

Research as Related to the Development of Aggregate Specifications*

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Not many years ago aggregates were considered inert materials which served as a filler and, when combined with certain cementitious materials, produced concrete. Years of laboratory study, combined with field experiences, have taught us that aggregates are not inert and that they are a very vital part of a bituminous-aggregate mixture or a portland cement-aggregate mixture. When it is considered that these materials constitute 75 percent of the total volume of a paving mixture, it is little wonder that engineers are considering the properties of aggregates with increasing interest.

Field surveys of the performance of pavements—both bituminous and portland cement concrete—show striking correlations between the source of coarse aggregates and the performance of the pavement. These findings have been taken to the laboratory, where large-scale research projects have been set up in many sections of the country. The results of both the field and laboratory work indicate that the standard tests, which have been used for many years for acceptance or rejection of mineral aggregates, are not adequate for an accurate determination of the important physical and chemical characteristics of aggregates. The research data developed to the present time indicate that new methods of test are required and that new ideas in specifications are to be forthcoming. The great number of reports that have appeared in the past ten years indicate that the major aggregate problems for which standard acceptance tests are inadequate are: (a) mapcracking, disintegration, and associated blowups of portland cement concrete in many sections of

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the Midwest; (b) portland cement concrete deterioration in which certain types of aggregates react adversely with high alkali cements; and (c) stripping of bituminous films from certain types of aggregate materials. This paper is concerned chiefly with the first of these problems, especially as it pertains to Indiana aggregates, with some mention of the problem of alkali-aggregate reactions.

FIELD-PERFORMANCE SURVEYS

For at least 20 years engineers have been able to correlate certain types of mapcracking and associated concrete deterioration with the source of coarse aggregates. In one of the early Highway Research Board reports, McCown (31)** included abstracts of several published reports from various state highway departments in connection with his committee report on "The Significance of Sodium Sulfate and Freezing and Thawing Tests of Mineral Aggregates." In this report, a discussion from Iowa described the mapcracking of certain structures and indicated that this difficulty may have been caused by the use of an argillaceous limestone obtained near Davenport, Iowa. In the same report, Pennsylvania indicated a correlation between poor performance of a particular section of portland cement concrete pavement and the use of an argillaceous limestone as coarse aggregate.

In 1938 Gibson (13) reported an extensive study in connection with the use of sand and gravel from the Kaw, Arkansas, and Platte rivers. He indicated that portland cement concrete pavements were severely cracked in Kansas and that sand and gravel from the Platte River in Nebraska has caused serious mapcracking of concrete pavements in Kansas, Missouri, and Nebraska. Gibson described these aggregates as predominantly siliceous in character. A few years later, White and Peyton (55) reported an extensive performance survey of Kansas portland cement concrete pavements. These authors reported extensive mapcracking with Moline and Kansas City limestones, Bazaar gravel, and Joplin flint.

In 1939, Cantrill and Campbell (9) reported on the use of gravels from the Cumberland and Tennessee Rivers in Kentucky. The materials are cherty in character and have relatively high absorptions (approximately 5.5 percent). These authors concluded, on the basis of performance surveys, that "the failure of concrete pavements throughout the western part of the state was due to the use of chert gravel obtained from the Tennessee and Cumberland Rivers in western Kentucky."

** Figures in parentheses indicate references listed in the Bibliography, page 168.

A great deal of field and laboratory work has been done in Missouri, with one of the early reports on the use of chert being made by Reagel (38). Later, Reagel and Gotham (40) reported the results of performance surveys on four thousand miles of concrete pavements in Missouri. They stressed the importance of transverse cracking and blowups as indications of inferior pavement performance.

Moyer (34) and Spangler (44) reported the performance of LeGrand limestone in connection with paving projects in and near Ames, Iowa. Moyer stated that "the LeGrand limestone when used in concrete pavements, contributes to considerable volume change or 'growth', as is evidenced from the large number of 'blowups' on the project where no expansion joints were used. At the same time, this aggregate exhibits properties of unsoundness when used in the pavement with expansion joints, which are not indicated by the usual laboratory freezing and thawing soundness testing." He also reported cracking and volume change of pavements made with aggregates from the Platte River. Spangler (44) stated that the incidence of corner breaks associated with the use of LeGrand limestone was nearly four times as great as on the Alden limestone sections.

In 1945, Woods, Sweet, and Shelburne (60) reported the results of an extensive performance survey made in Indiana covering 3,300 miles of portland cement concrete pavements which represented approximately 78 percent of all concrete pavements constructed in Indiana between 1921 and 1943. Two thousand six hundred and twenty-three miles of this total were constructed before 1935 and did not contain expansion joints. This mileage included a total of 725 projects, with cements from 17 sources, fine aggregates from 138 sources, and coarse aggregates from 155 sources. Considerable attention was given in the survey to mapcracking and blowups. It was concluded in this work that an outstanding correlation existed between certain sources of coarse aggregates incorporated in the concrete mix and the susceptibility of the finished pavement to blowing-up and mapcracking. Likewise, it was shown that correlation existed between the use of certain other coarse aggregates and the lack of blowups and mapcracking in the completed pavements. In regard to these two points, the following is quoted from the published report:

"316.8 miles of pavements constructed prior to 1935 from 17 sources of supply had a total of only two blowups."

"1715 miles constructed from 82 sources of supply contained a total of only 203 blowups."

"284 miles of pavement constructed from 5 sources of supply contained 1168 blowups (49 percent of the total blowups)."

“One of the five sources was used in the period from 1926 to 1934 to construct 97.1 miles of pavement and contained 708 blowups. (29.4 percent of the total blowups).”

When consideration is given to the fact that correlation did not exist between performance and the type of cement used, the type of fine aggregate used, the time of year constructed, the type of subgrade, and other similar variables, it appears that coarse aggregate is an important factor in the performance of portland cement concrete pavements in Indiana. When these data are combined with those from other Midwestern states, Kansas (13), Missouri (40), Kentucky (9), and Iowa (31), it appears that coarse aggregate is a matter of considerable concern throughout the Midwest. This point is further emphasized when it is pointed out that these coarse aggregates, at least those used in Indiana, met and still will meet most of the commonly employed acceptance tests developed for specification purposes.

LABORATORY RESEARCH PROGRAMS

PREVIOUS INVESTIGATIONS

In an endeavor to determine the reasons for the recorded pavement performances, many laboratories have developed extensive research programs. In 1931 McCown (31) reported an assemblage of data from many laboratories—particularly in regard to the significance of the sodium sulfate and freezing-and-thawing tests on mineral aggregates. Iowa reported inferior field results in the use of the Cedar Valley limestone, and Illinois reported poor resistance to the sodium sulfate soundness test of Cedar Valley limestone in Illinois. The later reports by Spangler and Moyer on the continued poor performance of pavements constructed with Cedar Valley limestone (upper Devonian Age) added emphasis to the suspicion that this particular argillaceous limestone is unsound when used in portland cement concrete. Not too different in appearance is the Kokomo limestone in Indiana (upper Silurian), which has a notoriously bad performance record. However, in the case of the Kokomo limestone, sodium sulfate tests do not always show the material to be unsound. In this same report (31) Sholer intimated that unsound aggregates can be identified by testing laboratory-made specimens when he stated that “tests of aggregate should include tests in concrete before any source is condemned.”

Gibson (13), in connection with studies of the gravels from the Kaw, Arkansas, and Platte rivers, reported the mapcracking of beams subjected to alternate cycles of wetting and drying. Withey (58), in

1944, in connection with a Highway Research Board committee on durability of concrete, encouraged the use of concrete-durability testing by freezing and thawing, using the dynamic modulus of elasticity to measure deterioration. The committee pointed out further: "The data emphasized the necessity for regulating carefully the methods of making and curing specimens, the air content of the specimens, the degree of saturation of the aggregate at the time of making, and the degree of saturation of the concrete at the time of freezing." Jackson and Kellermann (19) reported the results of an extensive laboratory series in which Platte River gravel was used as one of three aggregates. They subjected laboratory-made concrete beams containing the various coarse aggregates to alternate wetting at 70°F followed by drying in air at 130°F. They stated that "these tests revealed abnormal expansion in all combinations which involve the use of Platte River gravel as total aggregates." Axon, Willis, and Reigel (6) associated mapcracking and blowups with the source of coarse aggregate in a laboratory study and concluded that "freezing and thawing was the most active weathering agent causing the disintegration."

Much attention has also been devoted to the problem of concrete deterioration, which has been attributed to excessive expansion caused by reactions between certain aggregates and the alkalis of some cements. Stanton (46) was the first to describe this problem in detail, but much additional work has been done by the Bureau of Reclamation (41), by Committee C-9 on Concrete and Concrete Aggregates and Committee C-1 on Cement, ASTM (2), and by testing and research laboratories of states on the west coast (51, 52). Although much progress has been made in developing means of identification of reactive aggregates in concrete, this work may still be considered in the development stage. Physical testing includes the mortar-bar expansion test in which the aggregate in question is combined with a high-alkali cement. Some work has been done on chemical analyses of aggregates. Petrographic analyses (41) show good correlation between mineral content and the performance of aggregates in concretes.

RESEARCH WITH INDIANA AGGREGATES

Following the establishment of the definite and statistically-significant correlation of pavement performance with source of coarse aggregate in Indiana (60), comprehensive laboratory studies were set up in the Joint Highway Research Project laboratories. Both chemical and physical testing programs were established in an endeavor to determine the causes of the performance variations. Some results of the chemical

test program have been reported by Slate (43). To date, there appears to be no evidence of any detrimental chemical reactions between cements and the aggregates used in Indiana.

Physical testing, on the other hand, has resulted in some important results and correlations with field performance. These tests may be divided into two general classifications: tests of physical properties of the aggregates, and tests of concrete in which the various aggregates were used. Tests conducted on the aggregates have included sodium sulphate soundness, unconfined freezing and thawing, absorption, specific gravity, and determinations of pore space and size. The tests on concrete made with the various aggregates have consisted of freezing and thawing, wetting and drying, and thermal shock (heating and cooling) cycles with measurements of changes in strength, modulus of elasticity, and length to show the effects of the artificial weathering. Aggregates used in the tests range from very bad to outstandingly good in field-performance ratings, with the majority of tests conducted on those having the most definite good or bad records. Most of the tests were made on limestones; therefore the results discussed here pertain almost entirely to these materials, insofar as correlations of laboratory tests with field performance are concerned.

Physical Tests of Aggregates. Sweet (47) reported the results of tests on 16 coarse aggregate materials. The data reported show that there is no correlation between the sodium sulphate soundness test results and the field performance of the materials. The same conclusion has been made by other investigators, and is also shown by an analysis of the records of such tests made by the State Highway Commission of Indiana (26).

A correct separation of materials from the standpoint of field performance could be made from the freezing-and-thawing tests of the aggregates in a vacuum-saturated condition (47). However, the losses for the bad field-performing materials do not fall in a close range as do their field records, and in one case the loss was very low for a material with a very bad field-service record.

The results of the microscopic studies of void characteristics show an outstanding correlation with field performance. The volume of voids smaller than 0.005 mm in diameter was less than six percent of the volume of solids for the materials with good field performance, and more than 10 percent for those with poor field performance records. Sweet concluded that: "The volume of pores smaller than 0.005 mm in diameter appears to be a critical index of field durability of Indiana aggregates, probably because of the influence of pore size on water-retention and capillary characteristics of the rock material." Numerous

TABLE 1
ABSORPTION AND DEGREE OF SATURATION DATA FOR INDIANA
AGGREGATES

Aggregate	24-hour Immersion		Evacuation and Saturation		Ratio of 24-hr. Absorption to Evacuation
	Absorption %	Degree of Saturation	Absorption %	Degree of Saturation	
<i>Good Field Performance</i>					
1-1S*	1.4	55	2.2	82	.67
90-1S*	2.4	52	3.9	86	.62
67-2S	0.7	51	0.8	55	.93
59-1S	1.1	74	1.4	78	.79
	0.7	59	0.9	82	.78
60-1S	0.5	53	0.7	62	.71
	0.6	62	0.7	69	.86
	0.7	58	0.8	62	.88
<i>Bad Field Performance</i>					
9-1S	6.0	71	8.3	98	.72
35-2SCh	5.9	93	6.2	98	.95
47-2S	1.7	71	2.4	90	.71
3-1S "D"	5.7	75	7.4	97	.77
3-1S "H"	4.8	80	5.8	90	.83
40-3S	3.0	66	4.0	91	.75
34-2S	5.4	70	7.2	93	.75
<i>Unclassified Performance</i>					
71-1S	2.2	74	2.6	85	.85
67-8S	....	....	2.4	70	....
	....	....	2.0	75	....
	....	....	1.7	55	....
27-2S	0.7	83	1.0	86	.70
	1.9	73	2.0	80	.95
47-10S	1.4	77	1.5	88	.93
	0.3	54	0.4	67	.75
54-1S "A"	1.3	76	1.4	85	.93
54-1S "B"	3.9	72	5.3	97	.74
54-1S	3.2	92	3.5	96	.91
	3.8	72	5.2	96	.73
9-2S	1.8	47	3.6	93	.50
	2.9	58	4.8	95	.60
	6.5	73	8.5	96	.76
* 1.5	0.6	30	1.1	48	.55
	* 2.7	34	4.0	84	.38
* 2.7	* 2.7	51	5.1	97	.53
	28-2S*	4.3	59	6.3	91	.68
Reef Rock*	1.0	35	3.0	88	.33
	3.0	52	6.5	89	.46
	1.5	56	2.6	88	.58

* Aggregate samples known to have voids of macroscopic size.

field observations (49) also indicate that the moisture-absorption characteristics of the coarse aggregate materials have an important bearing on the durability characteristics of the resulting concrete.

Sweet shows no correlation of aggregate absorption or degree of saturation with field performance, possibly because of variation of individual tests and the inclusion of one gravel (82-1G) in the test results. Table 1 shows the *average* absorption and degree of saturation data reported by Sweet (excluding the gravel aggregate) and similar data for other Indiana aggregate sources. Where more than one set of values is given for an aggregate source, results for individual samples from different ledges and sample locations are shown. The aggregates referred to by Sweet as having "suspicious" field performance records are reclassified as "bad" on the basis of later performance surveys.

The average values for absorption by evacuation show only one bad material below 4.0 percent; none of the absorption values for the good aggregates are that high. The minimum absorption figure for a bad aggregate, 2.4 percent for 47-2S, is exceeded by only one good aggregate—90-1S, which has an absorption of 3.9 percent. 90-1S has a very low percentage of voids less than 0.005 mm in diameter, and might not become so fully saturated under natural conditions. The correlation of degree of saturation (percentage of the voids filled with water) by evacuation with field performance is very good. The degree of saturation for all the bad materials is 90 percent or higher, while that of the good aggregates is 86 percent or less. Only one of the aggregates with good field-performance records exceeded 82 percent saturation, 90-1S. The ratios of absorption by 24-hour immersion to absorption by evacuation show an interesting trend that may be indicative of the size of voids in the aggregate. All the aggregates known to have a considerable number of voids of macroscopic size have values of this ratio less than 0.69. Most of the other materials and all of those shown by microscopic study to contain a high percentage of very small voids show absorption ratio values higher than 0.69.

Tests of Concrete. The tests of concrete beams reported by Sweet (47) show that concrete made with aggregate in a highly saturated condition deteriorates rapidly in freezing-and-thawing tests, as shown by decreased strength and modulus of elasticity, and elongation and cracking of the specimens. Aggregates with a low degree of saturation at the time of incorporation in the concrete caused very little deterioration. The limestone aggregates tested fell into three groups: (a) those with more than 3.9 percent absorption and more than 86 percent saturation at the time of incorporation in the concrete caused rapid deterioration; (b) those with an absorption of two to three percent and degree

of saturation greater than 82 percent were intermediate in resistance to freezing and thawing; and (c) high resistance to freezing and thawing was shown by concrete containing aggregate with less than two percent absorption and a degree of saturation of less than 80 percent.

When the aggregates were incorporated in the concrete with degrees of saturation comparable to their natural "quarry-wet" moisture condition, the freezing and thawing durability correlated with field performance, without exception. The limestones with good field-performance records had less than 10 percent decrease in modulus of elasticity in more than 100 cycles of freezing and thawing, while those with poor performance records lost more than 30 percent of their original modulus of elasticity in less than 40 cycles.

It appears probable that the field moisture content is an indication of the susceptibility of the materials to absorption and retention of sufficient water to obtain a high degree of saturation. The materials which had a low degree of saturation in their natural state were those with small percentages of voids less than 0.005 mm in diameter and good field performance. The aggregates with poor field performance and high percentages of very small voids were found to have a high degree of saturation in their "quarry-wet" condition.

Sweet states:

As a result of this investigation, it is concluded that Indiana coarse aggregates with poor field performance can be differentiated from those with good performance by freezing-and-thawing tests of concrete beams containing the aggregates.

It is indicated further that Indiana aggregates without established field records can be evaluated on the basis of freezing-and-thawing tests on concrete. In such tests the aggregate should be incorporated in the concrete in a vacuum-saturated condition with the exception of materials with a ratio of less than 0.06 between the volume of pores smaller than 0.005 mm in diameter and the volume of solids. In the latter instance, the aggregates should be tested at a lower degree of saturation than that obtained by evacuation unless their moisture contents in the quarry-wet state correspond to those obtained by vacuum saturation.

Furthermore, the mortar in the concrete should have a low degree of saturation. Because the influence of other variables, such as the type of freezing-and-thawing test and the character of the cement, is imperfectly understood, the tests should be set up on a comparative basis, comparing the laboratory results on beams containing the aggregate in question to results of tests with other materials with established field performance.

Some indication of the maximum percentage of deleterious materials that might be permissible in an aggregate can be obtained from the data

reported by Sweet (47) on freezing-and-thawing tests of concrete made with combinations of aggregates. In these tests, aggregate 67-2S with good field performance was combined with varying percentages of 82-1G, 9-1S, and 35-2S chert, all of which have bad field-performance records. Concretes which contained more than 15 percent of 35-2S chert, 25 percent of 9-1S, or 75 percent of 82-1G were unsatisfactory in resistance to freezing and thawing—their rates of deterioration were in the same range as the deterioration rates for concretes in which all the aggregate was uniformly bad material. Gravel 82-1G is not homogeneous, and the percentage of deleterious material in it is unknown. However, the results with the more homogeneous materials 9-1S and 35-2S chert indicate that the percentage of highly saturated deleterious material in the coarse aggregate must be less than 25 percent if concrete of even intermediate durability is to be obtained. If good durability were obtained, a limit considerably less than 25 percent would probably be required.

The effects of air entrainment on the freeze-and-thaw durability of concrete containing aggregates with varying field-performance records and under different aggregate saturation conditions have been investigated and reported by Bugg (8) and Blackburn (7). The principal results of these studies as they affect the general aggregate problem may be summarized as follows:

- (a) With air contents of approximately three percent (sufficient air to prevent saturation of the mortar during curing) and vacuum-saturated limestone aggregates, the relative durabilities correspond to field-performance ratings.
- (b) Gravel aggregates cannot be compared with the limestones on the basis given above. Bugg (8) reports the deterioration of concrete made with a gravel (79-1G) having fairly good field performance that is very little less than the deterioration caused by 9-1S, a stone with a very poor field performance record. Similarly, a study of Blackburn's data indicates that concrete made with 79-1G deteriorated about as rapidly as did the bad stones tested (comparison made with approximately three-percent-air and vacuum-saturated aggregate).
- (c) Both studies show greater durability for aggregates at low moisture contents (24-hour immersion compared to vacuum saturation).
- (d) Air entrainment is shown by both to greatly increase the durability of concrete made with crushed stones which have poor field-performance records. Gravels were benefited very little

by air entrainment. Since all of the freeze-and-thaw tests were started at the end of a 28-day curing period, whether or not the increased durability with air entrainment would hold under other exposure conditions is unknown.

- (e) Blackburn's tests show improved durability for concretes that are permitted to partially dry before the start of freeze-and-thaw testing.

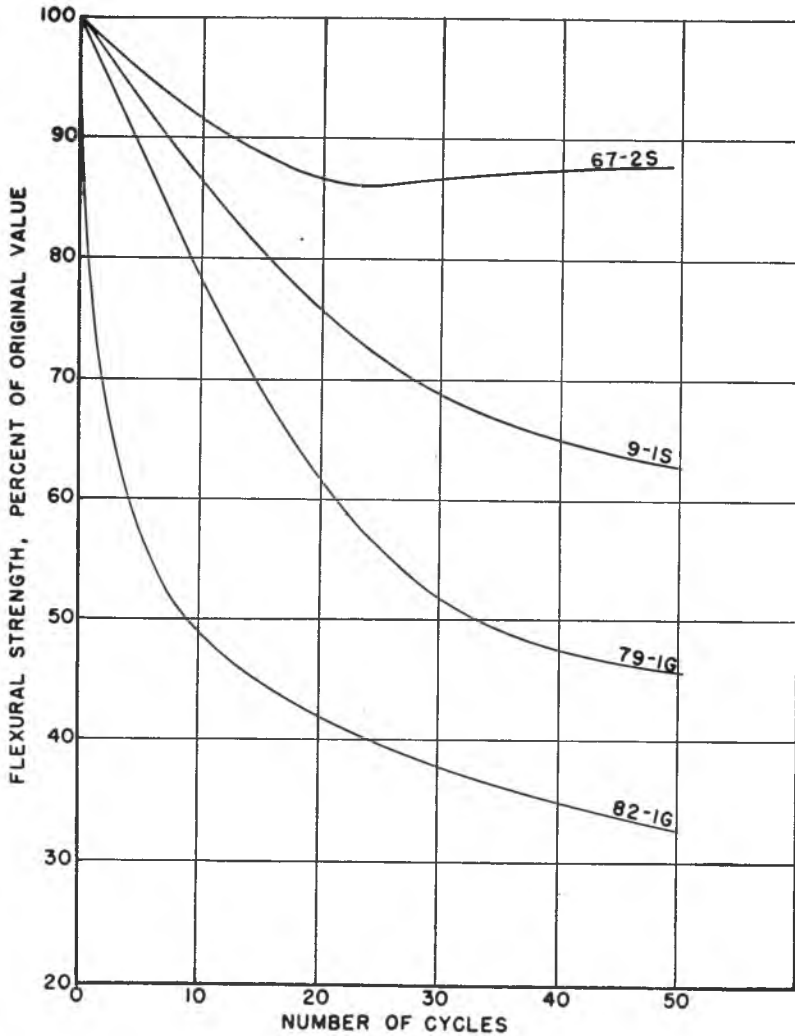


FIGURE 1. Effect of three-hour (34° - 130°) thermal shock test on flexural strength of 2" x 2" x 11" concrete beams.

These test series, in general, emphasize the importance of the effect of the moisture content of the aggregate on the durability of concrete in freezing and thawing, and indicate that the use of air entrainment and any construction practices that would aid in keeping the moisture content of the concrete and aggregate low would improve the durability of concrete made with poor aggregates. The extent of such improvement under field conditions cannot, however, be forecast on the basis of data available at the present time.

Other laboratory studies conducted by the Joint Highway Research Project include thermal-shock and coefficient-of-expansion tests of limestones and concretes. The coefficient-of-expansion tests (29) were limited in scope but showed higher coefficients for aggregate with a bad field-service record than for good material. The same trend was shown by concrete made with the aggregates, the bad material having the higher coefficient of expansion. This factor may, at least partially, account for the difference in blowup performance.

The results of the thermal-shock tests (29, 27) may provide a clue to the cause of the discrepancies between gravels and stones when subjected, in concrete, to the same freeze-and-thaw cycles. Typical results from this test are shown in Figure 1, where the loss in strength for concretes made with various aggregates is plotted against the number of cycles in which the beams were alternated from hot- to cold-water baths. Aggregate 67-2S, with good field performance, shows the least strength loss; 82-1G, a gravel with poor field performance, has the highest loss in strength. The other materials are reversed from their field-performance ratings, 9-1S having a very bad field record while 79-1G is a gravel with a fairly good record. These results indicate that the gravels are much more susceptible to damage by severe temperature changes without freezing than are the stones. The thermal shock involved in the freezing-and-thawing test, in transfer of the specimens between freezer and thawing tank, may be the cause of part of the apparently excessive deterioration suffered by concrete made with gravel aggregates.

CONCLUSIONS

The data and results of field and laboratory studies that are now available, not only in Indiana but throughout the Middlewest, indicate that:

1. A definite and serious problem of concrete durability exists.
2. In many instances, the field performance of the concrete pavements has been correlated with the source of the coarse aggregate used.

3. The standard commonly-used acceptance tests for aggregates, although probably of significance when testing materials for other types of exposure, are not adequate to differentiate between good and bad aggregates for portland cement concrete.
4. New tests and specifications are needed for concrete aggregates to prevent the continued use of materials that result in non-durable concrete.

In the case of Indiana aggregates a large amount of laboratory testing has been carried out. Information on the durability characteristics of concretes and aggregates is incomplete, and several laboratory and field studies are still under way with even more studies being planned. However, it is believed that the data now available justify the following conclusions regarding Indiana aggregates:

1. The effect of freezing and thawing on some materials in a highly-saturated state is the primary factor in their lack of durability in concrete. The absorption and pore or void characteristics of the materials determine their susceptibility to this type of damage.
2. Correlations with field-performance records justify consideration of the following for use in quality specifications of crushed stone for concrete aggregate:
 - a. Percentage of voids less than 0.005 mm in diameter based on microscopic studies.
 - b. Absorption and degree of saturation of the aggregates under vacuum. Proper consideration would have to be given the probability of the materials attaining high saturation by this test but not under field conditions. Apparently the "quarry-wet" degree of saturation, the ratio of 24-hour absorption to evacuated absorption, and the void-size characteristics all furnished an indication of this.
 - c. Freezing-and-thawing tests of concrete in which the aggregates are incorporated in a saturation condition comparable to the degree of saturation that may be attained in field use. Comparative tests should be used, with the unknown material compared to an aggregate of known service durability. Proper control of air content and degree of saturation of the mortar would be necessary.
3. If, for economic reasons, it seems desirable to use a doubtful or inferior aggregate, the concrete durability may be improved by:
 - a. Use of air entrainment.

- b. Drying of aggregate before incorporation in the concrete.
 - c. Use of base courses, subgrade drainage, summer construction, etc., to insure that the concrete becomes and remains as dry as possible before freezing and thawing begins.
4. More investigation is necessary before definite recommendations can be made regarding gravels. If any attempt were to be made to apply the tests suggested above to gravels, it would appear logical to conduct the void size, absorption, and degree-of-saturation tests on the separate lithologic components of the material, and to use a good-performing gravel as the standard for comparative freezing-and-thawing tests.

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