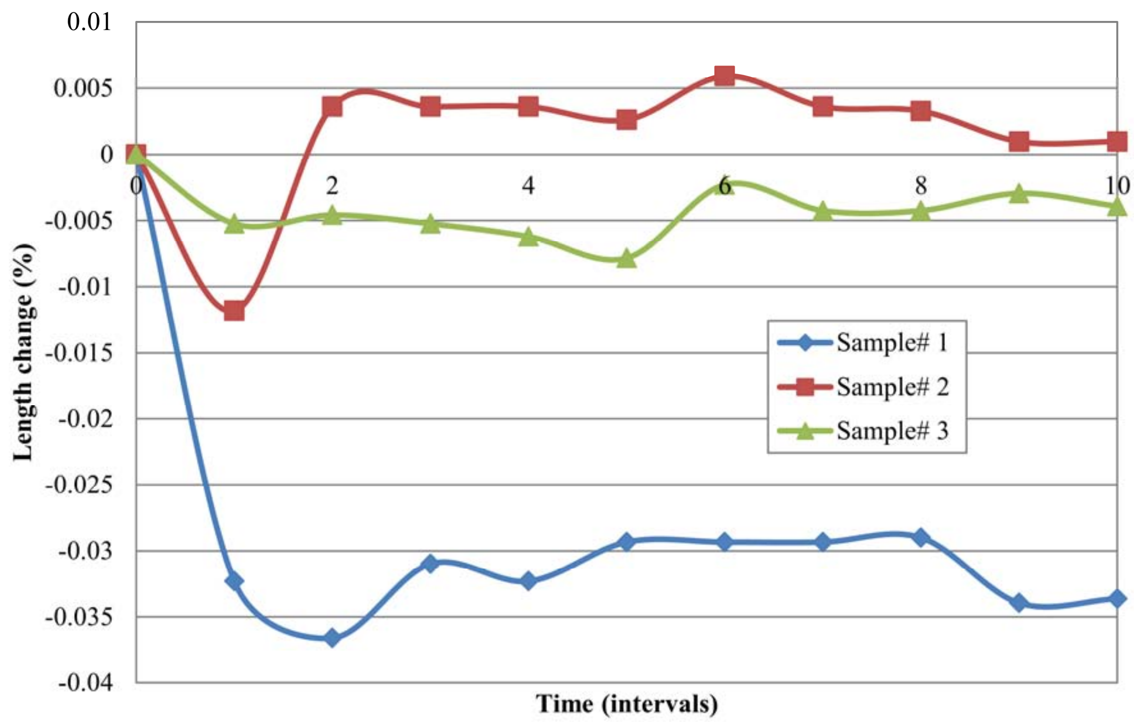

Fig. 2.18 Length changes vs. time for specimens from WCR28

2.4 Compressive Strength

The compressive strengths of the RCC specimens from the three different locations are shown in Table 2.3. The compressive strengths are quite high, which is adequate for the application in concrete pavement.

Table 2.3 Results of compressive strength of RCC specimens

Location	Average compressive strength (psi)
WB 66	8,896
EB 66	6,868
WCR 28	8,579

2.5 Splitting Tensile Strength

Table 2.4 shows the average splitting tensile strength results of the RCC samples from the three different locations. The splitting tensile strength is about 1/10 of the compressive strength, which is similar to conventional concrete.

Table 2.4 Results of splitting tensile strength of RCC specimens

Location	Average splitting tensile strength (psi)
WB 66	749
EB 66	661
WCR 28	631

2.6 Flexural Strength

The average flexural strength of the RCC samples from the three different locations are shown in Table 2.5. The flexural strength is higher than the splitting tensile strength, which is similar to conventional concrete.

Table 2.5 Flexural strength results of RCC specimens

Location	Average flexural strength (psi)
WB 66	1,022
EB 66	1,030
WCR 28	1,105

Note: The compressive strength, the splitting tensile strength, and the flexural strength were obtained from the CDOT concrete lab.

CHAPTER 3 - LONG-TERM PERFORMANCE EVALUATION

3.1 Field Observations

After nine months of exposure to weathering and traffic, the three pavement sections at westbound S.H. 66 (WB 66), eastbound S.H. 66 (EB 66), and Weld County Road 28 (WCR 28) were inspected to evaluate their performance. Observations were made on the surface texture and surface damage of the pavements. As seen from Figs 3.1 and 3.2, the surface of WCR 28 showed abrasions from traffic and weathering. Also, some fine surface material, which is the combination of fine aggregate and cement paste, was worn away, which is typical for RCC pavement (see Appendix A.5). The surface condition of the longitudinal, middle strip between the two traffic lanes was worse than the in-lane concrete surface, as illustrated in Fig. 3.2.

Fig. 3.1 Surface texture at WCR 28

Fig. 3.2 Surface texture in the longitudinal direction in the middle strip at WCR 28

The surface of this area was not smooth which may be due to lower compaction during construction. Thus, at WCR 28, concrete cores were taken from the in-lane and the middle strip as shown in Figs. 3.3 and 3.4, respectively. The cored samples from the in-lane locations in the south part of WCR 28 pavement were labeled as WCR 28S and the specimens from the middle strip (center) were called WCR 28C.


Fig. 3.3 Coring in-lane concrete samples at WCR 28

Fig. 3.4 Concrete cores are taken from the longitudinal middle strip at WCR 28

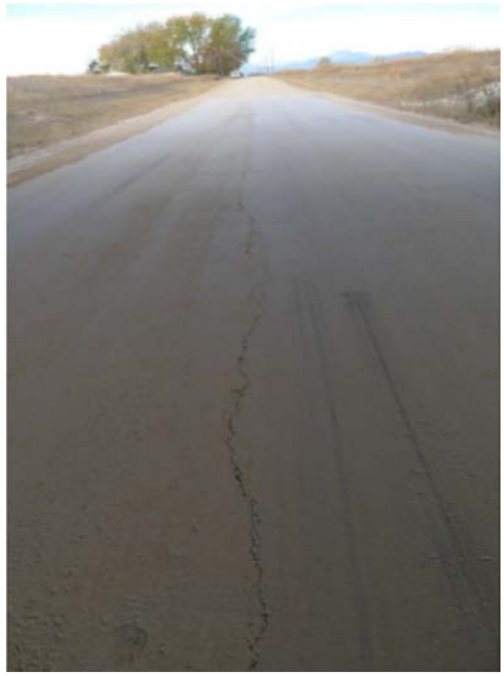

Fig. 3.5 The longitudinal crack on the pavement at WCR 28

Longitudinal cracks occurred in the pavement, as shown in Fig. 3.5. Fig. 3.6 illustrates the occurrence and variety of spacing of the transverse cracks. A sketch of the longitudinal and transverse cracks of WCR 28 is shown in Fig. 3.7. As noted in the sketch, there are some large cracks and chippings at the edge of the pavement, which are shown in Figs. 3.8, 3.9, and 3.10.

Fig. 3.6 The transverse cracks on the pavement at WCR 28

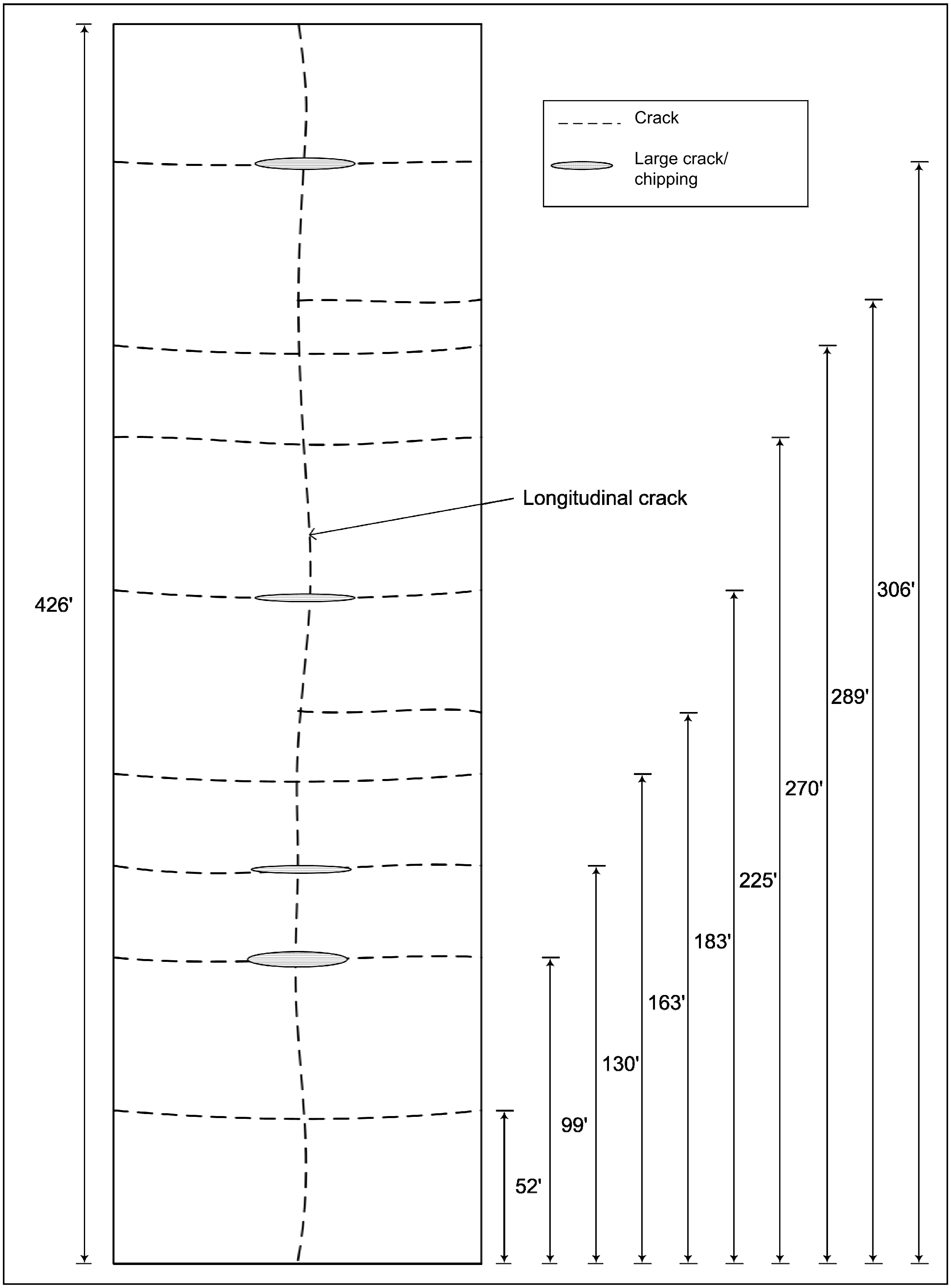

Fig. 3.7 Sketch of crack pattern on the pavement at WCR 28

Fig. 3.8 A large crack occurs on the surface of pavement at WCR 28

Fig. 3.9 The width of large crack on the surface of pavement at WCR 28

Fig. 3.10 Chipping of the pavement at WCR 28

Fig. 3.11 The surface texture of the pavement at EB 66

Compared with WCR 28, the surface conditions of RCC pavements at EB 66 and WB 66 are relatively good as shown in Figs. 3.11, 3.12, and 3.13. These lanes were diamond ground for smoothness, which would have removed the weaker surface layer and left the coarse aggregates embedded in pavement surface. Saw cut joints were made in EB 66 and WB 66 and there was no evidence of cracking in the longitudinal and transverse directions as shown in Figs. 3.14 and 3.15. It is important to mention that saw cut joints were not made in the pavement of WCR 28.

After two years of service, the inspection of the pavement in WCR 28 showed that the chippings of pavement were getting worse. Also, more new cracks had developed. The width of the existing cracks increased as well. Figs. 3.16 through 3.18 show the progress of crack development in WCR 28 pavement section two years after construction.

Fig. 3.12 The surface texture of the pavement at WB 66

Fig. 3.13 A close-up view of the surface texture of the pavement at EB 66

Fig. 3.14 A saw cut joint in the pavement at EB 66

Fig. 3.15 Saw cut joints on the pavement at WB 66

Fig. 3.16 Transverse cracks on the pavement at WCR 28 (Two years after construction)

Fig. 3.17 A large transverse crack on the pavement at WCR 28 (Two years after construction)

Fig. 3.18 The width of the transverse crack increased (Two years after construction)

3.2 Long-Term Performance Evaluation

Nine months after the construction of RCC pavements, concrete samples were taken from the three different locations for further testing of compressive strength, rapid chloride permeability, and freezing and thawing resistance. As mentioned in the previous section, the pavement at WCR 28 was inspected in the longitudinal middle strip (marked as WCR 28C) and in the traffic lane located in the south section of the pavement (marked as WCR 28S). As shown in Fig. 3.19, the CDOT team was preparing to take concrete specimens from the traffic lane; while Fig 3.20 shows the drilling of the samples in the longitudinal middle strip at WCR 28. Unlike the RCC pavement of WCR 28, there was no evidence of major cracks in the other two locations so only one concrete sample was taken from each location. Figs. 3.21 and 3.22 show coring of concrete samples from EB 66 and WB 66.

Fig. 3.19 Preparation for taking concrete samples from the traffic lane at WCR 28

Fig. 3.20 Extracting concrete cores from the longitudinal middle strip at WCR 28

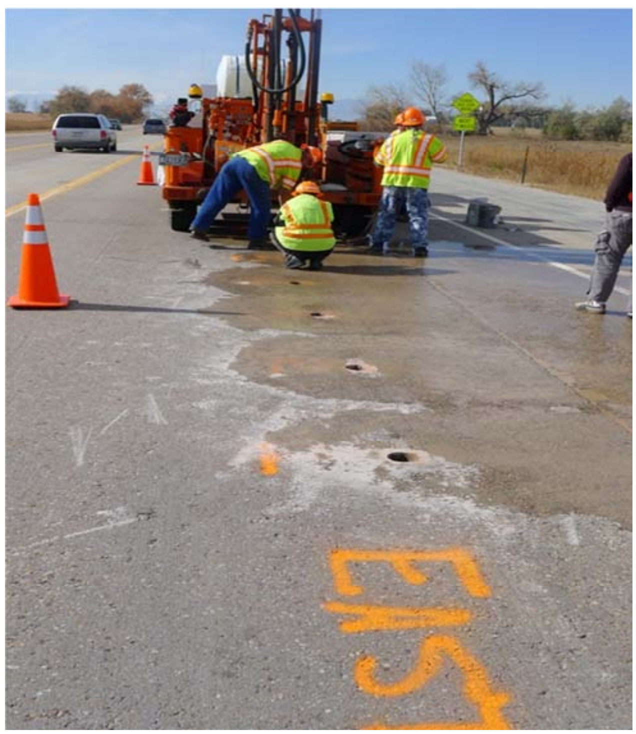

Fig. 3.21 Extracting concrete samples at EB 66

Fig. 3.22 Extracting concrete samples at WB 66

3.2.1 Compressive Strength

The average compressive strengths of the RCC specimens from the four different locations are shown in Table 3.1. The compressive strength of the concrete samples from WCR 28 at the longitudinal middle strip (WCR 28C) is lower than those from other locations. This result is consistent with the field observation from the surface of the concrete slab as shown in Figs 3.4 – 3.9.

Table 3.1 Results of testing for compressive strength of RCC specimens

Location	Average compressive strength (psi)
WB 66	7,243
EB 66	7,776
WCR 28 S	7,524
WCR 28 C	5,736

3.2.2 Rapid Chloride Permeability Test (RCPT)

The results of RCPT on concrete samples taken from four different locations are listed in Table 3.2. Comparing the results in Table 3.2 and those in Table 2.1, it is evident that the permeability of RCCs after nine months of exposure to traffic and environment increased, which indicated that the traffic and environmental loading in the nine-month period caused some damage to the concrete. More testing in the future is highly recommended in order to provide useful information on the long-term performance of the RCC pavements.

Table 3.2 RCPT test results on the RCCs after nine months of exposure

Location 1 (WB 66)	Coulombs	Chloride ion penetrability
Sample# 1	1,460	Low
Sample# 2	1,596	Low
Location 2 (EB 66)	**Coulombs**	**Chloride ion penetrability**
Sample# 1	1,254	Low
Sample# 2	1,691	Low
Location 3 (WCR 28 S)	**Coulombs**	**Chloride ion penetrability**
Sample# 1	1,151	Low
Sample# 2	1,859	Low
Location 3 (WCR 28 C)	**Coulombs**	**Chloride ion penetrability**
Sample# 1	3,484	Moderate
Sample# 2	3,087	Moderate

The results in Table 3.2 also show that the total charges passed through the concrete specimens are in the low range for WB 66, EB 66, and WCR 28S when compared with the ASTM standard shown in Table 2.2. However, the testing results are in the moderate range for WCR 28C. This is consistent with the test result on compressive strength of WCR 28C as shown in Table 3.1. The RCC for WCR28C has lower compressive strength and higher permeability than other RCCs.

3.2.3 Rapid Freeze-Thaw Test

The Rapid Freeze-Thaw test of the nine-month old samples was conducted following the same procedures mentioned in Section 2.3. The profiles of dynamic elastic modulus of the RCCs from the four locations are shown in Figs. 3.23 through 3.26. As shown from the figures, by increasing the time intervals (i.e. freeze-thaw cycles) the dynamic elastic modulus of specimens decreased due to increasing freeze-thaw damage. The reduction in the modulus is not as significant as in Figs. 2.10, 2.11, and 2.12 after the same number of freeze/thaw cycles. This means that the freeze/thaw resistance of the matured concretes has improved after nine months. It is also indicated in Fig. 3.26 that the dynamic elastic modulus of concrete samples from WCR 28C, at the longitudinal middle strip of WCR 28, is lower than others. Thus, the concrete at this location has low compressive strength, high chloride permeability, and low freeze-thaw resistance.

The relationships between weight loss and freeze/thaw cycles are shown in Fig. 3.27 through 3.30. Again, the weight loss of specimens taken from WCR 28C is higher than the other locations. Similar to the change in dynamic elastic modulus, the weight loss is not as significant as in Figs. 2.13, 2.14, and 2.15 after the same number of freeze/thaw cycles. This shows that the freeze/thaw resistance of the matured RCC has improved over the nine-month period.

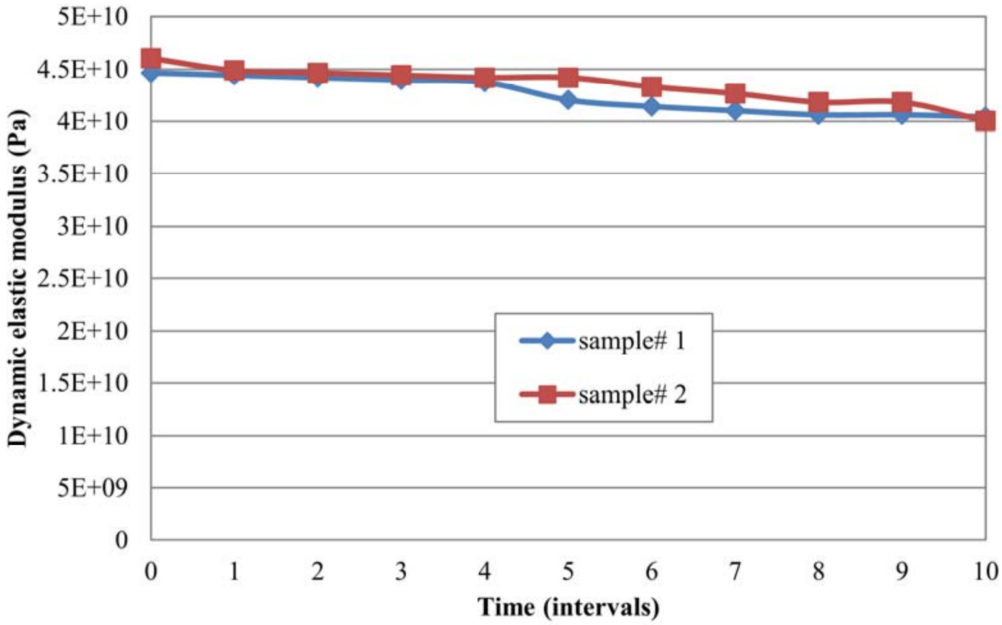

Fig. 3.23 Dynamic elastic modulus vs. freeze/thaw cycles for the specimens from EB 66

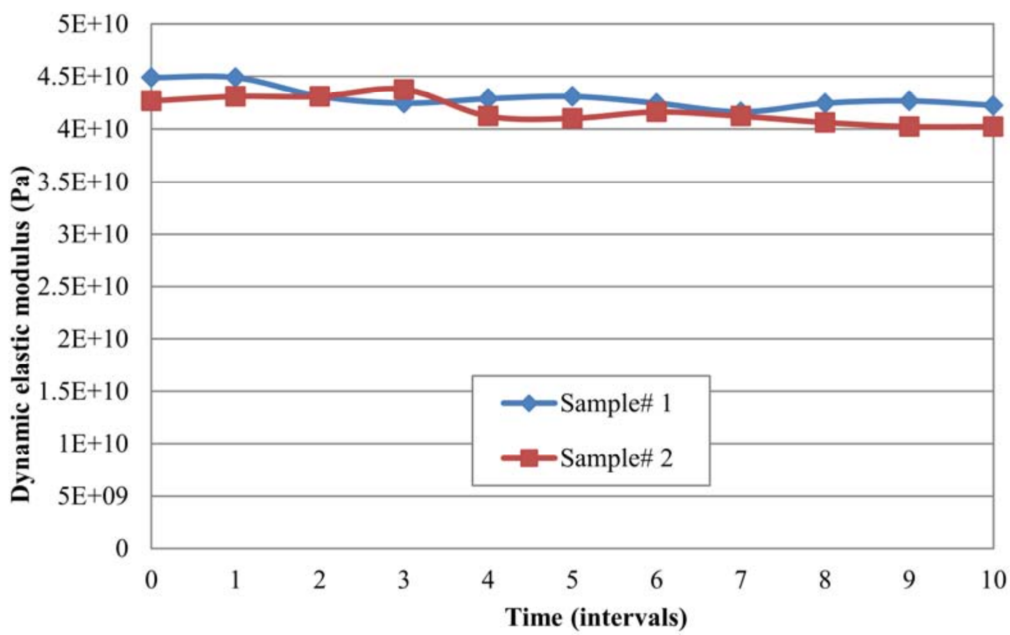

Fig. 3.24 Dynamic elastic modulus vs. freeze/thaw cycles for the specimens from WB 66

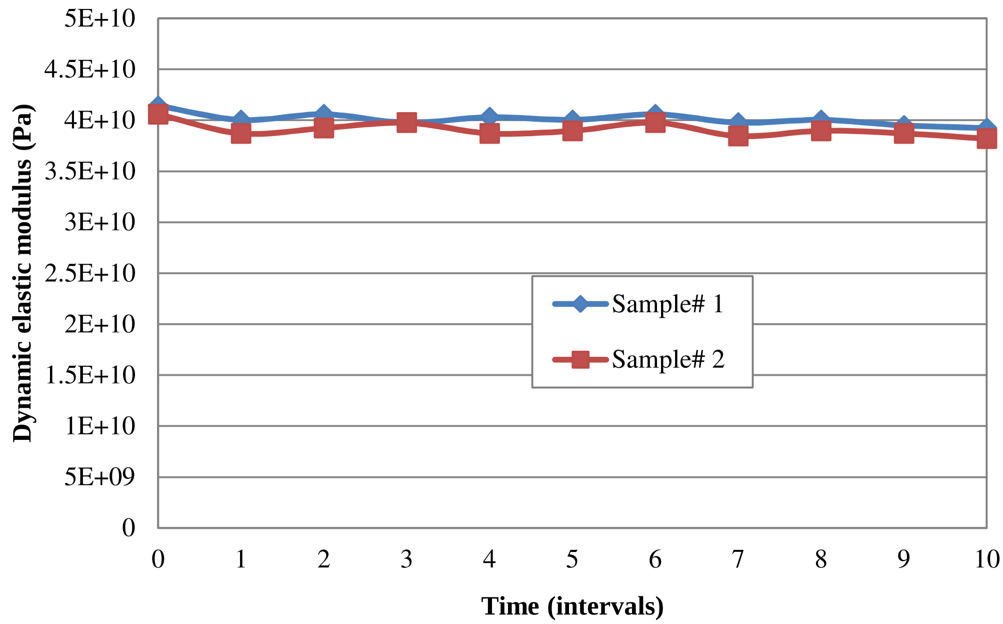

Fig. 3.25 Dynamic elastic modulus vs. freeze/thaw cycles for the specimens from WCR 28S

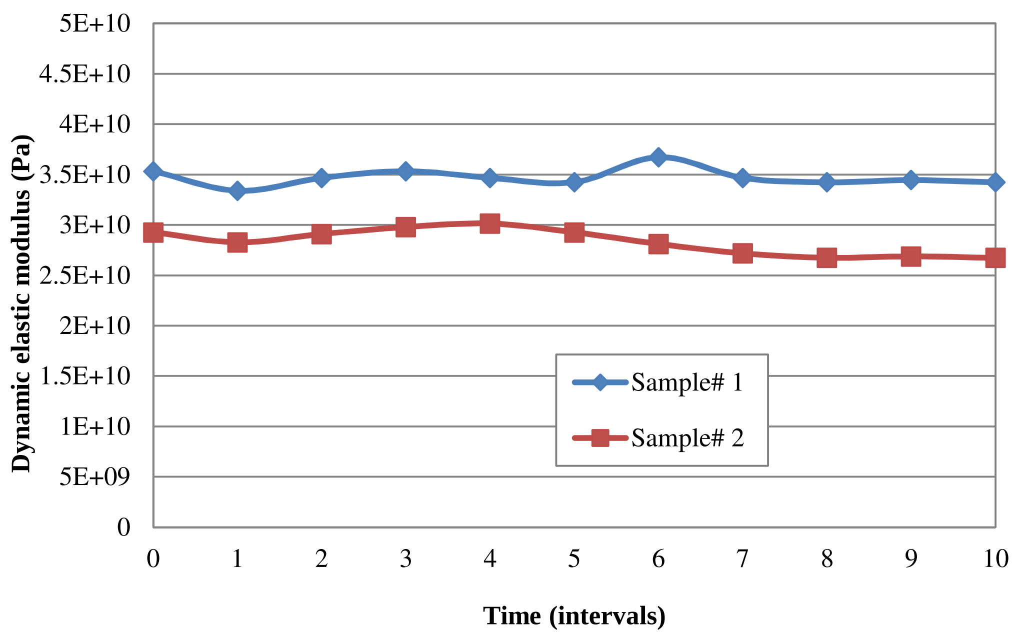

Fig. 3.26 Dynamic elastic modulus vs. freeze/thaw cycles for the specimens from WCR 28C

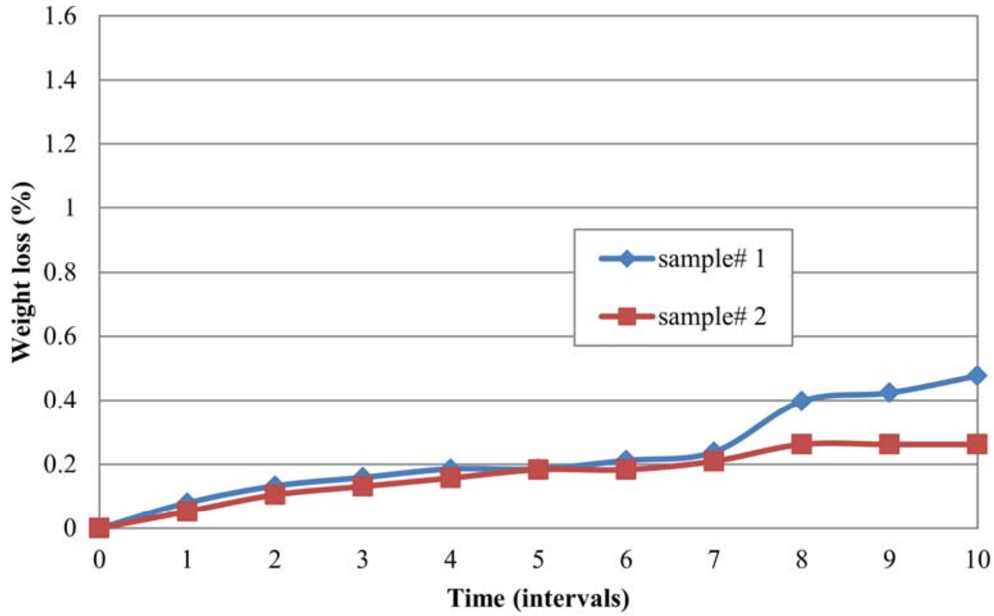

Fig. 3.27 Weight loss vs. freeze/thaw cycles for the specimens from EB 66

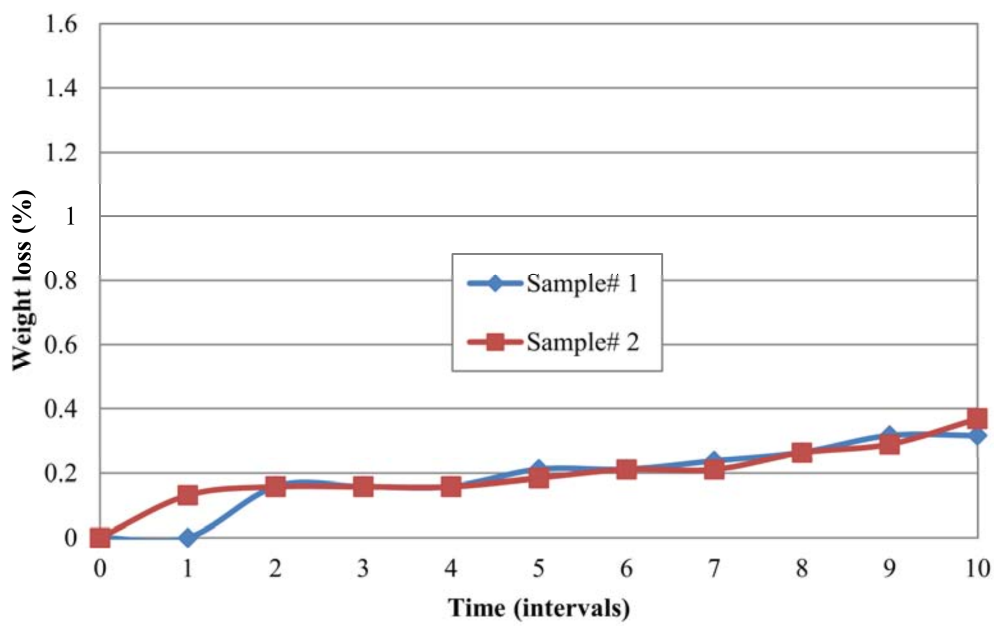

Fig. 3.28 Weight loss vs. freeze/thaw cycles for the specimens from WB 66

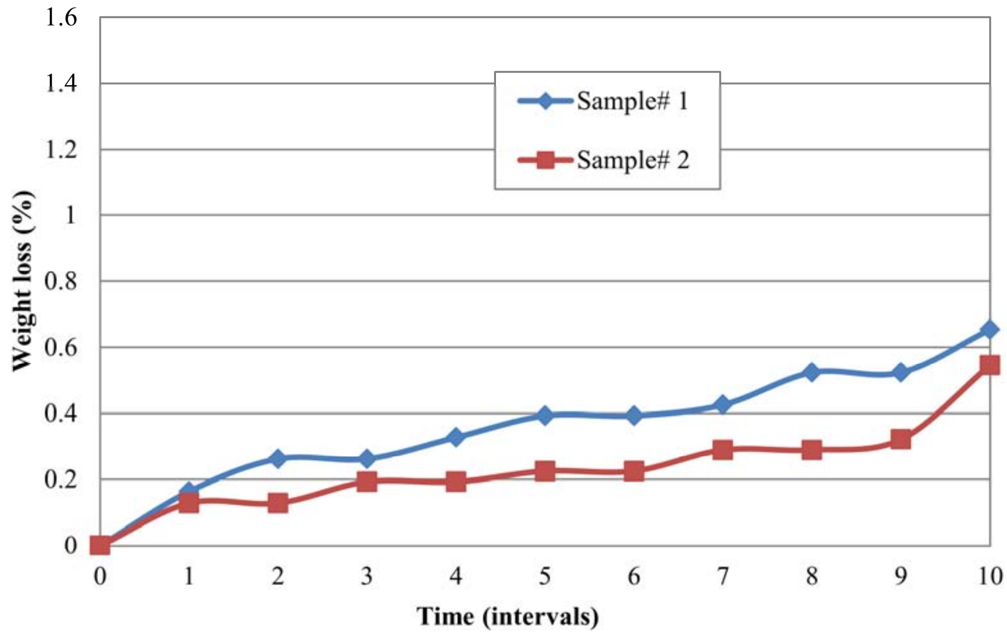

Fig. 3.29 Weight loss vs. freeze/thaw cycles for the specimens from WCR 28S

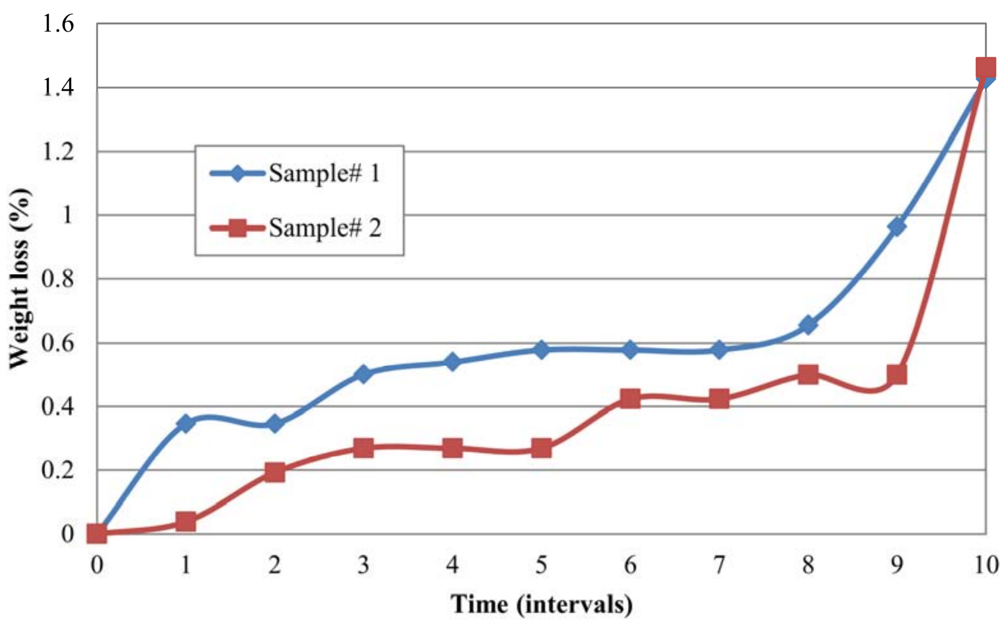

Fig. 3.30 Weight loss vs. freeze/thaw cycles for the specimens from WCR 28C

CHAPTER 4 – OBSERVATIONS AND CONCLUSIONS

RCCs were used to construct three sections of pavement in Weld County Road 28 (WCR 28), eastbound of State Highway (EB 66), and westbound of State Highway (WB 66). Three sets of field inspections were conducted: 1) during construction; 2) nine months after construction; and 3) two years after construction. Strength and durability behaviors of the RCCs were tested right after construction, and some of the material properties of the RCCs were further tested nine months after construction. The following is a summary of the observations and conclusions derived from this investigation:

1. Field inspections showed that the diamond ground surface texture of EB 66 and WB 66 is better and smoother than the surface of WCR 28. In all three locations, some fine surface material was worn away, but the coarse aggregates remained embedded in the pavement s. For WCR 28 test site, large cracks and chipping occurred along both longitudinal and transverse directions. The spacing of transverse cracks varied. Surface erosion also occurred in the longitudinal middle strip of WCR 28. On the other hand, there was no evidence of major cracks at EB 66 and WB 66. One main difference in the construction of these three RCC pavements was that saw cut joints were used for EB 66 and WB 66 but not for WCR 28. Similar to conventional concrete pavement, saw cut joints seemed to be very effective in reducing cracks on RCC pavements.

2. After construction, concrete core samples were taken from three locations that include WCR 28, EB 66, and WB 66. The concrete specimens were used to test for rapid chloride permeability, drying shrinkage, freeze-thaw resistance, compressive strength, splitting tensile strength, and flexural strength. The results indicate that the chloride permeabilities are in the low to very low ranges, and the drying shrinkages are in the normal range comparing reasonably well with those of conventional concrete. The specimens performed well in the test for freeze-thaw resistance. The compressive strength, splitting tensile strength, and flexural strength are also in the normal range similar to that of conventional concrete.

3. After nine months of construction, concrete core samples were taken from four locations, EB66, WB 66, WCR 28S, and WCR 28C. WCR 28S was from the traffic lane in the south section of WCR 28 that has a good surface condition, and WCR 28C was from the longitudinal middle strip located at the center between two traffic lanes that has cracks and erosion in the pavement. Compared with earlier test results from initial construction, the chloride resistances of RCCs decreased. Concrete specimens are in the low and moderate range of chloride penetrability values. The freeze-thaw resistances of RCCs decreased. These reduced freeze-thaw resistance values can be attributed to the higher weight loss and lower dynamic elastic modulus in WCR 28C test site. The compressive strengths also decreased. The higher chloride penetrability, the lower freeze-thaw resistance, and the decrease in compressive strength of the RCC specimens are considered to be the results of progressive increase in traffic loading and weathering.

4. Comparing all of the RCC samples collected, WCR 28C specimens are of lowest quality. Since the RCC pavement sections have been under the same service condition, the relatively poor quality of RCC samples at WCR 28C location may be due to the different quality of concrete mix and the degree of compaction used during construction. Also, the absence of saw cut joints in this test section may have contributed to the substandard performance of RCC pavement.

5. One preliminary observation in the use of RCC mix in roadway pavements is the high rate of deterioration. After only nine months of service, the RCCs already showed noticeable changes in all of the selected properties tested. More tests and field inspections should be conducted in the future after a longer monitoring period to verify and validate the initial findings observed in the material properties and surface conditions of the RCC pavements. This will ensure that future applications of RCC technology in any transportation related projects will be supported by proper consideration of its technical merit and potential economic benefits.

APPENDIX A - LITERATURE REVIEW OF RCCs

A.1 Introduction

Roller Compacted Concrete (RCC) is a no-slump concrete mixture that is transported, placed, and compacted with the same construction equipment as asphalt pavement. It can be used for earth and rock-fill dams as well as pavements. RCC is considered to be different from conventional concrete in two major aspects: (1) mix proportions and material properties; and (2) construction methods. Over the years, it has been widely used for construction of rigid pavements that require fast construction and lower initial costs. In general, it can save 15 to 30 % of the initial cost when compared with conventional concrete pavement.

A.2 RCC for Pavement Applications

In 1942, the U.S. Army Corps of Engineers (USACE) constructed a runway by using RCC in Yakima, Washington. In the 1980s, the USACE invested more in RCC pavement and since then RCC has become widely used for pavement applications such as highways and roadways in North America. For example, in Tennessee, one of the first RCC pavement projects was the Savannah-Hardin County Industrial Park. The Saturn Auto plant in Spring Hill, Tennessee was constructed in 1988. The pavement for this project covered 135 acres of roads, parking lots, and staging areas (Ambrose 2002) with 18 miles of 24-foot-wide pavement varying in thickness between six and ten inches. The performance of the RCC pavement has been excellent with minimal maintenance requirements during the first 15 years of service and is expected to continue to perform in the near future.

RCC can also be used for pavements at industrial facilities such as ports and intermodal container terminals (PCA 2006). Recently, the Virginia Port Authority used RCC to build a large container storage and handling area at the Norfolk International Terminals in Norfolk, Virginia. The construction of a RCC slab of 16 inches thick was completed that covered 26 acres and used 57,300 cubic yards of RCC concrete. RCC provided benefits such as low-cost and fast construction. Other similar projects built using RCC are the ports at Conley Terminal in Boston, Massachusetts and Pier300 in Los Angeles, California; and container facilities at rail-truck intermodal yards at the Burlington yard in Denver, Colorado and at the Canadian National yard in Calgary, Alberta.

In addition to the advantages mentioned above, a thin asphalt pavement overlay can be used to rehabilitate worn out RCC pavement. Some residential areas in Columbus, Ohio (PCA 2006) have adopted this idea. One of the city's roadway projects constructed by using RCC was Lane Avenue which has over 30,000 Annual Average Daily Traffic (AADT). The pavement was seriously distressed, and thus replaced by 8-in. RCC overlaid with 3 inches of asphalt for a smooth surface. The road was opened to traffic within 24 hours after construction. The City of Alliance in Nebraska also had success using RCC. One of its residential streets was constructed without an asphalt overlay, but saw cuts were made every 27 ft. for aesthetic purposes. The pavement has performed well for 11 years with no faulting or surface distress (PCA 2005). The City of Fort McMurray, Alberta, Canada applied RCC as pavement structure for inlays by using a 10 inches of RCC overlaid with a 2-inch asphalt layer. This helped to reduce rutting and as a result no maintenance was required.

Georgia Department of Transportation (GDOT) used RCC for 17.3 miles of shoulder reconstruction on I-285 (Atlanta Beltway) by replacing the existing distressed asphalt shoulders with a 10-foot wide and 8-inch deep section of RCC. The RCC was applied with no surface layer because RCC alone provided adequate smoothness for shoulder speeds.

A fast-track intersection in the City of Calgary, Alberta, Canada was built by using RCC in 1994. The existing pavement had rutted and shoved. The existing pavement was milled out and replaced with 2 inches of RCC. Then, the pavement was overlaid by 2 inches of asphalt. The project started on Friday evening and the intersection was opened to traffic early the following Monday morning.

A.3 Mix Proportions and Material Properties

RCC differs from conventional concrete principally in its workability. For effective consolidation, RCC mixes must be dry enough to prevent sinking of the vibratory roller equipment. On the other hand, the concrete mix must be wet enough to permit an adequate distribution of the cement paste throughout the material during the mixing and vibratory compaction operations to have sufficient strength. Optimal strength of RCC is obtained from the best compaction, which occurs at the optimum moisture content in the mixture that will support an operating vibratory roller. The mix design principle is totally different from that of conventional concrete in which the water/cement ratio is minimized in terms of the maximized strength and durability. Various degrees of aggregate processing and a range of cement contents have been used for RCC construction. Typical mix design for RCC recommended by Portland Cement Association contains

- Cementitious materials 400-600 lb/yd^3
- Coarse aggregate 1,700-2,200 lb/yd^3
- Fine aggregate 1,300-1,700 lb/yd^3
- Water content 170-250 lb/yd^3 (20-30 gallons)
- Water-to-cement ratio 0.30-0.45

Table A.1 Material specifications for the present RCC mixture

Fine Aggregate	ACI 703.01
Coarse Aggregate	ACI 703.02
Portland Cement	ACI 701.01
Fly Ash	ACI 701.02
Water	ACI 712.01
Curing Materials	ACI 711.01
Chemical Admixtures	ACI 711.03

Mix design of the present project was developed following the revision of ACI 412 (Roller Compacted Concrete Pavement). The specifications of materials used in the RCC mixture are shown in Table A.1.

The RCC used in the present project was controlled by the following requirements: the minimum cement content is 500 lb/yard^3 when fly ash is to be used in the mix; no more than 20% fly ash can be incorporated into the cementitious content when Class C fly ash is used or 30% of the cementitious content when Class F fly ash is employed. The minimum cement content should be 400 lb/yard^3 when no fly ash is included in the mixture. The allowed maximum water cement ratio is 0.44. The minimum compressive strength of concrete specimens at 28 days is 4,200 psi. The gradation of aggregate for the concrete mix should meet the requirements as shown in Table A.2.

Table A.2 The required gradation of the aggregate for the RCC mix

Sieve Size	Percent Passing by Weight
1”	100
3/4”	90-100
1/2”	70-90
3/8”	60-85
No. 4	40-60
No. 16	20-40
No. 100	6-18
No. 200	2-8

It should be noted that the contractor must submit the concrete mix design prior to actual construction. Concrete cannot be placed until the concrete mix design is approved by the Engineer. The mix design is specified by CP 62 and the mixture proportion should follow the requirements of ACI 312.10R (Report on Roller Compacted Concrete).

Cementitious materials and cement contents

Generally, ASTM C150 Type I and Type II Portland cements are used in RCC. The U.S. Army Corps of Engineers (USACE) found that the benefit of using Type II Portland cement is low heat of hydration. Type III Portland cement is not recommend to use for RCC because it may set up rapidly not allowing enough time for the construction process. Ghafoori and Zhang (1998) used Type V Portland cement to study the sulfate attack in RCC. The cement content of RCC for mass concrete dams is much lower than conventional concrete, 80 to 320 lb/yd^3, while RCC for pavement has a cement content equal to or less than conventional Portland cement concrete pavement. Cement content is one of the factors that significantly affect the compressive strength of RCC. Ghafoori and Zhang (1998) found that with increasing cement content from 9% to 12%, the compressive strength increased from 82% and 64% for 28 and 180 days of curing time, respectively.

Fly ash is a pozzolanic material that can be used in RCC to reduce cost and improve the performance. Fly ash in RCC mixtures can improve the degree of compaction. Furthermore, fly ash can be used to replace Portland cement and thus to reduce the heat of hydration. The compressive strength of RCC with fly ash develops slowly in the early stage, but the strength gains rapidly with a longer curing time, resulting in a higher long-term strength. The particle size of fly ash is very small, in the range of 10 micrometers. By using high volume of fly ash, the porosity of RCC can be reduced leading to higher compaction. Fly ash can also be used as fine aggregate replacement. With 10% and 20% of fly ash replacing fine aggregate, the compressive strength of RCC increases 19% and 23% respectively compared with plain concrete. Atis et al. (2004) studied the influence of high calcium fly ash in RCC. In their study, fly ash was used to replace Portland cement in RCC mixtures up to 70%. The results showed that the highest strength occurred in the concrete with 50% fly ash replacement.

Type of aggregates and aggregate contents

Gradation control for aggregates used in RCC is less stringent than those typically required for conventional concrete because the relationship between water/cement ratio and strength for conventional concrete does not apply for RCC. The detailed requirements of mix proportions for RCC can be found in ACI 207-5R-89. The USACE uses 3 inches as the nominal maximum aggregate size for RCC construction and they suggest that the required amount of aggregate passing No. 200 sieve can be greater than that for conventional concrete because the fine particles can improve the degree of compaction and increasing the strength of RCC.

Ghafoori (2005) found that by increasing the coarse aggregate content in the mixture from 45% to 60%, the compressive strength of RCC increased from 6% to 10%, respectively. Crushed aggregates tend to have high angularity which increases the possibility of aggregate interlocking, reduces the degree of segregation, and thus increases the strength of RCC. It is suggested by ACI and PCA that dense, well-graded aggregates with a nominal maximum aggregate size less than or equal to 1 inch should be used for RCC to reduce segregation and provide smooth surfaces. Gradation of aggregates used in RCC mixes recommended by PCA is shown in Table A.3.

Table A.3 PCA recommendation for aggregate gradation of RCC mixes

Sieve size	Percent passing by weight	
	Minimum	Maximum
1 in.	100	100
3/4 in.	90	100
1/2 in.	70	90
3/8 in.	60	85
No. 4	40	60
No. 16	20	40
No. 100	6	18
No. 200	2	8

Water content

Proper water content in RCC mixture is very important to achieve the maximum dry density. This can be determined using AASHTO T99 or T180 in a laboratory as shown in Fig. A.1.

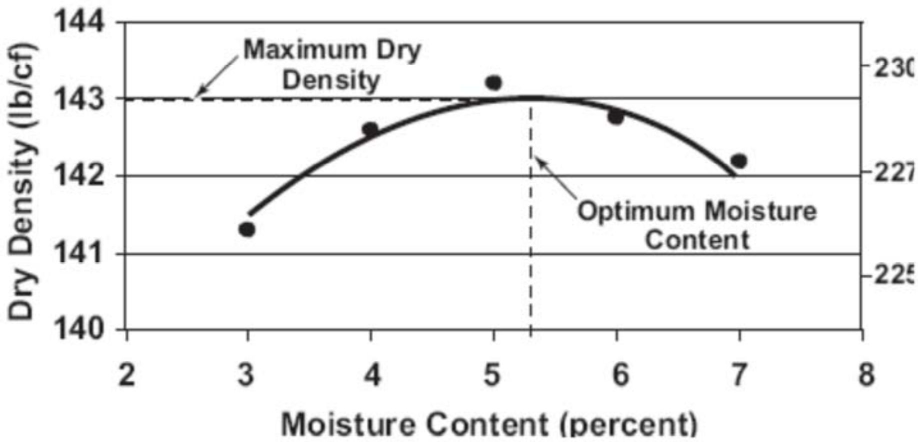

Fig. A.1 The relationship between moisture content and dry density

Chemical admixtures

There are several types of chemical admixtures used in RCC.

Water reducing and retarding admixtures

By using water reducers and retarders, the duration of placement can last for at least 1 hour, keeping the lift surface moist and unhardened until the next layer is placed and resulting in a good bonding between the two layers. The required amounts of these admixtures in RCC are detailed in a USACE report (1990).

Air entraining admixtures

The use of air entraining admixtures can improve the freeze/thaw resistance of RCC. The amount of air entraining admixtures used in RCC may be greater than that for conventional concrete (USACE, 1990).

A.4 Mechanical Properties of RCC

The strength of RCC depends strongly on the degree of compaction which minimizes the amount of air voids and maximizes the strength of RCC. USACE (1990) found that the degree of compaction of RCC is considered sufficient when there is no more than 1.5 % of air voids. An early study by Kaplan (1960) concluded that 20 % air voids in RCC can result in a strength loss of 80%.

Compressive strength

There are several influential parameters for the compressive strength of RCC in addition to the degree of compaction. They are cement type, cement content and quality, and grading of aggregate. The requirements for these parameters were discussed in previous sections. To monitor the compressive strength during construction, drilled core samples are tested following ASTM C 42.

In other countries, the compressive strength of RCC has a broad range. De Winne (2005) in Belgium used two types of RCCs, RCC20 and RCC30. The average compressive strength of RCC20 was 2,900 psi and RCC30 was 4,351 psi for 90 days. RCC20 is suitable for pavement foundations, and RCC30 is used for pavement of local roads and foundations in rapid repair and renovation projects.

Tensile strength

The lift joints are the weakest location of RCC structures and thus the tensile strength of lift joints is considered to be the critical tensile property of RCC (USACE, 1990). The tensile strength of RCC can be tested by several methods similar to those used for conventional concrete, i.e. the direct tension test (CRD-C 164), the splitting tensile test (ASTM C 496), and the flexural test (ASTM C 78). Typically, the tensile strength ranges from 5 to 15 % of the compressive strength.

Modulus of elasticity

The modulus of elasticity can be simply calculated by using ACI formulas:

$$E = 57{,}000\sqrt{f_c'}$$

E = modulus of elasticity (psi x 10^6)
f_c' = compressive strength (psi)

A.5 Durability of RCC

Under service condition, RCC is subjected to physical and chemical deteriorations such as abrasion, erosion, freezing and thawing, sulfate attacks, chloride attacks, and alkali-silica reaction. The resistance of RCC to these long-term deteriorations can be evaluated by several experimental methods. PCA investigated the long-term performance of RCC pavements constructed over the past 25 years and found that the RCC pavements performed very well. Specifically, there was no cracking, faulting, freezing or thawing damage found shortly after construction. However, in the first 2-3 years of service, there was a loss of a thin layer of fine aggregate and cement paste that was not more than 1/16 in. depth of the pavement. The coarse aggregates at the surface are firmly bonded with the cement paste (Piggott, 1999). Since this layer is relatively small, RCC is considered to have excellent long-term performance.

Abrasion/erosion resistance

The abrasion/erosion resistance of RCC is primarily controlled by the compressive strength and the quality of aggregate used in RCC. High strength and high quality aggregate lead to better abrasion/erosion resistance. Abrasion/erosion resistance can be evaluated by ASTM C1138.

Drying shrinkage

Drying shrinkage of RCC is dependent on water content (water-cement ratio), volume and characteristics of aggregate. High water content results in large shrinkage. Aggregate does not shrink upon drying, so more and a higher quality of aggregate will result in smaller shrinkage of RCC. The shrinkage of RCC can be determined by the testing method specified in ASTM C 157.

Freezing and thawing resistance

The freezing and thawing resistance of concrete can be improved by using air entraining admixtures. USACE (1990) suggested that higher contents of air entraining admixtures be used in RCC than in conventional concrete. The freezing and thawing resistance of RCC is related to its porosity. Kuzu (1990) conducted an experimental study on compaction properties of RCC and suggested that the porosity of RCC should not be more than 3% for freezing and thawing resistance. In general, a higher compaction results in higher resistance to freezing and thawing. ASTM C 666 is the testing method used to determine the resistance of freezing and thawing. Scaling resistance can be tested by ASTM C 672.

Liu (1995) studied the freezing-thawing resistance of RCC pavement and the results showed that RCC performed very well in cold climates. The RCC pavements in the Boston and Denver areas used in the study showed good freezing-thawing resistance. In order to make a durable RCC in a freezing and thawing environment, RCC needs to be made with an adequate cement content that is very well mixed, properly compacted, and cured. Piggott (1999) conducted a study and showed that very little damage was found in RCC pavements located in the cold regions of the U.S. and Canada that were exposed to freezing and thawing conditions. Also, no evidence of scaling was found on the RCC pavements located in the U.S. and Canada that were subjected to deicers.

Sulfate resistance

Sulfate resistance of RCC can be obtained by using Type V Portland Cement. Ghafoori and Zhang (1998) conducted a study to investigate the effect of fly ash, cement type, and aggregate contents on the sulfate resistance of RCC. Type V Portland cement has high sulfate resistance with or without the use of low-calcium fly ash. The use of fly ash can improve sulfate resistance. Test results by Zhang (1998) showed a good sulfate resistance of RCC when 20% - 40% of cement and 10% - 20% of fine aggregate was replaced with Class F fly ash.

A.6 Production of RCC

RCC mix can be produced with different types of equipment dependent on the size and type of construction projects. Three types of equipment are commonly used for RCC projects (PCA 2006).

Transit mixers – Due to their slower mixing and discharge rates, transit mixers are suitable for producing RCC mixes for small projects.

Tilt drum mixers – Tilt drum mixers are operated with fast and quality-consistent production so they are typically used for most RCC jobsites. Both portable and permanent tilt drum mixers are commonly used.

Horizontal shaft mixers – For large RCC projects, horizontal shaft mixers are the best choice because of their high production rate. There are many types of horizontal shaft mixers used in RCC projects such as single-shaft or dual-shaft, portable or permanent, continuous flow or compulsory batch, and spiral ribbon or paddle.

Production rate of RCC mix

The production rate of RCC is related to the speed of construction at the site. The mixing, transporting, placing, and compacting of RCC mixture must be well planned in order to avoid any delays during a RCC construction project. It is very important to operate the equipment at a consistent speed on construction sites so that fresh RCC can be continuously supplied to the paver. The production rate of RCC (yd^3/hr) can be calculated by a method proposed by PCA (2006), which takes into account the width and depth of pavement slab and the speed of paving operation (ft/min.). For example:

Pavement width = 20 feet
Pavement thickness = 8 inches
Unit weight of RCC material = 150 pound per cubic foot
Speed of paving operations = 4 feet per minute
(20 ft.)(8 in./12)(150 pcf)(4 fpm)(60 min) = 480,000 pounds per hour ≈ 120 cubic yard per hour

The above example shows that, in order to keep the paver working consistently, the plant should produce RCC mixes at a minimum rate of 120 cubic yards per hour.

Batching, mixing, and placing

The mixing time for RCC is dependent on the size of the batch, the gradation of aggregate, the water-to-cement ratio, and the type of mixer as shown in Table A.4 (PCA 2006). The RCC mixing process is very important for the required strength and durability. This is because the water content of RCC is lower than that for conventional concrete, so the RCC must be mixed thoroughly in order to distribute the water uniformly. To obtain the maximum density and long-term durability, RCC mixes are required to have the proper moisture content within the range of plus or minus 0.5 % of the optimum moisture content (PCA 2006).

A twin-shaft pug mill mixer is frequently used to produce RCC because it can work well with low workability concrete. The mixer can yield a production of RCC mix up to 250 tons per hour. It is suggested by Delatte et al. (2003) that a RCC mix be placed within 45 minutes after water is added. In order to avoid the formation of cold joints between passes, subsequent passes must be placed within 60 minute. The time can be decreased or increased depending on ambient temperature and humidity on the construction site. RCC should be placed 10% - 25% thicker than the design thickness to account for the loss of thickness through the compaction of the material. The additional thickness depends on the type of paver.

Table A.4 Recommended mixing times and batch sizes for RCC

Mixer Type	Mixing Time	Batch Size
Transit	4 to 5 minutes*	70% to 100% of drum capacity (up to 3 yd^3)
Tilt Drum	2 to 4 minutes	70% to 100% of drum capacity (up to 5 yd^3)
Horizontal Compulsory	20 to 60 seconds	Up to 12 yd^3
Mobile Truck Mixer	Continuous	12 yd^3 capacity; up to 75 yd^3 per hour
Horizontal Continuous Flow	Continuous	Up to 250 yd^3/hr

* assuming a mixing speed of 20 revolutions per minute

Transportation and construction methods for RCC pavements

Dump trucks are commonly used for transportation of RCC. RCC mixes can be placed directly into dump trucks from tilt drum and horizontal shaft mixers. Using transit mixers, the step of discharge into a dump truck will be involved in the process of delivery. When transit mixers are employed, superplasticizers should be used to maintain the workability of RCC mixes. Usually, dump trucks or transit mixers are used for small projects to transport RCC from a central-mix plant or from transit mixers to jobsites.

For pavement construction, RCC is moved using heavy-duty pavers with tamping and vibrating screeds made especially for RCC construction. Conveyor belts and earth equipment are often used. Consolidation of RCC is usually accomplished using vibratory rollers. Typically, it can be produced at 50 to 230 yd^3/hr for a small project, 230 to 460 yd^3/hr for a medium sized project, and 460 to 1000 yd^3/hr for a large project.

The compacted lift thickness commonly used for RCC pavements in North America is about 12 inches. In Belgium, it is found that the lift thickness of RCC pavement is about 8 to 10 inches for heavily loaded pavements. However, it is recommended by the revision of ACI 412, Roller Compacted Concrete Pavement, that if the thickness of RCCP is greater than 10 inches, multiple lifts should be used. Lift should not be less than 4 inches. More details can be found in the ACI 412.10. Lift thickness depends on size of placement area, plant and transport operation, mixture proportions, rate of placement, and the spreading and compacting processes. The construction cost of RCC pavement can be reduced by increasing lift thickness.

Spreading and compaction procedures

Small dozers are successfully used to spread and level RCC for lift thickness not more than 12 in. Various equipment can be used for compacting RCC pavement. Four to six passes with a round trip of double-drum rollers are required in order to get the adequate density of 6 to12-in. lift thickness. Excessive rolling can have a negative effect by decreasing the density of mixtures. To obtain the maximum density and required strength, compaction operation should be finished as soon as possible after the spreading process, especially in hot weather. The period of compaction recommended by USACE (1990) is within 15 minutes after spreading and within 45 minutes from the time of mixing when temperatures range between 50 and 80°F. The compaction time can be extended in cold regions. Delatte et al. (2003) found that the performance of RCC pavement can be correlated to the density of the mixture. They also concluded that a proper RCC mix can be identified by observing the pavement surface after two static passes of a 10-ton vibratory roller. Deeply rutted pavements may be due to a wet mix while dry mix will not consolidate easily.

Curing of RCC pavements

Curing is very important to RCC. There are three curing methods used for RCC, water curing, curing compound, and asphalt emulsion. For water curing, a typical curing period is seven days. Water curing can be done using water spray trucks, sprinkler systems, or wet burlap. This curing method may cause erosion of the pavement. Various curing compounds have been used on RCC pavements. Application rates of concrete curing compounds are dependent on surface texture. Manufacturer's instructions should be followed. Asphalt emulsion is considered to be a good curing method for RCC and can be applied at approximately 0.15 to 0.30 gallon/yd^2. When RCC pavements are to be used soon after placement, the asphalt emulsion is a good curing method because it can prevent drying of moisture in the concrete. For light traffic loading (< 7,000 lb) RCC pavement can be used immediately after compacting, but it has to wait 3-5 days for heavy traffic loading (Heuninck et al., 2001).

The process of RCC pavement construction

Based on the studies of ACI committee 325 (1995), USACE (1995), and Delatte et al. (2003), the construction process of RCC can be summarized as follows:

- Sub-grade and base course are prepared (which can be performed in the same way).
- The base course needs to be moistened with water prior to placing RCC.
- RCC should be mixed continuously and the mix can be transported by dump trucks.
- RCC is paved by paving machines similar to those used for asphalt pavement.
- Dual-drum vibrators are used to compact RCC immediately after placing.
- Prior to curing, fogger-spray water can be used to provide sufficient moisture.
- RCC pavements are cured using sprinklers, curing compounds, or asphalt emulsion.
- In order to avoid the cold joints, the placing process between two concrete pours should not be longer than 1 hour.
- Saw-cut joints can be made 4 to 20 hours after placing and compacting. The best time to saw joints is 12 hours and the spacing of the joints should be from 20 ft. to 30 ft.

A.7 Surface and Jointing of RCC Pavement

The quality of the finished surface is one of the limitations of RCC pavements as shown in Fig. A.2, which shows many voids of different sizes and shapes on the surface. The surface texture of RCC pavements can be improved by using a smaller nominal maximum aggregate size. Typically, RCC pavements are designed for roadways with a traffic speed below 35 to 40 miles per hour. In order to obtain a smoother surface, using asphalt paving equipment is recommended. Asphalt overlays have been used on RCC pavements to provide a smoother surface for some RCC pavement projects, such as the internal roads at the General Motors' Saturn plant in Tennessee.

Fig. A.2 Surface texture of RCC pavement

The asphalt overlays can improve surface smoothness and help the curing of RCC pavement. However, when an overlay is used cracking and debonding between the surface layer and the RCC slab is a concern and must be considered (Delatte 2004). Hot-mix asphalt is commonly used for overlays in conventional concrete. It can also be applied to RCC pavements. The bonding at the interface between asphalt overlay and RCC is actually better than that of conventional concrete because of the rougher surface of RCC (Delatte 2004).

Lift surface preparation

The lift surfaces should be kept in moist condition at all times until the next layer is placed. A dry surface may make it difficult for the new and old layers to bond. In order to have a good bond, the lift surface should be cleaned before the next layer is placed. This include the removal of all loose materials, curing compounds, debris, standing or running water, snow, ice, oil, and grease.

Bedding mortars can be applied to increase the bond between the lift surfaces and to improve the water tightness at the bottom of RCC lift during placement and compaction processes. The bedding mortars are conventional Portland cement mortar with high slump and high cement content. Generally, the bedding mortar is placed 10 to 15 minutes before the placement of the next layer. Mehta and Monteiro (2006) concluded that, generally, the mixture of bedding mortar contains 607 to 775 lb/yd^3 of cement, 286 to 371 lb/yd^3 of fly ash, and No. 4 (4.75 mm) nominal maximum size of aggregate.

Joints

The construction joints of RCC can be classified as fresh joints, cold joints, or horizontal or lift joints. The construction joints are considered the weakest area of RCC pavement structures. Joints must be constructed properly to avoid damages that may affect the long term durability of RCC pavements.

Saw-cut joints can be used to control cracks. The joints should be sawed within 4 to 20 hours after placing and compaction, 12 hours on average. The saw cut depth is 1/3 to 1/4 of the thickness of the pavement. Saw cut joints are sealed later to prevent the intrusion of fines into the joint. PCA (2005) recommends that the spacing of control joints be from 20 ft. to 30 ft. Practically, the transverse joint spacing should be about 40 times the pavement thickness with a maximum spacing of 30 ft. For RCC pavement projects in Belgium, the depths of saw-cut joints are over 1/3 of the thickness and the spacing is less than 5.45 yd. (16.35 ft.). The width of the cut is 1/8 in. (De Winn et al., 2005).

Based on Piggott's study (1999), there is no evidence for major problems with cracking in RCC pavements. Minor cracks are mostly found at the surface with a depth of 1/4 in. and less than 1/16 in. wide. These minor cracks are sometimes considered to be surface cracks that are worn away by traffic. In cold regions, pavement erosion can be found in the form of edge chipping.

Piggott (1999) inspected 18 RCC pavements and found that only one project exhibited minor faulting. Small cracks ranging from "hair line" to 1/4 in. were found with no significant faulting at the cracks. Saw cut joints for shrinkage control were used on four RCC pavement projects, 112th Ave., Edmonton; Fort Drum, NY; Bighorn Ave., Alliance, NE; and the Saturn Plant Roads at Spring Hill, TN. The joint spacing varied, ranging from 20 ft. to 30 ft. Bituminous joint filler was used for all joints on Bighorn Ave. Some joint sealing was used at Fort Drum and the Saturn plant. No sealer was applied at 112th Ave. Transverse saw cut joints were made 12 months after the project completed at the Burlington Northern Santa Fe Railroad in Colorado. The joints were 3 in. deep and at 50 ft. spacing.

Longitudinal joints can be made in a similar manner to conventional concrete pavements. RCC pavement should use longitudinal joints when the lane widths exceed 12 ft. for 6 in. to 8 in. thick pavement. Based on the Piggott study (1999), joint sealer may reduce joint edge chipping. However, most of the unsealed joints perform very well. A major concern of pavement deterioration is the longitudinal joints or cold joints. These joints may be eroded by traffic or weathering if they are not compacted sufficiently.

A.8 Cost of RCC

The cost of RCC pavements is usually lower than that of conventional Portland cement concrete pavement because RCC pavement uses less cement, requires less formwork, has fewer joints, does not use dowels, has less finishing, requires less maintenance, and has a shorter construction period. In 1998, the Tennessee DOT (TnDOT) used RCC to construct two projects in Chattanooga. One was a 600-foot-long by 12-foot-wide lane on State Route 27 at the Signal

Mountain Cement production facility. This project used approximately 270 yd^3 of RCC. The other was an access road at the Lookout Valley Industrial Park. This project started on a Saturday morning in March, and the road was opened to traffic the following afternoon. The 14-day compressive strength of RCC was 5,000 psi which is higher than the required strength (3,500 psi). The bidding cost comparison between RCC and asphalt on this project is shown in Table A.5. As seen, the cost for RCC was lower (Ambrose, 2002).

Table A.5 RCC, asphalt bids, Lookout Valley Industrial Park pavement (Ambrose, 2002)

	RCC	**Asphalt State-Constructed**	**Asphalt In-Place Bid**
RCC or asphalt material	$ 20,948.00	23,159.00	
Base material	$ 2,145.00	$ 4,274.00	
Haul	$ 3,812.00	$ 4,112.00	
Placing	$ 2,206.00	$ 2,941.00	
In-place bid			$ 46,961.00
Total	$ 29,111.00	$ 34,486.00	$ 46,961.00
Cost per square yard	$ 12.35	$ 14.63	$ 19.92

In the spring/summer 1998 RCC Newsletter, PCA stated that TnDOT saved more than $5,000 by using RCC. Another cost saving project was the Port in Virginia. This project used an Aran pug mill operating at 881,840 lb/hr to produce on-site RCC mixes. Three ABG Titan pavers were used for the paving process. The 16.5 in. pavement was placed in two lifts. In order to obtain good bonding, the second lift was placed within one hour after the first lift. The final cost of the project was $\$42/yd^2$ and the operation rate was 2.2 days/acre. This project had a lower cost and faster construction time than any other paving project at Norfolk International Terminals (PCA 1998). The Dufferin Construction Company in Canada found that the in-place cost of RCC pavement with 3,600 psi compressive strength is 89% of asphalt pavement and 62% of Portland cement concrete pavement.

Table A.6 Comparison between conventional concrete and RCC pavements
(Rapid to Construct 2001)

Pavement type	Max. aggregate Size (in.)	Unit weight (lb/yd^3)							Water content (%)
		Fine aggregate ratio (%)	Water	Cement	Fine aggregate	Coarse aggregate	Additive	Weight ratio of cement (%)	
RCC	3/4	44	175	431	1577	2091	1.08	10.6	5.4
PCC	1 1/2	33	233	548	1010	2260	1.37	14.5	7.8

The cost comparison of RCC and PCC pavements was investigated by USACE in 1995. 49 different RCC projects for tank hardstands, tank trails, municipal streets, parking areas, and other applications were studied. By using RCC, the cost saving was 14% to 58%. It should be noted that the cost of RCC constructed for USACE projects might be higher than that for general applications because the requirements of USACE projects were very strict (Delatte et al., 2003).

The cost savings could be even higher for general applications of RCC. Table A.6 shows the comparison of mix designs between conventional concrete and RCC for pavements. RCC has less water and cement than conventional concrete (Rapid to Construct, 2001). For RCC on USACE projects, the mix designs have the cement content between 9% and 12% by weight. The nominal maximum aggregate size in RCC mixes is not greater than 3/4 in. which is recommended by ACI (1995). Mix designs of the RCC used in this project compared with other projects reported by USACE (1995) as illustrated in Table A.7.

Table A.7 RCC Mix designs of the present project and other projects by USACE (1995)

Location	Cement (Type I) Weight	Fly Ash		Water Weight	W/C Ratio	Coarse Aggregate Max. Size	Fine Aggregate		Weight Ratio of Cement	Water Content
		Class	Weight				Weight	Weight	%	%
Austin, TX	260	C	260	182	0.35	3/4 in.	1,610	1,610	6.6	4.6
Ft. Campbell, KY	400	F	212	205	0.34	3/4 in.	1,785	1,465	9.8	5.0
Ft. Drum, NY	450	F	150	210	0.35	3/4 in.	2,321	988	10.9	5.1
Spring Hill, TN	400	F	150	192	0.35	3/4 in.	1,890	1,550	9.6	4.6
Ft. Hood, TX	293	F	146	176	0.40	7/8 in.	2,006	1,669	6.8	4.1
The present project (CDOT mix# 2008175)	403	-	-	152	0.37	3/4 in.	1,707	1,744	10.0	3.8
The present project (CDOT mix# 2008176)	438	-	-	145	0.33	3/4 in.	1,707	1,744	10.8	3.6

REFERENCES

1. AASHTO T 99. *Standard Method of Test for Moisture-Density Relations of Soils Using a 2.5-kg (5.5-lb) Rammer and a 305-mm (12-in.) Drop*.
2. ACI Committee 207 (1999). *Roller Compacted Mass Concrete*. ACI 207. 5R-99.
3. ACI Committee 325 (1995). *State-of-the-Art Report on Roller-Compacted Concrete*
4. ACI Committee 325 (2001). *Report on Roller-Compacted Concrete Pavements*. ACI 325. 10R-95.
5. Ambrose, J. (2002). Beating Asphalt on Price. *The Concrete Producer/Concrete Journal Magazine*, Publication #J02C041.
6. ASTM C 1176. (2002). *Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table.*
7. ASTM C 1202. *Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*.
8. ASTM C 157. *Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete*.
9. ASTM C 42. *Standard Test Method for Obtaining and Testing Drilled Cores and Sawed Beams of Concrete*.
10. ASTM C 496. (2002). *Standard Test Method for Splitting Tensile Strength of Cylindrical*
11. ASTM C 597. *Standard Test Method for Pulse Velocity Through Concrete*.
12. ASTM C 666. *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing*.
13. ASTM C 672. *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals*.
14. ASTM C 78. *Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)*.
15. Atis, C.D., Sevim, U.K., Ozcan, F., Karahan, O., Tanrikulu, A.H., and Eksi, A. (2004). Strength properties of roller compacted concrete containing a non-standard high calcium fly ash. Materials Letters, 58(9), 1446-1450.
16. De Winne, E., De Corte, W., Heuninck, S., Rens, L., and De Winne, P. (2005). Roller Compacted Concrete. *Concrete for transportation infrastructure: proceedings of the international conference held at the University of Dundee, Scotland UK on 5-7 July 2005:edited by Ravindra K. Dhir, Michael J. McCarthy, and Sinan Caliskan*, 35-46.
17. Delatte, N. (2004). Simplified Design of Roller-Compacted Concrete Composite Pavement. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1896, 57-65.
18. Delatte, N., Amer, N., and Storey, C. (2003). *Improved Management of RCC Pavement Technology*. Birmingham, Alabama: The University of Alabama, Department of Civil and Environmental Engineering.

19. Ghafoori, N. (2005). *Sulfate Resistance of Roller Compacted Concrete* [Handouts], Las Vegas, NV: University of Nevada, Department of Civil and Environmental Engineering.
20. Ghafoori, N. and Zhang, Z. (1998). Sulfate Resistance of Roller Compacted Concrete. *ACI Materials Journal*, 95(4), 347-355.
21. Hamel, S. (2005). Effects of Freezing and Freeze-Thaw Damage to the Transport Properties of Concrete. M.S. Thesis of the University of Colorado at Boulder.
22. Kaplan (1960). Effects of Incomplete Consolidation on Compressive and Flexural Strength, Ultrasonic Pulse Velocity, and Dynamic Modulus of Elasticity of Concrete. *ACI Journal*, American Concrete Institute, 853-867.
23. Kuzu, T., Hara, J., and Kokubu, K. (1990). Study on Resistance to Freezing and Thawing of Roller-Compacted Concrete. Proceedings of JCI, Vol.12, No.1, PP.697-702.
24. Liu, T.C. and Tatro, S.B. (1995). Performance of Roller Compacted Concrete Dams. *Proceedings of International Symposium on Roller Compacted Concrete*, 1189-1201.
25. Mehta, P.K., and Monteiro, P.J.M. (2006). *Concrete: Microstructure, Properties, and Materials* (3rd Ed.). New York, NY:McGraw-Hill.
26. Piggott, R.W. (1999). *Roller Compacted Concrete Pavements – A Study of Long Term Performance*. RP 366, Portland Cement Association, Skokie, Il.
27. Poole, B. (2007). *Roller Compacted Concrete: Shoulder Application* [Handouts], Georgia Department of Transportation.
28. Portland Cement Association (1998). Spring/summer RCC Newsletter.
29. Portland Cement Association (2005). *Roller-Compacted Concrete Pavements for Highways and Streets*. Retrieved from http://cement.org/pavements.
30. Portland Cement Association (2006). Production of Roller-Compacted Concrete. Retrieved from http://cement.org/pavements.
31. Portland Cement Association (2006). Roller-Compacted Concrete Pavements for Ports. Retrieved from http://cement.org/pavements.
32. Rapid to Construct, Rapid to Open for Traffic, Concrete Pavement, RCCP, (2001). Retrieved from http://www.watanabegumi.co.jp/pavements/concretes/rccpe.html.
33. Stanish, K.D., Hootan, R.D., Thomas, M.D.A., (1997). *Testing the Chloride Penetration Resistance of Concrete: A Literature Review*. FHWA Contract DTFH61-97-R-00022, Department of Civil Engineering, University of Toronto, Toronto, Ontario, Canada.
34. U.S. Army Corps of Engineers (2000). Roller-Compacted Concrete. Department of the Army, Washington, D.C.
35. U.S. Army Corps of Engineers (USACE). (1995). Roller Compacted Concrete Pavement Design and Construction. *Engineer Technical Letter 1110-3-475*, Department of the Army, Washington, D.C.