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Bulletin 94

# Deleterious Constituents Of Indiana Gravels

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# *Deleterious Constituents Of Indiana Gravels*

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# Deleterious Constituents of Indiana Gravels

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This paper reports results of tests on Indiana gravels ranging from good to poor in field performance in portland-cement concrete. The gravels were separated by liquid flotation into various specific-gravity ranges. The gravel fractions thus obtained were tested to determine absorption, specific gravity, degree of saturation, lithologic composition and durability in air-entrained concrete subjected to freezing and thawing.

The results show that the principal deleterious constituents of Indiana gravels are sandstones and cherts. They are characterized by low specific gravity, high absorption and degree of saturation, and produce nondurable concrete when used as the coarse aggregate. The concrete durability can be improved by heavy-media separation of the aggregate. Greater durability is obtained as the specific gravity at which the separation is made is increased.

● FIELD performance surveys have shown that the durability of concrete pavements in Indiana was dependent upon the source of coarse aggregate used (1). Laboratory studies to find the cause of the poor concrete durability associated with the use of some aggregates have been underway for several years. A number of reports of the results of these studies have been published (2, 3, 4, 5, 6).

Among the more-important results to date are: (a) freezing and thawing of concrete containing highly saturated coarse aggregates is the major cause of the disintegration (4); (b) durability of concrete made with some poor aggregates can be improved with air entrainment (2, 3); (c) fine aggregate has little effect on durability of air-entrained concrete (6); (d) laboratory freezing-and-thawing tests on concrete containing vacuum-saturated aggregates correlate with the field performance of the materials (4); and (e) nondurable crushed stones are characterized by a high proportion of voids smaller than 5 μ in diameter and by a high degree of saturation (percentage of voids filled with water) under vacuum (4).

The tests for void size and degree of saturation cannot be applied to gravels since they consist of a heterogeneous mixture of many rock types. Some of the particles are durable, others are not; the average degree of saturation may be low even though the material has poor durability. Tests are needed to identify the nondurable materials in gravel aggregates and to determine the permissible limits of these constituents.

This paper reports the results of tests run on typical Indiana gravel aggregates to determine (a) the nature of the deleterious materials present, (b) their absorption and degree of saturation characteristics, and (c) the durability of concrete mixes in which they are used. Four gravels, ranging from good to bad in field performance, were tested. Initial tests (7) indicated the possibility of using heavy liquid flotation to separate the durable from the nondurable particles. This procedure had previously been applied to cherts by Wuerpel and Rexford (8) and Sweet (9). After heavy liquid separation, the gravels were subjected to absorption and degree of saturation tests, were separated by rock types, and were used in concrete subjected to freezing and thawing.

Two series of tests were conducted. The first, Series A, was designed primarily to determine the nature and characteristics of the deleterious materials in the gravels. Series B was conducted to find the effect on the durability of concrete of heavy media separation of one of the gravels at various specific gravity levels. This test series shows the results that might be obtained by field treatment of the type used in other localities (10, 11).

## MATERIALS AND TEST PROCEDURES

The sources and field performance records of the gravels used in this study are shown in Table 1. A fine aggregate from Source 79-1 was used in all concrete mixes. It has a good performance record.

Type I portland cement was used, with

TABLE 1

COARSE AGGREGATES

| Aggregate Source No | Field Performance | Geologic Source |
|---|---|---|
| 20-1G | Good | Glacial outwash, northern Indiana |
| 79-1G | Good | Glacial terrace, upper Wabash River |
| 84-1G | Poor | Glacial terrace, lower Wabash River |
| 82-1G | Bad | Dredged river gravel, Ohio River |

all mixes in a given test series made with cement from a single clinker batch. Cement 307 was used in Test Series A, Cement 310 in Series B. Since no comparisons are made between the two series of tests, the cement characteristics do not affect the conclusions and, therefore, are not included here. Vinsol resin, added at the mixer, was used as the air-entraining agent.

The heavy liquids were prepared by mixing carbon tetrachloride (specific gravity 1.58) and acetylene tetrabromide (specific gravity 2.97). The specific gravities of the mixtures were checked with a hydrometer.

½ to ¾ inch, ¾ to 1 inch and over 1 inch. After 24 hours immersion in water, each size of material was surface dried and separated into the specific gravity ranges < 2.44, 2.44-2.55, 2.55-2.66, and > 2.66 by use of heavy liquids. The resulting gravel fractions were washed and dried.

The absorption, bulk and true specific gravity, and the degree of saturation were then determined for each of the size and specific gravity fractions, using vacuum-saturation techniques. Samples from each fraction were also classified by rock type, basing the separation entirely on megascopic identification.

The difficulty of separating large quantities of the smaller sizes of the gravels with heavy liquids led to the use of a known durable crushed stone in the size range No. 4 to ½ inch for the concrete mixes. The ½-inch to 1-inch sizes were gravel, with the individual specific gravity ranges used where possible. In some cases, lack of sufficient material made it necessary to combine two of the ranges for the concrete mixes. The gravel fractions were vacuum

TABLE 2

CONCRETE MIX DATA FOR TEST SERIES A

| Aggregate Source | Flotation Sp. Gr. Range | Unit Weight | Cement Content | W/C by Wt | Air Content | Slump |
|---|---|---|---|---|---|---|
| | | lb./cu.ft | sacks/cu. yd. | | percent | in. |
| 20-1G | All | 144.0 | 6.35 | 0.427 | 4.5 | 2½ |
| | >2.66 | 145.6 | 5.80 | 0.486 | 4.0 | 3 |
| | 2.55-2.66 | 138.8 | 5.65 | 0.470 | 3.7 | 2 |
| | <2.55 | 138.8 | 6.10 | 0.463 | 4.4 | 3 |
| 79-1G | All | 151.9 | 6.48 | 0.480 | 3.6 | 2 |
| | >2.66 | 153.7 | 6.24 | 0.465 | 2.9 | 2 |
| | 2.55-2.66 | 148.7 | 6.32 | 0.472 | 3.1 | 6 |
| | <2.55 | 139.5 | 6.12 | 0.405 | 6.7 | 3½ |
| 84-1G | All | 147.2 | 6.35 | 0.540 | 4.4 | 3 |
| | >2.66 | 150.2 | 6.38 | 0.436 | 4.4 | 4 |
| | 2.55-2.66 | 144.0 | 6.08 | 0.520 | 3.4 | 4 |
| | 2.44-2.55 | 141.0 | 6.06 | 0.503 | 4.9 | 3 |
| | <2.44 | 142.5 | 6.40 | 0.450 | 4.9 | 4 |
| 82-1G | All | 147.3 | 6.30 | 0.476 | 4.1 | 3½ |
| | 2.55-2.66 | 148.0 | 6.30 | 0.500 | 4.3 | 2 |
| | 2.44-2.55 | 143.0 | 6.25 | 0.470 | 6.9 | 3½ |
| | <2.44 | 138.6 | 6.30 | 0.474 | 5.7 | 3 |

## Test Series A

Approximately a ton of gravel (State Highway Department of Indiana Size 5) was obtained from each of the four sources. Each gravel was then sieved into the size fractions No. 4 to ⅜ inch, ⅜ to ½ inch,

saturated before use in the concrete.

All concrete was machine mixed and cast into 3-by-4-by-16-inch beams, following the same procedures used in previous studies (2, 3). The beams were cured by immersion in water for 28 days. Three specimens from each mix were then frozen

in air at -15 F. to -20 F. and thawed in running tap water at 55 F. to 60 F. One cycle per day was obtained, with 16 hours freezing and 8 hours thawing. Periodic determinations of dynamic modulus of elasticity were made to measure the deterioration of each specimen.

The characteristics of the concrete mixes in Series A are shown in Table 2.

Test Series B

Only aggregate 84-1G was used in Series B. The general procedures for heavy liquid separation, concrete mixing, curing and testing were the same as those for Series A.

Four large samples of each size of the aggregate were obtained and each one separated by heavy liquids at one specific gravity level. The separations were made at 2.30, 2.40, 2.50, and 2.60. The fractions heavier and lighter than each of these values were vacuum saturated and the absorption and bulk specific gravity determined. No degree of saturation tests or separations by rock type were made on these samples.

Concrete mixes were made using the gravel fractions heavier than each specific gravity level. For these mixes in Test Series B, the separated gravel fractions were used as the entire coarse aggregate from No. 4 to 1 inch in size. The aggregate treatment and use, therefore, was similar to that obtained by field heavy media treatment methods.

Data on the concrete mixes in this test series are shown in Table 3.

all sizes of material from No. 4 to 1 inch, are shown in Table 4. The major difference in the results for the various sizes of gravel particles was the occurrence of higher percentages of low-specific-gravity material in the smaller sizes. The greatest difference was found in gravel 20-1G (good field performance) where the No. 4 to ⅜ inch size contained more than four times as much material in the < 2.44 specific gravity group as did the ¾ to 1 inch size. The least difference was shown by 84-1G (poor field performance) where only 1.5 times as much was found in the smallest size.

The average results for all sizes of particles from No. 4 to 1 inch are shown graphically in Figure 1. This data shows that the gravels with good field performance contained the smallest percentage of light-weight material. These sources, 20-1G and 79-1G, had 20 and 18 percent, respectively, of the total material below 2.55 in specific gravity. Gravels 84-1G (poor field performance) and 82-1G (bad performance) had 29 and 46 percent in these ranges. The percentage of light-weight material in the gravels is, therefore, correlated with the field performance; the larger amounts of low specific gravity particles resulting in poorer durability.

Absorption values vary greatly with specific gravity range but cannot be correlated with field performance. Materials in the specific gravity range > 2.66 had absorptions of one percent or less, regardless of the field performance of the gravel from which they were obtained. These values varied from 0.9 to 1.8 percent for

TABLE 3

CONCRETE MIX DATA FOR TEST SERIES B

Data shown are the average values for two mixes made with gravel 84-1G in the flotation specific gravity ranges indicated.

| Specific Gravity Range of Aggregate | Unit Weight | Cement Factor | W/C by Wt. | Air Content | Slump |
|---|---|---|---|---|---|
| | lb /cu. ft | sacks/cu. yd | | percent | in |
| All | 146.0 | 6.21 | 0.432 | 5.1 | 2⅛ |
| >2 30 | 148.1 | 6.30 | 0.452 | 4.8 | 2 |
| >2 40 | 147 4 | 6 23 | 0 439 | 5 7 | 3 |
| >2.50 | 147.5 | 6.20 | 0.445. | 6 0 | 3 |
| >2 60 | 148.0 | 6.20 | 0 471 | 6.1 | 4 |

## TEST RESULTS

Series A

Absorption, Specific Gravity, and Degree of Saturation. The results of the absorption, specific gravity, and degree of saturation tests on the individual samples of Series A, and the average results for

the 2.55 to 2.66 specific gravity range and from 2.8 to 3.9 percent for the 2.44 to 2.55 material. Much greater absorptions were found in the specific gravity range < 2.44, the test values varying from 6.7 to 8.5 percent.

The degree-of-saturation data vary in approximately the same manner as the

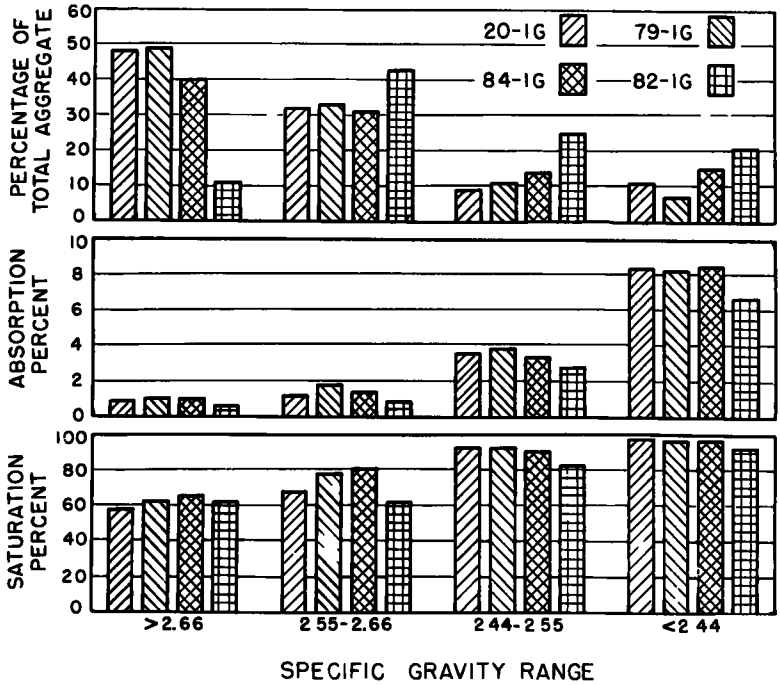


Figure 1. Specific gravity, absorption, and degree of saturation for Test Series A. All values shown are the averages for the particle sizes No. 4 to 1-inch.

absorptions. Materials in the higher specific gravity range had degrees of saturation of 58 to 66 percent. The values for the lowest-specific-gravity materials were 93 to 98 percent.

These data show that, regardless of source or field-performance record of the aggregate, the absorption and degree of saturation increased as the specific gravity of the gravel fraction decreased. It will be noted that the gravel with the poorest record (82-1G) had the lowest actual absorption and degree of saturation values. This gravel appeared to have a concentration of iron compounds in a thin surface zone of each particle. In addition to any possible effect on the amount of absorption, the true specific gravity would be increased by such a condition. This could result in the calculation of a lower degree of saturation than actually existed in the interior of the particles.

Separation by Rock Type. The data on percentages of the various rock types present in each specific gravity range of the four gravels tested in Series A are shown in Table 5. The results shown are the averages for the sizes No. 4 to 1 inch. The predominant materials in the lower ranges of specific gravity were sandstones and cherts with calcareous materials next in quantity, except in 82-1G which contained no limestone or dolomite. Igneous, calcareous and nonfoliated metamorphics were the predominant materials in the higher ranges. It was observed that most of the material, other than sandstone and chert, in the two-lowest ranges of specific gravity appeared to be badly weathered. The low-specific-gravity sandstones were much softer than those in the high specific gravity ranges.

The gravels with the poorest field-performance records contained the highest percentages of sandstone and chert. In addition, larger portions of these materials were in the lower ranges of specific gravity. This tendency was especially pronounced in the case of the cherts. In the gravels with good field performance, 70 percent of all chert present had a specific gravity less than 2.55. Corresponding figures for the poor and bad sources were 73 and 86 percent, respectively.

Freezing and Thawing in Concrete. Figure 2 shows the results obtained in the freezing-and-thawing tests on concrete containing the gravel fractions of varying

specific gravity ranges. Similar results were obtained for each of the gravel sources tested: the durability of the concrete varied with the specific gravity range of the aggregate. All concretes made with aggregate fractions less than 2.55 in specific gravity lost 25 percent of their original E values in less than 15 cycles of freezing and thawing. Those containing the higher specific gravity aggregates required at least 60 cycles to cause the same loss, and only the mixes with the lowest air contents deteriorated to that extent in 150 cycles. It is evident that, in air-entrained concrete, the use of the gravel fractions < 2.55 in specific gravity resulted in poor durability; use of the heavier aggregate fractions produced durable concrete.

For each of the gravels tested, the durability curve for all specific gravities (unseparated) occupied an intermediate position with respect to the curves for the individual specific gravity ranges. This position reflects the effect of their composition: mixtures of both the durable and nondurable fractions. The durabilities of the unseparated gravels correspond to their field-performance records, with 20-1G and 79-1G the best, 84-1G intermediate and 82-1G the poorest.

## Series B

Absorption and Specific Gravity. The specific gravity and absorption values for the various flotation-specific-gravity fractions of gravel 84-1G tested in Series B are shown in Table 6. As in the previous test series, the smaller sizes of the aggregate contained the larger amounts of low-specific-gravity material. The absorptions decreased as the specific gravity increased. Based upon the average values for all sizes, the absorption varied from 15.0 percent for the <2.30 group to 1.1 percent in the >2.60 fraction.

Despite the great differences in lithologic composition of the various specific-gravity groups, the absorption and BSSD specific gravity values plotted in Figure 3 form a smooth curve. This would indicate that an aggregate having values of specific gravity and absorption corresponding to any point on the curve could be obtained by separating gravel 84-1G at the proper specific gravity level. Data from the Series A tests, when plotted, produces curves nearly identical to that shown in Figure 3, indicating that all of the gravels have the same characteristic in this respect.

Freezing and Thawing in Concrete. Only the aggregate fractions heavier than each of the specific gravity levels at which separations were made were used in concrete mixes. The results of the freezing-and-thawing tests on these concretes are shown in Figure 4.

The poorest durability is shown by all specific-gravity ranges (unseparated gravel). Use of the material >2.30 in specific gravity increased the durability only slightly, raising the separation level to 2.40 resulted in considerable improvement. Both of the heaviest fractions, >2.50 and > 2.60, had excellent durability. The increase from 2.40 to 2.50 provided the greatest improvement of any single in-

TABLE 4

SPECIFIC GRAVITY, ABSORPTION, AND DEGREE OF SATURATION DATA FOR TEST SERIES A

Each value shown for the individual aggregate sizes is the average for three tests on material in the flotation specific gravity range indicated

| Aggregate Source and Sp Gr Range | No 4 to ⅜-in | | | | ⅜ to ¼-in | | | | ¼ to ⅜-in | | | | ⅜ to 1-in | | | | Average, No 4 to 1-in | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Portion of Sample | Sp Gr (BSSD) | Absorption | Saturation | Portion of Sample | Sp Gr (BSSD) | Absorption | Saturation | Portion of Sample | Sp Gr (BSSD) | Absorption | Saturation | Portion of Sample | Sp Gr (BSSD) | Absorption | Saturation | Portion of Sample | Sp Gr (BSSD) | Absorption | Saturation |
| | percent | | percent | percent | percent | | percent | percent | percent | | percent | percent | percent | | percent | percent | percent | | percent | percent |
| 20-1G | | | | | | | | | | | | | | | | | | | | |
| >2 66 | 40 | 2 80 | 1 0 | 62 | 42 | 2 80 | 0 9 | 65 | 50 | 2 79 | 0 9 | 60 | 59 | 2 81 | 0 8 | 43 | 48 | 2 80 | 0 9 | 58 |
| 2 55-2 66 | 31 | 2 66 | 1 3 | 72 | 33 | 2 65 | 1 3 | 71 | 32 | 2 65 | 1 2 | 69 | 31 | 2 65 | 1 2 | 60 | 32 | 2 65 | 1 2 | 68 |
| 2 44-2 55 | 12 | 2 57 | 3 2 | 92 | 10 | 2 56 | 3 7 | 100 | 9 | 2 55 | 3 8 | 88 | 6 | 2 54 | 3 5 | 93 | 9 | 2 56 | 3 6 | 93 |
| <2 44 | 17 | 2 36 | 8 2 | 97 | 15 | 2 38 | 8 2 | 97 | 9 | 2 35 | 9 3 | 96 | 4 | 2 37 | 7 8 | 100 | 11 | 2 36 | 8 4 | 98 |
| 79-1G | | | | | | | | | | | | | | | | | | | | |
| >2 66 | 29 | 2 75 | 1 1 | 49 | 56 | 2 78 | 1 1 | 51 | 59 | 2 79 | 1 0 | 74 | 52 | 2 81 | 0 9 | 79 | 49 | 2 78 | 1 0 | 63 |
| 2 55-2 66 | 44 | 2 68 | 1 6 | 80 | 26 | 2 65 | 1 8 | 52 | 27 | 2 65 | 1 8 | 93 | 36 | 2 66 | 1 8 | 87 | 33 | 2 66 | 1 8 | 78 |
| 2 44-2 55 | 16 | 2 60 | 2 9 | 92 | 10 | 2 56 | 4 0 | 94 | 9 | 2 56 | 4 3 | 97 | 8 | 2 56 | 4 5 | 90 | 11 | 2 57 | 3 9 | 93 |
| <2 44 | 11 | 2 41 | 7 5 | 98 | 8 | 2 40 | 7 9 | 95 | 5 | 2 41 | 8 6 | 100 | 4 | 2 39 | 9 1 | 94 | 7 | 2 40 | 8 3 | 97 |
| 84-1G | | | | | | | | | | | | | | | | | | | | |
| >2 66 | 34 | 2 80 | 1 1 | 82 | 42 | 2 81 | 1 1 | 56 | 42 | 2 82 | 0 9 | 64 | 44 | 2 82 | 0 9 | 63 | 40 | 2 81 | 1 0 | 66 |
| 2 55-2 66 | 34 | 2 65 | 1 6 | 92 | 30 | 2 64 | 1 5 | 66 | 28 | 2 66 | 1 3 | 83 | 31 | 2 67 | 1 4 | 84 | 31 | 2 66 | 1 4 | 81 |
| 2 44-2 55 | 14 | 2 54 | 3 4 | 96 | 13 | 2 52 | 3 7 | 93 | 15 | 2 56 | 3 1 | 96 | 13 | 2 56 | 3 2 | 80 | 14 | 2 55 | 3 4 | 91 |
| <2 44 | 18 | 2 36 | 8 1 | 99 | 15 | 2 36 | 8 9 | 100 | 15 | 2 37 | 8 3 | 91 | 12 | 2 37 | 8 8 | 99 | 15 | 2 36 | 8 5 | 97 |
| 82-1G | | | | | | | | | | | | | | | | | | | | |
| >2 66 | 10 | 2 83 | 0 7 | 60 | 11 | 2 78 | 0 7 | 40 | 10 | 2 80 | 0 6 | 63 | 11 | 2 76 | 0 6 | 83 | 11 | 2 79 | 0 6 | 62 |
| 2 55-2 66 | 36 | 2 63 | 0 9 | 69 | 45 | 2 66 | 0 8 | 50 | 48 | 2 64 | 1 0 | 70 | 45 | 2 62 | 1 0 | 58 | 43 | 2 64 | 0 9 | 62 |
| 2 44-2 55 | 27 | 2 57 | 2 1 | 84 | 24 | 2 53 | 2 8 | 87 | 23 | 2 53 | 3 3 | 83 | 27 | 2 52 | 3 1 | 79 | 25 | 2 54 | 2 8 | 83 |
| <2 44 | 27 | 2 42 | 5 7 | 86 | 20 | 2 39 | 7 1 | 95 | 19 | 2 39 | 7 3 | 93 | 17 | 2 40 | 6 8 | 99 | 21 | 2 40 | 6 7 | 93 |

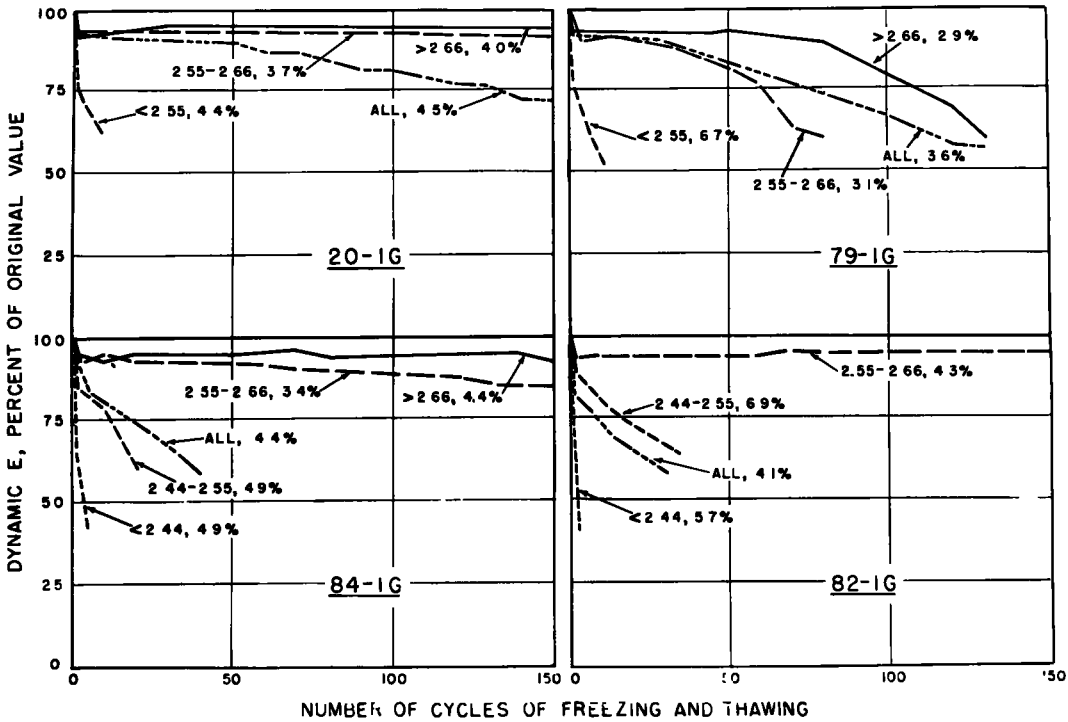


Figure 2. Freezing-and-thawing test for Series A. Figures on the curves indicate the specific-gravity range of the aggregate and the air content of the concrete mixes.

TABLE 5

CLASSIFICATION OF GRAVEL PARTICLES BY ROCK TYPE FOR TEST SERIES A

| Aggregate Source and Flotation Sp. Gr Range | Rock Type, Percent of Total in Specific Gravity Range | | | | | |
|---|---|---|---|---|---|---|
| | Igneous | Sedimentary | | | Metamorphic | |
| | | Calcareous | Siliceous | | Foliated | Non-foliated |
| | | Limestone & Dolomite | Sandstone | Chert | | (Quartzite) |
| **20-1G** | | | | | | |
| <2.44 | - | 18 | 44 | 38 | - | - |
| 2.44-2.55 | 4 | 30 | 23 | 35 | - | 7 |
| 2.55-2.66 | 18 | 35 | 10 | 6 | 3 | 26 |
| >2.66 | 21 | 56 | 9 | 1 | 8 | 5 |
| All | 17 | 43 | 14 | 10 | 4 | 12 |
| **79-1G** | | | | | | |
| <2.44[a] | - | 29 | 26 | 41 | - | 1 |
| 2.44-2.55 | 1 | 43 | 11 | 41 | - | 4 |
| 2.55-2.66 | 14 | 52 | 4 | 8 | 2 | 20 |
| >2.66 | 21 | 60 | 9 | - | 2 | 7 |
| All | 14 | 54 | 9 | 10 | 2 | 11 |
| **84-1G** | | | | | | |
| <2.44 | - | 14 | 54 | 29 | - | 2 |
| 2.44-2 55 | 2 | 24 | 17 | 48 | - | 9 |
| 2 55-2 66 | 15 | 43 | 8 | 11 | 2 | 20 |
| >2 66 | 22 | 62 | 5 | 1 | 3 | 7 |
| All | 14 | 44 | 14 | 15 | 2 | 11 |
| **82-1G** | | | | | | |
| <2.44 | - | - | 24 | 73 | - | 2 |
| 2 44-2.55 | - | - | 30 | 66 | - | 4 |
| 2.55-2 66 | 8 | - | 34 | 12 | 2 | 44 |
| >2.66 | 20 | - | 18 | 1 | 4 | 57 |
| All | 5 | - | 29 | 37 | 1 | 27 |

[a] Contained nearly 3 percent shale

Note Failure of some of the separations to total 100 percent is due to reporting results to the nearest one percent and to the presence of small amounts of other materials, chiefly shale

TABLE 6

ABSORPTION AND SPECIFIC GRAVITY DATA FOR TEST SERIES B

Values shown for individual aggregate sizes are the averages for three tests on gravel 84-1G separated into the flotation specific gravity ranges shown

| Specific Gravity Range | No 4 to ⅜ in size | | | ⅜ to ½ in size | | | ½ to ¾ in size | | | ¾ to 1 in size | | | Average, No 4 to 1 in | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Portion of Sample | Sp Gr (BSSD) | Absorption | Portion of Sample | Sp Gr (BSSD) | Absorption | Portion of Sample | Sp Gr (BSSD) | Absorption | Portion of Sample | Sp Gr (BSSD) | Absorption | Portion of Sample | Sp Gr (BSSD) | Absorption |
| | percent | | percent | percent | | percent | percent | | percent | percent | | percent | percent | | percent |
| >2 30 | 93 | 2 65 | 2 2 | 94 | 2 66 | 2 3 | 96 | 2 67 | 2 1 | 97 | 2 67 | 2 0 | 95 | 2 66 | 2 2 |
| <2 30 | 7 | 2 24 | 13 6 | 6 | 2 22 | 15 0 | 4 | 2 22 | 14 8 | 3 | 2 19 | 16 8 | 5 | 2 22 | 15 0 |
| >2 40 | 88 | 2 67 | 1 9 | 89 | 2 68 | 1 8 | 90 | 2 69 | 1 8 | 90 | 2 68 | 1 7 | 89 | 2 68 | 1 8 |
| <2 40 | 12 | 2 34 | 9 6 | 11 | 2 33 | 10 0 | 10 | 2 32 | 10 4 | 10 | 2 32 | 11 1 | 11 | 2 33 | 10 3 |
| >2 50 | 74 | 2 71 | 1 4 | 76 | 2 72 | 1 4 | 81 | 2 72 | 1 4 | 81 | 2 71 | 1 6 | 78 | 2 72 | 1 4 |
| <2 50 | 26 | 2 44 | 6 5 | 24 | 2 42 | 7 0 | 19 | 2 42 | 7 4 | 19 | 2 38 | 8 2 | 22 | 2 42 | 7 3 |
| >2 60 | 58 | 2 74 | 1 1 | 63 | 2 75 | 1 1 | 66 | 2 74 | 1 2 | 70 | 2 75 | 1 1 | 64 | 2 74 | 1 1 |
| <2 60 | 42 | 2 48 | 5 2 | 37 | 2 48 | 5 2 | 34 | 2 47 | 6 2 | 30 | 2 47 | 5 9 | 36 | 2 48 | 5 6 |
| All | 100 | 2 63 | 2 8 | 100 | 2 65 | 2 6 | 100 | 2 66 | 2 5 | 100 | 2 66 | 2 5 | 100 | 2 65 | 2 6 |

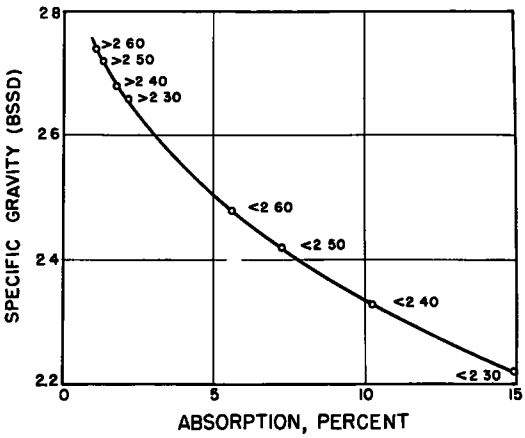


Figure 3. Relationship of absorption and specific gravity for Series B. The flotation specific gravity range of the aggregate is shown for each point on the curve.

crease in separation level.

Similar improvement in actual construction should be possible by the use of field heavy-media-separation processes. Separation at 2.40 specific gravity would improve the durability considerably, at 2.50 aggregate with good durability would be obtained. Separation at 2.40 and 2.50 would necessitate the discarding of 11 and 22 percent, respectively, of the total aggregate.

## CONCLUSIONS

Based upon the test results reported and discussed above, the following general conclusions are drawn:

1. The deleterious constituents of the gravels consist principally of sandstones and cherts with lesser amounts of badly weathered calcareous, igneous and metamorphic rocks.

2. These nondurable particles are characterized by low specific gravity, high absorption and degree of saturation and poor durability in concrete subjected to freezing and thawing.

3. They can be separated from the durable particles by heavy media separation techniques.

4. The durability, both in the field and in the laboratory, of concrete made with the gravels from various sources is dependent upon the quantities of low-specific-gravity material contained in the aggregate.

5. Heavy-media separation can be used to improve the durability of concrete made with these gravels.

6. The durability of concrete made with the separated gravel fractions increases as the specific gravity of the gravel is increased.

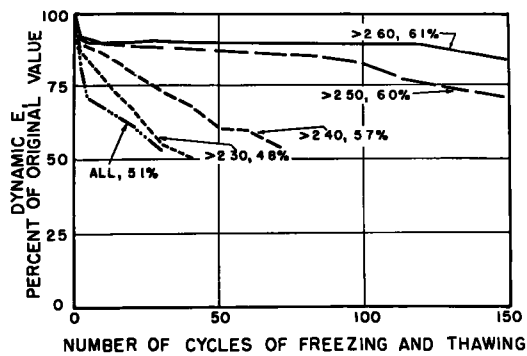


Figure 4. Freezing-and-thawing test for Series B. The specific-gravity range of the aggregate and the air content of the concrete are shown on each curve.

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## *Discussion*

F. E. LEGG, JR., Assistant Supervisor, Michigan State Highway Department Testing Laboratory — Using laboratory flotation techniques similar to those reported in this paper, the Michigan State Highway Department Testing Laboratory recently made an exploratory study of the improvement of produced gravel from several pits well distributed over Michigan. Locations of the pits are shown in Figure A. Since the basis of judgment of beneficiation by heavy-media separation is different from that reported in the present paper, the data is briefly presented here as a supplement to the authors' findings.

Michigan specifications set permissible limits on three classes of deleterious materials which have been found to be susceptible to heavy media separation: (1) soft particles, (2) chert, and (3) hard absorbent particles. The specifications provide that in no case, for concrete aggregates, is a limit of 3 percent of soft particles permitted to be exceeded and the maximum sum of the three types is variable between 8 and 10 percent, depending upon the nominal maximum size of the aggregate. An important exception to the above occurs in the case of aggregate to be used in exposed concrete where avoidance of unsightly pop-outs is paramount, such as on bridge or grade-separation superstructures. In this

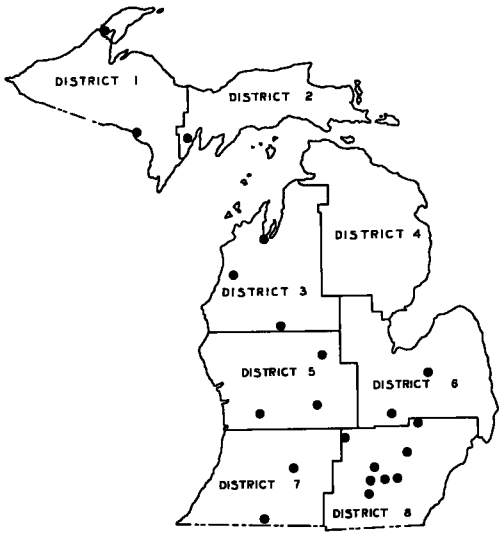


Figure A. Location of Michigan gravel pits on which laboratory heavy-media separations have been made.

TABLE A

SEPARATION OF AGGREGATES BY FLOTATION-EFFECT ON PERCENTAGE OF DELETERIOUS MATERIAL OF PROCESSING GRAVEL AT ANY ONE OF THREE SPECIFIC GRAVITIES

| District | Pit | Total Deleterious | 2.40 | | | 2.50 | | | 2.60 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Deleterious Removed | Satisfactory Wasted | Deleterious Remaining | Deleterious Removed | Satisfactory Wasted | Deleterious Remaining | Deleterious Removed | Satisfactory wasted | Deleterious Remaining |
| I | A | 3.7 | 0.6 | 0.6 | 3.1 | 1.5 | 4.1 | 2.2 | 3.2 | 19.1 | 0.5 |
| | B | 8.2 | 5.5 | 2.4 | 2.7 | 6.4 | 5.9 | 1.8 | 7.0 | 13.5 | 1.2 |
| | B | 5.9 | 4.5 | 3.3 | 1.4 | 5.4 | 7.1 | 0.5 | 5.9 | 15.9 | 0.0 |
| II | A | 7.8 | 1.7 | 1.6 | 6.1 | 3.8 | 5.6 | 4.0 | 6.8 | 16.0 | 1.0 |
| III | A | 7.0 | 2.9 | 1.4 | 4.1 | 5.4 | 4.0 | 1.6 | 6.9 | 17.3 | 0.1 |
| | B | 3.9 | 1.3 | 0.6 | 2.6 | 2.7 | 1.6 | 1.2 | 3.9 | 12.5 | 0.0 |
| | C | 16.2 | 8.7 | 2.6 | 7.5 | 13.6 | 7.3 | 2.6 | 15.4 | 20.8 | 0.8 |
| V | A | 5.5 | 1.5 | 1.6 | 4.0 | 2.8 | 2.8 | 2.7 | 4.0 | 10.0 | 1.5 |
| | B | 10.6 | 3.8 | 1.4 | 6.8 | 7.7 | 5.0 | 2.9 | 10.1 | 16.1 | 0.5 |
| | C | 6.1 | 2.5 | 0.5 | 3.6 | 4.6 | 2.0 | 1.5 | 5.9 | 12.5 | 0.2 |
| VI | A | 7.1 | 2.6 | 0.2 | 4.5 | 4.7 | 0.9 | 2.4 | 6.5 | 8.1 | 0.6 |
| | B | 10.4 | 2.7 | 0.0 | 7.7 | 6.1 | 0.7 | 4.3 | 10.2 | 10.8 | 0.2 |
| | B | 7.0 | 2.5 | 1.3 | 4.5 | 4.8 | 3.3 | 2.2 | 7.0 | 10.7 | 0.0 |
| VII | A | 9.4 | 5.8 | 1.1 | 3.6 | 7.2 | 1.4 | 2.2 | 7.5 | 13.4 | 1.9 |
| | B | 10.9 | 4.5 | 2.7 | 6.4 | 7.55 | 5.9 | 3.35 | 10.2 | 16.8 | 0.7 |
| VIII | A | 7.5 | 1.8 | 0.2 | 5.7 | 4.6 | 1.7 | 2.9 | 7.1 | 7.4 | 0.4 |
| | B | 9.0 | 4.0 | 0.5 | 5.0 | 7.6 | 1.2 | 1.4 | 9.0 | 5.8 | 0.0 |
| | B | 5.7 | 1.7 | 0.4 | 4.0 | 2.9 | 2.5 | 2.8 | 5.5 | 12.9 | 0.2 |
| | D | 8.5 | 3.1 | 0.0 | 5.4 | 3.9 | 0.3 | 4.6 | 7.7 | 7.2 | 0.8 |
| | E | 6.8 | 3.0 | 0.9 | 3.8 | 4.8 | 3.9 | 2.0 | 6.6 | 15.8 | 0.2 |
| | F | 10.2 | 3.6 | 1.6 | 6.6 | 6.6 | 3.0 | 3.6 | 10.0 | 10.7 | 0.2 |
| | G | 12.6 | 6.9 | 0.7 | 5.7 | 9.6 | 4.8 | 3.0 | 12.1 | 16.0 | 0.5 |
| | G | 7.7 | 3.7 | 1.7 | 4.0 | 5.6 | 2.2 | 2.1 | 7.7 | 17.3 | 0.0 |
| | H | 10.9 | 6.0 | 2.3 | 4.9 | 8.4 | 3.8 | 2.5 | 10.9 | 9.1 | 0.0 |
| | I | 4.0 | 2.2 | 0.6 | 1.8 | 3.4 | 1.8 | 0.6 | 4.0 | 11.3 | 0.1 |
| Average | | 8.1 | 3.5 | 1.2 | 4.6 | 5.7 | 3.3 | 2.4 | 7.6 | 13.1 | 0.5 |

case, the total deleterious is limited to 3 percent and soft-particle content may not exceed 1 percent. Soft particles are defined by the specifications as "shale, soft sandstone, ochre, coal, iron bearing clay, weathered schist, shells, floaters, partially disintegrated particles, cemented gravel and any other particles which are structurally weak or which fail to meet the soundness test." The specifications do not define chert, but accepted lithological classification is used. Hard absorbent particles are less-easily defined but cover, in general, an intermediate class of particles, less objectionable than the soft particles, which experience over the years have proven deleterious. Exclusive use of air-entrained concrete in all exposed concrete in recent years, particularly that exposed to deicing salts, has not removed the necessity for such deleterious-particle requirements in the specifications.

Table A indicates the results, based upon laboratory separation, which would be obtained by processing gravels from these pits through a flotation plant at any one of three specific gravities. Deleterious-particle determinations on these samples were independently made by two experienced operators. For the sake of brevity, only the total deleterious is shown without breakdown into the three classes. In only 7 of 25 cases would more than 50 percent of the deleterious material be removed by flotation at 2.40 gravity and in only three cases would the deleterious content be reduced below 3 percent. However, if the flotation were run at 2.50 specific gravity, more than 50 percent of the deleterious material would be removed in all but three cases. In only five cases would there remain more than 3 percent of deleterious material. A comparison of the results at 2.50 and at 2.60 specific gravity indicates that a high-quality aggregate containing less than 1 percent of deleterious material could be produced in most cases by using a specific gravity somewhere between 2.50 and 2.60. Moreover, wastage of good material apparently need not be excessive by careful choice of specific gravity.

To the extent that commercial heavy-media-separation equipment can economically approach the results shown in these laboratory studies, it would seem that concrete, highly resistant to severe frost exposure, may be provided using suitably processed local aggregates in areas where the designer has been hampered heretofore because of the necessity of importing satisfactory aggregates.

D. W. LEWIS, and EDUARDS VENTERS, Closure — Legg's discussion illustrates another case in which heavy-media sep-

aration has considerable promise in improving the quality of concrete aggregates. Data now available indicate that consideration should be given the possible use of commercial plants for aggregate improvement in a number of areas. The cost of such treatment would have to be carefully weighed against the benefits derived, of course, to determine the economic feasibility of its use in each case.

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