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D-Cracking Field Performance of Portland Cement Concrete Pavements Containing Limestone in Kansas: Phase 1 Report

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Kansas Department of Transportation
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16 Abstract

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The results indicate that the failure rate has decreased, but not to an acceptable level. Limestone source material appears to be the dominant parameter affecting D-Cracking, while other design parameters, such as base type, joint sealant type, joint spacing, and joint orientation do not appear to significantly affect the presence of D-Cracking. Subsidiary aggregate-related reaction mechanisms were observed at locations with surface D-Cracking likely due to the increased amount of water penetration. The subsidiary reactions generally do not appear to be present at locations away from the D-Cracking.

Kansas Department of Transportation policies (any actions, requirements, or decisions) that affect the risk of D-Cracking were reviewed. Recommendations included implementation of field performance criteria for aggregate material sources, improvement and unification of quarry monitoring and sampling procedures, to perform life-cycle cost analyses for various aggregate materials in concrete, and future monitoring of quarry field performance.

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Final Report

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KANSAS DEPARTMENT OF TRANSPORTATION
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NOTICE

DISCLAIMER

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Abstract

Premature deterioration of concrete pavement due to D-cracking has been a problem in Kansas since the 1930s. Limestone is the major source of coarse aggregate in eastern Kansas where the majority of the concrete pavements are constructed. D-cracking field performance was investigated to determine whether aggregate freeze-thaw durability specifications implemented in the 1980s have reduced materials-related failures to an acceptable level.

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Chapter 1: Introduction

Deterioration of concrete pavements due to D-cracking has been a problem in Kansas since the 1930s. It is generally recognized that freeze-thaw deterioration of non-durable limestone coarse aggregate is the cause of D-cracking (Stark 1976; Stark and Klieger 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; Wallace 1990). Multiple studies investigating the causes and prevention of D-cracking have been completed in Kansas over the past 80 years (KDOT and FHWA 1990; Wallace 1990; Gibson 1941; Scholer 1928; Bukovatz et al. 1973; Myers and Stallard 1978; Montney et al. 2008). Findings from these and other studies were the basis for the decision by the Kansas Department of Transportation (KDOT) to implement durability requirements for the limestone aggregates used in concrete. The KDOT Standard Specification Section 1102 Aggregates for Concrete requires the prequalification of limestone coarse aggregate materials by freeze-thaw testing with the intent of preventing D-cracking before 20 years.

This study investigates the D-cracking field performance of Portland Cement Concrete Pavements (PCCP) containing limestone in Kansas built under the current specifications, with the ultimate goal of increasing concrete pavement life in Kansas. Phase 1 of this study focuses on evaluating the success of the current aggregate durability specifications (implemented between 1981 and 1987) and whether KDOT pavements constructed under the specifications are achieving the intended 20-year design life (Miller and Bellinger 2003). This was completed by conducting field-performance evaluations, determining the rate of success, and comparing the results with materials, design, and environmental parameters. Phase 2 investigates methods to extend the life of concrete pavements in Kansas. A future Phase 3 could focus on determining the extent and severity of D-cracking damage, as well as monitoring the rate of deterioration of D-cracking pavements over time.

1.1 What is D-Cracking?

D-cracking is concrete pavement distress due to freezing and thawing of water-saturated aggregates, cracking the aggregate particles and progressing through the slab (Neville 2000;

Mindess et al. 2003; American Concrete Institute 2008). Cracked aggregate particles distinguish D-cracking from other material-related distress. For other types of materials- or loading-related distress, cracks are generally located in the cement paste and form around the aggregate particles, not through them.

D-cracking in concrete pavements is most frequently identified symptomatically, by observing the distress at the surface of the concrete. Typically D-cracking of a concrete slab manifests itself on the surface of the concrete as closely spaced, crescent-shaped hairline cracks occurring adjacent to and following along joints, cracks, or free edges (KDOT 2007). The surface cracks begin primarily at the intersection of joints (slab corners) and follow the joints as the condition progresses, until eventually all joints and ultimately the entire slab are affected. In advanced stages of D-cracking, only rubble is found when penetrating a joint because no solid concrete remains.

1.2 Significance of D-Cracking

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

1.3 Aggregate Durability

The primary coarse aggregate in eastern Kansas is limestone. KDOT aggregate durability specifications are based on initial inspection of the quarry by geologists, sampling and testing of aggregate materials for prequalification, as described later in section 5.12 of this report. The resistance of a limestone material to freeze-thaw damage is initially tested according to KTMR-21 Soundness and Modified Soundness of Aggregates by Freezing and Thawing. Concrete beams containing 50% limestone are then cast, conditioned, and subjected to 300 cycles of freezing and thawing according to KTMR-22 Resistance of Concrete to Rapid Freezing and Thawing, a test similar to ASTM C666. Testing by ASTM C666 generally includes 300 or 350 cycles of freezing and thawing. KDOT specifications define Class 1 and Class 2 aggregates as those that meet the durability factor (DF), percent expansion (%EXP), and soundness requirements shown in Table 1.1 Once approved, production samples are regularly tested and must meet the testing requirements. All on-grade concrete is constructed using only Class 1 or Class 2 aggregate.

TABLE 1.1
KDOT Specification Limits for Limestone Aggregate for Concrete

	Class 1	Class 2
DF (min.)	95	97
%EXP (max.)	0.025%	0.015%
Modified Soundness (min.)	0.85	0.85

1.4 Previous Work

Significant work has been completed by KDOT to understand the causes and extent of D-cracking in Kansas concrete pavements. Much of the focus has been on the limestone coarse aggregate. Other parameters may affect the rate of D-cracking development but, as mentioned previously, it is widely accepted that limestone coarse aggregate is the major contributing parameter to D-cracking deterioration. This section provides a brief outline of the research studies completed in Kansas and some background on the development of the KDOT limestone aggregate durability specifications.

1.4.1 Previous Studies in Kansas

Four D-cracking surveys have been conducted on Kansas highways, in 1944–45, 1951–52, 1964–65, and 1980. The first three studies were conducted on approximately 1200 miles of 24 ft wide concrete pavement. The fourth study included 279 miles of 24 ft wide concrete pavement, representing approximately 39% of the concrete pavement on the state highway system.

The first three surveys, in 1944–45, 1951–52, and 1964–65, used similar rating systems reporting a rating of "good" if 0%–12% of the pavement panels (one in eight panels) were D-cracked. If 13%–50% of the panels were D-cracked the pavement was rated "fair." If more than 50% of the panels were D-cracked the pavement was rated "poor." The 1951–52 survey combined the "fair" and "poor" ratings into one category. The comparison in Table 1.2 shows that the first three surveys all indicated improvement in the D-cracking field performance. The 1980 survey used a system from 0 to 10 to rate the level of D-cracking. Any rating above 0 exhibited some level of D-cracking. The ratings were then grouped into "good" (0–3), "fair" (3.1–6), and "poor" (6.1–10). For all four surveys, a pavement rating of "good" did not mean that there was an absence of D-cracking. Rather, it simply meant that the level of D-cracking was acceptable at the time.

TABLE 1.2
Comparison of Results from the First Three D-Cracking Surveys Conducted in Kansas

Comparison of First Three Kansas Surveys				
		Year		
Rating	**Description**	**1944–45**	**1951–52**	**1964–65**
Good	1 in 8 panels or fewer D-cracked	54%	65%	74%
Fair	Between 1 in 8 and 1 in 2 panels D-cracked	8%	*	8%
Poor	More than 1 in 2 panels D-cracked	38%	*	18%

* Only rated as good or "otherwise"

The first four surveys were also conducted on pavements containing any coarse aggregate, all joint spacings were 61.5 ft, and percentages were based on 24 ft wide roadway miles.

The 1944–45 survey indicated that most of the D-cracking was associated with limestone from the Argentine, Ervine Creek, Plattsmouth, and Stoner members. The maximum size of coarse aggregate in paving mixes was reduced from 2 inches to 1 inch based on recommendations from this investigation. This first survey included only bare concrete pavements constructed between 1919 and 1945 (0–25 years old). Age was not considered as a parameter when evaluating these pavements. It is unknown what percentage of the pavements constructed during that time period had already been overlaid.

The 1951–1952 study again identified the Ervine Creek, Plattsmouth, and Stoner members as major contributors to D-cracking. The survey included concrete pavements constructed between 1919 and 1949 (3–31 years old) and overlaid pavements constructed between 1919 and 1937 (15–33 years old). Some of the pavement had been overlaid with asphalt. The age of pavement was identified as a parameter, with the older pavements receiving the poorer ratings.

The 1964–1965 survey was initiated because D-cracking was noticed in pavements that were less than five years old. The survey was conducted on bare concrete pavements constructed between 1921 and 1964 (1–44 years old). Overlaid pavements were not included in the survey. The survey concluded that all limestone aggregate produced from members in Kansas were associated with D-cracking. The survey considered age and percent of limestone as parameters in causing D-cracking. Pavements with less than 35% limestone had less D-cracking than pavements with over 35% limestone of the same age. In general, older pavements received poorer ratings than younger pavements with the same percentages of limestone, and some pavements less than five years old receiving poor ratings.

A fourth survey was initiated in 1980 as an effort to respond to the Federal Highway Administration's refusal to participate in concrete paving in Kansas until the D-cracking problem was adequately addressed. The survey included pavements constructed between 1961 and 1974 (6–19 years old), and correlated quarry source with pavement performance. As with the previous surveys, this survey was conducted on bare PCCP. As described previously, a rating system from 0 (no D-cracking) to 10 (extreme D-cracking) was used to rate the pavements. All pavements with ratings above 0 exhibited some D-cracking. The rating incrementally increased above 0 depending on width of the affected area and extent of the joint spalling. Results from the 1980 survey showed that of the pavements surveyed, 29% exhibited D-cracking, all failures as defined by the current study. The report estimated that 40% of the pavements constructed between 1961 and 1974 (6–19 years old) had been overlaid before the 1980 survey (Marks and Dubberke

1982). Therefore, an estimated 57% of all the pavements constructed during this time period were either overlaid or exhibited D-cracking before 20 years. The remaining 43% in the study were less than 20 years old and did not exhibit D-cracking at the time of the survey.

The first four surveys concluded that all limestones in Kansas are susceptible to D-cracking, and once D-cracking begins it cannot be stopped.

1.4.1.1 Differences between the Current Study and Previous Studies

For the 2009–2010 survey, pavements were evaluated simply to identify the presence or absence of D-cracking. If D-cracking was found on a pavement then the project was rated as "Yes" and all other projects were rated as "No." Any pavement that had been removed and replaced due to D-cracking was rated "Yes" and the year the D-cracking was discovered was recorded. If overlaid pavements were D-cracked at the time of the overlay then those projects were rated "Yes," and the year D-cracking was observed was recorded; otherwise overlaid pavements were rated "No" in 2010. If a pavement did not exhibit D-cracking and was less than 20 years old, then it was rated as "Inconclusive" because it had not yet reached the design life. Severity was not measured and, although observed, other forms of deterioration were not reported.

The previous surveys were conducted on Portland Cement Concrete Pavements with a 61.5 ft joint spacing. The joint spacings on the pavements evaluated for the 2009–2010 survey were 15 ft and 30 ft with the majority having 15 ft joint spacing. The increase in the number of joints may increase the opportunity for D-cracking as compared to the 61.5 ft joint spacing because the number of joints increases for a given length of pavement. However, Meyers and Stallard (1978) reported that shorter joint spacing may decrease the incidence of D-cracking.

Other differences between the current study and previous studies include the type of coarse aggregate and age. The previous surveys were conducted on only bare pavements constructed within the given timeframes and included some pavements that were less than five years old, and regardless of the aggregates used. The current study was conducted on only the pavements that contained limestone, met specified criteria for length and location, and included pavements that had been overlaid. The current survey only included pavements that were 10 years old or older with the exception of four projects.

1.4.2 Other States

Acceptance criteria for coarse aggregate in PCCP were reviewed for thirteen state DOTs in the Midwest. Table 1.3 shows that five states used performance history of an aggregate source in concrete pavements as an acceptance criterion. Four of the five states with performance criteria (Indiana, Minnesota, Nebraska and Wisconsin) allowed the rejection of aggregates based on pavement performance as one of a number of criteria, including test results, the nature of the deposit, and the behavior of the rock under natural exposure conditions. Iowa was the only state to use performance history as the primary criterion for the acceptance of aggregate in PCCP. Iowa was also the only state to use specific performance criteria for multiple levels of durability classification with the highest level allowing no deterioration on interstate pavements for 30 years of service and less than 5% deterioration of joints after 35 years.

TABLE 1.3
Aggregate Performance History Evaluation Statements from Midwestern DOTs.

State	Specification Number	Performance History Evaluation Statement
Colorado	703.02	No
Illinois	1004.02	No
Indiana	904.03	Coarse aggregate may be rejected based on previous performance service records.
Iowa	4115.01 Materials IM 409	Approval by Service History: Aggregate will be considered durable when it does not contribute to the premature deterioration in concrete. Durability classes will be assigned on the basis of qualifying performance in air-entrained pavements of appropriate age.
Michigan	902.03	No
Minnesota	3137	To determine the suitability of any aggregate, the Engineer may consider the results of laboratory tests, the behavior of the rock under natural exposure conditions, the behavior of Portland Cement Concrete in which aggregate from the same or similar geological formations or deposits has been used, or such other tests or criteria as may be deemed appropriate.
Missouri	1005	No
Nebraska	1033.02	Aggregate shall be evaluated based upon its past performance in concrete pavement and in laboratory test results.
North Dakota	816.02	No
Ohio	703.02	No
Oklahoma	701.06	No
South Dakota	820.1	No
Wisconsin	501.2.5.4.3	The department may prohibit using crushed stone from limestone/dolomite deposits having thinly bedded strata, or strata of a shale nature; it may also prohibit using aggregates from deposits or formations known to produce unsound material.

1.4.3 KDOT Design and Maintenance History

Design parameters are examined in the current study. The following items represent some of the changes in KDOT pavement design over time.

1.4.3.1 Joint Design

Previous to 1978 KDOT's design standard included dowel-jointed reinforced (wire mesh) concrete with 61.5 ft joint spacing and hot pour joint sealants. In 1978 the joint spacing was decreased to 15 ft non-reinforced and the joints were skewed joints. Most projects were constructed with this design through 1990, but some interstates were constructed with 30 ft reinforced perpendicular joints. From 1980 to 1990 KDOT constructed concrete pavements with both 15 ft skewed and 30 ft perpendicular joints. Thirty-foot joint spacings were mostly used until 1992, with two additional projects in 1996. From 1990 to the present, 15 ft perpendicular joints have been constructed.

1.4.3.2 Bases

Prior to 1980, granular base was used in Kansas. Portland Cement treated bases were constructed from 1980 to the present. Bound drainable bases were also constructed from 1989 to 2001.

1.4.3.3 Subgrade

Lime-treated subgrades were used previous to 1961 through the present (where needed) to mitigate swell-potential of the soils.

1.4.3.4 Joint Sealant

Hot pour with backer rod was used to seal joints until about 1987. Silicone joint sealants were predominantly used from 1983–1994. The joint sealant policy changed in 1994 with the special provision 90P-0077-R09, eliminating silicone as a joint sealant. This special provision was dated July 6, 1994 with a let date of January 1995, and KDOT has used, nearly exclusively, neoprene since. In 2010 a new alternate design was adopted to allow unsealed joints cut at narrow width.

1.4.3.5 Patching

KDOT's standard full-depth patching specification for joints includes a 6 ft wide patch, with 3 ft on each side of the joint. Replacing one out of every two joints, or 50% of the joints, constitutes 5% of the surface area of a concrete pavement with 61.5 ft joint spacing (6 ft out of 120 ft). Economically, 5% of the surface area of a pavement represented the maximum amount of patching with a thin overlay. If the patching was greater than 5% of the surface area (50% of the joints), then no patching was done and a thicker overlay was constructed instead. This continues to be the policy for KDOT.

1.5 Objective and Scope

This study provides a 20-plus year follow-up to the implementation of aggregate durability specifications on the D-cracking field performance of PCCP built in Kansas under the current specifications and containing limestone. The ultimate goal is to increase concrete pavement life in Kansas. The focus is to evaluate the success of current aggregate durability specifications (implemented between 1981–1987) and whether pavements constructed under these specifications are achieving the intended 20-year design life (KDOT 2007). One hundred and thirty-three field performance evaluations were conducted on PCCP projects, representing 73% of the length of the current concrete state highway system in Kansas, determining the rate of success, and comparing the results with aggregate source parameters. Results indicate that nearly one-third failure rate in preventing D-cracking before 20 years and that a limited number of quarries were linked with a high percentage of the failures. The required testing did not fully predict failure, but it did reduce the rate of failure. KDOT policies and practices were reviewed, with several identified as increasing the risk of D-cracking.

Chapter 2: Methods

Significant efforts were made to systematically identify the pavements to be included in this study, measure the field performance, and gather accurate construction data for each project. Significant efforts were made to identify the pavements included in the study, measure pavement field performance, and gather the appropriate and accurate historical data from over 25 sources regarding these pavements including aggregate source and testing data. Because the results could have a negative economic effect on a quarry operation, the benefit of the doubt was routinely given to the aggregate material source (quarry) if there remained any question as to the results. Therefore the results, from an owner’s (not a supplier’s) perspective, are conservative and may not reflect the full nature of the problem. In other words, the true failure rate is likely higher than shown in this study.

Criteria were developed to identify concrete paving projects to be included in the study. The purpose was to minimize variability of design and construction parameters and to support the proper population of pavements was considered. Over 400 projects were compared to the criteria and 133 projects met the criteria and were included in the study. The list of projects was cross-checked with the state highway inventory database, the Control Section Analysis System (CANSYS), the Pavement Management System (PMS) database, and was reviewed by district personnel. Field performance surveys were completed for each of the 133 projects to identify D-cracking. Historical data for each project, including design, materials, testing, and construction information was gathered.

In general, discussion of this survey is based on both a project-basis and on a lane-miles (12 ft wide and 1 mile long) basis. Project-basis is used in the analysis for success/failure rates because each parameter considered (limestone source, joint spacing, base type, etc.) represents a “decision” made for the project, regardless of the length and scope of the project. Lane-miles are used for comparison to previous surveys and to estimate the cost of the damage on the current system.

2.1 Sources of Data

Various sources were utilized to gather information about each of the projects included in this study. Construction records were utilized to determine dates, age, and quarry source information and districts were contacted to confirm the information. At times, sources did not agree and determining the accurate and appropriate data was a complex and demanding task. All efforts were made to provide accurate data, but no guarantees are given or implied.

The following is a list of resources used to gather information for this study:

- CMS
- Concrete Research Core Reports[†] (paper)
- Concrete Research Core Reports Database[†]
- Strip Maps
- Quarry Source Files (paper)
- Ledge Files (paper)
- Production Database[†]
- Durability Database[†]
- Video Log
- Network Optimization System (NOS) Survey
- Original Plans
- As-built Plans
- K-Gate
- WINCPMS
- Research files for special projects (paper)
- District Personnel
- M&R Personnel
- Google Maps
- Industry Representatives
- Historical Photos
- Receiving Diaries[†]
- Completed Rehabilitation Forms[†]
- Quarry Inspection Files
- Construction Files
- HYNERES (CANSYS Blackbook)

[†] Information from this source is contained within Laboratory Information Management System (LIMS)

Pavement condition information from the annual Network Optimization Survey (NOS) was not utilized for this study. There was concern that the results for the NOS Joint Distress rating were not detailed enough for the purposes of this study. The NOS survey is completed from inside a slow moving vehicle. The crew may not adequately see the level of D-cracking in this study.

Record keeping for KDOT is generally focused on tracking the completion of a construction project and contractor payment. The data management systems are designed with these purposes in mind. Historical record keeping for the purpose of tracking performance of different types of pavement has not been a goal for KDOT. As a result, the KDOT data management systems are often not easy to “mine” for research purposes.

KDOT needs to solve the problem of storing and accessing historical construction information about the Kansas state highway system. Data management systems should be taken seriously and considered carefully by KDOT. District construction personnel should be trained and required to accurately record information in all information management systems. It may be necessary for Materials and Research staff to provide ongoing support to the districts to enhance accuracy of information documentation.

2.2 Project Selection

Criteria were developed for the selection of projects included in the 2009–2010 D-cracking survey to identify concrete paving projects representative of the KDOT highway system and of the implementation of the aggregate durability specifications. This also minimized variability of design and construction parameters. The criteria support the objective of evaluating the KDOT aggregate specifications and the resulting performance of the concrete over time.

The intent of the criteria was to include all major mainline concrete pavements containing limestone that are older than 10 years. The aggregate durability specifications were implemented in 1981 (80P-103) with initial aggregate testing beginning as early as 1980. By 1987, all concrete pavements constructed were constructed under the new specifications. The intended structural design life for new pavements is 20 years before first rehabilitation action. Any materials-related distress (D-cracking) before 20 years indicates failure.

Specifically, the criteria for project selection include mainline concrete pavements containing limestone, that were more than 10 years old in 2010 (constructed between 1979 and 2000), more than 1 mile in length, and were still on the Kansas state highway system. Only mainline projects were included, excluding bridge approaches, ramps, rest areas, shoulders, and all other non-mainline PCCP. Pavements within city limits were excluded except for those within the major metropolitan areas of Kansas City, Wichita, and Topeka metro areas that met all the other criteria. Concrete projects that were overlaid were also included with an attempt to document whether D-cracking was present at the time of the overlay. The one-mile minimum length limit and the exclusion of projects within city limits served to attempt to restrict the pavements to contractor operated concrete batch plants only. Concrete delivered from a Ready-Mix plant has more opportunity for unacceptable material being included in the concrete simply because various coarse aggregates are available at a Ready-Mix plant. A contractor operated batch plant for paving jobs in Kansas typically handle only the coarse aggregate approved for use on that job. Projects that were overlaid were also included with an attempt to document whether D-cracking was present at the time of the overlay. Three projects were not included in the study because the aggregate source could not be determined. Three projects were included with a construction date of 2001 and one in 2002. After the analysis was completed it was determined that these four projects had construction dates of 2001 and 2002 instead of 2000. Since all four of the projects exhibited no D-cracking, they were left in the analysis. The effect on the analysis success/failure described in Section 3.0 was approximately 1.0%.

In summary, the project criteria included:

1. Contain limestone
2. Minimum of 10 years old (constructed between 1979 and 2000)
3. On the Kansas state highway system
4. Mainline pavement only. Exclude intersections, bridge approaches, ramps, rest areas, shoulders, and all other non-mainline pavement.
5. Length is greater than or equal to 1 mile
6. Exclude pavements within city limits except for Kansas City, Wichita, and Topeka

Over 400 concrete paving projects were compared to the project selection criteria and 133 projects, representing approximately 2,177 lane-miles, were selected to include in the study. For comparison, the KDOT system currently has approximately 3,173 lane-miles of bare concrete pavements. The project list was cross-checked with the state highway inventory database, the Control Section Analysis System (CANSYS), the Pavement Management System (PMS) database, and was reviewed by district personnel. The projects meeting the study criteria are identified in Appendix A, Table A.1. Eighteen of the projects, 14% (248 lane-miles, 11%), were overlaid prior to the field surveys. The overlaid projects are identified in Table A.6.

2.3 Aggregate Source

The source of limestone coarse aggregate was determined using various resources described in Section 2.1. The quarry number, location, geological classification (geoclass), and beds used were determined. Several of the study projects contained material from more than one quarry. In these cases, the location of each material was determined through construction records and the field performance of each project segment was matched with the corresponding quarry source. This was done to avoid associating a quarry with D-cracking unless it was documentable.

2.4 Weather

Twelve years of weather data was extracted from KDOT's Road Weather Information System (RWIS) for 68 sites across Kansas. The data was analyzed to examine the potential effects of variation in regional Kansas climates (freeze-thaw) on D-cracking, and also to estimate the typical annual number of freeze-thaw cycles. Sixty-eight RWIS sites were active (had data) for some portion of the period from 1998 to 2010. The maximum pavement surface temperature (sensor 0) for each day was compared to the minimum temperature for the next day. If the maximum temperature was above 32°F and the minimum for the following day was below 32°F, then it was considered to be one freeze-thaw cycle. Hard freeze-thaw cycles were also determined for the cases when the maximum was above 32°F and the minimum was below 24°F.

The results for the average number of regional (each weather station) 32°F freeze-thaw cycles indicate large overall variation, with values ranging from 40 to 111 cycles per year. The western half of the state generally experienced more freeze-thaw cycles than the eastern half of the state. The eastern half of the state experienced more variability in the number of cycles than the western half, as shown in Figure 2.1. The radius of the circle represents the number of cycles. Appendix D contains larger maps with a legend detailing the average number of cycles for each station.

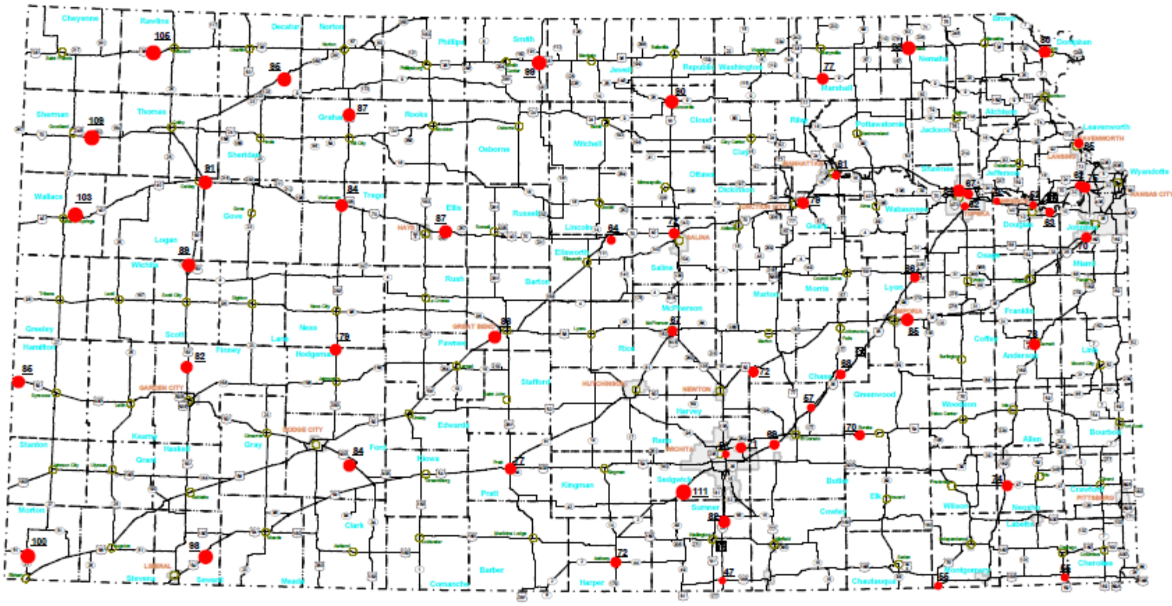

FIGURE 2.1
Average Number of Annual Freeze-Thaw Cycles (Max. Temp. Greater than 32°F; Min. Temp. Less than 32°F)

The results for the average number of regional hard (24°F) freeze-thaw cycles, as shown in Figure 2.2, indicate less overall variation than for the 32°F freeze-thaw cycles. Average values range from 14 to 52 hard freeze-thaw cycles per year. There exists less variation in the number of hard freeze-thaw cycles across the state than for the 32°F freeze-thaw cycles.

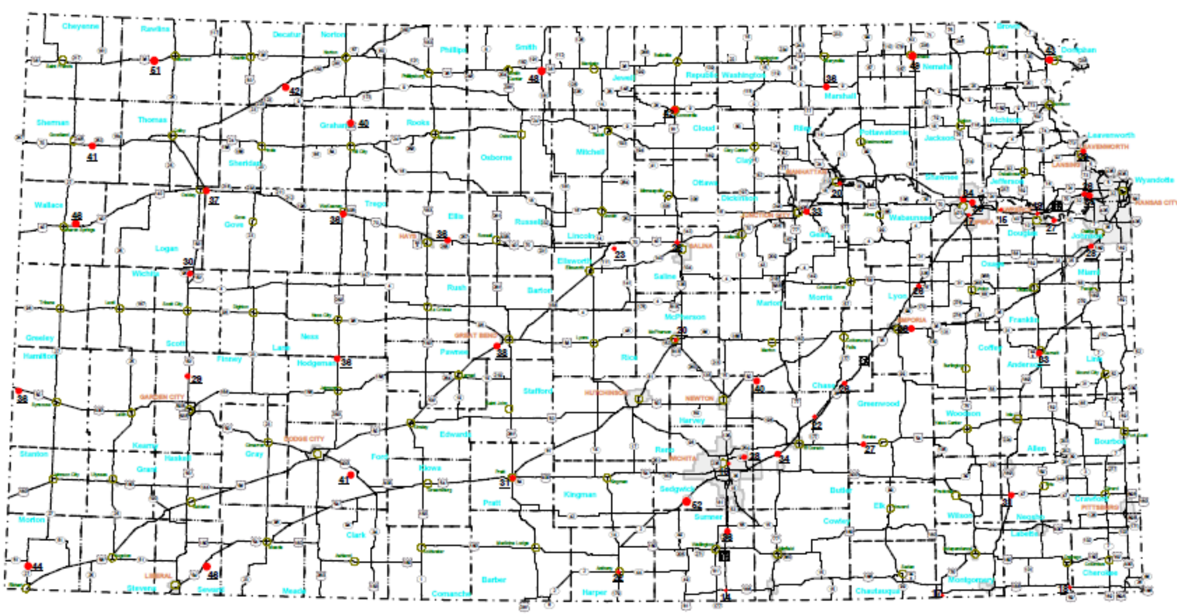

FIGURE 2.2
Average Number of Annual Hard Freeze-Thaw Cycles (Max. Temp. Greater than 32°F; Min. Temp. Less than 24°F)

The data indicating the variation in the estimated average number of annual freeze-thaw cycles by year in Kansas are provided in Table 2.1 and shown graphically in Figure 2.3. These data were estimated as a percentage basis of the days with data for all station sites across Kansas. The average number of annual freeze-thaw cycles range from 58 to 94, with an average of 78 cycles. The hard freeze-thaw results range from 16 to 42 with an average of 33 cycles. Kansas roads did experience a peak in the number of freeze-thaw cycles (94) during the winter of 2010. This is, however, only five more cycles than the 2002 and 2003 winter seasons. The 2007 winter season exhibited the most hard freeze-thaw cycles (43), with the 2010 and 2003 seasons having 42 and 41 hard freeze-thaw cycles, respectively.

TABLE 2.1
Estimated Average Annual Number of Freeze-Thaw Cycles for the State of Kansas

Year	Average Annual F/T Cycles	Average Annual Hard F/T Cycles
1998	74	29
1999	58	16
2000	69	23
2001	86	37
2002	89	38
2003	89	41
2004	72	33
2005	63	25
2006	68	23
2007	84	43
2008	81	38
2009	82	39
2010	94	42
Average	**78**	**33**
Minimum	**58**	**16**
Maximum	**94**	**43**

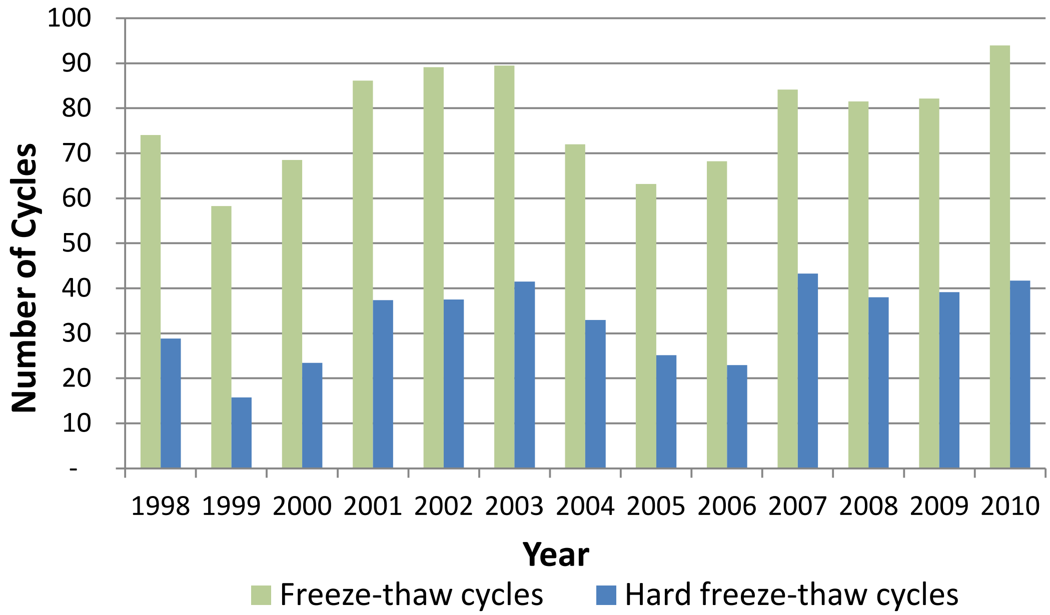

FIGURE 2.3
Estimated Average Annual Freeze-Thaw and Hard Freeze-Thaw Cycles

It was determined that limited variability of weather by region within the state would not be included in the current analysis.

2.5 Field Survey Methods

Field surveys were completed to evaluate field performance of the concrete pavements included in the study. As the research study was beginning in 2009, researchers sent a crew to the field to perform an informal initial evaluation of D-cracking. Ninety-nine concrete paving projects in Kansas were surveyed during the summer of 2009. The purpose was to acquire a feel for how much D-cracking existed on Kansas pavements and to test out various methods of surveying and documentation. For each project, three test sections of 20 panels each were surveyed with roughly one test section in each one-third of the project length. For each test section the crew walked on the shoulder and made notes about the types of deterioration identified on a drawing of the pavement. All lanes and shoulders (inside and out) were included in the survey, although at times only the driving lane and adjacent shoulder were included. For divided highways, both directions were surveyed.

The summer survey of 2009 provided a valuable starting point for the development of the systematic and comprehensive survey methods and training of survey crews. Based on the conservative nature of the 2009 surveys, 22 of the surveys with a result of “no” were accepted as official survey results. Fourteen percent of the 22 surveys were re-surveyed in 2010 to verify the negative results. In the analysis for this study, the surveys for the 19 projects with a “no” result that were not re-surveyed were assumed to have occurred in 2010 rather than the actual 2009 date of survey. This assumption is conservative and gives the material the benefit of the doubt, assuming one additional year of no D-cracking. All of the criteria projects that were rated “yes” in 2009 were re-surveyed in 2010 to verify the field performance.

The summer survey 2010 was the foundation for the performance data presented in this study. A training program for field survey methods based on nationally accepted definitions of D-cracking was developed. Definitions and training to identify D-cracking were based on various resources including industry-accepted guides on concrete pavement deterioration, American Concrete Institute (ACI), other state departments of transportation and Federal Highway Administration (FHWA) reports. The training program for survey crews included instruction on detailed definition of D-cracking and the theory of why and how the deterioration occurs, many photographic examples, the standard survey methods developed for the 2010 survey, and a review quiz-game compiled to check consistency of identification. The training program was presented to non-KDOT industry representatives for review of accuracy and completeness of methodology. The training materials received favorable responses from industry representatives.

A four-person leader-team based approach was developed for the 2010 surveys. The team leader made the decision for the result (yes, there is D-cracking or no, there is no D-cracking). The three other team members provided assistance such as support observations, record keeping, and traffic safety. Six team leaders were chosen for their experience and knowledge. Leaders participated in evaluating the training program and then went to the field together on multiple occasions to “calibrate” their eyes to provide as much continuity of survey results as possible. More than thirty supporting team members were trained, with the training program on the definition of D-cracking (what it looks like, how to identify it, common mistakes in identifying D-cracking) and survey methods. Leaders assembled teams that were available to go to the field on the days that the leader was available. Leaders could request assistance from any of the trained personnel, even those from outside their unit. If the result (D-cracking = yes or no) of any field survey was unclear, then cores were taken from the pavement and the final result was determined by petrographic examination.

The 2010 surveys were completed systematically for each project included in the study. The survey team located the project to be surveyed and stopped the vehicle at the beginning of the project setting the trip odometer to zero. At a minimum, the first 20 joints at each state mile marker post (green sign) within the boundaries of the project (in each direction) were surveyed. The team drove to the first state mile marker post, then stopped and exited the vehicle. One team member provided safety by watching for and waving traffic over to the opposite lane. The first 20 joints starting at the state mile marker post were surveyed for signs of D-cracking. For the 20 joints at each mile marker the presence of D-cracking (yes or no) was noted, the presence of cracked aggregate (yes or no) was noted, and any remarks deemed necessary or descriptive by the team leader were recorded. If the visual survey of the project resulted in any question whether D-cracking was present, then coring locations were marked with paint, a lathe was placed at the fence row, and a note was made in the survey sheet. Photos of the pavement were sometimes taken. The process of surveying 20 joints was repeated for each state mile marker post within the project boundaries. While traveling between survey sections (mile marker posts) the team observed the roadway and the team leader could choose to stop and survey additional locations, noting the odometer reading.

In total, 81 person-days were required to complete the 2010 field surveys, and over 3,100 person-hours were required to develop the training, implement the field survey process from initial development of methods through implementation (for more than 150 projects), and document the final field performance data. Since the field surveys were concluded, the data analysis and completion of Phase 1 has included over 1,700 person-hours, and a total effort estimate of well over 5,000 person-hours. This does not include efforts expended in 2009 and up to April 2010, or after January 2011. Support from upper management, cooperation, and communication were critical to the success of completing this large effort.

2.6 Coring and Laboratory Methods

Concrete cores were taken from select study pavements, and a petrographic investigation was performed on the cores to confirm concrete surface cracking patterns as D-cracking. Initially, cores were taken from five projects to confirm the positive visual identification of D-cracking. During the 2010 field survey, cores were taken from a project if the results of the visual field survey were unclear.

2.6.1 Linking Visual Observation to Petrographic Confirmation of D-Cracking

Project 135-40 K-5634-01 in Harvey County was cored in 2009 because premature deterioration of this project was identified by KDOT, increasing awareness of the D-cracking problem in Kansas. These cores from the Harvey County project were examined and D-cracking was confirmed.

Four projects with distinctive D-cracking found during the 2009 summer survey list, and one additional project in Harvey County were chosen for coring in 2010. Each of the four projects were revisited to verify that the D-cracking pattern was present on the pavement surface and to take cores for laboratory verification. The projects cored were 50-57 K-3219-02, 50-57 K-3220-01, 68-30 K-5998-01, and 196-8 K-3321-01 (K-254 at El Dorado). The projects were chosen because they represented typical D-cracking patterns in both the shape of the cracking and how the crack patterns migrated outwards from the transverse/longitudinal joint corners and along the transverse joint.

Micro- and macro-cracking of the coarse aggregate was observed in cores taken from all five of the projects indicating that D-cracking was present. The surface expression of D-cracking on these five projects served as a “template” example to which the surface cracking patterns of subsequent field surveys were compared.

Photographs and cores from the petrographic investigation were sent to two independent laboratories for independent determination. The results will be discussed in future reports.

2.6.2 Coring

Some of the projects which exhibited extensive D-cracking on the surface were selected for coring. Cores were taken at randomly chosen locations throughout the length of the project.

On the four projects cored in 2010, six to nine cores were collected depending on the condition of the core once coring was complete. Cores were typically taken at the transverse/longitudinal joint corners at a distance varying from 6 to 14 inches away from the corner, depending on the severity of the surface cracking and the location of the steel dowel bars. Core locations were marked and the surface condition was photographed. Additional surface condition photographs were taken throughout the project to record the overall cracking/distress condition. As the cores were retrieved, they were marked and bagged. Additional photographs were taken of the hollow core holes remaining in the pavement showing the extent of cracked aggregate, the depth of damage, and the crack patterns in situ.

2.6.3 Laboratory Petrographic Investigation Methods

A petrographic analysis can consist of a simple visual and microscopic examination to the use of highly technical methods such as scanning electron microscopy, x-ray analysis, thin section studies, and various chemical testing methods. The chosen method depends on what is being studied and what answers are sought from the analysis. When looking for D-cracking in a petrographic analysis, one is looking for signs of cracked aggregate and crack patterns through the aggregate and paste. KDOT verifies D-cracking through a visual and microscopic examination to reveal signs of micro- and macro-cracking in the coarse aggregate and crack patterns through the aggregate and extending into the paste.

For the current study, each core was photographed in its original condition and visual examinations were performed with the unaided eye, with a hand lens at magnifications up to 5X, and, with binocular microscopes at magnifications up to 100X. Signs of cracked aggregate were identified, verifying that D-cracking was present.

The cores that were able to be cut were then cut lengthwise through the middle of the core in order to get a flat, cross-sectional view of the cores through the entire depth of the pavement. Half of the core was polished for clear viewing of the flat surface, while the other half was left unpolished. The cores were again photographed and examined using the unaided eye, and with magnifications up to 100X to identify signs of cracked aggregate and verify D-cracking in the pavement.

The petrographic analysis of the cores in this study consisted of photographing, visually examining, both unaided and with the aid of magnification of up to 100X. Items examined included intact cores and core pieces, the hollow bore holes, pieces of highway pavement around the bore holes that became dislodged during the coring activity and the cut and polished core sections. The purpose of the analysis was to determine whether D-cracking was present in the pavement and use that information to establish surface cracking patterns for the identification of D-cracking on other projects.

2.6.3.1 Migration of D-Cracking within a Panel

One panel was chosen on every project for which migration of D-cracking within the panel was investigated. These projects had classic D-cracking patterns visible on the pavement surface near the joints between panels but did not show other deterioration crack patterns. For the chosen panel, one core was taken at the transverse/longitudinal joint corner as close to the corner as possible, one core at 5 ft away from the corner on a diagonal line splitting the panel, called the "¼ panel core," and one core in the center of the panel, called the "center panel core," 10 ft from the corner on the same diagonal line. By taking cores at these three locations, it was possible to examine how far the D-cracking had migrated from the corner joint. Also, concrete affected by D-cracking was compared to concrete unaffected by D-cracking within the same concrete panel. For all of the cored projects, the center panel core was not yet affected by D-cracking. Only one of the ¼ panel cores (K-68) had D-cracking. This core also had observable cracking on the surface of the pavement. The extent of D-cracking on K-68 highway is extensive and on this project, D-cracking had migrated at least 5 ft away from the joint corners on some panels.

Visible surface signs of deterioration were not seen outside of the areas in which D-cracking patterns were visible on any of the project panels cored. However, the cores taken near the joint corners and some of the cores taken at the ¼ and center panel locations revealed characteristic reaction rings around many of the aggregate pieces once they were sliced or broken open for examination. Some of the cores taken at the ¼ and center panel locations that showed no signs of surface distress still exhibited these rings.

All of the ¼ panel and center panel cores, as well as at least one core at the joint corner were treated with uranyl acetate solution to reveal any possible signs of Alkali Silica Reaction (ASR) or Alkali Carbonate Reaction (ACR). Once the sample is treated with uranyl acetate, the powder/gel formed by reaction processes in the sample absorbs the uranyl acetate and glow yellow-green under shortwave ultra-violet (UV) light indicating where ASR/ACR may be forming or occurring. All of the joint corner cores that were treated with uranyl acetate indicated that indeed some form of reactive mechanism is occurring in addition to D-cracking. These joint corner cores revealed that over 70% of the course aggregate had some form of reactive mechanism occurring along with D-cracking. One of the ¼ panel cores (K-68) indicated a strong possibility that ASR/ACR might be present in addition to the D-cracking observed. On this core, an estimated 70% or greater of the course aggregate pieces had some form of reactive mechanism occurring along with D-cracking. All of the other ¼-panel and center panel cores which did not exhibit D-cracking were found to have some reaction rings around the aggregate under UV light after uranyl acetate treatment, but exhibited no deterioration in the core or around the ringed aggregate. These glowing rings indicate that some sort of reaction may be occurring on a smaller scale in these cores at locations where D-cracking is not prevalent, but are not currently causing pavement deterioration. Table 2.2 provides an estimate of the percentage of aggregate that was found to have some form of reactive mechanism occurring in the cores taken at the ¼ panel and center panel locations on each project. A more in-depth investigation of reactivity is ongoing as part of Phase 2.

TABLE 2.2
Estimated Percentage of Aggregates with a Reactive Mechanism

Project Number	Project Location	Estimated percentage of aggregate with a reactive mechanism	
		¼-Panel Core	Center-Panel Core
50-57 K-3219-02	US-50 West side of Peabody, Kansas	< 15%	< 10%
50-57 K-3220-01	US-50 at Florence, Kansas	< 10%	< 10%
196-08 K-3321-01	K-254 NW side of El Dorado, Kansas	Up to 20%	Up to 20%
68-30 K-5998-01	K-68 east side of Ottawa, Kansas	70 % or more†	< 20%

† Surface was previously cracked from deterioration.

2.7 Analysis and Assumptions

Years to D-cracking was calculated based on the last date of paving and the year D-cracking was first noticed. In the cases where the overlay was due to D-cracking, then the year of the overlay was used as the year D-cracking was first noticed unless documented otherwise.

The aggregate durability specifications were implemented in 1981 with initial aggregate testing beginning as early as 1980. By 1987, all PCCP were constructed under the new specifications. The intended structural design life for new pavements is 20 years before first rehabilitation action (maintenance or structural). Any materials-related distress, such as D-cracking before 20 years indicates failure.

Four D-cracked projects contained material from more than one quarry. For these projects, the location of each material within the project was determined and compared to the results from the field surveys to properly attribute field performance to the correct material source. For those projects that the D-cracking results could not be correlated with project locations of each individual aggregate source, the field results were not included in the quarry field performance analysis, and the D-cracking was not counted against the quarries.

Results are presented for both a project-basis and in lane-miles (12 ft wide and 1 mile long) basis. Project-basis is used in the analysis for success/failure rates because each parameter considered (such as limestone source, joint spacing, base type, etc.) represents a “decision” made for the project, regardless of the length and scope of the project. Lane-miles are used for comparison to previous surveys and to estimate the future effect of the damage on the current system.

As stated previously, for the current study, a rating of “yes” indicates that D-cracking was observed on the project, a rating of “no” indicates that D-cracking was not observed on the project. A project would have 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 would have 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.

Chapter 3: Results and Discussion

Over 230 quarries in Kansas have been evaluated for Class 1 status since 1980. Aggregate from 52 quarries were used to construct the criteria projects. Fifty of the quarries used were evaluated for Class 1 status and two quarries were never evaluated for Class 1 status. The quarry source information for each of the criteria projects is provided in Table A.2.

To calculate the overall percentages of success (pass) and failure, 131 of 132 projects surveyed were included in the calculations. One project, K-2611-02, was not used for the overall pass/fail analysis because it was located on a divided highway constructed in different years with aggregate from different quarries, with each direction having different performance results. Therefore a definitive pass/fail rating for the entire project was not assigned. The effect of removing this project from the following analysis was negligible.

3.1 Overall Analysis of Field Performance

For the overall analysis, the data indicates that D-cracking was observed on 54 of the 131 projects, 41% (693 lane-miles, 32%). There were 41 of the 131 projects, 31% (523 lane-miles, 25%), that were less than 20 years old when D-cracking was observed and are termed "fail" for the purpose of this study. The "fail" projects are listed in Table A.5. Thirteen projects, 10% (170 lane-miles, 8%), were 20 years old or more when D-cracking was observed and are termed "pass." These "pass" projects are listed in Table A.3. There were 35 projects, 26% (562 lane-miles, 26%), that were 20 years or older and exhibited no D-cracking in 2010, and are also termed "pass," These projects are listed in Table A.4. Forty-two projects, 32% (878 lane-miles, 42%), exhibited no D-cracking and were less than 20 years old. These projects (exhibiting no D-cracking at an age less than 20 years) are termed "inconclusive" for the purposes of this study, because a "pass" cannot be determined until the pavement reaches the design life of 20 years. Maps indicating the location and results for the projects in this survey are located in Appendix C, Figures C.1–C.4. Figure 3.1 and Figure 3.2 illustrate the distribution of overall field performance. Overall, on a project basis, there was a 31% failure rate, 37% success rate, and 32% are indeterminate (inconclusive) at this time.

	D-Cracked 54 Projects, 41% [693 lane-miles, 32%]	Not D-Cracked 77 Projects, 59% [1440 lane-miles, 68%]
<20yr Life 83 Projects, 63% [1401 lane-miles, 66%]	**FAIL** 41 Projects, 31% [523 lane-miles, 25%]	**INCONCLUSIVE** 42 Projects, 32% [878 lane-miles, 42%]
>20yr Life 48 Projects, 37% [732, lane-miles, 34%]	**PASS** 13 Projects, 10% [170 lane-miles, 8%]	**PASS** 35 Projects, 26% [562 lane-miles, 26%]

FIGURE 3.1
Distribution of Field Performance for the 131 Criteria Projects

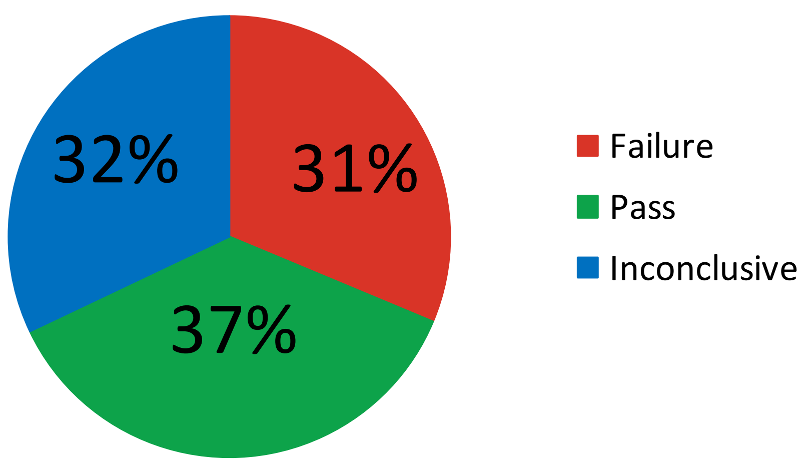

FIGURE 3.2
Survey Results on a Project Basis

The failure rate for the 2009–2010 study represents the minimum D-cracking failure rate for concrete pavements in Kansas. The "inconclusive" (blue) project results will, with annual monitoring, become either "pass" (not D-cracked at 20 years) or "fail" (D-cracking observed before 20 years). The number and percentage of projects that are inconclusive (blue) will shrink each year, with the projects becoming either "pass" (green) or "fail" (red). If all the inconclusive (blue) projects become "pass," then the final failure rate will be 31%. If any of the inconclusive (blue) projects fail, the final failure rate will increase above 31%. It is impossible to predict the final failure rate, but if the failure rate of the inconclusive (blue) projects is the same as the minimum (current) failure rate, 31%, the final failure rate will be 41%.

The legislative dates for the Comprehensive Highway Program (CHP) were from 1988 to 1997. The dates for the Comprehensive Transportation Program (CTP) were from 2000 to 2009 (KDOT 2001). These two transportation programs increased demand for Class 1 and Class 2 aggregate because of the increase in construction. Table 3.1 indicates the average number of criteria projects constructed annually for different eras of construction. The average number of projects in the 1980s was 4.4 projects per year. During the CHP, the average increased to nine projects per year.

The distribution of successes and failures by year of construction is of interest in evaluating field performance over time. The survey results by year of construction are presented in Figure 3.3. The rate of failures during the 1980s (before the CHP) is generally lower than during the 1990s (during the CHP). If the final results for the inconclusive projects during CHP are all "success" (best possible result) then 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 freeze-thaw 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 difficult to delineate exactly which occurred for each project in this report, but it is the general view of the authors that both have occurred and although improving inspection/monitoring may have some limited impact on field performance, it is not likely to reduce the rate of D-cracking to an acceptable level.

TABLE 3.1
Average Number of Criteria Projects Constructed per Year between 1979 and 2000

Construction Era	Average No. of Projects per Year
1979–1987	4.2
1988–1997 (CHP)	7.3
1998	6
1999	10
2000 (CTP)	2

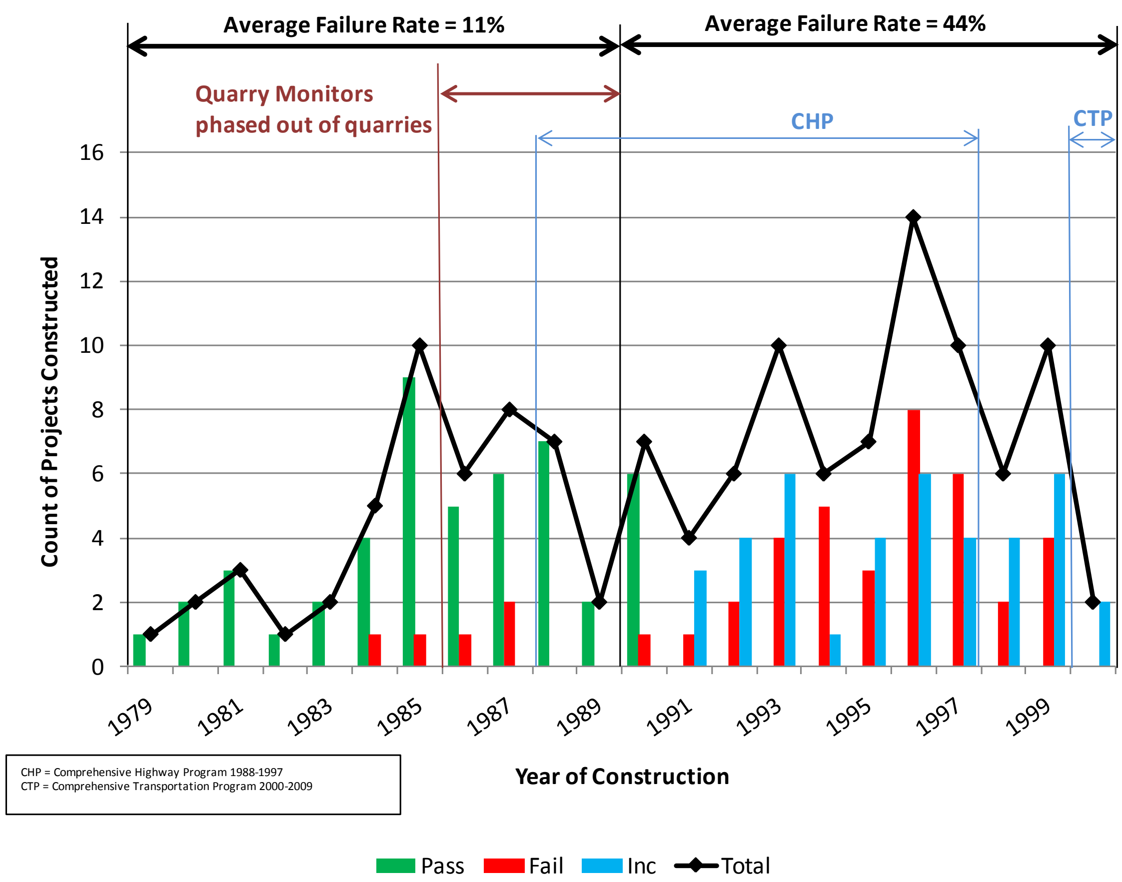

FIGURE 3.3
Survey Results for Survey Projects by Year of Construction and Legislative Dates for CHP and CTP

3.2 Quarry Analysis

For completeness, project K-2611-01 was included in the quarry analysis. Therefore the total number of criteria projects used in the quarry analysis was 132 and the total number of projects that D-cracked before 20 years was 42.

For the quarry analysis, 52 quarries supplied material for the 132 criteria projects at an average rate of 2.5 projects per quarry. Twenty-four quarries provided aggregate to the 42 criteria projects that D-cracked before 20 years at an average rate of 1.8 projects per quarry. Considering the quarries with the highest numbers of D-cracking projects, six of the 24 quarries (25%) supplied material to 23 of the 42 (55%) projects with D-cracking before 20 years of age. Therefore 55% of the D-cracking before 20 years (by project) came from six quarries. There were three other quarries that D-cracking was observed in less than 20 years on 50% or more of the projects to which they provided aggregate. Each of these quarries provided aggregate to two projects that displayed D-cracking before 20 years. This makes a total of nine quarries that provide aggregate to 29 projects that displayed D-cracking before 20 years. The overall results are shown in Figure 3.4 with the projects containing material from these nine quarries shaded. These nine quarries account for approximately 69% of the premature failures, shown in Figure 3.5, which is significantly higher than the 14% failure rate for the remaining 44 quarries with acceptable field performance, shown in Figure 3.6.

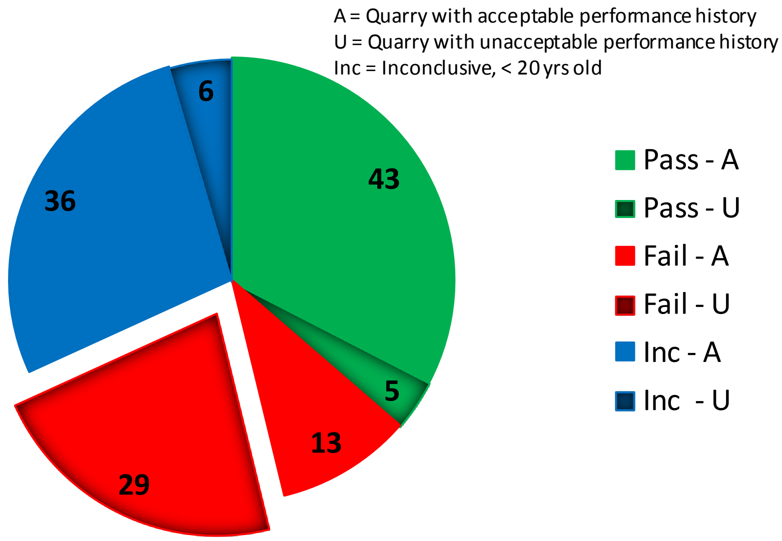

FIGURE 3.4
Overall Number of Passing, Failing, and Inconclusive Results for the 2010 Study

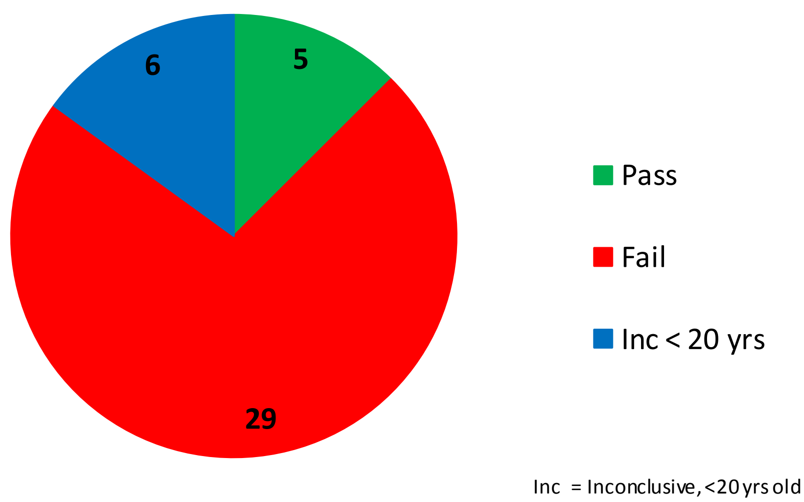

FIGURE 3.5
Results (Number of Projects) for the Nine Quarries Removed from the Approved List (Unacceptable Field Performance)

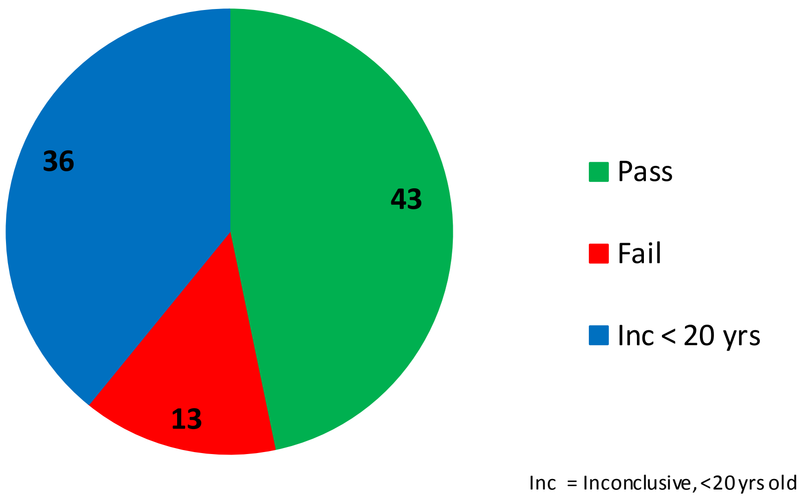

FIGURE 3.6
Results (Number of Projects) for the 44 Quarries with Acceptable Field Performance

For comparison with Figure 3.3 in the previous Section, Figures 3.7 and 3.8 provide the results over time for the quarry groups analyzed separately. For the quarries with unacceptable field performance, Figure 3.7 indicates an average failure rate in the 1990s of 81%. This is in stark contrast to the results for the quarries with acceptable field performance, where Figure 3.8 shows a much lower failure rate in the 1990s of 17%.

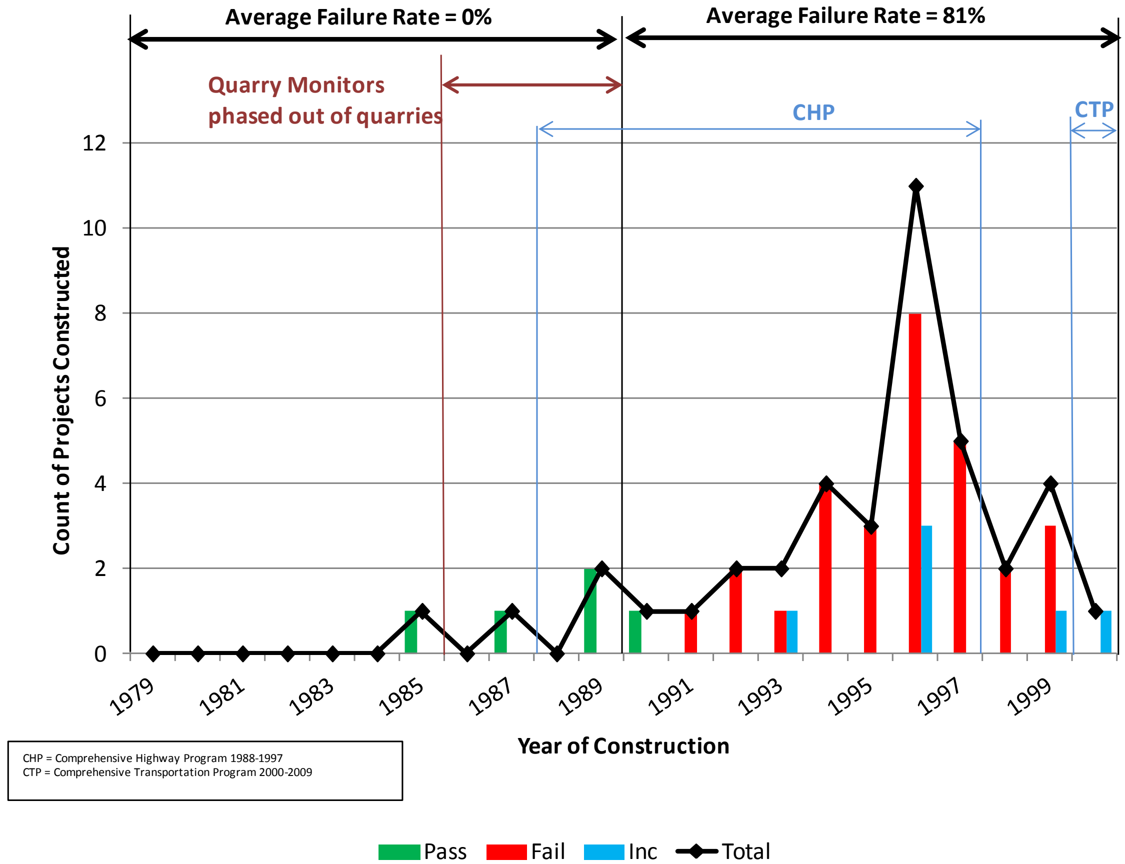

FIGURE 3.7
Survey Results for Survey Projects Containing Material from the Nine Quarries with Unacceptable Field Performance, by Year of Construction and Legislative Dates for CHP and CTP

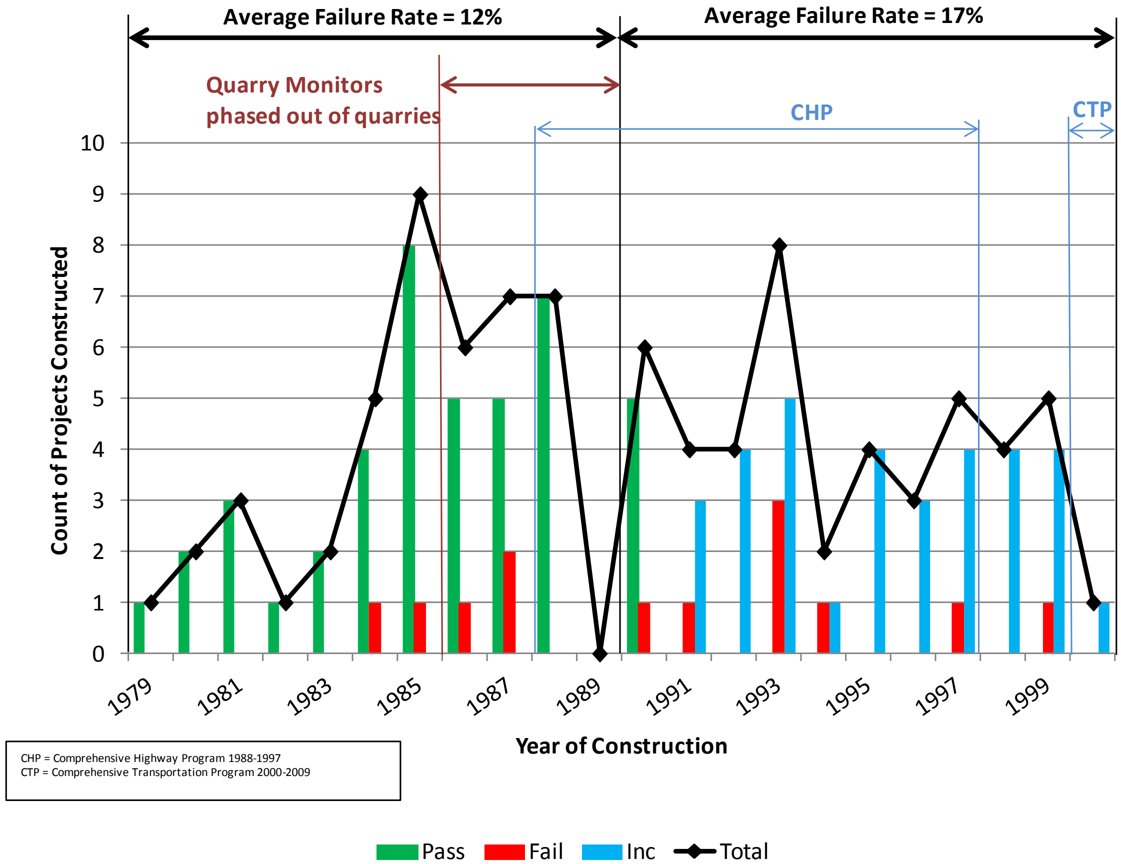

FIGURE 3.8
Survey Results for Survey Projects Containing Material from the Quarries with Acceptable Field Performance, by Year of Construction and Legislative Dates for CHP and CTP

3.3 Projects Containing Aggregate from Multiple Quarries

Three D-cracked projects contained material from more than one quarry. For these projects, the location of each material within the project was determined and compared to the results from the field surveys to properly attribute field performance to the correct material source. For those projects that the D-cracking results could not be correlated with project locations of each individual aggregate source, the field results were not included in the quarry field performance analysis and the D-cracking was not counted against the quarries.

For project 435-105 K-0989-02, material from three quarries, 4-030-02, 4-061-05, and 4-054-02, were used in the project. It was determined that only Quarry 4-061-05 could be connected with D-cracking on the mainline paving. Quarries 4-030-02 and 4-054-02 were not associated with mainline paving results by comparing aggregate production sample submission dates with mainline paving dates.

For project 70-31 K-2611-02, material from two quarries, 2-031-03 and 2-031-01 were used in the project. Construction records indicate that the west-bound mainline contained material from quarry 2-031-03. The east-bound mainline contained material from quarry 2-031-01. Figure 3.9 indicates the location of each quarry's material on the mainline paving. This project was not included in the overall analysis (section 3.1) but was included in the quarry analysis (section 3.2) as described previously.

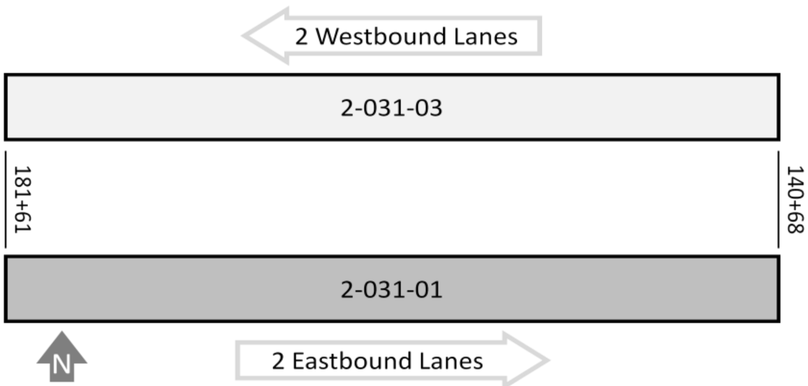

FIGURE 3.9
Quarry Material Usage on Project K-2611-02

For project 40-89 K-3362-08, construction records indicate that material from two quarries, 4-030-02 and 4-030-04, were included in the pavement. The location of each material was not determined, and the project is no longer on the state highway system. Therefore the project was removed from the study.

For project 135-40 K-5089-01, material from three quarries, 2-057-06, 5-018-02, and 4-025-02, was used in the project mainline paving. Construction records indicate that all three quarries are associated with D-cracking. Figure 3.10 indicates the location of each quarry's material on the mainline paving.

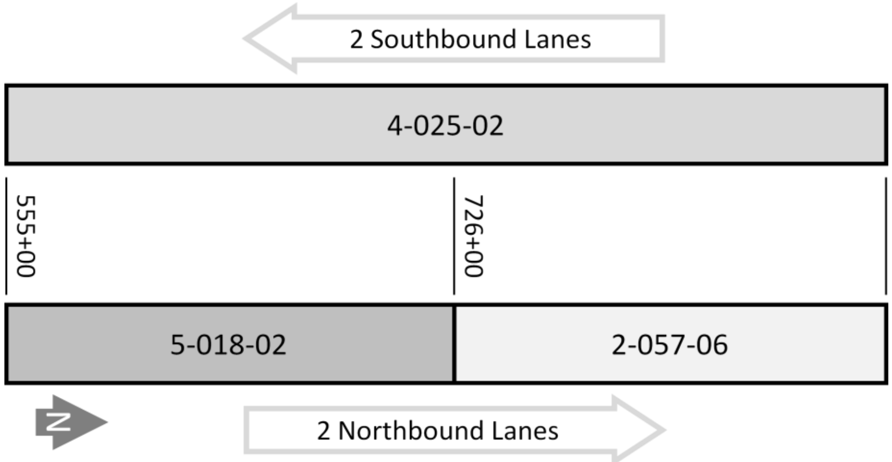

FIGURE 3.10
Quarry Material Usage on Project K-5089-01

Therefore, only two of the four projects contain material from multiple quarries that can be associated with D-cracking at this time. Table 3.2 summarizes the projects containing material from multiple quarries that have been traced to specific locations on criteria projects.

TABLE 3.2
Projects Exhibiting D-Cracking and Containing Material from Multiple Quarries

Rt.	Cnty	Project	Direction	Quarry No.	Quarry No.
70	31	K-2611-02	EB	2-031-01	-
70	31	K-2611-02	WB	2-031-03	-
135	40	K-5089-01 NB	NB	2-057-06	5-018-02
135	40	K-5089-01 SB	SB	4-025-02	-

3.4 Individual Quarry Performance

The field performance of each of the nine quarries associated with 69% of the failures is outlined next. Two of the nine quarries had been previously removed from the A-List. The remaining seven were subsequently removed on November 2, 2010, based on the following criteria.

a. Any set of beds within a quarry that has provided aggregate to two KDOT projects, and both of the projects D-cracked before 20 years (100%) should be removed from the A-List and not allowed to provide Class 1 or Class 2 aggregate to KDOT projects.

b. Any set of beds within a quarry that has provided aggregates to three or more KDOT projects and 50% or more of those projects exhibit D-cracking before 20 years should be removed from the A-List and not allowed to provide Class 1 or Class 2 aggregate to KDOT projects.

Table 3.3 shows the quarries removed from KDOT's A-List based on field performance criteria a and b.

TABLE 3.3
Quarries Removed from the A-List on November 2, 2010

Quarry
1-046-15
1-070-06
1-089-01†
2-021-10
2-057-04
2-057-05
4-030-02
4-030-04†
4-037-03

†Previously removed from A-List

Appendix C contains maps related to the individual quarry analysis.

3.4.1 Quarry 1-046-15

Quarry Number 1-046-15, Johnson County, provided aggregate to three of the criteria projects in 1995 and 1996. This aggregate was from Beds 1, 2, 3, 4, and 5, in the Upper Farley and Argentine members. D-cracking was observed in two of the projects at 12 and 13 years of age. One project at 14 years of age did not exhibit D-cracking in 2010. All of the aggregate used on these projects came from this quarry.

TABLE 3.4
Field Performance for Quarry No. 1-046-15

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
635	105	K-1023-01	1996	None	14	1,2,3,4,5	UFRLY(1), ARGN(2,3,4,5)	1-046-15
435	46	K-3637-01 WB (NB)	1995	None	15	2,3,4,(5)	ARGN	1-046-15
435	46	K-3637-01 EB (SB)	1996	2009	13	1;2,3,4, 5	UFRLY(1); ARGN(2,3,4,5)	1-046-15
73	52	K-4443-01	1996	2008	12	2,3,4,5	ARGN	1-046-15

3.4.2 Quarry 1-070-06

Quarry Number 1-070-06, Osage County, provided aggregate to three of the criteria projects in 1996 and 1997. This aggregate was from Bed B, in the Kerford member. D-cracking has been observed on two of the projects at 12 and 14 years of pavement age. One project at 14 years of age did not exhibit D-cracking in 2010. All of the aggregate used on these projects came from this quarry.

TABLE 3.5
Field Performance for Quarry No. 1-070-06

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
4	89	K-3362-10	1996	2010	14	B	KRFD	1-070-06
35	30	K-3596-02	1996	None	14	B	KRFD	1-070-06
75	89	K-3371-01	1997	2009	12	B	KRFD	1-070-06

3.4.3 Quarry 1-089-01

Quarry Number 1-089-01, Shawnee County, provided aggregate to six projects between 1989 and 1993. All of these projects were on 4-lane divided Interstates in Shawnee County. This aggregate was from Bed A in the Hartford member. Three of the six projects displayed D-cracking between 16 to 18 years of age. All of the aggregate used on these projects came from this quarry. This quarry is no longer on the list of available Class 1 or 2 aggregates, the A-List.

TABLE 3.6
Field Performance for Quarry No. 1-089-01

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
70	89	K-2445-01	1989	2009	20	A	HRFD	1-089-01
70	89	K-2446-01	1992	2009	17	A	HRFD	1-089-01
70	89	K-2446-02	1993	None	17	A	HRFD	1-089-01
470	89	K-2454-01	1990	2010	20	A	HRFD	1-089-01
70	89	K-3344-01	1993	2009	16	A	HRFD	1-089-01
470	89	K-3831-01	1991	2009	18	A	HRFD	1-089-01

3.4.4 Quarry 2-021-10

Quarry Number 2-021-10, Dickinson County, provided aggregate to six of the criteria projects from 1998 to 2001. This aggregate was from Beds 1, 2, 3, and 4, in the Towanda member. D-cracking was observed on three of the six projects at 11 years. All of the aggregate used on these projects came from this quarry.

TABLE 3.7
Field Performance for Quarry No. 2-021-10

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
81	15	K-4956-03	1999	2010	11	1,2,3,4	TWND	2-021-10
81	79	K-5021-02	1999	2010	11	1,2,3,4	TWND	2-021-10
81	79	K-5022-02	1999	2010	11	1,2,3,4	TWND	2-021-10
70	31	K-5086-01	1999	None	11	1,2,3,4	TWND	2-021-10
135	85	K-5263-01	2000	None	10	1,2,3,4	TWND	2-021-10
70	99	K-5633-01	2001	None	9	1,2,3,4	TWND	2-021-10

3.4.5 Quarry 2-057-04

Quarry Number 2-057-04, Marion County, provided aggregate to eight of the criteria projects between 1994 and 1997. This aggregate was from Beds 2 and 3 in the Cresswell member. All eight projects are currently D-cracked. The D-cracking appeared between 9 and 16 years of age. All of the aggregate used on these projects came from this quarry. This quarry has a history of encountering chert, shale and mud seams causing contamination of the Class 1 aggregate, and it had restrictions placed on it in 2005. The quarry has failed to comply with the restrictions.

TABLE 3.8
Field Performance for Quarry No. 2-057-04

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
50	57	K-3046-03	1994	2010	16	2,3	CRSL	2-057-04
50	57	K-3219-02	1994	2009	15	2,3	CRSL	2-057-04
50	57	K-3220-01	1994	2009	15	2,3	CRSL	2-057-04
50	40	K-4058-03	1994	2005	11	2,3	CRSL	2-057-04
254	8	K-3321-01	1995	2009	14	2,3	CRSL	2-057-04
50	9	K-3217-02	1996	2009	13	2,3	CRSL	2-057-04
50	40	K-4350-01	1997	2009	12	2,3	CRSL	2-057-04
135	59	K-5084-01	1997	2006	9	2,3	CRSL	2-057-04

3.4.6 Quarry 2-057-05

Quarry Number 2-057-05, Marion County, provided aggregate to two of the criteria projects in 1997 and 1998. This aggregate was from Bed 2 in the Fort Riley member. Both of these projects were D-cracked at 11 and 13 years of age. All of the aggregate used on these projects came from this quarry.

TABLE 3.9
Field Performance for Quarry No. 2-057-05

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
50	9	K-3216-02	1997	2010	13	2	FRRL	2-057-05
50	57	K-3221-02	1998	2009	11	2	FRRL	2-057-05

3.4.7 Quarry 4-030-02

Quarry Number 4-030-02, Franklin County, provide aggregate to four of the criteria projects between 1985 and 1999. This aggregate was from Beds 4 and 5 in the Stoner member and Beds 13 and 14 in the Springhill member. Two of the three projects constructed with aggregates from the Stoner were D-cracked from 9 to 14 years of age. The one project constructed with aggregate from the Springhill was D-cracked at 12 years. Of the four projects constructed with aggregate from this quarry D-cracking was observed in three of them between 9 and 14 years. D-cracking was also found on a project containing material from quarry 4-030-02 that was less than 10 years old, discussed later in Section 3.4.

TABLE 3.10
Field Performance for Quarry No. 4-030-02

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
435	105	K-0987-02	1985	2005	20	4,5	STNR	4-030-02
75	89	K-3371-03	1996	2010	14	4,5	STNR	4-030-02
68	30	K-5998-01	1996	2005	9	4,5	STNR	4-030-02
35	30	K-5085-01	1998	2010	12	13,14	SPGH	4-030-02

3.4.8 Quarry 4-030-04

Quarry Number 4-030-04, Franklin County, provided aggregate to five of the criteria projects between 1987 and 1995. This aggregate was from Beds 4 and 5 in the Stoner member, and Beds 10, 11, 12, and 13 in the Springhill member. D-cracking was observed in one of the projects from the Stoner at 23 years of age. Two projects were constructed with aggregate from both the Stoner and Springhill members. Both of these projects were D-cracked at 14 years. One project constructed with aggregate from the Springhill was D-cracked at 18 years, and one is not D-cracked after 21 years. Out of the five projects constructed with aggregate from this quarry D-cracking was observed in three of the projects between 14 and 18 years of age. This Quarry is no longer on the list of available Class 1 or 2 aggregates, (A-List.)

TABLE 3.11
Field Performance for Quarry No. 4-030-04

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
35	46	K-2434-02	1987	2010	23	4,5	STNR	4-030-04
35	46	K-2434-04	1989	None	21	10,11,12,13	SPGH	4-030-04
75	70	K-3247-01	1992	2010	18	10,11,12,13	SPGH	4-030-04
35	30	K-3596-01	1995	2009	14	4,5; 10,11,12,13	STNR(4,5); SPGH(10, 11,12,13)	4-030-04
35	70	K-5028-01 NB	1995	2009	14	4,5; 10,11,12,13	STNR(4,5); SPGH(10, 11,12,13)	4-030-04
35	70	K-5028-01 SB	1995	None	15	4,5; 10,11,12,13	STNR(4,5); SPGH(10, 11,12,13)	4-030-04

3.4.9 Quarry 4-037-03

Quarry Number 4-037-03, Greenwood County, provided aggregate to four of the criteria projects in 1996 and 1997. This aggregate was from Beds 2 and 3 in the Ervine Creek member.

Three of these projects were D-cracked at 13 and 14 years of age. One project has not yet D-cracked after 14 years. All of the aggregate used on these projects came from this quarry.

TABLE 3.12
Field Performance for Quarry No. 4-037-03

Rt.	Cnty	Project	Paving Complete	D-cr noted	Age	Beds	Geo Class	Quarry No.
400	37	K-3292-02	1997	2010	13	2,3	EVCK	4-037-03
400	37	K-3293-03	1996	None	14	2,3	EVCK	4-037-03
96	78	K-4458-01	1996	2010	14	2,3	EVCK	4-037-03
96	87	K-4459-01	1996	2010	14	2,3	EVCK	4-037-03

3.5 D-Cracking in Less than 10 Years

During the 2010 field survey, crews observed D-cracking on pavements that were less than 10 years old. A comprehensive survey has not been completed on projects that are less than 10 years old, but the observations indicate that D-cracking is occurring in Kansas before 10 years. Table 3.13 contains some information identifying projects with observed D-cracking in less than 10 years. Note that K-4890-02 (WB) contained material from quarry 4-030-02, which was removed from the A-List.

TABLE 3.13
Projects Less than 10 Years Old with D-Cracking

Route	County	Project	Year Paving Completed	Years to D-cr	Quarry No.	Length (miles)
32	105	K-5277-02	2003	7	4-061-05	0.8
81	79	K-5022-04	2002	8	2-021-07	9.9
70	89	K-6252-01	2001	9	1-089-06	2.1
70	89	K-6358-01	2003	7	1-070-04	4.2
169	61	K-7141-01	2003	7	4-061-05	10.3
70	105	K-4890-02 (WB)	2004	6	4-030-02	1.3

3.6 Notable Field Performance

3.6.1 Quarries with Notable Field Performance

Eight quarries were identified as providing limestone aggregates that performed well in Kansas concrete pavements. The quarries met one of the following criteria.

1. Any set of beds within a quarry that has provided aggregate to two KDOT projects and neither of the projects produced D-cracked pavement before 20 years (100% success).
2. Any set of beds within a quarry that has provided aggregates to three or more KDOT projects and 75% or more of those projects produced no D-cracking pavement before 20 years.

Table 3.14 shows the eight quarries and the performance of the projects produced from those quarries.

TABLE 3.14
Quarries with Best Field Performance Record

Quarry No.	Rt.	Cnty	Project	Paved	Age	Years to D-cr	Beds	Geo Class
1-046-08	35	105	K-1775-03	1988	22	None	1,2	UFRLY
	435	46	K-2345-01	1987	23	None	1,2	UFRLY
1-046-09	435	46	K-0457-05	1984	25	25	(3),4,5	ARGN
	70	105	K-0987-01	1985	25	None	1,2;5,6,7	LFRLY(1,2); ARGN(5,6,7)
	70	105	K-1423-01	1986	24	None	3,4,5	ARGN
	10	46	K-1492-01	1984	26	18	(3),4,5	ARGN
1-052-02	73	3	K-0117-02	1985	25	None	1,2	STNR
	36	22	K-0248-01	1983	27	None	1,2	STNR
	36	22	K-0251-01	1984	26	None	1,2	STNR
	36	22	K-1773-01	1984	26	None	1,2	STNR
2-021-01	56	57	K-0561-02	1988	22	None	1,2,3	CRSL
	56	57	K-0562-02	1987	23	None	1,2,3	CRSL
	70	21	K-2588-01	1986	24	None	1,2,3	CRSL
4-001-01	169	1	K-0106-02	1986	24	None	1,2,3,4	RYTN
	169	67	K-0619-02	1985	25	None	1,2,3,4	RYTN
	169	67	K-0620-02	1985	25	None	1,2,3,4	RYTN
	296	1	K-1281-02	1981	29	None	1,2,3,4	RYTN
4-037-02	54	8	K-0152-02	1985	25	None	1,2,3,4	WKRS
	54	87	K-0764-02	1987	23	18	1,2,3,4	WKRS
	81	87	K-0768-01	1986	24	None	1,2,3,4	WKRS
	400	8	K-1879-01	1987	23	None	1,2,3,4	WKRS
	235	87	K-2515-01	1985	25	None	1,2,3,4,5	WKRS
4-054-02	69	6	K-0135-02	1985	replaced	12	1,2,3	BFLS
	435	46	K-0456-04	1985	25	None	1,2,3	BFLS
	435	105	K-0988-02	1985	25	20	1,2,3	BFLS
	435	105	K-0990-03 SB	1984	26	25	1,2,3	BFLS
	435	105	K-0990-03 NB	1984	26	None	1,2,3	BFLS
	169	46	K-1310-01	1987	23	22	1,2,3	BFLS
4-061-05	169	61	K-0590-02	1986	24	24	4,5; 6	ARGN
	70	105	K-0966-03	1988	22	None	4,5,6	ARGN
	435	105	K-0989-02	1986	24	19	4, 5	ARGN
	70	105	K-1421-01	1987	23	22	4,5,(6)	ARGN
	70	105	K-1422-01	1988	22	21	4,5	ARGN
	35	46	K-2500-01	1992	18	None	4,5	ARGN

3.7 Comparison with Previous KDOT Studies

3.7.1 Summary of Previous KDOT Studies

The first four surveys in 1944–45, 1951–52, 1964–65, and 1980 were conducted on pavements containing any coarse aggregate. All joint spacings were 61.5 ft and percentages were based on 24 ft wide roadway miles. The 2009–2010 survey was conducted only on pavements that contained limestone as the coarse aggregate. These pavements had joint spacings of 15 ft or 30 ft. Percentages are based on 12 ft wide lane miles. A pavement rating of “Good” in the first 4 surveys did not mean there was an absence of D-cracking. Rather, it simply meant that the level of D-cracking was acceptable.

The first three surveys in 1944–45, 1951–52, and 1964–65 used similar rating systems. The survey reports indicated that if 0% to 12% (or one in every eight panels) of the pavement panels were D-cracked then the pavement was rated “good.” If 13% to 50% of the panels were D-cracked then the pavement was rated “fair.” If more than 50% of the panels were D-cracked then the pavement was rated “poor.” The 1951–52 survey combined the fair and poor ratings into one category. The 1980 survey used a system from 0 to 10 to rate the level of D-cracking. Any rating above 0 exhibited some level of D-cracking. The ratings were then grouped into good (0–3), fair (3.1–6), and poor (6.1–10).

The 1944–45 survey was conducted on bare concrete pavements constructed between 1919 and 1945, a period of 27 years. Overlaid pavements were not included in that survey. It is unknown what percent of the pavements constructed during these years had been overlaid at the time of the survey. The age of the pavements ranged from 1 to 26 years, but was not considered as a parameter when evaluating these pavements.

The 1951–1952 survey was conducted on bare concrete pavements constructed between 1921 and 1949 (3 to 31 years old) and overlaid pavements constructed between 1919 and 1937 (15 to 33 years old). The age of pavement was identified as a parameter, with the older pavements receiving the poorer ratings.

The 1964–1965 survey was conducted on bare concrete pavements constructed between 1921 and 1964 (1 to 44 years old). Overlaid pavements were not included in that survey. The age of pavement was identified as a parameter, with some pavements less than five years old receiving poor ratings.

The 1980 survey was conducted on bare concrete pavements constructed between 1961 and 1974 (6 to 19 years old). The report on the 1980 study estimated that 40% of the pavement constructed in those years had already been overlaid by the time of the survey. Of the pavements surveyed in the 1980 survey, 29% exhibited D-cracking. Therefore, an estimated 57% of all the pavements constructed during this time period were either overlaid, or exhibited D-cracking before 20 years.

The 2009–2010 survey was conducted on concrete pavements containing limestone constructed between 1979 and 2000 (10 to 31 years old), and included overlaid pavements. Fourteen percent of the pavement constructed during these years had been overlaid. The condition of the pavements at the time of the overlay was determined with historical records.

The 2009–2010 survey used a different rating system than the previous studies. Pavements were evaluated either yes, D-cracking does exist, or no, D-cracking does not exist. These two criteria were used because D-cracking cannot be stopped or reversed, therefore once D-cracking is identified, the useable life of that pavement becomes limited and maintenance action must be taken. The pavements were further separated into those that were under 20 years old and those that were 20 years old or older.

3.7.2 Limited Success of the Current Specification

KDOT's current specification has improved the D-cracking performance of the concrete pavements in Kansas. The 1980 survey estimated that 57% of all the miles of the pavements (including those containing no limestone) constructed between 1961 and 1974 had either been overlaid or exhibited D-cracking before 20 years. The results for the other 43% were inconclusive because they were less than 20 years old and the reason for the overlays was not determined. The 2009–2010 survey indicated that 24% of the lane-miles of pavements containing limestone D-cracked before 20 years, and 42% are inconclusive (not yet 20 years old). The 57% failure rate in 1980 versus the 24% failure rate in 2009–2010 demonstrates the current specification is having some effect in controlling the D-cracking. It is generally accepted that

95% of the concrete pavements would last 20 years before D-cracking under the current aggregate specifications. The current data shows that 95% of the concrete pavements in this study lasted 11 years.

TABLE 3.15
Comparison of KDOT D-Cracking Studies

	Year[†††]				2009–2010 study[††]		
Rating	**1944–45**	**1951–52**	**1964–65**	**1980[†]**	**< 20 yrs old**	**> 20 yrs old**	**Rating**
Good	54%	65%	74%	86 %	42% Inconclusive	26% Success	No D-Cracking
Fair	8%	¥	8%	11 %	24% Failure	8% Success	Yes D-cracking
Poor	38%		18%	3 %			

¥ Only rated as good or "otherwise"
† Survey of 279 miles that were not overlaid. Forty percent of the concrete paving miles on the state system constructed between 1961 and 1974 had already been overlaid and were not included in the survey
††Results are based on lane-miles.
†††Results are in miles.

Exhibited life can be defined as the minimum (shortest) life of all the "successful" (acceptable) projects for a given acceptable failure rate. Projects (pavements) that failed at the youngest ages failed first and are assumed to be members of the set of "failing" projects.

In the current study, for example, the failure rate is 31%. The youngest age that a project failed was nine years and the oldest age that a pavement failed was 19 years. The minimum age of the remaining "successful" (acceptable) projects is 20 years (the design life for PCCP in Kansas). This 20-year age represents the exhibited life for a failure rate of 31%. Reversing the analysis, if the failure rate is chosen to be 5% (instead of specifying the design life), then out of the 132 projects included in the study, the seven projects (5%) with the youngest (minimum) age at failure would be considered "failing" projects and the minimum age of all the remaining "successful" projects is 11 years. Therefore, the current exhibited life for a 5% failure rate (on a project basis) is 11 years.

3.8 D-Cracking, Durability Factor, Expansion, and Soundness Results

Production test results for the average, minimum, and maximum durability factor, expansion, and soundness, organized by year are provided in Appendix B, and the number of passing and failing production test results for each year, quarry, and set of beds are in Appendix E.

Although the current specifications have reduced the amount of D-cracking, the current aggregate testing does not fully predict field performance. It appears that projects may receive material with all passing test results, yet fail. It also appears there are projects that have been constructed from material with failing test results, yet passes. Freeze-thaw testing of concrete prisms (“beams”) is a generally accepted method of testing the durability of aggregate. As discussed in Section 3.6.2, however, these results indicate that in Kansas, field performance history is also necessary.

3.9 Geologic Units

As previously discussed, the 1944 survey indicated that most of the D-cracking was associated with limestone from the Argentine, Ervine Creek, Plattsmouth, and Stoner members while the 1951–1952 study again identified the Ervine Creek, Plattsmouth, and Stoner members as major contributors to D-cracking. The current study indicates that the correlations between D-cracking and Geologic unit may not be as strong as the earlier surveys had indicated. This may be, in part, because the durability testing requirements for the aggregate included in this study may have excluded failing material which was previously unidentified and used in the pavements.

3.9.1 Argentine (ARGN)

The current study indicates that only 30% of the PCCP constructed with limestone from the Argentine member has D-cracked before 20 years of life. The aggregate in one pavement (K-0461-01, on I-435 in Johnson County) constructed with the Argentine member came from a quarry that was not evaluated for Class 1 status, yet the pavement has served over 30 years with no D-cracking. This quarry discontinued operations soon after the project was constructed.

3.9.2 Stoner (STNR)

Four out of 13 PCCPs constructed with limestone from the Stoner member exhibited D-cracking before 20 years. This represents a 31% failure rate. However, all 4 of the D-cracked pavements were constructed with Stoner aggregate from Franklin County, and none of the 4 projects constructed with Stoner aggregate from Leavenworth County have D-cracked in over 20 years. The average life of the four Leavenworth County pavements is 26 years with no D-cracking.

3.9.3 Ervine Creek (EVCK)

The current survey indicates that 56% of the PCCP constructed with Ervine Creek aggregate has exhibited D-cracking before 20 years. Location may again be an important parameter with three of the five failures coming from quarry number 4-037-03 in Greenwood County.

3.9.4 Plattsmouth (PLSM)

Three of the criteria projects were constructed with limestone from the Plattsmouth member. One of those projects has lasted over 20 years without D-cracking, one has failed before 20 years, and the third is not yet 20 years old.

3.9.5 Cresswell (CRSL)

The influence of location (or county) of the quarry is best illustrated by examining the Cresswell member in Dickinson and Marion Counties. There have been nine projects that have D-cracked before 20 years that were constructed with limestone from the Cresswell member in Marion County. No projects constructed with limestone from the Cresswell member in Marion County have lasted 20 years without D-cracking. There have been three projects that have not D-cracked after 20 years that were constructed with limestone from the Cresswell member in Dickinson County. No projects constructed with limestone from the Cresswell member in Dickinson County have D-cracked before 20 years. Three of the projects are not yet 20 years old.

3.9.6 Distance from Quarries with Unacceptable Performance

A preliminary analysis of failures from geologic members in quarries located in adjacent counties indicates that in some cases, such as the Ervine Creek member in Elk and Greenwood counties, high failure rates correspond with material from the same geologic member and from adjacent counties. For Ervine Creek, five of eight projects have failed and three are inconclusive.

As discussed previously, all the projects constructed from the Dickinson county Cresswell member (three quarries) have passed, while all the projects constructed from the Marion county Cresswell member (two quarries) have failed.

KDOT should consider eliminating adjacent quarries or quarries in the immediate vicinity of quarries with unacceptable field performance. KDOT should develop a definition of "vicinity quarries."

3.10 Petrographic Analysis

In addition to D-cracking, there exists strong indication of other secondary destructive reactive mechanisms, possibly ASR or ACR, in locations where D-cracking surface patterns are present. Deterioration by this reactivity alone (ASR, ACR, etc.), in this study and in general, does not appear to be a significant problem in PCCP in Kansas. In the past, KDOT implemented measures to control ASR through long-term wetting and drying testing of siliceous aggregate sources, and other testing.

For the projects in this study, the cracking in the areas of surface distress were typical D-cracking patterns, as described in Section 1.1. The cores taken at locations away from the D-cracking surface patterns exhibited only small amounts of reactive mechanisms inside the cores and no evidence of deterioration around the few pieces of limestone aggregate with reaction rings. Also, at the locations of these cores, there were no signs of deterioration at the pavement surface or in the interior of the concrete pavement. Because of the lack of evidence of reactivity away from the D-cracking patterns, the pattern of the joint cracking itself (D-cracking pattern), and the lack or absence of other crack patterns, such as ASR, at or away from joints, it is apparent that the dominant and initial cracking is from D-cracking.

It is likely that the initial D-cracks allow increased amounts of water to enter the pavement thus initiating or accelerating other destructive reactive mechanisms, accelerating D-cracking damage, and increasing the overall rate of pavement deterioration at these locations. It is apparent that the destructive reactivity does exist in combination with the D-cracking, and is probably due to increased water penetration caused by the D-cracking. For the cores in this study, D-cracking appears to be the primary mechanism and the other reactive mechanisms appear to be subsidiary.

3.11 Analysis of Additional Parameters

Some have proposed that parameters other than the coarse aggregate material source may contribute to or accelerate D-cracking. These parameters include the percent of coarse aggregate, the joint spacing, the joint sealants, the use of dowel bars, the type of base under the pavement, and the use of lime treated subgrade. Many of these parameters can be discounted by comparing the 1980 survey to the 2009–2010 survey.

A review of the design history in section 1.4.3 and the difference in the failure rates between the 1980 survey, 57%, and the 2009–2010 survey, 24%, makes it difficult to conclude that cement-treated bases, bituminous-treated bases, bound-drainable bases, 30 ft and 15 ft joint spacing, dowel bars, or silicone joint sealant contribute to D-cracking. Each of these parameters will be discussed separately and results provided on a project basis.

3.11.1 Joint Spacing and Orientation

The pavements in this study were constructed with one of three types of spacing and/or joint orientation.

3.11.1.1 30 Ft Transverse Normal Joints

Thirty criteria projects were identified as being constructed with 30 ft joint spacing, oriented normal (perpendicular) to the centerline. Three of the projects exhibited D-cracking before 20 years, as shown in Figure 3.11. This represents a failure rate of 10% of the projects, which is well below the 31% overall failure rate in the 2009–2010 survey.

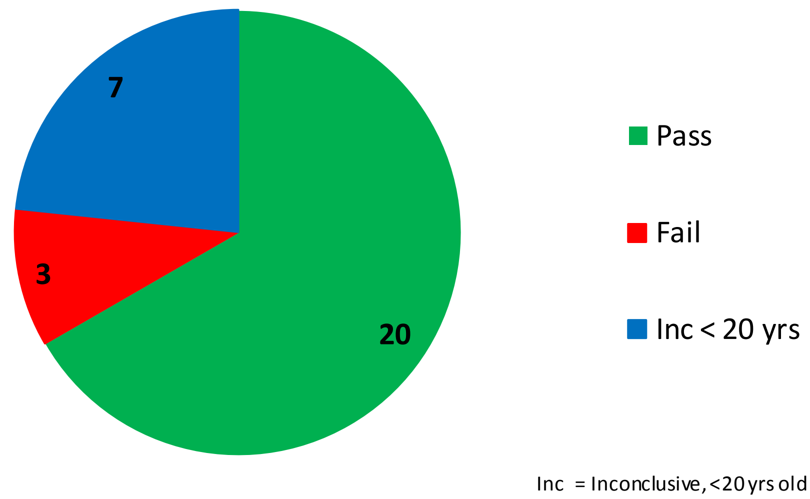

FIGURE 3.11
Results for the 30 Criteria Projects with 30 Ft Transverse Normal Joints

Two of the three failed projects (67%) with 30 ft joint spacing also contain aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.12. Because of the low overall failure rate and the high percentage of failures that also contain material from at least one of the nine quarries, the failures are likely due to the aggregate source material rather than the 30 ft joint spacing.

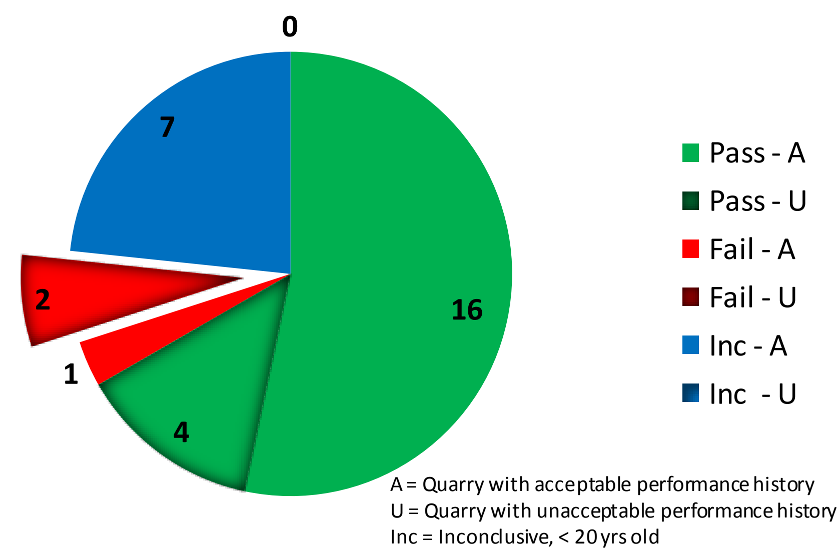

FIGURE 3.12
Results for 30 Ft Transverse Normal Joints by Quarry Performance Category

3.11.1.2 15 Ft Skewed Joints

Thirty-three criteria projects were identified as being constructed with 15 ft skewed joints. Five of the projects exhibited D-cracking before 20 years as shown in Figure 3.13. This represents a failure rate of 15%, which is below the 31% overall failure rate in the 2009–2010 survey.

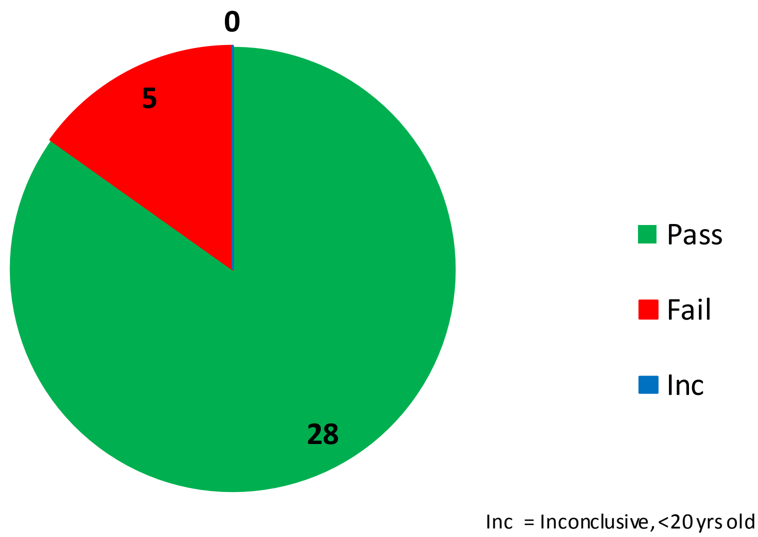

FIGURE 3.13
Results for the 33 Criteria Projects with 15 Ft Skewed Joints

None of the failed projects with 15 ft skewed joint spacing received aggregate from any of the nine quarries with unacceptable field performance as shown in Figure 3.14. Only one of the 28 successful projects (4%) contained material from at least one of the nine quarries with unacceptable field performance. Because of the low overall failure rate and the very low percentage of successful projects that contain material from the nine quarries, 15 ft skewed joint spacing does not appear to contribute to or prevent D-cracking.

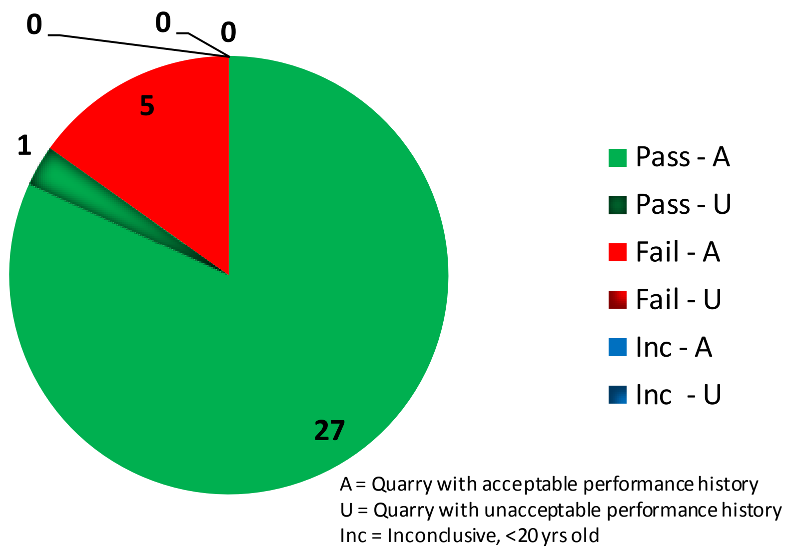

FIGURE 3.14
Results for 15 Ft Skewed Joints by Quarry Performance Category

3.11.1.3 15 Ft Transverse Normal Joints

Seventy criteria projects were identified as being constructed with 15 ft transverse normal joints. Thirty-four of the projects exhibited D-cracking before 20 years, as shown in Figure 3.15. This represents a failure rate of 49%, which is higher than the 31% overall failure rate in the 2009–2010 survey.

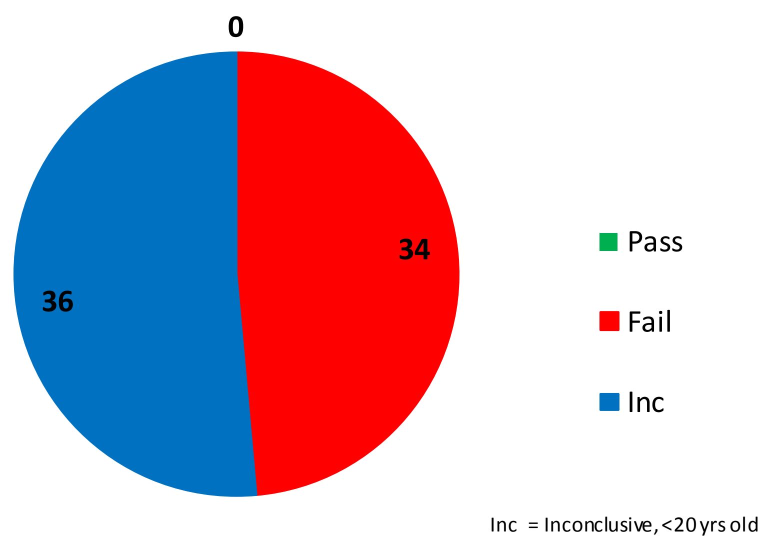

FIGURE 3.15
Results for the 70 Criteria Projects with 15 Ft Transverse Normal Joints

For the failing projects with 15 ft normal joint spacing, 79% received aggregate from the nine quarries with unacceptable field performance, as shown in Figure 3.17. Because there were a large percentage of the failed projects and a no successful projects that contained material from the nine quarries, it is therefore likely that the failures were due to the aggregate source material rather than the 15 ft normal joint spacing. Because none of the projects with 15 ft normal joints were 20 years old at the time of the survey, none had a successful result.

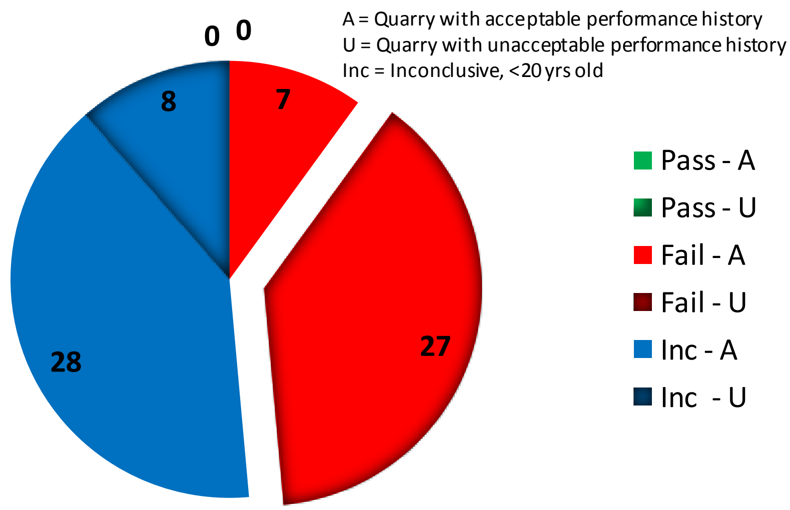

FIGURE 3.16
Results for 15 Ft Transverse Normal Joints by Quarry Performance Category

3.11.1.4 Discussion of Joint Spacing

The results for joint spacing are shown in Figure 3.18 and 3.19, and are best discussed in relation to the construction era (see Figure 3.3), and the KDOT history of joint design (Section 1.4.3.1).

For the projects constructed with 30 ft joint spacings, 30 of 32 were constructed before 1992. This construction era had a low overall failure rate of 15%, which helps to explain the large number of "pass" results for the projects with 30 ft joint spacing for both quarries performance categories, Figure 3.5 and 3.18.

The projects with 15 ft skewed were all constructed before 1990. Because this construction era had a low overall failure rate of 11% (see Figure 3.3) and only one project was constructed with 15 ft skewed joints and contained material from at least one of the quarries with unacceptable field performance, it is therefore likely that the high success rate is due to the absence of material with unacceptable field performance as well as other factors contributing to overall high success rate of the era, discussed previously in Section 3.0, such as better quarry monitoring and overall demand due to rate of construction.

The projects with 15 ft normal joints were all constructed since 1990. Therefore, there are no “pass” results because all the projects are less than 20 years old. Because these projects were constructed in an era with a much higher overall failure rate of 44% and the fact that 27 of the 34 failures contained material from the quarries with unacceptable field performance, the higher failure rate for the projects constructed with 15 ft normal joints, is therefore likely due to the construction era and unacceptable field performance material and not the joint design.

To summarize, no clear correlation between the presence of D-cracking and joint design is observed. It is likely that other contributing factors influenced the numbers of “pass” and “fail” results and not the joint design.

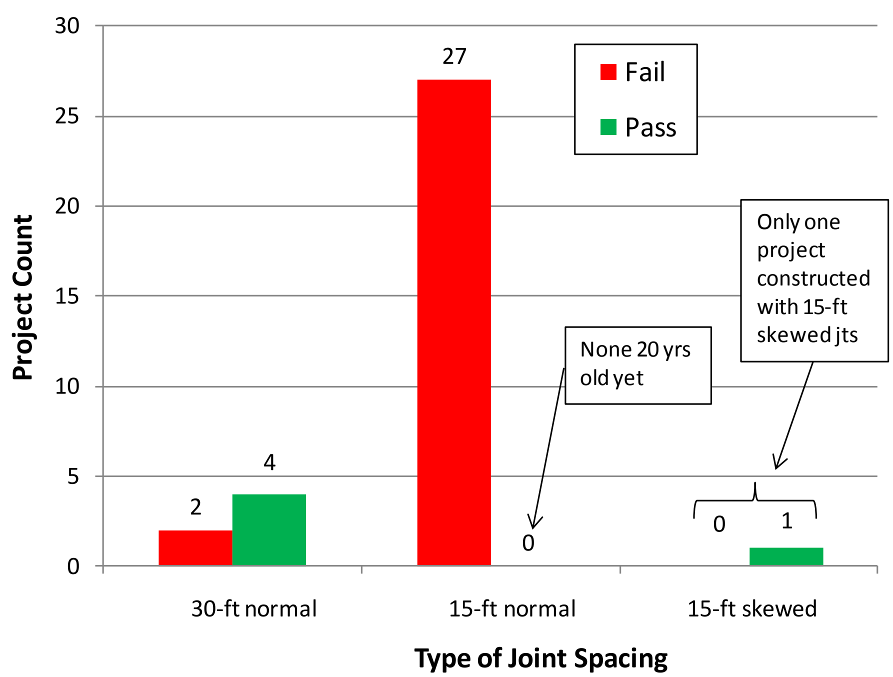

FIGURE 3.17
Results for Type of Joint Spacing and Orientation for Projects Containing Material from at Least One of the Nine Quarries with Unacceptable Field Performance

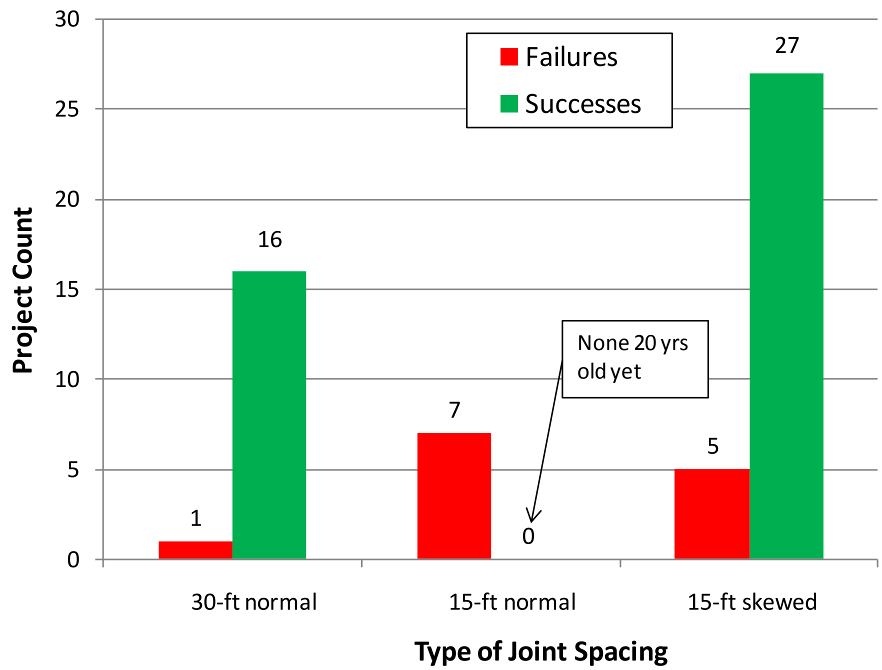

FIGURE 3.18
Results for Type of Joint Spacing and Orientation for Projects Containing Material from the 44 Quarries with Acceptable Field Performance

3.11.2 Joint Sealant

Three types of joint sealant were used for the projects in this study: hot pour, silicone, and neoprene. The original joint sealant could not be determined for four of the criteria projects. These four projects did not exhibit D-cracking.

3.11.2.1 Hot Pour Joint Sealant

Ten criteria projects were identified as being constructed with backer rod and hot pour joint sealant. Only 1 of the 10 projects exhibited D-cracking before 20 years, as shown in Figure 3.19. This represents a failure rate of 10%, which is well below the 31% overall failure rate in the 2009–2010 survey.

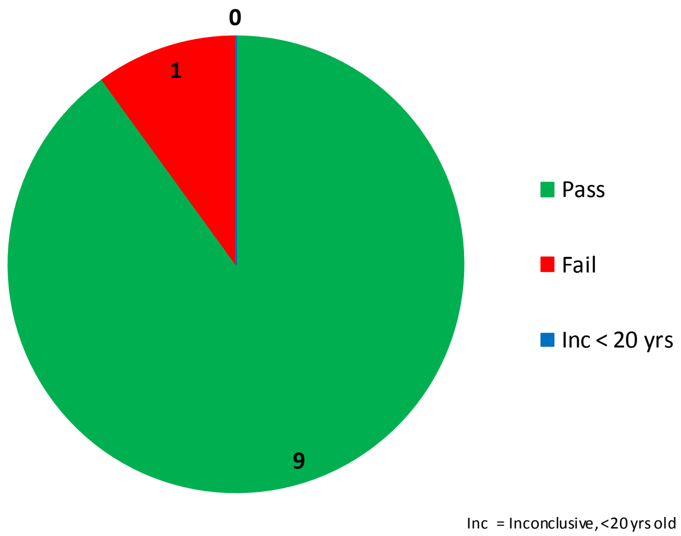

FIGURE 3.19
Results for the 10 Criteria Projects with Hot Pour Joint Sealant

The one failing projects with hot pour joint sealant did not receive aggregate from any of the nine quarries with unacceptable field performance, as shown in Figure 3.20. Since the failure rate for hot pour is approximately 1/3 of the overall failure rate and none of the projects contained any material from the nine quarries with unacceptable field performance, the low failure rate is therefore likely due to the absence of the material from the nine quarries with unacceptable field performance.

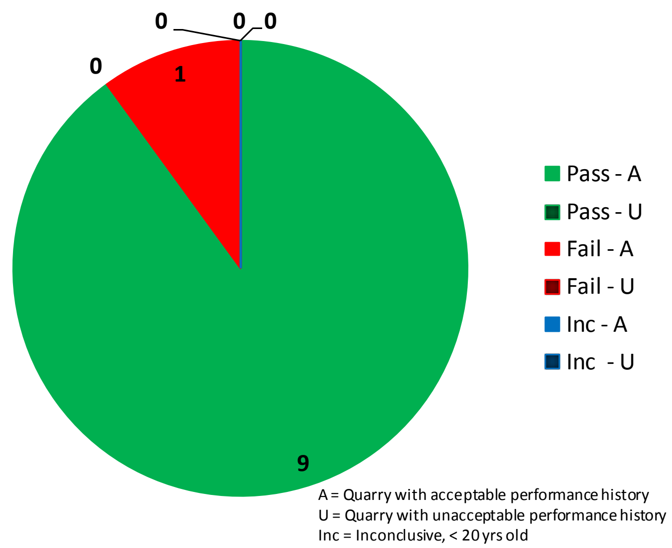

FIGURE 3.20
Results for Hot Pour Joint Sealant by Quarry Performance Category

3.11.2.2 Silicone Joint Sealant

Seventy-four criteria projects were identified as being constructed with backer rod and silicone joint sealant. Twenty-one of the projects exhibited D-cracking before 20 years as shown in Figure 3.21. This represents a failure rate of 28%, which is comparable to the 31% overall failure rate in the 2009–2010 survey.

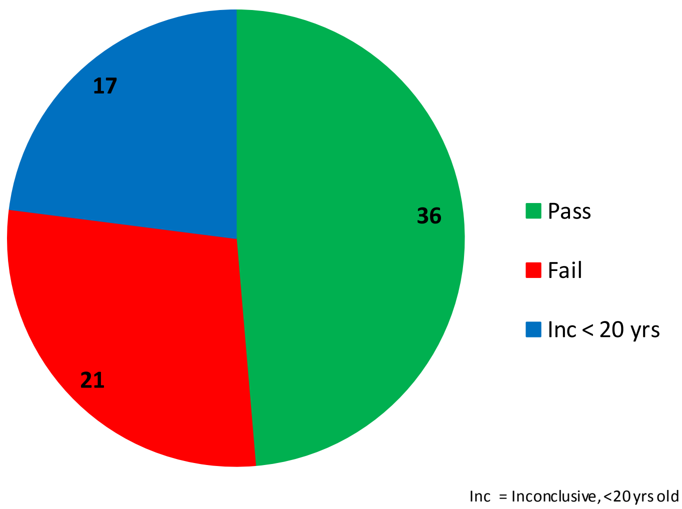

FIGURE 3.21
Results for the 74 Criteria Projects with Silicone Joint Sealant

For the projects with silicone joint sealant, 52% of the failed projects received aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.22. Because a large percentage of the failed projects and a very small percentage of the successful projects contained material from the nine quarries with unacceptable field performance, it is therefore likely that the failures were due to the aggregate source material rather than the silicone joint sealant.

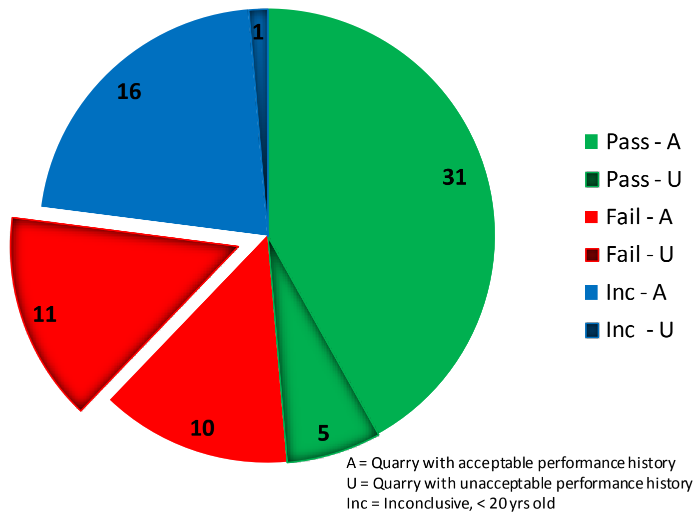

FIGURE 3.22
Results for Silicone Joint Sealant by Quarry Performance Category

3.11.2.3 Neoprene Joint Sealant

Forty-five criteria projects were identified as being constructed with neoprene joint sealant. Twenty of the projects exhibited D-cracking before 20 years, as shown in Figure 3.23. This represents a failure rate of 44%, which is above the 31% overall failure rate in the 2009–2010 survey. There were no projects with a "pass" result because none of the projects were 20 years old yet.

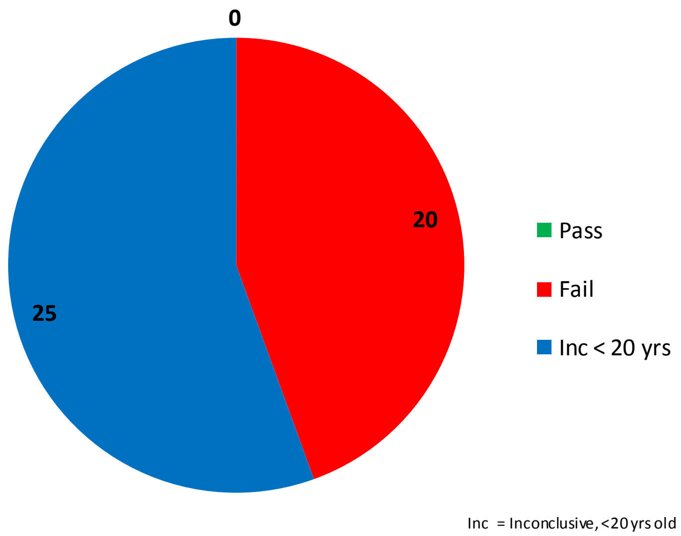

FIGURE 3.23
Results for the 45 Criteria Projects with Neoprene Joint Sealant

For the projects with neoprene joint sealant, 90% of the failed projects received aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.24. Because 90% of the failed projects contained material from at least one of the nine quarries with unacceptable field performance, it is unlikely that the failures are due to the neoprene joint sealant.

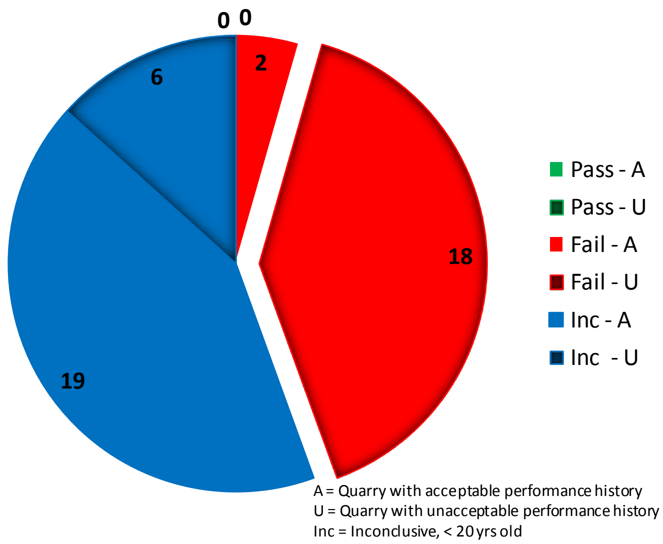

FIGURE 3.24
Results for Neoprene Joint Sealant by Quarry Performance Category

3.11.2.4 Discussion of Joint Sealant

As shown in Figure 3.25, the results of this study show the number of "fail" results was much higher than the number of "pass" results for projects built with material from at least one of the nine quarries with unacceptable field performance. Figure 3.26 indicates that the opposite is also generally true. The number of "pass" results is considerably higher than the number of "fail" results for hot pour and silicone joint sealant projects built with material from the 44 quarries with acceptable field performance. There were no "pass" results for neoprene because none of the projects were 20 years old yet.

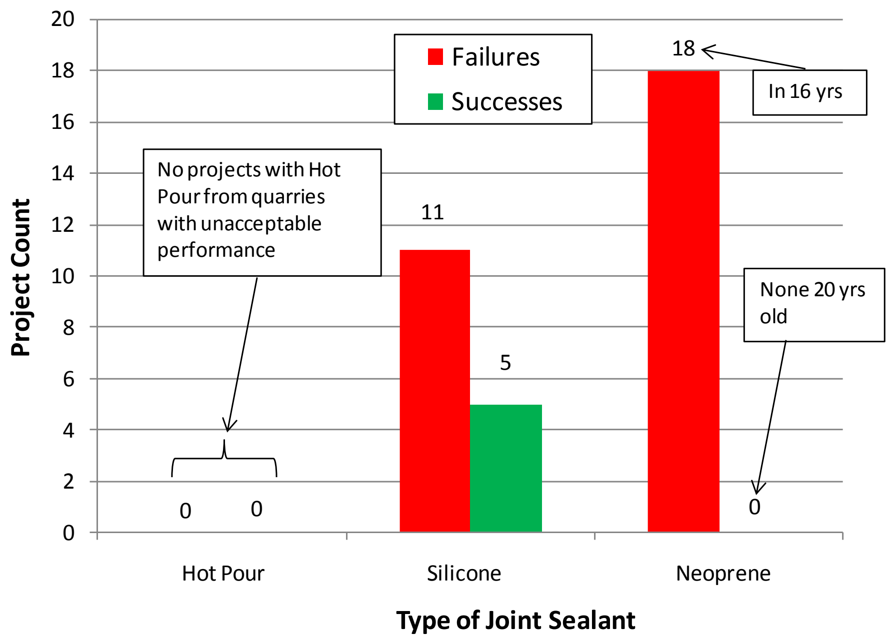

FIGURE 3.25
Results for Joint Sealant for Projects Containing Material from at Least One of the Nine Quarries with Unacceptable Field Performance

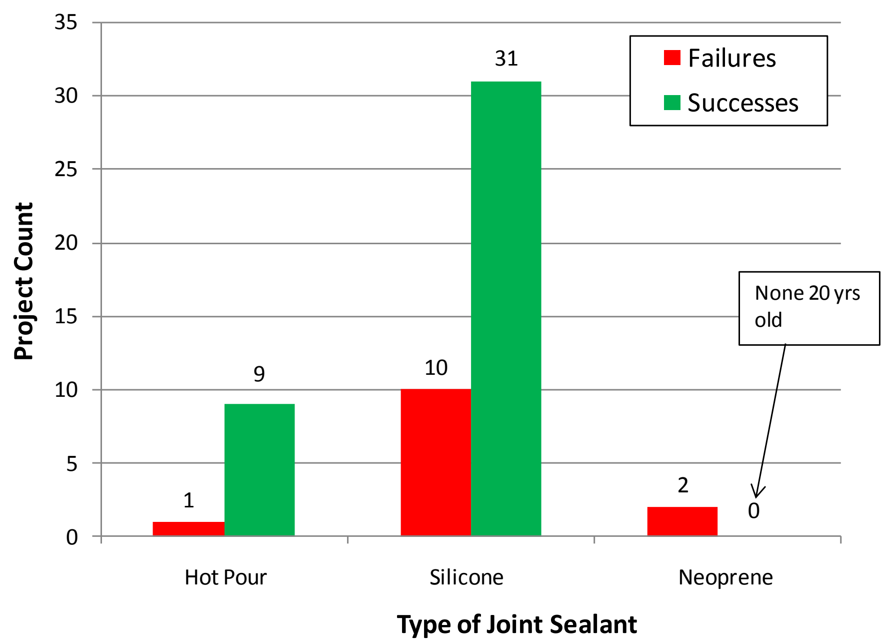

FIGURE 3.26
Results for Joint Sealant for Projects Containing Material from the 44 Quarries with Acceptable Field Performance

3.11.3 Base/Subgrade

Three categories of base and/or subgrade were examined in this study: lime-treated subgrade (LTSG), bound drainable base (BDB), and Portland Cement treated base (PCTB). Each is examined individually.

3.11.3.1 Lime-Treated Subgrade

Ninety-one criteria projects were identified as being constructed with LTSG. Many of the projects with LTSG were also constructed with BDB or PCTB. Thirty-two of the projects exhibited D-cracking before 20 years, as shown in Figure 3.27. This represents a failure rate of 35%, which is comparable to the 31% overall failure rate in the 2009–2010 survey.

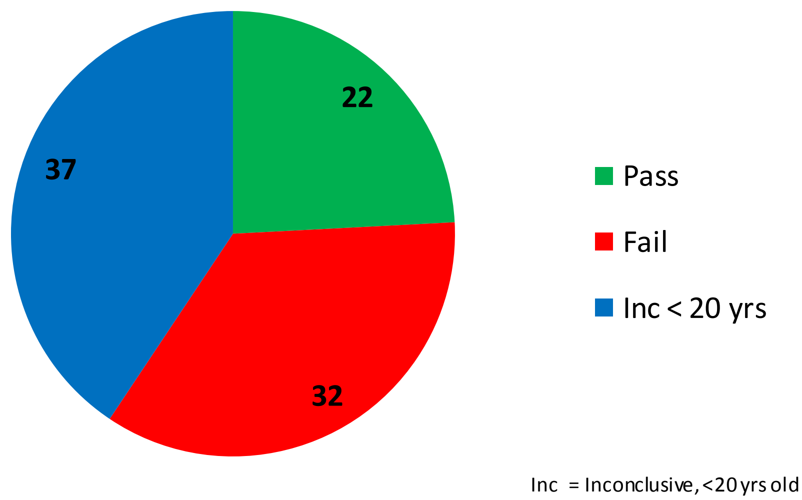

FIGURE 3.27 Results for the 91 Criteria Projects with Lime-Treated Subgrade

For the projects with LTSG, 78% of the failed projects received aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.28. Because a large percentage of the failed projects and a very small percentage of the successful projects contained material from at least one of the nine quarries with unacceptable field performance, it is therefore likely that the failures are due to the aggregate source material rather than the LTSG.

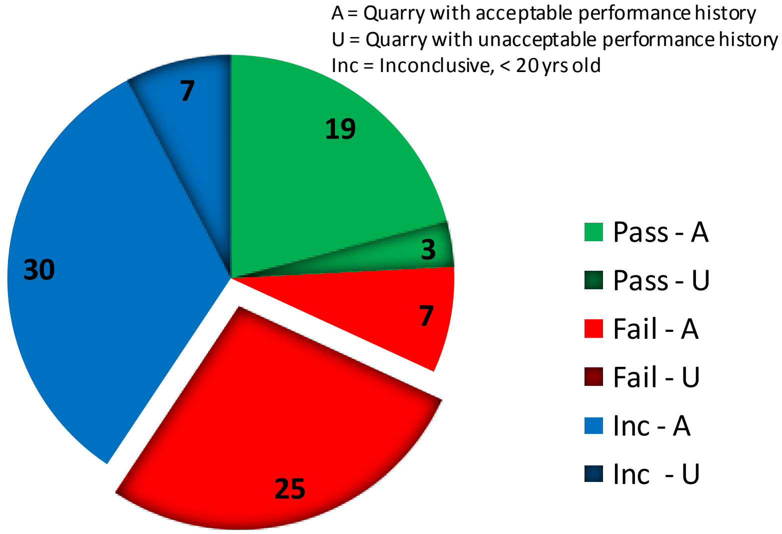

FIGURE 3.28
Results for Lime-Treated Subgrade by Quarry Performance Category

3.11.3.2 Bound Drainable Base

Forty-four criteria projects were identified as being constructed with BDB. Twenty of the projects exhibited D-cracking before 20 years, as shown in Figure 3.29. This represents a failure rate of 45%, which is higher than the 31% overall failure rate in the 2009–2010 survey.

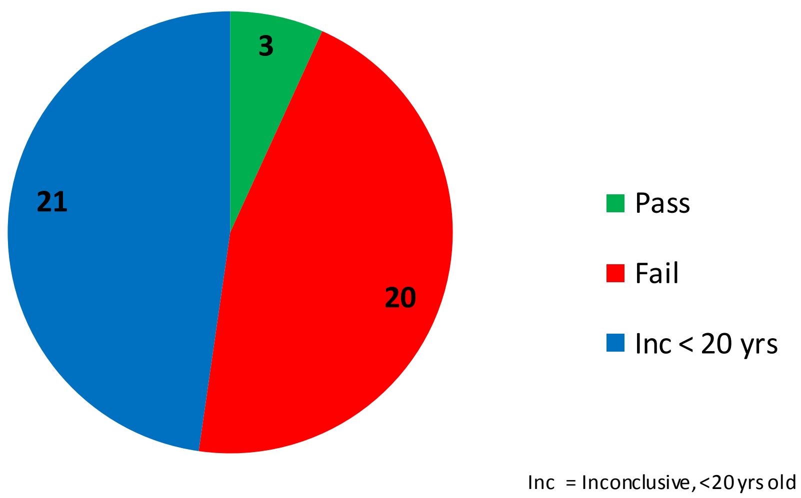

FIGURE 3.29
Results for the 44 Criteria Projects with Bound Drainable Base

For the projects with BDB, 90% of the failed projects received aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.30. Because a large percentage of the failed projects contained material from at least one of the nine quarries with unacceptable field performance, it is therefore likely that the failures were due to the aggregate material source rather than the BDB.

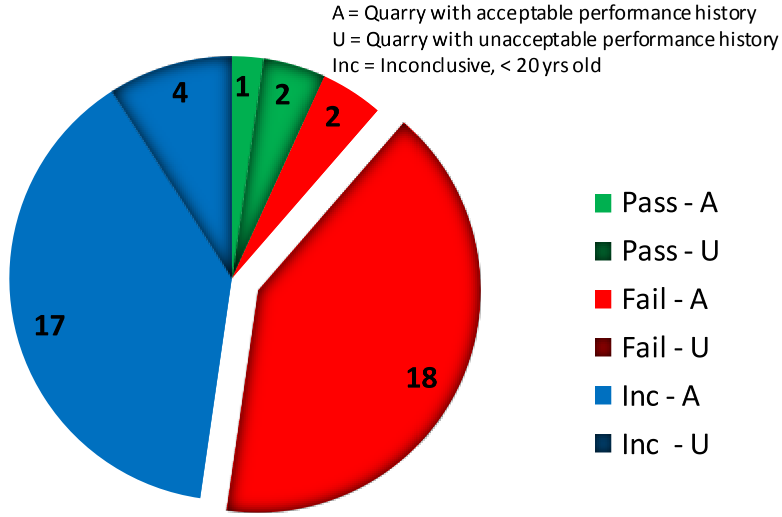

FIGURE 3.30
Results for Bound Drainable Base by Quarry Performance Category

3.11.3.3 Portland Cement Treated Base

Sixty-six criteria projects were identified as being constructed with PCTB. Nineteen of the projects exhibited D-cracking before 20 years, as shown in Figure 3.31. This represents a failure rate of 29%, which is comparable to or lower than the 31% overall failure rate in the 2009–2010 survey.

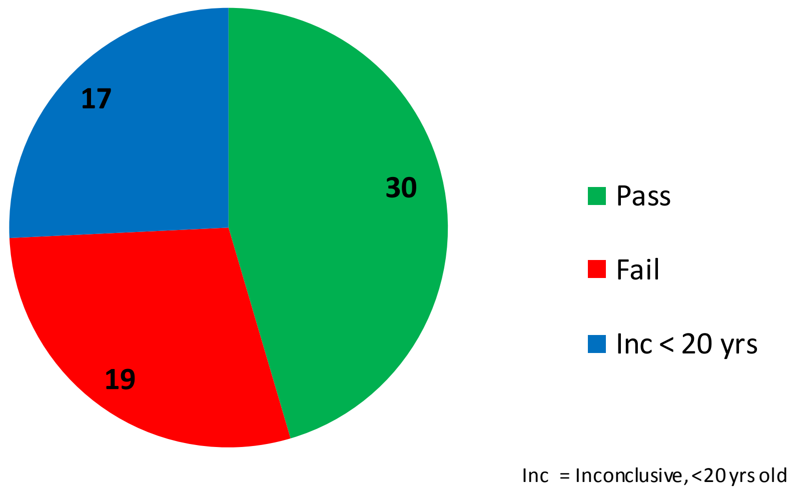

FIGURE 3.31
Results for the 66 Criteria Projects with Portland Cement Treated Base

For the projects with PCTB, 47% (9 of 19) of the failed projects contained aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.32. Since the PCTB failure rate is comparable to the overall failure rate and nearly half of the failures with PCTB received aggregate from the nine quarries with unacceptable field performance, there is nothing to indicate that PCTB contributes to D-cracking. It is likely that failures were due to material source rather than PCTB.

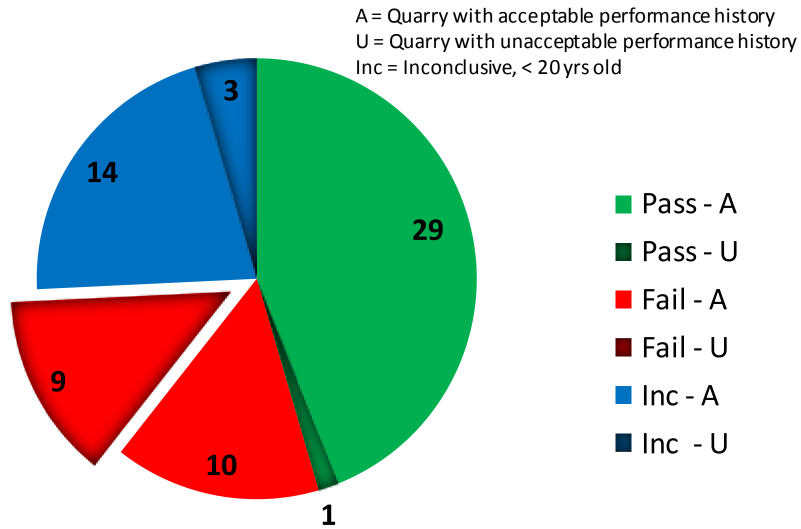

FIGURE 3.32
Results for Portland Cement Treated Base by Quarry Performance Category

3.11.3.4 Discussion of Base/Subgrade

As shown in Figure 3.33, for this study the number of "fail" results was much higher than the number of "pass" results for projects containing material from at least one of the nine quarries with unacceptable field performance, regardless of base/subgrade. Figure 3.34 indicates that the opposite is also generally true. The number of "pass" results was considerably higher than the number of "fail" results for projects containing material from the 44 quarries with acceptable field performance except BDB for which the results were nearly the same.

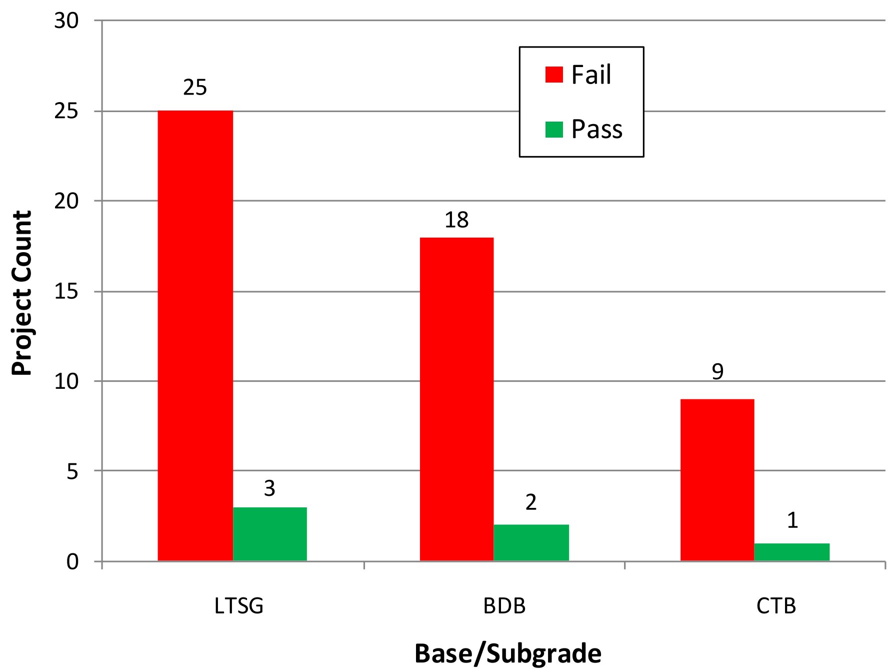

FIGURE 3.33
Results for Base/Subgrade for Projects Containing Material from at Least One of the Nine Quarries with Unacceptable Field Performance

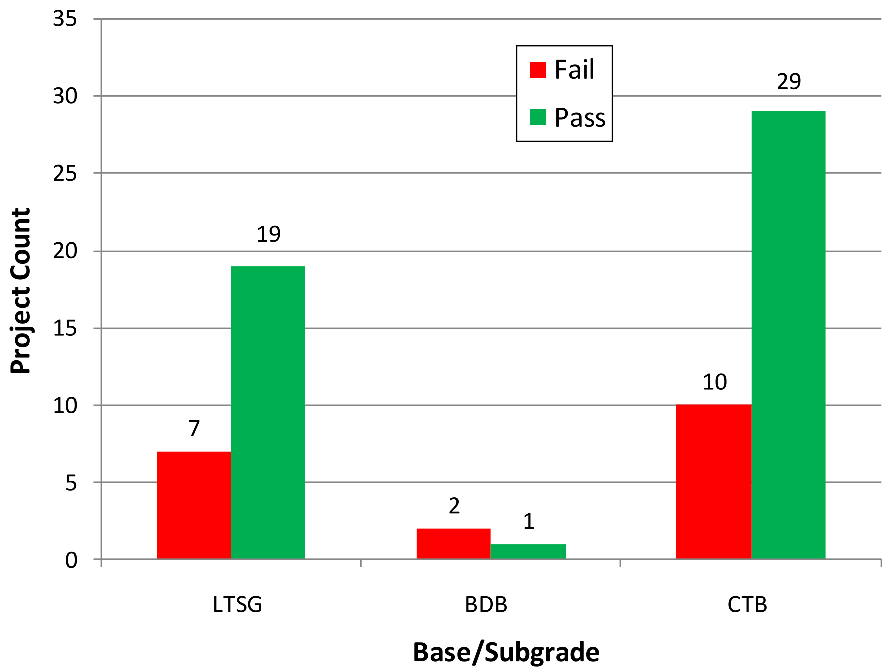

FIGURE 3.34
Results for Base/Subgrade for Projects Containing Material from the 44 Quarries with Acceptable Field Performance

3.11.4 Combinations of Joint Sealant and Base Type

Fifty-nine criteria projects were constructed with silicone joint sealant and either BDB or PCTB. There are 41 projects that were constructed with neoprene joint sealant and either BDB or PCTB.

3.11.4.1 Silicone and Bound Drainable Base

Fifteen projects were identified as being constructed with silicone joint sealant and BDB. Eight of the 15 projects exhibited D-cracking before 20 years, as shown in Figure 3.35. This represents a failure rate of 53%, which is higher than the 31% overall failure rate in the 2009–2010 survey.

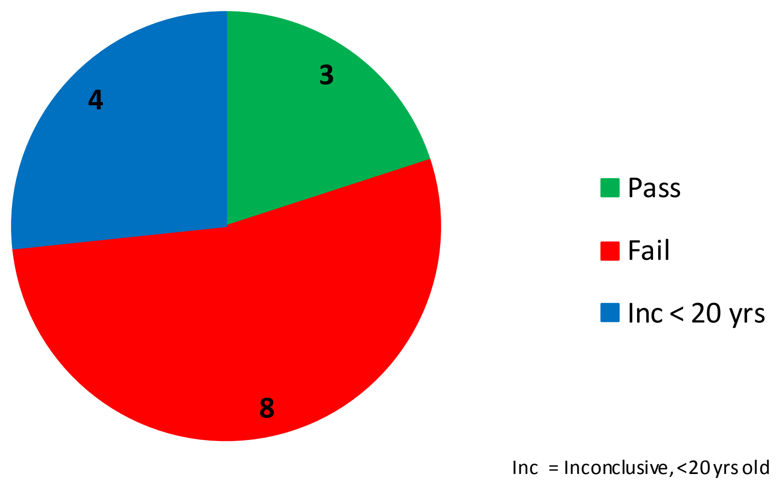

FIGURE 3.35
Results for the 15 Criteria Projects with Silicone and Bound Drainable Base

For the projects constructed with silicone and BDB, 88% of the failed projects contained aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.36. Even though the failure rate for this combination of parameters is higher than the overall failure rate, the large percentage of failed projects containing material from at least one of the nine quarries with unacceptable field performance indicates the failures were likely due to the aggregate material source rather than the silicone and BDB combination.

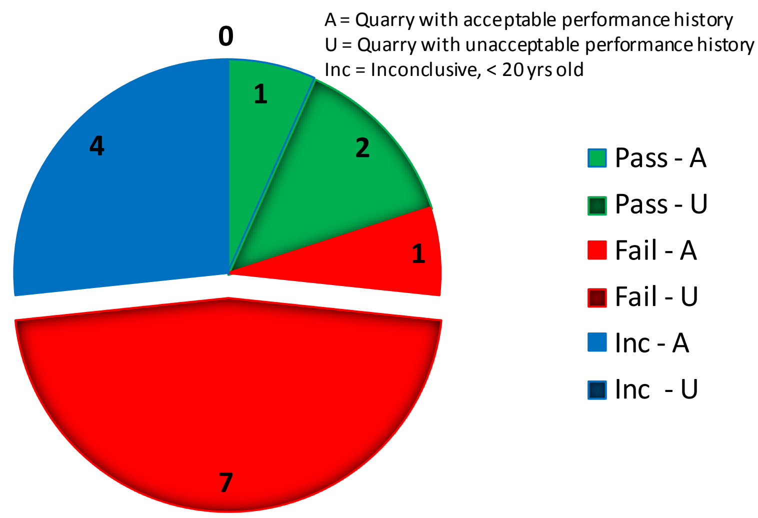

FIGURE 3.36
Results for Silicone and Bound Drainable Base by Quarry Performance Category

3.11.4.2 Silicone and Portland Cement Treated Base

Forty-four projects were identified as being constructed with silicone joint sealant and PCTB. Twelve of the projects exhibited D-cracking before 20 years, as shown in Figure 3.37. This represents a failure rate of 27%, which is lower than but comparable to the 31% overall failure rate in the 2009–2010 survey.

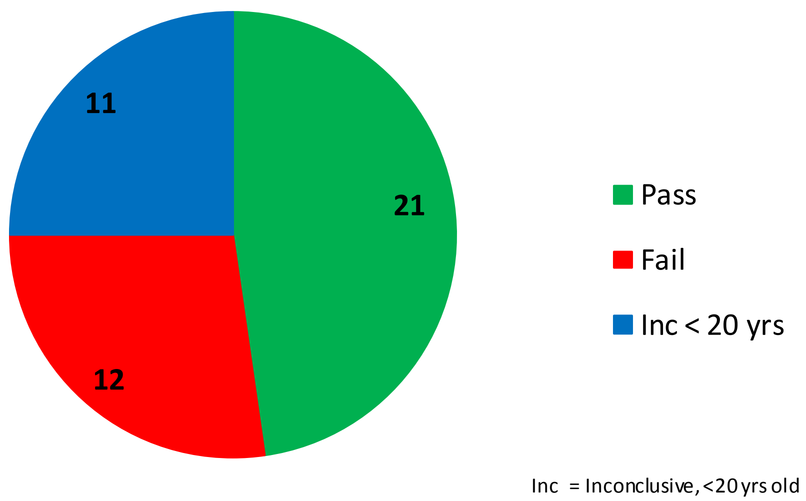

FIGURE 3.37
Results for the 44 Criteria Projects with Silicone and Portland Cement Treated Base

For the projects constructed with silicone and PCTB, 33% (4 of 12) of the failed projects contained aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.38. Because the failure rate for this parameter combination is very similar to the overall failure rate, and only one of 21 projects with a "pass" result contained material from the quarries with unacceptable field performance, it is likely that the higher "pass" was due to an absence of unacceptable material rather than the joint sealant and base design.

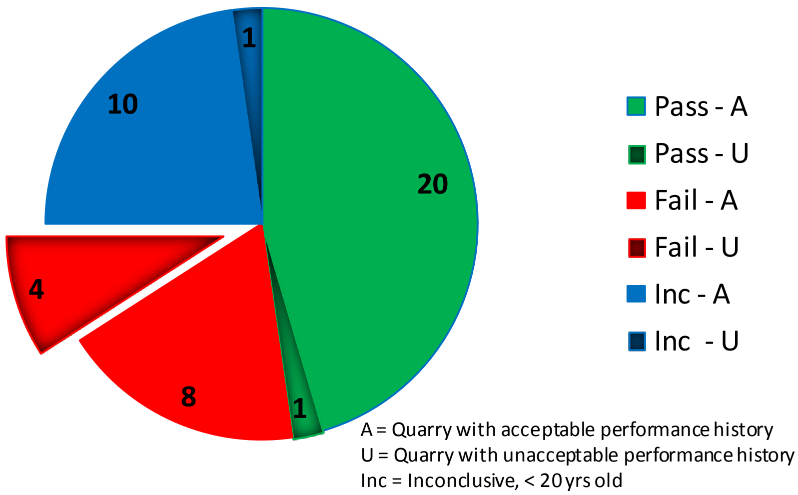

FIGURE 3.38
Results for Silicone and Portland Cement Treated Base by Quarry Performance Category

3.11.4.3 Neoprene and Bound Drainable Base

Twenty-nine projects were identified as being constructed with neoprene joint sealant and bound drainable base. Twelve of the projects exhibited D-cracking before 20 years, as shown in Figure 3.39. This represents a failure rate of 41%, which is higher than the 31% overall failure rate in the 2009–2010 survey. There were no projects with a "pass" result because none were 20 years old yet.

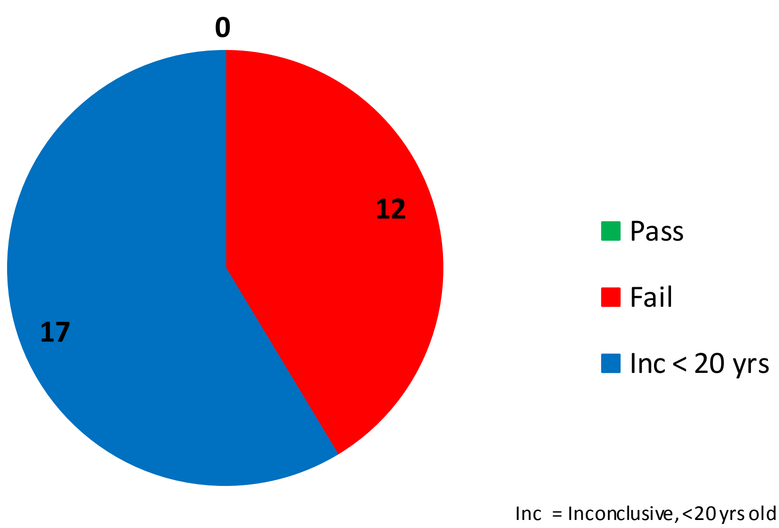

FIGURE 3.39
Results for the 29 Criteria Projects with Neoprene and Bound Drainable Base

For the projects with neoprene and BDB, 92% of the projects with a "fail" result contained aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.40. Because a very large percentage of all the "failed" projects contained material from at least one of the nine quarries with unacceptable field performance, it is likely that the failures were due to the aggregate material source and not the combination of neoprene and BDB.

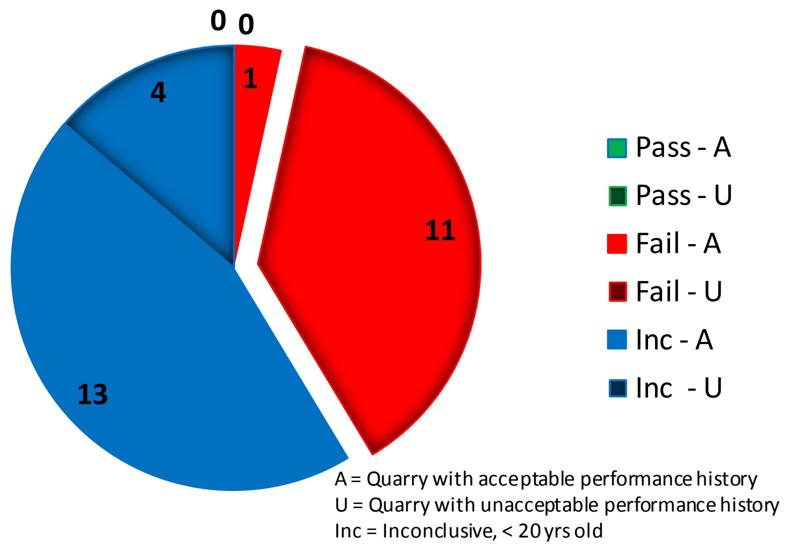

FIGURE 3.40
Results for Neoprene and Bound Drainable Base by Quarry Performance Category

3.11.4.4 Neoprene and Portland Cement Treated Base

Twelve of the projects were identified as being constructed with neoprene joint sealant and PCTB. Six of the projects exhibited D-cracking before 20 years, as shown in Figure 3.41. This represents a failure rate of 50% which is higher than the 31% overall failure rate in the 2009–2010 survey. There were no projects with a "pass" result because none were 20 years old yet.

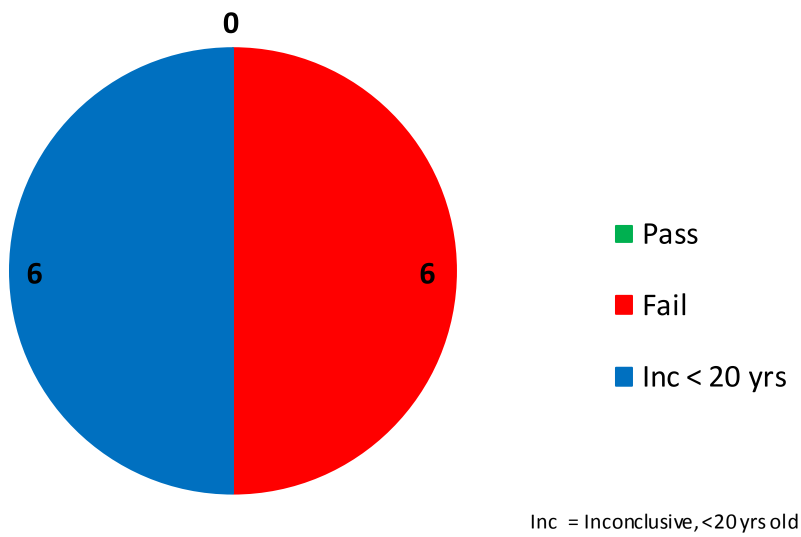

FIGURE 3.41
Results for the 12 Criteria Projects with Neoprene and Portland Cement Treated Base

For the projects with neoprene and PCTB, 83% of the failed projects contained aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.42. The large percentage of failed projects containing material from at least one of the nine quarries with unacceptable field performance indicates that the failures are likely due to the aggregate material source and not the combination of neoprene and PCTB.

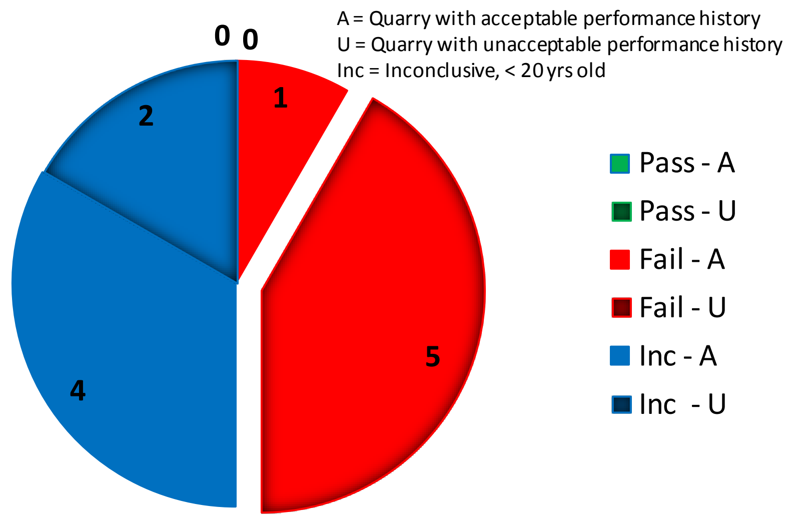

FIGURE 3.42
Results for Neoprene and Portland Cement Treated Base by Quarry Performance Category

3.11.4.5 Discussion of Sealant and Base Combinations

The young age of the projects with neoprene and BDB makes it difficult to draw strong conclusions. The oldest projects with neoprene are 15 years old, and the oldest projects with BDB are 20 years old with most of the BDB projects less than 20 years old. From the available data, we can make the following observations:

The results indicate that for projects constructed with silicone and either BDB or PCTB and containing material from at least one of the nine quarries with unacceptable field performance, the number of “fail” results is more than three times higher than the number of “pass” results, as shown in Figure 3.43. Figure 3.44 indicates that for the same combinations, the number of “pass” results is either the same or significantly larger than the number of “fail” results. The projects containing neoprene did not have any “pass” results due to their age, therefore for each design combination only the number of “fail” results can be compared between the two quarry performance categories. For both neoprene and either BDB or PCTB the number of “fail” results is at least five times higher for the quarries with unacceptable field performance (Figure 3.43) than for the quarries with acceptable field performance (Figure 3.44). The significantly higher number of “fail” results for projects containing material from the nine quarries with unacceptable field performance indicates that the failures are likely due to aggregate material source rather than any particular combination of joint sealant and base type.

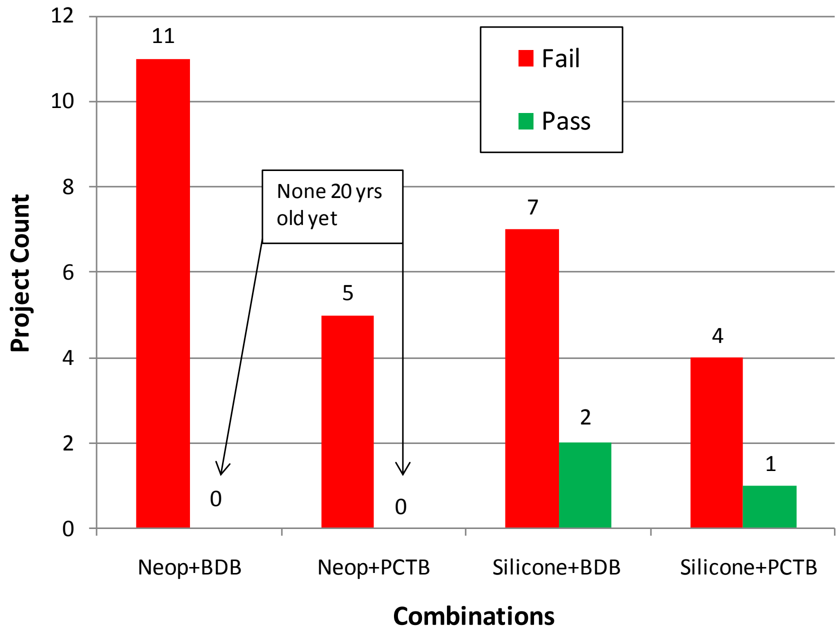

FIGURE 3.43
Results for Combinations of Joint Sealant and Base Type for Projects Containing Material from at Least One of the Nine Quarries with Unacceptable Field Performance

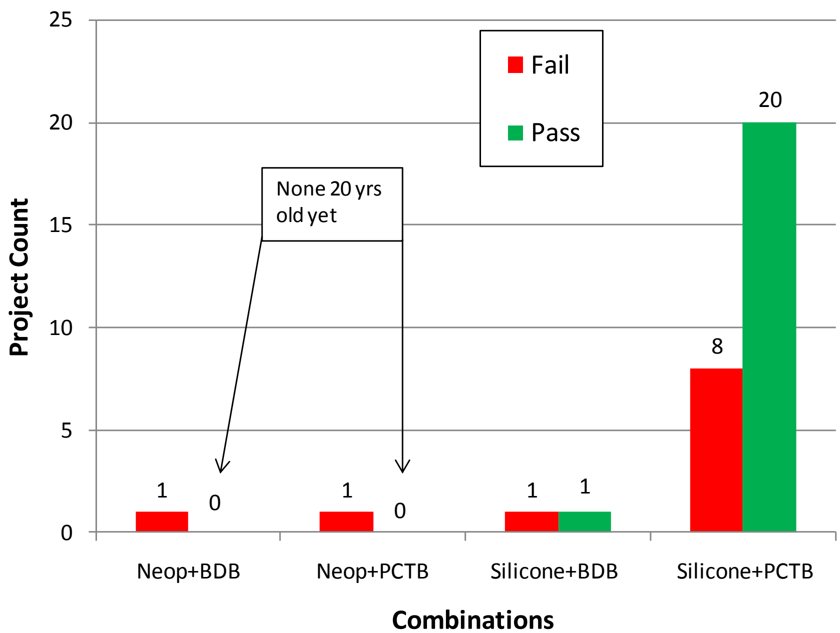

FIGURE 3.44
Results for Combinations of Joint Sealant and Base Type for Projects Containing Material from the 44 Quarries with Acceptable Field Performance

3.11.5 Limestone Content

Ninety-two criteria projects were identified as containing 30–36% limestone (by weight) in the concrete mixture. Thirty-one of the projects exhibited D-cracking before 20 years as shown in Figure 3.45. This represents a failure rate of 34%, which is higher but comparable to the 31% overall failure rate in the 2009–2010 survey.

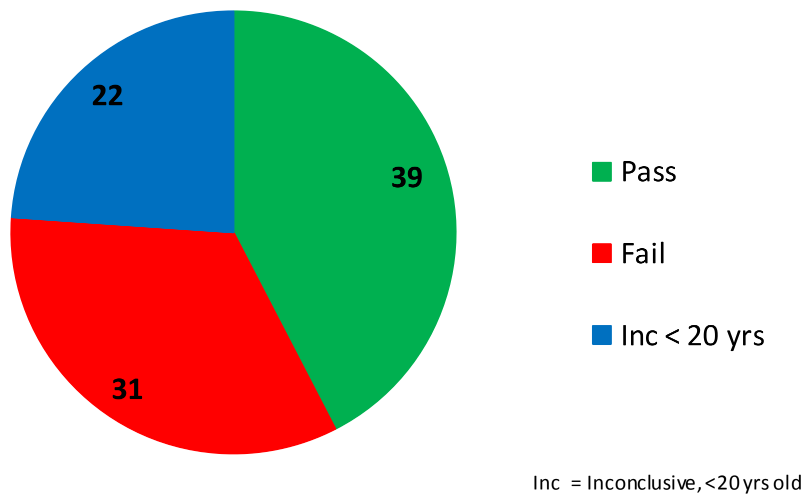

FIGURE 3.45
Results for the 92 Criteria Projects Containing 30%–36% Limestone

For the projects containing 30%–36% limestone, 65% percent of the projects with a "fail" result contained aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.46. This is comparable to the 69% for the overall study. Because the rate of "fail" results (34% versus 31%) and the percentage of projects containing material from the nine quarries with unacceptable field performance (65% versus 69%) are similar to the overall results, it appears that limestone content of 30%–36% does not significantly affect the failure rate. The source of the coarse aggregate has a greater influence on performance than the limestone content of the concrete mixture.

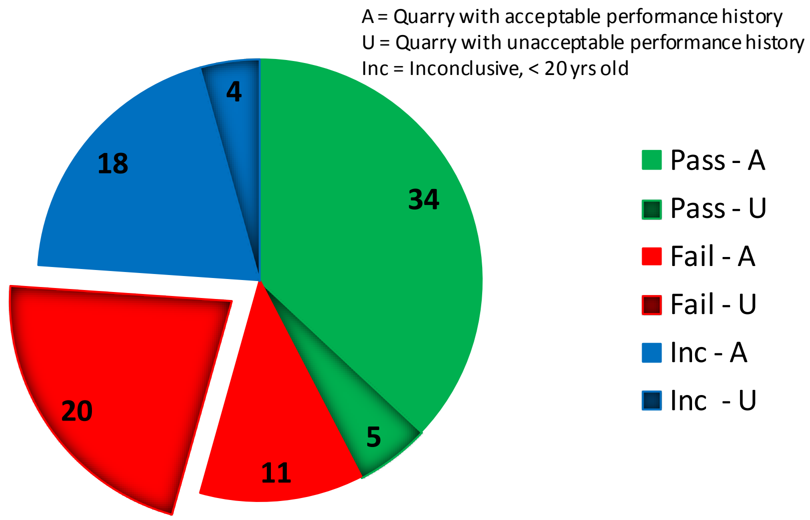

FIGURE 3.46
Results for 30%–36% Limestone Content by Quarry Performance Category

Thirty-seven criteria projects were identified as containing more than 36% limestone (by weight) in the concrete mixture. Ten of the projects exhibited D-cracking before 20 years, as shown in Figure 3.47. This represents a failure rate of 27%, which is lower than but comparable to the 31% overall failure rate in the 2009–2010 survey.

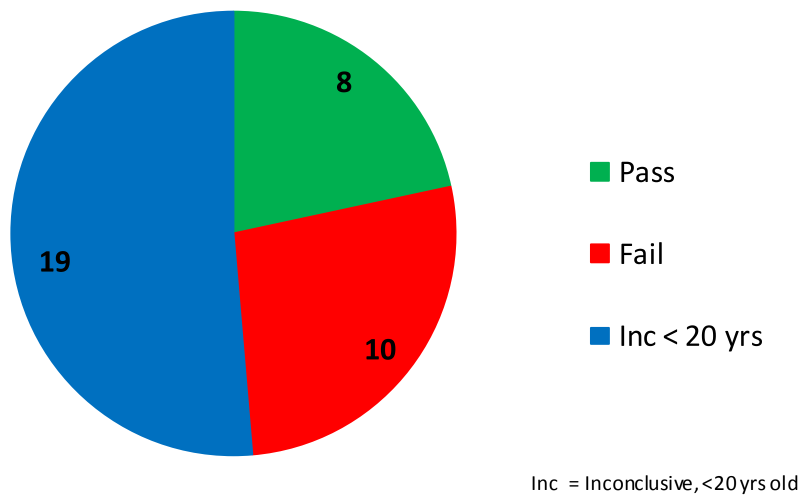

FIGURE 3.47
Results for the 37 Criteria Projects Containing More than 36% Limestone

For the projects containing more than 36% limestone, 90% of the projects with a "fail" result received aggregate from at least one of the nine quarries with unacceptable field performance, as shown in Figure 3.48. Because the large percentage of projects with "fail" results (90%) contained material from at least one of the nine quarries with unacceptable field performance, it is likely that the failures were due to the aggregate material source rather than the limestone content. The source of the coarse aggregate has a greater influence on performance than the limestone content of the concrete mixture.

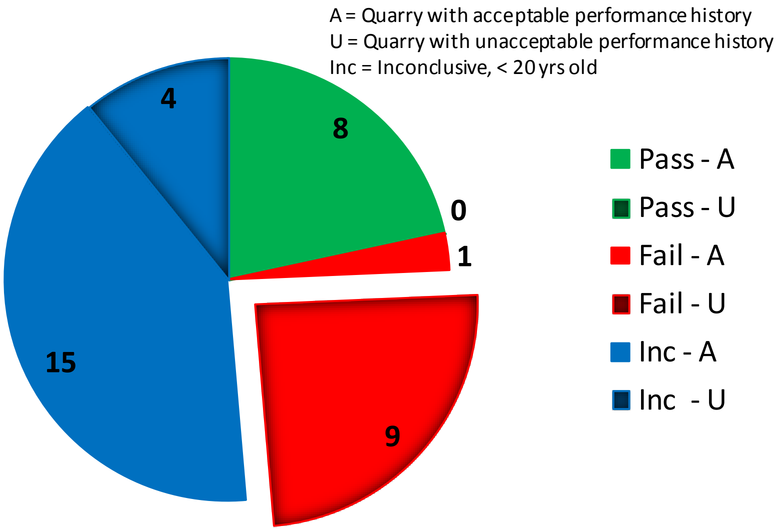

FIGURE 3.48
Results for Greater than 36% Limestone Content by Quarry Performance Category

Previous Kansas research concluded that greater amounts of limestone in the concrete mixture increased the rate of failure. However, previous Iowa DOT research suggested that 15% limestone content is enough to cause D-cracking (Schwartz 1987). The results of this study indicate the failure rate for 30%–36% limestone content is 34% and for greater than 36% limestone content the failure rate is 27%. The failure rate for the higher limestone-content projects was lower than the lower limestone-content projects, as shown in Figure 3.49 and 3.50. These results indicate that the failure rate is not necessarily lower for the concrete mixes with lower limestone contents. Continued monitoring of criteria projects may determine if limestone content affects D-cracking performance.

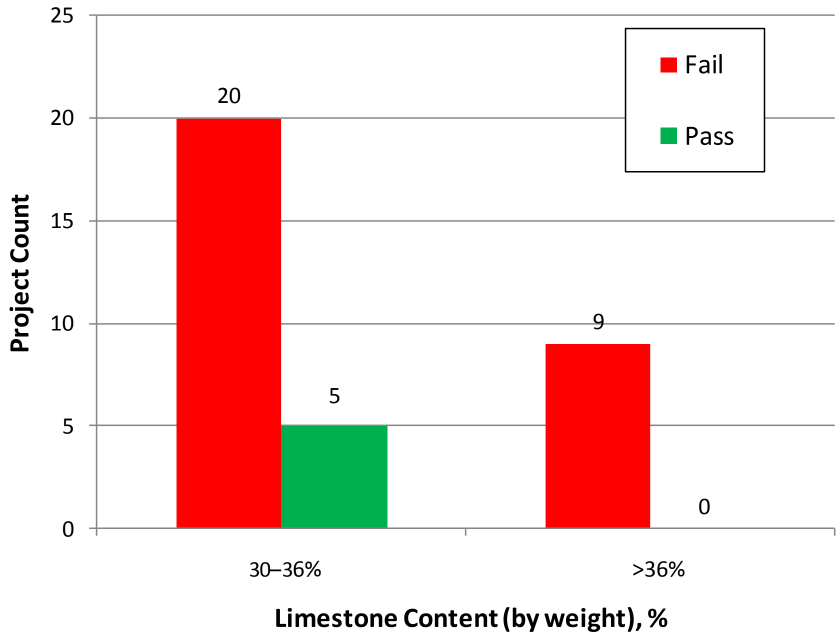

FIGURE 3.49
Results for Limestone Content (by Weight) for Projects Containing Material from at Least One of the Nine Quarries with Unacceptable Field Performance

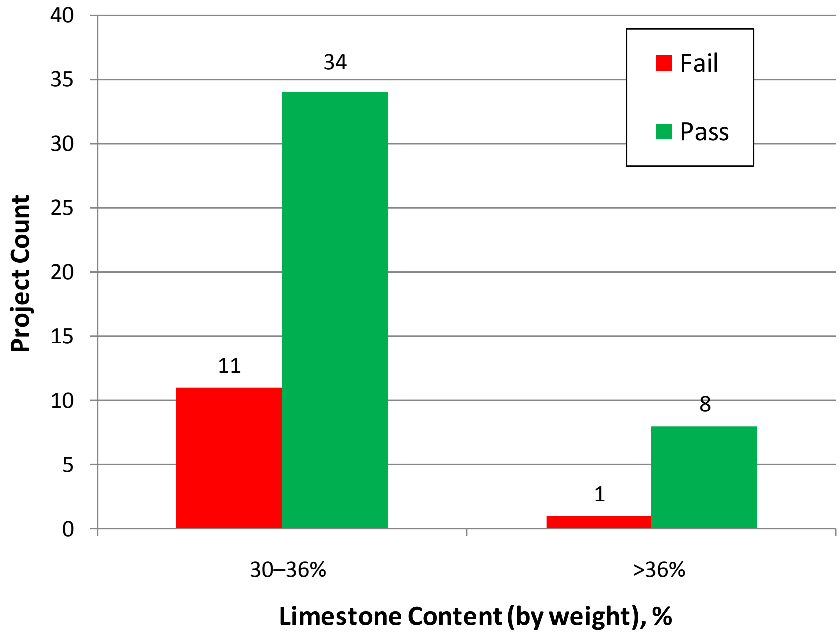

FIGURE 3.50
Results for Limestone Content (by Weight) for Projects Containing Material from the 44 Quarries with Acceptable Field Performance

Table 3.16 and Figures 3.51–3.53 provide a summary and comparison of the results of the effect of each parameter on D-cracking as well as the contribution due to poor performance quarries. Project K-2611-02 is included in the parameter analysis and the quarry analysis (Section 3.2), but not in the overall analysis as discussed previously in Section 3.1.

TABLE 3.16
Summary of Parameters and Project Results

Parameter	No. of Projects	Failure (D-cr < 20 years)		Contains Unacceptable Field Performance Aggregate	
		No.	%	No.	%
Overall Study Results (All 52 Quarries)	131	41	31%	29	69%
9 Quarries with unacceptable field performance	42	29	69%	29	100%
Silicone Joint Sealant and Bound Drainable Base, BDB	15	8	53%	7	88%
Neoprene Joint Sealant and Portland Cement Treated Bases, PCTB	12	6	50%	5	83%
15 ft Perpendicular Joints	70	34	49%	27	79%
Neoprene Joint Sealant	45	20	44%	18	90%
Bound Drainable Bases, BDB	44	20	45%	18	90%
Neoprene Joint Sealant and Bound Drainable Base, BDB	29	12	41%	11	92%
Lime-Treated Subgrade, LTSG	91	32	35%	25	78%
Less than or equal to 36% Limestone	92	31	34%	20	65%
Overall Study Results (All 52 Quarries)	131	41	31%	29	69%
Portland Cement Treated Bases, PCTB	66	19	29%	9	47%
Silicone Joint Sealant	74	21	28%	11	52%
Silicone Joint Sealant and Portland Cement Treated Bases, PCTB	44	12	27%	4	33%
More than 36% Limestone	37	10	27%	9	90%
15 ft Skewed Joints	33	5	15%	0	0%
44 Quarries with Acceptable Field Performance	91	13	14%	0	0%
Hot Pour Joint Sealant	10	1	10%	0	0%
30 ft Perpendicular Joints	30	3	10%	2	67%

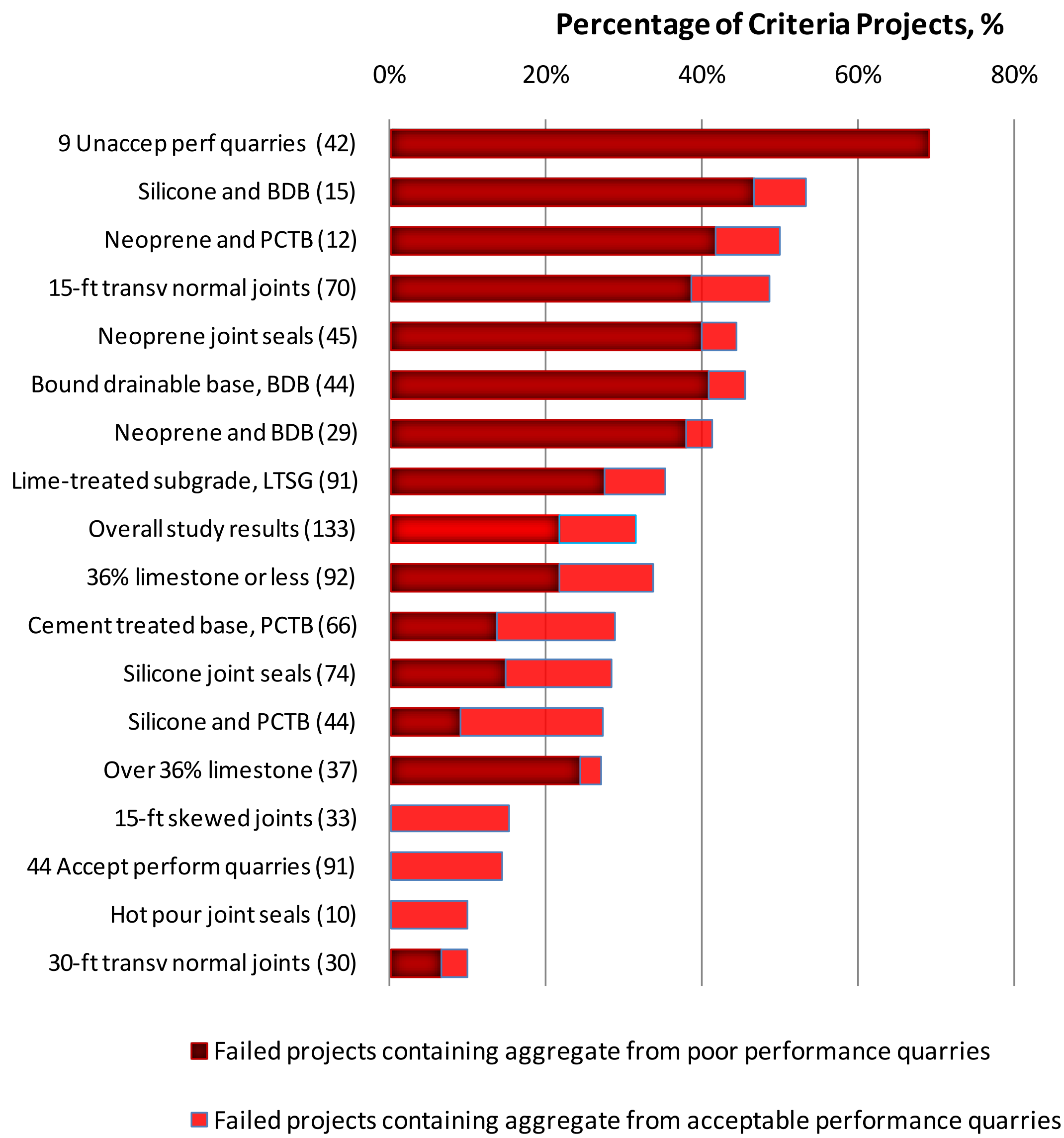

FIGURE 3.51
Summary of Parameters and Results for Criteria Projects with "Fail" Results

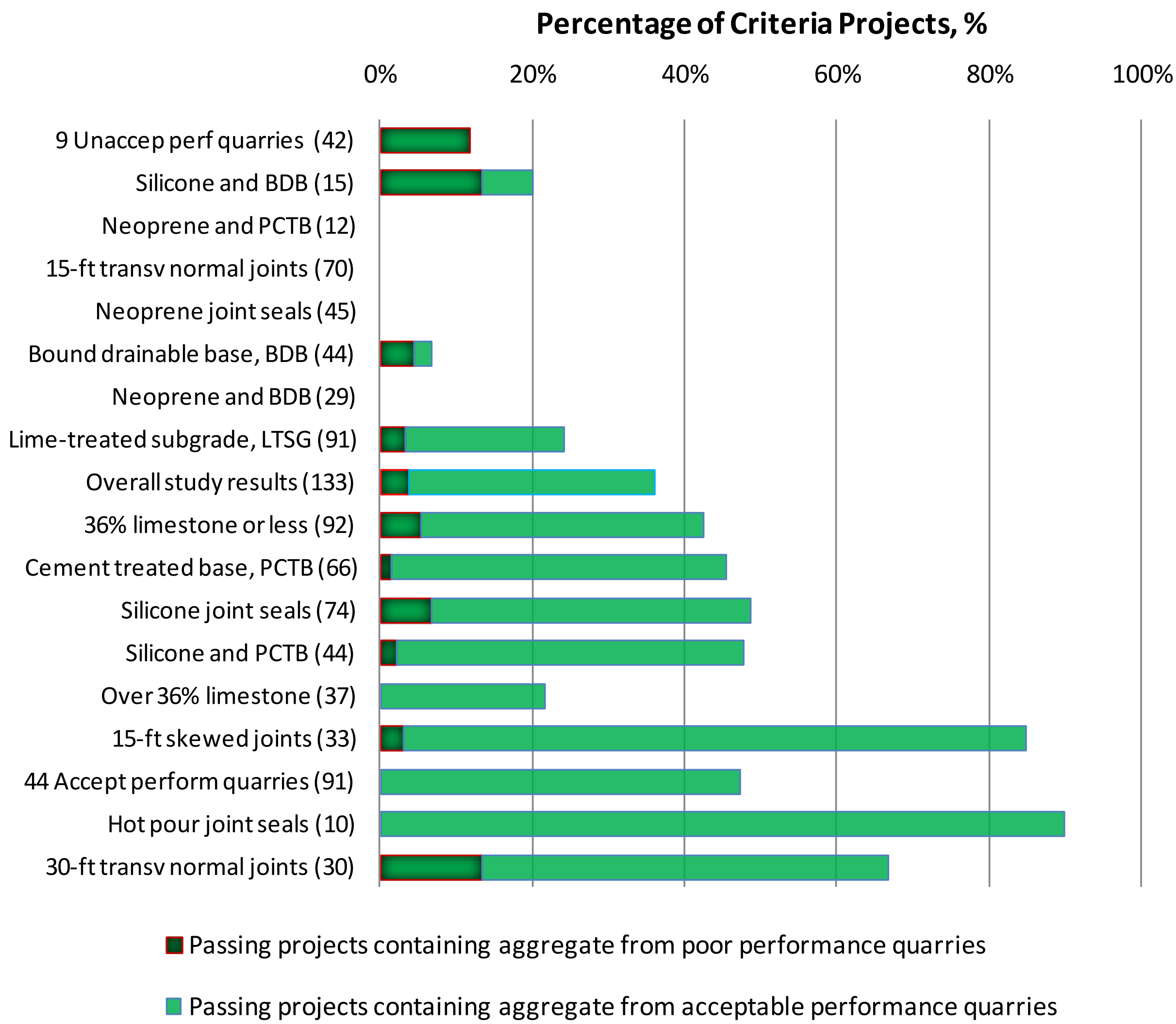

FIGURE 3.52
Summary of Parameters and Results for Criteria Projects with "Pass" Results

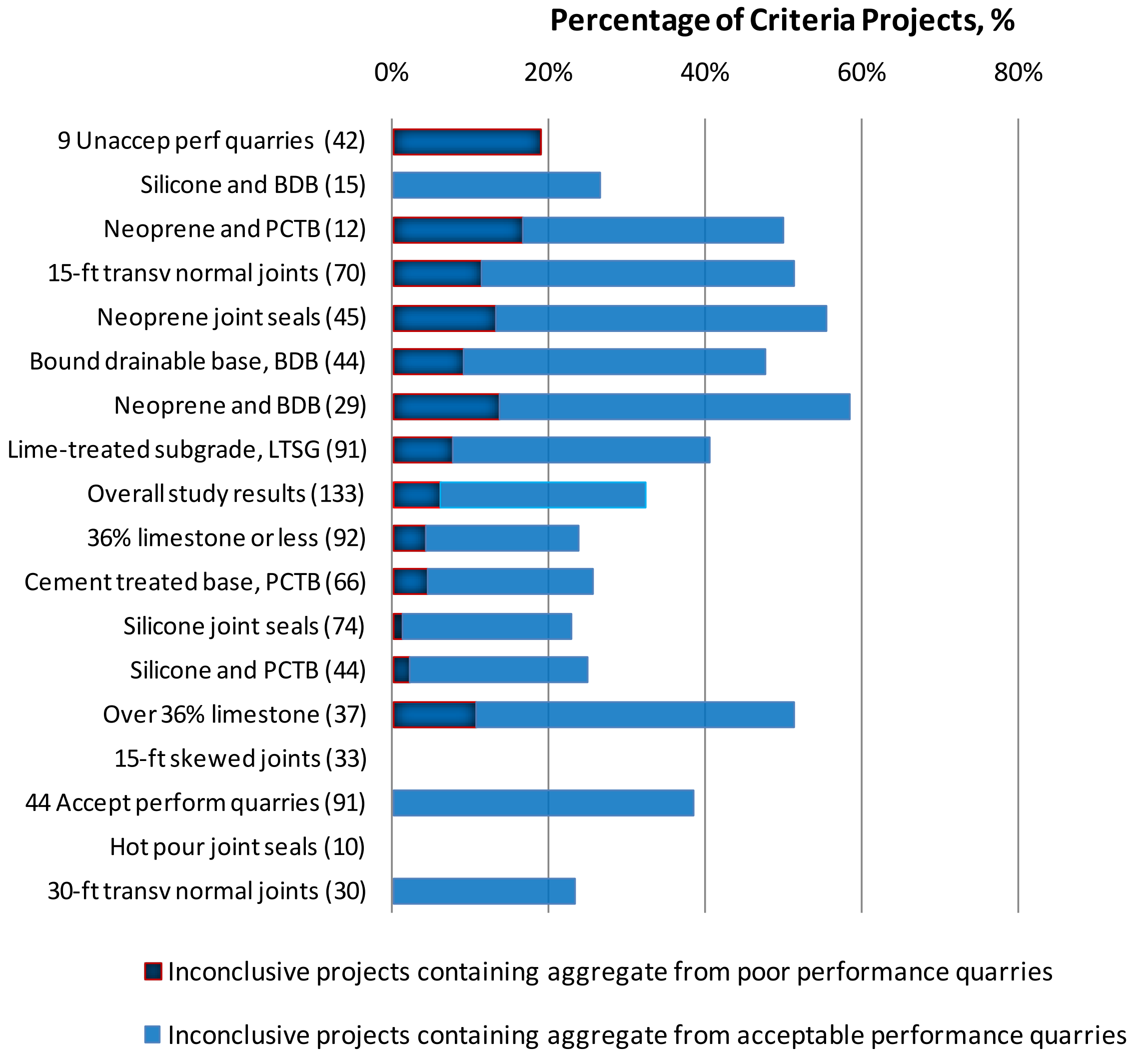

FIGURE 3.53
Summary of Parameters and Results for Criteria Projects with "Inconclusive" Results

The dominant parameter for the cause of the D-cracking is the quarry or source of the aggregate, with 69% of all the D-cracking before 20 years coming from just nine quarries. The nine quarries with unacceptable field performance represent 17% of the 52 quarries that provided aggregate to the criteria projects. None of the other parameters discussed has a failure rate as high as the failure rate (69%) of the nine quarries with unacceptable field performance. The failure rates for projects with 15 ft perpendicular joints (49%), drainable bases (44%), neoprene joint sealants (44%), and the combinations of Silicone/Drainable Base (53%), Neoprene/Drainable Base (40%), and Neoprene/Cement-Treated Base (50%), are greatly influenced by the fact that 79%–90% of those projects that failed contained aggregates from the nine quarries with unacceptable field performance. Even the use of less than or equal to 36% limestone in the mixes did not slow the rate of D-cracking in the criteria projects as the failure rate of 34% is nearly the same as the overall failure rate of 31%. Ninety percent of the D-cracking in projects with over 36% limestone in the mixes contained aggregate from the nine quarries with unacceptable field performance.

Chapter 4: Estimating the Extent of D-Cracking in Kansas

If a pavement exhibited D-cracking, it was assumed that the entire project was D-cracked. This is a reasonable assumption for Phase 1 because, by definition, D-cracking is not an isolated occurrence. D-cracking cannot be stopped or reversed, and early identification only means that additional D-cracking will occur. Additional study on the extent (percent of miles D-cracked within each project), severity, and rate of progression of D-cracking will be examined in Phase 3. As discussed previously, estimates for the time to action range from 4 to 6 years (Montney et al. 2008; Applied Research Associates Inc. et al. 2008). Therefore 693 lane-miles may require action within the next six years. Recent KDOT experience (last two years) has included D-cracking deteriorating quickly and needing to be repaired within one to two years from the time that early stages of D-cracking was identified. Because there is variation in the condition and percentage of lengths exhibiting D-cracking, better estimates will be possible as the extent and severity of D-cracking for each project is investigated.

It is important to note that not all concrete pavements are included in this study, and that some of those that were not included in this study are not only of unknown condition, but may have greater likelihood of D-cracking due to greater opportunity for non-Class 1/Class 2 material to have been incorporated into the concrete. Therefore the percentages of projects and miles of D-cracking not included in this study may be greater than the results of this study. These estimates are provided for the purpose of KDOT planning (maintenance and management) and to draw attention to the negative impact of non-durable coarse aggregate on concrete pavements in Kansas.

Chapter 5: Policy Risks

For the purpose of this study, a policy is defined as any action, requirement, or decision that affects KDOT's risk of constructing PCCP that may D-crack. The goal of this section is to document issues, both historical and current and the effects of the issue on the risk of D-cracking. To increase the initial life of PCCP in Kansas, KDOT must address the policy risks. Different combinations of solutions exist.

5.1 Historical Field Performance Criteria

KDOT policy does not provide a method to stop using material from a quarry based on past field performance. KDOT accepts material based on test results and production plans, and therefore continues to utilize aggregate sources with a proven history of D-cracking.

5.2 Failing Test Results and Resampling

Historically, when failing test results occur, KDOT has allowed for resampling and retesting of production samples. Because testing requires approximately six months, this decision increases KDOT's risk of using D-cracking aggregate on a project to 12 months or more. Paving projects can be completed or nearly completed using failing material due to unwillingness to trust test results and reject the failing material.

5.3 Failing Test Results and Enforcement

Historical unwillingness by KDOT to enforce specifications and reject contaminated or failing aggregate piles increases KDOT's risk for D-cracking.

5.4 Location and Tracking of Production Sampling

Production sampling occurs at the quarry, with only one sample required to be taken at the concrete batching site for each project. Although it is specified, frequently no sampling at the batch plant occurs and therefore the material used in the concrete is generally not directly sampled.

KDOT documentation of quality production samples (QPS) has not always been as detailed and complete as should have been. Often, information is left off of sample ID sheets, including bed numbers and project numbers, which makes it impossible to track QPS samples.

5.5 Quarry Monitoring

A lack of consistency in quarry monitoring and sampling activities exists because each district has unique and subjective interpretations of the KDOT policies, often varying even within a single district. Variation occurs regarding the number of inspectors that visit quarries, when and how they sample, what procedures are followed for a given sample or inspection type, and the load of additional duties (non-monitoring) assigned to the quarry monitors. Because aggregate is an inherently variable material in both how it is produced and its physical attributes, inconsistency in the methods of performing quarry monitoring duties and variability in interpretation of specifications and policies exacerbates the variability of the quality of product being used on KDOT projects.

5.6 Complex Requirements

The complexity of the KDOT specifications involving quarry monitoring and testing (splitting the beds, observing, sampling, testing, transporting, etc.) has, in some cases, become more difficult to successfully complete with reductions in staff. Additional requirements will add layers of complexity to an existing web of sampling, testing, and tracking requirements. Feasibility of existing and new requirements is important. The cost of complex testing requirements adds to the cost of using material. Additional complexity is not the solution.

5.7 Quarry Monitor Stationing

Initially quarry monitors were stationed in the quarry, resulting in more continuous monitoring of the production processes. Quarry monitors were phased out from the quarries in the late 1980s, from 1986 to 1989. This limited KDOT's knowledge of quarry activities and increased KDOT's risk of D-cracking.

5.8 Quarry Monitor Qualifications and Training

The complexity of monitoring quarry production requires a certain level of technical expertise and training. If the required level of expertise is not achieved, then duties become reporting rather than monitoring. In many cases, the monitor may not be aware that he is, along with the quarry owner, responsible for identifying a change in the material and has the authority to take appropriate action.

Historically, quarry monitors have not been uniformly trained. Usually training was by on-the-job training and word of mouth, and the institutional knowledge was not always transferred completely with personnel changes. This inconsistency represents a hole in our procedures and increases KDOT’s risk of D-cracking. Currently the new Quarry Monitoring Class is offered but not required for quarry monitors. Requiring quarry monitors to pass the Quarry Monitoring class and refresher classes appears to be feasible.

5.9 Tracking Aggregate

Trip tickets are not required for material shipped from the quarry to the batch plant. Therefore, there is no assurance that the material from the quarry actually reaches the batch plant, leaving opportunity for undesirable material to be used in KDOT projects.

5.10 Reluctance by KDOT to Pay the Differential to Switch to a Better Material

KDOT should consider paying extra to use material with long-life performance history. KDOT’s performance history shows that D-cracking can end the planned usable service life of a pavement in as little as nine years, or it can last 20-plus years. Nationally, long-life pavements are expected to perform for 30 to 50 years or more. Therefore pavements that last approximately 20 years barely meet current expectations and won’t meet future expectations. It is not good engineering practice to expect the same performance from two pavements constructed of the same thickness which will have different lives due to differences in aggregate durability. Economic benefits may be derived by constructing thinner pavements if less durable aggregates are used and the expected life of the pavement is shorter than 20 years.

The life of a pavement is dependent on its structure, the environment, and functional needs. The structure is determined by its thickness or ability to carry traffic. The environmental conditions are defined by the pavement's ability to resist moisture and freeze-thaw damage. The functional needs are measured by its capacity to carry traffic, the safety of the alignment, and the need for the roadway. Ideally, the structural, environmental, and functional life should be nearly equivalent so that everything wears out at the same time. Because it is difficult to predict the future traffic with accuracy, the structural aspects can be met by incremental improvements to its structure in the form of resurfacing actions. The initial design and subsequent "overlays" will meet the environmental and functional needs. Aggregates that cause an environmental failure, such as D-cracking, reduce the value of a pavement by rendering it useless before its expected structural or functional life is reached. The cost to initially construct these pavements that fail environmentally is a lost investment and an increased cost burden in the future.

5.11 Life Cycle Cost Analysis (LCCA) Based on Aggregates

A life cycle cost analysis (LCCA) can show the value of using various aggregates that have varying performance histories. Assumptions on life expectancy of PCCP containing various limestone aggregates can be made based on the results of this study or additional studies. Based on the results of the LCCA, recommendations could be made regarding the economic impact to the taxpayers.

Kansas aggregates with proven acceptable performance history are often available for as low as two additional dollars per ton. Only four months of additional service life would be required to break even if this more expensive, better performing aggregate were used. The highest current additional cost for aggregates with acceptable performance histories is $16 per ton. Less than three years of additional service life would be required to break even if this more expensive, better performing aggregate were used. This appears to be achievable.

5.12 Ledge Sampling Procedures

Since the late 1970s, the ledge sampling procedures have changed very little. A request to conduct a ledge sample is sent to the district materials engineer, it is then passed on to the chief geologist to obtain the samples. Since 1984, all ledge samples have been collected by the Chanute Regional Geology Office for uniformity. The regional geologist divides the ledge into beds and approximately 400 lbs from each bed is brought into Topeka for Class 1 testing. Unless the appearance or thickness of the ledge of rock changed or the quarry moved into a separate pit, the ledge was never resampled.

Since 1994, an additional quarry visit has been required by the regional geologist every two years to allow the quarry to produce Class 1 aggregate. There are still several quarries on the A-List that have not been visited within this two year requirement. These quarries should also be visited to monitor changes. There is a need to check up and see what is happening and if the material has changed. Resampling ledges periodically, possibly every five years and/or whenever the active quarry face has moved over ¼ mile would increase KDOT's knowledge of changes in the material. At the inception of such a policy, many additional samples will be submitted to Topeka for testing. Phasing in testing would avoid an influx of samples in a short timeframe.

5.13 Time Requirements for Testing

The time requirement for completing production testing once the material reaches the laboratory is approximately six months. KDOT assumes the risk of constructing with potentially failing material for this time period. KDOT has recently instituted a policy that requires the last two production samples pass Class 1 testing before the quarry is allowed to ship to a KDOT project. New quarries must have two production samples tested and passed before delivery to projects. This new policy may relieve KDOT from some of the risk.

Other possible solutions include methods for shared risk with the contractor by warranty or bond, design-build-operate, performance-based testing, payment in percentages per year for the life of the structure, using other materials, and developing a quicker method of testing.

Quicker methods of testing have been investigated by other researchers, but a reliable quicker method is not yet available. Development of new testing methods would require significant cost and time, possibly 10 or more years. Greater understanding of the fundamental mechanism of D-cracking may be necessary to develop tests to better characterize future field performance. Such understanding and testing development would be a long-term process.

Because of the long-term nature of developing a quicker or more accurate test method, a short-term solution may be necessary. KDOT continues to support the development of quicker test methods or test methods that more accurately predict field performance.

5.14 Mixing Geologic Units

Quarries that produce Class 1 aggregate often produce aggregate from more than one geologic unit. Due to limited amounts of storage space, producers have requested to mix stockpiles of Class 1 aggregates produced in different processes, and possibly from different geologic units. There are very few quarries where different geologic units can be produced concurrently without separating beds due to shale seams or other reasons.

Unless sequential geologic units can be produced concurrently, mixing the stock piles of different production processes or geologic units would make it impossible for KDOT to track the aggregate source and performance history of the individual geologic units. Using aggregate from different geologic units or from different quarries on the same project makes it difficult or impossible to track the source of the material and material field performance. In cases where material has been rejected, switching to aggregate from a different sources is likely preferable.

Stockpiling each geologic unit separately would allow the tracking of aggregates back to the geologic unit, thus benefiting both KDOT and the aggregate producer. If one of the geologic units is found to be contributing to unacceptable test results or field performance, then only that geologic unit would need to be removed from the A-List. The quarry could continue to produce and sell aggregate from other approved geologic units within the quarry with acceptable testing and field performance history. If, on the other hand, they are mixed or stored in one stockpile, then all of the material sources in that pile would be removed from the A-List if unacceptable test results or field performance occur. Keeping the stockpiles separate reduces risk for both KDOT and quarries.

5.15 Continued Use of Limestone While Waiting for "the Answer"

KDOT has worked on solving the D-cracking problem for over 80 years. We continuously partner with industry to utilize local sources of limestone. Ongoing research includes, but is not limited to, the current study, nanotechnology, variations of current testing, new test methods, revisiting old test methods, and changing concrete mix designs. All of the ongoing and past research has been at significant effort and cost to KDOT. In the meantime there has been limited scope of the effort put forth by industry in the way of research funding and self-policing as an industry when non-compliance of their members is noted. For most products used by KDOT, the burden of proof is on the producer and the industry to develop, test, and show that their material is durable. It may be time for industry to invest in their product and the next major effort at legitimately addressing the D-cracking problem.

Future development of new testing or treatment methods will require significant financial commitment and will likely not be solved quickly. Historically, improvement has generally been achieved in the lab, and incremental improvement has been shown in the field after long waiting periods of testing in real pavements. The time-frame for the development of new test methods is likely to be long. In the meantime, the continued use of the same limestone materials using current methods of testing will result only in the same field performance results.

Chapter 6: Summary of Survey Results

- 41% of the projects [32% of the lane-miles] surveyed exhibited D-cracking.
- **31%** of the projects [24% of the lane-miles] surveyed exhibited D-cracking in less than 20 years. This constitutes premature **failure** by material related deterioration.
- **36%** of the projects [34% of the lane-miles] either exhibited no D-cracking and were 20 years or older, or exhibited D-cracking at 20 years or older. This constitutes **success**.
- 33% of the projects [42% of the lane-miles] exhibited no D-cracking and were less than 20 years of age.
- 69% of the projects with premature D-cracking (failure) contained material from nine quarries.
- Aggregate source was found to be the dominant parameter causing D-cracking.

Chapter 7: Conclusions

1. D-cracking is still a problem in Kansas.
2. The aggregate durability specifications implemented in the 1980s appear to have improved field performance and reduced the D-cracking problem.
3. Aggregate durability specifications implemented in the 1980s have not mitigated D-cracking on KDOT projects to the expected levels.
4. D-cracking is occurring in Kansas PCCP before 10 years.
5. Current specifications and testing procedures do not fully predict field performance of concrete pavement containing limestone in Kansas.
6. The dominant parameter influencing D-cracking is the source of the aggregate.
7. Removal of quarries from the A-List will not ensure future success nor protect from future failures by quarries approved by test results alone, but does eliminate quarries with known history of failures.
8. KDOT policies discussed in section 5.0 increase KDOT's risk of D-cracking.

KDOT will, in cooperation with industry, develop a feasible plan for preventing D-cracking susceptible aggregates from being included in KDOT PCCP. A complete plan will address reducing D-cracking in both the short term and long term.

Chapter 8: Future Work

1. Track and report the outcomes of actions taken to reduce D-cracking.
2. Investigate methods to extend the life of concrete pavements in Kansas.
3. Monitor projects and quarries for field performance.

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Appendix A: Project Information

Appendix A contains the project information pertaining to the 2009–2010 "D-Cracking Field Performance of Portland Cement Concrete Pavement Containing Limestone in Kansas: D-Cracking Mitigation Phase 1 Report."

Table A.1 provides the identification information for the projects included in the study, and the route, county, location, year the paving was completed, and whether or not D-cracking was present for each of the projects.

Table A.2 provides the quarry information for each project included in the study, as well as some of the project identifying information. It includes the quarry number, bed, and geoclass of the source material for each project. The table also indicates whether or not a project has exhibited D-cracking and, if applicable, the age of the pavement at which D-cracking was observed.

Table A.3 lists all of the projects that have met the 20-year design criteria before D-cracking was observed. These projects are considered successes because they met the expected design life. All of the projects listed have exhibited D-cracking.

Table A.4 lists all of the projects that have met the 20-year design criteria and have not exhibited D-cracking. These projects are considered successes.

Table A.5 identifies the projects that exhibited D-cracking before the 20-year design criteria was met. These projects are considered failures for the purposes of this study.

Table A.6 identifies the projects that were overlaid at the time of the survey and reports whether D-cracking was present at the time of the overlay.

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
169	1	K-0104-03	1.9 MI S OF FAS 2 SE OF HUMBOLDT N	1981	no
169	1	K-0106-02	NO-AL CO LINE N TO 0.3 MI SE OF HUMBOLDT	1986	no
169	1	K-1280-02	NE HUMBOLDT N TO JCT OF US-169 SPUR	1980	no
296	1	K-1281-02	US-169 SPUR TO US-54	1981	no
73	3	K-0117-02	LANCASTER E TO ATCHISON UL	1985	no
69	6	K-0135-02	N JCT US-54 AT FT SCOTT N TO BB-LN CO LN. North jct. US-54 in Fort Scott - north to the Linn County line.	1985	yes
69	6	K-4066-01	CR-BB COUNTY LINE NORTH TO 0.75 MILE SOUTH OF K-7	1997	no
54	8	K-0152-02	0.4 mi E of E UL Augusta to JCT US-54/US-77 and US-400 (new alignment)	1985	no
254	8	K-3321-01	1 MI W K-254 E TO DIAGONAL RD(EL DORADO); 2.2 mi E of Towanda Cl, E 2.4 mi to El Dorado Ref. Post 23–24	1995	yes
400	8	K-1879-01	1.0 M E OF LEON E TO 1.0 M W OF KEIGHLEY Ref. Post 307–311	1987	no/overlaid
400	8	K-2826-01	1.0 M W OF KEIGHLEY E TO BU-GW CO L Ref. Post 312–318	1988	no/overlaid
50	9	K-2813-01	0.2 MI W OF K-177 E TO WCL STRONG CITY	1990	no
50	9	K-3216-02	MN-CS COUNTY LINE, NE TO 2.7 M NE RS 1076	1997	yes
50	9	K-3217-02	2.7 M NE RS 1076 NE & E TO .2 M W K-177	1997	yes
50	57	K-3222-01	E OF E CITY LIMIT PEABODY, NE TO W CITY LIMIT FLORENCE	1994	yes
166	10	K-4729-02	4 M E OF RS-1566 SE TO S JCT US-166/K-99. LPS81: 4.1 M E OF CL-CQ CL, E TO 4 M E RS 1566	1997	no/overlaid
499/166	10	K-0171-01	SCL OF SEDAN SOUTH & EAST TO WCL NIOTAZE	1988	no
81	15	K-4956-03	EX 4-LANE S EDGE CONCORDIA, N ON US-81 TO COUNTY LANE location: END OF K-3389-01 IN CONCORDIA NORTH TO RS 145	1999	yes
81	15	K-4956-03	EX 4-LANE S EDGE CONCORDIA, N ON US-81 TO COUNTY LANE location: END OF K-3389-01 IN CONCORDIA NORTH TO RS 145	1998	no

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
77	18	K-0212-02	0.6MI N OF K-15 JCT N TO CL-BU CO LINE	1981	no/overlaid
77	18	K-7711-01	ARK CITY BYPASS,MADISON AVE N TO JCT OLD US-77. LPS81: ARK CITY BYPASS, FROM US-166, NORTH TO E	1999	No
360	18	K-4432-02	WINFIELD BYPASS(US77 E&N TO 12TH/BRANDT	1995	no
69	19	K-3276-01	NORTH JUNCTION ARMA BYPASS NORTH TO CR-BB COUNTY LINE	1998	no
70	21	K-2588-01	0.9 MI W OF K-15 E TO 2.3 MI E OF K-43	1986	no/overlaid
70	21	K-2609-01	2.3 MI E OF K-43 EAST TO DK-GE CO LINE	1992	no
36	22	K-0248-01	S OF ELWOOD E TO MISSOURI RIVER BRIDGE	1983	no/overlaid
36	22	K-0251-01	1.6 SE WATHENA E TO .7 MI W OF MISSOURI RIVER BRIDGE	1984	no/overlaid
36	22	K-1773-01	ECL WATHENA, SE 1.6 MI	1984	no/overlaid
36	22	K-1876-02	1 MI E OF BR-DP C LN E TO E SIDE OF TROY	1990	no
35	30	K-3596-01	OS-FR COUNTY LINE, NE TO 1.0 MILE EAST JUNCTION K-273	1995	Yes
35	30	K-3596-02	1.0 MILE EAST K-273, NE TO 0.63 MILE EAST RS-1647	1996	no
35	30	K-5085-01	0.7 M E OF RURAL SECONDARY 1647, NE TO .24 M W W US-50B(in Ottawa) Ref. Post 178–182	1998	Yes
68	30	K-5998-01	0.07 MI E I-35, E TO 0.1 MI E OF NEVADA	1996	yes
70	31	K-2611-01	DK-GE CO LN E TO ECL OF GRANDVIEW Tech Location: DK-GE CO LN E TO 1 MI E OF US-77	1990	no
70	31	K-2611-02	DK-GE CO LN E TO ECL OF GRANDVIEW Tech Location: 7.0 M E DK-GE CO LN E TO ECL GRANDVIEW	1991	yes
70	31	K-2611-02	DK-GE CO LN E TO ECL OF GRANDVIEW Tech Location: 7.0 M E DK-GE CO LN E TO ECL GRANDVIEW	1992	no
70	31	K-5086-01	EAST CITY LIMITS OF GRANDVIEW PLAZA, NE AND E 7.8 MI	1999	no
70	31	K-5090-01	1 MILE E MCDOWELL CREEK RD, E TO THE GE-RL COUNTY LINE Ref. Post 309–315	1999	no

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
400	37	K-3292-02	1.3 MILES W BU-GW COUNTY LINE, E TO E JUNCTION RS 227	1997	yes
400	37	K-3293-03	E JT RS-227 E TO 5 M E OF E JT K-99.	1996	no
400	37	K-3293-04	5 MI E OF E JCT K-99 E TO GW/WL CO LINE.	1998	no
50	40	K-4058-03	ECL WALTON, NE TO HV-MN CO LINE	1994	yes/overlaid
50	40	K-4350-01	NORTH JUNCTION I-135, NE TO EAST CITY LIMITS OF WALTON	1997	yes
135	40	K-5089-01 NB	SG-HV COUNTY LINE, N TO 0.3 M S OF S JUNCTION K-15. South of Newton.	1999	yes
135	40	K-5089-01 SB	SG-HV COUNTY LINE, N TO 0.3 M S OF S JUNCTION K-15. South of Newton.	1999	yes
135	40	K-5634-02	Newton Bypass: 0.3 mi S of S Jct K-15 N to 0.9 mi N of N Jct K-15 Ref. Post: 30–35	1999	no
75	43	K-3250-01	SN-JA CO LINE N TO FAS 321 AT MAYETTA	1993	no
75	43	K-3251-01	FAS 321 AT MAYETTA N TO K-16 IN HOLTON	1995	no
75	43	K-3251-01	FAS 321 AT MAYETTA N TO K-16 IN HOLTON	1996	no
7	46	K-3382-01	0.17 MI N K-150 N TO 2L/4L DIV	1995	no
10	46	K-1492-01	JCT K-7/K-10 EAST TO I-435/K-10 INTERCHANGE.	1984	yes/overlaid
35	46	K-1774-01	US-69 NE TO I-35/I-635 EX .8M @ I-35/75TH Ref. Post 226	1990	no
35	46	K-2434-02	MI-JO CO LINE NE at 6.8 miles, north to US-169 in Olathe	1987	yes
35	46	K-2434-04	MI-JO CO LINE NE to 6.8 miles	1989	no
35	46	K-2500-01	I-35/K-150 (135th St) @ OLATHE NE TO RENNER ROAD/Mur-Len (no exit there)	1992	no
35	46	K-2501-01	I-35 & US-169 INTERCHANGE IN S OLATHE	1991	no
35	46	K-2578-01	I-435 NE TO US-69 (EX 95TH ST INTERCHG)	1991	no
35	46	K-4088-02	US-169/K-7 INTERCH, NE TO I-35/K-150	1996	no
169	46	K-1310-01	2.6 MI N MI-JO CO LN N TO JCT I-35	1987	yes
435	46	K-0456-04	W of QUIVIRA RD W TO E of I-35 Ref. post 1	1985	no
435	46	K-0457-05	SANTA FE TRAIL W & N TO 87TH ST	1984	yes
435	46	K-0460-02	N OF 87TH ST TO S OF MIDLAND DR	1982	yes
435	46	K-0461-01	MIDLAND DR TO S END OF KS RV BR	1980	no/overlaid

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
435	46	K-2345-01	W OF QUIVIRA RD E TO E OF METCALF Ref. Post 2-3	1987	no
435	46	K-3637-01 EB (SB)	US-169 (METCALF AVENUE) EAST TO KS-MO STATE LINE Tech Location: METCALF AVENUE EAST ABOUT 2.9 MILES	1996	yes
435	46	K-3637-01 WB (NB)	US-169 (METCALF AVENUE) EAST TO KS-MO STATE LINE Tech Location: METCALF AVENUE EAST ABOUT 2.9 MILES	1995	no
400	50	K-4891-02	MA/LB CO LN E 9.9 MI. LPS81: MG-LB COUNTY LINE EAST 9.9 MILES	1997	No
73	52	K-1875-03	NW EDGE LEAVENWORTH NW TO LOWEMONT	1990	yes/overlaid
73	52	K-4443-01	CENTENNIAL BR W TO 16TH ST-LEAVENWORTH	1996	yes
35	56	K-2633-01	KTA, EAST TO EAST JCT OF US-50	1993	no
50	56	K-2853-01	CS-LY CO L E TO GRAPHIC RD @ EMPORIA	1993	no
50	57	K-3046-03	690 FT W OF WCL PEABODY, E 1.4 MI	1994	yes
50	57	K-3219-02	HV-MN CL, E TO 690 FT W WCL PEABODY. West of Peabody.	1994	yes
50	57	K-3220-01	WEST CITY LIMIT FLORENCE EAST TO 0.1 MILE EAST FAS 1410	1994	yes
50	57	K-3221-02	E OF E CITY LIMIT PEABODY, NE TO W CITY LIMIT FLORENCE	1998	Yes
56	57	K-0561-02	FAS 428 SPUR E OF CANADA E TO US-77	1988	no
56	57	K-0562-02	EJCT K-15 TO FAS 428 SPUR E OF CANADA	1987	no
135	59	K-5084-01	HV-MP COUNTY LINE, NW TO N OF N JUNCTION K-260	1997	yes
69	61	K-5760-01	9.5 KM N K-68, N TO MI-JO COUNTY LINE (4-LANES)	1999	no
169	61	K-0590-02	MI-JO CO LINE SOUTHEAST 1.74 MI	1986	yes
400	63	K-4892-02	WL-MG COUNTY LINE S AND E TO MG-LB COUNTY LINE	1998	no
169	67	K-0619-02	S OF EARLTON N TO JCT K-39 (2 MI 4 LANE)	1985	no
169	67	K-0620-02	JCT K-39 NEAR CHANUTE N TO NO-AL CO LINE	1985	no

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
35	70	K-5028-01	0.3 M E E JCT K-31, NE TO OS-FR CO LINE	1995	yes
75	70	K-3247-01	NCL LYNDON N TO JCT K-31/K-268	1992	yes
24	75	K-2592-01	5.3 MI E OF K-99, E 1.1 mi to 0.3 mi W of Belvue city limit Ref. Post 337	1990	no
24	75	K-3325-02	3.9 mi east of RI/PT Co Line, then E 8.8 mi Ref. Post 321–329 Strip Maps: 3.899 to 12.732	1997	no
96	78	K-4457-01	WB asphalt; EB PCCP. K-17/K-96 JCT, SE 11.2 MI TO FAS-1809/FAS-556 (SE OF HAVEN) Ref. Post 249–259	1997	yes
96	78	K-4458-01	WB asphalt; EB PCCP. JCT RS 556 @ HAVEN SE TO RN-SG CO LINE Ref. Post 260–264	1996	yes
81	79	K-5021-02	Belleville Insp. Sta.-1.3 mi N U36	1999	yes
81	79	K-5021-04	Scol-Belleville Insp. Sta.	2001	no
81	79	K-5022-02	1.3 mi N U36-N 1.9 mi	1999	yes
135	85	K-5263-01	Junction K-104 N to N junction I-70. Ref. posts 87–95	1999	no
135	85	K-5644-01	MCPHERSON/SALINE CO LINE N TO 0.5 KM N K-104 JUNCTION. Ref. post 77–86	2001	no
15	87	K-3324-01	NCL OF DERBY, N TO SCL OF WICHITA	1993	yes
15	87	K-3684-01	S OF SU-SG CL, NW TO SUNNY DELL ST(DERBY	1996	No
54	87	K-0764-02	HOOVER RD E TO JCT K-42 IN WICHITA Tech Location: US-54 IN WICHITA FROM I-235, E TO K-42	1987	yes/overlaid
54	87	K-3181-01	JCT K-163, E TO ECL GODDARD(NL & SL)	1994	no
54	87	K-3388-01	ECL GODDARD E TO WCL WICHITA(NL & SL)	1992	no
81	87	K-0768-01	SCL HAYSVILLE N TO 47TH ST IN WICHITA	1986	no
96	87	K-4433-03	JCT I-135 E TO ECL OF WICHITA (CITY LET) location: I135/K96 IC, E TO GROVE ST (CITY LET)	1992	no
96	87	K-4434-03	MAINLINE SURFACE (WCL TO 13TH ST)(CO LET) Mileposts: 296.3 to 298.5 .WinCPMS Work Type: Surfacing	1993	Yes
96	87	K-4434-04	MAINLINE SURFACE(13TH ST TO US54) CO LET - farthest east of two. 13th to US-54 (2.3 miles). Mileposts: 298.5–300.8	1993	No

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
96	87	K-4459-01	RN-SG CO LINE SE TO W JCT K-296	1996	Yes
96	87	K-4460-01	W JCT K-296 SE TO EXIST 4-LANES @ MAIZE	1995	no
135	87	K-2617-01	JCT I-235 N TO PAWNEE ST IN WICHITA	1991	no
235	87	K-2514-01	S JCT I-135 W & N TO JCT US-54	1988	no
235	87	K-2515-01	JCT US-54 N & E TO BROADWAY	1985	no
4	89	K-3362-10	Oakland Expressway: US-40 N TO S end KS RV BR	1996	yes
70	89	K-2445-01	FROM W END OF VIADUCT IN TOPEKA TO KTA	1989	yes
70	89	K-2446-01	0.4 MI E OF W JCT US-75 E TO THE VIADUCT Tech Location: DANBURY LANE, EAST TO THE VIADUCT	1992	no
70	89	K-2446-01	0.4 MI E OF W JCT US-75 E TO THE VIADUCT Tech Location: DANBURY LANE, EAST TO THE VIADUCT	1992	yes
70	89	K-2446-02	0.4 M E OF W JT US-75, E TO DANBURY LANE Strip Map: 0.5 mi E of Wanamaker, then E 1 mi. Strip Map: 10.537–11.484	1993	no
70	89	K-3344-01	I-70/I-470, E TO 2000FT E OF W JCT US-75	1992	no
70	89	K-3344-01	I-70/I-470, E TO 2000FT E OF W JCT US-75	1993	yes
70	89	K-5087-01	0.3 M W OF VALENCIA ROAD, E 1.6 M E JUNCTION K-4. SMP349.7–354.7.	2000	no
75	89	K-2866-01	0.6 MI S OF 4LDIV/2L N TO SN-JA CO L	1993	no
75	89	K-3371-01	END EXIST 4-LN N TO I-470/BURLINGAME RD Tech Location: 49TH ST, N TO I-470/BURLINGAME RD	1997	yes
75	89	K-3371-03	END EXIST 4-LN N TO I-470/BURLINGAME RD. Tech Location: EXIST 4-LN N TO I-470/BURLINGAME RD	1996	yes
75	89	K-4341-01	0.7 MI N US-24 N TO 0.65 MI S OF 4L/2L	1995	no
470	89	K-2454-01	0.2 mi SE of WANAMAKER, then SE 4.1 mi to 1.1 mi SE of Gage Blvd Ref. Post: 2-5	1990	yes
470	89	K-3831-01	JCT I-70 SE TO JCT WANAMAKER ROAD(US-75)	1991	Yes

TABLE A.1
133 Criteria Projects Included in the Current Study

Route	County	Project	Original Location Description	Year Paving Completed	D-Cracking Present?
166	96	K-0888-02	JCT US-81 AT SOUTH HAVEN EAST	1979	no
70	99	K-5628-01	W of K99, E to W of Junction K138, ref. post 328–333	1999	no
70	99	K-5633-01	W of K138, E to W of Junction K30, ref. post 334–341	2001	no
400	103	K-3295-02	JCT K-47 SE TO WL/MG CO LN.	1998	no
35	105	K-1775-03	0.25 M S JO-WY Co. line NE TO 0.1 mi N of SW BLVD Ref. Post 232–233	1988	no
70	105	K-0966-03	I-70, I-635 EAST TO I-670	1988	no/overlaid
70	105	K-0968-01	W OF 78TH ST TO E OF 72ND Strip Maps: 7.858–9.089	1983	yes
70	105	K-0987-01	Grading on I-435 from 3.462 to 5.062	1985	no
70	105	K-1421-01	W OF 61ST TO BEGIN CONST OF I-635	1987	yes
70	105	K-1422-01	E OF 72ND ST TO W OF 61ST ST	1988	Yes
70	105	K-1423-01	W OF 94TH ST TO W OF 78TH ST ON I-70	1986	no
70	105	K-2447-01	JCT 7TH ST N TO JCT US-24	1993	no
70	105	K-2447-01	JCT 7TH ST N TO JCT US-24	1993	yes
435	105	K-0986-02	N OF K-32 TO N OF KANSAS AVE	1987	yes/overlaid
435	105	K-0987-02	N OF KANS AVE TO S OF STATE AVE (KTA IC)	1985	yes/overlaid
435	105	K-0988-02	0.2 M S STATE AV TO .5 M N LEAVENWORTH RD	1985	yes/overlaid
435	105	K-0989-02	0.5 M N OF LEAVENWORTH ROAD N TO K-5	1986	yes/overlaid
435	105	K-0990-03	K-5 TO MISSOURI RIVER	1984	yes
435	105	K-0990-03	K-5 TO MISSOURI RIVER	1984	no
635	105	K-1023-01	MERRIAM DRIVE, NORTH TO K-32 (EL AND WL)	1996	no

TABLE A.2
Quarry Information and Age at Time of D-Cracking for the Criteria Projects, Listed by County, Route, and Project Number

Route	County	Project	Quarry No.	Beds	Geo Class	Year Paving Completed	Year D-Cr noticed	Age when D-Cr noticed
169	1	K-0104-03	NE1/4 S2 T25S R18E	0–30 ft from top of ledge	RYTN	1981	-	29
169	1	K-0106-02	4-001-01	1,2,3,4	RYTN	1986	-	24
169	1	K-1280-02	NE1/4 S2 T25S R18E	0–30 ft from top of ledge	RYTN	1980	-	30
296	1	K-1281-02	4-001-01	1,2,3,4	RYTN	1981	-	29
73	3	K-0117-02	1-052-02	1,2	STNR	1985	-	25
69	6	K-0135-02	4-054-02	1,2,3	BFLS	1985	1997	12
69	6	K-4066-01	4-006-11	1,2,3,(4)	LBRD	1997	-	13
54	8	K-0152-02	4-037-02	1,2,3,4	WKRS	1985	-	25
400	8	K-1879-01	4-037-02	1,2,3,4	WKRS	1987	-	23
400	8	K-2826-01	4-037-05	4,5	BLGM	1988		22
254	8	K-3321-01	2-057-04	2,3	CRSL	1995	2009	15
50	9	K-2813-01	1-056-01	1,2,3	HRFD	1990	-	20
50	9	K-3216-02	2-057-05	2	FRRL	1997	2010	13
50	9	K-3217-02	2-057-04	2,3	CRSL	1997	2009	13
50	9	K-3222-01	1-056-01	(1),2,3	HRFD	1994	2009	16
499/ 166	10	K-0171-01	4-010-01	1,2	PLSM	1988	-	22
166	10	K-4729-02	5-018-03	5, 6, 7	HOWE(5), BNNTR(6),GLCK(7)	1997	-	13
81	15	K-4956-03	2-021-10	1,2,3,4	TWND	1999	2010	11
81	15	K-4956-03	2-021-10	1,2,3,4	TWND	1998	-	12
77	18	K-0212-02	5-018-01	1,2,3,4	HOWE(1,2), BNNTR(3),GLCK(4)	1981	-	29
			4-103-01	1,2	STNR			
360	18	K-4432-02	5-018-02	1,2,3	BNNTR	1995	-	15
77	18	K-7711-01	5-018-03	5,6,7	HOWE(5),BNNTR(6),GLCK(7)	1999	-	11
69	19	K-3276-01	4-006-11	1,2,3,(4)	LBRD	1998	-	12
70	21	K-2588-01	2-021-01	1,2,3	CRSL	1986	-	24

TABLE A.2
Quarry Information and Age at Time of D-Cracking for the Criteria Projects, Listed by County, Route, and Project Number

Route	County	Project	Quarry No.	Beds	Geo Class	Year Paving Completed	Year D-Cr noticed	Age when D-Cr noticed
70	21	K-2609-01	2-021-03	1,2,3,4,5	TWND	1992	-	18
36	22	K-0248-01	1-052-02	1,2	STNR	1983	-	27
36	22	K-0251-01	1-052-02	1,2	STNR	1984	-	26
36	22	K-1773-01	1-052-02	1,2	STNR	1984	-	26
36	22	K-1876-02	1-022-02	5,6,7	AMZN	1990	-	20
35	30	K-3596-01	4-030-04	4,5;10,11,12,13	STNR(4,5); SPGH(10,11,12,13)	1995	2009	15
35	30	K-3596-02	1-070-06	B	KRFD	1996	-	14
35	30	K-5085-01	4-030-02	13,14	SPGH	1998	2010	12
68	30	K-5998-01	4-030-02	4,5	STNR	1996	2005	14
70	31	K-2611-01	2-021-03	1,2,3,4,5	TWND	1990	-	20
			2-021-08	1,2,3,4,5	TWND			
70	31	K-2611-02	2-031-01	2	TWND	1991	2009	19
			2-021-03	1,2,3,4,5	TWND			
70	31	K-2611-02	2-031-01	2	TWND	1992	-	18
			2-021-03	1,2,3,4,5	TWND			
70	31	K-5086-01	2-021-10	1,2,3,4	TWND	1999	-	11
70	31	K-5090-01	1-081-05	1,2,3,4,5	TRKO	1999	-	11
400	37	K-3292-02	4-037-03	2,3	EVCK	1997	2010	13
400	37	K-3293-03	4-037-03	2,3	EVCK	1996	-	14
400	37	K-3293-04	4-037-06	1,2,3	PLSM	1998	-	12
50	40	K-4058-03	2-057-04	2,3	CRSL	1994	2005	16
50	40	K-4350-01	2-057-04	2,3	CRSL	1997	2009	13
135	40	K-5089-01 NB	2-057-06	1,2,3,4	CRSL	1999	2010	11
			5-018-02	1,2,3	BNNTR			
135	40	K-5089-01 SB	4-025-02	1,2,3	EVCK	1999	2010	11
135	40	K-5634-02	4-030-02	4,5	STNR	1999	-	11
75	43	K-3250-01	1-089-02	1,2,3	BLGM	1993	-	17
75	43	K-3251-01	1-089-02	1,2,3	BLGM	1995	-	15
75	43	K-3251-01	1-089-02	1,2,3	BLGM	1996	-	14
435	46	K-0456-04	4-054-02	1,2,3	BFLS	1985	-	25
435	46	K-0457-05	1-046-09	(3),4,5	ARGN	1984	2009	26
435	46	K-0460-02	1-046-04	4,5	CPCK	1982	2010	28
435	46	K-0461-01	1-046-03	1,2	ARGN	1980	-	30

TABLE A.2
Quarry Information and Age at Time of D-Cracking for the Criteria Projects, Listed by County, Route, and Project Number

Route	County	Project	Quarry No.	Beds	Geo Class	Year Paving Completed	Year D-Cr noticed	Age when D-Cr noticed
169	46	K-1310-01	4-054-02	1,2,3	BFLS	1987	2009	23
10	46	K-1492-01	1-046-09	(3),4,5	ARGN	1984	2002	26
35	46	K-1774-01	1-046-02	(3),4,5,6	ARGN	1990	-	20
435	46	K-2345-01	1-046-08	1,2	UFRLY	1987	-	23
35	46	K-2434-02	4-030-04	4,5	STNR	1987	2010	23
35	46	K-2434-04	4-030-04	10,11,12,13	SPGH	1989	-	21
35	46	K-2500-01	4-061-05	4,5	ARGN	1992	-	18
35	46	K-2501-01	1-046-02	4,5,6	ARGN	1991	-	19
35	46	K-2578-01	1-046-02	4,5,6	ARGN	1991	-	19
7	46	K-3382-01	1-046-11	5,6,7	UFRLY	1995	-	15
435	46	K-3637-01 EB (SB)	1-046-15	1;2,3,4,5	UFRLY(1); ARGN(2,3,4, 5)	1996	2009	14
435	46	K-3637-01 WB (NB)	1-046-15	2,3,4,(5)	ARGN	1995	-	15
35	46	K-4088-02	1-046-11	5,6,7	UFRLY	1996	-	14
400	50	K-4891-02	4-063-06	1,2,3	WNRS	1997	-	13
73	52	K-1875-03	1-046-02	4,5,6	ARGN	1990	2008	18
73	52	K-4443-01	1-046-15	2,3,4,5	ARGN	1996	2008	14
35	56	K-2633-01	1-056-01	1,2,3	HRFD	1993	-	17
50	56	K-2853-01	1-056-01	1,2,3	HRFD	1993	-	17
56	57	K-0561-02	2-021-01	1,2,3	CRSL	1988	-	22
56	57	K-0562-02	2-021-01	1,2,3	CRSL	1987	-	23
50	57	K-3046-03	2-057-04	2,3	CRSL	1994	2010	16
50	57	K-3219-02	2-057-04	2,3	CRSL	1994	2009	16
50	57	K-3220-01	2-057-04	2,3	CRSL	1994	2009	16
50	57	K-3221-02	2-057-05	2	FRRL	1998	2009	12
135	59	K-5084-01	2-057-04	2,3	CRSL	1997	2006	13
169	61	K-0590-02	4-061-05	4,5; 6	ARGN	1986	2010	24
69	61	K-5760-01	4-054-11	1,2,3/B,C, D	BFLS (1,2,3) WNRS(B,C, D)	1999	-	11
400	63	K-4892-02	4-063-06	1,2,3	WNRS	1998	-	12
169	67	K-0619-02	4-001-01	1,2,3,4	RYTN	1985	-	25
169	67	K-0620-02	4-001-01	1,2,3,4	RYTN	1985	-	25

TABLE A.2
Quarry Information and Age at Time of D-Cracking for the Criteria Projects, Listed by County, Route, and Project Number

Route	County	Project	Quarry No.	Beds	Geo Class	Year Paving Completed	Year D-Cr noticed	Age when D-Cr noticed
75	70	K-3247-01	4-030-04	10,11,12,13	SPGH	1992	2010	18
35	70	K-5028-01	4-030-04	4,5;10,11,12,13	STNR(4,5); SPGH(10,11, 12,13)	1995	2009	15
24	75	K-2592-01	1-081-01	1,2,3,4	TRKO	1990	-	20
24	75	K-3325-02	1-081-05	1,2,3,4,5	TRKO	1997	-	13
96	78	K-4457-01	4-037-06	1,2,3	PSLM	1997	2010	13
96	78	K-4458-01	4-037-03	2,3	EVCK	1996	2010	14
81	79	K-5021-02	2-021-10	1,2,3,4	TWND	1999	2010	11
81	79	K-5021-04	2-021-11	(1),(2),3,4	CRSL	2001	-	9
81	79	K-5022-02	2-021-10	1,2,3,4	TWND	1999	2010	11
			Lincoln Quartzite, APAC-Kansas, Shears Div.					
135	85	K-5644-01	2-021-06	4,5	CRSL	2001	-	9
			2-021-11	(1),(2),3,4				
			2-021-12	1,2,3	TWND			
135	85	K-5263-01	2-021-10	1,2,3,4	TWND	1999	-	11
54	87	K-0764-02	4-037-02	1,2,3,4	WKRS	1987	2005	23
81	87	K-0768-01	4-037-02	1,2,3,4	WKRS	1986	-	24
235	87	K-2514-01	5-018-01	1,2,3,4	HOWE(1,2), BNNTR(3),GLCK(4)	1988	-	22
235	87	K-2515-01	4-037-02	1,2,3,4,5	WKRS	1985	-	25
			I-235 Recycle shoulders only					
135	87	K-2617-01	4-025-01	3	EVCK	1991	-	19
54	87	K-3181-01	5-018-01	1,2,3,4	HOWE(1,2), BNNTR(3),GLCK(4)	1994	-	16
15	87	K-3324-01	5-018-01	1,2,3,4	HOWE(1,2), BNNTR(3),GLCK(4)	1993	2010	17
			4-025-01					

TABLE A.2
Quarry Information and Age at Time of D-Cracking for the Criteria Projects, Listed by County, Route, and Project Number

Route	County	Project	Quarry No.	Beds	Geo Class	Year Paving Completed	Year D-Cr noticed	Age when D-Cr noticed
54	87	K-3388-01	5-018-01	1,2,3,4	HOWE(1,2), BNNTR(3),GLCK(4)	1992	-	18
15	87	K-3684-01	5-018-02	1,2,3	BNNTR	1996	-	14
96	87	K-4433-03	2-057-02	1,2,3,4	FRRL	1992	-	18
96	87	K-4434-03	4-025-01	3	EVCK	1993	2010	17
96	87	K-4434-04	4-025-01	3	EVCK	1993	-	17
96	87	K-4459-01	4-037-03	2,3	EVCK	1996	2010	14
96	87	K-4460-01	5-018-01	(1),2,3,(4)	HOWE(1,2), BNNTR(3),GLCK(4)	1995	-	15
70	89	K-2445-01	1-089-01	A	HRFD	1989	2009	21
70	89	K-2446-01	1-089-01	A	HRFD	1992	-	18
70	89	K-2446-01	1-089-01	A	HRFD	1992	2009	18
70	89	K-2446-02	1-089-01	A	HRFD	1993	-	17
470	89	K-2454-01	1-089-01	A	HRFD	1990	2010	20
75	89	K-2866-01	1-089-02	1,2,3	BLGM	1993	-	17
70	89	K-3344-01	1-089-01	A	HRFD	1992	-	18
70	89	K-3344-01	1-089-01	A	HRFD	1993	2009	17
4	89	K-3362-10	1-070-06	B	KRFD	1996	2010	14
75	89	K-3371-01	1-070-06	B	KRFD	1997	2009	13
75	89	K-3371-03	4-030-02	4,5	STNR	1996	2010	14
470	89	K-3831-01	1-089-01	A	HRFD	1991	2009	19
75	89	K-4341-01	1-089-02	1,2,3	BLGM	1995	-	15
70	89	K-5087-01	1-089-06	1,2	BLGM	2000	2010	10
			1-070-05	1,2	EVCK			
166	96	K-0888-02	5-018-01	1,2,3,4	HOWE(1,2), BNNTR(3),GLCK(4)	1979	-	31
70	99	K-5628-01	1-081-05	1,2,3,4,5	TRKO	1999	-	11
70	99	K-5633-01	1-081-05	1,2,3,4,5	TRKO	2000	-	10
			2-021-10	1,2,3,4	TWND			
400	103	K-3295-02	4-103-01	1,2	STNR	1998	-	12
70	105	K-0966-03	4-061-05	4,5,6	ARGN	1988	-	22
70	105	K-0968-01	1-046-01	5	ARGN	1983	2009	27
435	105	K-0986-02	1-105-02	8,9,10,11	ARGN	1987	2004	23

TABLE A.2
Quarry Information and Age at Time of D-Cracking for the Criteria Projects, Listed by County, Route, and Project Number

Route	County	Project	Quarry No.	Beds	Geo Class	Year Paving Completed	Year D-Cr noticed	Age when D-Cr noticed
70	105	K-0987-01	1-046-09	1,2;5,6,7	LFRLY(1,2); ARGN(5,6,7)	1985	-	25
			1-105-02	SPGH(1),(2),(3); ARGN(8,9, 10,11)	(SPGH);(ARGN)			
435	105	K-0987-02	4-030-02	4,5	STNR	1985	2007	22
435	105	K-0988-02	4-054-02	1,2,3	BFLS	1985	2005	25
435	105	K-0989-02	4-030-02	4,5	STNR	1986	2005	24
			4-061-05	4, 5				
435	105	K-0990-03	4-054-02	1,2,3	BFLS	1984	2009	26
435	105	K-0990-03	4-054-02	1,2,3	BFLS	1984	-	26
635	105	K-1023-01	1-046-15	1,2,3,4,5	UFRLY(1), ARGN(2,3,4, 5)	1996	-	14
70	105	K-1421-01	4-061-05	4,5,(6)	ARGN	1987	2009	23
70	105	K-1422-01	4-061-05	4,5	ARGN	1988	2009	22
70	105	K-1423-01	1-046-09	3,4,5	ARGN	1986	-	24
35	105	K-1775-03	1-046-08	1,2	UFRLY	1988	-	22
70	105	K-2447-01	1-046-10	4,5,6	ARGN	1993	-	17
70	105	K-2447-01	1-046-10	4,5,6	ARGN	1993	2010	17

TABLE A.3
Projects Exhibiting D-Cracking and Were at Least 20 Years Old in 2010

Route	Co.	Project	Length (MI)	Direction	Year Paving Completed	Age	Quarry No.	D-Cr present?	Years to D-Cr
435	46	K-0457-05	2.6	NB/SB	1984	26	1-046-09	yes	25
435	46	K-0460-02	2	NB/SB	1982	28	1-046-04	yes	28
169	61	K-0590-02	1.74	NB/SB	1986	24	4-061-05	yes	24
70	105	K-0968-01	1.231	EB/WB	1983	27	1-046-01	yes	26
435	105	K-0987-02	1.6	n/a	1985	25	4-030-02	yes/overlaid	20
435	105	K-0988-02	2.7	n/a	1985	25	4-054-02	yes/overlaid	20
435	105	K-0990-03	1.348	SB	1984	26	4-054-02	yes	25
169	46	K-1310-01	5.6	NB/SB	1987	23	4-054-02	yes	22
70	105	K-1421-01	1.8	EB/WB	1987	23	4-061-05	yes	22
70	105	K-1422-01	1.065	EB/WB	1988	22	4-061-05	Yes	21
35	46	K-2434-02	6.59	NB SB	1987	23	4-030-04	yes	23
70	89	K-2445-01	1.65	EB/WB	1989	21	1-089-01	Yes	20
470	89	K-2454-01	4.052	n/a	1990	20	1-089-01	yes	20

TABLE A.4
Projects Exhibiting No D-Cracking and Were at Least 20 Years Old in 2010

Route	Co.	Project	Length (MI)	Direction	Year Paving Completed	Age	Quarry No.	D-Cr present?
435	46	K-0456-04	1.017		1985	25	4-054-02	no
35	105	K-1775-03	1.8		1988	22	1-046-08	no
35	46	K-2434-04	6.7	NB SB	1989	21	4-030-04	no
36	22	K-0248-01	1		1983	27	1-052-02	no/overlaid
36	22	K-0251-01	2.36		1984	26	1-052-02	no/overlaid
36	22	K-1773-01	1.6	EB	1984	26	1-052-02	no/overlaid
54	8	K-0152-02	7.2	EB/WB	1985	25	4-037-02	no
56	57	K-0561-02	7.011		1988	22	2-021-01	no
56	57	K-0562-02	6.913		1987	23	2-021-01	no
70	105	K-0966-03	1.72		1988	22	4-061-05	no/overlaid
70	105	K-0987-01	1.6		1985	25	1-046-09	no
							1-105-02	
70	105	K-1423-01	2.1	EB/WB	1986	24	1-046-09	no
70	21	K-2588-01	8.524		1986	24	2-021-01	no/overlaid
73	3	K-0117-02	8.7	n/a	1985	25	1-052-02	no
77	18	K-0212-02	10.222		1981	29	5-018-01	no/overlaid
							4-103-01	
81	87	K-0768-01	3.032	NB/SB	1986	24	4-037-02	No
166	96	K-0888-02	9	0	1979	31	5-018-01	No
169	1	K-0104-03	2.4	0	1981	29	Quarry never evaluated for Class 1	no
169	1	K-0106-02	5.2	SB	1986	24	4-001-01	no
169	67	K-0619-02	8.162	NB/SB	1985	25	4-001-01	no
169	67	K-0620-02	3.341	SB	1985	25	4-001-01	no
169	1	K-1280-02	4	0	1980	30	Quarry never evaluated for Class 1	no
235	87	K-2514-01	6.8	SB/NB	1988	22	5-018-01	no
235	87	K-2515-01	8.6	NB/SB	1985	25	4-037-02	no
296	1	K-1281-02	3.1		1981	29	4-001-01	no
400	8	K-1879-01	5.322		1987	23	4-037-02	no/overlaid
435	46	K-2345-01	1.352		1987	23	1-046-08	no
435	46	K-0461-01	3.031		1980	30	Quarry never evaluated for Class 1	no/overlaid

TABLE A.4
Projects Exhibiting No D-Cracking and Were at Least 20 Years Old in 2010

Route	Co.	Project	Length (MI)	Direction	Year Paving Completed	Age	Quarry No.	D-Cr present?
499/166	10	K-0171-01	9.449		1988	22	4-010-01	no
35	46	K-1774-01	4.7		1990	20	1-046-02	no
36	22	K-1876-02	14.58	EB/WB	1990	20	1-022-02	no
24	75	K-2592-01	1.108		1990	20	1-081-01	no
70	31	K-2611-01	7	EB/WB	1990	20	2-021-03 2-021-08	no
50	9	K-2813-01	1		1990	20	1-056-01	no
400	8	K-2826-01	8.391		1988	22	4-037-05	no/overlaid

TABLE A.5
Projects with D-Cracking in Less Than 20 Years

Rt.	Cnty.	Project	Project Length (MI)	Direction w/ D-cr	Year Paved	D-Cr noted	Age to D-cr	Quarry No.
73	52	K-1875-03	1.0	NB/SB	1990	2008	18	1-046-02
10	46	K-1492-01	4.4		1984	2002	18	1-046-09
70	105	K-2447-01	1.5	EB	1993	2010	17	1-046-10
73	52	K-4443-01	1.5	NB/SB	1996	2008	12	1-046-15
435	46	K-3637-01	2.9	EB (SB)	1996	2009	13	1-046-15
50	9	K-3222-01	1.7		1994	2009	15	1-056-01
75	89	K-3371-01	7.0	NB/SB	1997	2009	12	1-070-06
4	89	K-3362-10	2.4	NB/SB	1996	2010	14	1-070-06
70	89	K-3344-01	1.3	WB	1993	2009	16	1-089-01
70	89	K-2446-01	2.6	EB	1992	2009	17	1-089-01
470	89	K-3831-01	1.3	EB/WB	1991	2009	18	1-089-01
435	105	K-0986-02	1.9		1987	2004	17	1-105-02
81	15	K-4956-03	2.1	NB	1999	2010	11	2-021-10
81	79	K-5021-02	2.6	NB/SB	1999	2010	11	2-021-10
81	79	K-5022-02	1.9	NB/SB	1999	2010	11	2-021-10
70	31	K-2611-02	4.3	EB	1991	2009	18	2-031-01
135	59	K-5084-01	5.6	NB/SB	1997	2006	9	2-057-04
50	40	K-4058-03	6.7		1994	2005	11	2-057-04
50	9	K-3217-02	10.2		1997	2009	12	2-057-04
50	40	K-4350-01	5.8	WB/EB	1997	2009	12	2-057-04
254	8	K-3321-01	1.1	EB/WB	1995	2009	14	2-057-04
50	57	K-3219-02	1.9		1994	2009	15	2-057-04
50	57	K-3220-01	2.1		1994	2009	15	2-057-04
50	57	K-3046-03	1.4		1994	2010	16	2-057-04
50	57	K-3221-02	9.7		1998	2009	11	2-057-05
50	9	K-3216-02	9.2		1997	2010	13	2-057-05
135	40	K-5089-01	7.4	NB	1999	2010	11	2-057-06
96	87	K-4434-03	2.2	NB/SB	1993	2010	17	4-025-01
135	40	K-5089-01	7.4	SB	1999	2010	11	4-025-02
68	30	K-5998-01	1.3	NB	1996	2005	9	4-030-02
35	30	K-5085-01	5.1	NB/SB	1998	2010	12	4-030-02
40	89	K-3362-08	1.4	WB/EB	1997	2010	13	4-030-02
75	89	K-3371-03	1.1		1996	2010	14	4-030-02
35	30	K-3596-01	3.2	SB/NB	1995	2009	14	4-030-04
35	70	K-5028-01	5.1	NB/SB	1995	2009	14	4-030-04
75	70	K-3247-01	1.7		1992	2010	18	4-030-04
54	87	K-0764-02	1.5		1987	2005	18	4-037-02
400	37	K-3292-02	10.6		1997	2010	13	4-037-03
96	78	K-4458-01	3.3	EB	1996	2010	14	4-037-03
96	87	K-4459-01	3.9	WB/EB	1996	2010	14	4-037-03
96	78	K-4457-01	10.7	EB	1997	2010	13	4-037-06
69	6	K-0135-02	12.7		1985	1997	12	4-054-02
435	105	K-0989-02	4.1	NB/SB	1986	2005	19	4-061-05
15	87	K-3324-01	4.7	NB/SB	1993	2010	17	5-018-01
135	40	K-5089-01	7.4	NB	1999	2010	11	5-018-02

TABLE A.6
Overlaid Projects Included in the Current Study

Route	County	Project	Year Paving Completed	D-Cr present?	Reason for Overlay
77	18	K-0212-02	1981	no/overlaid	unknown
36	22	K-0248-01	1983	no/overlaid	Overlaid due to skewed joints and no load transfer at 21 and 22 years old.
36	22	K-0251-01	1984	no/overlaid	Overlaid due to skewed joints and no load transfer at 21 and 22 years old.
435	46	K-0461-01	1980	no/overlaid	About 1990 the inside NB lane was milled and inlaid due to high steel. Later a segment in the SB lanes was also milled and inlaid. The spalling continued and the interpanel cracks faulted.
54	87	K-0764-02	1987	yes/overlaid	D-cracked?
70	105	K-0966-03	1988	no/overlaid	unknown
435	105	K-0986-02	1987	yes/overlaid	unknown
70	105	K-0987-01	1985	no	D-Cracking
435	105	K-0987-02	1985	yes/overlaid	D-Cracking
435	105	K-0988-02	1985	yes/overlaid	D-Cracking
435	105	K-0989-02	1986	yes/overlaid	unknown
10	46	K-1492-01	1984	yes/overlaid	unknown
36	22	K-1773-01	1984	no/overlaid	unknown
73	52	K-1875-03	1990	yes/overlaid	D-Cracking
400	8	K-1879-01	1987	no/overlaid	Overlaid due to skewed joints, faulting, no CTB.
70	21	K-2588-01	1986	no/overlaid	unknown
400	8	K-2826-01	1988	no/overlaid	Skewed joints, faulting, no CTB.
50	40	K-4058-03	1994	yes/overlaid	Erosion of subgrade caused slab cracking.
166	10	K-4729-02	1997	no/overlaid	unknown

Appendix B: Materials Testing Results

Appendix B tables report the average, minimum, and maximum values for the production (QPS) test results of each quarry and set of beds reported in the production database before the year 2002. Table B.1 reports the durability factor (DF) results. Table B.2 lists the percent expansion results. Table B.3 contains the freeze-thaw (soundness) results. Each table includes test results for every quarry and bed combination that was submitted for testing before 2002 regardless of whether or not a given quarry is associated with this study. Therefore, there are quarries and sets of beds in these tables that are not associated with any project in this study. All of the results were included for completeness. Also, the quarry numbers and bed sets reported are correct for time the samples were tested. Some quarry numbers and/or bed renumbering may have occurred. Any questions regarding such changes should be directed to the KDOT Bureau of Materials and Research for clarification. The information was obtained from KDOT's Production Database. For a given result, the average value is the first number listed. The values in the parenthesis are the minimum and maximum values, respectively, from that quarry, bed number, and year combination.

B.1 Durability Factor Test Results

Table B.1
Durability Factor Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-022-02	5,6,7						98.0 (98–98)											
1-023-01	5,6														79.0 (79–79)			
1-023-03	4,5																	89.6 (78–98)
1-046-01	5	96.0 (96-96)	97.0 (97-97)	99.0 (99-99)														
1-046-02	3,4,5,6					98.0 (96-99)	93.5 (89-98)											
1-046-02	4,5,6						97.0 (97-97)	97.8 (96-99)	97.0 (97-97)									
1-046-08	1,2		98.0 (98-98)	95.5 (95-96)	86.0 (75-97)												96.5 (95-98)	
1-046-08	4,5																97.5 (97-98)	
1-046-08	4,5,6			97.0 (96-98)			91.0 (91-91)											
1-046-09	3,4,5	97.0 (97-97)	96.0 (94-98)						96.0 (95-97)			95.0 (95-95)			95.0 (94-96)	97.0 (95-98)	96.6 (96-97)	90.6 (77-98)
1-046-09	4,5		92.0 (92-92)															
1-046-09	8,9							96.0 (96-96)	87.5 (84-91)									
1-046-10	4,5,6						94.0 (94-94)	99.0 (99-99)	98.0 (97-99)	98.3 (98-99)	98.0 (98-98)							
1-046-10	6,7					97.0 (97-97)												
1-046-11	1									99.0 (99-99)	98.7 (98-99)							
1-046-11	2									85.5 (80-91)								
1-046-11	4,5									79.0 (79-79)								
1-046-11	5,6,7											99.0 (98-100)	97.3 (97-98)			98.0 (98-98)	98.3 (98-99)	97.0 (97-97)
1-046-15	1												92.2 (87-97)					
1-046-15	2,3,4											95.0		95.1				

Table B.1
Durability Factor Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
												(95-95)		(92-97)				
1-046-15	2,3,4,5											97.0 (97-97)	97.4 (95-99)					
1-052-02		94.0 (94-94)																
1-052-02	1,2	97.0 (96-98)				93.0 (93-93)												
1-052-03	1		98.0 (98-98)															
1-056-01	1,2,3					98.0 (98-98)	95.0 (95-95)	97.0 (97-97)	95.0 (95-95)	93.3 (88-97)								
1-056-01	2,3										96.0 (96-96)							
1-056-02	3										98.0 (98-98)							
1-070-04	2,3																	94.7 (94-96)
1-070-05	1,2															82.0 (76-89)		
1-070-06	B												98.3 (98-99)	96.3 (95-97)	94.5 (93-96)	96.0 (96-96)		
1-081-01	1,2,3,4					99.3 (99-100)												
1-081-01	3,4			100 (100-100)														
1-081-02	3,4						99.6 (99-100)											
1-081-05	1,2,3,4,5											98.0 (98-98)		98.6 (98-99)	98.6 (98-99)	99.0 (97-100)	88.6 (67-100)	98.3 (98-99)
1-089-01	A						96.0 (96-96)	94.0 (94-94)	95.0 (95-95)									
1-089-01	OA										98.0 (98-98)							
1-089-02	1,2,3									98.0 (98-98)	98.0 (97-99)	97.5 (97-98)	97.6 (97-98)					
1-089-05	5																96.5 (96-97)	77.0 (77-77)
1-089-06	1,2																97.1 (96-99)	

Table B.1
Durability Factor Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
2-021-01	1,2,3	99.5 (99-100)	98.7 (98-99)	99.4 (99-100)		99.6 (99-100)	97.0 (96-98)											
2-021-03	1,2,3,4					100 (100-100)												
2-021-03	1,2,3,4,5					99.6 (99-100)	95.2 (83-99)	98.0 (98-98)	99.3 (99-100)	97.0 (97-97)								
2-021-03	3,4,5	99.0 (99-99)				99.0 (99-99)												
2-021-10	1,2,3,4														98.0 (97-99)	98.0 (96-99)	98.3 (97-99)	99.0 (99-99)
2-021-11	1,2,3,4																99.0 (99-99)	85.8 (64-97)
2-021-11	3,4																	99.0 (99-99)
2-021-12	1,2,3																	99.0 (99-99)
2-031-01	1,2											99.0 (99-99)	100 (100-100)				99.0 (98-100)	
2-031-01	2						98.3 (98-99)	99.5 (99-100)	98.0 (98-98)	99.0 (99-99)	99.0 (98-100)							
2-057-02	1,2,3,4							96.6 (96-98)	97.2 (96-98)									
2-057-03	1,2,3					98.0 (98-98)	98.0 (98-98)	98.3 (98-99)										
2-057-04	2,3									98.2 (98-99)	97.6 (96-99)	98.0 (98-98)	98.2 (97-99)					97.0 (96-98)
2-057-05	2													98.2 (98-99)	97.6 (97-98)			
2-057-06	1,2													96.0 (96-96)				
2-057-06	3,4													97.0 (96-98)		88.2 (84-94)		
4-001-01	1,2,3,4	98.5 (98-99)	98.0 (98-98)						98.0 (98-98)	98.0 (98-98)	98.0 (98-98)	97.5 (97-98)			98.0 (98-98)	98.5 (98-99)	98.0 (98-98)	98.0 (97-99)
4-006-03	5											98.0 (98-98)						
4-006-03	7,8																98.0 (98-98)	

Table B.1
Durability Factor Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-006-11	1,2,3														97.0 (97-97)			
4-006-11	1,2,3,4													97.5 (97-98)	97.0 (97-97)			
4-010-01	1,2				98.0 (98-98)													
4-016-03	2,3		99.0 (99-99)															
4-019-01	4,5								98.3 (98-99)									
4-025-01	3						96.0 (96-96)	98.0 (98-98)	97.0 (97-97)	97.0 (95-98)	97.6 (97-98)							
4-025-02	1,2,3															97.7 (96-99)	98.2 (98-99)	97.6 (97-98)
4-025-03	1,2,3																98.0 (98-98)	
4-025-03	A,1,2,3																98.0 (98-98)	98.3 (98-99)
4-030-01	13,14												99.0 (99-99)	98.0 (98-98)				
4-030-02	1	93.0 (93-93)	89.5 (88-91)															
4-030-02	13,14													96.0 (96-96)	97.0 (97-97)	98.0 (98-98)	97.6 (97-98)	97.0 (97-97)
4-030-02	4,5	97.5 (97-98)		96.0 (96-96)									97.0 (97-97)	97.0 (97-97)	95.0 (95-95)	97.5 (97-98)	98.0 (98-98)	98.0 (96-100)
4-030-04	10,11,12,13				96.0 (94-99)	97.0 (97-97)	95.0 (95-95)		94.0 (94-94)	96.5 (96-97)		93.6 (92-95)						
4-030-04	4,5	98.0 (98-98)	97.5 (97-98)	97.6 (97-98)		97.0 (97-97)	98.0 (98-98)	99.0 (99-99)		99.0 (99-99)	97.4 (97-98)	95.0 (95-95)						
4-037-02	1,2,3,4			99.0 (99-99)														
4-037-03	2,3												98.0 (97-99)	98.0 (97-99)	95.5 (93-97)	96.0 (96-96)		
4-037-05	4,5				99.6 (99-100)													
4-037-06	1,2,3												95.5 (94-97)	96.2 (92-99)	97.3 (97-98)			
4-037-06	3															95.0 (95-95)		

Table B.1
Durability Factor Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-050-01	1,2			98.6 (98-99)														
4-050-06	1,2													98.0 (97-99)		98.0 (98-98)		
4-054-02	1,2,3	97.2 (97-98)		97.0 (97-97)	98.3 (97-100)	97.0 (97-97)					98.0 (98-98)	98.0 (98-98)			97.6 (97-98)	98.0 (98-98)		
4-054-06	5,6,7					97.3 (97-98)												
4-054-11	1,2,3												97.0 (97-97)	98.0 (98-98)		97.0 (96-98)	95.3 (94-97)	97.0 (97-97)
4-054-11	B,C,D															95.0 (95-95)		
4-054-11	B,C,D,															71.0 (71-71)		
4-061-05	4,5		97.8 (97-98)	95.5 (95-96)														
4-061-05	4,5,6			97.0 (97-97)	98.0 (98-98)	98.0 (97-99)			97.0 (97-97)						96.6 (96-98)	97.5 (97-98)	97.0 (97-97)	95.7 (94-98)
4-061-05	6		91.0 (91-91)		94.3 (92-96)													
4-061-05	9															98.0 (98-98)		
4-061-08	1,2,3,4													98.0 (98-98)	96.0 (96-96)			
4-061-08	2,3,4							96.0 (94-98)										
4-061-08	3,4							99.0 (99-99)										
4-063-02	1,2,3							98.0 (98-98)				99.0 (99-99)						99.0 (99-99)
4-063-05	1,2,3,4,5										96.3 (96-97)					96.0 (96-96)		
4-063-06	1,2,3													97.6 (97-98)	97.0 (95-99)	96.0 (96-96)	98.0 (98-98)	98.0 (98-98)
4-103-01	1,2				97.5 (97-98)					96.6 (96-97)			97.0 (97-97)		96.0 (95-97)			
4-103-01	2														97.0 (97-97)			
5-018-01	1,2; 3											99.0 (99-99)						

Table B.1
Durability Factor Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
5-018-01	1,2; 3;4			98.5 (98-99)	98.5 (98-99)	98.5 (97-99)	97.0 (97-97)	100 (100-100)	97.4 (96-99)	99.4 (98-100)	99.0 (99-99)	98.3 (97-99)						
5-018-01	2;3; 4											99.0 (99-99)	98.5 (98-99)				100 (100-100)	
5-018-01	5,6,7												97.0 (97-97)					
5-018-02	1,2,3											99.0 (99-99)	99.0 (98-100)		96.0 (96-96)	98.0 (97-99)		
5-018-03	5;6; 7													98.0 (98-98)	99.0 (99-99)	100 (100-100)		
MO-020	1,2												94.0 (94-94)					
MO-023	2,3															98.0 (98-98)		

B.2 Percent Expansion Test Results

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-022-02	5,6,7						0.0065 (0.003-0.01)											
1-023-01	5,6														0.0510 (0.051-0.051)			
1-023-03	4,5																	0.0250 (0.015-0.036)
1-046-01	5	0.0040 (0.004-0.004)	0.0090 (0.009-0.009)	0.0130 (0.013-0.013)														
1-046-02	3,4,5,6					0.0105 (0.007-0.015)	0.0105 (0.01-0.011)											
1-046-02	4,5,6						0.0130 (0.004-0.022)	0.0091 (-0.001-0.018)	0.0083 (0.007-0.009)									
1-046-08	1,2		0.0150 (0.015-0.015)	0.0167 (0.013-0.024)	0.0385 (0.018-0.059)												0.0095 (0.004-0.015)	
1-046-08	4,5																0.0105 (0.006-0.015)	
1-046-08	4,5,6			0.0140 (0.009-0.019)			0.0180 (0.018-0.018)											
1-046-09	3,4,5	0.0180 (0.018-0.018)	0.0080 (0.005-0.011)						0.0080 (0.002-0.014)			0.0050 (0.005-0.005)			0.0060 (0.003-0.009)	0.0073 (0.006-0.009)	0.0116 (0.007-0.017)	0.0266 (0.003-0.067)
1-046-09	4,5		0.0130 (0.013-0.013)															
1-046-09	8,9							0.0190 (0.019-0.019)	0.0585 (0.058-0.059)									

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-046-10	4,5,6						0.0180 (0.018-0.018)	0.0100 (0.01-0.01)	0.0082 (0.005-0.014)	0.0070 (0.005-0.009)	0.0090 (0.009-0.009)							
1-046-10	6,7					0.0080 (0.008-0.008)												
1-046-11	1									0.0000 (0-0)	0.0072 (0.003-0.011)							
1-046-11	2									0.0365 (0.027-0.046)								
1-046-11	4,5									0.0470 (0.047-0.047)								
1-046-11	5,6,7											0.0092 (0.007-0.015)	0.0146 (0.012-0.019)			0.0090 (0.009-0.009)	0.0056 (0.005-0.006)	0.0050 (0.005-0.005)
1-046-15	1												0.0277 (0.011-0.048)					
1-046-15	2,3,4											0.0130 (0.013-0.013)		0.0136 (0.012-0.017)				
1-046-15	2,3,4,5											0.0070 (0.007-0.007)	0.0102 (0.005-0.016)					
1-052-02		0.0220 (0.022-0.022)																
1-052-02	1,2	0.0085 (0.008-0.009)				0.0190 (0.019-0.019)												
1-052-03	1		0.0110 (0.011-0.011)															
1-056-01	1,2,3					0.0140 (0.014-0.014)	0.0130 (0.013-0.013)	0.0160 (0.016-0.016)	0.0130 (0.013-0.013)	0.0176 (0.013-0.027)								
1-056-01	2,3										0.0050 (0.005-0.005)							

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-056-02	3										0.0110 (0.011-0.011)							
1-070-04	2,3																	0.0092 (0.006-0.015)
1-070-05	1,2															0.0630 (0.032-0.101)		
1-070-06	B												0.0120 (0.007-0.018)	0.0156 (0.013-0.02)	0.0190 (0.015-0.023)	0.0165 (0.014-0.019)		
1-081-01	1,2,3,4					0.0100 (0.007-0.013)												
1-081-01	3,4			0.0063 (0.005-0.007)														
1-081-02	3,4						0.0100 (0.009-0.013)											
1-081-05	1,2,3,4,5											0.0070 (0.007-0.007)		0.0056 (0.002-0.011)	0.0033 (0-0.005)	0.0076 (0.004-0.011)	0.0433 (0.006-0.109)	0.0046 (0.001-0.007)
1-089-01	A						0.0140 (0.014-0.014)	0.0190 (0.019-0.019)	0.0090 (0.009-0.009)									
1-089-01	OA										0.0030 (0.003-0.003)							
1-089-02	1,2,3									0.0120 (0.011-0.013)	0.0153 (0.013-0.018)	0.0080 (0.007-0.009)	0.0150 (0.009-0.021)					
1-089-05	5																0.0115 (0.011-0.012)	0.0910 (0.091-0.091)
1-089-06	1,2																0.0110 (0.004-0.018)	
2-021-01	1,2,3	0.0132 (0.011-0.016)	0.0100 (0.007-0.013)	0.0070 (0.002-0.014)		0.0103 (0.007-0.013)	0.0146 (0.009-0.024)											

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
2-021-03	1,2,3,4					0.0110 (0.011-0.011)												
2-021-03	1,2,3,4,5					0.0138 (0.007-0.02)	1.4080 (0.002-7)	0.0150 (0.015-0.015)	0.0086 (0.006-0.011)	0.0110 (0.011-0.011)								
2-021-03	3,4,5	0.0120 (0.009-0.018)				0.0120 (0.012-0.012)												
2-021-10	1,2,3,4														0.0096 (0.009-0.01)	0.0115 (0.007-0.017)	0.0093 (0.009-0.01)	0.0090 (0.009-0.009)
2-021-11	1,2,3,4																0.0110 (0.011-0.011)	0.0295 (0.009-0.096)
2-021-11	3,4																	0.0050 (0.003-0.007)
2-021-12	1,2,3																	0.0050 (0.003-0.007)
2-031-01	1,2											0.0040 (0.004-0.004)	0.0110 (0.011-0.011)				0.0065 (0.005-0.009)	
2-031-01	2						0.0143 (0.012-0.016)	0.0135 (0.011-0.015)	0.0100 (0.01-0.01)	0.0110 (0.011-0.011)	0.0123 (0.007-0.018)							
2-057-02	1,2,3,4							0.0032 (0-0.006)	0.0047 (0.002-0.007)									
2-057-03	1,2,3					0.0070 (0.007-0.007)	0.0130 (0.013-0.013)	0.0126 (0.007-0.018)										
2-057-04	2,3									0.0062 (0-0.011)	0.0064 (0.001-0.011)	0.0050 (0.005-0.005)	0.0104 (0.002-0.015)					0.0100 (0.008-0.012)
2-057-05	2													0.0047 (0.003-0.007)	0.0053 (0.004-0.007)			
2-057-06	1,2													0.0020 (0.002-0.002)				

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
2-057-06	3,4													0.0094 (0.009-0.011)		0.0327 (0.008-0.074)		
4-001-01	1,2,3,4	0.0025 (0-0.005)	0.0050 (0.005-0.005)						0.0090 (0.009-0.009)	0.0050 (0.005-0.005)	0.0073 (0.002-0.011)	0.0070 (0.007-0.007)			0.0080 (0.005-0.011)	0.0080 (0.008-0.008)	0.0085 (0.006-0.011)	0.0066 (0.006-0.008)
4-006-03	5											0.0080 (0.008-0.008)						
4-006-03	7,8																0.0110 (0.011-0.011)	
4-006-11	1,2,3														0.0060 (0.006-0.006)			
4-006-11	1,2,3,4													0.0080 (0.006-0.01)	0.0090 (0.007-0.011)			
4-010-01	1,2				0.0130 (0.005-0.021)													
4-016-03	2,3		0.0145 (0.011-0.018)															
4-019-01	4,5								0.0066 (0.003-0.011)									
4-025-01	3						0.0190 (0.019-0.019)	0.0135 (0.009-0.018)	0.0050 (0.005-0.005)	0.0088 (0.002-0.018)	0.0130 (0.008-0.016)							
4-025-02	1,2,3															0.0107 (0.009-0.012)	0.0087 (0.004-0.017)	0.0096 (0.007-0.011)
4-025-03	1,2,3																0.0155 (0.014-0.017)	
4-025-03	A,1,2,3																0.0075 (0.006-0.009)	0.0100 (0.004-0.016)

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-030-01	13,14												0.0105 (0.009-0.012)	0.0120 (0.012-0.012)				
4-030-02	1	0.0400 (0.04-0.04)	0.0365 (0.031-0.042)															
4-030-02	13,14													0.0090 (0.009-0.009)	0.0093 (0.008-0.011)	0.0090 (0.009-0.009)	0.0112 (0.008-0.02)	0.0120 (0.012-0.012)
4-030-02	4,5	0.0115 (0.009-0.013)		0.0080 (0.008-0.008)									0.0120 (0.01-0.013)	0.0140 (0.011-0.017)	0.0170 (0.017-0.017)	0.0085 (0.008-0.009)	0.0070 (0.007-0.007)	0.0078 (0.003-0.013)
4-030-04	10,11,12,13				0.0170 (0.01-0.025)	0.0190 (0.019-0.019)	0.0000 (0-0)		0.0180 (0.018-0.018)	0.0105 (0.01-0.011)		0.0173 (0.015-0.019)						
4-030-04	4,5	0.0130 (0.013-0.013)	0.0090 (0.007-0.011)	0.0093 (0.006-0.011)		0.0130 (0.013-0.013)	0.0010 (0.001-0.001)	0.0000 (0-0)		0.0090 (0.009-0.009)	0.0122 (0.006-0.022)	0.0150 (0.015-0.015)						
4-037-02	1,2,3,4			0.0060 (0.006-0.006)														
4-037-03	2,3												0.0124 (0.006-0.017)	0.0112 (0.009-0.015)	0.0131 (0.004-0.022)	0.0150 (0.015-0.015)		
4-037-05	4,5				0.0036 (0.002-0.006)													
4-037-06	1,2,3												0.0265 (0.02-0.033)	0.0214 (0.008-0.045)	0.0106 (0.009-0.013)			
4-037-06	3															0.0230 (0.023-0.023)		
4-050-01	1,2			0.0053 (0.002-0.009)														
4-050-06	1,2													0.0130 (0.009-0.015)		0.0150 (0.015-0.015)		
4-054-02	1,2,3	0.0080 (0.004-0.013)		0.0060 (0.006-0.006)	0.0100 (0.006-0.016)	0.0130 (0.013-0.013)					0.0070 (0.007-0.007)	0.0090 (0.009-0.009)			0.0070 (0.003-0.011)	0.0120 (0.012-0.012)		

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-054-06	5,6,7					0.0133 (0.007-0.02)												
4-054-11	1,2,3												0.0130 (0.011-0.015)	0.0130 (0.013-0.013)		0.0125 (0.01-0.015)	0.0133 (0.008-0.017)	0.0100 (0.004-0.016)
4-054-11	B,C, D															0.0150 (0.015-0.015)		
4-054-11	B,C, D,															0.0540 (0.054-0.054)		
4-061-05	4,5		0.0128 (0.009-0.022)	0.0100 (0.007-0.013)														
4-061-05	4,5,6			0.0110 (0.011-0.011)	0.0220 (0.022-0.022)	0.0180 (0.018-0.018)			0.0140 (0.011-0.017)						0.0093 (0.004-0.014)	0.0105 (0.01-0.011)	0.0090 (0.009-0.009)	0.0092 (0.005-0.014)
4-061-05	6		0.0130 (0.013-0.013)		0.0146 (0.01-0.018)													
4-061-05	9															0.0090 (0.009-0.009)		
4-061-08	1,2,3 ,4													0.0070 (0.007-0.007)	0.0140 (0.014-0.014)			
4-061-08	2,3,4							0.0100 (0.008-0.012)										
4-061-08	3,4							0.0100 (0.01-0.01)										
4-063-02	1,2,3							0.0146 (0.014-0.015)				0.0050 (0.005-0.005)						0.0010 (0.001-0.001)
4-063-05	1,2,3 ,4,5										0.0103 (0.008-0.012)					0.0140 (0.014-0.014)		
4-063-06	1,2,3													0.0066 (0.004-0.01)	0.0096 (0.003-0.018)	0.0110 (0.011-0.011)	0.0070 (0.007-0.007)	0.0030 (0.003-0.003)

TABLE B.2
Percent Expansion Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-103-01	1,2				0.0080 (0.008-0.008)					0.0096 (0.004-0.018)			0.0130 (0.013-0.013)		0.0136 (0.011-0.017)			
4-103-01	2														0.0080 (0.008-0.008)			
5-018-01	1,2; 3											0.0080 (0.008-0.008)						
5-018-01	1,2; 3;4			0.0100 (0.007-0.015)	0.0080 (0.005-0.011)	0.0110 (0.004-0.022)	0.0250 (0.025-0.025)	0.0100 (0.01-0.01)	0.0078 (0.003-0.013)	0.0073 (0.005-0.011)	0.0040 (0-0.008)	0.0086 (0.006-0.011)						
5-018-01	2;3; 4											0.0085 (0.007-0.01)	0.0105 (0.008-0.013)				0.0180 (0.018-0.018)	
5-018-01	5,6,7												0.0200 (0.02-0.02)					
5-018-02	1,2,3											0.0090 (0.009-0.009)	0.0095 (0.007-0.011)		0.0150 (0.015-0.015)	0.0125 (0.011-0.014)		
5-018-03	5;6; 7													0.0140 (0.014-0.014)	0.0095 (0.009-0.01)	0.0140 (0.014-0.014)		
MO-020	1,2												0.0210 (0.021-0.021)					
MO-023	2,3															0.0090 (0.009-0.009)		

B.3 Freeze-Thaw (Modified Soundness) Test Results

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-022-02	5,6,7						0.970 (0.96-0.98)											
1-023-01	5,6														0.960 (0.96-0.96)			
1-023-03	4,5																	0.900 (0.87-0.94)
1-046-01	5	0.940 (0.94-0.94)	0.970 (0.97-0.97)	0.950 (0.95-0.95)														
1-046-02	3,4,5,6					0.966 (0.95-0.99)	0.960 (0.95-0.97)											
1-046-02	4,5,6						0.965 (0.96-0.97)	0.963 (0.94-0.97)	0.950 (0.93-0.96)									
1-046-08	1,2		0.980 (0.98-0.98)	0.965 (0.95-0.99)	0.925 (0.92-0.93)												0.965 (0.95-0.98)	
1-046-08	4,5																0.960 (0.95-0.97)	
1-046-08	4,5,6			0.945 (0.94-0.95)			0.960 (0.96-0.96)											
1-046-09	3,4,5	0.950 (0.95-0.95)	0.905 (0.89-0.92)						0.950 (0.94-0.96)			0.960 (0.96-0.96)			0.940 (0.93-0.95)	0.956 (0.94-0.98)	0.954 (0.94-0.97)	0.962 (0.95-0.98)
1-046-09	4,5		0.890 (0.89-0.89)															
1-046-09	8,9							0.940 (0.94-0.94)	0.925 (0.92-0.93)									

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-046-10	4,5,6						0.970 (0.97-0.97)	0.960 (0.96-0.96)	0.940 (0.93-0.96)	0.973 (0.97-0.98)	0.960 (0.96-0.96)							
1-046-10	6,7					0.970 (0.97-0.97)												
1-046-11	1									0.960 (0.96-0.96)	0.957 (0.94-0.98)							
1-046-11	2									0.900 (0.89-0.91)								
1-046-11	4,5									0.950 (0.95-0.95)								
1-046-11	5,6,7											0.943 (0.93-0.97)	0.950 (0.93-0.97)			0.940 (0.94-0.94)	0.963 (0.95-0.97)	0.970 (0.97-0.97)
1-046-15	1												0.942 (0.92-0.96)					
1-046-15	2,3,4											0.960 (0.96-0.96)		0.946 (0.91-0.96)				
1-046-15	2,3,4,5											0.950 (0.95-0.95)	0.962 (0.93-0.98)					
1-052-02		0.900 (0.9-0.9)																
1-052-02	1,2	0.880 (0.88-0.88)				0.910 (0.91-0.91)												
1-052-03	1		0.960 (0.96-0.96)															
1-056-01	1,2,3					0.970 (0.97-0.97)	0.940 (0.94-0.94)	0.960 (0.96-0.96)	0.940 (0.94-0.94)	0.926 (0.91-0.94)								
1-056-01	2,3										0.930 (0.93-0.93)							

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
1-056-02	3										0.950 (0.95-0.95)							
1-070-04	2,3																	0.900 (0.85-0.95)
1-070-05	1,2															0.906 (0.89-0.92)		
1-070-06	B												0.973 (0.96-0.99)	0.970 (0.96-0.98)	0.945 (0.93-0.96)	0.955 (0.93-0.98)		
1-081-01	1,2,3,4					0.940 (0.93-0.95)												
1-081-01	3,4			0.963 (0.95-0.97)														
1-081-02	3,4						0.950 (0.93-0.98)											
1-081-05	1,2,3,4,5											0.880 (0.88-0.88)		0.916 (0.9-0.93)	0.923 (0.91-0.94)	0.888 (0.86-0.91)	0.930 (0.91-0.97)	0.900 (0.85-0.94)
1-089-01	A						0.960 (0.96-0.96)	0.970 (0.97-0.97)	0.950 (0.95-0.95)		0.920 (0.92-0.92)							
1-089-01	OA										0.940 (0.94-0.94)							
1-089-02	1,2,3									0.930 (0.92-0.94)	0.936 (0.91-0.96)	0.915 (0.89-0.94)	0.910 (0.88-0.94)					
1-089-05	5																0.880 (0.88-0.88)	0.870 (0.87-0.87)
1-089-06	1,2																0.913 (0.86-0.95)	
2-021-01	1,2,3	0.930 (0.91-0.95)	0.952 (0.92-0.97)	0.956 (0.94-0.97)		0.963 (0.96-0.97)	0.950 (0.94-0.96)											

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
2-021-03	1,2,3,4					0.960 (0.96-0.96)												
2-021-03	1,2,3,4,5					0.952 (0.93-0.98)	0.928 (0.91-0.94)	0.980 (0.98-0.98)	0.950 (0.94-0.97)	0.970 (0.97-0.97)								
2-021-03	3,4,5	0.940 (0.93-0.96)				0.940 (0.91-0.98)												
2-021-10	1,2,3,4														0.970 (0.96-0.98)	0.951 (0.93-0.97)	0.940 (0.92-0.96)	0.940 (0.94-0.94)
2-021-11	1,2,3,4																0.920 (0.92-0.92)	0.920 (0.88-0.95)
2-021-11	3,4																	0.900 (0.87-0.93)
2-021-12	1,2,3																	0.965 (0.95-0.98)
2-031-01	1,2											0.920 (0.92-0.92)	0.960 (0.96-0.96)				0.950 (0.93-0.97)	
2-031-01	2						0.923 (0.89-0.95)	0.915 (0.86-0.95)	0.880 (0.88-0.88)	0.940 (0.94-0.94)	0.940 (0.92-0.97)							
2-057-02	1,2,3,4							0.866 (0.82-0.9)	0.880 (0.84-0.93)									
2-057-03	1,2,3					0.940 (0.94-0.94)	0.890 (0.87-0.92)	0.963 (0.96-0.97)										
2-057-04	2,3									0.924 (0.89-0.95)	0.914 (0.9-0.94)	0.920 (0.92-0.92)	0.950 (0.94-0.96)					0.910 (0.9-0.92)
2-057-05	2													0.930 (0.86-0.96)	0.965 (0.96-0.98)			
2-057-06	1,2													0.950 (0.95-0.95)				

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
2-057-06	3,4													0.922 (0.91-0.94)		0.872 (0.83-0.94)		
4-001-01	1,2,3,4	0.960 (0.95-0.97)	0.980 (0.98-0.98)						0.970 (0.97-0.97)	0.920 (0.9-0.95)	0.955 (0.9-0.97)	0.950 (0.95-0.95)			0.940 (0.94-0.94)	0.950 (0.94-0.96)	0.940 (0.92-0.98)	0.943 (0.93-0.96)
4-006-03	5											0.940 (0.94-0.94)						
4-006-03	7,8																0.930 (0.93-0.93)	
4-006-11	1,2,3														0.960 (0.96-0.96)			
4-006-11	1,2,3,4													0.965 (0.96-0.97)	0.970 (0.96-0.98)			
4-010-01	1,2				0.945 (0.94-0.95)													
4-016-03	2,3		0.965 (0.96-0.97)															
4-019-01	4,5								0.943 (0.93-0.96)									
4-025-01	3						0.964 (0.95-0.98)	0.956 (0.95-0.97)	0.880 (0.88-0.88)	0.956 (0.91-0.98)	0.956 (0.94-0.97)							
4-025-02	1,2,3															0.945 (0.92-0.96)	0.957 (0.94-0.97)	0.926 (0.91-0.95)
4-025-03	1,2,3																0.950 (0.94-0.96)	
4-025-03	A,1,2,3																0.960 (0.96-0.96)	0.956 (0.95-0.96)
4-030-01	13,14												0.935 (0.92-0.95)	0.950 (0.95-0.95)				

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-030-02	1	0.960 (0.96-0.96)	0.945 (0.93-0.96)															
4-030-02	13,14													0.950 (0.95-0.95)	0.946 (0.92-0.97)	0.950 (0.95-0.95)	0.952 (0.95-0.96)	0.970 (0.97-0.97)
4-030-02	4,5	0.927 (0.91-0.94)		0.940 (0.94-0.94)									0.943 (0.93-0.95)	0.960 (0.96-0.96)	0.970 (0.97-0.97)	0.900 (0.87-0.93)	0.940 (0.94-0.94)	0.955 (0.93-0.97)
4-030-04	10,11,12,13				0.930 (0.88-0.96)	0.960 (0.96-0.96)	0.930 (0.93-0.93)		0.950 (0.95-0.95)	0.935 (0.93-0.94)		0.925 (0.91-0.94)						
4-030-04	4,5	0.930 (0.93-0.93)	0.950 (0.94-0.96)	0.946 (0.93-0.96)		0.960 (0.96-0.96)	0.960 (0.96-0.96)	0.960 (0.96-0.96)		0.980 (0.98-0.98)	0.956 (0.94-0.97)	0.950 (0.95-0.95)						
4-037-02	1,2,3,4			0.950 (0.95-0.95)														
4-037-03	2,3												0.937 (0.89-0.97)	0.922 (0.89-0.97)	0.955 (0.92-0.98)	0.940 (0.94-0.94)		
4-037-05	4,5				0.916 (0.9-0.93)													
4-037-06	1,2,3												0.940 (0.94-0.94)	0.935 (0.92-0.97)	0.938 (0.9-0.97)			
4-037-06	3															0.930 (0.93-0.93)		
4-050-01	1,2			0.960 (0.94-0.97)														
4-050-06	1,2													0.913 (0.9-0.93)		0.910 (0.91-0.91)		
4-054-02	1,2,3	0.946 (0.91-0.97)		0.970 (0.97-0.97)	0.943 (0.93-0.96)	0.980 (0.98-0.98)					0.980 (0.98-0.98)	0.930 (0.93-0.93)			0.922 (0.9-0.95)	0.930 (0.93-0.93)		
4-054-06	5,6,7					0.970 (0.97-0.97)												

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-054-11	1,2,3												0.925 (0.89-0.96)	0.970 (0.97-0.97)		0.950 (0.94-0.96)	0.886 (0.86-0.93)	0.915 (0.89-0.94)
4-054-11	B,C,D															0.880 (0.88-0.88)		
4-054-11	B,C,D,															0.870 (0.87-0.87)		
4-061-05	4,5		0.968 (0.93-0.98)	0.910 (0.9-0.92)														
4-061-05	4,5,6			0.960 (0.96-0.96)	0.960 (0.96-0.96)	0.965 (0.96-0.97)			0.945 (0.94-0.95)						0.970 (0.96-0.98)	0.910 (0.87-0.95)	0.965 (0.95-0.98)	0.950 (0.94-0.96)
4-061-05	6		0.950 (0.95-0.95)		0.916 (0.89-0.94)													
4-061-05	9															0.970 (0.97-0.97)		
4-061-08	1,2,3,4													0.960 (0.96-0.96)	0.960 (0.96-0.96)			
4-061-08	2,3,4							0.960 (0.96-0.96)										
4-061-08	3,4							0.980 (0.98-0.98)										
4-063-02	1,2,3							0.913 (0.9-0.93)				0.980 (0.98-0.98)						0.980 (0.98-0.98)
4-063-05	1,2,3,4, 5										0.940 (0.93-0.96)					0.920 (0.92-0.92)		
4-063-06	1,2,3													0.913 (0.86-0.94)	0.921 (0.86-0.97)	0.940 (0.94-0.94)	0.960 (0.96-0.96)	0.900 (0.9-0.9)
4-103-01	1,2				0.965 (0.95-0.98)					0.970 (0.95-0.98)			0.970 (0.97-0.97)		0.967 (0.95-0.99)			

TABLE B.3
Freeze-Thaw (Modified Soundness) Test Results for QPS Samples

Quarry No.	Bed No.	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
4-103-01	2														0.980 (0.98-0.98)			
5-018-01	1,2;3											0.920 (0.92-0.92)						
5-018-01	1,2;3;4			0.917 (0.89-0.95)	0.905 (0.89-0.92)	0.910 (0.86-0.95)	0.925 (0.91-0.95)	0.898 (0.83-0.95)	0.899 (0.86-0.93)	0.923 (0.86-0.96)	0.925 (0.92-0.93)	0.893 (0.84-0.94)						
5-018-01	2;3;4											0.895 (0.89-0.9)	0.910 (0.9-0.92)				0.880 (0.88-0.88)	
5-018-01	5,6,7												0.940 (0.94-0.94)					
5-018-02	1,2,3											0.935 (0.9-0.97)	0.951 (0.93-0.97)		0.940 (0.94-0.94)	0.885 (0.86-0.91)		
5-018-03	5;6;7													0.890 (0.89-0.89)	0.885 (0.85-0.92)	0.920 (0.92-0.92)		
MO-020	1,2												0.960 (0.96-0.96)					
MO-023	2,3															0.930 (0.93-0.93)		

Appendix C: Maps

Appendix C contains maps of PCCP on the KDOT system, the criteria projects, the projects with and without D-cracking, the projects that pass, fail, or are inconclusive, as well as several maps relating the quarries with unacceptable field performance to their corresponding projects.

C.1 Survey Project Maps

The following section contains the maps regarding the criteria projects and survey results. Figure C.1 is a map of PCCP on the KDOT system where PCCP is shown in blue. Figure C.2 is a map of the criteria projects for the study shown in orange. Figure C.3 is the raw data from the 2009–2010 D-cracking Phase 1 survey. It illustrates the criteria projects as either D-cracked (red) or not D-cracked (green). Figure C.4 is the results from the 2009–2010 D-cracking Phase 1 D-cracking field survey. It illustrates the criteria projects based on whether it was a failure (red), a success (green), or is inconclusive (blue).

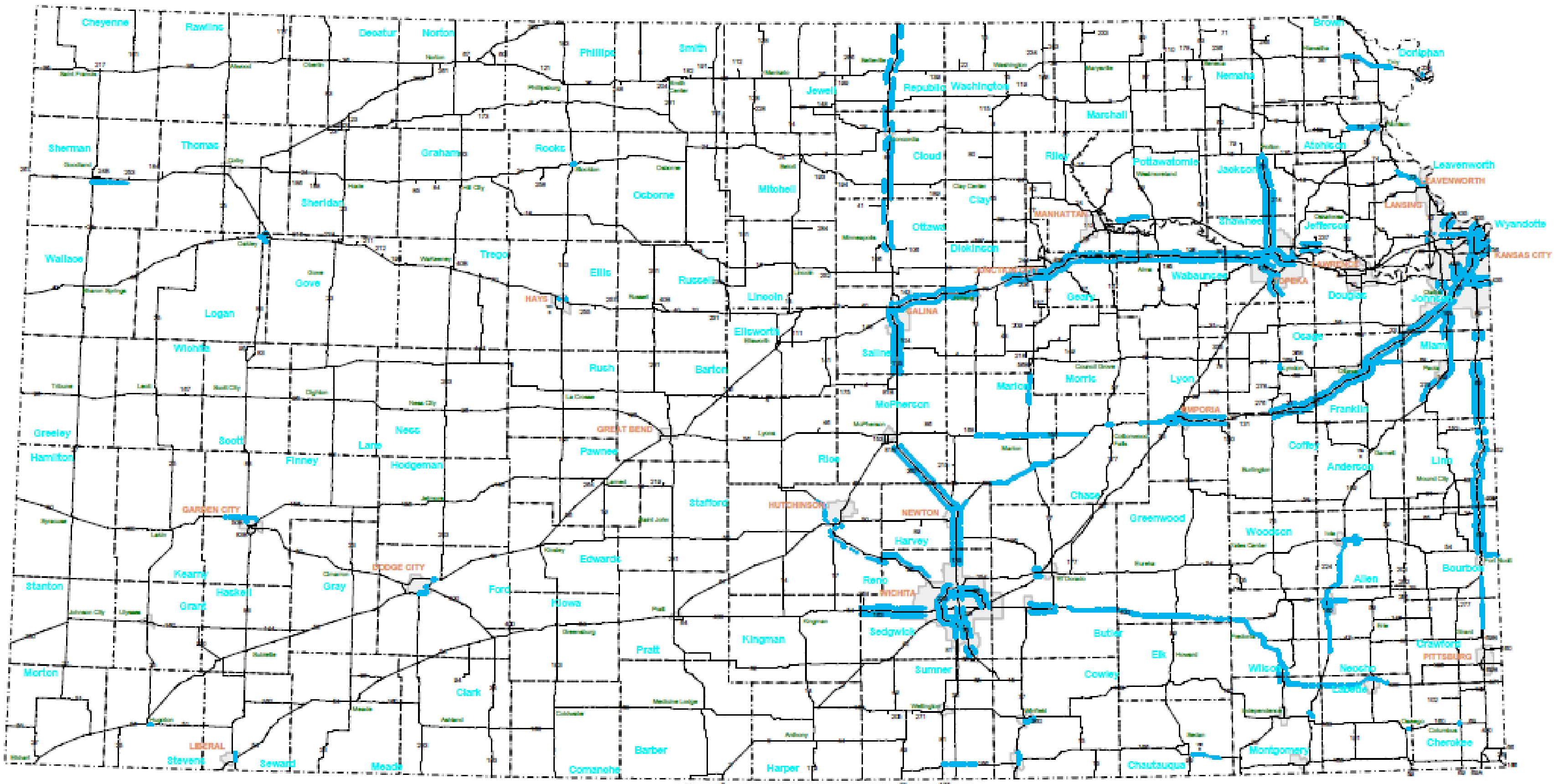


FIGURE C.1
PCCP on KDOT System

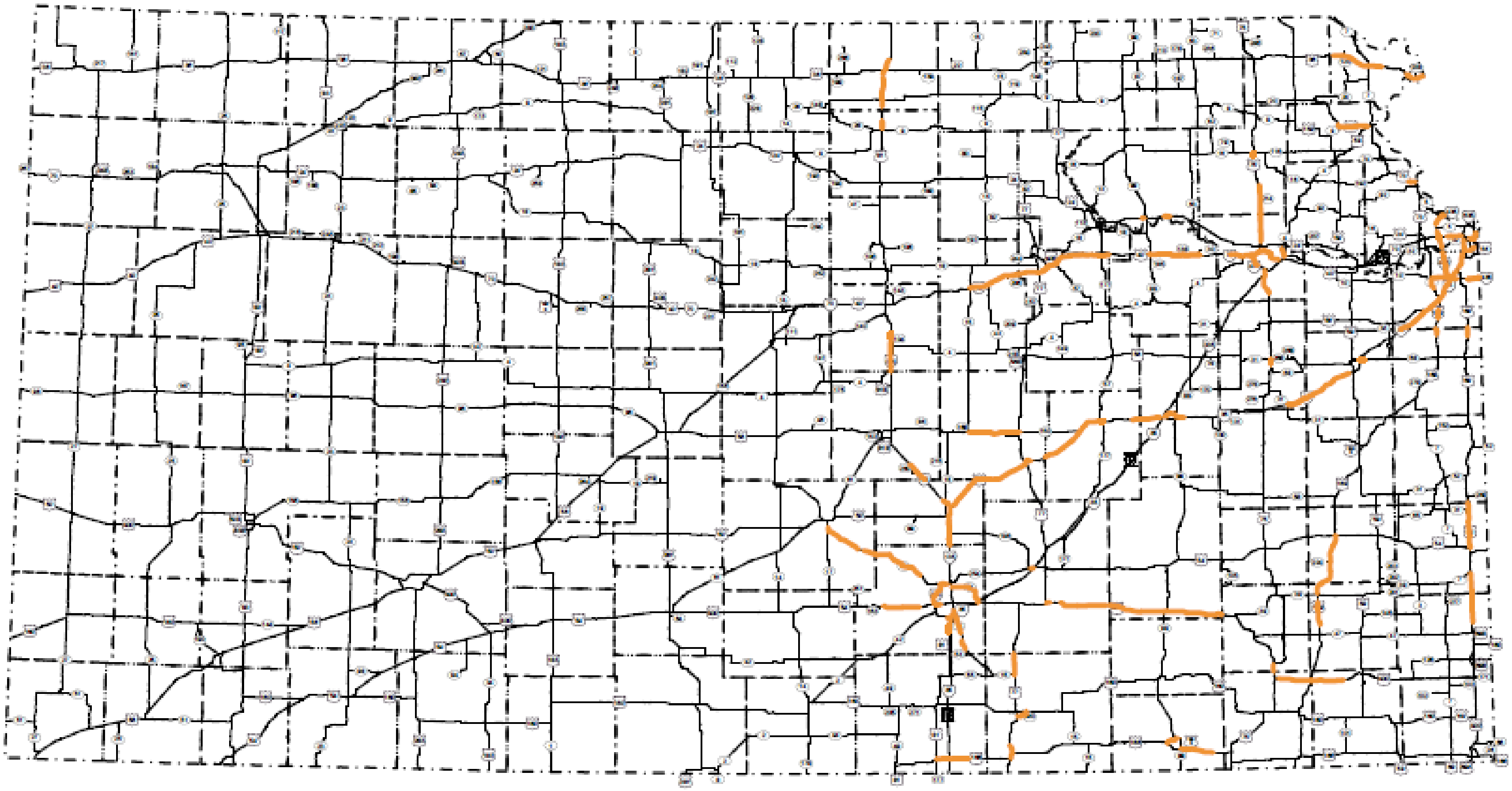


FIGURE C.2
Criteria Projects for the 2009–2010 D-Cracking Phase 1 Survey

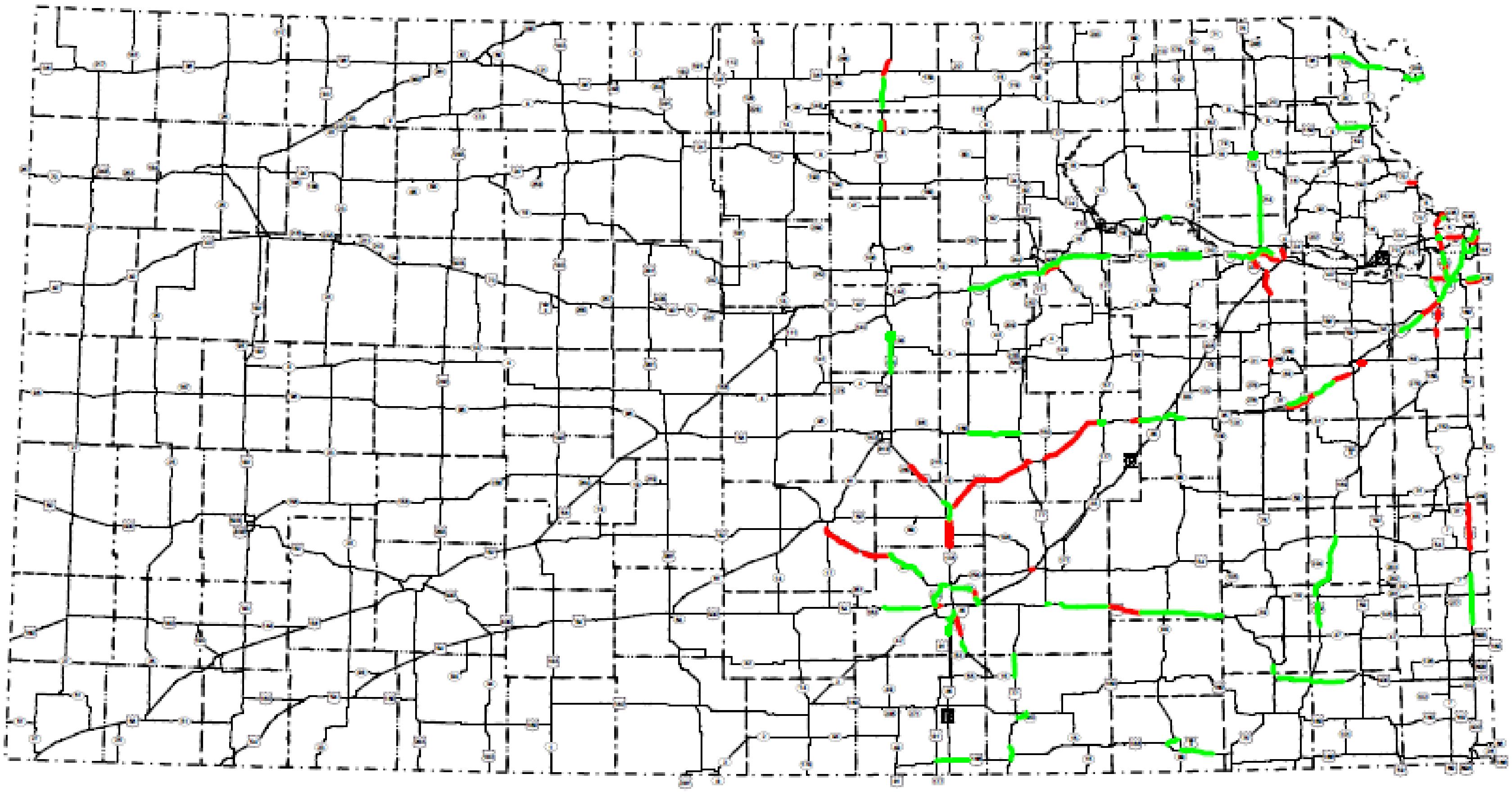


FIGURE C.3
2009–2010 D-Cracking Phase 1 Raw Data

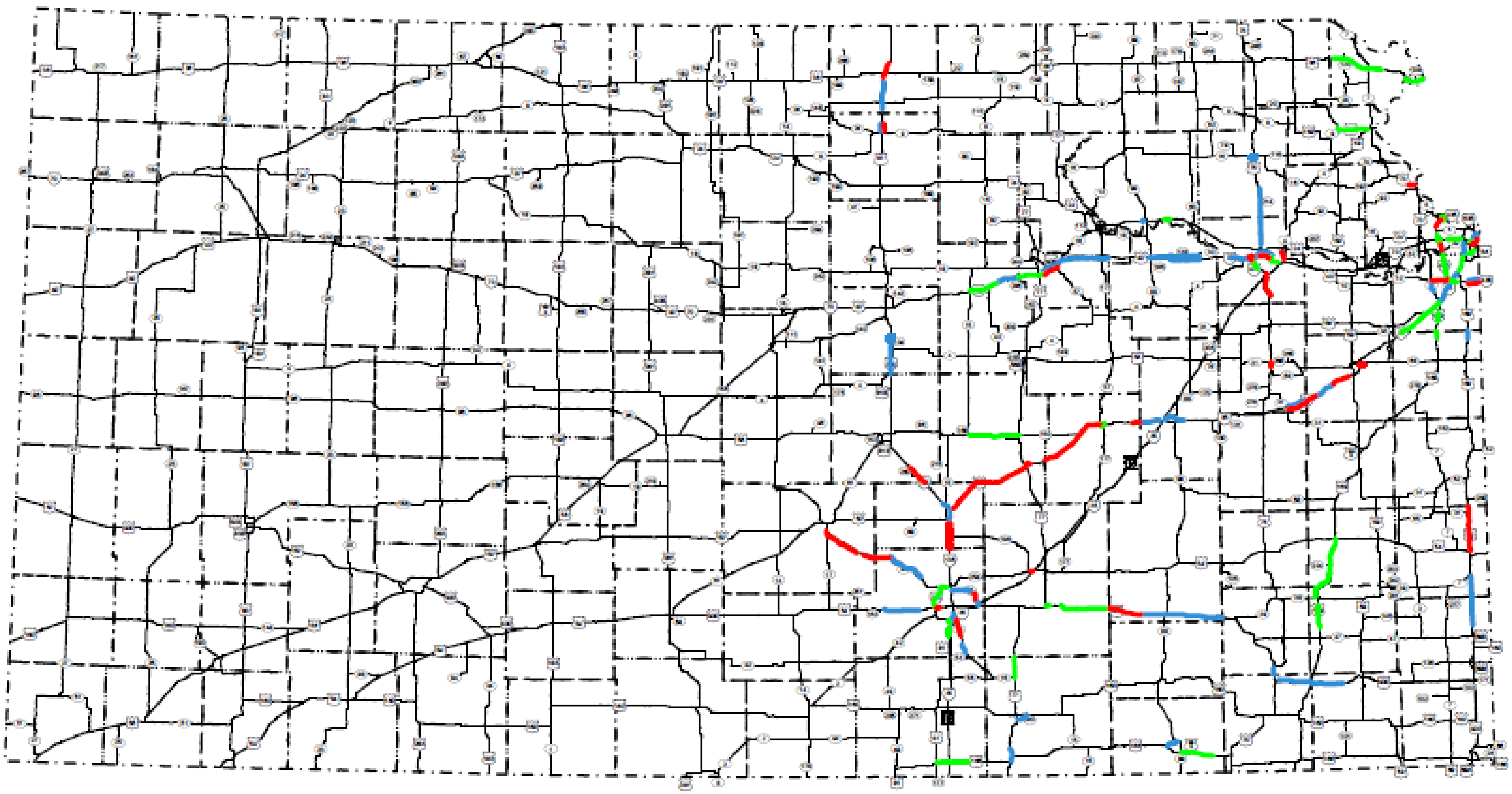


FIGURE C.4
2009–2010 D-Cracking Phase 1 Survey Results

C.2 Quarry Maps

The following section contains the maps regarding the nine quarries with unacceptable field performance that have been removed from the A-List. Figure C.5 shows all nine quarries, indicated by a star, and all criteria projects related to all nine quarries. The red represents failure, the green represents success, and the blue represents inconclusive. The remaining maps in Figures C.6 through C.14 show each removed quarry individually with its corresponding projects with the same symbol and color notations.

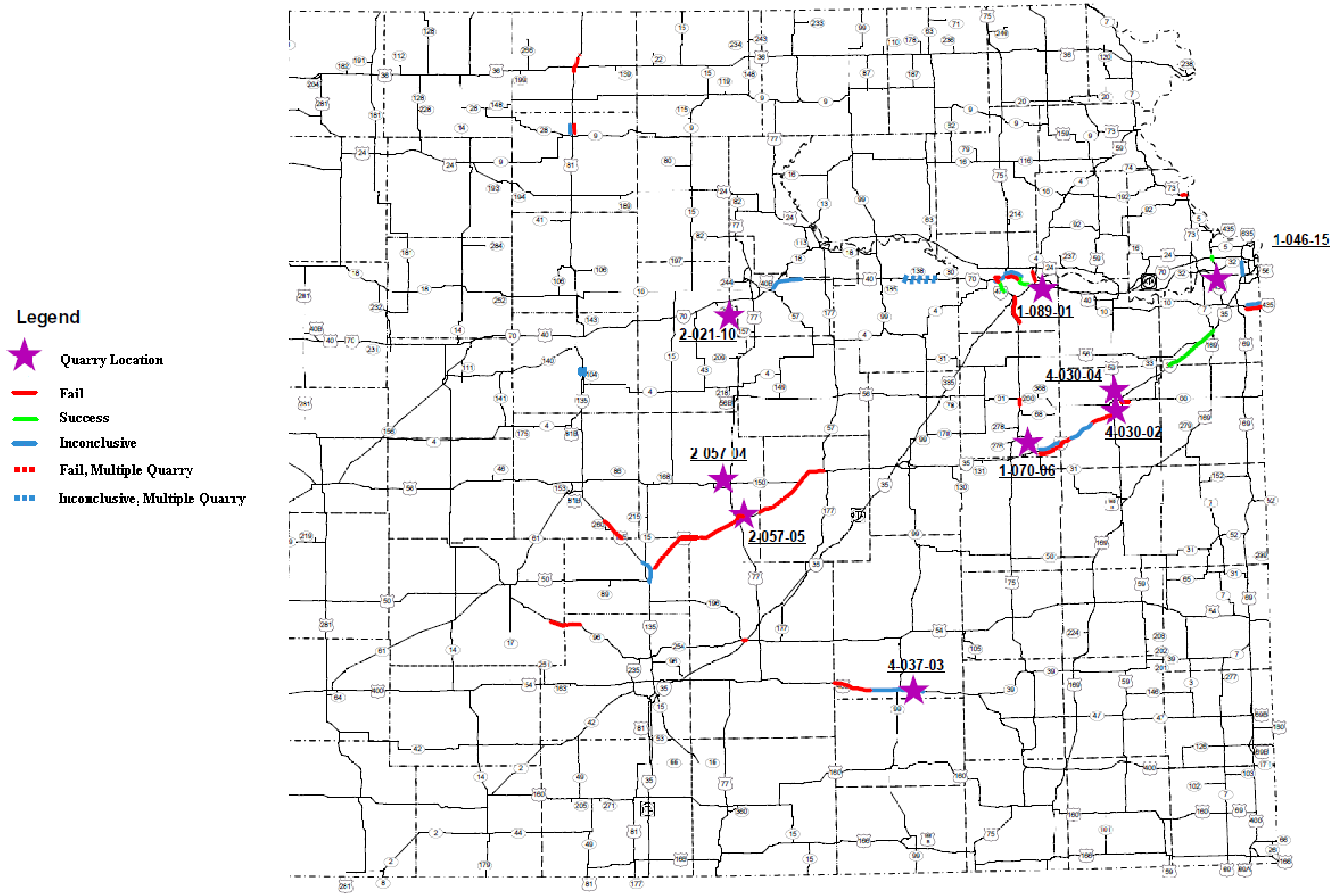
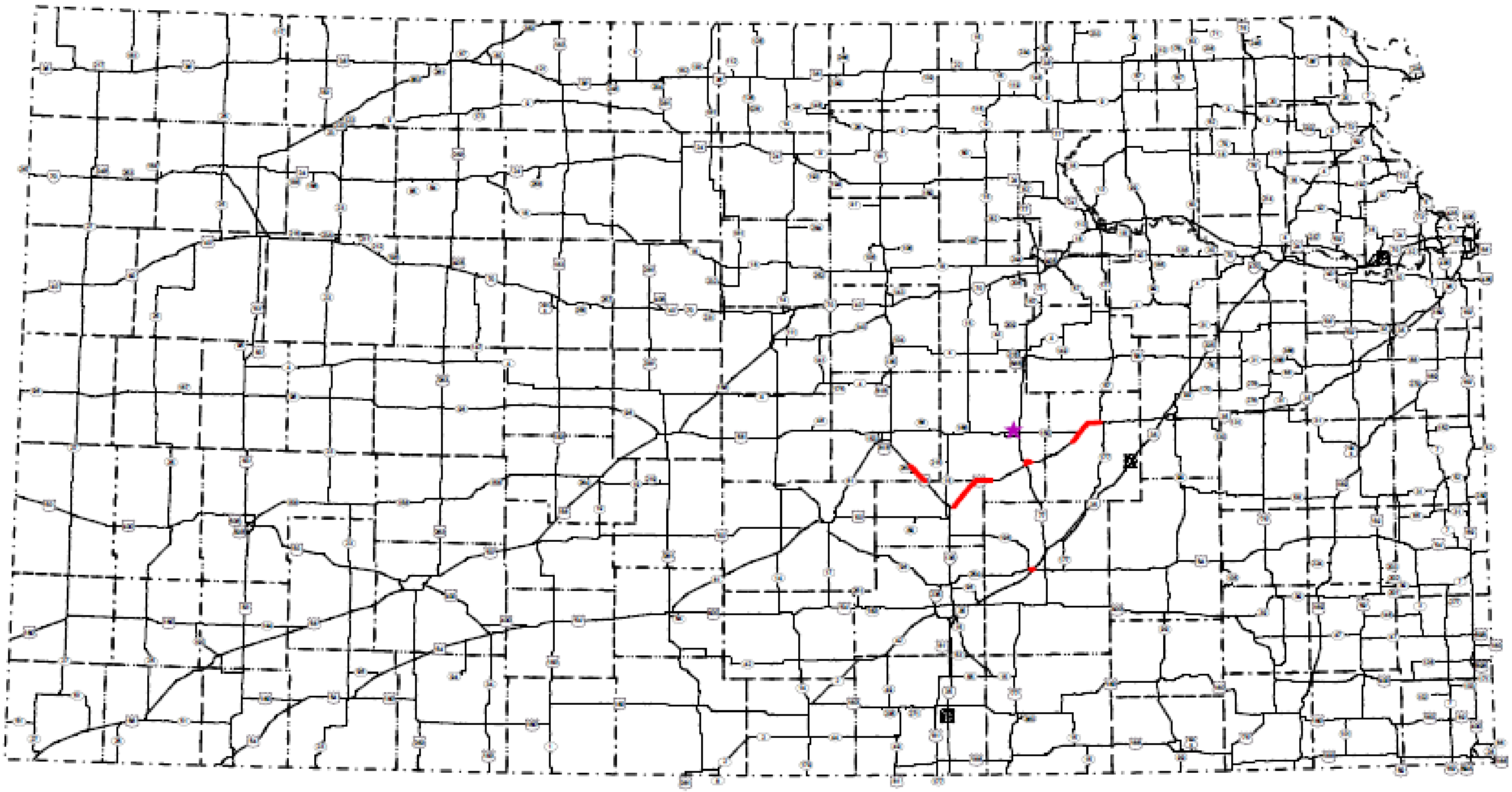
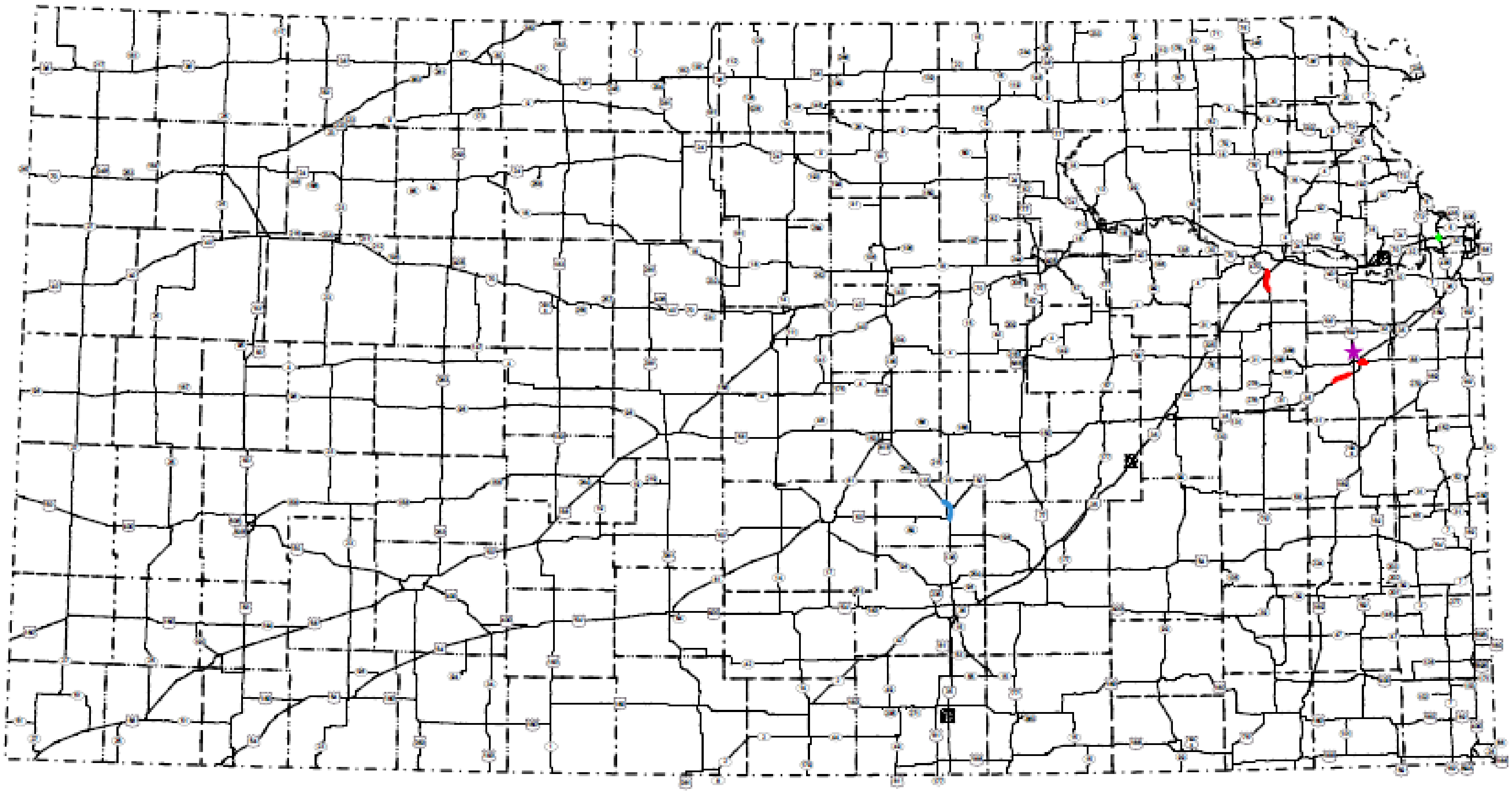


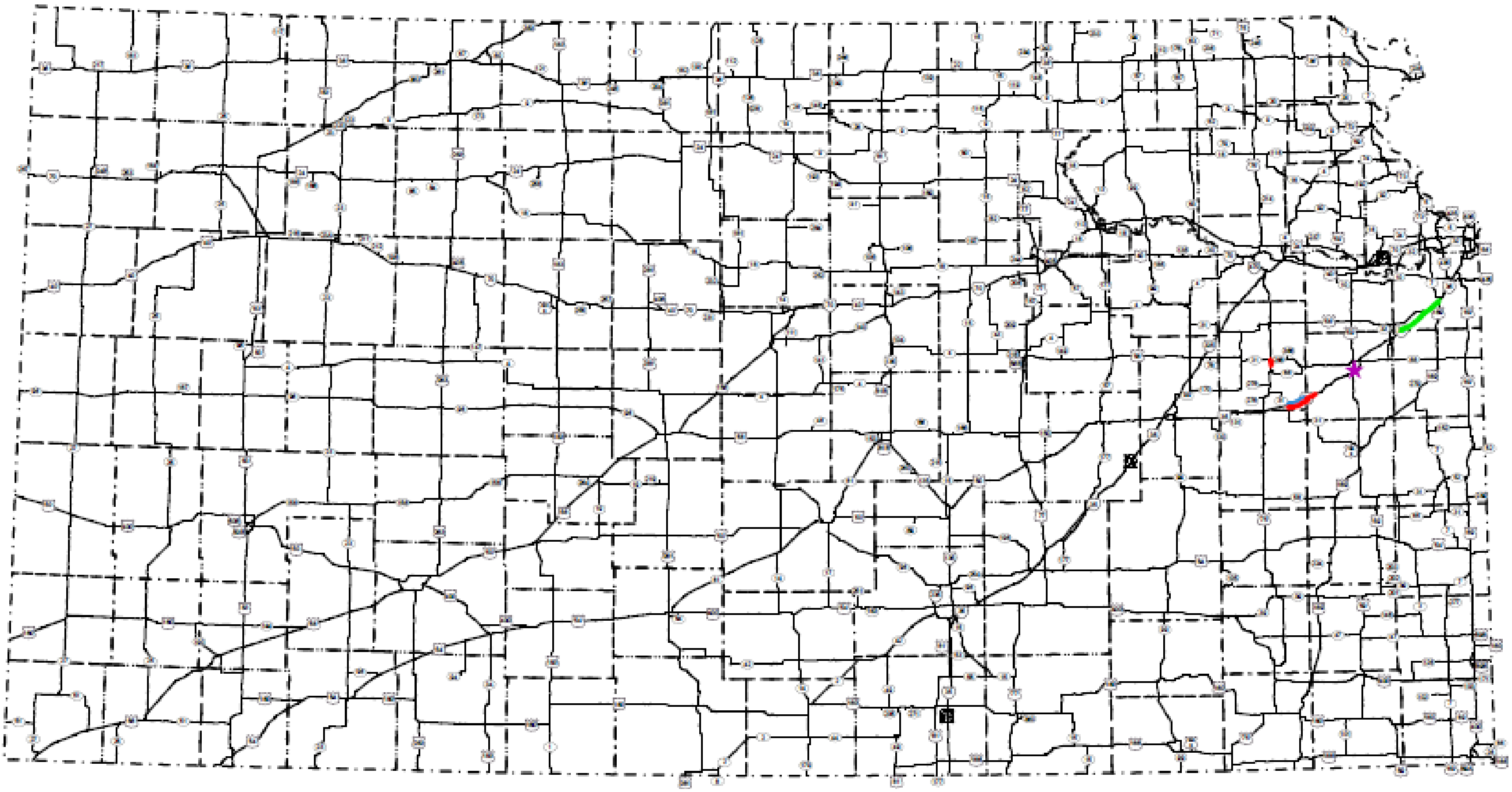
FIGURE C.5
Quarries Removed from A-List on November 2, 2010



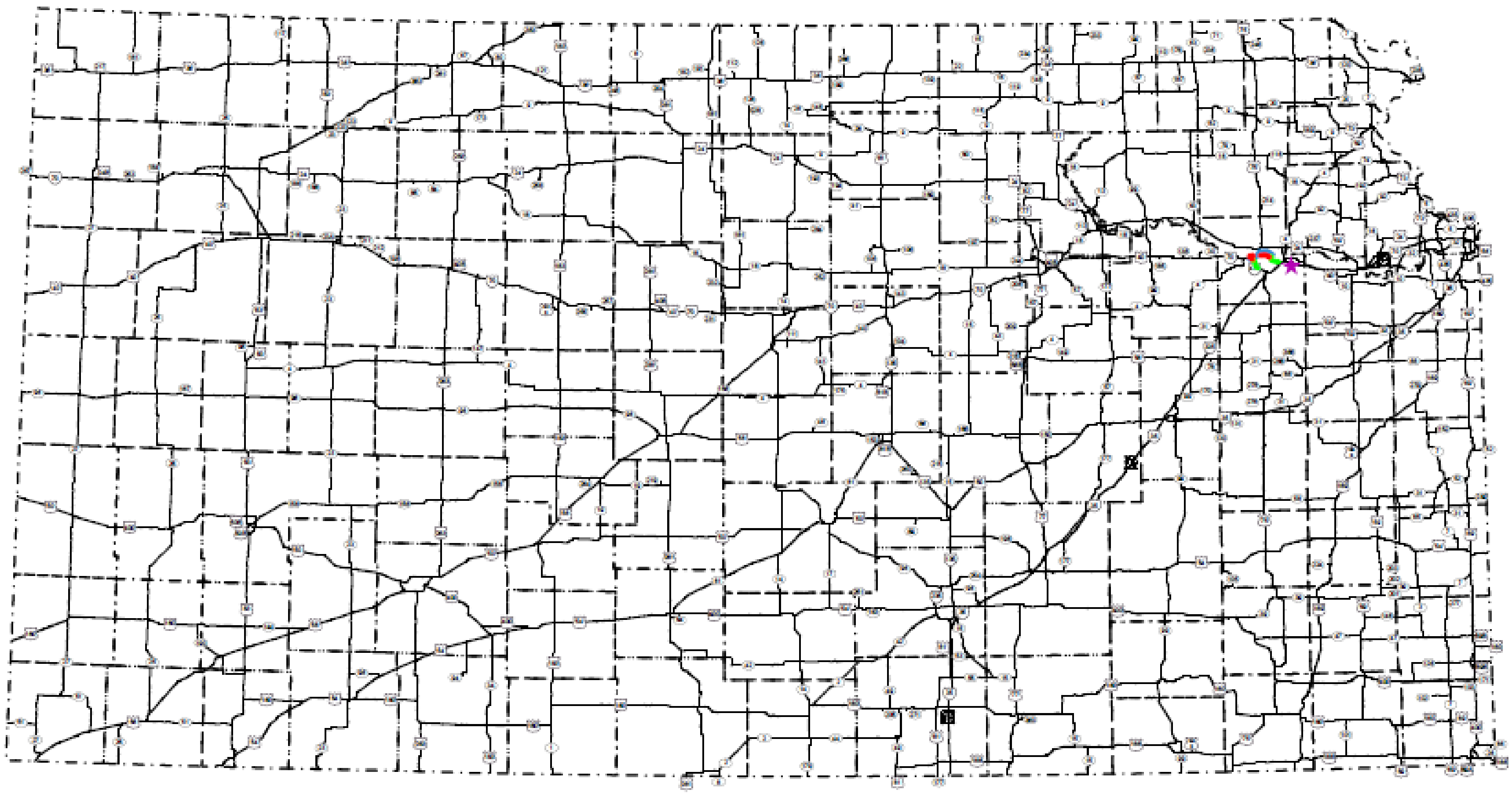
FIGURES C.6
Quarry 2-057-04 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry



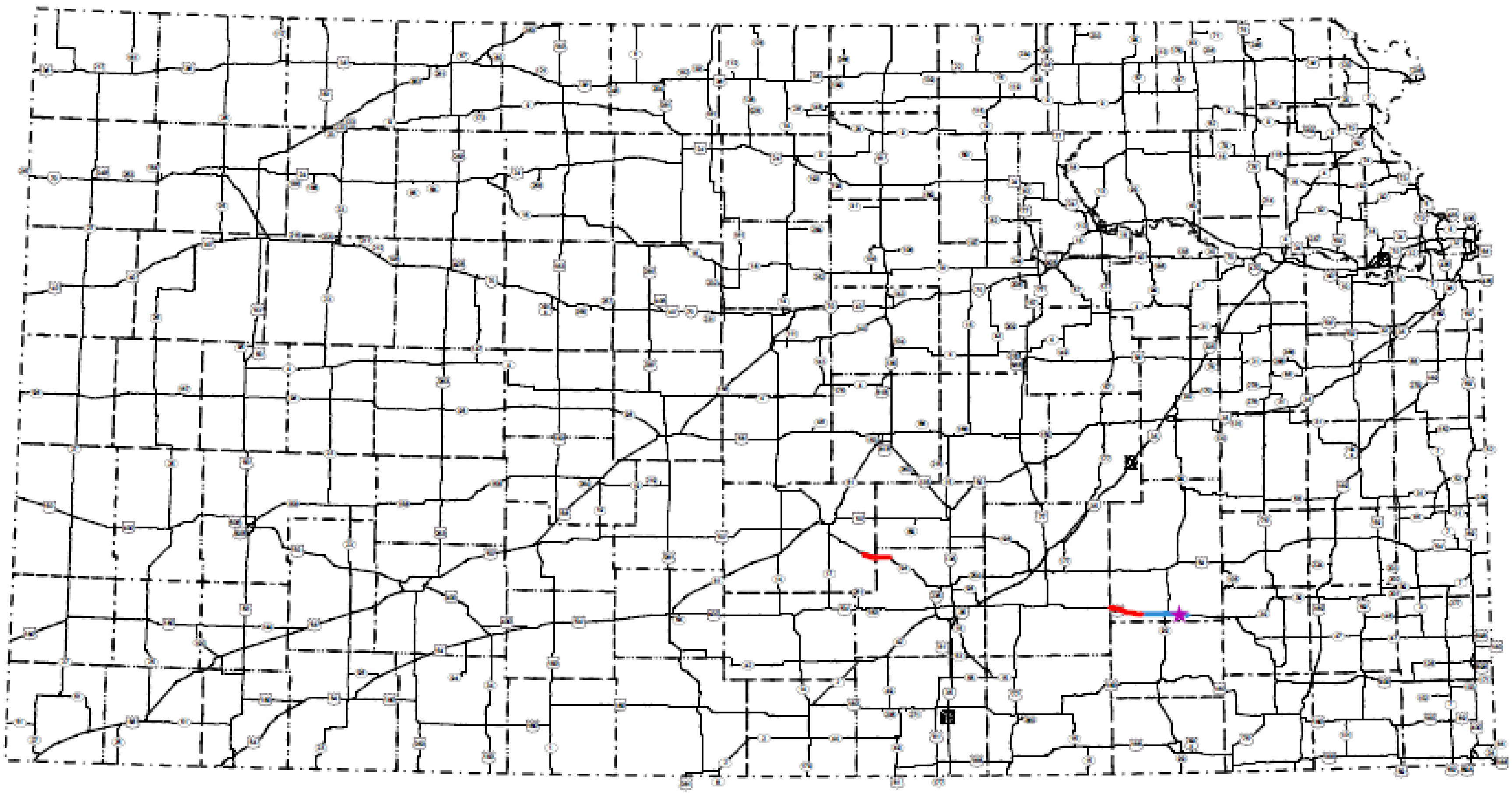
FIGURES C.7
Quarry 4-030-02 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry



FIGURES C.8
Quarry 4-030-04 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry



FIGURES C.9
Quarry 1-089-01 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry



FIGURES C.10
Quarry 4-037-03 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry

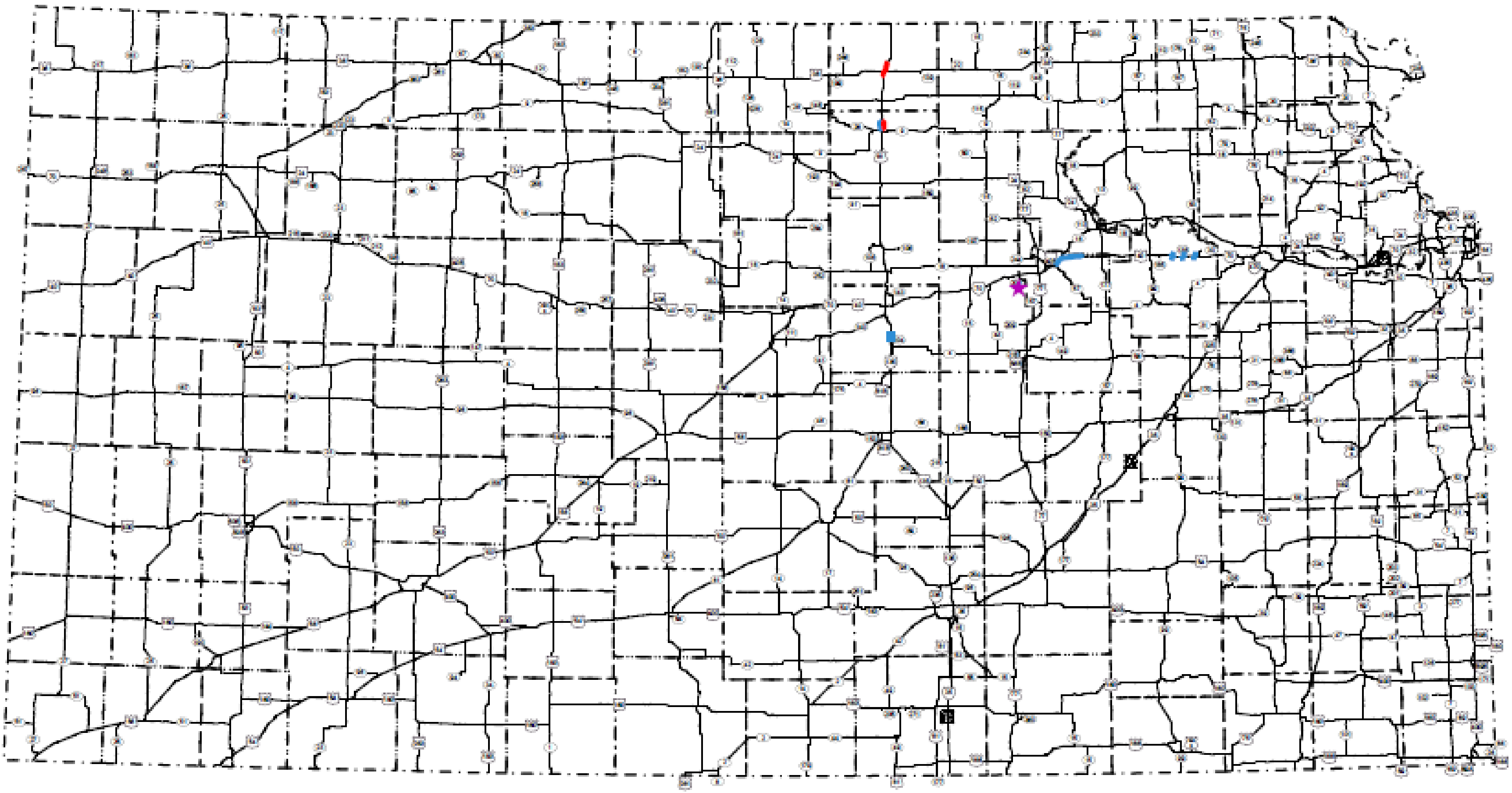
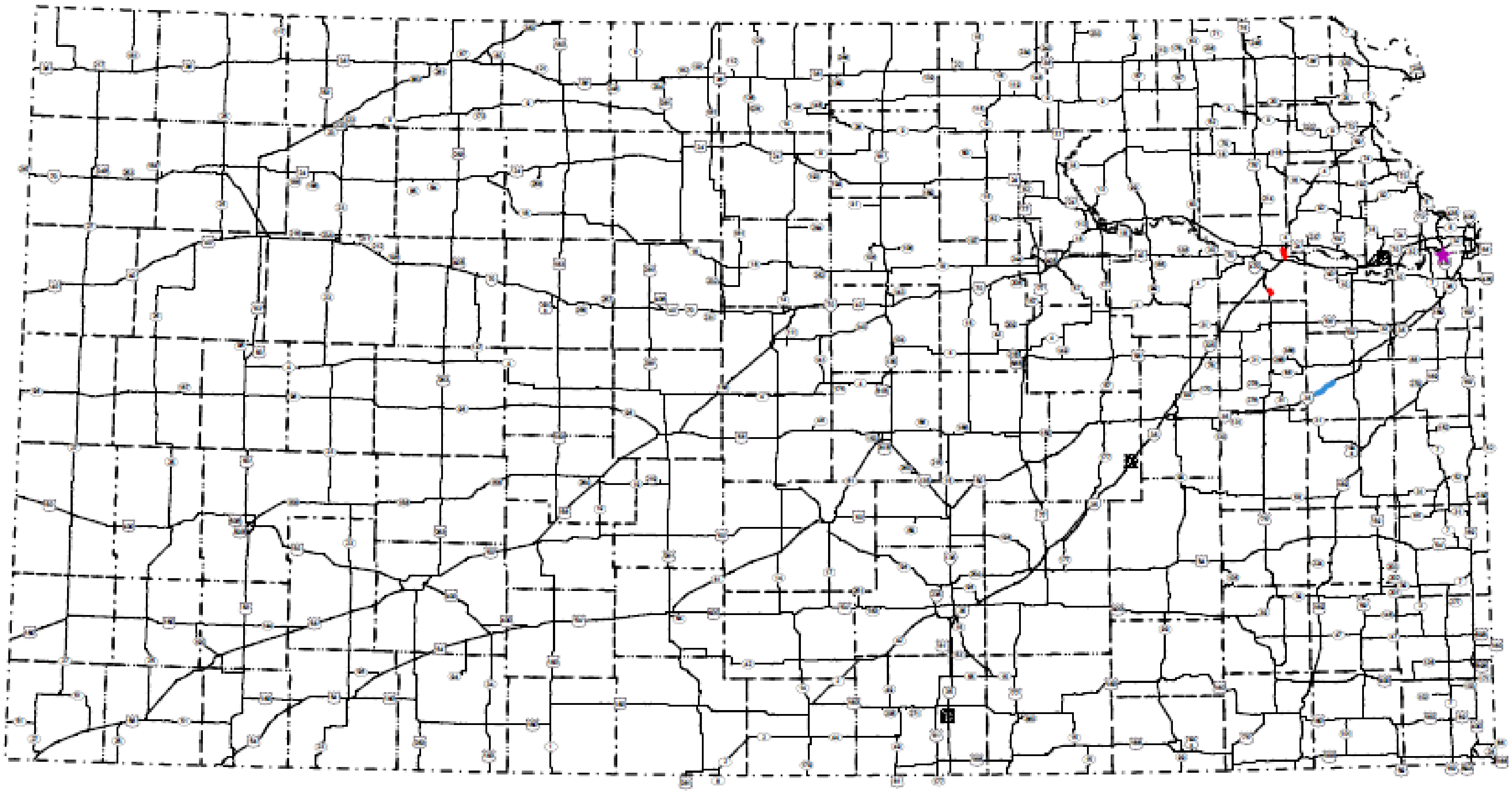


FIGURE C.11
Quarry 2-021-10 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry



FIGURES C.12
Quarry 1-070-06 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry

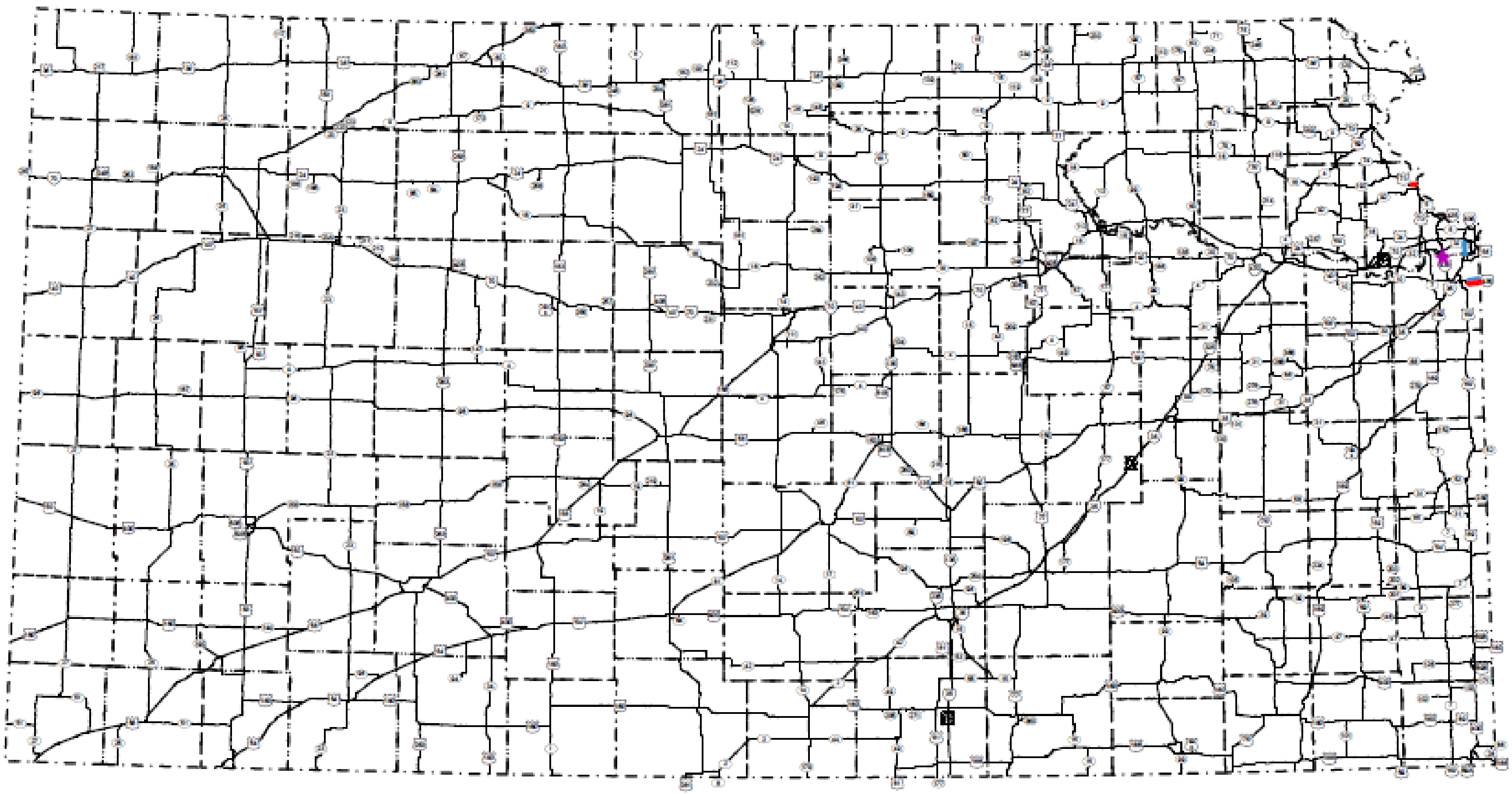


FIGURE C.13
Quarry 1-046-15 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry

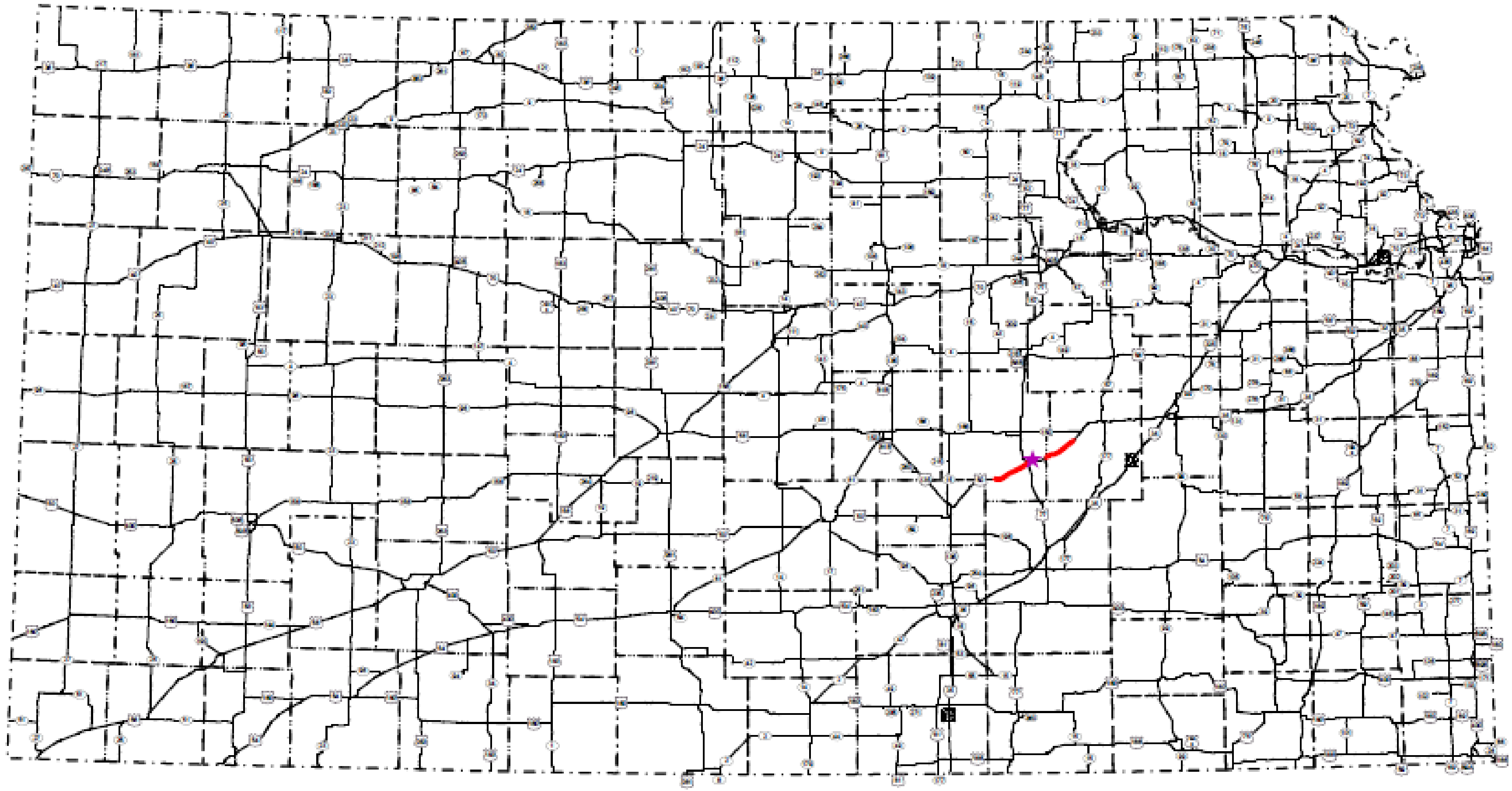


FIGURE C.14
Quarry 2-057-05 and the 2009–2010 D-Cracking Phase 1 D-Cracking Survey Results for Criteria Projects Containing Material from the Quarry

Appendix D: Weather

Appendix D contains maps indicating the average number of annual freeze-thaw cycles (Figure D.1) and the average number of annual hard freeze-thaw cycles (Figure D.2). If the maximum temperature was above 32°F and the minimum for the following day was below 32°F, then it was considered to be one freeze-thaw cycle. Hard freeze-thaw cycles were defined as when the minimum temperature reached below 24°F and the maximum on the next day was above 32°F. The map legends indicate that the diameter of the red dots illustrates the average number of freeze-thaw or hard freeze-thaw at each station across Kansas.

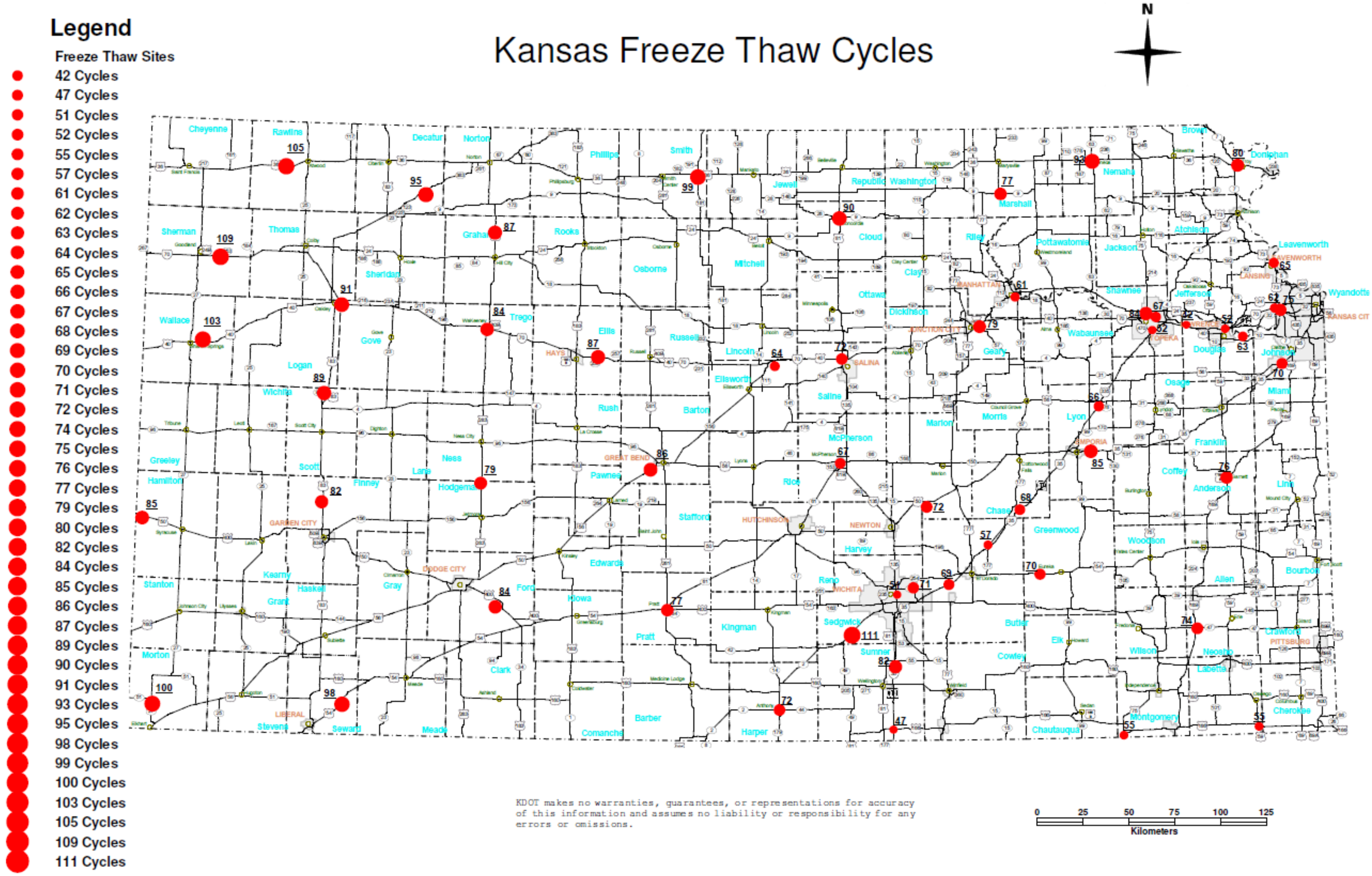


FIGURE D.1
Average Number of Annual Freeze-Thaw Cycles (Max. Temp. Greater Than 32°F; Min. Temp. Less Than 32°F)

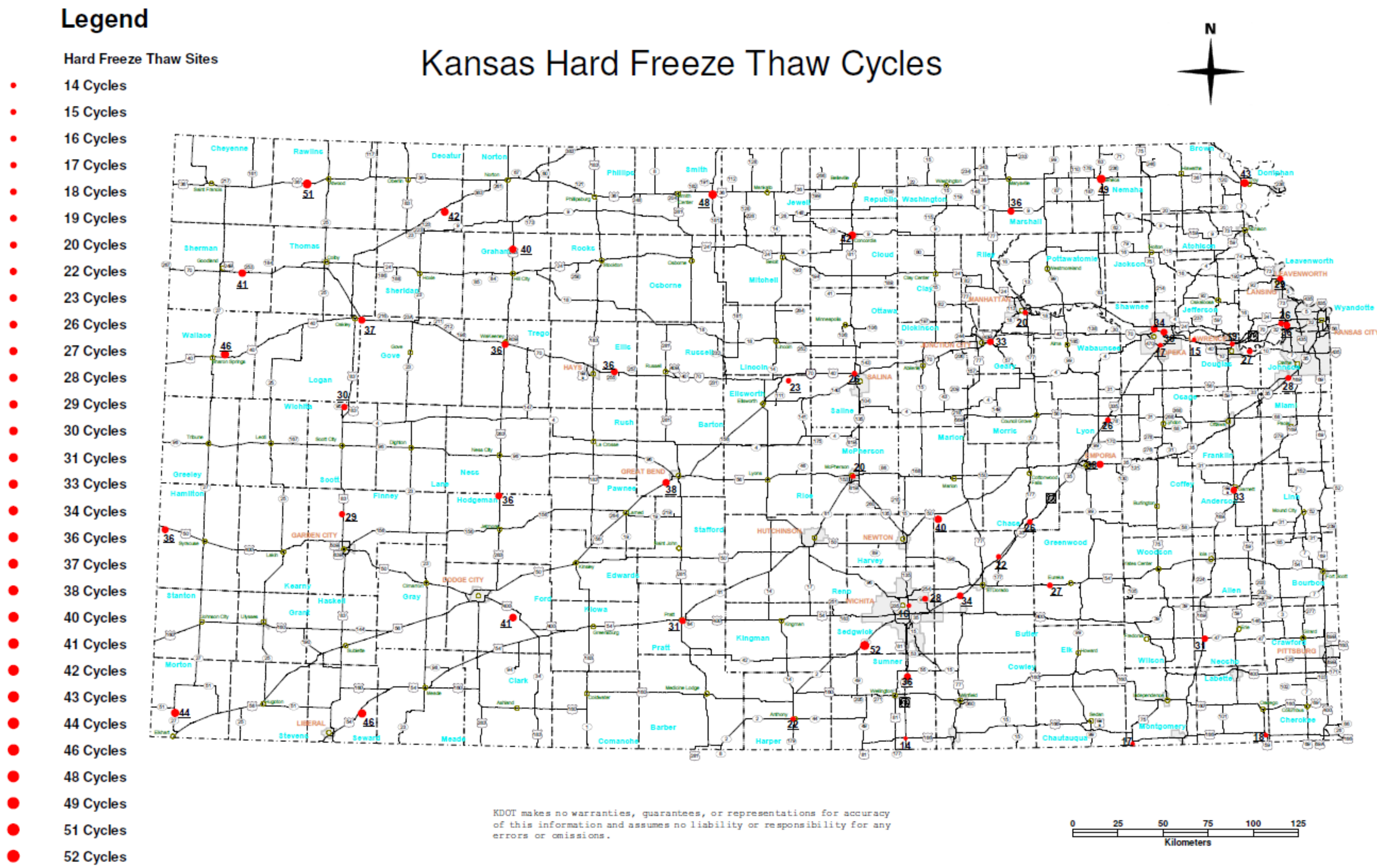


FIGURE D.2
Average Number of Annual Hard Freeze-Thaw Cycles (Max. Temp. Greater Than 32°F; Min. Temp. Less Than 24°F)

Appendix E: Production (QPS) and Project Data

Appendix E reports the number of passing and/or failing production samples (QPS) tested for each given quarry, set of beds, and year, as well as the criteria projects (by project number) containing material from specific quarries, beds, and year of construction (completion). The criteria projects are also listed with a "P" if the survey result was "pass," "F" if the result was "fail," and "Inc" if the result was "inconclusive." In the tables, a comma "," separates beds, whereas a semicolon ";" separates sets of beds and geoclass. For example,

LFRLY; ARGN
1,2; 5,6,7

indicates material from beds 1 and 2 of the Lower Farley, and beds 5,6, and 7 of the Argentine were used. Parenthesis "()" surrounding a bed number indicates that sometimes that bed number may have been included and sometimes it may have not been included. For example,

ARGN
(3),4,5

indicates that material from beds 4 and 5 was definitely used and that bed 3 may have been included for one or more of the samples.

The quarry numbers and bed sets reported are correct for time the samples were tested. Some quarry numbers and/or bed renumbering may have occurred. Some of these updated quarry and bed numbers are reflected in Appendix E and noted. Any questions regarding such changes should be directed to the KDOT Bureau of Materials and Research for clarification. The information was obtained from KDOT's Production Database.

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Projects
Quarry No.	1-022-02	1-022-02	1-023-01	1-046-01	1-046-01
GeoClass	AMZN	AMZN	CPCK	ARGN	ARGN
Bed No.	5,6,7	5,6,7	5,6	5	5
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					K-0968-01 P
1983F					
1984P					
1984F					
1985P				1	
1985F					
1986P				1	
1986F					
1987P				1	
1987F					
1988P					
1988F					
1989P					
1989F					
1990P	2	K-1876-02 P			
1990F					
1991P					
1991F					
1992P					
1992F					
1993P					
1993F					
1994P					
1994F					
1995P					
1995F					
1996P					
1996F					
1997P					
1997F					
1998P					
1998F			1		
1999P					
1999F					
2000P					
2000F					
2001P					
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Projects	Projects	Projects	Projects
Quarry No.	1-046-02	1-046-02	1-046-02	1-046-02	1-046-03	1-046-04
GeoClass	ARGN	ARGN	ARGN	ARGN	ARGN	CPCK
Bed No.	3,4,5,6	4,5,6	(3),4,5,6	4,5,6	1,2	4,5
1980P					K-0461-01 P	
1980F						
1981P						
1981F						
1982P						K-0460-02 P
1982F						
1983P						
1983F						
1984P						
1984F						
1985P						
1985F						
1986P						
1986F						
1987P						
1987F						
1988P						
1988F						
1989P	6					
1989F						
1990P	1	2	K-1774-01 P	K-1875-03 F		
1990F	1					
1991P		7		K-2501-01 Inc K-2578-01 Inc		
1991F						
1992P		3				
1992F						
1993P						
1993F						
1994P						
1994F						
1995P						
1995F						
1996P						
1996F						
1997P						
1997F						
1998P						
1998F						
1999P						
1999F						
2000P						
2000F						
2001P						
2001F						

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Production	Production	Projects
Quarry No.	1-046-08	1-046-08	1-046-08	1-046-08	1-046-08
GeoClass	ARGN	ARGN	ARGN	UFRLY	UFRLY
Bed No.	1,2	4,5	4,5,6	1,2	1,2
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P				1	
1986F					
1987P			2	4	K-2345-01 P
1987F					
1988P				1	K-1775-03 P
1988F				1	
1989P					
1989F					
1990P					
1990F			1		
1991P					
1991F					
1992P					
1992F					
1993P					
1993F					
1994P					
1994F					
1995P					
1995F					
1996P					
1996F					
1997P					
1997F					
1998P					
1998F					
1999P					
1999F					
2000P	2	2			
2000F					
2001P					
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Production	Projects	Projects	Projects
Quarry No.	1-046-09	1-046-09	1-046-09	1-046-09	1-046-09	1-046-09
GeoClass	ARGN	ARGN	RYTN	ARGN	ARGN	LFRLY; ARGN
Bed No.	3,4,5	4,5	8,9	(3),4,5	3,4,5	1,2; 5,6,7
1980P						
1980F						
1981P						
1981F						
1982P						
1982F						
1983P						
1983F						
1984P				K-0457-05 P K-1492-01 F		
1984F						
1985P	1					K-0987-01 P
1985F						
1986P	1				K-1423-01 P	
1986F	1	1				
1987P						
1987F						
1988P						
1988F						
1989P						
1989F						
1990P						
1990F						
1991P			1			
1991F						
1992P	2					
1992F			2			
1993P						
1993F						
1994P						
1994F						
1995P	1					
1995F						
1996P						
1996F						
1997P						
1997F						
1998P	1					
1998F	1					
1999P	3					
1999F						
2000P	5					
2000F						
2001P	3					
2001F	2					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Projects
Quarry No.	1-046-10	1-046-10	1-046-10
GeoClass	ARGN	ARGN	ARGN
Bed No.	4,5,6	6,7	4,5,6
1980P			
1980F			
1981P			
1981F			
1982P			
1982F			
1983P			
1983F			
1984P			
1984F			
1985P			
1985F			
1986P			
1986F			
1987P			
1987F			
1988P			
1988F			
1989P		1	
1989F			
1990P			
1990F	1		
1991P	1		
1991F			
1992P	4		
1992F			
1993P	3		K-2447-01 Inc K-2447-01 F
1993F			
1994P	1		
1994F			
1995P			
1995F			
1996P			
1996F			
1997P			
1997F			
1998P			
1998F			
1999P			
1999F			
2000P			
2000F			
2001P			
2001F			

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Production	Production	Projects
Quarry No.	1-046-11	1-046-11	1-046-11	1-046-11	1-046-11
GeoClass	ARGN	LFRLY	UFRLY	UFRLY	UFRLY
Bed No.	4,5	2	1	5,6,7	5,6,7
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P					
1986F					
1987P					
1987F					
1988P					
1988F					
1989P					
1989F					
1990P					
1990F					
1991P					
1991F					
1992P					
1992F					
1993P			1		
1993F	1	2			
1994P			4		
1994F					
1995P				4	K-3382-01 Inc
1995F					
1996P				3	K-4088-02 Inc
1996F					
1997P					
1997F					
1998P					
1998F					
1999P				1	
1999F					
2000P				3	
2000F					
2001P				1	
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Production	Projects	Projects	Projects	Projects
Quarry No.	1-046-15	1-046-15	1-046-15	1-046-15	1-046-15	1-046-15	1-046-15
GeoClass	ARGN	ARGN	UFRLY	ARGN	ARGN	UFRLY; ARGN	UFRLY; ARGN
Bed No.	2,3,4	2,3,4,5	1	2,3,4,(5)	2,3,4,5	1; 2,3,4,5	1; 2,3,4,5
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P							
1985F							
1986P							
1986F							
1987P							
1987F							
1988P							
1988F							
1989P							
1989F							
1990P							
1990F							
1991P							
1991F							
1992P							
1992F							
1993P							
1993F							
1994P							
1994F							
1995P	1	1		K-3637-01 WB (NB) Inc			
1995F							
1996P		5	1		K-4443-01 F	K-1023-01 Inc	K-3637-01 EB (SB) F
1996F			3				
1997P	4						
1997F	2						
1998P							
1998F							
1999P							
1999F							
2000P							
2000F							
2001P							
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Projects	Production	Production	Projects	Projects
Quarry No.	1-052-02	1-052-02	1-052-02	1-056-01	1-056-01	1-056-01	1-056-01
GeoClass	STNR	STNR	STNR	HRFD	HRFD	HRFD	HRFD
Bed No.		1,2	1,2	1,2,3	2,3	(1),2,3	1,2,3
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P			K-0248-01 P				
1983F							
1984P			K-0251-01 P K-1773-01 P				
1984F							
1985P		2	K-0117-02 P				
1985F	1						
1986P							
1986F							
1987P							
1987F							
1988P							
1988F							
1989P				1			
1989F		1					
1990P				1			K-2813-01 P
1990F							
1991P				1			
1991F							
1992P				1			
1992F							
1993P				2			K-2633-01 Inc K-2853-01 Inc
1993F				1			
1994P					1	K-3222-01 F	
1994F							
1995P							
1995F							
1996P							
1996F							
1997P							
1997F							
1998P							
1998F							
1999P							
1999F							
2000P							
2000F							
2001P							
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Projects	Production	Production	Projects
Quarry No.	1-070-05	1-070-05	1-070-06	1-070-06	1-081-01	1-081-01	1-081-01
GeoClass	EVCK	EVCK	KRFD	KRFD	TRKO	TRKO	TRKO
Bed No.	1,2	1,2	B	B	1,2,3,4	3,4	1,2,3,4
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P							
1985F							
1986P							
1986F							
1987P						3	
1987F							
1988P							
1988F							
1989P					3		
1989F							
1990P							K-2592-01 P
1990F							
1991P							
1991F							
1992P							
1992F							
1993P							
1993F							
1994P							
1994F							
1995P							
1995F							
1996P			3	K-3362-10 F			
1996F							
1997P			3	K-3371-01 F			
1997F							
1998P			1				
1998F			1				
1999P			2				
1999F	2						
2000P		K-5087-01 Inc					
2000F							
2001P							
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Projects
Quarry No.	1-081-05	1-081-05	1-089-01	1-089-01	1-089-01
GeoClass	TRKO	TRKO	HRFD	HRFD	HRFD
Bed No.	1,2,3,4,5	1,2,3,4,5	A	OA	A
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P					
1986F					
1987P					
1987F					
1988P					
1988F					
1989P					K-2445-01 P
1989F					
1990P			1		K-2454-01 P
1990F					
1991P					K-3831-01 F
1991F			1		
1992P			1		K-2446-01 Inc K-2446-01 F K-3344-01 Inc
1992F					
1993P					K-2446-02 Inc K-3344-01 F
1993F					
1994P				1	
1994F					
1995P	1				
1995F					
1996P					
1996F					
1997P	3	K-3325-02 Inc			
1997F					
1998P	3				
1998F					
1999P	6	K-5090-01 Inc K-5628-01 I			
1999F					
2000P	2	K-5633-01 WB Inc			
2000F	1				
2001P	3	K-5633-01 EB Inc			
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Projects	Projects	Projects
Quarry No.	1-089-02	1-089-02	1-089-06	1-089-06	1-105-02	1-105-02
GeoClass	BLGM	BLGM	BLGM	BLGM	SPGH; ARGN	
Bed No.	1,2,3	1,2,3	1,2	1,2	(1),(2),(3); (8,9,10,11)	
1980P						
1980F						
1981P						
1981F						
1982P						
1982F						
1983P						
1983F						
1984P						
1984F						
1985P					K-0987-01 P	
1985F						
1986P						
1986F						
1987P						K-0986-02 F
1987F						
1988P						
1988F						
1989P						
1989F						
1990P						
1990F						
1991P						
1991F						
1992P						
1992F						
1993P	2	K-2866-01 Inc K-3250-01 Inc				
1993F						
1994P	3					
1994F						
1995P	2	K-3251-01 Inc K-4341-01 Inc				
1995F						
1996P	3	K-3251-01 Inc				
1996F						
1997P						
1997F						
1998P						
1998F						
1999P						
1999F						
2000P			6	K-5087-01 Inc		
2000F						
2001P						
2001F						

TABLE E.1

Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Production	Projects	Projects
Quarry No.	2-021-01	2-021-01	2-021-03	2-021-03	2-021-03	2-021-03	2-021-06
GeoClass	CRSL	CRSL	TWND	TWND	TWND	TWND	CRSL
Bed No.	1,2,3	1,2,3	1,2,3,4	1,2,3,4,5	3,4,5	1,2,3,4,5	4,5
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P	4				3		
1985F							
1986P	8	K-2588-01 P					
1986F							
1987P	5	K-0562-02 P					
1987F							
1988P		K-0561-02 P					
1988F							
1989P	3		1	5	3		
1989F							
1990P	3			3		K-2611-01 P	
1990F				2			
1991P				1			
1991F							
1992P				3		K-2609-01 Inc	
1992F							
1993P				1			
1993F							
1994P							
1994F							
1995P							
1995F							
1996P							
1996F							
1997P							
1997F							
1998P							
1998F							
1999P							
1999F							
2000P							
2000F							
2001P							K-5644-01 Inc
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Projects
Quarry No.	2-021-10	2-021-10	2-021-11	2-021-11	2-021-11
GeoClass	TWND	TWND	CRSL	CRSL	CRSL
Bed No.	1,2,3,4	1,2,3,4	1,2,3,4	3,4	(1),(2),3,4
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P					
1986F					
1987P					
1987F					
1988P					
1988F					
1989P					
1989F					
1990P					
1990F					
1991P					
1991F					
1992P					
1992F					
1993P					
1993F					
1994P					
1994F					
1995P					
1995F					
1996P					
1996F					
1997P					
1997F					
1998P	3	K-4956-03 Inc			
1998F					
1999P	6	K-4956-03 F K-5021-02 F K-5263-01 NB F			
1999F					
2000P	3	K-5263-01 SB F, K-5633-01 WB Inc	1		
2000F					
2001P	1	K-5633-01 EB Inc	3	2	K-5021-04 Inc, K-5644-01 Inc
2001F			3		

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Projects	Production	Projects
Quarry No.	2-021-12	2-021-12	2-031-01	2-031-01	2-031-01	2-057-02	2-057-02
GeoClass	TWND	TWND	TWND	TWND	TWND	FRRL	FRRL
Bed No.	1,2,3	1,2,3	1,2	2	2	1,2,3,4	1,2,3,4
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P							
1985F							
1986P							
1986F							
1987P							
1987F							
1988P							
1988F							
1989P							
1989F							
1990P				3			
1990F							
1991P				4	K-2611-02 F	3	
1991F						2	
1992P				1	K-2611-02 Inc	3	K-4433-03 Inc
1992F						1	
1993P				1			
1993F							
1994P				3			
1994F							
1995P			1				
1995F							
1996P			1				
1996F							
1997P							
1997F							
1998P							
1998F							
1999P							
1999F							
2000P			4				
2000F							
2001P	2	K-5644-01 Inc					
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Projects
Quarry No.	2-057-04	2-057-04	2-057-05	2-057-05
GeoClass	CRSL	CRSL	FRRL	FRRL
Bed No.	2,3	2,3	2	2
1980P				
1980F				
1981P				
1981F				
1982P				
1982F				
1983P				
1983F				
1984P				
1984F				
1985P				
1985F				
1986P				
1986F				
1987P				
1987F				
1988P				
1988F				
1989P				
1989F				
1990P				
1990F				
1991P				
1991F				
1992P				
1992F				
1993P	7			
1993F				
1994P	9	K-3046-03 F K-3219-02 F K-3220-01 F K-4058-03 F		
1994F				
1995P	1	K-3321-01 F		
1995F				
1996P	5	K-3217-02 F		
1996F				
1997P		K-4350-01 F K-5084-01 F	4	K-3216-02 F
1997F				
1998P			3	K-3221-02 F
1998F				
1999P				
1999F				
2000P				
2000F				
2001P	2			
2001F				

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Projects	Production	Projects
Quarry No.	2-057-06	2-057-06	2-057-06	4-001-01	4-001-01
GeoClass	CRSL	CRSL	CRSL	RYTN	RYTN
Bed No.	1,2	3,4	1,2,3,4	1,2,3,4	1,2,3,4
1980P					
1980F					
1981P					K-1281-02 P
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P				2	K-0619-02 P K-0620-02 P
1985F					
1986P				1	K-0106-02 P
1986F					
1987P					
1987F					
1988P					
1988F					
1989P					
1989F					
1990P					
1990F					
1991P					
1991F					
1992P				1	
1992F					
1993P				3	
1993F					
1994P				6	
1994F					
1995P				2	
1995F					
1996P					
1996F					
1997P	1	5			
1997F					
1998P				2	
1998F					
1999P			K-5089-01 NB F	2	
1999F		4			
2000P				4	
2000F					
2001P				3	
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Projects	Production	Projects	Production	Projects
Quarry No.	4-006-11	4-006-11	4-006-11	4-010-01	4-010-01	4-025-01	4-025-01
GeoClass	LBRD	LBRD	LBRD	PLSM	PLSM	EVCK	EVCK
Bed No.	1,2,3	1,2,3,4	1,2,3,(4)	1,2	1,2	3	3
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P							
1985F							
1986P							
1986F							
1987P							
1987F							
1988P				2	K-0171-01 P		
1988F							
1989P							
1989F							
1990P						1	
1990F							
1991P						2	K-2617-01 Inc
1991F							
1992P						1	
1992F							
1993P						9	K-4434-03 F K-4434-04 Inc
1993F							
1994P						3	
1994F							
1995P							
1995F							
1996P							
1996F							
1997P		2	K-4066-01 Inc				
1997F							
1998P	1	2	K-3276-01 Inc				
1998F							
1999P							
1999F							
2000P							
2000F							
2001P							
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Production	Projects	Projects
Quarry No.	4-025-02	4-025-02	4-030-02	4-030-02	4-030-02	4-030-02	4-030-02
GeoClass	EVCK	EVCK	SNBD	SPGH	STNR	SPGH	STNR
Bed No.	1,2,3	1,2,3	1	13,14	4,5	13,14	4,5
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P					4		K-0987-02 P
1985F			1				
1986P							
1986F			2				
1987P					1		
1987F							
1988P							
1988F							
1989P							
1989F							
1990P							
1990F							
1991P							
1991F							
1992P							
1992F							
1993P							
1993F							
1994P							
1994F							
1995P							
1995F							
1996P					3		K-5998-01 F K-3371-03 F
1996F							
1997P				1	2		
1997F							
1998P				3	1	K-5085-01 F	
1998F							
1999P	4	K-5089-01 SB F		1	2		K-5634-02 Inc
1999F							
2000P	4			5	1		
2000F							
2001P	3			1	6		
2001F							

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Projects	Projects	Projects
Quarry No.	4-030-04	4-030-04	4-030-04	4-030-04	4-030-04
GeoClass	SPGH	STNR	SPGH	STNR	STNR; SPGH
Bed No.	10,11,12,13	4,5	10,11,12,13	4,5	4,5; 10,11,12,13
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P		1			
1985F					
1986P		2			
1986F					
1987P		3		K-2434-02 P	
1987F					
1988P	2				
1988F	1				
1989P	1	1	K-2434-04 P		
1989F					
1990P	1	1			
1990F					
1991P		1			
1991F					
1992P			K-3247-01 F		
1992F	1				
1993P	2	1			
1993F					
1994P		5			
1994F					
1995P	1	1			K-5028-01 F, K-3596-01 F
1995F	2				
1996P					
1996F					
1997P					
1997F					
1998P					
1998F					
1999P					
1999F					
2000P					
2000F					
2001P					
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Projects	Production	Projects
Quarry No.	4-037-02	4-037-02	4-037-02	4-037-03	4-037-03
GeoClass	WKRS	WKRS	WKRS	EVCK	EVCK
Bed No.	1,2,3,4	1,2,3,4	1,2,3,4,5	2,3	2,3
1980P					
1980F					
1981P					
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P		K-0152-02 P	K-2515-01 P		
1985F					
1986P		K-0768-01 P			
1986F					
1987P	1	K-0764-02 F K-1879-01 P			
1987F					
1988P					
1988F					
1989P					
1989F					
1990P					
1990F					
1991P					
1991F					
1992P					
1992F					
1993P					
1993F					
1994P					
1994F					
1995P					
1995F					
1996P				7	K-3293-03 Inc K-4458-01 F K-4459-01 F
1996F					
1997P				7	K-3292-02 F
1997F					
1998P				4	
1998F					
1999P				1	
1999F					
2000P					
2000F					
2001P					
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Projects	Projects
Quarry No.	4-037-05	4-037-05	4-037-06	4-037-06	4-037-06	4-037-06
GeoClass	BLGM	BLGM	PLSM	PLSM	PLSM	PLSM
Bed No.	4,5	4,5	1,2,3	3	1,2,3	1,2,3
1980P						
1980F						
1981P						
1981F						
1982P						
1982F						
1983P						
1983F						
1984P						
1984F						
1985P						
1985F						
1986P						
1986F						
1987P						
1987F						
1988P	3	K-2826-01 P				
1988F						
1989P						
1989F						
1990P						
1990F						
1991P						
1991F						
1992P						
1992F						
1993P						
1993F						
1994P						
1994F						
1995P						
1995F						
1996P			1			
1996F			1			
1997P			4		K-4457-01 F	
1997F			3			
1998P			3		K-3293-04 Inc	
1998F						
1999P				1		
1999F						
2000P						
2000F						
2001P						
2001F						

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Production	Projects
Quarry No.	4-054-02	4-054-02	4-054-11	4-054-11	4-054-11	4-054-11
GeoClass	BFLS	BFLS	BFLS	WNRS	WNRS	BFLS; WNRS
Bed No.	1,2,3	1,2,3	1,2,3	B,C,D	B,C,D,	1,2,3; B,C,D
1980P						
1980F						
1981P						
1981F						
1982P						
1982F						
1983P						
1983F						
1984P		K-0990-03 P K-0990-03 P				
1984F						
1985P	5	K-0456-04 P K-0988-02 P K-0135-02 F				
1985F						
1986P						
1986F						
1987P	1	K-1310-01 P				
1987F						
1988P	3					
1988F						
1989P	1					
1989F						
1990P						
1990F						
1991P						
1991F						
1992P						
1992F						
1993P						
1993F						
1994P	1					
1994F						
1995P	1					
1995F						
1996P			2			
1996F						
1997P			1			
1997F						
1998P	3					
1998F						
1999P	1		2	1		K-5760-01 Inc
1999F					1	
2000P			2			
2000F			1			
2001P			2			
2001F						

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Production	Production	Projects	Projects	Projects
Quarry No.	4-061-05	4-061-05	4-061-05	4-061-05	4-061-05	4-061-05	4-061-05
GeoClass	ARGN	ARGN	ARGN	ARGN	ARGN	ARGN	ARGN
Bed No.	4,5	4,5,6	6	9	4,5	4,5,(6)	4,5,6
1980P							
1980F							
1981P							
1981F							
1982P							
1982F							
1983P							
1983F							
1984P							
1984F							
1985P							
1985F							
1986P	5				K-0989-02 F		K-0590-02 P
1986F			1				
1987P	2	1				K-1421-01 P	
1987F							
1988P		1	2		K-1422-01 P		K-0966-03 P
1988F			1				
1989P		2					
1989F							
1990P							
1990F							
1991P							
1991F							
1992P		2			K-2500-01 Inc		
1992F							
1993P							
1993F							
1994P							
1994F							
1995P							
1995F							
1996P							
1996F							
1997P							
1997F							
1998P		2					
1998F							
1999P		2		1			
1999F							
2000P		2					
2000F							
2001P		2					
2001F		2					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Projects	Production	Production	Projects
Quarry No.	4-063-06	4-063-06	4-103-01	4-103-01	4-103-01
GeoClass	WNRS	WNRS	STNR	STNR	STNR
Bed No.	1,2,3	1,2,3	1,2	2	1,2
1980P					
1980F					
1981P					K-0212-02 P
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P					
1986F					
1987P					
1987F					
1988P			2		
1988F					
1989P					
1989F					
1990P					
1990F					
1991P					
1991F					
1992P					
1992F					
1993P			3		
1993F					
1994P					
1994F					
1995P					
1995F					
1996P			1		
1996F					
1997P	3	K-4891-02 Inc			
1997F					
1998P	5	K-4892-02 Inc	2	1	K-3295-02 Inc
1998F					
1999P	1				
1999F					
2000P	1				
2000F					
2001P	1				
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

Source	Production	Production	Production	Projects	Projects
Quarry No.	5-018-01	5-018-01	5-018-01	5-018-01	5-018-01
GeoClass	HOWE; BNNTR	HOWE; BNNTR; GLCK	HOWE; BNNTR; GLCK	HOWE; BNNTR; GLCK	HOWE; BNNTR; GLCK
Bed No.	1,2; 3	1,2; 3; 4	2; 3; 4	(1),2; 3; (4)	1,2; 3; 4
1980P					
1980F					
1981P					K-0212-02 P
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P					
1986F					
1987P		4			
1987F					
1988P		2			K-2514-01 P
1988F					
1989P		12			
1989F					
1990P		1			
1990F					
1991P		1			
1991F					
1992P		11			K-3388-01 Inc
1992F					
1993P		14			K-3324-01 F
1993F					
1994P		2			K-3181-01 Inc
1994F					
1995P	1	3	2	K-4460-01 Inc	
1995F					
1996P			2		
1996F					
1997P					
1997F					
1998P					
1998F					
1999P					
1999F					
2000P			1		
2000F					
2001P					
2001F					

TABLE E.1
Pass-Fail Data for Production Samples (QPS) and Projects

[1] Never ledge sampled.

Source	Production	Projects	Production	Projects	Projects
Quarry No.	5-018-02	5-018-02	5-018-03	5-018-03	NE1/4S2T25SR18E
GeoClass	BNNTR	BNNTR	HOWE; BNNTR; GLCK	HOWE; BNNTR; GLCK	RYTN
Bed No.	1,2,3	1,2,3	5; 6; 7	5; 6; 7	0-30 ft from top of ledge[1]
1980P					K-1280-02 P
1980F					
1981P					K-0104-03 P
1981F					
1982P					
1982F					
1983P					
1983F					
1984P					
1984F					
1985P					
1985F					
1986P					
1986F					
1987P					
1987F					
1988P					
1988F					
1989P					
1989F					
1990P					
1990F					
1991P					
1991F					
1992P					
1992F					
1993P					
1993F					
1994P					
1994F					
1995P	2	K-4432-02 Inc			
1995F					
1996P	4	K-3684-01 Inc	1[2]		
1996F					
1997P			1	K-4729-02 Inc	
1997F					
1998P	1		2		
1998F					
1999P	2	K-5089-01 NB F	1	K-7711-01 Inc	
1999F					
2000P					
2000F					
2001P					
2001F					

[2] This entry has been adjusted from the original production database and ledge file sample sheet. The original "Production Sample Investigation" sheet Lab No. 96-2537 indicated the source is Quarry 5-018-01. It was determined from other sources that this sample was likely from Quarry 5-018-03. Documentation (dated 6/17/2011) is in the ledge file.

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