# Durability of Concrete and the Iowa Pore Index Test

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**An overview of the problem of D-cracking in portland cement concrete (PCC) is provided, and the Iowa pore index test for determining the quality of coarse aggregate for concrete is evaluated. The Iowa pore index test was developed to evaluate the durability of coarse aggregate. The test measures the amount of water that can be injected into oven-dried aggregate during a period from 1 to 15 min after application of 35 psi (241 kPa) of pressure. The test is very effective in identifying aggregates with substantial pore system of the 0.04- to 0.2-μm-diameter size and correlates very well with aggregate service records. Test results of nonhomogeneous samples can be misleading. Laboratory tests have shown that a small amount (15 percent) of unsound material in the coarse aggregate can produce nondurable concrete. Studies with the scanning electron microscope show that coarse aggregates associated with D-cracking are normally fine grained whereas durable aggregate is either coarse grained or extremely fine grained. The pore-size distribution of coarse aggregates was determined by using a mercury porosimeter. Aggregates associated with D-cracking exhibit a predominance of 0.04- to 0.2-μm-diameter pore sizes.**

Very simply, durability is the quality of being able to last. In portland cement concrete (PCC), design, materials, mix proportion, and construction practices are factors that affect durability. The life of PCC pavement is becoming more important due to the severe shortage of highway funds. The only factor to be considered in this paper is the quality of the coarse aggregate. All references to durability relate to the effect of the coarse aggregate and, more specifically, to D-cracking.

D-cracking (see Figures 1 and 2), a type of PCC pavement deterioration attributed to the coarse aggregate in the mixture, was first recognized on Iowa's primary road system in the late 1930s. The term D-cracking dates back to the 1930s and was used in reference to deterioration characterized by the appearance of fine, parallel cracks along joints, random cracks, or free edges of the pavement slab (1). Generally, the first signs of D-cracking are a discoloration or staining at the intersection of the transverse and longitudinal joints.

The Portland Cement Association (PCA) has conducted extensive research on the D-cracking problem. The PCA research has shown that essentially all aggregates that contribute to D-cracking are of sedimentary origin and of both carbonate and silicate composition. These range from essentially pure limestone to dolomite (2). This research has further established that D-cracking in Iowa is a distress that results from freeze-thaw failure in the coarse-aggregate particles.

There are variations between bedded layers, but in general the limestones of southwestern Iowa result in severe D-cracking at a relatively early pavement age. There are many limestone and dolomite beds in northeastern Iowa that have service records of 30 years without any signs of D-cracking. Evidence of D-cracking can appear in as few as three years (3).

## OBJECTIVE

The objective of this paper is to provide an overview of the PCC D-cracking problem and an evaluation of the pore index test for determining the quality of coarse aggregate for concrete.

## IDENTIFICATION OF PAVEMENT DETERIORATION

Iowa, like many other states, was reluctant at one time to identify pavement deterioration as D-cracking. In the 1960s, severe D-cracking was recognized on major primary pavements. This precipitated an extensive condition inventory of all PCC pavement that has continued to the present.

D-cracking has resulted in rapid failure of the pavement; therefore, any rapid deterioration of originally sound concrete has generally been identified as D-cracking. There have been a few incidents of rapid pavement failure in Iowa in which the entire slab developed crack patterns that, although generally identified as D-cracking, did not exhibit the typical distress progression. This leads to the consideration that there may be other modes of rapid failure not yet identified by research. There is some evidence that the use of deicing salts may accelerate the D-cracking process.

## EVALUATION OF COARSE AGGREGATE

### Soundness Test

The basic Iowa Department of Transportation (DOT)

Figure 1. Pavement exhibiting severe D-cracking deterioration.

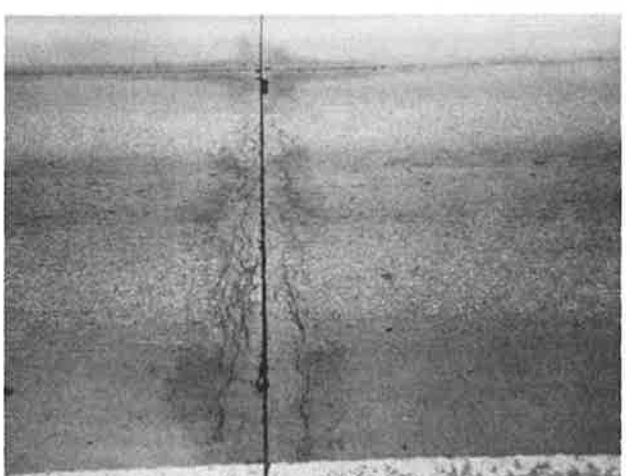


Figure 2. Close-up of D-cracking at intersection of transverse and longitudinal joints.

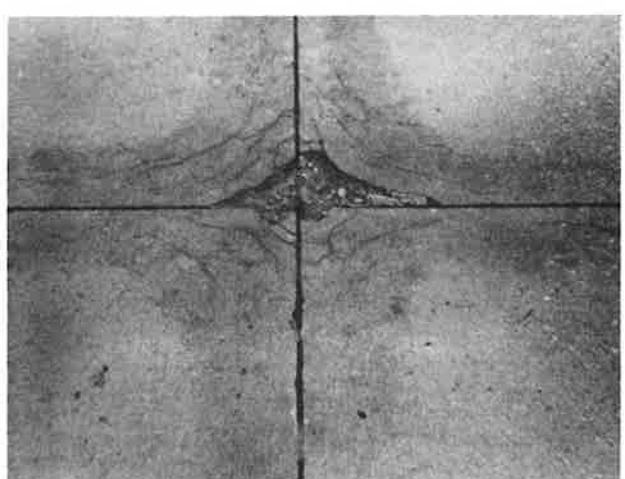


**Table 1. Coarse-aggregate data.**

| Aggregate No. | Producer | Location | Bed(s) | Aggregate Composition | Grain Size | Service Record | Specific Gravity | Absorption (%) | Freeze-Thaw Loss[a] (%) | Durability Factor[b] | Pore Index (mL) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Weaver | Alden, IA | 3 | Limestone | Very coarse | Excellent | 2.58 | 2.8 | 2 | 95 | 13 |
| 2 | Niemann | Lamont, IA | 1-7 | Dolomite | Very coarse | Excellent | 2.70 | 1.8 | 2 | 96 | 19 |
| 3 | Niemann | Festina, IA | 1-4 | Dolomite | ? | Very good | 2.69 | 0.4 | 1 | 96 | 7 |
| 4 | Cessford | Farmington, IA | 3 | Argillaceous limestone | Very fine | Very good | 2.69 | 0.5 | 8 | 95 | 21 |
| 5 | Western material | Kankakee, IL | A | Argillaceous dolomite | Coarse | Very good | 2.73 | 0.8 | 7 | 99 | 44 |
| 6 | Anderson | Montour, IA | 1-7 | Oolitic limestone | Medium | Good | 2.61 | 2.0 | 2 | 75 | 18 |
| 7 | Green | Floyd, IA (Warnholtz) | 17D | Argillaceous limestone | Very fine | NA | 2.70 | 2.0 | 7 | 97 | 83 |
| 8 | Green | Floyd, IA (Warnholtz) | 18 | Argillaceous dolomite | Fine | NA | 2.70 | 1.8 | 7 | 93 | 65 |
| 9 | Columbia | Ullin, IL | NA | Limestone | Medium | D-cracking | 2.67 | 0.9 | 1 | 17 | 48 |
| 10 | Alpha | Prairieburg, IA (Plower) | 4 | Dolomite | Fine | Severe D-cracking | 2.62 | 3.9 | 2 | 21 | 95 |
| 11 | Martin Marietta | Waterloo, IA (South) | 17-18 | Limestone | Medium | Severe D-cracking | 2.66 | 2.0 | 1 | 71 | 44 |
| 12 | Schildberg | Crescent, IA | 25 | Limestone | Fine | Severe D-cracking | 2.65 | 1.2 | 2 | 48 | 42 |
| 13[c] | Green | Floyd, IA (Warnholtz) | 16 | Very argillaceous limestone | Fine | NA | NA | NA | 31 | NA | 120 |
| 14[c] | – | – | – | Tripolitic chert | Fine | – | 2.49 | 4.4 | – | – | 82 |
| 15[c] | – | – | – | Dense chert | Very fine | – | – | – | – | – | 14 |

[a] Method A.
[b] ASTM C666 method B.
[c] Selected fractions.

"Coarse Aggregate for Concrete" soundness test is a 16-cycle (9-cycle/day) water-alcohol "method A" freeze-and-thaw test that, except for automation, remains essentially as adopted in the 1948 Standard Specifications. An aggregate sample retained on the no. 4 (0.48-cm) sieve is subjected to alternate freezing [2 h to -15°F (-26°C)] and thawing [40 min to 70°F (21°C)] in a 0.5 percent methyl alcohol solution. The percentage passing the no. 8 (0.24-cm) sieve after 16 cycles is reported as loss. The maximum loss of 6 percent allowed by specification has remained unchanged since 1948.

Until the general recognition of D-cracking, this method A freeze-and-thaw test, as referred to by the Iowa DOT, was accepted as the main criterion for the exclusion of coarse aggregates that would contribute to nondurable concrete. Service records have identified concrete that exhibited D-cracking of varying severity and that contained aggregate that had passed the method A freeze-and-thaw test.

It is apparent from a more critical analysis of the method A freeze-and-thaw test that it excludes coarse aggregate primarily on the basis of the amount of shale, clay, and tripolitic chert. In the past, it has been generally accepted that these materials are detrimental to the quality of concrete. The method A freeze-and-thaw test relates to petrography and in general restricts the acceptance of coarse aggregate to materials containing less than 5 percent shale, clay, or tripolitic chert.

## Durability Test

Research on the rapid freeze-and-thaw test of concrete beams was initiated in 1962. The procedure used was essentially that described in ASTM C291 (now ASTM C666 method B) for freezing in air and thawing in water. Various preparation or curing treatments were tested, and it was determined that a 90-day cure in the moist room was necessary to ensure "critical" saturation and allow completion of the major portion of the cement hydration to yield the maximum display of subsequent distress of concrete containing nondurable aggregate. After several years of investigation proved that laboratory freeze-and-thaw results correlated well with service records, this test was incorporated into the 1972 Standard Specifications for quarry approval prior to acceptance of coarse aggregate. Both the dynamic modulus and the growth are recorded, and the durability factor at 300 cycles is calculated from the dynamic modulus (see Table 1).

Even though the modified ASTM C666 method B correlates well, there are undesirable features. Concrete beams measuring 4x4x18 in (10.16x10.16x45.72 cm) and made from aggregates with satisfactory service records may fail (durability factor less than 80 percent) if small amounts of deleterious materials (such as tripolitic chert) are present in the aggregate. With a 90-day moist preparation and 38 days (8 cycles/day) for the test, it takes nearly five months to complete the aggregate evaluation.

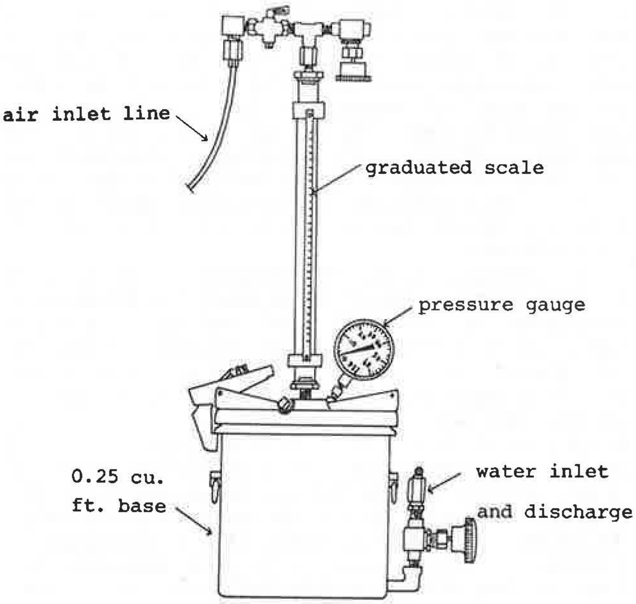
## Other Tests

The Iowa DOT has investigated the use of the absorption-adsorption test to determine the quality of aggregate, and the test was found to be overly restrictive for Iowa aggregates. Aggregates with satisfactory service records would fail the test. Iowa studies of sodium sulphate and magnesium sulphate tests resulted in poor correlation with the aggregate service records.

## DEVELOPMENT OF IOWA PORE INDEX TEST

Recognizing that the D-cracking problem was freeze and thaw related (1), and more specifically related to pore sizes (3), Dubberke began investigations of measuring the amounts of water, under low air pressure, that could be injected into oven-dried aggregate. A Washington Press-Ur-Meter (used to measure entrained air in PCC) was modified for use in the test (see Figure 3). During development of the pore

Figure 3. Pore index test apparatus.




index test (4), pressures ranging from 10 to 60 psi (69-414 kPa) were applied while the incremental amount of water injected into the aggregate during a 2-h period was recorded. This early testing indicated that any pressure in this range could be used by selecting the appropriate corresponding time (a lower pressure requires a longer time). High pressures with some aggregates resulted in such a rapid lowering of the water that accurate manual readings at the beginning of the test were very difficult to obtain. With a pressure of 35 psi (241 kPa), all necessary water-injection information was obtained in 15 min and manual readings could be obtained with adequate reliability.

## PORE INDEX TEST APPARATUS AND PROCEDURE

### Test Unit Apparatus

A modified Press-Ur-Meter is used to perform the pore index test. The pump, valve, and gauge were removed from the lid and replaced by a 320-mL plexiglas tube, graduated by 2-mL increments. The addition of a standard 60-psi (414-kPa) pressure gauge completes the lid modifications. A hole drilled through the side of the pot at the bottom and fitted with a valve is used for loading and unloading the pot with cold tap water. Two valves are located at the top of the plexiglas tube. One valve is connected to a line that supplies air at a constant 35 psi (241 kPa). The other valve is a vent valve and is opened while the unit is being charged with water.

### Test Procedure

1. Place 9000 g (minimum of 4500 g) of oven-dried, 0.5x0.75-in (1.27x1.91-cm) aggregate in the pot. During the evaluation phase of the pore index test, samples ranging from 3000 to 10 000 g were accepted for testing. Since the secondary load (pore index test result) is directly proportional to the size of the sample, values were adjusted to reflect a projected 9000-g sample. Many of the adjusted test results were from small samples received from the districts, but in a few cases half-samples were necessary because of high absorption. If the capacity of the 320-mL tube is exceeded during the test, the test is rerun with a 4500-g sample.
2. Attach the lid, open the vent valve, and fill the base and plexiglas tube with cold tap water to the 0-mL mark. The pressure gauge on the lid must remain at the zero pressure mark during this filling stage.
3. Close the water supply and vent valves and then open the 35-psi (241-kPa) air supply valve as soon as possible. The air valve remains open throughout the duration of the test.
4. Take a water-level reading at 1 min. The amount of water injected during this first minute fills the aggregate's macropores and is referred to as the primary load. A large primary load is considered to be an indication of a beneficial limestone property. A well-developed macropore system may function in a manner similar to air-entrainment voids in concrete paste. The primary load is not used in calculations of the pore index test result.
5. Take a water level reading at 15 min. The volume of water injected between 1 and 15 min is the secondary load and represents the amount of water injected into the aggregate's micropore system. A secondary load of 27 mL or more indicates a negative limestone property that correlates with a saturated aggregate's incapacity to withstand internal pressures caused by freezing. The secondary load in milliliters is reported out as the final pore index test result.

## PORE INDEX CORRELATION

Routine aggregate testing began in 1978. The pore index was determined for aggregates from 28 different sources. These were compared with the service record and the ASTM C666 method B concrete durability results. The pore index test correlated very well. Aggregates with a history of producing D-cracking concrete consistently yielded indices greater than 27 mL. There were a few tests that did not initially appear to correlate with service record. Further investigation of these samples revealed variations in material and verified the pore index results.

## NONHOMOGENEOUS COARSE AGGREGATE

Possibly the major problem in developing a reliable test to identify coarse aggregate that causes D-cracking is the variation in both the composition and the structure of the material. Stark of PCA (2) notes that "nearly all rock types known to be associated with D-cracking are of sedimentary origin" and "materials of igneous origin are not known to be associated with D-cracking." River gravels are probably the best example of nonuniform composition. In Iowa, gravel deposits can have from 30 to 80 percent particles of igneous origin. The remaining 20-70 percent are predominately limestone and dolomite particles, but Iowa gravels may contain from 1 to 10 percent deleterious particles such as shale, siltstone, chert, and iron oxides. Samples from gravel deposits have been manually separated, and laboratory freeze-and-thaw testing (ASTM C666 method B) of the igneous fraction has yielded excellent durability factors. The capacity of a gravel to produce durable concrete depends on the carbonate fraction. Where the carbonate fraction was nondurable, D-cracking has been identified in as few as eight years.

Even though it is not readily apparent to the casual observer, both the composition and the structure of carbonates can exhibit extreme variations. The dolomites (calcium-magnesium carbonates) generally have much larger grain sizes and pore

sizes than the limestones (calcium carbonates). The dolomites are generally not associated with D-cracking, but there are exceptions.

Kaneuji (5) in a Purdue University study recognized the variability of aggregate of a quarry face and recommended the sampling of individual ledges instead of stockpiles. Adjacent beds can vary tremendously in pore structure, and consequently one may be very durable while the other may result in severe D-cracking. Pertinent characteristics of the aggregates used in this paper are given in Table 1.

Figure 4. Pore volume versus pore size for nondurable aggregates.

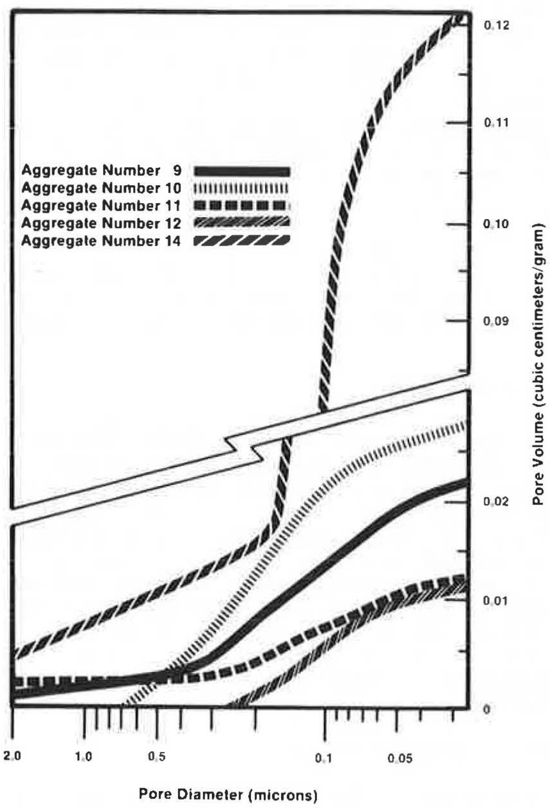
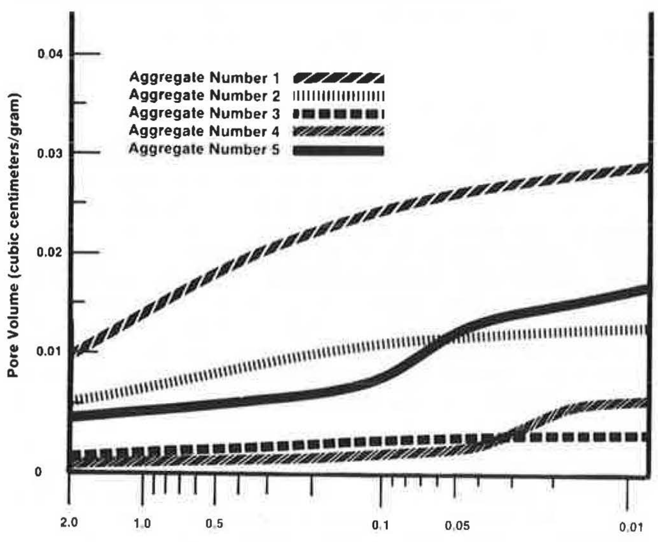



Figure 5. Pore volume versus pore size for durable aggregates.




In general, the aggregates are listed from those with the best service record to those with the poorest service record. It should also be noted that the aggregates listed are either very good or very bad in regard to D-cracking. This is true because the middle range generally results from a nonuniform blend of aggregates and test results are more variable depending on the proportion of good and bad particles. Only relatively consistent and uniform coarse aggregates are included in the table, since a small fraction of nondurable aggregate can produce concrete that is susceptible to freeze-and-thaw distress.

A laboratory study of concrete beams made by blending coarse aggregates was conducted by using an evaluation by the ASTM C666 method B concrete freeze-and-thaw test. A coarse aggregate associated with severe D-cracking was blended with two sources of coarse aggregate that had an excellent service record. The poor aggregate constituted 15, 30, and 45 percent of the total coarse aggregate. When 15 percent of an aggregate with a durability factor of 54 was blended with 85 percent of an aggregate with a durability factor of 90, the result was a durability factor of 78. This agrees with a conclusion by Lindgren (6) in Purdue University research that "greater than 10% nondurable aggregate present in a pavement has a detrimental effect on the pavement." One relatively thin bed of nondurable stone in a quarry face may cause the coarse aggregate to result in D-cracking. The pore index test can be used to identify rapidly these nondurable beds. Benching a quarry so as to remove these nondurable beds from coarse-aggregate production can improve the final product.

## DURABLE AGGREGATE THAT FAILS THE PORE INDEX TEST

As stated previously, Iowa specifications for coarse aggregate exclude materials with a method A freeze-and-thaw loss greater than 6. Materials with a low freeze-and-thaw loss are consistently classified correctly by the pore index test. The State of Illinois is using the pore index test and has indentified Western Materials (Kankakee, Illinois) coarse aggregate (aggregate 5 in Table 1) as having a very good service record and exhibiting a failing pore index of 44. Iowa testing has since confirmed Illinois data. This aggregate is an argillaceous dolomite that would have been excluded from further testing by the Iowa method A freeze-and-thaw test. Subsequent testing has identified an Iowa aggregate that is similar to the Illinois aggregate (aggregates 7 and 8 of Table 1). Mercury porosimeter testing included later in this paper supports pore index results by identifying pore sizes that normally coincide with aggregates associated with D-cracking. The Illinois aggregate (aggregate 5) contains 10 percent nonexpansive clay (illite or glauconite) finely dispersed in a dolomite matrix, which may be a factor in the very good service record.

## MERCURY POROSIMETER STUDIES

A Quantachrome Scanning Porosimeter has been used on all of the aggregates in Table 1 to determine the pore sizes and volumes. An oven-dried 3-g sample of material passing the 0.25-in (0.64-cm) sieve and retained on the no. 4 (0.48-cm) sieve was used for the analysis of each source. All aggregates were scanned from 0 to 60 000 psi (414 MPa). The porosimeter is computer controlled and makes all necessary corrections and automatically plots the pore volume/pore radius output. The pore radii are changed to diameters for presentation in this paper. With one exception, all nondurable aggre-

gates analyzed to date exhibit a predominance of pore sizes in the 0.04- to 0.2-μm-diameter range, which is indicated by the steep slope in the plots shown in Figure 4. With the exception of aggregate 5 (discussed earlier), the aggregates with good to excellent service records do not exhibit a predominance of the 0.04- to 0.2-μm-diameter pore sizes (see Figure 5). Mercury porosimeter testing has shown that the pore index test is very effective in identifying aggregates with substantial pores of the 0.04- to 0.2-μm size.

SCANNING ELECTRON MICROSCOPE STUDIES

Durable coarse aggregates have been observed and photographed with a scanning electron microscope (SEM). All photographs included in this paper were magnified 1000 times. Aggregates 1 and 2 have excellent service records. The very coarse grain size and large pore size are shown in Figures 6 and 7, respectively. Nondurable aggregates 9, 10, and 12 (see Figures 8-10, respectively) generally exhibit a fine-grained texture. Figure 8 shows some coarse grains in a predominately fine-grained matrix. Comparison of the pore-size data from the mercury porosimeter with the grain-size data from the SEM would indicate that a coarse-grained structure generally results in larger pore sizes.

The SEM also has the capability of identifying localized elements at high magnification, and current studies will use this capability in the analysis of D-cracking or other rapid failure mechanisms.

Figure 6. SEM photograph (1000x) of aggregate 1 (Weaver, Alden, Iowa).

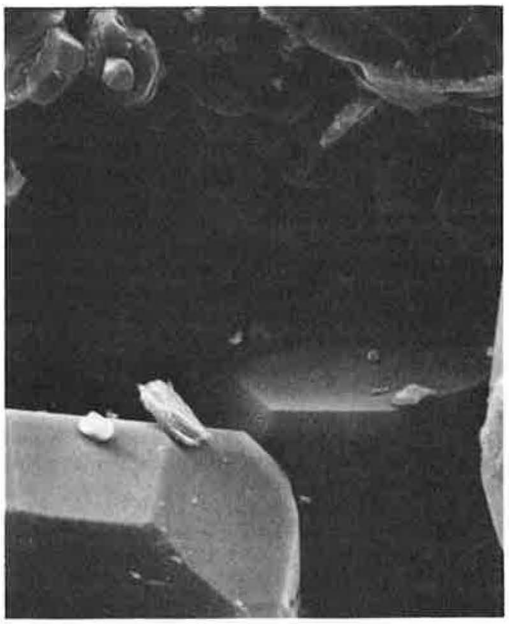


Figure 7. SEM photograph (1000x) of aggregate 2 (Niemann, Lamont, Iowa).

Figure 8. SEM photograph (1000x) of aggregate 9 (Columbia, Ullin, Illinois).

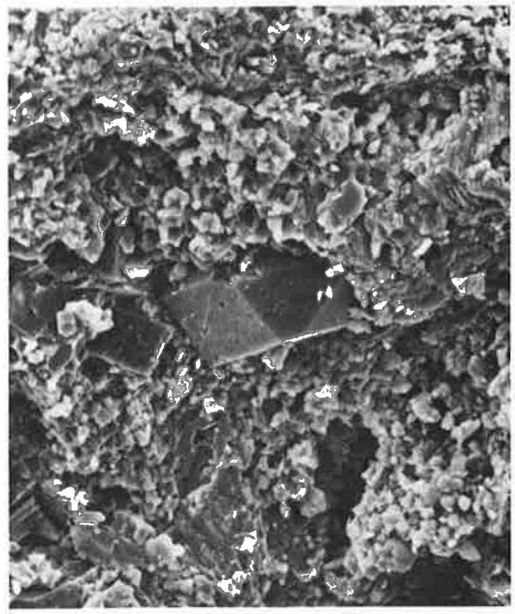


Figure 9. SEM photograph (1000x) of aggregate 10 [Alpha, Prairieburg, Iowa (Plower)].

Figure 10. SEM photograph (1000x) of aggregate 12 (Schildberg, Crescent, Iowa).

ANALYSIS OF INSOLUBLE FRACTION

Aggregate 5 has been acidized to remove the carbonate fraction. Mercury porosimeter, SEM, and chemical analyses of the residue are in progress. The analysis of the insoluble fraction of other aggregates is being initiated to determine whether they may contribute to the resulting aggregate durability.

CONCLUSIONS

1. The pore index test is very effective in identifying aggregates with a substantial system of pores in the 0.04- to 0.2-μm-diameter size.
2. The pore index test correlates very well with service records of nonargillaceous coarse aggregates used in PCC.
3. If 15 percent or more of the coarse aggregate is nondurable, the PCC will probably exhibit D-cracking.
4. Pore index tests of nonuniform material are not conclusive.
5. If possible, homogeneous fractions of coarse aggregates should be evaluated separately. Gravel should be separated into igneous and carbonate fractions for analysis. Individual beds of carbonate materials should be sampled separately.
6. Nondurable, nonargillaceous carbonate aggregates associated with D-cracking pavements exhibit a predominance of 0.04- to 0.2-μm-diameter pore sizes.
7. Nondurable coarse aggregates are generally fine grained and aggregates with a good to excellent service record are generally coarse grained or extremely fine grained.

ACKNOWLEDGMENT

We wish to thank Charles L. Huisman and James D. Myers of the Iowa DOT for their assistance in the durability research. The assistance of Turgut Demirel and Jerry Amenson in the use of the Iowa State University mercury porosimeter and SEM was very much appreciated.

This paper does not constitute a standard, specification, or regulation.

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*Publication of this paper sponsored by Committee on Performance of Concrete.*