D-Cracking: Pavement Design and Construction Variables

ROBERT J. GIRARD, EUGENE W. MYERS, GERALD D. MANCHESTER, AND WILLIAM L. TRIMM

Reported map cracking and D-cracking problems observed on portland cement concrete (PCC) pavements in Missouri from the late 1930s to 1981 are briefly discussed. Investigations involving studies in the laboratory and constructed pavements have contributed significantly to a better understanding of the deterioration process and its cause. Type, characteristics, and maximum size of coarse aggregate; source of cement; design of concrete mix; and type of base have been or are being studied in the field or laboratory to determine their influence to frost susceptibility of concrete. Missouri has increased the service life of its PCC pavements. This has been accomplished by (a) not using river and glacial gravels in construction of PCC pavements and (b) subjecting limestones that have a known history of D-cracking problems to increased quality restrictions, which has resulted in some ledges and entire quarries and formations being eliminated. However, D-cracking remains and, in terms of required maintenance and service life, is still a problem.

"Map cracking" and "D-cracking" are terms that have been used in Missouri to discuss the phenomenon of concrete pavement deterioration that occurs when a frost-susceptible aggregate is used in a freeze-and-thaw environment. Map cracking was used in the earliest recorded field surveys to describe visual surface deterioration of gravel aggregate pavements, and D-cracking has been used in recent years to describe visual surface deterioration of limestone aggregate pavements.

D-cracking today is defined as cracking in a slab surface in a pattern that appears first in an orientation parallel to transverse and longitudinal joints and cracks, continues around corners, and may progress into the central area of the slab. Staining, a slight darkening of the concrete at joints or cracks, may precede D-cracking.

As noted above, D-cracking is a phenomenon of concrete pavements. On the Missouri highway system, there are no known concrete bridge decks that exhibit D-cracking.

MAP CRACKING

Early History

The first concrete pavement in Missouri was constructed in 1913 on MO-30 (Gravois Road) in St. Louis. It was 20 ft wide and 1 mile long. By 1922, Missouri had 121 miles of concrete pavement, and, prior to 1928, 1200 miles of two-lane (16-, 18-, and 20-ft) pavement and 359 miles of 9-ft pavement. The coarse aggregates used in these concrete pavements were gravel, crushed flint, or limestone. Crushed flint is a colloquialism used in the identification of crushed chert fragments produced as residue from mining and processing of lead and zinc ores.

In 1930, personnel of the Missouri Highway Department and the Portland Cement Association surveyed all concrete pavements constructed before 1928 (1). Numerous types of pavement distress were reported from this survey; however, the emphasis of the report was on structural cracking and joint blowups. No deterioration other than structurally related was mentioned.

After this report was finished, correspondence indicated that a new type of deterioration, noted on several projects, was becoming important. This deterioration, referred to as map cracking, was considered to be a defect that was peculiar to individual projects and would be confined to those respective locations.

One pavement constructed in 1925, which used river gravel as the coarse aggregate, was partially replaced and the remainder was resurfaced by 1936. The reason for reconstruction of this pavement, after an effective service life of only 11 years, was excessive map-cracking deterioration. Costs for maintenance patching of map-cracked areas on this and other isolated projects had become excessive as early as 1931. Field observations recorded during the 1930s noted that the occurrence of map cracking was much more pronounced on pavements that contained either chert gravel or 2-in crushed flint than on pavements that contained limestone as coarse aggregate. Not all projects constructed with chert gravel were map-cracked. In some instances, map-cracked and non-map-cracked areas were noted within the same project when both areas were constructed with the same coarse aggregate.

Period from 1940 to Late 1950s

In 1940, the map-cracking problem became significant statewide in terms of maintenance costs and rideability. A limited investigation, consisting of a sampling of projects that showed joint distress and a search of correspondence regarding various projects, indicated that deterioration was not simply due to one factor. Map cracking was apparently caused by a combination of conditions and not necessarily the same combination of conditions between projects.

The 13 variables listed below were extracted from the field survey data collected from 1927 to 1940 and studied:

1. Climate--A well-defined trend was found in the variance of freezing cycles from North to South, and the intensity of joint deterioration pointed toward a correlation with freeze-and-thaw cycles.
2. Topography--Topography was considered an indirect influence related to drainage.
3. Moisture and drainage--Deterioration was greater in areas of the projects where drainage was poor.
4. Type of subgrade soil--No correlation was established between map-cracking deterioration and type of subgrade soil except for soils that retain high moisture contents.
5. Type of coarse aggregate--Type of coarse aggregate was determined to be the single most significant contributing factor in map-cracking deterioration. With few exceptions, all severe map cracking had been found in pavements that contained either chert gravel or 2-in crushed flint as coarse aggregate. Some difference was noted, however, between crushed limestones produced from different formations.
6. Fine aggregate--Fine aggregate was determined to have little influence on the problem of map-cracking deterioration.
7. Brand of cement--Observations in Missouri did not indicate that the brand of cement caused variance in the amount of deterioration.
8. Concrete proportions--Variations in mix design did not appear to influence the deterioration process.
9. Quality of concrete--Density of concrete did not appear to be a cause of deterioration in itself, but when honeycombing was present the deterioration process was accelerated.
10. Pavement design--Deterioration was found in

all pavement designs. Neither uniform nor variable thickness of pavement, bar mat or wire-mesh reinforcement, or the use or nonuse of subgrade paper prevented deterioration.

11. Method of curing--No correlation was found between curing methods.

12. Weather conditions during construction--Available records indicated that projects completed in cooler temperatures had less deterioration.

13. Traffic and loading conditions--Traffic did not appear to be responsible for the occurrence of deterioration, although it may influence the rate of progression.

Based on the results of this 1940 field investigation and data contained in correspondence on the map-cracking problem, coarse-fraction river or glacial gravels have not been accepted for use in concrete pavements since 1941. These data also showed that some pavements containing limestone coarse aggregate had a deterioration problem similar to map cracking but it was not severe or extensive enough to cause concern.

Extensive laboratory experimentation was begun on freeze and thaw of concrete specimens that contained various coarse aggregates, mix designs, and air entrainment. Gravels were found to be extremely frost susceptible when used in a stream-wet or partially saturated condition, regardless of the mix design or the use of air-entraining agents. Observations from field surveys were reduced to the probable cost of maintenance per mile of pavement with various types of coarse aggregates. Comparisons of these results continued to reinforce the previous decision to eliminate the use of gravels in portland cement concrete (PCC) pavements.

Missouri experienced a lull in concrete pavement construction during the 1940s and early 1950s. During this period, some laboratory work was conducted to determine the feasibility of beneficiation of limestones to eliminate deleterious particles based on specific gravity. No specific work was conducted on the problem of map cracking, which was then thought to have been remedied.

D-CRACKING

Construction Program Booms in Late 1950s

A significant increase in construction during the late 1950s and 1960s resulted in many new miles of Interstate and primary highways being placed into service. Because of the heavy demand for coarse aggregate, many new quarry sites were developed. The aggregates used in the new pavements were limestones that met specifications in existence at the time. By 1965, many of the newer concrete pavements located in the northwest and west-central area of the state exhibited deterioration that was identified as D-cracking. Preliminary field surveys indicated that concrete pavements constructed with several different limestones had an alarming rate of incidence of D-cracking. Field surveys conducted extensively from 1965 through 1967 projected that the design service life of many of these projects would not be realized. Where annual field survey data were available, they showed the problem to be accelerating and becoming a very expensive maintenance problem. One particular coarse aggregate was identified as a frost-susceptible aggregate. Because of its abundance in the northwest part of the state, it was designed as the prime source for data analysis in both the field surveys and laboratory freeze-and-thaw studies.

Addition of Special Provisions to Missouri Specifications: 1967-1977

Missouri had for many years approved limestone coarse aggregate for use in PCC pavement construction by first sampling and testing material by individual ledges for quality. A ledge is normally established by natural-parting seams of shale or the configuration of the rock itself. The crushed product is then sampled and tested for acceptance for quality requirements, gradation, specific gravity, absorption, weight per cubic foot, and deleterious substances. To attack the deterioration problem, the State of Missouri, based on analysis of field survey data, revised the specifications to identify and restrict the use of frost-susceptible limestones.

Beginning in 1967, special provisions added to the specifications were imposed on all contracts for concrete pavement construction in the northwest and west-central areas of the state. The following modifications to the specifications were made:

1. Maximum size of coarse aggregate was reduced from the existing 2-in gradation requirements to the following:

Sieve Size	Percent Passing
1 in	100
0.75 in	90-100
0.375 in	15-40
No. 4	0-5

2. Quality guidelines were revised for each ledge of limestone in each quarry to meet the following standards:

Property	Value
Water alcohol freeze loss	10% max
Bulk specific gravity	2.60 min
Absorption	1.5% max

These revised quality guidelines eliminated the use of a number of ledges and some entire formations and quarries previously approved for coarse aggregate for concrete pavement.

3. A moisture barrier of 4-mil polyethylene sheeting was placed between the base and the concrete pavement. For evaluation purposes, projects with this design feature were required to leave 10 percent of the main-line pavement as a control section without the polyethylene moisture barrier.

4. With the reduction in size of coarse aggregate, sand content was increased from 33 percent to approximately 45 percent by volume of the total aggregate fraction.

In conjunction with the above special provision, a three-phase investigation (2-4) was initiated: (a) a laboratory study to evaluate freeze-and-thaw resistance of concrete by using Bethany Falls limestone from eight different sources; (b) a laboratory study to evaluate freeze-and-thaw resistance of concrete by using Bethany Falls limestone from one source with 11 type 1 cements, each from a different source; and (c) a field study to evaluate pavement performance based on the special provision outlined above.

The first phase of the investigation was designed to determine whether frost resistance of laboratory concrete could be correlated with the physical properties of the coarse aggregates used. The freeze-and-thaw test method, similar to Procedure B of ASTM C-666, was modified to include only one cycle per week, which consisted of a 16-h freeze, and storage in water between cycles. Eleven Bethany Falls

Figure 1. Location of sampling sites and test section.

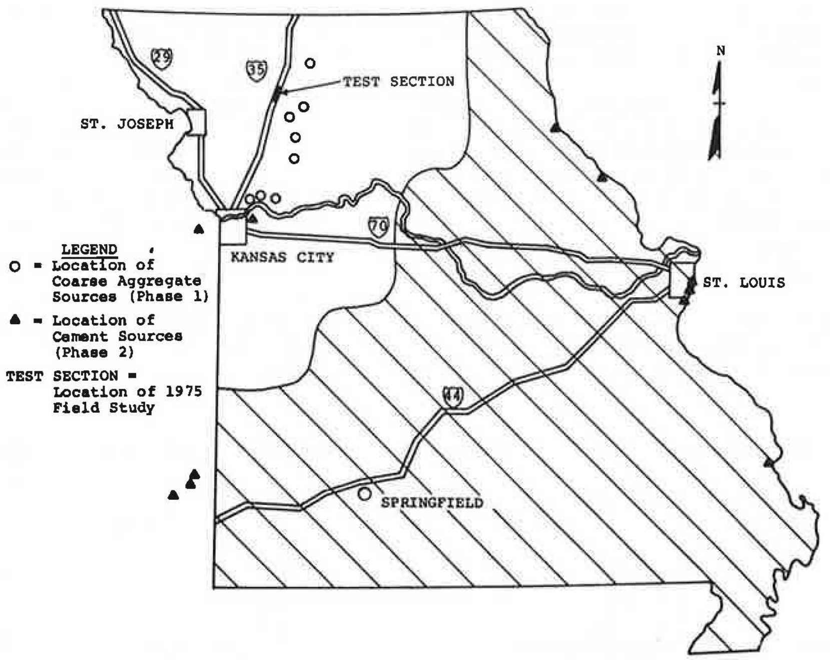
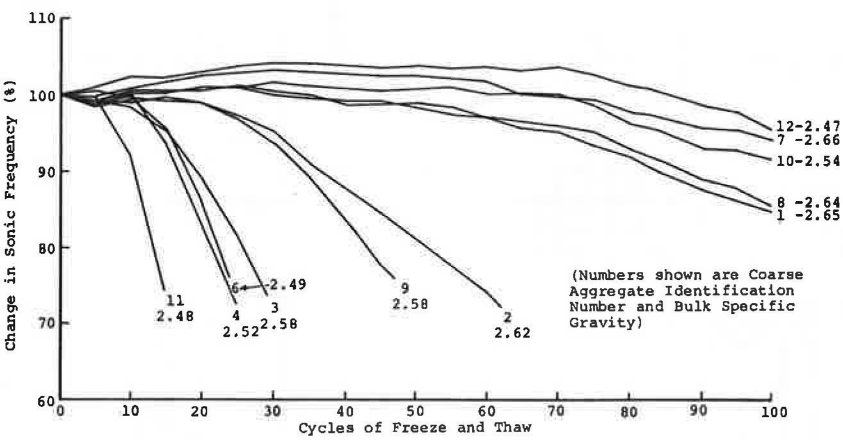


Figure 2. Failure of specimens.



coarse aggregates from the D-crack-susceptible area of the state were sampled from various locations, as shown in Figure 1. Samples were picked by ledges in anticipation of obtaining two samples from each of the bulk-specific-gravity groups of >2.63, 2.63-2.56, 2.55-2.51, and <2.51. The main variables in the design of concretes were air-entrainment and non-air-entrainment, and sand contents were 33, 37, and 45 percent of total aggregate fraction based on the air-entrained design.

Results from this study indicated the following:

1. Frost susceptibility of concrete specimens increased as bulk specific gravity of coarse aggregate decreased, as shown in Figure 2. There were two exceptions: Coarse aggregates 10 and 12 were determined to be of an oolitic pelletal limestone structure rather than finely crystalline or microcrystalline calcitic limestone as determined for the other coarse aggregates. These two coarse aggregates are not typical of the Bethany Falls limestone stratum. These results proved that the bulk-specific-gravity limitation of 2.60 in the special provisions was beneficial.

2. Gravity gradation of the coarse aggregate, based on bulk specific gravity (vacuum-saturated surface dry), influenced frost resistance of the aggregate. An almost unlimited array of gravity gradations may exist for any particular "mean" gradation. Gravity gradations of the various samples of coarse aggregates in this study are shown in Figures 3 and 4.

3. Permanent dilation of concrete specimens after the first 10 freeze-and-thaw cycles was found to be a good indicator of ultimate failure of concrete specimens. As shown in Figure 5, the slope of the curves at the end of 10 freeze-and-thaw cycles could be used to rank the aggregates in order of ultimate failure.

4. Increased sand content of the aggregate fraction, from 33 to 45 percent, indicated a trend toward increased frost resistance of concrete. However, as shown in Figures 6 and 7, the actual difference in the number of cycles at ultimate failure may be small.

5. Air entrainment added to the resistance of the concrete, but the actual difference in the number of freeze-and-thaw cycles required for failure of specimens was small, as shown in Figures 6 and 7.

The second phase of this study, also a laboratory study, was to determine whether source of cement was related to frost susceptibility of Bethany Falls limestone. Field surveys made immediately prior to 1967 on limestone pavements indicated that the rate of deterioration was different for projects with different brands of cement. However, the concrete mix designs of the surveyed projects were not the same, nor was the coarse aggregate from the same source. This study was designed to use a Bethany Falls limestone from a known frost-susceptible source with various brands of cement. The coarse aggregate used for this study had a 2.60 bulk specific gravity and was used in a 1-in maximum-size gradation.

Twelve cements, meeting AASHTO M85 and representing type 1 production, were obtained from sources distributed as shown in Figure 1. Cement sources located in western Missouri and eastern Kansas were those normally used in the area where the deterioration problem exists.

The design of concrete used in this study included both air-entrainment and non-air-entrainment. The gradation and volume of coarse aggregate were held constant. A limited experiment on the effect of high-alkali cement was included, in which a cement with 0.8 percent alkali equivalent was used.

The results of this study produced the following conclusions:

1. Failure of the concrete specimens was significantly different between cements, as shown in Figures 8 and 9 (the X cement is the high-alkali cement).

Figure 3. Gravity gradation of coarse aggregate from west-central Missouri.

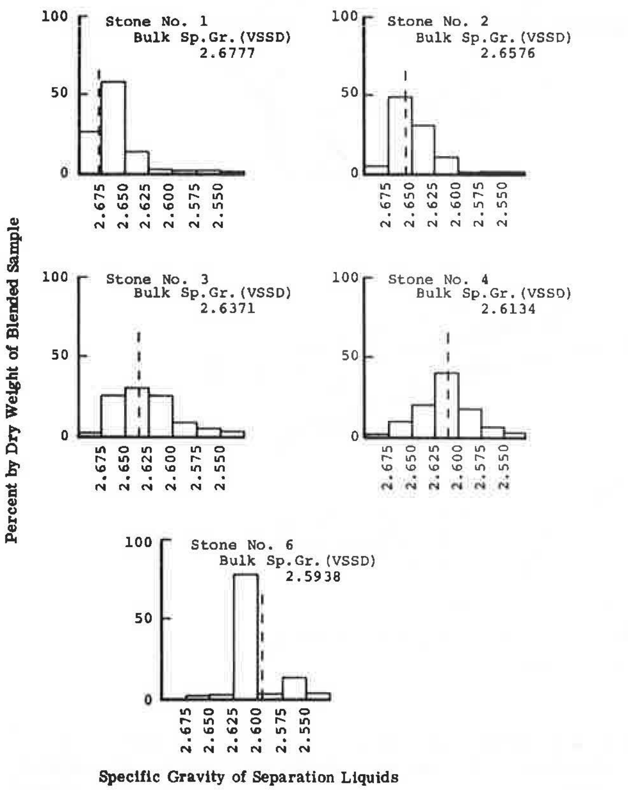


Figure 4. Gravity gradation of coarse aggregate from northwestern Missouri.

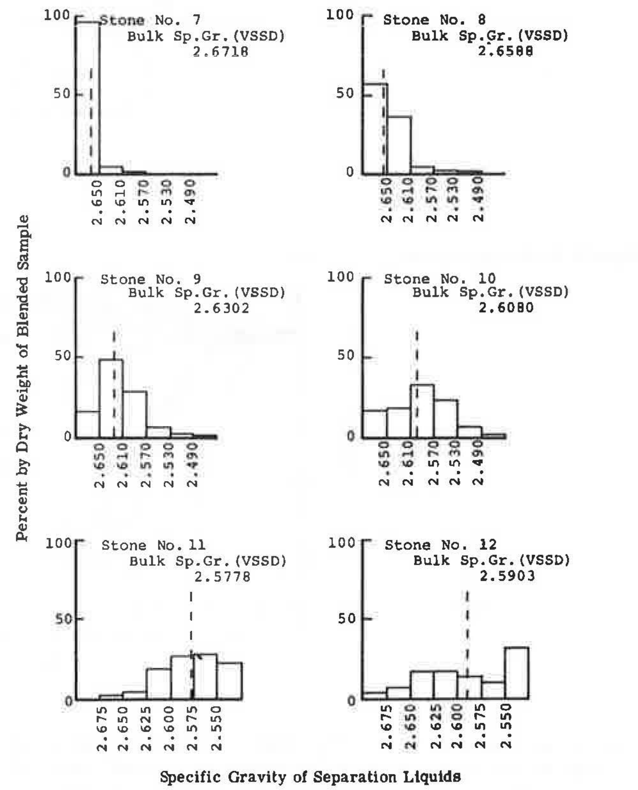


Figure 5. Expansion of concrete specimens.

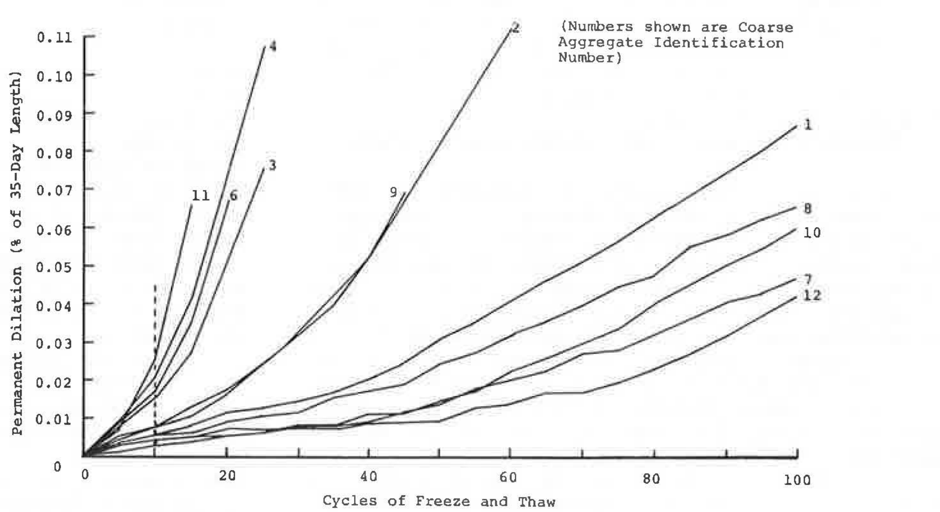


Figure 6. Failure of air-entrained concrete specimens with various sand contents.

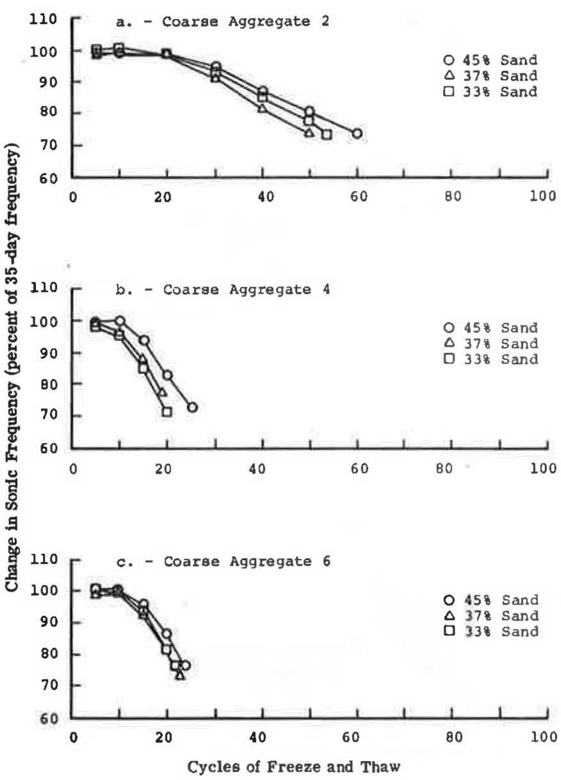


Figure 7. Failure of non-air-entrained concrete specimens with various sand contents.

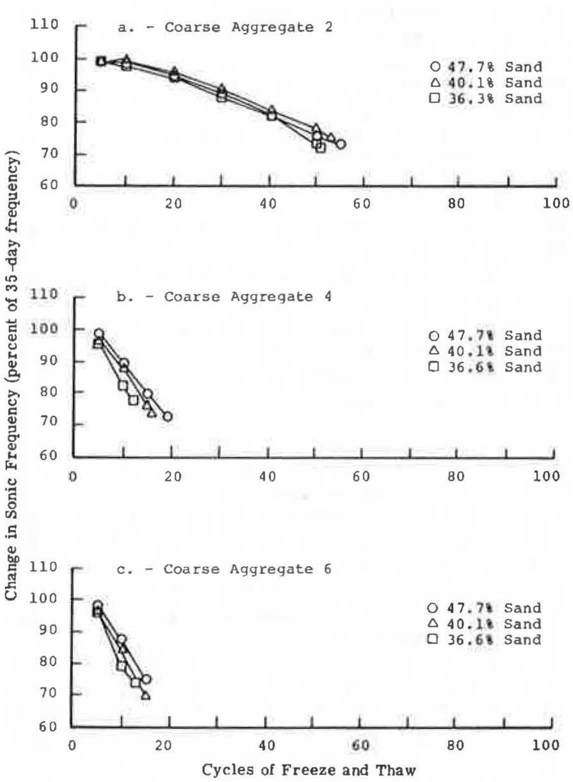


Figure 8. Failure of air-entrained concrete specimens.

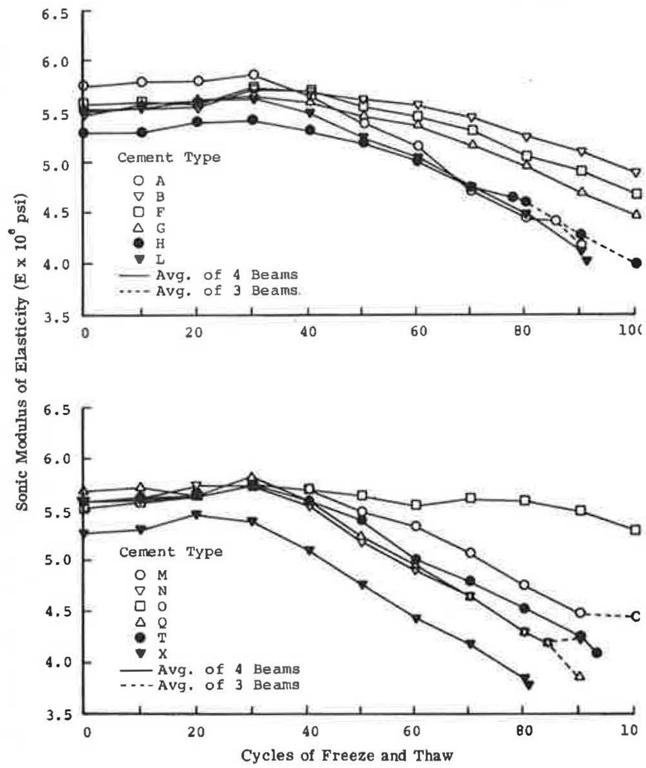


Figure 9. Failure of non-air-entrained concrete specimens.

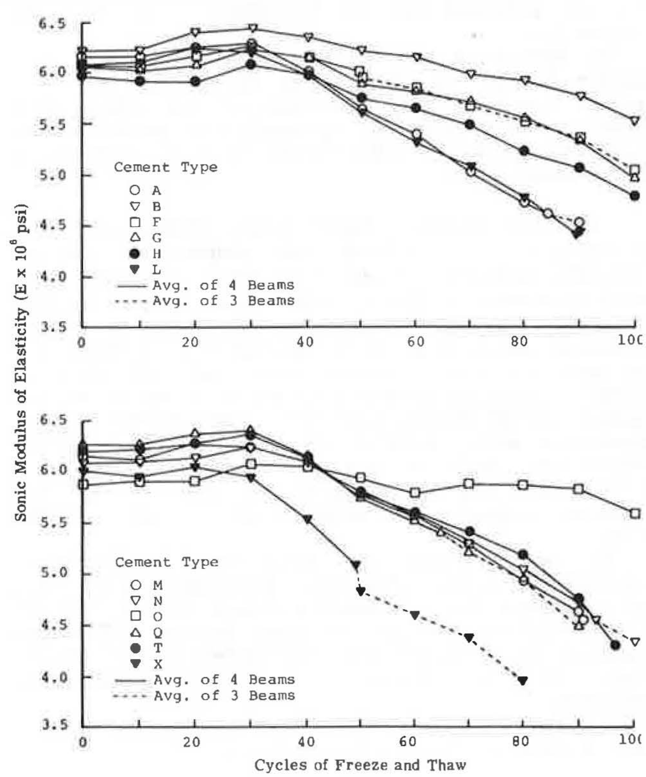
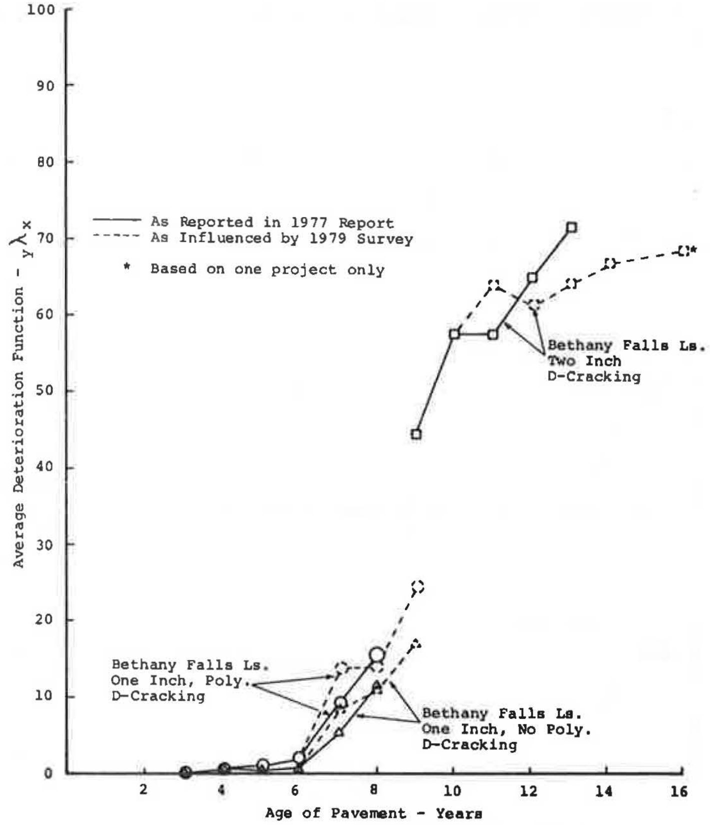


Figure 10. D-cracking on PCC pavement with Bethany Falls limestone as coarse aggregate.



2. The effect of air-entrainment on the durability of specimens was not significant, as shown in Figure 10.
3. Specimens made with high-alkali cement (X) failed before the same brand of cement with low alkali content (L) regardless of air-entrainment levels. This relation, although not perfect, did point to possible interaction of the effects of high-alkali cement.

The third phase, a field study, investigated the occurrence of D-cracking with respect to age of concrete pavements constructed under the 1967 special provisions. Twenty-eight projects, which had the 1-in maximum-size coarse aggregate and polyethylene sheeting moisture barrier placed under all or part of the pavement, were included in this study. Thirteen projects constructed prior to the specification change with 2-in maximum-size coarse aggregate were included for comparative purposes. Therefore, analysis was accomplished by testing within projects for effects of polyethylene and between projects for effects of coarse-aggregate size.

To reduce observation data to a mathematical equivalent, a parameter was established that would be influenced by a weighted relation of the area of D-cracking visible at the sawn joints. This parameter was labeled the "deterioration function" (λ). The mathematics of the parameter were as follows:

$$y^{\lambda_x} = A + 0.8B + (0.8)^2C + (0.8)^3D + \ldots + (0.8)^7H \quad (1)$$

where

y = calendar year in which survey was made,
x = project identification code,
A = percentage of cracks or joints with 25 ft^2 or more of affected area,
B = percentage of cracks or joints with 15-25 ft^2 of affected area,
C = percentage of cracks or joints with 10-15 ft^2 of affected area,
D = percentage of cracks or joints with 5-10 ft^2 of affected area,
E = percentage of cracks or joints with 2-5 ft^2 of affected area,
F = percentage of cracks or joints with 1-2 ft^2 of affected area,
G = percentage of cracks or joints with 0.5-1 ft^2 of affected area, and
H = percentage of cracks or joints with 0-0.5 ft^2 of affected area.

The limits of the deterioration function were 0 for clear pavement to 100 for all observed joints that had 25 ft^2 or more of deterioration.

This phase of the D-cracking study was designed as a 10-year study. However, the age span of the 28 polyethylene projects (4-9 years) at the completion of the study caused evaluation of the data to be restrained. Generally, the analysis was based on trends of the older projects.

The conclusions reported at the termination of this study indicated that PCC pavement constructed with 1-in maximum-size Bethany Falls limestone coarse aggregate and a 4-mil polyethylene moisture barrier exhibited D-cracking at an earlier age than identical pavement without polyethylene. A 1980 addendum to this study (5) indicated that the conclusions in 1977 were basically sound. The rate of increase in D-cracking was adjusted slightly upward for polyethylene sections and remained essentially the same for no-polyethylene sections for the Bethany Falls limestone. Curves in the lower-right-hand portion of Figure 10 show the relative change from the original reported data to those with the addendum, for the 1-in maximum-size gradation.

Data obtained for 2-in maximum-size Bethany Falls coarse-aggregate projects, shown in Figure 10, could not be directly correlated with those obtained for the 1-in maximum size because of lack of comparable age of pavement at the time the survey began. With available data, D-cracking was observed as occurring at a higher yearly rate of increase for the 2-in than for the 1-in maximum-size coarse aggregate. Extrapolation of the D-cracking curve for the 2-in maximum size indicates that D-cracking started at an earlier age than it did for the 1-in maximum size. Again, the 1980 addendum to this study (shown as broken lines) indicated that the average yearly increase was estimated high in the original study. The fact that the projects with the revised requirements for quality control and reduced coarse-aggregate size tend to have lesser amounts of D-cracking at nine years of age than the projects with 2-in maximum-size coarse aggregate indicates that the special-provision changes are of significant benefit. The first observation of significant D-cracking was generally made at 5.5-6 years of age regardless of pavement design for 1-in maximum-size coarse aggregate.

Based on results of the third-phase field study, it was decided to

1. Eliminate the polyethylene sheeting moisture barrier,
2. Continue using 1-in maximum size for frost-susceptible coarse aggregate with increase in sand content of the total aggregate fraction, and
3. Continue using revised quality controls for approval of frost-susceptible coarse aggregate.

Roadway Design Variables to Reduce D-Cracking: 1977

In 1975, Missouri initiated another field study to determine the effectiveness of certain design variables in preventing or reducing the occurrence of D-cracking in PCC pavement. The project selected for incorporating various design variables was constructed in 1977 on I-35 in Daviess County (Figure 1). The project site was located in the area susceptible to D-cracking. Shoulder design throughout the project limits included a type 4, permeable, open-graded aggregate for drainage. The following design variables were included:

1. Bethany Falls limestone coarse aggregate, 1-in maximum size;
2. Bethany Falls limestone coarse aggregate from the same source as above, 0.5-in maximum size;
3. Burlington limestone coarse aggregate, 2-in maximum size, produced from a source in central Missouri some 100 miles from the project and with no known history of a D-cracking problem;
4. Pavement constructed with and without polyethylene moisture barrier; and
5. Four different types of base using crushed limestone aggregate: (a) type 3 base (impermeable, dense-graded), (b) bituminous base (impermeable, dense-graded), (c) type 4 base, bituminous-treated (permeable, open-graded), and (d) type 1 base, cement-treated (impermeable, dense-graded).

The plan layout and material descriptions of the test sections are shown in Figure 11. Each test section was placed on tangent with a cross-section design, as shown in Figure 12.

The variables included in this study should provide additional information on the ability to eliminate the occurrence or reduce the magnitude of D-cracking based on (a) maximum size and type of coarse aggregate, (b) type of base, and (c) use or nonuse of polyethylene moisture barrier.

This project is not of sufficient age to make conclusions at this time. No D-cracking had been observed on any of the test sections as of the August-September 1981 survey.

Pavements With or Without Controlled Drainage

Profile design of all projects mentioned thus far in this paper has allowed surface water to drain to or across the shoulders into earth ditches on either side of the roadway surface. The type of shoulder, either earth or aggregate, has not significantly influenced the D-cracking problem. In the Kansas City area, however, many projects built in the late 1950s, middle 1960s, and 1970s were constructed with a concrete curb-and-gutter design with a drop inlet and pipe drainage system. Several of these projects have long sections that are constructed in cut areas or depressed sections. Observations of these pavements indicated little or no D-cracking. The ability of the drainage system to effectively carry the bulk of the surface water away from the pavement should reduce the subbase or base moisture conditions. Effective reduction of the available moisture in the base materials should reduce the yearly rate of D-cracking. Continued observation of these projects should give more insight as to the ultimate effectiveness of the drainage systems in reducing the D-cracking problem.

Cement Studies by Battelle Columbus Laboratories

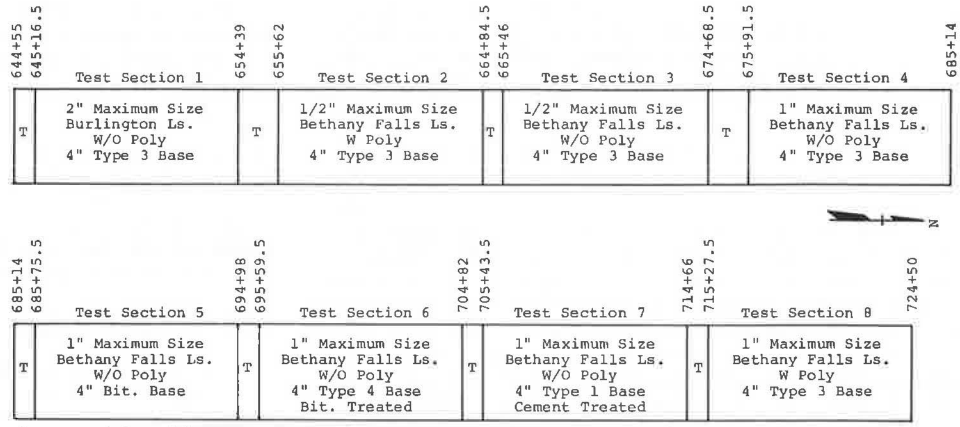
Based on knowledge gained from the previously mentioned laboratory studies and field observations, the D-cracking problem was postulated to be a function of moisture migration within the concrete. Battelle Columbus Laboratories was contracted by the States of Missouri, Iowa, and Kansas, in cooperation with the Federal Highway Administration, to investigate and determine whether such a correlation existed between cement sources (6).

Phase A of the project studied movement of moisture into and from hardened cement pastes and dimensional changes that accompany the moisture changes. It was established that statistically significant differences did exist between moisture change and related linear dimensional change behavior in the 32 cements studied.

Phase B continued with a study of moisture migration in simulated concretes. Sixteen of the 32 cements were selected for study based on the results of phase A. The broad objective of phase B was to determine the influence of cement in controlling resistance to destructive freezing action in concretes that contain D-crack-prone aggregates. Missouri submitted for test in this study a sample of the D-crack-susceptible Bethany Falls limestone. Only 8 of the 16 cements were used with the Bethany Falls limestone in the freeze-and-thaw behavior test.

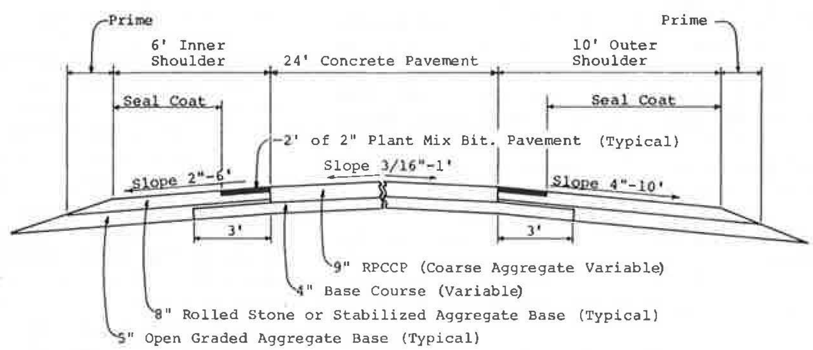
The results of this phase indicated that, under the conditions of the study, cement source did not significantly influence the onset of potentially disruptive forces during freezing of concretes that contained D-crack-prone limestone aggregates, even though cement source did have a statistically significant influence on the moisture migration properties of the concretes. That is, under a given set of environmental conditions, the time at which ex-

Figure 11. Layout and description of test sections for northbound lane, I-35, Daviess County.



T = Transition Slab
NOTE: Stationing shown is for centerline of northbound lane.

Figure 12. Typical cross section of test areas.



pansion of the aggregate particles commences in concretes that are subjected to freezing is not influenced by cement source. It was possible, however, to ascertain qualitatively that, once expansion of the aggregate particles does begin, the magnitude of dilation can influence the amount of structural damage that occurs in the concrete. Cement sources did have an effect on the magnitude of dilation during freezing in concretes prepared with the Bethany Falls limestone in the laboratory. The practical significance of these observed effects remains questionable.

Present research has answered some questions and raised others regarding the effect of cement source on the D-cracking of concretes prepared with limestone aggregates.

Pennsylvania State University Study on Upgrading of Low-Quality Aggregate

Missouri has also been interested in research concerning the upgrading of low-quality coarse aggregates and has participated in committees that have such responsibilities. The most recent research done under such circumstances is work completed by Pennsylvania State University and published in a National Cooperative Highway Research Program report (7). Three aggregates were selected for inclusion in this study with regard to the D-cracking problem, one of which was from Missouri. This aggregate, Bethany Falls limestone, was the same aggregate used in the field study currently under way on I-35 in Daviess County.

Research conducted in the Pennsylvania State University study was basically oriented toward use of impregnation treatments on the aggregate prior to its incorporation into the concrete. According to the report (7), "All of the impregnants tested were successful in controlling D-cracking as determined by expansion during rapid freeze and thaw cycling." However, reductions in strength, mix-design adjustments, paste-aggregate bond, cost/benefit ratios, and many other aspects must also be researched before an impregnation treatment is applied to a particular construction project.

Suggestions from this study were that further laboratory studies be carried out before a field evaluation program is instituted in order to optimize the choice of methods and treatment materials. Specifically, it was suggested that an expanded range of treatment materials for aggregates sensitive to freeze-thaw and D-cracking be investigated in order to identify the least costly, but most effective, treatment materials.

SUMMARY

This paper presents a history of D-cracking problems in Missouri, including changes made in source and type of coarse aggregates, mix design, and construction design over a period from 1913 to 1981. Chert gravel and glacial gravels have not been used since 1941. Since 1967, each aggregate source and limestone formation in the D-crack-susceptible area of the state has been subjected to increased quality requirements. Reduced coarse-aggregate size has been beneficial, but D-cracking persists and is still a problem in terms of required early maintenance and service life.

Missouri will continue to investigate possible beneficiation processes when D-cracking-susceptible aggregates are used. However, the processes must be effective in terms of material costs, reduced maintenance, and increased service life. Missouri will continue to express interest in the efforts of other organizations to successfully eliminate or significantly reduce the rate of deterioration of PCC pavements.

ACKNOWLEDGMENT

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Efforts to Eliminate D-Cracking in Illinois

MARVIN L. TRAYLOR

Severe D-cracking on Interstate pavements prompted the Illinois Department of Transportation to initiate a program to identify and eliminate the use of D-cracking aggregate. More than 200 crushed-stone and gravel sources were evaluated by using both the Iowa pore index and ASTM C-666 freeze-thaw tests. Shortcomings in the Iowa pore index test have resulted in its use being limited to a screening test. The results of the freeze-thaw program have formed the basis for a specification that the state believes will guarantee the durability of future pavements.

D-cracking had been observed for years in Illinois but had not been considered a serious problem until 1978. In that year, two sections of D-cracked Interstate pavement had deteriorated seriously and required immediate rehabilitation. One section, 9 miles long and 10 years old, received a 5-in bituminous overlay, and the other section, 8 miles long and 11 years old, received a 6-in bituminous overlay. Both sections were continuously reinforced concrete pavement, designed for a 20-year life. As a result of these failures, the Illinois Department of Transportation (DOT) initiated a program to identify and eliminate the use of D-cracking aggregate.

BACKGROUND INVESTIGATION

The first step in the investigation was a review of the technical literature on D-cracking. The literature review, combined with visits to the University of Illinois, the Portland Cement Association (PCA) Laboratories, and the Iowa DOT, provided the Illinois DOT with some basic knowledge of the D-cracking problem. The following items summarize the principal findings:

1. The coarse aggregate is responsible for D-cracking, and sedimentary aggregates are the most susceptible. Once the distress is initiated, it cannot be stopped.
2. Fine aggregates, cement type, drainage systems, and type of subbase have no significant effect on the occurrence of D-cracking.
3. The distress is a result of freeze-thaw stresses, and serious deterioration may occur even without traffic loading.
4. The pore structure of the aggregate is thought to be the characteristic that determines the degree of susceptibility.
5. Removal of moisture or prevention of freezing and thawing would eliminate D-cracking. Neither has been accomplished economically in the field.
6. Reducing the top size of the coarse aggregate lessens the rate of D-cracking and may eliminate the problem altogether with marginal aggregate.
7. A laboratory freeze-thaw test developed by PCA has been successful in predicting the susceptibility of aggregate to D-cracking.
8. A rapid evaluation of D-cracking susceptibility (the Iowa pore index test) has been developed by the Iowa DOT.

Since the only known means of controlling D-cracking was the elimination of susceptible aggregate, a program was established to identify the degree to which the various aggregate sources in Illinois were vulnerable to the distress. Both the PCA freeze-thaw procedure and the Iowa pore index test were selected for use in the evaluation. In January 1979, the necessary equipment for both tests was ordered. At the same time, based on the knowledge that top-size reduction often improved aggregate performance, Illinois issued its first D-cracking specification, which restricted all concrete paving aggregate to a maximum top size of 1 in. (Previously, 1.5-in top-size material had been the standard paving aggregate.) The Illinois DOT realized that this first specification was needlessly restrictive for some aggregates and not severe enough for others. However, because of the state's inability to differentiate between durable and nondurable aggregates, it was a necessary safeguard.

FIELD PERFORMANCE SURVEY

While the necessary equipment for the laboratory