show distress, or the criteria may be conservative in that they reject all the bad aggregate and also some durable aggregate as well. Continued observation of these sections is required to answer this question.

All the aggregate in all 47 sections passed the durability acceptance test in force at the time of construction: a 24-h absorption test. Yet almost two-thirds of the sections are in distress; 3 are less than 10 years old. The criteria developed in this study consider the median pore size as well as the pore volume of an aggregate rather than merely a measure of the pore volume. Furthermore, they consider that a comparatively small amount of poor material can destroy a pavement even when a large amount of good aggregate is present. For these reasons, they are considered to do a better job of discriminating among aggregates.

If the criteria developed here were used for acceptance testing of aggregate in relation to freeze-thaw durability, it would be necessary to measure a great many pore-size distributions. Even with the advent of automatic instruments to perform the tests, this would be an expensive undertaking. However, the cost of resurfacing D-cracked pavement is vastly more expensive. Compared with this extraordinary maintenance cost, the expense of the more refined testing described here would be small.

CONCLUSIONS

1. The pore structure of the coarse aggregate in a pavement can be used to calculate an EDF that is representative of the pavement.
2. The representative EDF correlates well with the presence or absence of observed pavement D-cracking distress.
3. The pore structure of a potential coarse-aggregate source may be a useful predictor of potential D-cracking problems in pavements made with that aggregate.

ACKNOWLEDGMENT

This research was carried out by the Joint Highway Research Project, Purdue University, in cooperation with the Indiana State Highway Commission and the Federal Highway Administration. Their assistance is appreciated.

REFERENCES

1. M. Kaneuji, D.N. Winslow, and W.L. Dolch. The Relationship Between an Aggregate's Pore Size Distribution and Its Freeze/Thaw Durability in Concrete. Cement and Concrete Research, Vol. 10, 1980, pp. 433-441.
2. M.K. Lindgren. The Prediction of the Freeze/Thaw Durability of Coarse Aggregate in Concrete by Mercury Intrusion Porosimetry. Purdue Univ., West Lafayette, IN, Joint Highway Research Project, Rept. 80/14, 1980.

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

Ohio Aggregate and Concrete Testing to Determine D-Cracking Susceptibility

JOHN T. PAXTON

Several laboratory test methods were analyzed to determine their capability of indicating the D-cracking susceptibility of coarse aggregates. Two methods were modified versions of ASTM C666 A and B, two were unconfined freeze-thaw tests of the aggregate, and the remaining two were standard sodium and magnesium soundness tests. The major modification of the ASTM C666 test methods was to determine the elongation of the test specimens versus routine weight-loss determinations and/or sonic modulus determinations. Results are evaluated by plotting the percentage of expansion versus the number of cycles completed and calculating the area under the curve generated. Although 10 specimens are used in the testing, the 2 high and 2 low test results are removed before final analysis. The correlation of this test method with service records of various aggregates was found to be good; however, when the same coarse aggregates were tested in sodium sulfate, magnesium sulfate, or unconfined freeze and thaw, the results did not correlate well with the service records.

D-cracking in portland cement concrete (PCC) pavements has been and is a serious problem in Ohio. Early in 1969, it was decided that research was needed to investigate the causes of and determine solutions for this problem. In June 1969, the Ohio Department of Transportation (ODOT) entered into a cooperative research agreement for this purpose with the Portland Cement Association (PCA). By March 1972, PCA had published an interim report on D-cracking of concrete pavements in Ohio that indicated that the coarse aggregate in the concrete was a cause of the problem. In addition, this interim report indicated that a freeze-thaw test similar to ASTM C666 could be used to determine the D-cracking susceptibility of coarse aggregates. It was at this time that ODOT decided to conduct research to evaluate the capability of various test methods for indicating which coarse aggregates used in Ohio were likely to cause D-cracking. This paper deals with the results obtained by using these various test methods to test coarse aggregates from 16 sources in Ohio that had service records indicating D-cracking in less than 15 years or no D-cracking in 15 years or more. The aggregate sources and their service records are given in Table 1.

AGGREGATE TESTING BY FREEZE-THAW

Confined

The initial testing undertaken by ODOT was freeze-thaw testing of the coarse aggregate incorporated in a concrete. The freeze-thaw tests used were similar to ASTM C666 methods A and B; however, instead of a determination of the sonic modulus of concrete specimens undergoing freeze-thaw cycling, the expansions of the specimens were checked and recorded throughout the test period. It was determined from the PCA research that the specimens that exhibited the larger expansions were those made with coarse aggregate from sources whose service records showed D-cracking in less than 15 years.

All of the coarse aggregates were sieved into fractions and then recombined in the proportions shown in Figure 1. The fine aggregate, a natural sand, for all concrete mixes was from one source. The gradation and other properties are shown in Figure 1. The fine and coarse aggregates for all concrete were soaked, completely immersed in water, for a period of 16 h prior to mixing. Type 1 cement from a single source was used in all batches. The chemical composition and physical properties are shown in Figure 1. The specimens were 3x4x15-in prisms that had a gage stud embedded in each end. The gage length of the specimens was 14 in. All specimens were moist cured for 24 h at a temperature of 73°F ± 3°F and 13 days in saturated lime water at 73°F ± 3°F. At the end of the curing period, the specimens were cooled to 40°F ± 3°F and the initial length measurements were made by using a length comparator similar to the type specified in ASTM C490.

Table 1. Coarse-aggregate sources used in various tests.

Source	Location	Type of Material	Service Record D-Cracking	Service Record No. of Years
Cng-1	Urbana	Gravel	Yes	<15
Cln-1	Melvin	Crushed Stone	No	>15
Del-5	Delaware	Crushed Stone	Yes	<15
Fn-6	Columbus	Gravel	Yes	<15
Kx-13	Fredericktown	Gravel	Yes	<15
Mn-3	Marion	Crushed Stone	Yes	<15
Mi-6	Piqua	Gravel	Yes	<15
My-16	Dayton	Gravel	Yes	>15
Rs-8	Kinnikiniick	Gravel	Yes	<15
Pm-4	Rimer	Crushed Stone	No	>15
Sy-2	Woodville	Crushed Stone	No	>15
Sy-6	Bellevue	Crushed Stone	No	>15
Vt-3	Union	Crushed Stone	No	>15
Wt-1	Carey	Crushed Stone	No	>15
Wt-8	Carey	Crushed Stone	No	>15

The method A procedure of ASTM C666, freezing and thawing in water, was conducted at 8 cycles/day, and expansion measurements were made at intervals of 24 and 32 cycles until the specimens had undergone 250 cycles of testing (see Table 2). The method B procedure of ASTM C666, freezing in air and thawing in water, was conducted at 12 cycles/day, and expansion measurements were made at intervals of 36 and 48 cycles until the specimens had undergone 450 cycles of testing. All of the freeze-thaw testing was conducted in a Conrad Missimer apparatus capable of holding 60 specimens.

The results are given in tabular form in Tables 2 and 3 and are shown graphically in Figures 2 and 3. The results in Tables 2 and 3 are grouped according to the two service record categories. In Figures 2 and 3, the sources that showed D-cracking in less than 15 years are depicted by dashed lines and the sources that showed no D-cracking in 15 years or more are depicted by solid lines. Additional freeze-thaw testing was undertaken, and the same mixing and curing procedures discussed above were used. However, 20 specimens were produced from each batch of concrete, and 10 of these specimens were tested by using method A procedures and the remaining 10 by using method B procedures. At the completion of the testing, the two high and two low test results were removed from the data. The data were then plotted in the form of percentage expansion versus the number of cycles completed. Figures 4 and 5 show the areas generated under the curves at 250 and 350 cycles for methods A and B, respectively. The number of cycles used for methods A and B were chosen to be 250 and 350, respectively, because at this point the separation of the sources that exhibit D-cracking in service from those that do not exhibit D-cracking is apparent. The area under the curve can be computed by integration; however, many small calculators have the capacity to perform this operation. A computer program is in use in Ohio for this operation and is available on request from ODOT.

Figure 1. Materials and mix design for concrete prisms.

Cement Composition

Compound Composition (%)					Cement Composition (%)										
C_3S	C_2S	C_3A	C_4AF	-	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Loss on Ignition	Insoluble Residue	Blaine cm^2/g
51	23	11.5	8	-	64.61	21.36	6.01	2.61	1.75	0.15	0.78	1.83	0.60	0.21	3424

Fine-Aggregate Gradation

Percent Retained in Sieve Size Indicated						Specific Gravity	Absorption	Na_2So_4 Loss
No.4-No.8	No.8-No.16	No.16-No.30	No.30-No.50	No.50-No.100	-100			
9	23	30	26	8	4	2.66	1.78	2.0

Coarse-Aggregate Gradation

Percent Retained in Sieve Size Indicated				
1.5-1 in.	1-0.75 in	0.75-0.5 in	0.5-0.375 in	0.375-No.4
35	17	28	15	5.0

Mix Design for Concrete Prisms

Cement factor:	6.5 bags/yd^3	
Aggregate weights (dry)	Ls	Gr
Fine:	1190	1075
Coarse:	1775	1890
Water-cement ratio:	4.8 ± 0.1 gal/bag	
Air content:	6 ± 0.5%	
Slump:	1.0 - 2.5 in	

Table 2. Results of method A freeze-thaw test.

Source of Coarse Aggregate	Expansion by No. of Cycles (%)											
	25	50	75	100	125	150	175	200	225	250	300	350
No D-Cracking in 15 or More Years												
Cln-1	0.002	0.004	0.004	0.010	0.010	0.024	0.037	0.051	0.059	0.091	0.138	-
My-1	0.003	0.006	0.012	0.021	0.019	0.030	0.037	0.038	0.048	0.053	0.088	-
Pm-4	0.006	0.004[a]	0.008[a]	0.009[a]	0.027[b]	-	-	-	-	-	-	-
Sy-2	0.004	0.008[a]	0.010[a]	0.013[a]	0.016[a]	0.023[a]	0.028[a]	0.037[a]	0.048[a]	0.091[a]	0.121[b]	-
Sy-6	0.007	0.018	0.028	0.039	0.053	0.081	0.117[b]	0.145[b]	0.155[b]	0.197[b]	0.305[b]	-
Vt-3	0.003	0.005	0.008	0.014	0.018	0.024	0.031	0.036	0.036	0.041	0.055[a]	-
Wt-1	0.000	0.003	0.008	0.006	0.007	0.008	0.010	0.008[a]	0.016[a]	0.023[a]	0.030[a]	-
Wt-8	0.008	0.011	0.018	0.021	0.063	0.073[a]	0.054[a]	0.057[a]	0.056[a]	0.062[a]	0.048[b]	-
D-Cracking in Less Than 15 Years												
Cgn-1	0.006	0.006	0.008	0.010	0.018	0.023	0.027	0.036	0.098	0.122	0.094[a]	-
Del-5	0.010	0.015	0.020	0.025	0.033	0.044	0.049	0.063	0.073	0.081	0.126	-
Fn-6	0.004	0.004	0.007	0.008	0.016	0.019	0.024	0.036	0.073	0.077	0.131[a]	-
Kx-13	0.010	0.012	0.020	0.029	0.035	0.040	0.048	0.061	0.066	0.092	0.073	-
Mn-3	0.011	0.015	0.020	0.028	0.033	0.045	0.051	0.060	0.075	0.088	0.114	-
Mi-6	0.019	0.023	0.047	0.041[a]	0.051[a]	0.058[a]	0.076[a]	0.088[a]	0.098[a]	0.145[a]	0.160[b]	-
My-16	0.002	0.006	0.009	0.015	0.017	0.033	0.055	0.100	0.103[a]	0.156[a]	-	-
Rs-8	0.007[a]	0.024[b]	0.061[b]	-	-	-	-	-	-	-	-	-

Note: Each value represents the average expansion for three specimens unless otherwise noted.
[a]Two specimens.
[b]One specimen.

Table 3. Results of method B freeze-thaw test.

Source of Coarse Aggregate	Expansion by No. of Cycles (%)											
	25	50	75	100	125	150	200	250	300	350	400	450
No D-Cracking in 15 or More Years												
Cln-1	0.002	0.003	0.004	0.005	-	0.005	-	0.004	0.007	0.005	0.003	0.005
My-1	0.002	0.003	0.003	0.000	0.001	0.003	-	0.005	0.004	0.002	0.004	0.004
Pm-4	0.003	0.004	0.003	0.003	0.011	0.003	-	0.002	0.004	0.002	0.002	0.004
Sy-2	0.003	0.004	0.004	0.002	0.002	0.005	-	0.008	0.008	0.005	0.008	0.008
Sy-6	0.003	0.004	0.006	0.006	0.013	0.007	-	0.007	0.008	0.007	0.008	0.011
Vt-3	0.002	0.003	0.001	0.000	0.001	0.004	-	0.007	0.006	0.003	0.004	0.004
Wt-1	0.003	0.003	0.003	0.000	0.001	0.004	-	0.005	0.005	0.003	0.004	0.005
Wt-8	0.002	0.003	0.002	0.000	0.001	0.003	-	0.006	0.007	0.005	0.005	0.006
D-Cracking in Less Than 15 Years												
Cgn-1	0.002	0.003	0.005	0.005	0.012	0.006	-	0.008	0.009	0.009	0.009	0.012
Del-5	0.006	0.011	0.014	0.016	0.026	0.023	0.033	0.036	0.048	0.053	0.062	0.076
Fn-6	0.003	0.006	0.006	0.008	0.011	0.012	-	0.014	0.016	0.017	0.020	0.025
Kx-13	0.003	0.005	0.006	0.007	0.014	0.014	-	0.014	0.019	0.018	0.023	0.028
Mn-3	0.004	0.007	0.009	0.009	0.011	0.015	0.021	0.028	0.035	0.037	0.046	0.054
Mi-6	0.000	0.002	0.003	0.002	0.009	0.008	-	0.007	0.009	0.008	0.012	0.015
My-16	0.000	0.001	0.002	0.002	0.003	0.004	0.005	0.011	0.016	0.014	0.016	0.019
Rs-8	0.001	0.003	0.004	0.002	0.002	0.004	0.004	0.007	0.010	0.007	0.009	0.009

Note: Each value represents the average expansion for three specimens.

Figure 2. Expansions for freeze-thaw method A.

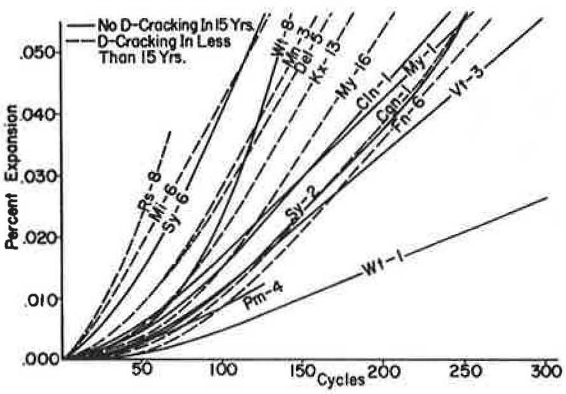
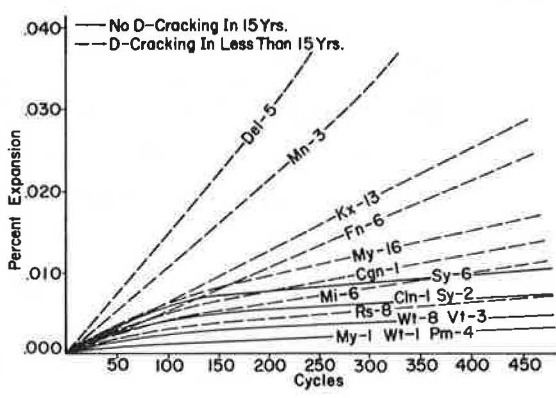


Figure 3. Expansions for freeze-thaw method B.



Unconfined

The four tests discussed previously have the disadvantage of requiring considerable time to complete. For this reason, it was decided to investigate other tests that could possibly give comparable results in less time. The New York DOT has such a test method: N.Y. 208A-68, entitled "Freezing and Thawing, Coarse Aggregates". The New York method called for testing material passing the 2-in sieve and retained on the 1.5-in sieve and material passing the 1.5-in sieve and retained on the 1-in sieve. The top size of material used in the earlier freeze-thaw test was the material retained on the 1-in sieve; therefore, it was decided to use this size and the material passing the 1-in sieve and retained on the 0.75-in sieve. The New York method called for using 3000 g of the larger material and 2000 g of the smaller material. In this testing, 2000 g of each of the sizes was tested. The temperatures required by the test method are -10°F ± 2°F and 70°F ± 5°F. The cycle used in New York consists of 17 ± 1 h at -10°F and the remainder of the 24-h cycle is used for thawing to 70°F. The test required that 25 cycles be run. With the equipment available at the ODOT Testing Laboratory, this cycle could be duplicated; in addition, it was found that the ODOT equipment had the capacity to complete four -10°F to 70°F cycles in a 24-h period. It was decided to run the test both ways and compare the results. The aggregates being tested are submerged in a 10 percent sodium chloride solution throughout the entire testing period. With the exceptions noted above, of the amount of material used and the number of cycles performed in a 24-h period, these tests were conducted in accordance with the New York DOT method. The same 16 coarse aggregates were tested by using these two methods, and the results are shown in Figures 6 and 7.

Figure 4. Area under curve for freeze-thaw method A at 250 cycles.

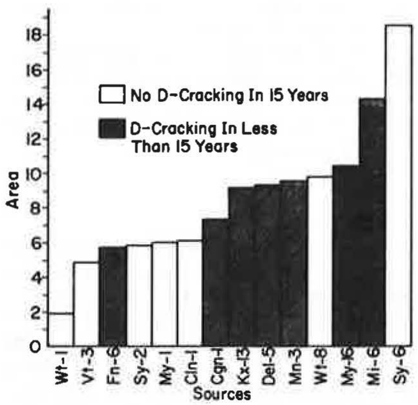


Figure 5. Area under curve for freeze-thaw method B at 350 cycles.

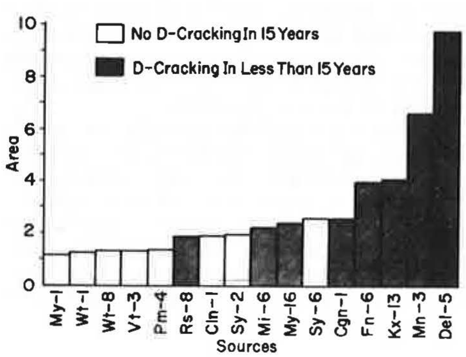
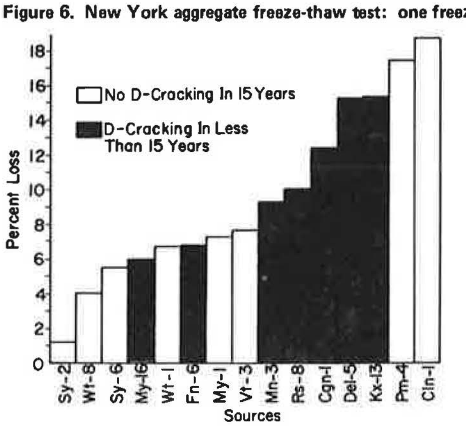


Figure 6. New York aggregate freeze-thaw test: one freeze-thaw cycle per day.



AGGREGATE TESTING FOR SOUNDNESS (SODIUM AND MAGNESIUM SULFATE)

The two other test methods used in this work were the American Association of State Highway and Transportation Officials (AASHTO) methods for testing for sodium sulfate soundness loss and magnesium sulfate soundness loss. The same 16 aggregate sources used in the previous testing were tested by using these two methods. These tests were conducted in accordance with AASHTO T-104, the standard AASHTO method. The results of these tests are shown in Figures 8 and 9. ODOT currently tests aggregates for soundness in sodium sulfate as a normal part of the aggregate specifications.

Figure 7. New York aggregate freeze-thaw test: four freeze-thaw cycles per day.

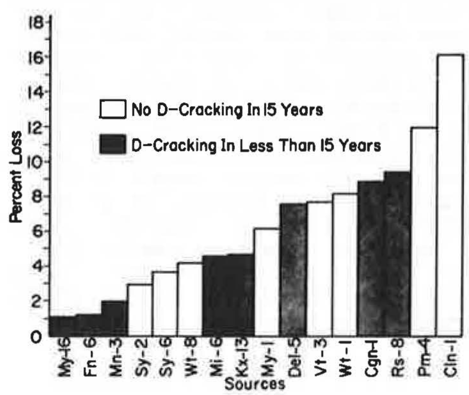


Figure 8. Sodium sulfate soundness test.

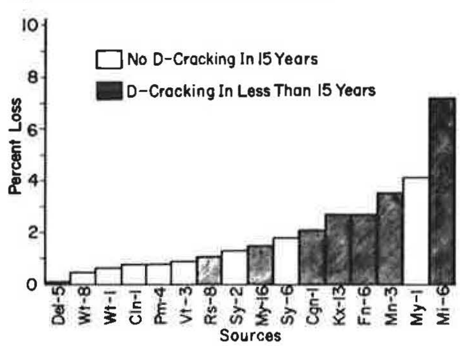
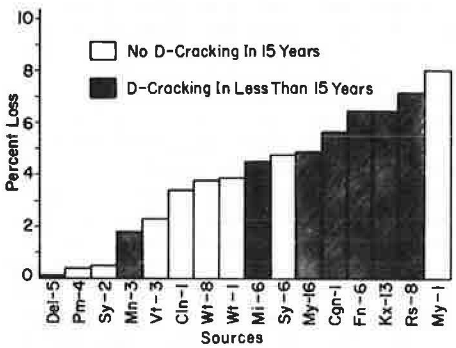


Figure 9. Magnesium sulfate soundness test.



DISCUSSION OF TEST RESULTS

Two major problems that have been encountered in freeze-thaw testing of concrete prisms by using method A of ASTM C666 are the gage pins falling out of the specimens and the specimens breaking before the testing reaches the desired number of cycles. This can be seen in Table 2 in that many of the specimen sets do not contain three specimens at the end of the testing. These two occurrences cannot always be attributed to the coarse aggregate in the specimens. In addition, the containers that hold the specimen and water for this test are a constant maintenance problem because of bulging and cracking caused by the pressures of the frozen water.

The freeze-thaw method B test is the most desirable, since any effect brought about by the containers is eliminated. The major drawback to using method B has been that the expansions produced are small and it is therefore difficult to differentiate between those aggregates that cause D-cracking and those that do not in the same number of cycles as is used with method A. It was found that 12 cycles could be completed in a 24-h period when testing with method B whereas only 8 cycles could be completed in the same period when testing with method A. This made it possible to extend the method B test to obtain the differentiation between the D-cracking and non-D-cracking aggregates. It can be seen in Tables 2 and 3 and Figures 2 and 3 that differentiation and correlation with service record data are obtained for all sources except Rs-8 and Sy-6 as early as 300 cycles; however, it is still very difficult to select a distinct separation point until at least 350 cycles have been completed. At 300 cycles, there is very little difference between the areas and expansions of the good and bad aggregates. At 350 cycles, the area shows good differentiation, but there is still little difference between the expansions. It can be said with a fair degree of confidence, from looking at Figure 5, that, if after 350 cycles of method B testing the prisms have not expanded so that the area under the curve is more than 2.05, the aggregate being tested is not susceptible to D-cracking. No explanation has been found for the behavior of sources Rs-8 and Sy-6.

If one looks at the freeze-thaw testing of the aggregates alone, it can be seen that the correlation with the service record data is not as good as it is with the freeze-thaw testing of the concrete prisms. In examining Figures 6 and 7 it can be seen that, as the number of cycles per 24-h period is increased, the correlation with service record becomes worse because in Figure 7 three of the worst sources show the least loss. In addition, two of the sources, Pm-4 and Cln-1, which have very good service records, show very poor performance in these tests, whereas source Fn-6, which has a poor service record, shows rather good performance.

Both of the soundness tests show fair correlation with service record data; however, source Del-5, which has a very poor service record, does very well in these tests, whereas My-1, which has a very good service record, does very poorly.

CONCLUSIONS

Although the freeze-thaw testing of concrete may not be the only method of determining coarse-aggregate susceptibility to D-cracking, it has the best correlation with the service record data of the eight tests conducted for this work. Method B of ASTM C666 is better for the determination of aggregate susceptibility to D-cracking than method A because any effect of the containers is eliminated. In addition, the determination of the area generated under the curve is more suitable for determining aggregate D-cracking susceptibility than is a comparison of expansions because, once the area generated exceeds the maximum permitted, it will never go below this maximum. In some cases, the expansion will just exceed the maximum and at the next measurement will be just below the maximum.

Freeze-thaw testing of concrete containing these same coarse aggregates has been conducted by the PCA Laboratory, and the performance of the concrete in the test ranked the coarse aggregates in very nearly the same order as did the testing reported here. At least two other laboratories are looking for test methods to determine D-cracking susceptibility, and both are investigating the freeze-thaw of concrete specimens.

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