continue to express interest in the efforts of other organizations to successfully eliminate or significantly reduce the rate of deterioration of PCC pavements.

ACKNOWLEDGMENT

The opinions, findings, and conclusions expressed in this paper are those of the Missouri Highway and Transportation Department.

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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:

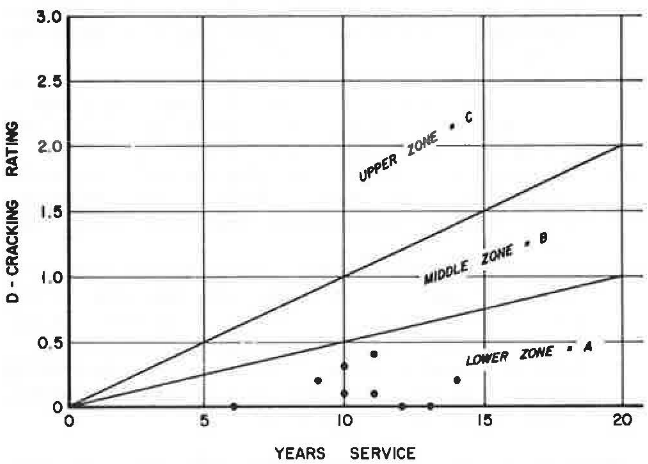
1. The coarse aggregate is responsible for D-cracking, and sedimentary aggregates are the most susceptible. Once the distress is initiated, it cannot be stopped.
2. Fine aggregates, cement type, drainage systems, and type of subbase have no significant effect on the occurrence of D-cracking.
3. The distress 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

Figure 1. Performance plot for an aggregate source.



testing program was being acquired, a statewide survey was scheduled to determine the extent and severity of D-cracking. A simple rating scale of zero (no D-cracking) to three (severe D-cracking) was used. Photographs depicting the distress in various stages of development were used to standardize the rating. The survey covered more than 3000 miles of pavement and showed that D-cracking was present in all areas of the state. Only 42 percent of the mileage surveyed was free of D-cracking. Forty percent had low-level D-cracking, 12 percent had intermediate-level D-cracking, and 6 percent was severely D-cracked.

In addition to assigning present condition ratings, the construction records for each mile of pavement were retrieved and the following information was compiled by construction sections: (a) location (county, route, and station limits), (b) length, (c) year built, (d) concrete thickness, (e) pavement type (jointed or continuously reinforced), (f) subbase type and thickness, (g) subsurface drainage type, and (h) coarse-aggregate source.

Since D-cracking is a progressive distress, a means of tempering current condition with the age of the pavement was needed before an evaluation could be made of the aggregate's performance. The fact that each construction section used a single source for the coarse aggregate, so that there was a uniform degree of distress throughout the section, made this task quite simple. First, the condition ratings for each mile of pavement within a construction section were averaged. This value was used to represent the condition of the entire section. Next, all construction sections containing the same coarse aggregate were grouped and a plot for each source was developed, as shown in Figure 1. Each dot on the graph represents one construction section (normally 5-10 miles of pavement).

Plots such as the one shown in Figure 1 were used to assign each aggregate source a field performance rating. If the majority of the construction sections fell in the lower zone, indicating very little D-cracking had developed in their 20-year design life, the source received an A-rating. If the majority of the construction sections fell in the middle zone, the aggregate was considered marginal and given a B-rating. Finally, if the majority of the sections fell in the upper zone, the aggregate source was considered unsatisfactory and given a C-rating. The example shown in Figure 1 received an A-rating.

The field survey, record search, and data analysis were completed by March 1979. Forty crushed-stone (limestone and dolomite) and 31 gravel sources had been rated. Some sources had been used in as many as 25 construction sections, whereas others appeared only once. The relative performance of the two classes of aggregates is indicated in the table below:

Aggregate Class	No. of Sources Receiving Rating A	B	C	Total
Crushed stone	25	11	4	40
Gravel	14	8	9	31

In addition to providing performance ratings, the survey revealed the following:

1. Because of its closely spaced shrinkage cracks, continuously reinforced concrete pavement was much more vulnerable to D-cracking than was jointed pavement.
2. Type of subbase, traffic, or drainage appeared to have had no significant effect on the behavior of the coarse aggregate.

IOWA PORE INDEX PROGRAM

In April 1979, the necessary equipment for the Iowa pore index test was in place and samples from aggregate sources had been gathered for testing. Illinois has roughly 400 crushed-stone and 600 gravel sources, but only 82 crushed-stone and 70 gravel sources are qualified for concrete aggregate. The other sources have been rejected on the basis of Los Angeles abrasion, $NaSO_4$ soundness, or deleterious count. The D-cracking program would test only those sources that had passed these normal quality tests and were currently qualified as concrete aggregate.

The Iowa pore index test measures certain characteristics of an aggregate's pore structure. Twenty-two pounds of washed, oven-dried aggregate (0.75x0.5 in) is placed in the bottom of an air-entrainment pot. The top of the pot has been modified to hold a clear plastic tube calibrated in cubic centimeters. The bottom of the tube is open to the inside of the pot, and the top is connected to a source of air pressure. After the top assembly has been securely fastened in place, water is introduced into the bottom of the pot. The water first fills the spaces among the aggregates and then rises to an established mark on the tube. The system is then sealed and 35 lb of air pressure is applied. This increase in pressure forces the water into the pores of the aggregate, causing the column of water to fall, rapidly at first, and then slowly stabilize (see Figure 2). The height of water in the tube is observed, and readings are taken after 30 s, 1, 2, 5, 10, and 15 min. The pore index is the volume of water (in cubic centimeters) that is forced into the aggregate during the time interval from 1 to 15 min after the air pressure is activated. A high pore index is supposed to indicate a nondurable aggregate.

By June 1979, all concrete aggregate sources in Illinois had been evaluated by use of the Iowa pore index test. The process was found to be fast and economical, and the results were easy to reproduce. Indices ranged from a low of 6 to a high of 150. An attempt was then made to correlate the field performance ratings with the results of the Iowa pore index test. The number of sources available for correlation was limited because many of the sources whose performance had been rated were no longer producing aggregate and many of the current sources had no field performance rating. However, 15 crushed-stone and 9 gravel sources were available for correlation. The geologic differences between gravels and crushed stones suggested that the corre-

Figure 2. Pore index determination.

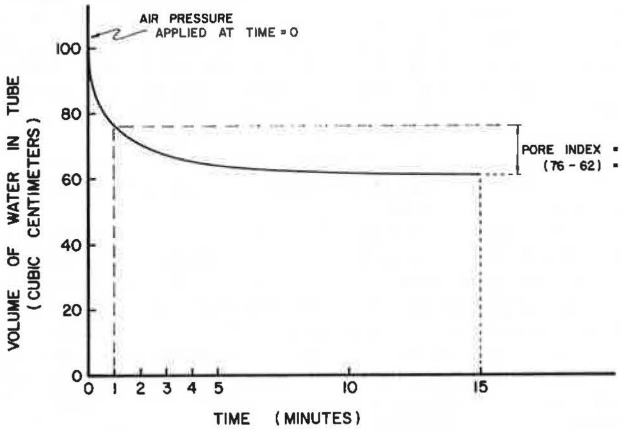
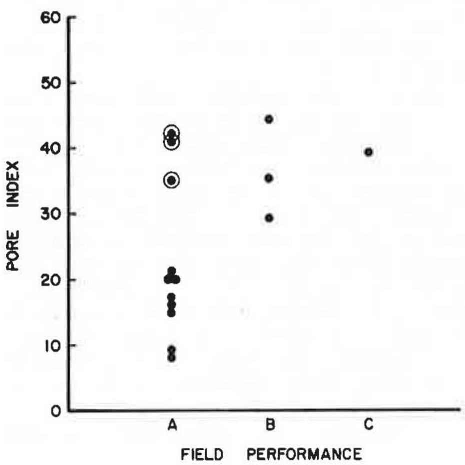


Figure 3. Pore index versus field performance.



lation be analyzed separately.

Crushed Stone

A plot of the Iowa pore index values versus field performance rating is shown in Figure 3. Although the data are limited, a trend can be identified. Lower values from the Iowa pore index test are associated with good field performance, and high pore indices are associated with poor field performance. However, three points (circled on the plot) appear to be contrary to this trend. Pavements built over the past 20 years with these three aggregates have shown little evidence of D-cracking, yet the pore indices for the current production ledges are extremely high. There are two possible explanations of this fact: Either (a) the pore index test is not an accurate indicator, or (b) the aggregate that is being produced now is of lesser quality than that used in the surveyed pavements.

Gravel

A plot of pore index versus field performance for gravels did not indicate any discernible trends, and the test was discontinued for gravels.

Based on the early results of the pore index testing in June 1979, the Illinois DOT developed and released its second specification aimed at eliminating D-cracking aggregate. The major points of this specification were the following:

1. Crushed-stone top size was controlled by the Iowa pore index, as shown below:

Pore Index	Top Size (in)
0-25	1.5
26-35	1
>35	0.75

2. Because the Iowa pore index test was not effective for gravel and gravel had generally demonstrated poor performance, gravel top size was restricted to 0.75 in.

There were some obvious problems with using the Iowa pore index test for predicting performance. They were as follows:

1. Although the correlation between the pore index and performance showed promise for crushed stone, there were several sources with high pore indices that had excellent performance histories.
2. The test did not appear useful for gravels.
3. The test could not indicate to what extent a reduction in top size would improve performance.

In spite of these shortcomings, the Illinois DOT felt that this new specification was a step closer to identifying the problem aggregates and imposing restrictions only where warranted. However, because of questions concerning the validity of the test, no aggregate sources were rejected. The specification was considered temporary until more data were available.

FREEZE-THAW TESTING

By July 1979, the Illinois DOT's two new freeze-thaw cabinets were operational. They were custom built by a local manufacturer to meet ASTM C-666 requirements. Cycles are controlled by programmable modules that use a step function to approximate the desired rise and fall rates for temperature. Once programmed, all functions are completely automatic and require no operator. The modules also constantly record the temperature at several locations inside the cabinets on both circular charts and digital printout tapes.

Although the equipment is sophisticated, the test is quite simple in principle. The aggregate is cast in a concrete beam that is cured, measured, subjected to a series of freeze-thaw cycles, and remeasured. A small increase in length indicates a durable aggregate, and a large increase indicates a nondurable aggregate. The following paragraphs give a general description of the test procedures. The actual test specifications can be obtained from the author.

A sample of the aggregate is obtained from stockpiles at the source, separated over a nest of sieves, and recombined to a standard laboratory gradation. It is then batched, by using a standard cement, sand, and air-entraining agent. The resulting concrete is formed into three 3x4x15-in beams, cured for two weeks, brought to 73°F, and measured to establish initial lengths.

The beams are placed in the freeze-thaw cabinets and exposed to eight freeze-thaw cycles (0°-40°F) each day. Water covers the beams during the thawing phase but is evacuated during the freezing phase of each cycle. The actual cycle is shown in Figure 4. A complete test consists of 350 freeze-thaw cycles.

Periodically, the beams are removed from the cabinets, warmed to 73°F, and measured. After each measurement, the length change, expressed as a percentage of the original length, is calculated and plotted. Total time for the test, including the 14

days for curing, is approximately nine weeks. Figure 5 shows the test results for two sources. Group 1, with the lower expansions, is superior to group 2.

After several weeks of equipment shakedown, the first freeze-thaw tests were scheduled during August 1980. The first sources tested were selected to represent the full range of field performance. Both crushed stones and gravels were included. The initial results were encouraging for both types of aggregate. Those with excellent field performance showed almost no increase in length (<0.005 percent). Those with marginal performance records lengthened 0.06-0.15 percent. Those with poor field performance had expansion in excess of 0.20 percent. The test appeared to have performed as well for gravels as for crushed stones. Since the early results showed such promise, the program proceeded with a goal of testing every source of concrete aggregate in the state.

In the early stages of testing, each source was evaluated in at least three different gradations (1.5-, 1-, and 0.75-in top sizes). The improvement that resulted from reducing top size for one limestone source is dramatically shown in Figure 6. However, since each test took nine weeks to complete and the objective was to stop the placement of susceptible aggregates in pavements as soon as possible, the program was soon streamlined. The 1.5-in top-size gradation was tested first. If this gradation passed the expansion criteria (established at 0.06 percent after 350 cycles), smaller gradations were not tested. However, if the largest gradation failed, successively smaller top-size gradations (down to 0.75 in) were tested until the expansion criteria were met.

Many of the crushed-stone quarries have more than one production ledge. Since early testing with the pore index had indicated that significant variability could exist between two ledges in the same quarry, each production ledge of each source was identified and tested separately. The 82 quarries contained a total of 137 separate production ledges. With the additional 70 gravel pits, 207 sources had to be evaluated, several in more than one gradation.

By June 1981, all sources had been evaluated. Each gravel pit and each production ledge of each quarry received a rating that indicated the maximum top-size material they could produce (1.5, 1, or 0.75 in).

The following observations were made during testing:

1. The two freeze-thaw cabinets could be used interchangeably with no significant effect on results.
2. The rate of expansion during the 350-cycle test was quite uniform, which suggested that the number of cycles could be reduced.
3. The three replicate beams for each crushed-stone source behaved very similarly. The variability among the beams was quite small even when total expansion was high.
4. The effect of top-size reduction for crushed stone was reflected in the freeze-thaw plots. The degree of improvement varied from source to source. One source had to be reduced to 0.25-in top size before passing the expansion criteria.
5. Many of the limestone quarries received different ratings for separate production ledges.
6. All dolomites (Illinois classifies carbonates with ≥11.0 percent MgO as dolomites) passed the freeze-thaw criteria at the 1.5-in top size.
7. The three quarries that had good field performance but high pore indices passed the freeze-thaw test in the 1.5-in top size.
8. Triplicate beams cast from a single gravel sample showed considerable variability.
9. Reducing the top size of gravels did not always reduce expansions.
10. An occasional large piece of chert or limonite sometimes caused one of the gravel beams to expand rapidly and eventually break while the two remaining beams showed only moderate expansion.

Figure 4. Freeze-thaw cycles.

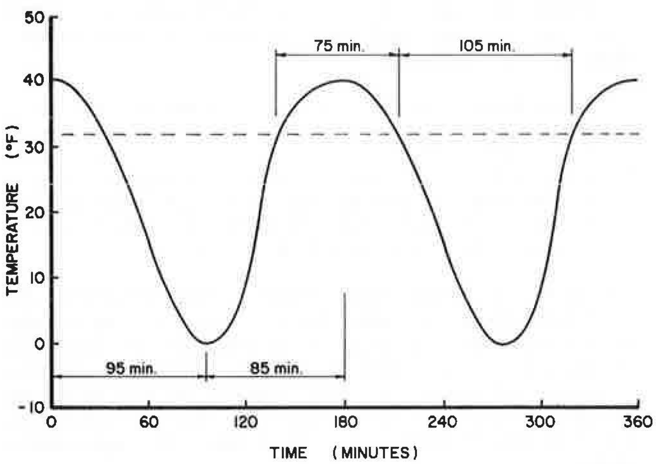


Figure 5. Typical freeze-thaw test results.

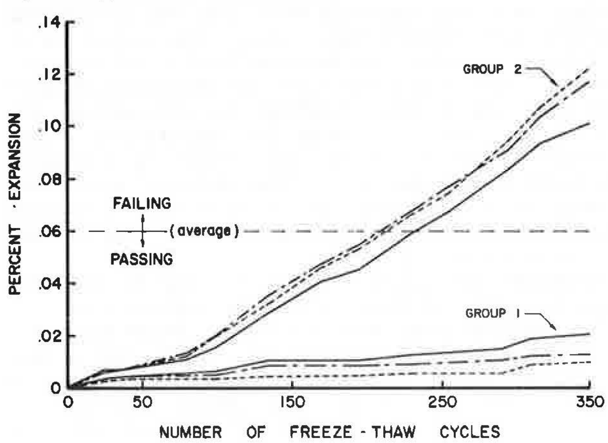
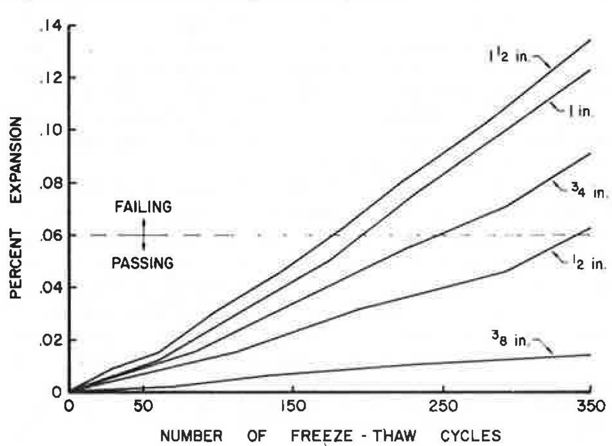


Figure 6. Effect of reduced top size on expansion.



A comparison of average expansion (for 1-in top-size gradation) versus field performance is shown in Figure 7. This plot displays the same sources that were used in Figure 3. Comparison of Figures 3 and 7 indicates that the freeze-thaw test produced the better correlation. A plot of freeze-thaw expansion (for 1-in top-size gradation) versus pore index is shown in Figure 8. This figure indicates the lack of agreement between the two tests. It does show, however, that all crushed stones with a pore index of 18 or less passed the freeze-thaw test, which suggests that the Iowa pore index may be useful as a screening test.

D-CRACKING SPECIFICATION

In July 1981, the Illinois DOT issued the third version of its D-cracking specification. The Iowa pore index test was replaced by the freeze-thaw test. Each aggregate source was permitted to produce material with a top size up to the rating received from the freeze-thaw test. If the material had not passed the expansion criteria when tested in the 0.75-in top size, it was no longer allowed for concrete pavement. The effect this specification had on the Illinois aggregate industry is shown below (the quarries with more than one rating are shown under the largest top-size rating they received):

Aggregate Class	No. of Sources Receiving Rating				
	Top Size (in)				
	1.5	1	0.75	Rejected	Total
Crushed stone	65	9	4	4	82
Gravel	12	11	27	20	70

Figure 7. Freeze-thaw results versus field performance.

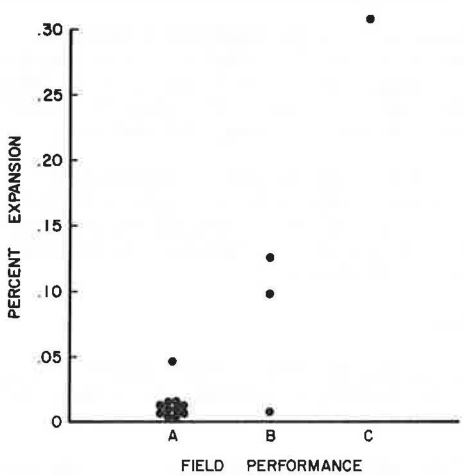


Figure 8. Freeze-thaw results versus pore index.

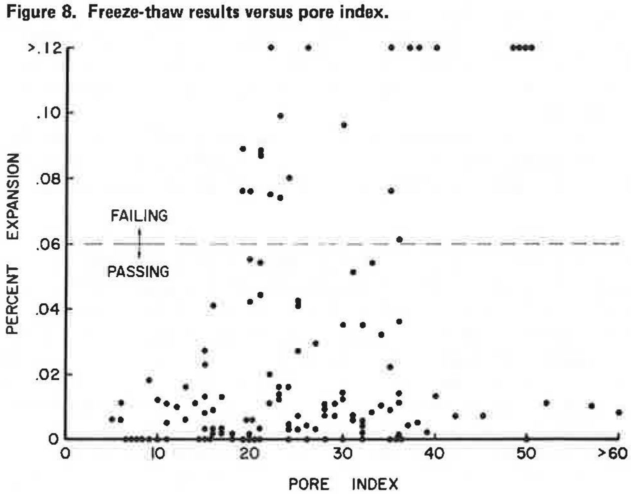


Figure 9. Effect of freeze-thaw specification on Illinois crushed-stone producers.

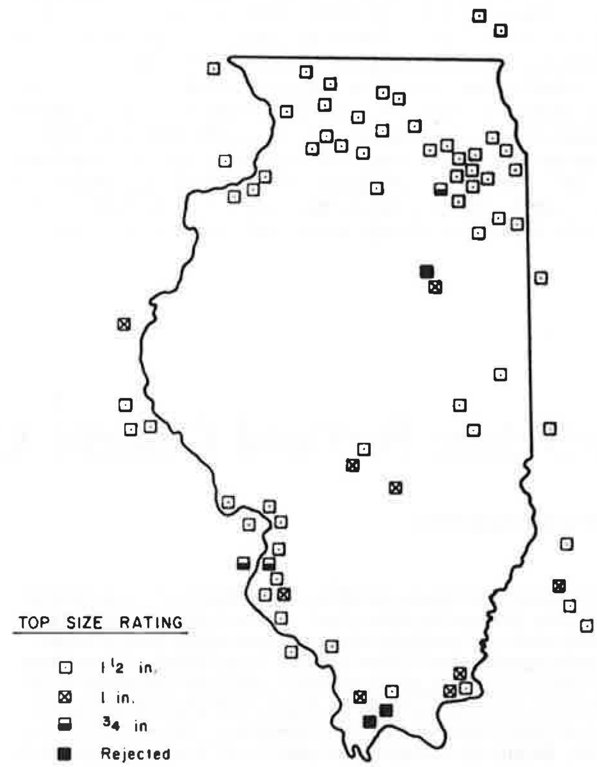
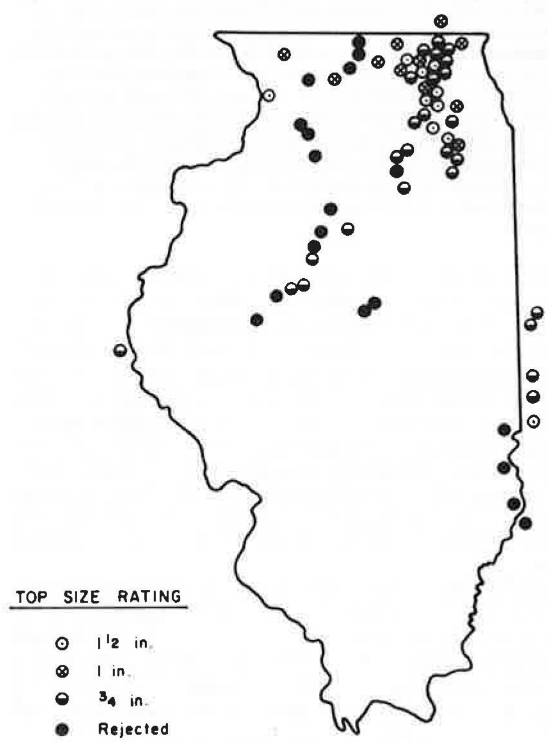


Figure 10. Effect of freeze-thaw specification on Illinois gravel producers.



The maps shown in Figures 9 and 10 indicate the geographic impact of this rating system.

After all sources had been rated and the freeze-thaw specification established, a second round of testing was started. For crushed stones, agreement with the initial results has been excellent. However, for gravels, especially those with moderate to high expansion, differences between the initial and follow-up tests were quite pronounced. The problem has been attributed to the extreme variability within the gravel deposits themselves. Obtaining samples that are "representative" is extremely difficult, and pronouncing judgment on the basis of one freeze-thaw test has proved inadequate. Therefore, numerous samples will be taken from production throughout the next year, after which the additional freeze-thaw results will be analyzed and new ratings will be issued. The Iowa pore index, although no longer used as an acceptance test, has proved to be an effective screening test and is still used to determine when a crushed-stone deposit has changed, which makes it necessary to do additional freeze-thaw testing.

The current freeze-thaw specification should eliminate the use of D-cracking aggregates in construction. The freeze-thaw test, although expensive and time-consuming, has proved to be extremely versatile. Since it can be used to evaluate any type of aggregate, each source can be judged by its performance rather than its geologic origin or geographic location.

Although the test is now being used to evaluate routinely processed aggregates, it can also be used to evaluate aggregate improvement techniques. The effectiveness of reduced top size, heavy media, new crushing processes, or additives can be judged by comparing freeze-thaw plots before and after treatment.

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Recycling Portland Cement Concrete Pavement

ANDREW D. HALVERSON

Quality aggregates for highway construction are in short supply in many parts of Minnesota. Although the current total supply is adequate, the distribution of sources results in localized shortages. It is sometimes necessary to import high-quality aggregates from distant locations. Haul distances can increase aggregate prices substantially, add to the overall project cost, and require the expenditure of sizable amounts of energy. One available source of aggregate is existing portland cement concrete (PCC) pavement currently in need of reconstruction. Reusing this aggregate would result in cost savings in aggregate-short areas, conserve natural resources, and conserve energy in the form of fuel savings when aggregates must be acquired from distant sources. A research study is described that was undertaken to determine the feasibility of recycling PCC pavement, evaluate the new recycled pavement, determine the cost-effectiveness of recycling versus conventional paving, and determine the amount of energy consumed and natural resources conserved. Economic and engineering factors led to the selection of a 16-mile segment of US-59 from Worthington to Fulda in southwestern Minnesota for the study. The in-place roadway, which was constructed in 1955 and consisted of 9-, 7-, 9-in-thick, 24-ft-wide, nonreinforced, D-cracked concrete pavement with soil shoulders, was broken, salvaged, and crushed. Material passing the no. 4 sieve was used for base stabilization and shoulder aggregate, and material retained on the no. 4 sieve but passing the 0.75-in sieve was used as the coarse aggregate for concrete paving. The project results are evaluated based on pavement performance and energy and cost comparisons.

High-quality aggregates for use in highway construction are in short supply in many parts of the country, including portions of Minnesota. Although the total supply is adequate to meet the country's needs, the distribution of sources is such that many local areas experience shortages. In these areas, it is often necessary to import high-quality aggregates from distant locations. Depending on the length of haul, aggregate prices can increase substantially and add significantly to the total project costs. In addition, sizable quantities of energy are expended in the form of fuel for hauling vehicles.

One available source of high-quality aggregates in aggregate-short areas is the many pavements in need of reconstruction. Some of these pavements have exceeded their design life and have failed due to overuse, some have simply become geometrically outdated, and others are exhibiting some form of premature distress due to inadequate design, use of marginal materials, or poor construction practices.

Many of these roads still contain durable aggregates. Reusing these aggregates would not only conserve natural resources but, in aggregate-short areas, could also result in energy and construction cost savings.

In November 1980, the Minnesota Department of Transportation (DOT) completed a major recycling project. That project can be discussed in terms of three distinct activities: selection, experimental work, and project evaluation.

PROJECT SELECTION

In September 1976, during the initial search for a recycling project, candidate projects were selected on the basis of several criteria:

1. The roadway should have adequate vertical and horizontal alignment to preclude extensive regrading.
2. The existing right-of-way should be sufficient to allow reconstruction without further land acquisition. The existing roadway should be in such an advanced state of deterioration that the reconstruction is either programmed or imminent, and the project should be located in an area of aggregate scarcity.
3. If the existing pavement is rigid, it should be nonreinforced; if it is flexible, it should be thick enough to minimize new material requirements.

In 1977, a 16-mile segment of US-59 in southwestern Minnesota was selected for a recycling project. The existing roadway had been constructed in 1955, and was a 9-, 7-, 9-in-thick, 24-ft-wide, nonreinforced concrete pavement with soil shoulders. The pavement had been placed on a minimum of 3 in of gravel base, which in turn had been placed over an in-place bituminous surface. The roadway exhibited no frost heaves, but the pavement exhibited extensive D-cracking, a series of crescent-shaped cracks on the pavement surface that usually start at the