# EFFECT OF MAXIMUM SIZE OF COARSE AGGREGATE ON D-CRACKING IN CONCRETE PAVEMENTS

David Stark and Paul Klieger, Portland Cement Association

Field and laboratory observations have indicated that D-cracking is caused by freeze-thaw failures in certain types of coarse aggregate particles. In areas where durable aggregates are not available, it has been found that the rate of development of D-cracking can be reduced by decreasing the maximum particle size. These observations were extended during a laboratory investigation that was carried out to find a test procedure that would distinguish between durable coarse aggregates and those that cause D-cracking and provide an indication of the benefits to be derived by reducing the maximum particle size. Exploratory work indicated that a rapid freeze-thaw procedure similar to ASTM Designation C 666-71 would be suitable. A failure criterion of 0.032 to 0.033 percent expansion in 350 or fewer cycles was established on the basis of the service records of 15 sources from which the test materials were obtained. Studies of the effect of maximum particle size on durability indicated that decreasing the size from 1½ in. to 1 in. and ½ in. reduced expansions to varying degrees. These findings are in line with the critical size concept for aggregate that was developed in previous work. It is recommended that, where D-cracking is a problem, similar testing programs be set up to evaluate coarse aggregate sources on an individual basis and to determine the benefits to be derived by reducing maximum particle sizes to improve durability.

•IN certain areas of eastern and west-central United States, and in Canada, D-cracking is a serious and costly durability problem affecting highways and airfields. Although it was initially observed in pavements more than 30 years ago, only within the past 10 years have efforts been made to develop an understanding of the mechanism of distress. The Portland Cement Association has been investigating this problem in the United States and Canada and has found that deterioration is initiated through freezing and thawing of coarse aggregate particles located in the lower and middle portions of pavement slabs. Observations have also indicated that subbase drainage affects the rate of development of deterioration but that factors such as joint spacing, air entrainment, and cement composition are of little or no significance in this problem.

Recent work on D-cracking has been concerned primarily with characterizing durable and nondurable coarse aggregates by laboratory test methods and determining ways by which the durability of materials from existing coarse aggregate sources can be improved. This paper will describe field observations and laboratory tests that indicate that, where durable coarse aggregates in existing gradations are not available, reducing the maximum particle size is an effective method of eliminating or reducing the rate of development of D-cracking.

## DEFINITION

The term D-cracking dates back to the 1930s and was used in reference to deterioration due to weathering as evidenced by the appearance of fine, parallel cracks along transverse and longitudinal joints and the free edges of pavement slabs (Fig. 1). Often these cracks contain deposits of secondary reaction products, primarily $CaCO_3$. Because our studies have revealed that, with few exceptions, this cracking is initiated through freezing and thawing of coarse aggregate particles, the term in this report will denote a cause and source of distress as well as the nature of the crack pattern observed at the pavement wearing surface.

## OBSERVATIONS OF PAVEMENTS

Observations of pavement concrete have indicated that the development of D-cracking depends primarily on the source of coarse aggregate. This is shown in Figure 2, where coarse aggregate from a different source was used on each side of the transerse joint. After 8 years of exposure, D-cracking is well developed on one side of the joint but not evident at the wearing surface on the other side. Examination of cores confirmed the absence of distress in the lower levels of the one slab, as shown by the comparison of core sections in Figure 3. Laboratory tests and other field observations indicate that D-cracking is unlikely to develop in the currently unaffected pavement.

A second example of this relation is shown in Figure 4. Here, it is seen that, after 15 years of exposure, one traffic lane is free of distress, whereas, with a change in source of coarse aggregate, D-cracking has developed in the abutting lane. Unlike the previous example, however, the examination of cores revealed that distress had developed in the lower levels of the pavement slab in the traffic lane that is free of distress at the wearing surface. In this case, both sources are vulnerable to D-cracking, but to varying degrees.

From the preceding figures it is apparent that coarse aggregates from different sources in a given area may show varying susceptibilities to D-cracking in concrete pavements. In some areas, however, materials from available sources all show marked susceptibilities to D-cracking, in which case there is no advantage in selecting one source over another. Under these circumstances, limited field observations have indicated that reducing the maximum particle size can greatly reduce the rate of development of D-cracking or possibly eliminate it. The following examples illustrate the improved durability to be gained.

In a pavement built in 1965, crushed-limestone coarse aggregates taken from the same source but containing 1½-in. and 1-in. maximum sizes were used in different sections. In this pavement, D-cracking is apparent at the joint intersections where the large aggregate was used (Fig. 5), whereas, in the section with the small size, D-cracking is not visible at the wearing surface. However, petrographic examination of cores taken from selected joint areas revealed that distress has developed in the pavement concrete with the 1-in. maximum particle size. In addition, cracking was observed in coarse aggregate particles of less than ½-in. size. Thus, although improved performance was obtained at the age of 5 years by reducing the maximum particle size of the coarse aggregate, the change only reduced the rate of development of D-cracking.

A second example of improved performance with a reduction in maximum particle size was seen in the Topeka test road in Kansas, which is a project of the "long-time study" (1). Here, a crushed-limestone coarse aggregate was used in all sections of pavement, and the maximum particle sizes were ¾ in. and 1½ in. After 13 years, D-cracking was well advanced in concrete containing the 1½-in. maximum particle size (Fig. 6), but it was not then apparent at the wearing surface in concrete containing the ¾-in. maximum size. It should be noted here that mix proportions and placing and curing procedures were also variables in this road, but observations elsewhere indicate that variables of these types are of little or no significance in this type of deterioration. Therefore, the conclusion on the effect of maximum particle size on the development of D-cracking in this pavement appears to be fully justified.

A secondary factor that has been found to affect the rate of development of D-cracking is subbase drainage. Where artificial drains have not been installed, conditions are most conducive to the development of D-cracking where a potentially nondurable coarse aggregate has been used. Where longitudinal tile drains have been installed, the rate of development of D-cracking is reduced if the fines in the subbase do not seal off subbase moisture migration to the drain inlets. However, to the best of our knowledge, a pavement drainage system has not yet been found that will obviate

Figure 1. Severe D-cracking along longitudinal and transverse joints of 9-year old pavement.

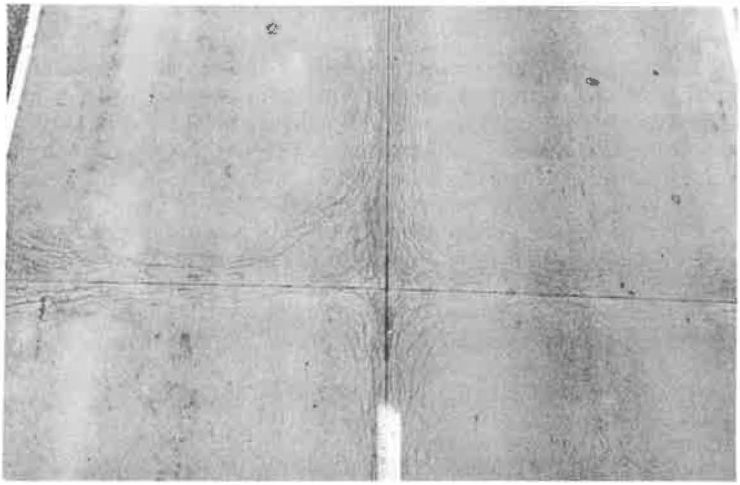

Figure 2. D-cracking along one side of transverse joint of 8-year old pavement.

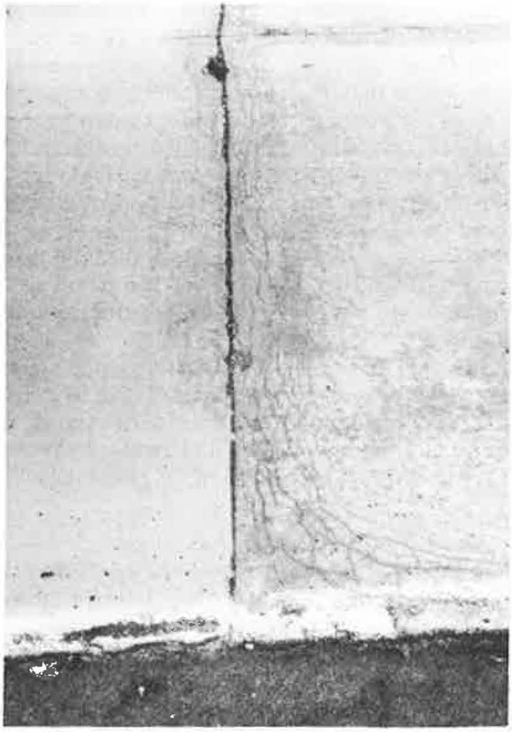

Figure 3. Vertical sections of cores taken on each side of transverse joint shown in Figure 2.

durability deficiencies in the coarse aggregate and eliminate the development of D-cracking.

## LABORATORY STUDIES

Laboratory studies were undertaken to determine if freezing and thawing tests could substantiate the service records of coarse aggregate sources with respect to D-cracking. It was anticipated that a failure criterion could be established that would distinguish between durable and nondurable materials and also provide a reference to judge the merits of decreasing maximum particle sizes to reduce or eliminate the susceptibility of various aggregates to D-cracking. Exploratory work indicated that a rapid freeze-thaw procedure in water, similar to ASTM Designation C 666-71, would be most suitable. In the procedure used, 3- by 3- by $11\frac{1}{4}$-in. concrete prisms were frozen and thawed in water at the rate of two cycles per day, and length-change measurements were made after every 25 cycles up to 300 cycles and at 350 cycles. Details of the materials, mix designs, procedures used, and test results are given in the following sections.

### Materials and Service Records

Coarse aggregates from 15 sources were used in this series of tests. These sources are given in Table 1 and are categorized according to service record for gradations with a $1\frac{1}{2}$-in. maximum particle size. Three categories of service record are shown: one for which D-cracking appears at the wearing surface in less than 8 years, one for which D-cracking appears between 8 and 15 years, and one for which D-cracking is not apparent in more than 15 years. For two sources in the latter group, 3C and 3E, D-cracking has not appeared at the wearing surface in more than 22 years. Examination of cores from pavement containing coarse aggregates from all sources in this group revealed no evidence of incipient distress in the lower portions of the pavement slabs. At these ages, this absence of distress would indicate that D-cracking will not appear at the wearing surface for at least 25 years. Service records of this length can be considered as satisfactory and will serve as a basis for evaluating laboratory test results.

It may be noted in Table 1 that all of the aggregate types with satisfactory service records are crushed dolomites. This does not mean that, where D-cracking is a problem, dolomite is the type of material that should be used. In much more extensive field observations, crushed dolomites as well as siliceous and other types of carbonate rock have been found to perform both poorly and satisfactorily. Most of the present work was based on observations in an area of dolomitic bedrock where the most extensive and complete service records were available.

Single sources of fine aggregate (mixed carbonate) and cement (ASTM Type I) were used for these tests. Both have been used with a variety of coarse aggregates in concrete pavements and, in comparing the performance of these pavements with others using coarse aggregates from the same sources but fine aggregates and cements from different sources, have shown no singular effect on the development of D-cracking.

### Mix Design and Procedure

Coarse aggregate gradations and mix design data for all tests are given in Tables 2 and 3 respectively. The fine aggregate gradations were as follows: No. 4 to No. 8 sieve size, 10 percent; No. 8 to No. 16, 20 percent; No. 16 to No. 30, 25 percent; No. 30 to No. 50, 25 percent; No. 50 to No. 100, 16 percent; and -No. 100, 4 percent. The compound composition of the cement was as follows: $C_3S$, 59 percent; $C_2S$, 16 percent; $C_3A$, 9.9 percent; and $C_4AF$, 7.9 percent. Chemical analysis of the cement showed the following: CaO, 64.85 percent; $SiO_2$, 20.90 percent; $Al_2O_3$, 5.42 percent; $Fe_2O_3$, 2.61 percent; MgO, 1.85 percent; $Na_2O$, 0.15 percent; $K_2O$, 0.74 percent; $SO_3$, 2.14 percent; loss value, 1.17 percent; and Blaine value, 3,640 $cm^2/g^2$. All concrete was mixed in a Lancaster mixer, $^2/_3$-$ft^3$ capacity, for $2\frac{1}{2}$ min. Neutralized Vinsol resin was added as an air-entraining admixture at the mixer. Air contents were measured immediately after mixing and were maintained at 5.5 to 6.5 percent. Slumps

Figure 4. D-cracking in one (lower) traffic lane; abutting lane free of visible distress.

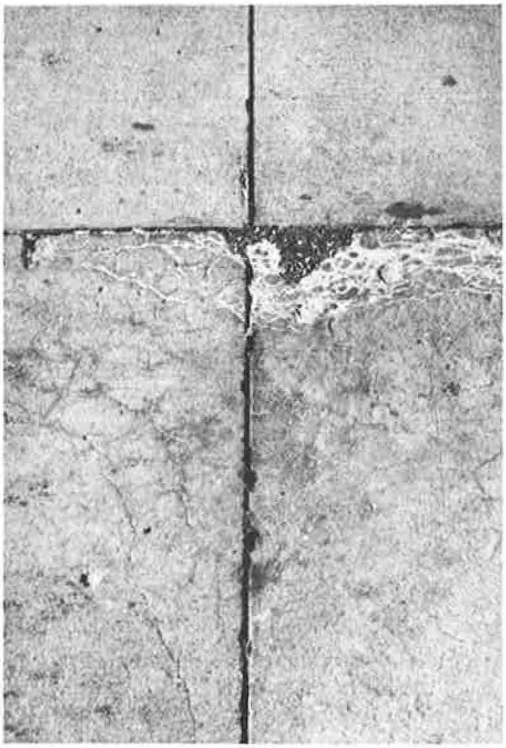

Figure 5. Early D-cracking at longitudinal-transverse joint intersection where 1½-in. maximum-sized coarse aggregate from source 1A was used.

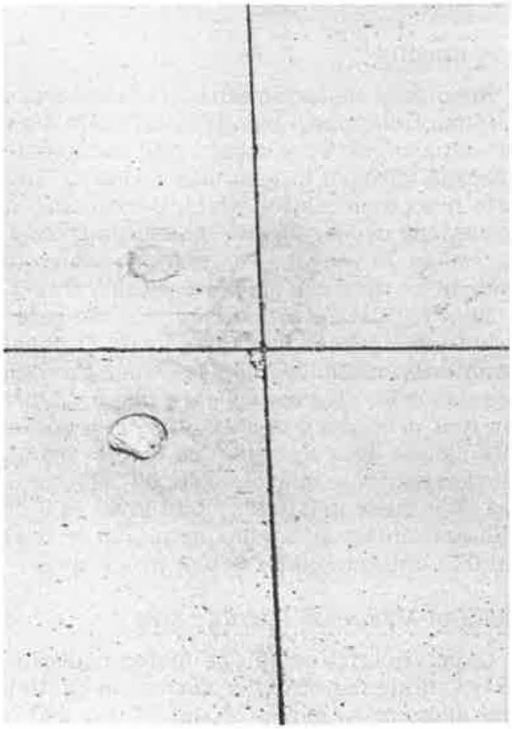

Figure 6. Typical D-cracking along a transverse joint in the Topeka test road, where 1½-in. maximum-sized aggregate particles were used.

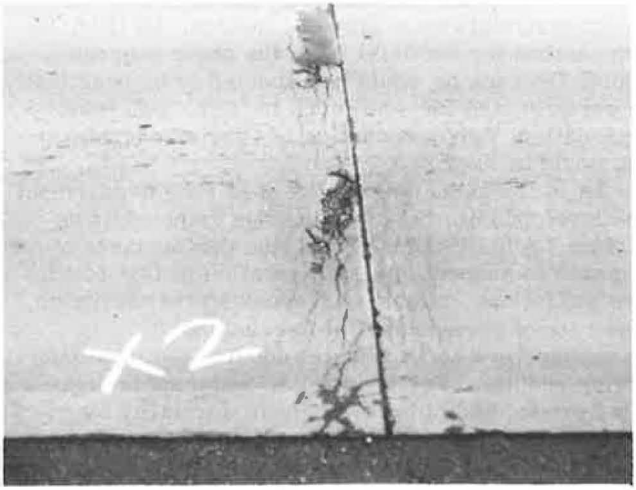

Table 1. Service record of coarse aggregates used in laboratory tests.

| Designation | Type |
|---|---|
| D-Cracking Appears in Less Than 8 Years | |
| 1A | Crushed limestone |
| 1B | Mixed carbonate gravel |
| 1C | Mixed siliceous gravel |
| 1D | Crushed dolomitic limestone |
| 1E | Crushed limestone |
| D-Cracking Appears in 8 to 15 Years | |
| 2A | Mixed carbonate gravel |
| 2B | Mixed carbonate gravel |
| 2C | Crushed dolomite |
| 2D | Crushed dolomite |
| 2E | Mixed carbonate gravel |
| D-Cracking Has Not Appeared in More Than 15 Years | |
| 3A | Crushed dolomite |
| 3B | Crushed dolomite |
| 3C | Crushed dolomite |
| 3D | Crushed dolomite |
| 3E | Crushed dolomite |

were held to between ½ in. and 2 in. Four 3- by 3- by 11¼-in. concrete prisms were made from each batch. One of the prisms was continuously moist-cured at 73 F and 100 percent relative humidity, whereas the remaining three were subjected to freezing and thawing following a 14-day moist cure.

### Test Results

Results of tests for all aggregate sources, using a gradation with a 1½-in. maximum particle size, are given in Table 4 and shown in Figure 7. These data indicate that expansions were most rapid and greatest for materials from sources for which D-cracking appears in less than 8 years. Intermediate expansions developed with materials from sources for which D-cracking appears in 8 to 15 years, whereas the smallest expansions occurred with materials from sources with satisfactory service records of more than 15 years. The test procedure thus appears to substantiate the field service records as they are categorized in Table 1.

The test data also indicate that the rate of expansion continues to increase for materials from sources associated with D-cracking, whereas the rate of expansion remains essentially unchanged or decreases for materials from sources with satisfactory service records. It thus appears that a failure criterion could be established for which this test procedure would distinguish between durable and nondurable coarse aggregates. This can be done by using the length-change level separating sources associated with D-cracking from sources with satisfactory service records. The test data indicate that, for these materials, this level is 0.032 to 0.033 percent expansion at 350 cycles. This percentage of expansion in 350 or fewer cycles is therefore considered to be a suitable criterion for the test procedure.

### Effect of Maximum Particle Size

Using this criterion, we tested materials from nine of the coarse aggregate sources to determine the effect of maximum particle size on durability. Three maximum particle sizes were used: 1½ in., 1 in., and ½ in. Mixing, curing, and testing were carried out as previously described.

The results of these tests are given in Table 5, whereas those for selected sources are shown in Figures 8 through 11. In the group for which D-cracking appears in less than 8 years, decreasing the maximum particle size from 1½ in. to 1 in. and ½ in. progressively reduced expansions as much as two to four times. However, decreasing the maximum particle size only to 1 in. failed to reduce expansions sufficiently for any of the sources to meet the selected criterion. When the maximum particle size was further reduced to ½ in., expansions for materials from only one source, 1B (Fig. 8), almost met the criterion, whereas expansions for material from the other sources still greatly exceeded this range. Thus, D-cracking would be expected to be practically eliminated by reducing the maximum particle size for source 1B to ½ in., whereas, for the other sources with the same gradation, only a reduction of varying degrees in the rate of development of D-cracking could be expected.

It should be noted here that source 1A is the same one as that used for the pavement described earlier in which the rate of development of D-cracking was reduced by decreasing the maximum particle size from 1½ in. to 1 in. Thus, the performance of the coarse aggregate in this pavement appears to support the interpretation of test results that, where expansions are still above the failure criterion, decreasing the maximum particle size serves only to reduce the rate of development of D-cracking.

In the group for which D-cracking appears in 8 to 15 years, reducing the maximum particle size produced somewhat varying results. For source 2A, reducing the maximum particle size from 1½ in. to 1 in. produced no improvement in durability as expansions remained essentially unchanged and well in excess of the failure criterion. When the maximum particle size was further reduced to ½ in., expansions were reduced by one-half but still exceeded the failure criterion. For this source, the results indicate that the maximum particle size would have to be reduced to less than 1 in. to show any improved durability, whereas a reduction to ½ in. would have the effect of only delaying and not eliminating the development of D-cracking.

Table 2. Coarse aggregate gradation.

| Maximum Particle Size (in.) | Sieve Size (percent retained) | | | | | |
|---|---|---|---|---|---|---|
| | 1½ to 1 in. | 1 to ¾ in. | ¾ to ½ in. | ½ to ⅜ in. | ⅜ in. to No. 4 | No. 4 to No. 8 |
| 1½ | 35 | 18 | 28 | 16 | 3 | — |
| 1 | — | 10 | 55 | 30 | 5 | — |
| ½ | — | — | — | 15 | 70 | 15 |

Table 3. Mix design for concrete prisms.

| Maximum Particle Size (in.) | Aggregate Content (percent) | | Cement Content (lb/yd³) | Water Content (lb/yd³) | Air Content (percent) |
|---|---|---|---|---|---|
| | Coarse | Fine | | | |
| Gravel | | | | | |
| 1½ | 64 | 36 | 611 | 258 to 267 | 5.5 to 6.5 |
| 1 | 60 | 40 | 611 | 258 to 267 | 5.5 to 6.5 |
| ½ | 55 | 45 | 611 | 267 to 283 | 5.5 to 6.5 |
| Crushed stone | | | | | |
| 1½ | 60 | 40 | 611 | 267 to 275 | 5.5 to 6.5 |
| 1 | 56 | 44 | 611 | 267 to 275 | 5.5 to 6.5 |
| ½ | 50 | 50 | 611 | 275 to 283 | 5.5 to 6.5 |

Table 4. Test results using gradation with 1½-in. maximum-sized particles.

| Aggregate Source | Percentage of Expansion at Cycle Indicated | | | | | | |
|---|---|---|---|---|---|---|---|
| | 50 | 100 | 150 | 200 | 250 | 300 | 350 |
| D-Cracking Appears in Less Than 8 Years | | | | | | | |
| 1A | 0.009 | 0.019 | 0.043 | 0.071 | 0.100 | — | — |
| 1B | 0.004 | 0.011 | 0.020 | 0.036 | 0.060 | 0.112 | — |
| 1C | 0.003 | 0.012 | 0.027 | 0.041 | 0.062 | 0.093 | 0.127 |
| 1D | 0.021 | 0.048 | 0.111 | — | — | — | — |
| 1E | 0.011 | 0.023 | 0.054 | 0.080 | 0.110 | — | — |
| D-Cracking Appears in 8 to 15 Years | | | | | | | |
| 2A | 0.005 | 0.007 | 0.012 | 0.018 | 0.028 | 0.045 | 0.078 |
| 2B | 0.008 | 0.011 | 0.018 | 0.026 | 0.034 | 0.046 | 0.068 |
| 2C | 0.005 | 0.010 | 0.012 | 0.017 | 0.022 | 0.027 | 0.034 |
| 2D | -0.001 | 0.001 | 0.006 | 0.008 | 0.017 | 0.027 | 0.046 |
| 2E | 0.005 | 0.005 | 0.011 | 0.015 | 0.021 | 0.031 | 0.039 |
| D-Cracking Has Not Appeared in More Than 15 Years | | | | | | | |
| 3A | 0.002 | 0.002 | 0.005 | 0.005 | 0.008 | 0.011 | 0.011 |
| 3B | 0.008 | 0.011 | 0.014 | 0.019 | 0.022 | 0.029 | 0.031 |
| 3C | 0.006 | 0.008 | 0.009 | 0.013 | 0.015 | 0.017 | 0.019 |
| 3D | 0.004 | 0.008 | 0.010 | 0.013 | 0.018 | 0.020 | 0.022 |
| 3E | 0.002 | 0.006 | 0.006 | 0.008 | 0.013 | 0.014 | 0.015 |

**Figure 7. Comparison of length changes during freezing and thawing.**

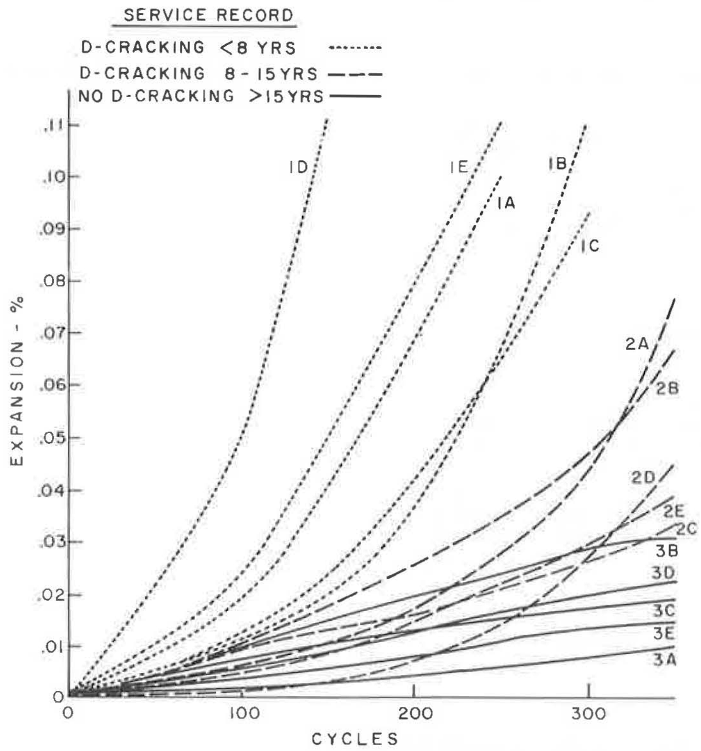

**Table 5. Effect of maximum particle size on durability.**

| Aggregate Source | Maximum Size (in.) | Percentage of Expansion at Cycle Indicated | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 50 | 100 | 150 | 200 | 250 | 300 | 350 |
| D-Cracking Appears in Less Than 8 Years | | | | | | | | |
| 1A | 1½ | 0.009 | 0.019 | 0.043 | 0.071 | 0.100 | – | – |
| | 1 | 0.010 | 0.014 | 0.032 | 0.050 | 0.074 | – | – |
| | ½ | 0.009 | 0.013 | 0.023 | 0.044 | 0.076 | – | – |
| 1B | 1½ | 0.004 | 0.011 | 0.020 | 0.036 | 0.060 | 0.112 | – |
| | 1 | 0.004 | 0.007 | 0.015 | 0.021 | 0.031 | 0.048 | 0.061 |
| | ½ | 0.003 | 0.004 | 0.009 | 0.014 | 0.019 | 0.030 | 0.035 |
| 1C | 1½ | 0.003 | 0.012 | 0.027 | 0.041 | 0.062 | 0.093 | 0.127 |
| | 1 | 0.001 | 0.007 | 0.015 | 0.025 | 0.040 | 0.062 | 0.091 |
| | ½ | 0.001 | 0.005 | 0.012 | 0.018 | 0.026 | 0.039 | 0.049 |
| 1D | 1½ | 0.021 | 0.048 | 0.111 | – | – | – | – |
| | 1 | 0.010 | 0.022 | 0.045 | 0.069 | 0.097 | 0.144 | 0.183 |
| | ½ | 0.006 | 0.009 | 0.018 | 0.027 | 0.040 | 0.061 | 0.079 |
| 1E | 1½ | 0.011 | 0.023 | 0.054 | 0.080 | 0.110 | – | – |
| | 1 | 0.009 | 0.021 | 0.044 | 0.081 | 0.122 | – | – |
| | ½ | 0.007 | 0.016 | 0.024 | 0.039 | 0.052 | 0.063 | 0.069 |
| D-Cracking Appears in 8 to 15 Years | | | | | | | | |
| 2A | 1½ | 0.005 | 0.007 | 0.012 | 0.018 | 0.028 | 0.045 | 0.078 |
| | 1 | 0.004 | 0.006 | 0.010 | 0.016 | 0.028 | 0.050 | 0.083 |
| | ½ | 0.003 | 0.006 | 0.008 | 0.014 | 0.019 | 0.027 | 0.041 |
| 2D | 1½ | -0.001 | 0.001 | 0.006 | 0.008 | 0.017 | 0.027 | 0.046 |
| | 1 | -0.001 | 0.003 | 0.009 | 0.013 | 0.023 | 0.035 | 0.057 |
| | ½ | -0.002 | 0.000 | 0.005 | 0.007 | 0.014 | 0.021 | 0.033 |
| 2E | 1½ | 0.005 | 0.005 | 0.011 | 0.015 | 0.021 | 0.031 | 0.039 |
| | 1 | 0.004 | 0.005 | 0.010 | 0.013 | 0.019 | 0.027 | 0.032 |
| | ½ | 0.003 | 0.004 | 0.008 | 0.010 | 0.014 | 0.021 | 0.024 |
| No D-Cracking in More Than 15 Years | | | | | | | | |
| 3A | 1½ | 0.002 | 0.002 | 0.005 | 0.005 | 0.008 | 0.011 | 0.011 |
| | 1 | 0.001 | 0.001 | 0.003 | 0.003 | 0.006 | 0.009 | 0.009 |

The data for source 2D (Fig. 9) indicate, like source 2A, no improvement in durability when the maximum particle size is reduced from 1½ in. to 1 in. In fact, somewhat greater expansions were recorded with the 1-in. maximum particle size. However, when the maximum size was reduced to ½ in., expansions met the failure criterion, which indicates that, for this source, D-cracking would be essentially eliminated by using the ½-in. maximum size.

The results for source 2E (Fig. 10) indicate progressively lesser expansions as the maximum particle size is reduced from 1½ in. to 1 in. and ½ in. For this source, however, the data indicate that a reduction in maximum particle size only to 1 in. would be sufficient to essentially eliminate the development of D-cracking because the expansion at 350 cycles is 0.032 percent. A further reduction would appear to be unnecessary to eliminate D-cracking.

The effect of maximum particle size on durability was studied for only one source, 3A (Fig. 11), in the group in which D-cracking has not appeared in more than 15 years. Here, expansions of 0.011 and 0.009 percent developed for gradations with maximum particle sizes of 1½ in. and 1 in. respectively. These expansions are well below the failure criterion range and substantiate the field observations that a reduction in maximum particle size is not needed for this material.

## DISCUSSION OF RESULTS

In the work here reported it is apparent that the nature of the coarse aggregate is a primary factor affecting freeze-thaw durability and the development of D-cracking in concrete pavements. The evidence that decreasing the maximum particle size improves durability and reduces the rate of development of D-cracking is in line with the work of Powers (2) and Verbeck and Landgren (3), who developed the critical-size concept to explain the behavior, during freezing and thawing, of aggregates with varying pore characteristics. Briefly, in a given concrete and environment, this concept involves the distances certain quantities of water can be moved through an aggregate particle or surrounding mortar to prevent the generation of excessive hydraulic pressures during freezing. With a given size, certain types of critically saturated particles may fail if their permeabilities are sufficiently low to prevent expulsion of adequate water into the surrounding cement paste and the relief of internal hydraulic pressures. For other types of particles, porosities and permeabilities may be sufficiently high to allow excessive quantities of water to be expelled into the surrounding cement paste where critical saturation can then be reached and excessive hydraulic pressures be generated. In either case, and in intermediate cases, a reduction in particle size would reduce the magnitude of hydraulic pressures generated during freezing.

In line with this concept, the failure criterion established in these laboratory tests can be used to provide an indication of the critical particle size above which the aggregate is not immune to the effects of freezing and thawing and may cause D-cracking. In this work, if expansions exceed 0.032 to 0.033 percent, the critical size is less than the maximum particle size of the aggregate gradation being tested. If expansions are less, the critical size is greater than the maximum particle size. The critical sizes for the coarse aggregate sources in this test series are given in Table 6. According to these data, D-cracking would be essentially eliminated with two of the nine sources if ½-in. maximum particle sizes were specified. With one source, a 1-in. size would be permissible, whereas, with another source, a 1½-in. or possibly larger size could be tolerated. For the remaining five sources, the maximum particle size would have to be less than ½ in. to eliminate the development of D-cracking.

## CONCLUSIONS

The rapid freeze-thaw test procedure described in this paper appears to have successfully distinguished between coarse aggregates from sources associated with the development of D-cracking and those from sources with known satisfactory service records. The test procedure also appears to have substantiated the limited but meaningful field observations on the benefits of reducing the maximum particle size of coarse aggregates from sources associated with D-cracking. It is thus recommended

Figure 8. Effect of maximum particle size on durability for source 1B.

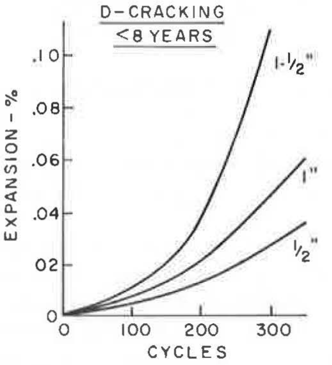

Figure 9. Effect of maximum particle size on durability for source 2D.

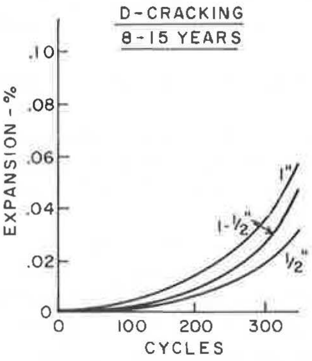

Figure 10. Effect of maximum particle size on durability for source 2E.

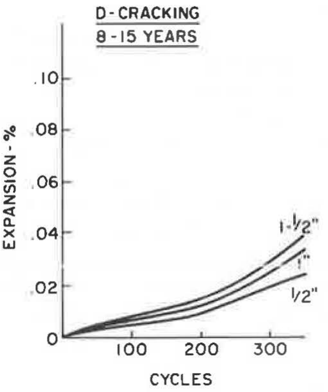

Figure 11. Effect of maximum particle size on durability for source 3A.

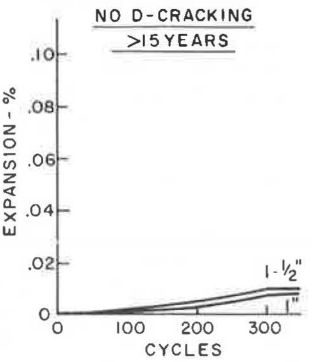

Table 6. Critical sizes for aggregate sources.

| Service Record | Source | Critical Size (in.) |
|---|---|---|
| D-cracking appears in less than 8 years | 1A | < 1/2 |
| | 1B | 1/2 |
| | 1C | < 1/2 |
| | 1D | < 1/2 |
| | 1E | < 1/2 |
| D-cracking appears in 8 to 15 years | 2A | < 1/2 |
| | 2D | 1/2 |
| | 2E | 1 |
| No D-cracking in more than 15 years | 3A | > 1 1/2 |

that, where D-cracking is a problem, similar testing programs be set up to evaluate coarse aggregate sources on an individual basis and to determine the benefits to be derived by reducing maximum particle sizes to improve durability.

## REFERENCES

1. Twenty-Year Report on the Long-Time Study of Cement Performance in Concrete. Advisory Committee, Long-Time Study of Cement Performance in Concrete, PCA Res. Dept. Bull. 175, 1965.
2. Powers, T. C. Basic Considerations Pertaining to Freezing and Thawing Tests. Proc. ASTM, Vol. 55, 1965.
3. Verbeck, G., and Landgren, R. Influence of Physical Characteristics of Aggregates on Frost Resistance of Concrete. Proc. ASTM, Vol. 60, 1960.