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# Aggregate Freeze-Thaw Testing and D-Cracking Field Performance: 30 Years Later

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In reaction to these results, KDOT implemented changes aimed at mitigating the risk of D-cracking. Implementation actions included increasing the number of freeze-thaw cycles for aggregate in concrete prisms from 300 to 660 cycles, freeze-thaw testing of all aggregate types (not just limestone) in concrete, focusing aggregate sampling at the point of concrete production, and including an “acceptable field-performance history” criterion for concrete aggregates. Ongoing research is being conducted to develop new methods to identify durable aggregates and faster testing techniques.

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## Final Report

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# Abstract

Premature deterioration of concrete pavement due to D-cracking has been a problem in Kansas since the 1930s. Kansas geology includes mineable limestone coarse aggregates with variable durability in the eastern portion of the state. Due to this variability and historically poor D-cracking field performance, the Kansas Department of Transportation (KDOT) initiated intensive identification and tracking of individual mined beds, as well as frequent durability testing during production in the 1980s. D-cracking field performance of concrete pavements containing limestone coarse aggregates was investigated in 2010-2012. Results of this investigation indicate that the rate of D-cracking decreased, but the minimum rate of D-cracking presence in concrete pavements is more than 30%.

In reaction to these results, KDOT implemented changes aimed at mitigating the risk of D-cracking. Implementation actions included increasing the number of freeze-thaw cycles for aggregate in concrete prisms from 300 to 660 cycles, freeze-thaw testing of all aggregate types (not just limestone) in concrete, focusing aggregate sampling at the point of concrete production, and including an "acceptable field-performance history" criterion for concrete aggregates. Ongoing research is being conducted to develop new methods to identify durable aggregates and faster testing techniques.

# Table of Contents

# List of Tables



# List of Figures

# Chapter 1: Introduction

## 1.1 D-Cracking

Deterioration of concrete pavements due to D-cracking has been a known problem since the 1930s. D-cracking is concrete pavement distress due to freezing and thawing of frost susceptible coarse aggregates containing water. The aggregate particles fracture internally, with cracks extending from the aggregate particles into the concrete paste and progress throughout the pavement slab (Neville 2000, Mindess, et al. 2003, and ACI 201.2R-08). Typically, well-developed D-cracking appears on the surface of the concrete as closely-space, crescent-shaped and concentric hairline cracks located adjacent to and following roughly parallel to joints, cracks, or free edges (KDOT 2007). The cracks may be interconnected, giving the appearance similar to map cracking. Under magnification, D-cracked aggregates in concrete appear as internally fractured with cracks extending from the aggregate into the surrounding concrete paste.

## 1.2 Significance

Premature deterioration of concrete pavements due to D-cracking represents a significant cost to the State of Kansas. The cost of reconstructing a two-lane concrete pavement can range from $0.8–1.15 million per lane-mile (KDOT 2009) and the cost of resurfacing/overlay (10-year life) can range from $300,000 to $500,000 per lane-mile (KDOT 2008). Earlier than expected maintenance and restoration actions significantly increase costs to owners. Based on previous KDOT experience, the time from the identification of D-cracking to a necessary action (generally patching and an overlay) is approximately 4–6 years (Montney, et al. 2008 and Hallin, et al. 2008).

## 1.3 Causes and Efforts to Prevent D-Cracking

It is generally recognized that freeze-thaw deterioration of frost susceptible limestone coarse aggregate containing water is the cause of D-cracking (Stark 1976; Stark 1973; Schwartz 1987; Cady, et al. 1979; Myers and Dubberke 1980; Girard, et al. 1982; Traylor 1982; Marks and Dubberke 1982; KDOT and FHWA 1990; and Wallace 1990). With approximately 78 F/T cycles (drops below 32°F) and 33 "hard" F/T cycles (drops below 23°F) per year (McLeod 2012), D-cracking has been a concern in Kansas since the 1930s. Multiple studies investigating the causes and prevention of D-cracking have been completed across many states with freeze-thaw conditions. KDOT alone has conducted five major investigations over the past 80 years (KDOT and FHWA 1990; Wallace 1990; McLeod 2012; Gibson 1941; Scholer 1928; Bukovatz, et al. 1973; Myers and Stallard 1978; and Miller and Bellinger 2003). As a result of previous studies many DOTs in freeze-thaw climates, including Kansas, implemented durability requirements for aggregates used in concrete. Many acceptance and testing approaches have been taken, but generally aggregate sources are prequalified based on freeze-thaw testing of the aggregate and of concrete containing the aggregate.

## 1.4 Overview of Kansas Aggregate Sources

Kansas has a wide variety of landscapes with 11 different geologic regions (physiographic provinces) each characterized by unique features and geologic history. For the purpose of analyzing Kansas aggregates used in concrete, several generalizations can be made. Variable limestone deposits are the dominant aggregate source in eastern Kansas, and alluvial sand-gravel deposits are the source of the majority of aggregates in western Kansas. Large sand deposits composed mostly of quartz are present in south central Kansas along the Arkansas and Kansas River valleys.

Eastern Kansas and North Central Kansas geologic history is dominated by the advancement and retreat of multiple shallow inland seas. These waters produced layered sedimentary deposits consisting largely of alternating layers of hard and soft rocks, mainly limestones, shales, and sandstones. The largest underlying strata in Eastern Kansas consist of the Pennsylvanian limestones (calcite, calcium carbonate, $CaCO_3$) and shales (hardened, compacted clay or silt). These deposits generally exist as alternating, thinly-layered beds that are highly variable with location, generally dipping (sloping) to the west and northwest. The shales are soft, easily erodible and often occur as bedding planes between limestone deposits. Sandstone is also common in eastern and north central Kansas, and is often interbedded with limestone and shale. The Pennsylvanian limestones are the main source of minable aggregate for roughly the eastern third of Kansas.

Other mineral deposits are found in select regions of Kansas, including gypsum and salt (halite) in central and south central Kansas, and loess (fine-grained deposits consisting mainly of silt) and glacial erratics, such as quartzite, in the glaciated region of northeastern Kansas. These materials are not considered as feasible sources of aggregate for building materials.

## 1.5 Historical D-Cracking Field Performance in Kansas

Five D-cracking studies have been conducted on Kansas highways, in 1944–45, 1951–52, 1964–65, 1980, and 2010-2012. The first three studies were conducted on approximately 1200 miles, or nearly all of the concrete pavement on the state highway system. The fourth and fifth studies included 279 miles and 2177 lane miles of concrete pavement, representing approximately 39% and 69% of the bare concrete pavement on the state highway system, respectively.

The first studies used rating systems reporting a rating of “good” if 0–12% of the pavement panels (one in eight panels) exhibited D-cracking. Any rating above zero exhibited some level of D-cracking. It is important to note that for all four surveys, a pavement rating of “good” did not mean an absence of D-cracking. Rather, it simply meant that the level of D-cracking was considered acceptable at the time. They all concluded that all limestone in Kansas are susceptible to D-cracking and that once D-cracking begins it cannot be stopped. These first surveys also each indicated improvement in the D-cracking field performance due to changes implemented in aggregate size and sources.

**TABLE 1.1: Results from Previous Kansas D-Cracking Studies**

<table>
<tr><th rowspan="2">Rating</th><th rowspan="2">Percentage of Panels D-cracked</th><th colspan="3">Survey Year</th></tr>
<tr><th>1944–45</th><th>1951–52*</th><th>1964–65</th></tr>
<tr><td>Good (0–3)</td><td>0–12%</td><td>54%</td><td>65%</td><td>74%</td></tr>
<tr><td>Fair (3.1–6)</td><td>13–50%</td><td>8%</td><td rowspan="2">35%</td><td>8%</td></tr>
<tr><td>Poor (6.1–10)</td><td>Greater than 50%</td><td>38%</td><td>18%</td></tr>
</table>

*Rated as good or "otherwise"

In 1979, the Federal Highway Administration (FHWA) required KDOT to stop using D-cracking aggregate in federally funded projects. As a result, another study was initiated and new aggregate durability specifications were implemented in the 1980’s with the goal of achieving the initial 20-year design life. The structural design life for KDOT concrete pavements is 20 years (KDOT 2007), with two rehabilitation actions to achieve a total life cycle of 40 years.

The study surveyed pavements constructed between 1961 and 1974 (6–19 years old), and correlated quarry source with pavement performance. The 1980 survey results showed that 57% of all the concrete pavements (including those that did not contain limestone) were either overlaid or exhibited D-cracking before 20 years had elapsed. Because D-cracking was the predominant source of early deterioration at that time, it could be assumed that many of the overlays were required due to D-cracking.

Since the 1980 study, the requirements for an “acceptable condition” rating for pavements have increased significantly. It was found during the 2010-2012 study, that the condition of pavements labeled “good” in previous studies was currently considered unacceptable. Any D-cracking present was considered unacceptable in the 2010-2012 study. Also, the “fair” pavements according to the original rating systems do not currently exist in the state system because KDOT has taken corrective action before any concrete pavement is allowed to get to such a poor condition.

# Chapter 2: 2012 D-Cracking Study Results

The 2010-2012 D-Cracking study provided a 20- to 30-year follow-up to the KDOT implementation (from 1981–1987) of the aggregate durability specifications in the 1980s. The objective was to study the D-cracking field performance of Portland Cement Concrete Pavements (PCCP) built in Kansas and whether they were achieving the intended 20-year design life. Field survey methods used are described previously (McLeod 2012). There were 133 PCCP projects were field performance evaluated, representing 73% of the current concrete state highway system in Kansas. The study was conducted on projects that contained limestone, were at least 10 years old, met specified criteria for length and location, and included pavements that had been overlaid. Over 230 quarries in Kansas have been evaluated for Class 1 status since 1980. Aggregates from 52 quarries were used to construct the projects surveyed in the 2010-2012 study. The rate of success was determined and the results compared with the aggregate source parameters. Results indicated that nearly one-third of the PCCP built in Kansas between 1981 and 2000 are exhibiting D-cracking before 20 years of service. The specified testing did not fully predict failure, but it did reduce the rate of failure. Of utmost interest was the observation that a limited number of quarries were linked with a high percentage of the failures.

For the 2010-2012 study, results were presented on a project basis because each project represented a “decision” made; (i.e., source of coarse aggregate selection) for that project, regardless of the length and scope of the project. A rating of “yes” indicated that D-cracking was observed on the project and  a rating of “no” indicated that D-cracking was not observed on the project. A project had a “Success” result if there was no D-cracking and the project had reached the 20-year design life or if there was D-cracking observed after the project had already reached the 20 years design life. A project had a “Fail” result if there was D-cracking observed before the project reached the 20 year design life. If a project was less than 20-years-old and D-cracking had not yet been observed, then the result was "Inconclusive" because the project had not yet reached the 20-year design life. Only after a non-D-cracking project reached 20-years-old could it be considered a "Success" as there would still be time for D-cracking to become evident before 20 years.

## 2.1 Overall Analysis of Field Performance

Overall, there was a 31% failure rate, 37% success rate, and 32% rate of indeterminate projects (no D-Cracking and not yet 20-years-old). The data indicated that D-cracking was observed on 54 of the 131 projects or 41%. There were 41 of the 131 projects, or 31%, that were less than 20-years-old when D-cracking was observed and were termed "FAIL." Thirteen projects, or 10%, were 20-years-old or more when D-cracking was observed and were termed "PASS." As well as 35 projects, or 26%, that were 20-years or older and exhibited no D-cracking in 2010 and were also termed "PASS." There were 42 projects, or 32%, exhibited no D-cracking and were less than 20-years-old. These projects (exhibiting no D-cracking at an age less than 20 years) were termed "INCONCLUSIVE" because a "PASS" cannot be determined until the pavement reaches the design life of 20 years. Figure 2.1 illustrates the distribution of overall field performance.

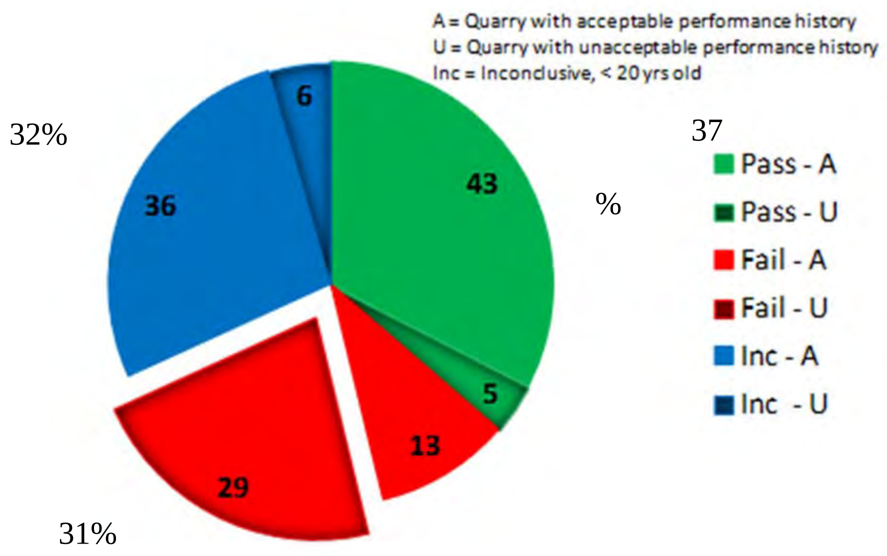



**FIGURE 2.1: Number of Passing, Failing, and Inconclusive Results in the 2010-2012 Study**

The failure rate for the 2009–2010 Study represents the D-cracking failure rate for concrete pavements in Kansas. If the failure rate of the inconclusive projects turns out to be the same as the current failure rate of 31%, then the final failure rate for the full data set will be 41%.

It is clear that the rate of failure has increased with time. In addition to material variability, multiple outside influences were considered. The distribution of successes and failures over time is displayed in Figure 2.2. The rate of failures during the 1980s, before the Comprehensive Highway Program (CHP), is generally lower than during the 1990s, which was during the CHP. If the final results for the inconclusive projects during CHP turn out to be all "successes" (or the best possible result), the rate of success during the CHP would still be worse than for the pre-1990 era. In addition, between 1986 and 1989 quarry monitors were phased-out of being stationed in the quarries. The 1990 KDOT Specification Book dictates acceptance at the point of usage (at the project), where prior to that acceptance was at the quarry. The number of annual failures increased after the quarry monitors were removed from the quarries and acceptance was changed to the project.

It is important to note that field performance can be affected by the material itself (e.g. not F/T durable), by production issues (e.g., contamination, the addition of unacceptable material to crushers or stockpiles, etc.), or a combination of these factors. It is the general view of the 2010-2012 contributing authors that the new changes to inspection and monitoring may have some limited impact on field performance, but it is not likely to reduce the rate of D-cracking to an acceptable level.

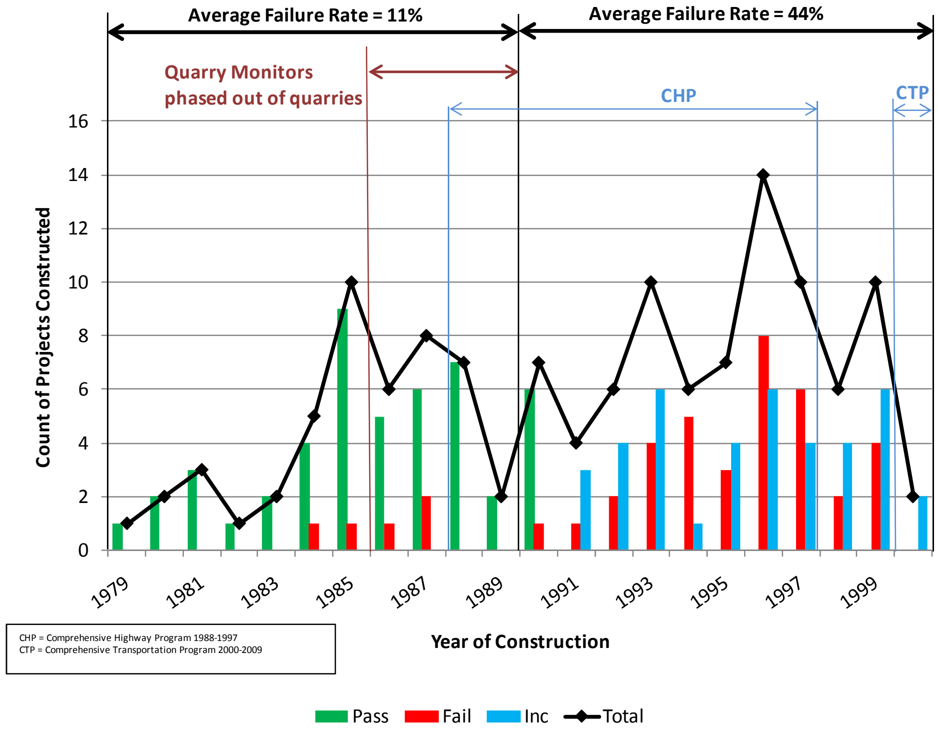



**FIGURE 2.2: Survey Results for Survey Projects by Year of Construction and Legislative Dates for Comprehensive Highway Program (CHP) and Comprehensive Transportation Program (CTP)**

## 2.2 Quarry Analysis

There were 52 quarries that supplied material for the 132 projects. There were 24 quarries that provided aggregate to the 42 criteria projects that exhibited D-cracking before 20-years of service. Considering the quarries with the highest numbers of D-cracking projects, 6 of the 24 quarries (25%) supplied material to 23 of the 42 (55%) failing projects. Nine quarries provided aggregate to 29 projects that failed. Therefore 55% of the failures came from six quarries and 69% of the failures came from nine quarries. The overall results are shown in Figure 2.3 with the projects containing material from these nine quarries shaded. These quarries account for approximately 69% of the premature failures, shown in Figure 2.3, which is significantly higher than the 14% failure rate for the remaining 44 quarries with acceptable field performance.

Figure 2.3 illustrates the results for these same nine quarries over time, including an average failure rate during the 1990s of 81%.

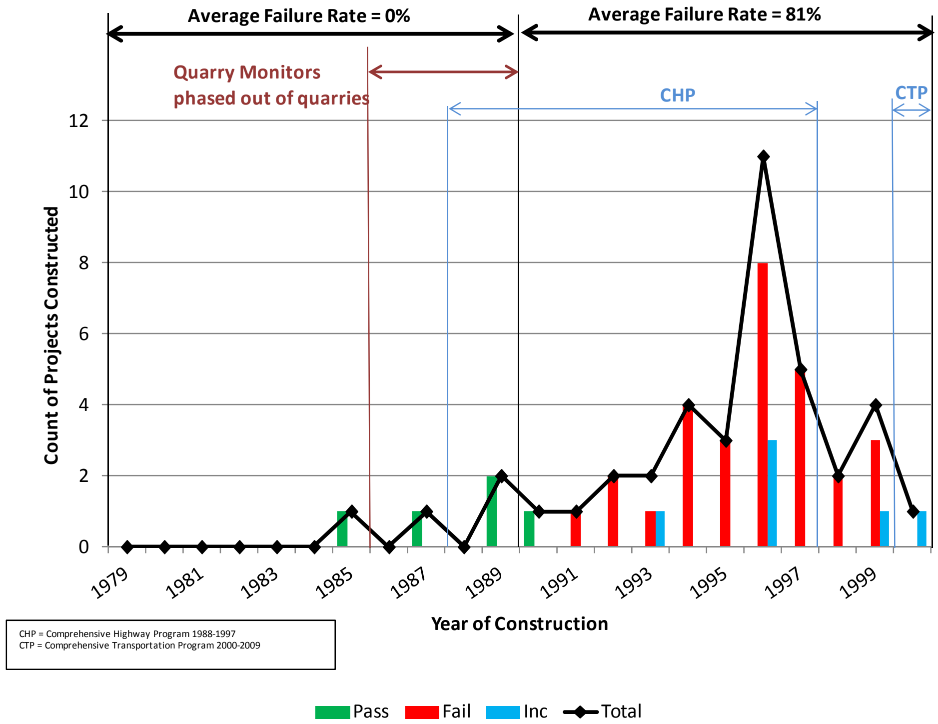



**FIGURE 2.3: Survey Results for Survey Projects Containing Material from the Nine Quarries with Unacceptable Field Performance, by Year of Construction and Legislative Dates for Comprehensive Highway Program (CHP) and Comprehensive Transportation Program (CTP)**

## 2.3 D-Cracking in Less than 10 years

On at least four projects surveyed during the 2010-2012 study, crews observed D-cracking on pavements that were less than 10 years old. The ages of the observed pavements were 6, 7, 8, and 9 years old.

## 2.4 Limited Success of the 1980s Specification

KDOT's 1980's specifications improved the overall D-cracking performance. On a mileage basis, the Annual Pavement Survey results indicated that the minimum D-cracking failure rate was about 45% in 1980 and 24% in 2010 for projects under 20 years old. On a mileage basis (and not considering projects under 10-years-old in 2009-2010), the new specifications decreased the failure rate from approximately 45% to 24%.

Under the 1980 specifications, 95% of the concrete pavements were expected to last 20 years before D-cracking. The 2010-2012 survey data showed that 95% of the concrete pavements in fact only lasted 11 years. With this data and supporting outside forensic agreement with the results, KDOT decided that with a 24% failure rate and 11-year life for concrete pavement, further improvement was necessary.

Exhibited life can be defined as the minimum (shortest) life of all the “successful” (acceptable) projects for a given acceptable failure rate. In the 2010-2012 study, the observed failure rate was 31%, the youngest age that a project failed under the failure category was 9 years after construction, and the oldest age that a pavement failed was 19 years after construction. The minimum age of the remaining “successful” (acceptable) projects was 20 years (the design life for PCCP in Kansas). This 20-year age represented the exhibited life for a failure rate of 31%. Reversing the analysis, if the failure rate was chosen to be 5% (instead of specifying the design life), then out of the 132 projects included in the study, the 7 projects (5%) with the youngest (minimum) age at failure would be considered “failing” projects and the minimum age of all the remaining “successful” projects was 11 years. Therefore, the current exhibited life for a 5% failure rate (on a project basis) was 11 years.

# Chapter 3: Freeze-Thaw Testing of Aggregate in Concrete: The KTMR-22 Procedure

KDOT instituted prequalification of calcareous stone sources for concrete paving aggregate by testing with KTMR-22, a concrete freeze-thaw test method based on a method developed by the state of Iowa for a similar purpose. KTMR-22 is a modification of the ASTM C666 Method B procedure with the exception that instead of a 14-day lime water cure, the specimens are stored in a 100% relative humidity room for 67 days, then a 50% relative humidity room for 21 days, followed by soaking in 70°F water for 24 hours, and finally tempered in ≤40°F water for 24 hours before taking initial readings and starting the freeze-thaw cycling.

The initial specification requirement in the 1980s was a Durability Factor (DF) of ≥95 and percent expansion (%E) of ≤0.025 at 300 cycles of freezing and thawing. Later modifications of KDOT specifications resulted in the addition of what was thought to be a higher performing class of calcareous stone. The initial specification limits became labeled "Class I" stone and a second classification or "Class II" stone was introduced with higher testing limits of DF ≥97 and percent expansion ≤0.015 at 300 cycles. Concrete paving mixes using Class II stone were allowed to have up to 20% aggregate retained on the ¾-in. sieve while Class I were limited to a maximum of 5%.

# Chapter 4: The 2013 Aggregate Specification Revision

In response to the findings of KDOT's 2010-2012 D-Cracking Study, KDOT changed the specification for concrete paving aggregates in January 2013. The changes are summarized:

## 4.1 Increased the Number of Freeze-Thaw Cycles from 300 to 660

Since KDOT's specifications for On Grade Concrete Aggregate (OGCA) were already a minimum Durability Factor (DF) of 95, the option of tightening the specification requirement was unrealistic. However, the evidence suggested the current method and specifications were not adequately predicting field performance. An alternative option was to increase the number of freeze-thaw cycles for the procedure and material specification. This option allowed minimal disruption to continuous testing using existing equipment and methodology. Weather data analyzed during the 2010-2012 D-Cracking Study showed that Kansas averages 33 hard freeze-thaw cycles per year. The new limit was based on a simple calculation of 33 average annual freeze thaw cycles multiplied by the KDOT expected design life of 20 years.

## 4.2 Replaced "Durability Factor" with "Relative Dynamic Modulus of Elasticity"

Durability Factor (DF) is a term defined in the ASTM C666 procedure. Extending the KTMR-22 testing to 660 cycles resulted in a higher frequency of samples that not only do not meet our materials specifications, but also in samples that perform so poorly that the testing must be terminated before 660 cycles to prevent damage to testing equipment due to disintegrating specimens. Following ASTM's procedure for calculating DF on these failed specimens leads to the reporting of questionable results, and is discussed later.

## 4.3 Changed Reference to "On Grade Concrete Aggregate"

Aggregate specifications for On Grade Concrete Aggregate (OGCA) was differentiated from specifications for Aggregate for Concrete Not Placed on Grade. D-cracking generally occurs in on-grade concrete, applications where the concrete has a drying gradient with one surface exposed to drying and another never fully drying. This method of distinction clarified which products in addition to mainline paving require a higher level of freeze-thaw durability, including curbs, gutters, and sidewalks.

### 4.4 Consolidated Specification to One Paving Class for All OGCA

By extending the testing to more than twice the original number of freeze-thaw cycles, it was not considered necessary to distinguish between multiple classes of concrete aggregates. Any aggregate meeting the new specification ((Relative Dynamic Modulus of Elasticity (RDME) ≥95 and %E ≤0.025 at 660 cycles)) is performing at a higher level than the original specification at 300 cycles, so all on-grade concrete mixes are allowed up to 20% retained on the ¾-in sieve.

### 4.5 Prequalification of OGCA Now Required for All Coarse Aggregate Types

Non-calcareous stone sources have generally been considered to be freeze-thaw resistant. However, during the 2010-2012 study, some river gravel deposits in western Kansas and Eastern Colorado failed extended KTMR-22 testing and field sites containing those materials indicated likely D-cracking. As a result, all aggregate sources currently must meet the same prequalification requirements, regardless of aggregate type.

### 4.6 Attempted Use of Acid Insoluble Residue Testing (KTMR-28) for Pre-Screening Sand-Gravel Sources

KDOT's KTMR-28 acid insolubility test is based on ASTM D3042. During initial extended KTMR-22 freeze-thaw testing, at least one gravel source exhibited poor freeze-thaw durability. This source also exhibited a lower KTMR-28 results as compared to other typical gravel sources. As a result, the revised OGCA specification initially required a 95% minimum acid insolubility result for sand-gravel sources as a screening test prior to freeze-thaw testing. The goal was to expedite the prequalification process, saving on manpower, materials, and freezer space.

For research purposes, all sand-gravel samples continue to be freeze-thaw tested per KTMR-22 for the purpose of collecting data to aid future review of this new requirement. Initial results indicated that seven screening tests on sand-gravel sources contradicted the KTMR-28 requirement. Five samples failed KTMR-28 yet passed KTMR-22 and two samples failed KTMR-22 yet passed KTMR-28. To date, the only source that has failed both the KTMR-22 and KTMR-28 requirements is the first sample that inspired the initial specification limits. As a result, the KTMR-28 requirement for sand-gravel sources has since been rescinded.

### 4.7 Focus on Production Sampling at Concrete Production Sites

The prequalification process for OGCA requires two samples from current aggregate production, consisting of “approved beds” for calcareous sources, be tested according to KTMR-22 and meet the OGCA specification requirements. Approved beds are beds that the producer has been actively working to supply aggregate for KDOT concrete paving projects and that are currently meeting specification requirements. If the beds did not meet previous specification requirements or if the source is a new producer for KDOT, the beds are approved by Ledge Sampling and Evaluation by KDOT’s Bureau of Structures and Geotechnical Services’ Geology Unit.

Continued prequalification for all sources is based on acceptable test results of active production aggregate samples. Previously, the required sampling frequency from each source was one sample for every 20,000 tons produced or a minimum of 3-per-year from any producing source, and one sample from the concrete production site at each project using 5,000 tons or more. The revised requirements for production sampling frequency of each source include one sample per year at the source, once every 5,000 tons from any ready-mix concrete plants supplying to KDOT projects, and once every 20,000 tons from any contractor batch plants supplying to KDOT projects. In addition to acceptable test results, the revised OGCA specification requires sources to demonstrate acceptable field performance when used in on-grade concrete placed on KDOT projects.

# Chapter 5: Impact of On Grade Concrete Aggregate Specification Changes

One of the aggregate sources that had been approved for use in on-grade concrete prior to the January 2013 specification revision was identified through the 2010-2012 Study to be a source that demonstrated poor field performance. Samples of the previously approved beds from that quarry were tested in order to determine their compliance with the new OGCA specification. The results of that test are shown in Figure 5.1.

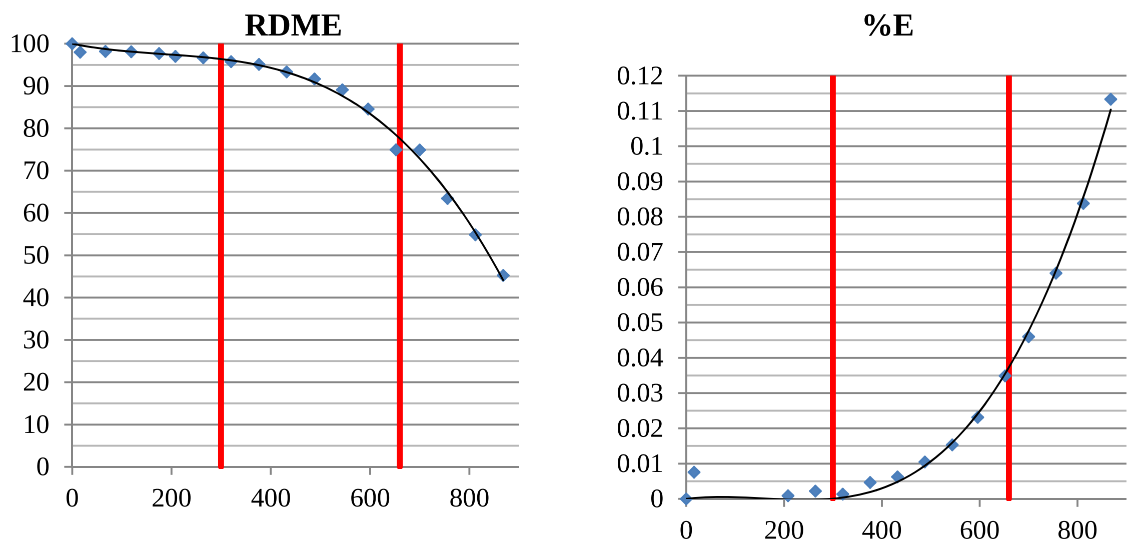



**FIGURE 5.1: Relative Dynamic Modulus of Elasticity and %E Plots for Source with Poor Performance History**

The results for this sample at the old specification limit of 300 cycles were RDME = 96, %E = 0.003 and the results at the new specification limit of 660 cycles were RDME = 77, %E = 0.037. Although the only true measurement of the success of the OGCA specification changes will be future field performance of on-grade concrete constructed with prequalified coarse aggregate sources, test results for this particular source have indicated that the new specification limits are at least a step in the right direction.

# Chapter 6: Challenges Due to Changing Testing and Material Specifications

## 6.1 Durability Factor vs. Relative Dynamic Modulus of Elasticity

### *6.11 Relative Dynamic Modulus of Elasticity (RDME)*

$P_c = (n_1^2/n^2) \times 100$ **(Equation 6.1)**

where:
$P_c$ = relative dynamic modulus of elasticity, after *c* cycles of freezing and thawing, percent,
n = fundamental transverse frequency at 0 cycles of freezing and thawing, and
$n_1$ = fundamental transverse frequency after *c* cycles of freezing and thawing.

### *6.12 Durability Factor (DF)*

DF = PN/M **(Equation 6.2)**

where:
DF = durability factor of the test specimen,
P = relative dynamic modulus of elasticity at *N* cycles, %,
N = number of cycles at which *P* reaches the specified minimum value for discontinuing the test or the specified number of cycles at which the exposure is to be terminated, whichever is less, and
M = specified number of cycles at which the exposure is to be terminated.

KDOT has defined the test parameters as follows:
N = lesser of 660 or cycles where either $P \leq 60$ or $\%E \geq 0.100$
M = 660 cycles

One of the first obstacles to performing this calculation correctly is that ASTM C666 provides no guidance for interpreting the collected data. The procedure requires recording measurements at intervals not to exceed 36 cycles. Therefore, the data will be represented by points on a plot of RDME or %E vs. number of cycles. Areas where guidance is lacking are:

- If the test is completed at X number of cycles with a result that is within the criteria for testing termination; (i.e., not showing excessively low RDME or excessively high %E), is the result a straight line interpolation between the points that surround M?

- Should all the points be fitted with a line or polynomial that is then used to interpolate the result at M?  The method KDOT has used since the January 2013 revision to the OGCA specification is to fit the data points with a polynomial (typically third order or higher) and use the equation of the polynomial to calculate the RDME or %E at 660 cycles.
- An additional obstacle is that there is no direction for correcting %E results if testing is terminated early.

When a third order or higher polynomial is used to graph results for a sample that performs significantly poorly during the test, it becomes apparent that the ASTM C666 calculation for DF assumes a linear relationship between RDME and number of cycles which has significant effect on the final result. This is illustrated in Figure 6.1.

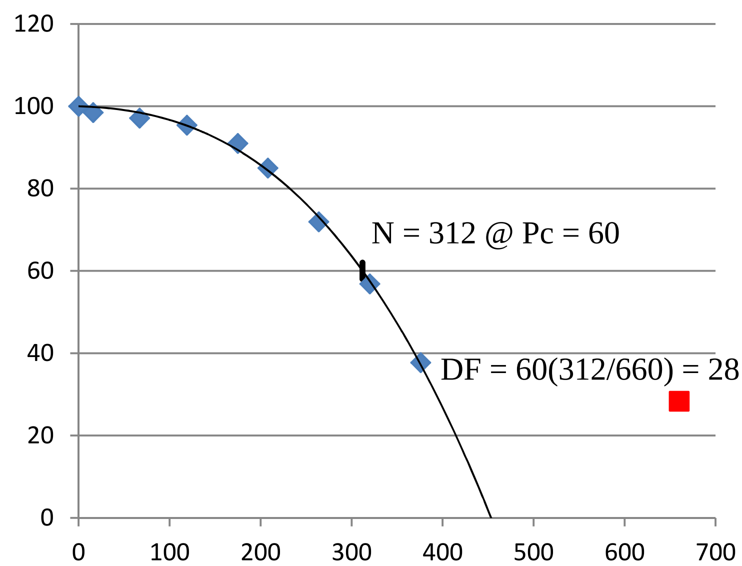



**FIGURE 6.1: Durability Factor vs. Relative Dynamic Modulus of Elasticity**

Figure 6.1 contains data points from an aggregate sample that was tested in KDOT's laboratory. The test data points, when connected using a third order polynomial, indicate the RDME at 660 cycles to be less than zero. While the validity of reporting a zero value versus a negative value for the result of this test could be argued, it is clear that reporting a result above zero at an M of 660 cycles would be incorrect. However, ASTM C666 would have the results of this particular test be reported as DF = 28, even though the point of 28 at 660 cycles clearly falls far from the plotted curve.

The extended freeze-thaw testing that KDOT has performed has shown similar evidence on many failing samples. The end result, regardless of method used, will not vary the prequalification of the source because this only becomes an issue when the sample has significantly failed the specification requirements and is terminated prior to 660 cycles. However, KDOT's concerns are surrounding the issues of proper terminology in test reporting and accurate data collection for historical and analytical purposes. Therefore, KDOT's OGCA specification references RDME instead of DF.

### 6.2 Relationship between Relative Dynamic Modulus of Elasticity and %E

So far, KDOT has performed over 230 KTMR-22 procedures at the new specification limit of 660 cycles of freeze-thaw. Figure 6.2 shows each test that has completed at the time of this publication plotting the average %E vs. the average RDME for each set of three specimens. The graph suggests there is sufficient correlation between increasing percent expansion and decreasing RDME and less than 8% of our samples have fallen in the quadrants of the graph where the sample is meeting one part of the specification requirements yet failing the other with respect to percent expansion and RDME (quadrants II and IV).

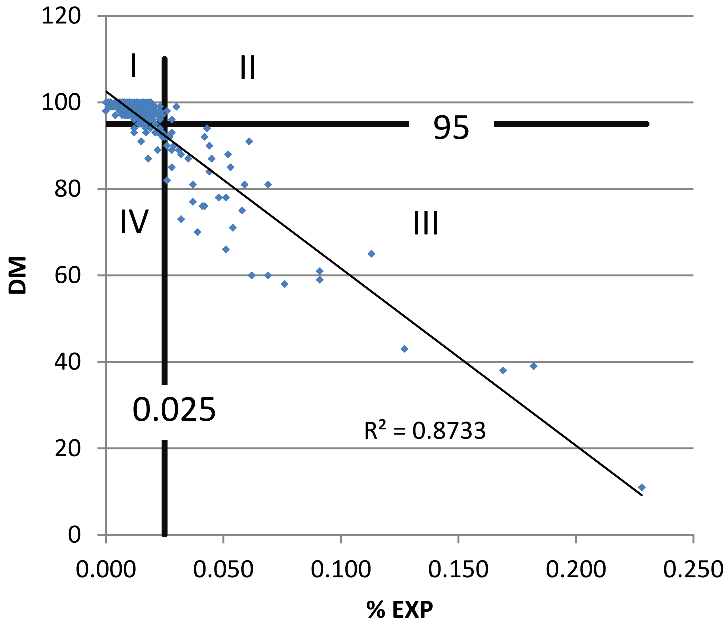



**FIGURE 6.2: %E vs. Relative Dynamic Modulus of Elasticity**

Even with a small percentage of the testing population falling into quadrants II and IV, there is still concern regarding how KDOT will react to such test results, especially when they are seen from sources that have some established history of meeting the KTMR-22 requirements.

One recent production sample from a dolomite source that is prequalified to supply OGCA in Kansas has demonstrated substantially high RDME values, yet did not meet the specification requirement for percent expansion. The results from this sample are shown in Figure 6.3.

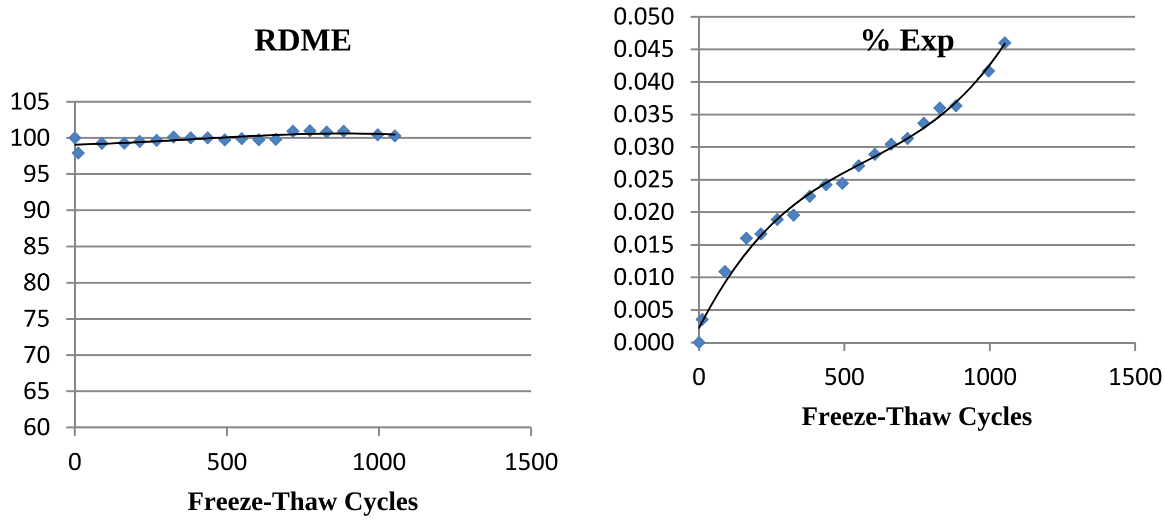



**FIGURE 6.3: Relative Dynamic Modulus of Elasticity and %E Plots for Recent Dolomite Sample**

One of the three prisms from this sample was removed and examined after measurements were collected at 661 cycles. The examination was performed by Randy Billinger, P.G., KDOT Research Geologist. Mr. Billinger's findings are summarized as:

> *I have looked at prism B and cannot definitively determine why the prism is failing expansion. The prism looks good. There is no external damage except for one pop out. We have cut the prism in many places and have looked at 12 internal surfaces (7 polished and 5 unpolished). I do not see any micro or macro cracking in the paste. I do not see any paste issues. The paste-aggregate bond is moderately tight to tight.*
>
> *The air void system is good. Total air is 7.3%, spacing factor is 0.11mm and specific surface is 31.71 mm2/mm3 (this number should be between 25 to 45 mm2/mm3).*
>
> *The aggregate does not appear to be cracking. There are some pieces that have what appear to be cracks, but I think most of these are part of the aggregate itself and were in the aggregate when it went in the mix. To investigate this, I took pieces of aggregate from this source that I have in the lab and polished about 40 pieces. Some of the aggregates show the same type of cracking as seen in the aggregate in the prism. The aggregate is very crystalline and I think the cracking seen is mostly within the rock as it sits in the outcrop. However, there may be some cracking being caused by freeze-thaw, I just cannot prove and state that at this time. Of the aggregates that show some type of crack, I don't see any cracks exiting the aggregate and cracking into the paste.*
>
> *As stated, the aggregate is crystalline and many of the pieces have numerous voids/mineral lined vugs in them. Vugs are cavities (in this case small cavities*

*with visible crystals in them). The porous nature of many of the aggregates may have something to do with the unusual expansion numbers. However, I just don't see positive evidence of freeze-thaw damage in the aggregate.*

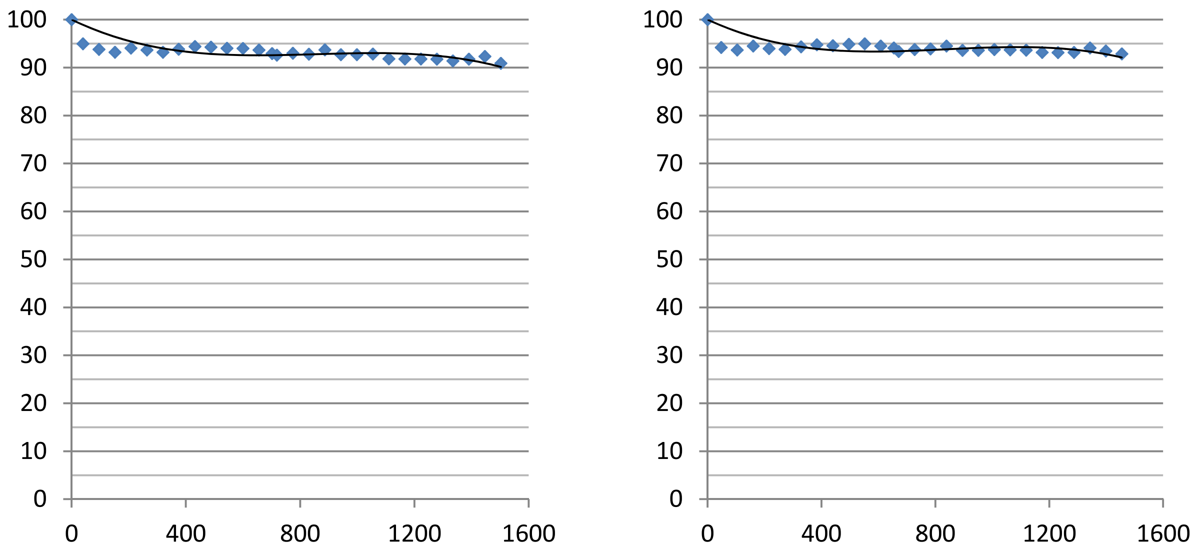
*I am not seeing any ASR or ACR at this time.*

The remaining two specimens are still being tested at the time of this publication and have undergone well over 1100 cycles of freeze-thaw. They still show little to no surface evidence of deterioration and have relatively high RDME with relatively high percent expansion. These prisms will be removed once they begin to show visible deterioration on their surfaces or at a time that the space they are occupying in the freezer is critically needed for ongoing production testing. At that time they will also be examined by Mr. Billinger and hopefully provide better evidence of the cause behind their unusual behavior.

Until the testing on this sample is terminated and, more likely, until KDOT sees similar results from additional samples in the future, it will be difficult to predict the changes that will be made to the OGCA specification. This sample may end up being an outlier that can never be fully explained. However, in the meantime, samples that exhibit non-typical test results may need to be examined for physical evidence of freeze-thaw related distress prior to publishing test results that could adversely affect a source's prequalification. Also, if additional evidence suggests that percent expansion is less accurate at predicting true freeze-thaw durability of the aggregate, the specification limit for percent expansion may either need to be revised or removed.

## 6.3 Unusual Relative Dynamic Modulus of Elasticity Results

One particular source has on multiple occasions exhibited unusual behavior. Two samples from this source have both showed similar results where the early measurements, taken after fewer than 50 freeze-thaw cycles, resulted in RDME results at or just below the specification limit; however, after more than 1500 cycles of freeze-thaw, the overall decrease in RDME after the initial freeze-thaw exposure was four or less. Results of the samples are shown in Figure 6.4.




(A) (B)

**FIGURE 6.4: (A) Sample 3037 (B) Sample 3039**

Again, more than two hundred and thirty samples have been freeze-thaw tested to greater than 660 cycles. Of those, only four samples have shown an RDME result that was less than 4 points from the RDME calculated after the first round of freeze-thaw cycles. Those results are summarized in Table 6.1.

**TABLE 6.1: Unusual Relative Dynamic Modulus of Elasticity Results**

| Sample | Initial Exp | Initial RDME | Initial Cycles | Result Exp | Result RDME | Difference Initial - 660 | Final RDME | Final Cycles | Difference Initial – Final |
|---|---|---|---|---|---|---|---|---|---|
| 2775 | 0.000 | 96 | 128 | 0.015 | 93 | 3 | 88 | 1048 | 8 |
| 2978 | 0.009 | 95 | 16 | 0.021 | 94 | 1 | 93 | 824 | 2 |
| 3037 | 0.011 | 95 | 40 | 0.024 | 94 | 1 | 91 | 1503 | 4 |
| 3039 | 0.013 | 94 | 48 | 0.016 | 95 | -1 | 93 | 1511 | 1 |

It should be noted that the %E for all four samples in Table 6.1 met the OGCA specification requirement. The samples in Table 6.1 represent less than 2% of the population of test results generated to date. It is intriguing that one source has supplied 50% of that small population and that both of those samples exhibited a drop in RDME of four or less over a span of 1,463 cycles.

At the time of this publication, samples 3037 and 3038 have been the only two samples from that source that have been tested beyond 660 cycles. Both sets of specimens have been retained for analysis by KDOT's Research Geologist but at the date of this publication, the examination has not yet been completed. Future samples from the same source will be closely monitored for a similar trend.

It will again be difficult to predict how this information will affect future testing or specification limits. Analysis of the 3037 and 3039 specimens will play a critical role in the future for determining the prequalification status of this source. If the specimens show no signs of aggregate related distress and future samples from this source exhibit similar performance, it is possible that KDOT may have to consider additional specification criteria such as waiving the 660 cycle requirements if additional, slightly more relaxed, criteria are met at a significantly higher number of freeze-thaw cycles.

## 6.4 Length of Test Procedure

The 90 day curing period combined with extending the freeze-thaw cycles to 660 has resulted in a test procedure that takes about six months to perform, once the concrete prisms are molded. Any backlog of samples or other delays in schedule only exacerbate this issue. Many concrete paving projects are completed in six months, which will limit the recourse KDOT will have if a sample collected during production of concrete on a project fails.

There is ongoing research being conducted as a joint effort between KDOT and Kansas State University to find ways to accelerate the schedule of the KTMR-22 test without negating all of KDOT's historic test results. However, this research is still relatively young and it will be some time before KDOT is in a position to adopt any significant changes to the KTMR-22 procedure.

## 6.5 Conflicting Test Results

Since the revised OGCA specification places more emphasis on sampling production aggregate at the concrete plant site and requires different sampling frequencies for the aggregate source, contractor plants, and ready-mix plants, it is likely that at some point in the future a source will have multiple samples being tested at or around the same time. Should a series of KTMR-22 test results demonstrate variable results where some pass and some fail the specification requirements, it will present a challenge for KDOT to determine a best course of action in terms of maintaining or revoking that source's prequalification status.

# Chapter 7: Conclusions

KDOT has a history of D-cracking pavements and significant efforts, including five extensive studies into the phenomenon of D-Cracking, have been made to mitigate the problem. Past changes in quarry production observation and QA/QC programs appear to have had some effect on the quality of pavements produced; however KDOT recognized that with the desire for longer lasting pavements, modifications to past testing of aggregate freeze-thaw durability are required to assess aggregate sources and achieve a longer exhibited pavement lives. As a result of the 2010-2012 study, KDOT has implemented significant changes in aggregate source testing requirements to further mitigate the risk of D-cracking. The current specifications require extended freeze-thaw testing with the specified number of testing cycles far exceeding other known DOT requirements. D-cracking is still a problem in Kansas today; however, modified testing and aggregate approval based on acceptable long-term freeze-thaw behavior is a step in the right direction toward extending anticipated pavement life.

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