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Freezing and Thawing Testing of Field and Lab Concretes with the Same Aggregates

Jennifer Distlehorst, P.E.

Kansas Department of Transportation
Bureau of Research

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Final Report

Prepared by

Jennifer Distlehorst, P.E.

Kansas Department of Transportation
Bureau of Research

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Abstract

Concrete and aggregates sampled on 20 field visits to Kansas Department of Transportation concrete paving projects constructed between 2010 and 2012 were tested to compare the KTMR-22 freeze-thaw durability of field-cast specimens with standard lab-cast specimens made with the same aggregates. No consistent differences were found between the field and lab specimen results, indicating that the results of the KTMR-22 (2012) *Resistance of Concrete to Rapid Freezing and Thawing* test are determined primarily by the durability of the aggregate used. Sampling concrete as delivered to the job site for freezing and thawing evaluation would provide assurance that the KTMR-22 test results reflect the performance of the aggregate used in the pavement.

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Chapter 1: Introduction

Durable concrete withstands the environmental conditions encountered in service over the design life of the pavement. The Kansas climate, with numerous freeze-thaw cycles every winter, poses particular challenges for the durability of concrete. Freezing and thawing of frost-susceptible coarse aggregates containing water in concrete pavements causes a distress known as D-cracking (Neville, 1995). D-cracking appears in pavements as closely spaced, crescent-shaped cracks that develop along and parallel to joints, pavement edges, and other cracks (KDOT, 2007a). D-cracking has been recognized as a problem in Kansas concrete pavements since the 1930s. An extensive survey of Kansas concrete pavements constructed in 2000 or before showed that D-cracking was still a significant factor in the durability of Kansas concrete pavements (McLeod, 2012).

The Kansas Department of Transportation (KDOT) has addressed the issue of D-cracking by implementing requirements for resistance to freezing and thawing in aggregates used in concrete pavements. Prequalification of aggregates prior to use in pavement concrete by Kansas Test Method KTMR-22 (2012) *Resistance of Concrete to Rapid Freezing and Thawing* has been required since the 1980s. KTMR-22 is a modification of ASTM C666 (2008) *Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing* (Procedure B) that tests 3 inch × 4 inch × 16 inch concrete prisms by freezing in air and thawing in water. The KTMR-22 method modifies the curing conditions of the ASTM C666 test method. The curing period is extended from 14 to 90 days, with the first 67 days spent in a standard 100% humidity curing environment, followed by 21 days at a relative humidity of 50% at 73° F. The prisms are then placed in a tempering tank at 70° F for 24 hours, followed by chilling at 40° F for 24 hours. At the end of the curing period, the specimens begin freeze-thaw cycling at the rate of approximately eight cycles a day. The specimens are removed from the thawing cycle for length and resonant frequency measurements at least once every 36 cycles.

The results of KTMR-22 are reported as durability factor or relative dynamic modulus of elasticity and percent expansion. As described in ASTM C666, durability factor is calculated from the relative dynamic modulus of elasticity (RDME). The RDME compares the fundamental transverse frequency at some number of cycles of freezing and thawing with the fundamental transverse frequency at zero cycles of freezing and thawing (ASTM C666, 2008). The durability factor is the RDME calculated at a specified number of freezing and thawing cycles. KDOT calculates the durability factor at 300 cycles.

Until 2013, KDOT specified KTMR-22 testing only for limestone and dolomite used in on-grade concrete (KDOT, 2007b). Class I aggregates were required to have a minimum durability factor of 95 and a maximum expansion of 0.025% at 300 freezing and thawing cycles. Class 2 aggregates used for gradations with more than 5 percent retained on the ¾ inch sieve were required to have a minimum durability factor of 97 and a maximum expansion of 0.015% at 300 freezing and thawing cycles.

In January 2013, the aggregate specifications were extensively revised in response to the 2012 study that showed D-cracking distress was present in Kansas concrete pavements containing aggregates that met the 300-cycle durability requirements. Under the 2013 *Special Provision to the Standard Specifications*, all types of coarse aggregates had to meet more stringent freezing and thawing durability requirements. The new requirements were a minimum RDME of 95 and a maximum expansion of 0.025% at 660 freezing and thawing cycles (KDOT, 2013). The new requirements were based on a 20-year material design life, where the average annual number of "hard" freeze-thaw cycles in Kansas (33) was multiplied by 20 years (McLeod, Welge, & Henthorne, 2014).

KTMR-22 testing is performed by the KDOT Materials Test Unit under laboratory conditions with a standard mix design, as shown in Table 1.1. Standard materials are used with a standard coarse aggregate gradation to limit the possible sources of variation in the durability testing results. Any variation in the test results may be reasonably attributed to the properties of the coarse aggregate itself. If no significant differences were found between lab and field specimens, KTMR-22 testing of field-cast concrete could be used to confirm the durability of the aggregates used in concrete pavement.

Table 1.1: Concrete Materials and Proportions Specified in KTMR-22

Property or Material	Proportion	Other Requirements
Coarse Aggregate, -3/4 inch +1/2 inch	25%	SSD by toweling
Coarse Aggregate, -1/2 inch +3/8 inch	25%	SSD by toweling
FA-A Kansas River sand, Shawnee Co.	50%	Correction made for moisture
Type I/II Cement	602 lbs/yd^3	
Tap Water	w/c = 0.40	
Air Content	5 to 7%	Using air entraining agent
Total batch volume	0.6 ft^3	

The goal of this study was to determine whether the differences in aggregate gradations, material proportions, and cementitious materials between standard KTMR-22 concretes mixed in the lab and field concretes made with the same aggregates would result in significant differences in freeze-thaw durability as measured by KTMR-22.

Chapter 2: Methods

Concrete and aggregates sampled on paving projects constructed between 2010 and 2012 were tested to compare the KTMR-22 freeze-thaw durability of field-cast specimens with standard lab-cast specimens. The four phases of the study were paving project selection, field sampling, laboratory testing, and conclusion and reporting.

2.1 Paving Project Selection

The first step was to identify significant concrete pavement projects that would be placing concrete during the course of the study. Projects were selected from the KDOT Comprehensive Program Management System and the Contract Status list to meet the following criteria:

- Projects let since 2006,
- On the Kansas highway system ("K" or "KA" designated projects),
- A total project length of at least 1 mile, and
- At least 2 lane-miles of non-reinforced dowel jointed concrete pavement.

The District Materials Engineers were notified of the intent to sample concrete from paving projects and their cooperation was requested. KDOT field construction personnel on each project and the District Materials Lab were contacted to coordinate sampling. All sampling was blind and the intent of this program was to sample the normal run of concrete and aggregates.

A total of 18 paving projects were selected for sampling, as shown in Figure 2.1 and Table 2.1. Two projects (50-28 K-8246-01 and 61-78 K-8252-01) were sampled twice, for a total of 20 site visits. Eleven projects were visited for sampling in 2010, four in 2011, and five in 2012.

Figure 2.1: Location Map of Projects Sampled
Note: See Table 2.1 for Location Key

Table 2.1: Concrete Paving Projects Sampled in 2010-2012

Map Key	Project Number	Route	County	Sample Number and Date	Paving Contractor	Concrete Producer
1	KA-1666-01	I-70	Wyandotte	1. 6/9/2010	J. M. Fahey	Fordyce Central Batch Plant, Kansas City, MO
2	K-8246-01	US-50	Finney	2. 6/15/2010 and 12. 4/5/2011	Koss	Koss
3	K-7332-01	I-135	Sedgwick	3. 6/23/2010	Cornejo	Cornejo South Plant
4	K-8251-07	US-69	Johnson	4. 6/29/2010	Clarkson	Clarkson
5	K-7925-02	K-7	Johnson	5. 8/3/2010	Miles Excavating	Penny's Ready Mix, Shawnee, KS
6	K-8253-02	K-61	McPherson	6. 8/19/2010	Koss	Koss
7	K-8243-03	US-54	Pratt	7. 9/15/2010	Koss	Koss
8	K-8253-01	K-61	McPherson	8. 9/29/2010	Koss	Koss
9	K-8251-11	US-69	Johnson	9. 10/28/2010	Clarkson	Clarkson
10	K-8244-04	US-54	Kingman	10. 10/14/2010	Koss	Koss
11	KA-0410-03	K-18	Riley	11. 10/20/2010	Pavers, Inc.	Penny's Ready Mix, Manhattan, KS
12	K-8252-01	K-61	Reno	13. 6/8/2011 and 16. 4/18/2012	Koss	Koss
13	KA-0729-01	I-70	Ellsworth	14. 8/11/2011	Koss	Koss
14	K-7888-02	US-59	Douglas	15. 10/11/2011	Upper Plains Contractors	Upper Plains Contractors
15	KA-0791-02	K-47	Wilson	17. 5/9/2012	Koss	Koss
16	K-8251-08	US-69	Johnson	18. 6/25/2012	Clarkson	Clarkson
17	KA-0728-01	I-70	Ellsworth	19. 6/27/2012	Koss	Koss
18	KA-0718-01	I-70	Sherman	20. 8/9/2012	Koss	Koss

2.2 Field Sampling

Concrete was sampled and specimens were cast according to KT-17 (2010) *Sampling Freshly Mixed Concrete* and KT-22 (2010) *Making and Curing Compression and Flexural Test Specimens in the Field*. The following information was recorded for each field visit:

- Sampling time and location,
- Contractor and concrete supplier,
- Mix design and aggregate source, and
- Slump, air content, concrete and air temperatures, and unit weight.

When the concrete was delivered in end-dump trucks to a spreader that placed the concrete on the subgrade ahead of the paver, samples were obtained from the concrete on-grade behind the spreader and in front of the paver. The concrete was shoveled into a wheelbarrow. Concrete delivered in transit-mix trucks was sampled by directing the discharge from the truck directly into a wheelbarrow. KDOT construction personnel or contractor quality control personnel collected concrete samples for fresh concrete tests, including slump, air content, and unit weight, at the same time and by the same method as the research samples.

The representative sample was taken immediately to cast 3 inch × 4 inch × 16 inch prisms for testing as per KT-17 (2010). The prisms were vibrated according to KT-22 (2010). The specimens were cured in the field overnight according to procedures outlined in KT-22 for standard curing. Prism specimens were placed in insulated curing containers in a level location out of construction traffic. Each prism was covered with a sheet of plastic or a metal lid, then saturated burlap was draped over the prism and another covered prism stacked on top. This was repeated twice for a total of three prisms in each container. A single sheet of burlap was folded back and forth between the prisms to cover all three prisms. After the final prism was added, a large sheet of plastic was wrapped around the top and sides of all three prisms and a small amount of water was added to the bottom of the container to maintain moisture levels. The curing containers were not moved until at least 12 hours after casting. The specimens were returned to the Materials and Research Center the following day by either local KDOT or Concrete Research section personnel. The samples cast in the field are referred to as "field specimens" in this report.

On the same day that specimens were cast, KDOT District personnel collected a standard-sized production sample of the coarse aggregates in use on the project from the stockpile at the concrete batch plant. The aggregate sample was submitted to the Physical Test Section at the Materials and Research Center for quality production sample (QPS) testing, including KTMR-22 freeze-thaw testing. The specimens cast in the lab with aggregates collected on the same day as the field specimens were cast are referred to as "lab specimens" in this report. Standard production specimens produced by Physical Test Section with aggregates collected at times other than the day that field specimens were cast are referred to as "production specimens."

2.3 Lab Testing

After the prism specimens arrived at the Materials and Research Center, they were removed from the molds and labeled with sample IDs. Curing was completed in the laboratory according to the requirements of KTMR-22. When curing was complete, specimens were tested according to KTMR-22. The lab specimens were treated according to the standard procedure in effect at the time they were tested. The lab specimens cast in 2010 and 2011 were removed from testing at the first measurement interval after the completion of 300 cycles of freezing and thawing. In 2012, the standard test was extended to 660 cycles, and the lab specimens cast in that year experienced at least 660 freezing and thawing cycles. The field specimens were tested for extended numbers of freeze-thaw cycles. Testing was continued until the field specimens were too deteriorated to remain intact through the testing process or were removed to make space in the freezers. Each field specimen received at least 776 cycles of freezing and thawing.

Chapter 3: Results

Durability factor, relative dynamic modulus, and expansion results of the field specimens were compared to results from lab specimens. The aggregates used in the lab specimens were collected at the project on the same day the field specimens were cast. Results are compared at 300 cycles and at 660 cycles. Where the companion lab specimens were not tested to 660 cycles, the field specimens were compared to production specimens cast from aggregate samples not collected on the same day the field specimens were cast.

Aggregates from 11 sources were tested, including limestone from five sources, crushed gravel from two sources, and sandstone, granite, nepheline syenite, and quartzite from one source each, as shown in Table 3.1. Limestone from Cornejo Stone in Elk County, Kansas, was used on five projects. Limestone from Hunt-Martin in Johnson County, Kansas, sandstone from APAC-Kansas in Lincoln County, Kansas, and quartzite from L.G. Everist in South Dakota were each used on two projects. Aggregate from each of the remaining sources was used on a single project.

Table 3.1: Sources of Aggregate Used on KDOT PCCP Projects Sampled in 2010-2012

No.	Project Number	Route	County	Aggregate Type	Aggregate Source
1	KA-1666-01	I-70	Wyandotte	Limestone	Hunt-Martin, Johnson Co. KS
2, 12	K-8246-01	US-50	Finney	Crushed Gravel	Eastern Colorado Aggregate Baca Co. CO
3	K-7332-01	I-135	Sedgwick	Limestone	Cornejo Stone, Elk Co. KS
4	K-8251-07	US-69	Johnson	Quartzite	L.G. Everist, South Dakota
5	K-7925-02	K-7	Johnson	Nepheline Syenite	Granite Mountain, AR
6	K-8253-02	K-61	McPherson	Limestone	Cornejo Stone, Elk Co. KS
7	K-8243-03	US-54	Pratt	Limestone	Cornejo Stone, Elk Co. KS
8	K-8253-01	K-61	McPherson	Limestone	Cornejo Stone, Elk Co. KS
9	K-8251-11	US-69	Johnson	Quartzite	L.G. Everist, South Dakota
10	K-8244-04	US-54	Kingman	Limestone	Martin Marietta, Elk Co. KS
11	KA-0410-03	K-18	Riley	Limestone	Bayer Construction, Riley Co. KS
13, 16	K-8252-01	K-61	Reno	Limestone	Cornejo Stone, Elk Co. KS
14	KA-0729-01	I-70	Ellsworth	Sandstone	APAC-Kansas, Lincoln Co. KS
15	K-7888-02	US-59	Douglas	Limestone	Hunt-Martin, Johnson Co. KS
17	KA-0791-02	K-47	Wilson	Limestone	Midwest Minerals, Wilson Co. KS
18	K-8251-08	US-69	Johnson	Granite	Martin Marietta, Johnston Co. OK
19	KA-0728-01	I-70	Ellsworth	Sandstone	APAC-Kansas, Lincoln Co. KS
20	KA-0718-01	I-70	Sherman	Crushed Gravel	Eastern Colorado Agg., Prowers Co. CO

The standard mix designs specified in KTMR-22 differ in significant aspects from the mix designs used in Kansas portland cement concrete pavement (PCCP), as shown in Table 3.2. In the field, aggregate proportions, gradations, and sources used differ from the standard lab mix design. The coarse aggregate gradations contain more than just particles retained on the ½ inch and $^{3}/_{8}$ inch sieves. The proportion of coarse aggregate varied from 30% to 60% of the total aggregate used. The remainder of the aggregate portion of the field mixes consisted of one to three additional aggregates, including sands, sand-gravels, and intermediate gradations of crushed stone or uncrushed gravel.

Table 3.2: Materials and Proportions Used on KDOT PCCP Projects Sampled in 2010-2012

No.	Project Number	Cement Factor, lbs/yd^3	SCM Types	SCM % Used	w/c	Coarse Agg %
1	KA-1666-01	525	Class F Fly Ash	25	0.43	55
2	K-8246-01	520	Class C Fly Ash	25	0.42	50
3	K-7332-01	565	Class C Fly Ash	15	0.40	50
4	K-8251-07	565	Class F Fly Ash	20	0.40	40
5	K-7925-02	540	Slag Class C Fly Ash	25 10	0.40	41
6	K-8253-02	540	Class C Fly Ash	25	0.41	30
7	K-8243-03	521	Class C Fly Ash	25	0.42	30
8	K-8253-01	520	Class C Fly Ash	25	0.41	30
9	K-8251-11	565	Class F Fly Ash	20	0.38	40
10	K-8244-04	540	Class C Fly Ash	25	0.42	30
11	KA-0410-03	565	Slag	25	0.41	60
12	K-8246-01	520	Class C Fly Ash	25	0.42	50
13	K-8252-01	520	Class C Fly Ash	25	0.42	35
14	KA-0729-01	520	Class C Fly Ash	25	0.44	43
15	K-7888-02	564	Class C Fly Ash	25	0.39	60
16	K-8252-01	540	None	0	0.42	35
17	KA-0791-02	540	Class C Fly Ash	25	0.42	49
18	K-8251-08	564	Class F Fly Ash	20	0.41	56
19	KA-0728-01	520	Class C Fly Ash	25	0.44	40
20	KA-0718-01	540	Class C Fly Ash	30	0.45	43

The proportion and types of cementitious materials used in the field were also different from those used in the lab concretes. The cementitious material content of the field concretes ranged from 520 to 565 lbs/yd^3. Since the implementation of permeability requirements in 2007, few Kansas pavement concretes have contained cement as the only cementitious material. Supplementary cementitious materials such as fly ash and slag replaced up to 35% of the portland cement in the pavement concretes. Only one of the concretes sampled for this study did not contain supplementary cementitious materials. The water-cement ratio of the field concretes varied from 0.38 to 0.45.

3.1 Durability Factor and Relative Dynamic Modulus of Elasticity

The durability factor at 300 cycles was compared for 20 pairs of field and lab specimens, as shown in Figure 3.1. Until 2013, KDOT specifications required a minimum durability factor of 95 at 300 cycles of freezing and thawing (KDOT, 2007b). Both the field and lab specimens met or exceeded this requirement for 90% (18 of 20) of the specimen pairs. Two specimen pairs containing crushed gravel had results that did not both meet or exceed the minimum durability factor of 95. The results for sample pairs 2 and 12 are shown in Table 3.3 and circled in Figure 3.1. The field result of pair number 2 failed; the field result of pair number 12 passed. Complete durability factor test results are listed in Appendix Table A.1.

Table 3.3: 300-Cycle Durability Factor Lab and Field Test Result Pairs Out of Agreement

No.	Producer	Aggregate	Field	Lab	Criteria
2	Eastern Colorado Aggregate	Gravel	92	95	Pass/fail
12	Eastern Colorado Aggregate	Gravel	98	94	Pass/fail, ASTM C666
14	APAC-Kansas	Sandstone	99	95	ASTM C666
19	APAC-Kansas	Sandstone	100	96	ASTM C666

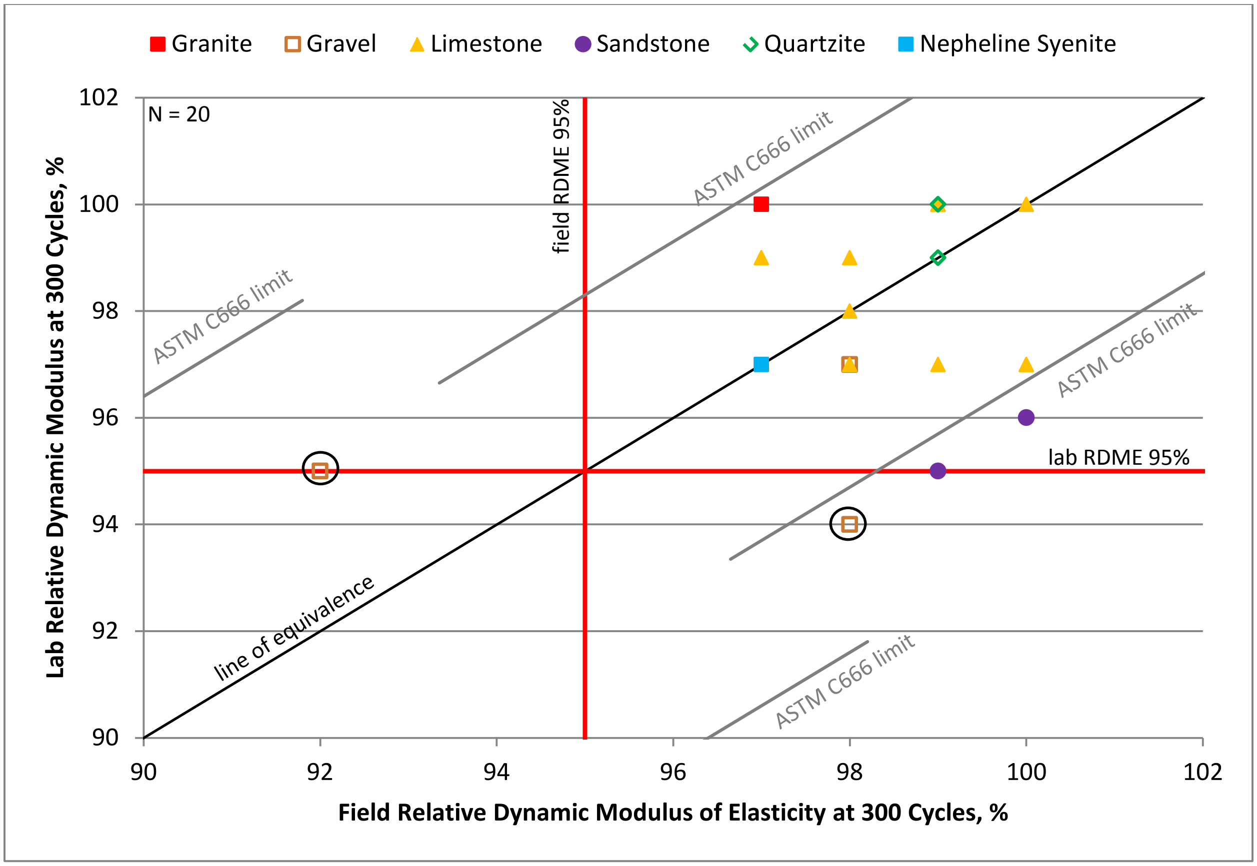

Figure 3.1: Durability Factor at 300 Cycles

The within-laboratory precision statement in ASTM C666 gives acceptable ranges for agreement of pairs of durability factor values at 300 cycles. The ranges are determined by the average of the durability factors compared and the number of prisms that were tested to determine the durability factors (ASTM C666, 2008). Three prisms are tested in the KDOT procedure. The limits of acceptable ranges of durability factor values are shown in Figure 3.1 and Table 3.4.

Table 3.4: ASTM C666 Procedure B Within-Laboratory Durability Factor Precisions for Averages of Three Prisms

Range of Average Durability Factor	Acceptable Range for Two Averages
Above 95	3.3
90 to 95	6.4
80 to 90	14.4
70 to 80	27.9

Seventeen of the 20 pairs of lab and field values agree within the acceptable ranges given in ASTM C666. Three pairs of lab and field test results did not agree within the ASTM C666 acceptable ranges. These points lie outside the ASTM C666 limits shown in Figure 3.1. The acceptable difference between these results was 3.3 points. Each of the pairs that did not agree differed by 4 points, indicating that 1 point of the difference in values could be attributed to factors besides the inherent variability of the test. Of the three pairs of field and lab results that did not meet the ASTM C666 criteria for data agreement, pairs 14 and 19 contained sandstone and pair 12 contained crushed gravel, as shown Table 3.3. All three of the data pairs that did not agree within the ASTM C666 criteria for agreement had field results higher than the lab results.

A pairwise *t*-test comparing the mean value of all lab results with the mean value of all field results showed that the mean values agreed within 95% confidence. The mean value of the durability factor of the field specimens was 98 and the mean value of the lab specimens was also 98.

No consistent bias was observed between field and lab test results, as shown in Figure 3.1. Of the 20 pairs of lab and field results of durability testing at 300 cycles, the field test result was higher than the lab test result in eight pairs, the lab test result was higher in another eight pairs, and the results were equal in four pairs.

The RDME at 660 cycles was compared for 14 pairs of specimens, as shown in Figure 3.2. Ten field specimens were compared with corresponding lab specimens. If lab specimen results at 660 cycles were not available, the average value of up to two production sample results was used in the comparison. Production sample results at 660 cycles were available for an additional four pairs of specimens. According to current KDOT specifications, specimens that completed 660 cycles of testing with an RDME of at least 95 were considered “passing” (KDOT, 2015). The RDME results of the field and the lab or production specimens either both passed or both failed the criteria for 86% (12 of 14) of specimens. The pass/fail results of two field specimens of limestone, numbers 10 and 13, did not agree with the production specimens used for comparison. These results are circled in Figure 3.2 and shown in Table 3.5. The field result of pair number 10 passed and the field result of pair number 13 failed. Complete RDME test results are listed in Appendix Table A.2.

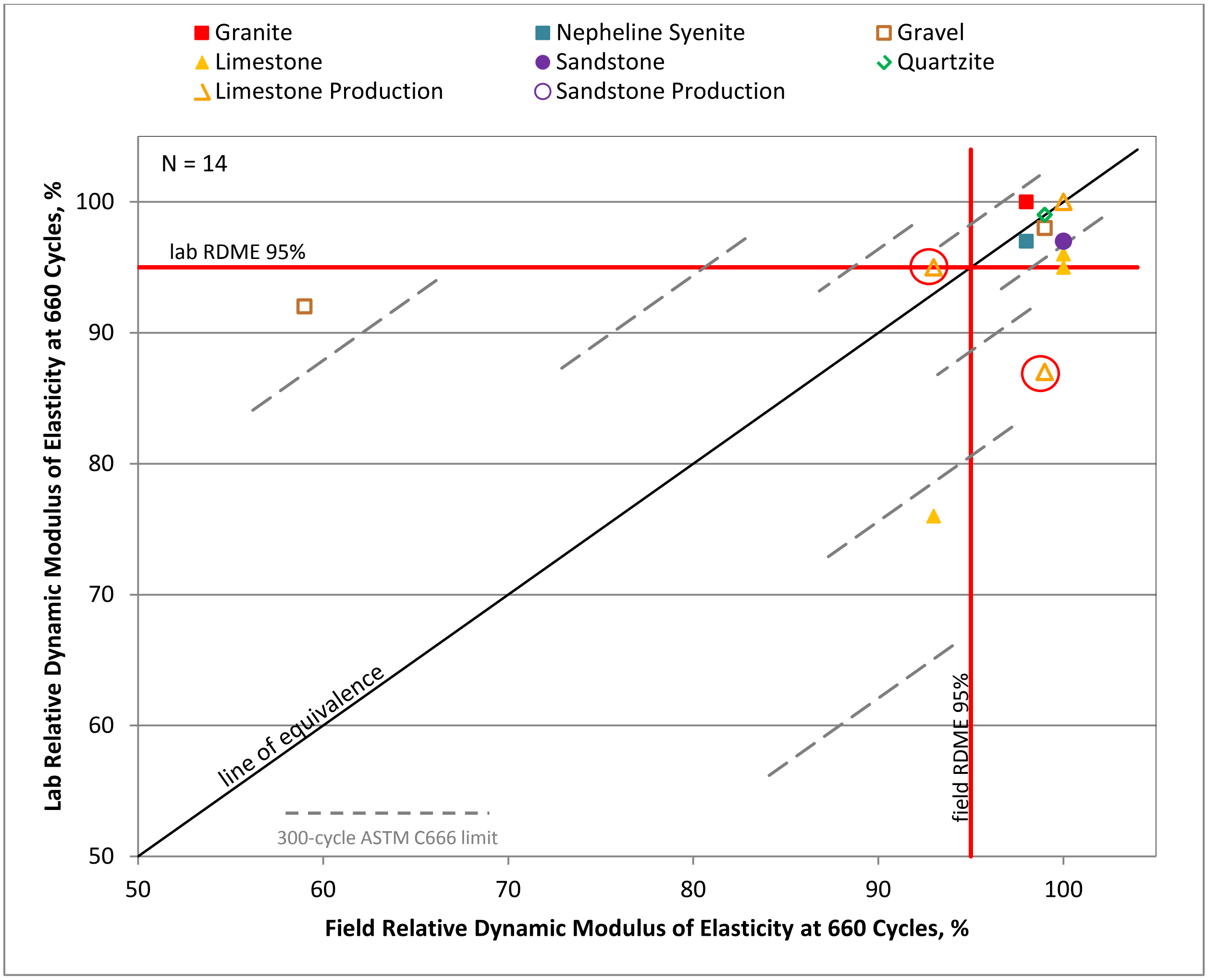

Figure 3.2: Relative Dynamic Modulus of Elasticity at 660 Cycles

Table 3.5: 660-Cycle RDME Lab and Field Test Result Pairs Out of Agreement

No.	Producer	Aggregate	Field	Lab	Ave. Prod.	Criteria
2	Eastern Colorado Aggregate	Gravel	59	92	-	ASTM C666
10	Martin Marietta	Limestone	99	-	87	Pass/fail, ASTM C666
13	Cornejo Stone	Limestone	93	-	95	Pass/fail
15	Hunt-Martin	Limestone	100	95	-	ASTM C666
16	Cornejo Stone	Limestone	93	76	-	ASTM C666
17	Midwest Minerals	Limestone	100	96	-	ASTM C666

ASTM C666 does not give criteria for agreement of RDME results measured at 660 cycles. The criteria given for agreement of results at 300 cycles were used to estimate the agreement of specimen pairs measured at 660 cycles, as shown in Figure 3.2. Nine of the 14 pairs of results agree within the acceptable range of results given in ASTM C666 for specimens tested to 300 cycles. These points lie outside the 300-cycle ASTM C666 limits shown in Figure 3.2, and are listed in Table 3.5. Of the five pairs that did not agree within 300-cycle ASTM C666 limits, pairs 10, 15, 16, and 17 contained limestone and pair 2 contained crushed gravel. A pairwise *t*-test showed that the mean value of the lab test results and the mean value of the field test results agreed within 95% confidence. The mean value of the RDME at 660 cycles of the field specimens with corresponding lab or production specimens was 96. The mean value of the lab and production specimens corresponding to the field specimens was 95.

No consistent bias was found between field and lab or production RDME test results at 660 cycles of freezing and thawing. The field test results were higher for eight of 14 pairs of test results. The lab and field results were equal for three pairs of test results and the lab results were higher for three pairs. The four pairs of limestone samples that did not agree within the ASTM C666 criteria for agreement of test results at 300 cycles had higher field results. The pair of crushed gravel test results that did not agree within 300-cycle ASTM C666 limits had higher lab test results.

3.2 Expansion

The percent expansion of 20 pairs of field and lab specimens was compared at 300 cycles of freezing and thawing, as shown in Figure 3.3. Until 2013, KDOT specifications required a maximum expansion of 0.025% at 300 cycles. All field and lab specimens met this criterion with expansions of 0.016% or less. ASTM C666 does not provide a precision statement for percent expansion. The field test results were higher than the lab test results for 13 pairs of samples and the lab test results were higher in 7 pairs. A pairwise *t*-test showed that the mean value of the field test results and the mean value of the lab test results agreed within 95% confidence. The mean expansion value of the field specimens at 300 cycles was 0.009% and the mean value of the lab specimens was 0.006%. Expansion test results at 300 cycles are listed in Appendix Table A.3.

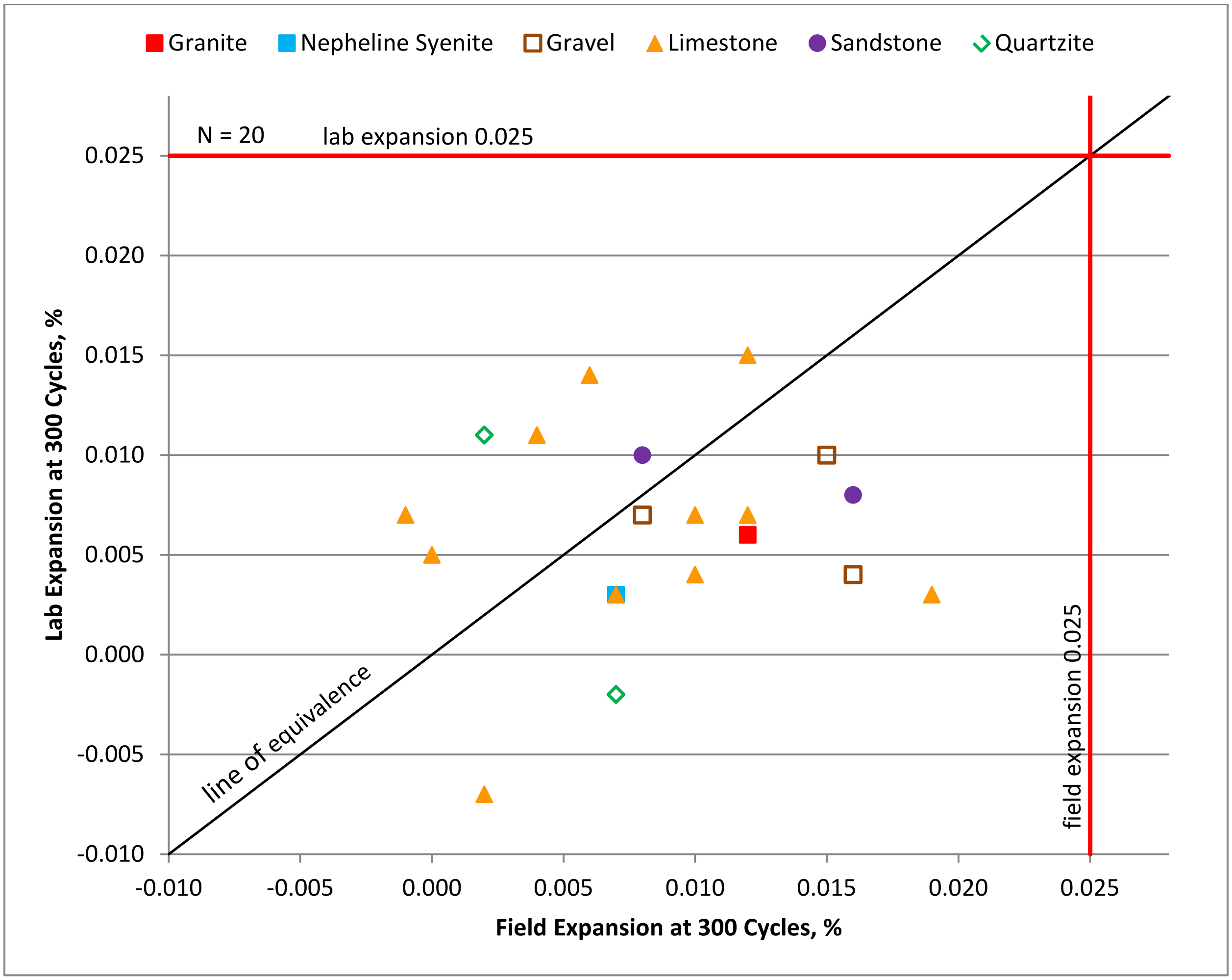

Figure 3.3: Percent Expansion at 300 Cycles

The percent expansion of 14 pairs of field and lab specimens or field and production specimens was compared at 660 cycles, as shown in Figure 3.4. Results at 660 cycles were available for 10 pairs of field and lab specimens. When lab specimen results at 660 cycles were not available, field specimen results were compared with the average value of up to two production sample results. Production sample results were available at 660 cycles for an additional four pairs of specimens. Current KDOT specifications require that specimens pass the expansion test with 0.025% expansion or less. The results of 79% of the pairs (11 of 14) either both passed or both failed the criteria. Three sets, one each containing gravel, limestone, and quartzite, had one specimen pass and the other fail, as shown in Table 3.6 and circled in Figure

3.4. The field test results were higher for seven pairs of test results and the lab or production test results were higher for seven pairs.

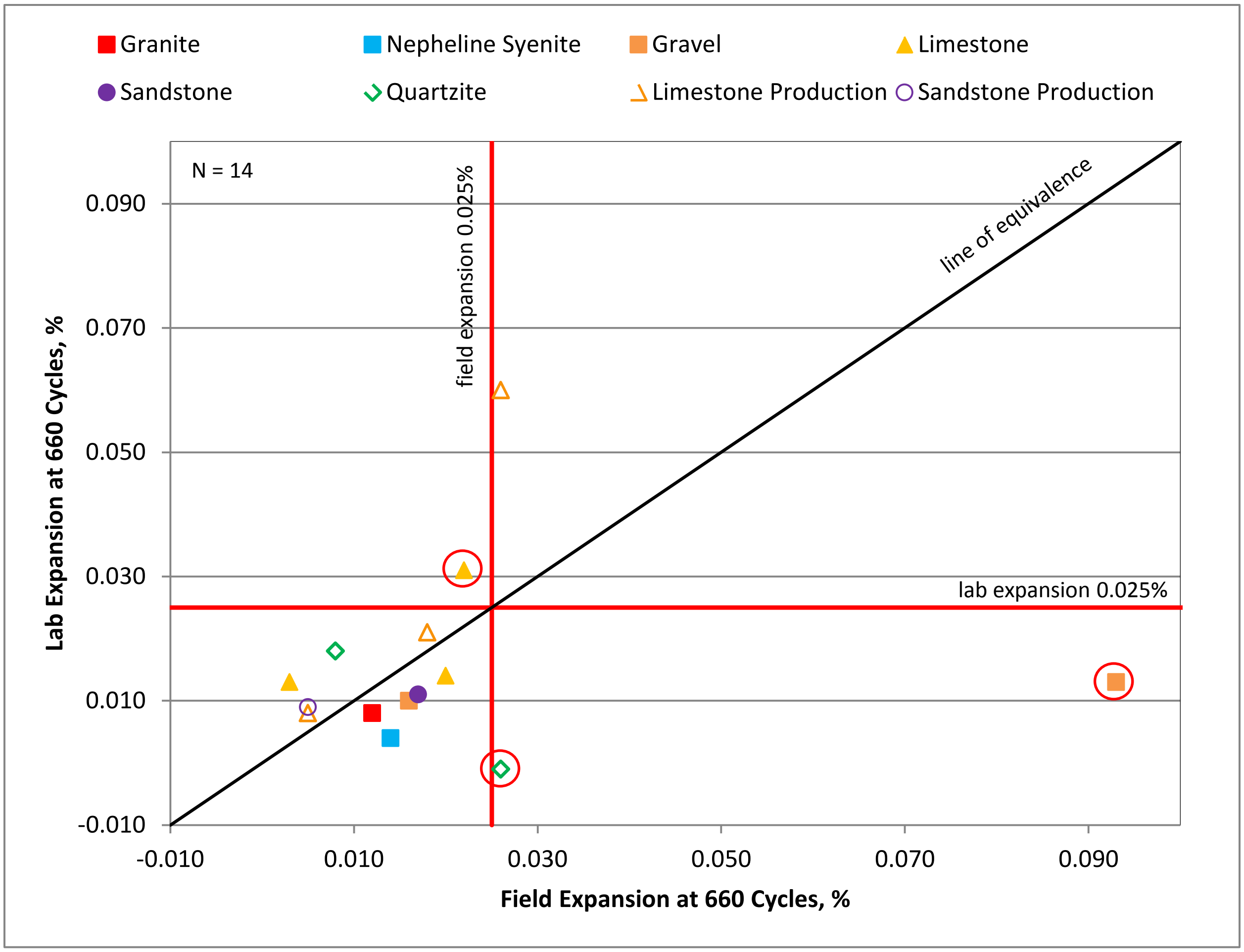

Figure 3.4: Percent Expansion at 660 Cycles

Table 3.6: 660-Cycle Expansion Lab and Field Test Result Pairs Out of Agreement

No.	Producer	Aggregate	Field	Lab	Criteria
2	Eastern Colorado Aggregate	Gravel	0.093	0.013	Pass/fail
4	L.G. Everist	Quartzite	0.026	-0.001	Pass/fail
16	Cornejo Stone	Limestone	0.022	0.031	Pass/fail

A pairwise *t*-test indicated that the mean value of the field specimens and the mean value of the corresponding lab or production specimens agree within 95% confidence. The mean expansion value of the field specimens at 660 cycles with corresponding lab or production specimens was 0.020%, and the mean value of the lab specimens and production specimens corresponding to the field specimens was 0.016%. Expansion test results at 660 cycles are listed in Appendix Table A.4.

3.3 Material Variability

Nonuniformity of natural materials may account for the variations of the durability factor and the RDME not accounted for in the inherent variability of the freeze-thaw test, as shown in Figure 3.5. The RDME at 660 cycles of 10 field, lab, and production samples containing Cornejo limestone was measured between June 2010 and April 2012. The consistency of values from any given year shows that testing was properly conducted. The variation in values between years shows that the aggregate properties varied by more than the variability of the test. The RDME from all 3 years ranged from 66 to 95 with an average of 86. The range of RDME values over all 3 years exceeded the acceptable range of values given in ASTM C666 for 300 cycles by 15 points, as shown in Table 3.7. The RDME values for all samples in any given year agree within the variability of the test, as shown in Table 3.7. The 2012 values had the highest range at 27 points but this variation is within the acceptable range of 27.9 points given in ASTM C666 at 300 cycles for values averaging between 70 and 80. The variation observed at 660 cycles was not observed in the lab and field specimens at 300 cycles.

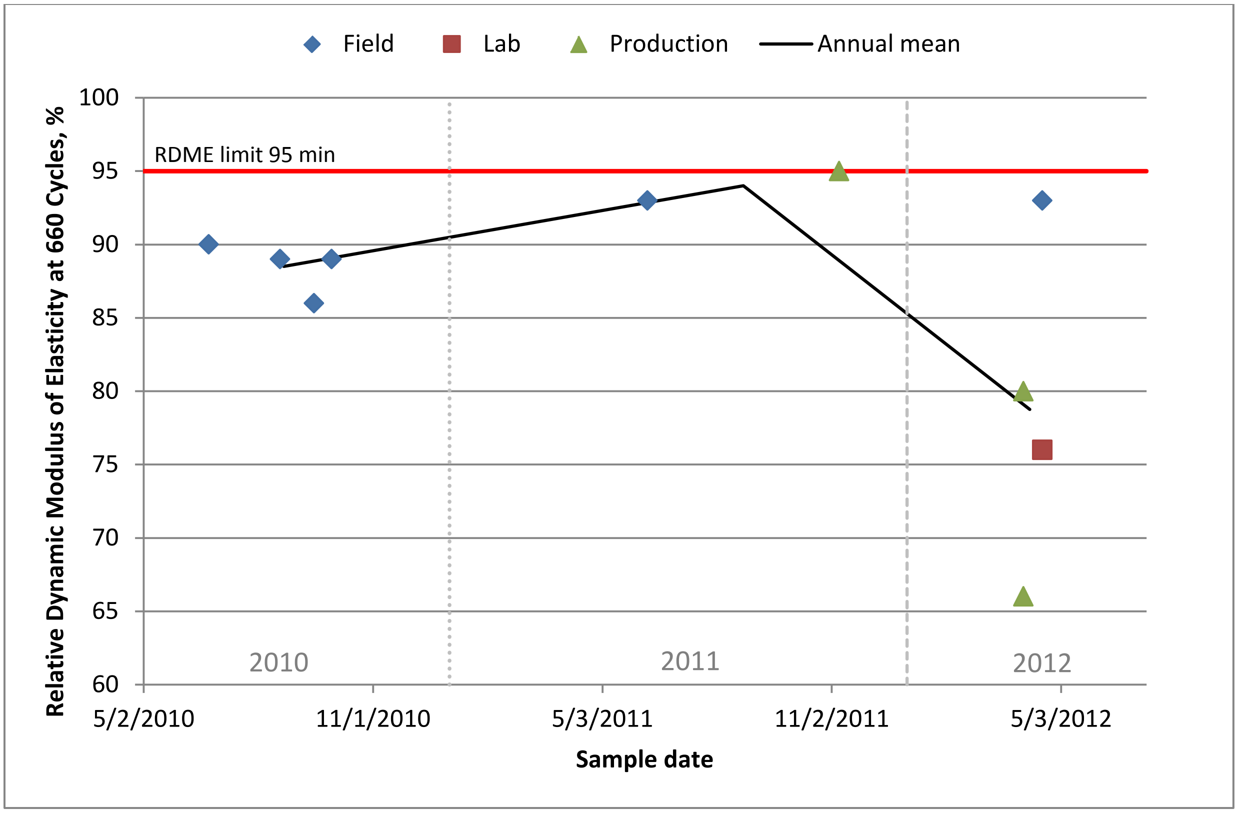

Figure 3.5: RDME of Cornejo Limestone at 660 Cycles by Date

Table 3.7: Annual 660-Cycle RDME Ranges of Cornejo Limestone Samples

Year	Annual Mean	Annual Range	Allowable Range*
2010	89	4	14.4
2011	94	2	6.4
2012	79	27	27.9
ALL	**86**	**29**	**14.4**

*as given in ASTM C666 precision statement for durability factor at 300 cycles

Chapter 4: Discussion

Concrete prism samples were cast and aggregate samples were collected on 20 visits to concrete paving projects in 2010, 2011, and 2012. Standard prism specimens were cast in the lab using the aggregate samples collected on the paving project. Both field and lab prisms were tested using the standard KDOT Freezing and Thawing Test KTMR-22. The durability factor, RDME, and expansion were measured at 300 and 660 freezing and thawing cycles. The results of available standard production samples of the same aggregate were used in analyses if lab specimen results were not available.

The pass-fail results agreed for 90% (18 of 20) of the dynamic modulus results at 300 cycles and for 86% (12 of 14) of RDME results at 660 cycles. The field and lab values agreed within the limits given in ASTM C666 precision statement at 300 cycles for 85% (17 of 20) of 300-cycle dynamic modulus values and 64% (nine of 14) of 660-cycle RDME values. The *t*-tests of dynamic modulus and RDME values also showed agreement of the field values with the lab or production values.

The pass-fail results of the expansion test at 300 cycles agreed for all 20 sample pairs. At 660 cycles, the pass-fail results of 79% (11 of 14) of the specimen pairs agreed. The *t*-tests of expansion results showed that the field and lab or production values agreed at both 300 and 660 cycles. ASTM C666 does not provide a precision statement for expansion values.

Although field and lab mix designs differed in materials and proportions, no consistent bias was found between the field and the lab tests. A consistent bias would result in significantly more field sample results passing or failing than lab or production sample results. Two of the five pairs of 660-cycle RDME and expansion tests with pass-fail results that did not agree had field results that passed and three had field results that failed. The pass/fail results of RDME tests at 660 cycles differed for two pairs of samples, one with a field result that passed and one with a field result that failed. The three pairs of 660-cycle field and lab expansion tests with pass/fail results that did not agree included one with a field result that passed and two with a field result that failed.

Variation among the test results can be caused by the variability of the freeze-thaw test, variations in natural materials, by differences in mix proportions, cementitious materials, and secondary aggregates, and by distress from causes other than freeze-thaw degradation of coarse aggregates.

The acceptable limits for test values given in the ASTM C666 precision statement represent the amount of variability present in properly conducted tests on the same material. The three aggregate types with results that did not agree within these limits were sandstone, gravel, and limestone.

The inherent variation of natural materials such as aggregate stone can cause variations between tests. Rocks are formed by natural processes that vary in time and by location, leading to variations in aggregate properties. The durability factors of the sandstone sample numbers 14 and 19 did not agree within the limits given in the precision statement of ASTM C666 for 300 cycles. The field test result of each pair was 4 points higher than the lab test result. Most of this difference can be accounted for by the allowable variation between the test results of 3.3 points given in the precision statement of ASTM C666. The variability of the aggregate itself would be at least equal to or greater than the testing variability; therefore, a 4-point difference is within the expected variation in durability factors for these samples.

Nearly all of the variation in the test results for the gravels, samples 2 and 12, was due to variations in the natural material. An investigation into the Eastern Colorado Aggregate deposit conducted during the course of this study found that this source had varying amounts of non-durable calcium carbonate and sandstone aggregates. The variability of the material caused the large differences in the freeze-thaw test results seen in this study. These variable results were part of the basis for KDOT requiring all coarse aggregates to pass KTMR-22.

Limestone aggregates were used in five of the six pairs of specimens with RDME values out of agreement at 660 cycles, as determined by the ASTM C666 limits or by pass/fail. Differences between corresponding values greater than the range specified in ASTM C666 indicate variability in the limestone material itself. This variation can be seen in the 660-cycle RDME values of the Cornejo limestone sampled from the same beds in 2010, 2011, and 2012 in Figure 3.5. The mean RDME value of the limestone varied each year by as many as 15 points from the year before. Variations in the limestone materials may account for the differences between field and production samples taken at different times and locations.

The overall strength of the agreement between the field and lab or production test results shows that the differences in the mix proportions, gradations, and mix materials did not contribute significant variability. The exception to this overall agreement may be one pair of specimens containing quartzite with pass/fail expansion results that did not agree due to alkali-silica reactivity.

Caution should be used in interpreting the results of field specimens containing alkali-silica reactive aggregates, such as quartzite and certain sands and gravels. Field sample number 4 with quartzite failed with an expansion of 0.026% at 660 cycles. The corresponding lab specimen had -0.001% expansion at 660 cycles and 0.007% expansion when it was removed from testing at 5,721 cycles. The RDME's of both the field and lab specimens were 99 at 660 cycles. An examination of one of the field prisms found cracking in the paste around coarse and fine aggregate particles but no cracking in the coarse aggregate (Billinger, 2013). Therefore, the expansion of the field specimens was not caused by freezing and thawing of the coarse aggregate. Signs of alkali-silica reactivity were also found in the spalled areas of the prism examined, causing the increased expansion in the field specimens. Quartzite and the Missouri River sand and sand-gravel used in the field specimens are alkali-silica reactive. A petrographic examination is recommended for specimens with expansion and RDME results that do not agree to determine the failure mechanisms.

Chapter 5: Conclusions and Recommendations

No consistent differences were found between the results of field and lab specimens containing the same aggregates. Differences in aggregate gradations and proportions, cement content, and the presence of supplementary cementitious materials did not affect the agreement of the lab and field test results. The similarities in performance between the lab and field concretes indicate that the results of the KTMR-22 Freezing and Thawing Test are determined primarily by the durability of the coarse aggregate. Sampling concrete as delivered to the job site for freezing and thawing evaluation would provide assurance that the KTMR-22 test results reflect the performance of the aggregate used in the pavement.

On the basis of this research, it is recommended that specimens be cast in the field for KTMR-22 testing to verify the durability of aggregates as actually used in pavements. A petrographic evaluation of the prism specimens should be performed any time the RDME results contradict the expansion results to determine the failure mechanism.

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Appendix: Data Tables

Table A.1: Durability Factor at 300 Cycles

No	Project Number	Aggregate Producer	Aggregate Type	Field	Lab	Prod 1	Prod 2
1	70-105 KA-1666-01	Hunt-Martin (046)	Limestone	97	99	98	95
2	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	92	95	-	-
3	135-87 K-7332-01	Cornejo Stone (025)	Limestone	98	98	98	96
4	69-46 K-8251-07	L.G. Everist, Inc.	Quartzite	99	99	-	-
5	7-46 K-7925-02	Granite Mountain (Ark)	Nepheline Syenite	97	97	-	-
6	61-59 K-8253-02	Cornejo Stone (025)	Limestone	99	100	99	100
7	54-76 K-8243-03	Cornejo Stone (025)	Limestone	98	99	99	96
8	61-59 K-8253-01	Cornejo Stone (025)	Limestone	99	100	99	99
9	69-46 K-8251-11	L.G. Everist, Inc.	Quartzite	99	100	-	-
10	54-48 K-8244-04	Martin Marietta (025)	Limestone	99	100	97	100
11	18-81 KA-0410-03	Bayer Construction Co. (081)	Limestone	100	100	100	100
12	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	98	94	-	-
13	61-78 K-8252-01	Cornejo Stone (025)	Limestone	100	97	96	92
14	70-27 KA-0729-01	APAC-Kansas (053)	Sandstone	99	95	96	-
15	59-23 K-7888-02	Hunt-Martin (046)	Limestone	100	97	97	97
16	61-78 K-8252-01	Cornejo Stone (025)	Limestone	98	97	96	97
17	47-103 KA-0791-02	Midwest Minerals(103)	Limestone	99	97	98	97
18	69-46 K-8251-08	Martin Marietta (OK)	Granite	97	100	-	-
19	70-27 KA-0728-01	APAC-Kansas (053)	Sandstone	100	96	96	-
20	70-91 KA-0718-01	Eastern Colorado Aggregate	Gravel	98	97	-	-

Table A.2: Relative Dynamic Modulus of Elasticity at 660 Cycles

No.	Project Number	Aggregate Producer	Aggregate Type	Field	Lab	Prod 1	Prod 2
1	70-105 KA-1666-01	Hunt-Martin (046)	Limestone	78	-	-	-
2	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	59	92	-	-
3	135-87 K-7332-01	Cornejo Stone (025)	Limestone	90	-	-	-
4	69-46 K-8251-07	L.G. Everist, Inc.	Quartzite	99	99	-	-
5	7-46 K-7925-02	Granite Mountain (Ark)	Nepheline Syenite	98	97	-	-
6	61-59 K-8253-02	Cornejo Stone (025)	Limestone	89	-	-	-
7	54-76 K-8243-03	Cornejo Stone (025)	Limestone	86	-	-	-
8	61-59 K-8253-01	Cornejo Stone (025)	Limestone	89	-	-	-
9	69-46 K-8251-11	L.G. Everist, Inc.	Quartzite	99	99	-	-
10	54-48 K-8244-04	Martin Marietta (025)	Limestone	99	-	87	-
11	18-81 KA-0410-03	Bayer Construction Co. (081)	Limestone	100	-	100	99
12	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	92	-	-	-
13	61-78 K-8252-01	Cornejo Stone (025)	Limestone	93	-	95	-
14	70-27 KA-0729-01	APAC-Kansas (053)	Sandstone	100	-	97	-
15	59-23 K-7888-02	Hunt-Martin (046)	Limestone	100	95	95	95
16	61-78 K-8252-01	Cornejo Stone (025)	Limestone	93	76	66	80
17	47-103 KA-0791-02	Midwest Minerals(103)	Limestone	100	96	97	97
18	69-46 K-8251-08	Martin Marietta (OK)	Granite	98	100	-	-
19	70-27 KA-0728-01	APAC-Kansas (053)	Sandstone	100	97	97	-
20	70-91 KA-0718-01	Eastern Colorado Aggregate	Gravel	99	98	-	-

Table A.3: Expansion at 300 Cycles

No.	Project Number	Aggregate Producer	Aggregate Type	Field, %	Lab, %	Prod 1, %	Prod 2, %
1	70-105 KA-1666-01	Hunt-Martin (046)	Limestone	-0.001	0.007	0.012	0.008
2	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	0.016	0.004	-	-
3	135-87 K-7332-01	Cornejo Stone (025)	Limestone	0.019	0.003	0.010	0.007
4	69-46 K-8251-07	L.G. Everist, Inc.	Quartzite	0.007	-0.002	-	-
5	7-46 K-7925-02	Granite Mountain (Ark)	Nepheline Syenite	0.007	0.003	-	-
6	61-59 K-8253-02	Cornejo Stone (025)	Limestone	0.010	0.007	0.005	0.003
7	54-76 K-8243-03	Cornejo Stone (025)	Limestone	0.000	0.005	0.005	0.007
8	61-59 K-8253-01	Cornejo Stone (025)	Limestone	0.007	0.003	0.005	0.005
9	69-46 K-8251-11	L.G. Everist, Inc.	Quartzite	0.002	0.011	-	-
10	54-48 K-8244-04	Martin Marietta (025)	Limestone	0.012	0.007	0.005	0.004
11	18-81 KA-0410-03	Bayer Construction Co. (081)	Limestone	0.002	-0.007	0.001	0.000
12	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	0.008	0.007	-	-
13	61-78 K-8252-01	Cornejo Stone (025)	Limestone	0.004	0.011	0.004	0.013
14	70-27 KA-0729-01	APAC-Kansas (053)	Sandstone	0.008	0.010	0.007	-
15	59-23 K-7888-02	Hunt-Martin (046)	Limestone	0.010	0.004	0.004	0.007
16	61-78 K-8252-01	Cornejo Stone (025)	Limestone	0.012	0.015	0.009	0.010
17	47-103 KA-0791-02	Midwest Minerals(103)	Limestone	0.006	0.014	0.013	0.012
18	69-46 K-8251-08	Martin Marietta (OK)	Granite	0.012	0.006	-	-
19	70-27 KA-0728-01	APAC-Kansas (053)	Sandstone	0.016	0.008	0.007	-
20	70-91 KA-0718-01	Eastern Colorado Aggregate	Gravel	0.015	0.010	-	-

Table A.4: Expansion at 660 Cycles

No.	Project Number	Aggregate Producer	Aggregate Type	Field, %	Lab, %	Prod 1, %	Prod 2, %
1	70-105 KA-1666-01	Hunt-Martin (046)	Limestone	0.037	-	-	-
2	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	0.093	0.013	-	-
3	135-87 K-7332-01	Cornejo Stone (025)	Limestone	0.056	-	-	-
4	69-46 K-8251-07	L.G. Everist, Inc.	Quartzite	0.026	-0.001	-	-
5	7-46 K-7925-02	Granite Mountain (Ark)	Nepheline Syenite	0.014	0.004	-	-
6	61-59 K-8253-02	Cornejo Stone (025)	Limestone	0.029	-	-	-
7	54-76 K-8243-03	Cornejo Stone (025)	Limestone	0.052	-	-	
8	61-59 K-8253-01	Cornejo Stone (025)	Limestone	0.065	-	-	-
9	69-46 K-8251-11	L.G. Everist, Inc.	Quartzite	0.008	0.018	-	-
10	54-48 K-8244-04	Martin Marietta (025)	Limestone	0.026	-	0.060	-
11	18-81 KA-0410-03	Bayer Construction Co. (081)	Limestone	0.005	-	0.001	0.014
12	50-28 K-8246-01	Eastern Colorado Aggregate	Gravel	0.043	-	-	-
13	61-78 K-8252-01	Cornejo Stone (025)	Limestone	0.018	-	0.021	-
14	70-27 KA-0729-01	APAC-Kansas (053)	Sandstone	0.005	-	0.009	-
15	59-23 K-7888-02	Hunt-Martin (046)	Limestone	0.020	0.014	0.014	0.017
16	61-78 K-8252-01	Cornejo Stone (025)	Limestone	0.022	0.031	0.052	0.069
17	47-103 KA-0791-02	Midwest Minerals(103)	Limestone	0.003	0.013	0.012	0.008
18	69-46 K-8251-08	Martin Marietta (OK)	Granite	0.012	0.008	-	-
19	70-27 KA-0728-01	APAC-Kansas (053)	Sandstone	0.017	0.011	0.009	-
20	70-91 KA-0718-01	Eastern Colorado Aggregate	Gravel	0.016	0.010	-	-


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