

A Study of Chert and Shale Gravel in Concrete

R. L. SCHUSTER, * Associate Professor of Civil Engineering, University of Colorado, and J. F. McLAUGHLIN, Research Engineer, Joint Highway Research Project, and Associate Professor of Civil Engineering, Purdue University

Certain chert and shale gravels have long been recognized as harmful when included in portland cement concrete exposed to freezing and thawing. Many organizations have specifications limiting percentages of these materials in concrete aggregates, but few of these specifications distinguish between types of chert and shale from different geographical areas nor do they always take into account the basic physical properties of these materials.

In this study, pore characteristics, mineralogy, texture, and structure were determined for cherts and shales from nine Indiana glacial gravel deposits by means of microscopic petrography, X-ray diffraction, and the common specific gravity and absorption techniques. Blends of 2, 4, 6, and 10 percent of chert or shale from each source were made with a standard durable crushed limestone coarse aggregate, and these blends were used in 3- x 4- x 16-in. air-entrained concrete beams subjected to up to 300 cycles of freezing and thawing. A measure of the amount of deep-seated deterioration of the beams was provided by durability factors calculated from the results of non-destructive sonic testing of the beams at intervals during freeze-thaw testing. Severity of surface deterioration was also evaluated. The influence of the basic properties of the chert and shale gravels on the results of the freeze-thaw tests was then determined. On the basis of the results of these tests, the existing specifications on cherts and shales were studied to determine whether the specifications realistically categorize these materials.

Despite significant differences in their mineralogies, no difference was noted in the freeze-thaw durabilities of the various chert samples. For all the cherts, significant deep-seated and surface deterioration occurred only in beams containing 6 to 10 percent of material with a bulk specific gravity (saturated surface-dry basis) of less than 2.45.

Although the basic properties of the shales varied even more widely than those of the cherts, none of the shales caused deep-seated failure of the concrete. However, the most porous shales caused "popout" damage, which was especially severe at the 6 and 10 percent levels.

*Formerly Instructor in Civil Engineering, Purdue University, Lafayette, Indiana

● **THERE IS** still much to be learned about the physical properties of cherts and shales, and their effects on the durability of concrete in spite of considerable past study.

In the past little has been done to differentiate between cherts and shales of the same general type, but that are obtained from different geographic areas. A purpose of this study was to determine if the basic properties of cherts and shales from one part of Indiana differ significantly from those of cherts and shales from other parts of the state, and if significant differences in the properties of these materials were found, to attempt to determine if these differences also result in differences in durability.

Another objective was to quantify the effects of different chert and shale gravels on the freeze-thaw durability of concrete test specimens containing small percentages of these materials.

The cherts and shales used in this investigation were obtained by hand picking from glacial gravel deposits widely scattered throughout the State of Indiana. In this way six chert and five shale samples, constituting as widely divergent a group of cherts and shales as could be found in Indiana, were obtained. The geographic locations of the sources for these samples are shown in Figure 1.

In order to determine the effect of presence of the deleterious materials on freeze-thaw durability of concrete, small percentages of the cherts and shales being studied were incorporated in 3- by 4- by 16-in. air-entrained portland cement concrete beams made with a standard portland cement, crushed stone coarse aggregate, and natural sand fine aggregate. The aggregates were obtained from sources of proven good quality. The only variables purposely introduced into the experiment were the deleterious materials themselves. The mix design was held constant for all beams made except that varying small percentages of chert or shale were substituted for part of the crushed limestone coarse aggregate in all but the control beams. A water-cement

ratio of 0.46 by weight was used throughout the study. This water-cement ratio produced a mix with good workability and a slump of about 3 in. The cement factor was kept constant at six bags per cubic yard. An air-entraining agent was used to entrain approximately 4 percent air in each batch.

In all beams the coarse aggregate was used in equal amounts of the No. 4 to $\frac{3}{8}$ -in., $\frac{3}{8}$ -in. to $\frac{1}{2}$ -in., $\frac{1}{2}$ -in. to $\frac{3}{4}$ -in., and $\frac{3}{4}$ -in. to 1-in. sizes. Chert or shale was substituted for the $\frac{3}{8}$ -in. to $\frac{1}{2}$ -in., $\frac{1}{2}$ -in. to $\frac{3}{4}$ -in., and $\frac{3}{4}$ -in. to 1-in. crushed stone in 2, 4, 6, and 10 percent blends in all but a few control beams in which the coarse aggregate consisted of 100 percent crushed limestone. In the beams containing the deleterious materials, no deleterious materials in the No. 4 to $\frac{3}{8}$ -in. size range were substituted for the crushed limestone because a previous study by Sweet (1) has shown that deleterious particles passing a $\frac{3}{8}$ -in. screen have little effect on the freeze-thaw durability of concrete. All the coarse aggregate was vacuum saturated before mixing. The fine aggregate was not vacuum saturated, but was mixed with enough water to fill all surface-connected pores and left in this condition for 24 hr before mixing.

Mixing was accomplished by means of a modified food mixer with $\frac{1}{4}$ -cu ft capacity.

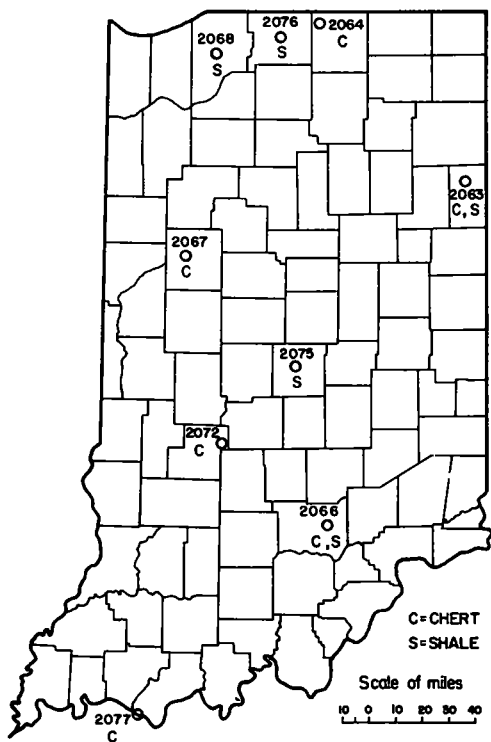


Figure 1. Map of Indiana locating sources of chert and shale gravels used in this study.

The concrete was molded into 3- by 4- by 16-in. beams, and these were cured by immersion in lime water for 13 days following removal of the specimens from the molds one day after casting.

Freeze-thaw testing of the beams was conducted according to the ASTM Method of Test for Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water, ASTM Designation C 291-57 T (2). The end point adopted for this series of tests was 50 percent relative dynamic modulus of elasticity of 300 cycles of freezing and thawing, whichever occurred first.

A durability factor was determined for each beam by the method shown in ASTM Designation C 291-57 T. These durability factors provided an index of the amount of deep-seated deterioration taking place in each beam.

During the freeze-thaw testing program, a number of popouts occurred on the surfaces of some of both the chert and shale beams. These popouts often occurred on beams which showed no deep-seated failure such as would be evidenced by low durability factors. Since these popouts were all found to be caused by failure of pieces of chert and shale during the freeze-thaw testing, this was further studied. During the freeze-thaw testing program, visual observation of any new popouts was made each time a beam was tested for its fundamental transverse frequency (that is, every 10-20 cycles of freezing and thawing). The position of each popout was noted as well as the approximate size of the piece of deleterious material causing it.

In order to compare the relative severity of surface deterioration of the beams, it was necessary to determine an index number for each beam which would give an indication of the relative popout damage suffered by that beam. An arbitrary numerical index based on sizes of the deleterious particles causing the popouts, number of popouts, and numbers of cycles at which the popouts occurred was developed and can be explained as follows:

$$\text{SDF} = \frac{s_1}{c_1} + \frac{s_2}{c_2} + \frac{s_3}{c_3} + \dots + \frac{s_n}{c_n}$$

in which

SDF = surface durability factor for each beam;

s = size factor, s_1 for popouts caused by deleterious particles $\frac{3}{8}$ to $\frac{1}{2}$ in. in size, s_2 for popouts $\frac{1}{2}$ to $\frac{3}{4}$ in. in size (average of 2 diameters); and

c = cycle factor, c_1 for cycles 1 to 100, c_2 for cycles 101 to 200, c_3 for cycles 201 to 300.

For beams whose relative moduli of elasticity dropped below 50 before 300 cycles of freezing and thawing were attained, this arbitrary equation does not result in an index that can be compared with beams undergoing the full 300 cycles. In many cases the beams that were removed from the freeze-thaw test before 300 cycles would have suffered additional surface deterioration if they had been allowed to reach 300 cycles. It is difficult to devise a correction factor which would satisfactorily eliminate this failing of the equation. However, only a few of the beams tested fall in this category, and these were especially noted in tabulating the data so that no direct comparisons would be made.

CHERT STUDIES

An experimental outline was set up in which three variables were introduced into the production of beams containing chert with all other controlled factors remaining constant. The three variables were as follows:

1. Source of chert—material from each of the six sources of chert from throughout the State of Indiana was used.

2. Specific gravity of chert—the chert from each of the six sources was separated into three groups based on bulk specific gravity (saturated surface-dry basis). The specific gravity ranges selected for these groups were 2.55 plus, 2.45-2.55, and 2.45

minus. Separation was accomplished using mixtures of carbon tetrachloride (specific gravity 1.58) and acetylene tetrabromide (specific gravity 2.97). Beams were made containing chert from each source and at each level of specific gravity.

3. Percentage of chert—chert from each combination of source and specific gravity group was included with the crushed stone coarse aggregate in the beams in amounts of 2, 4, and 10 percent, and a 6 percent level was included for chert from the 2.45 minus specific gravity group.

Statistical analysis of durability factors obtained from freeze-thaw studies of the chert beams (Table 1) indicated that the sources of the chert had no effect on resistance of concrete to deep-seated freeze-thaw deterioration. Even though the cherts were from different sources throughout Indiana, they resulted in nearly equal degrees of freeze-thaw deterioration when used in concrete in equal amounts having the same specific gravity ranges.

A definite difference in durability factors was found, however, for beams containing cherts of different specific gravity ranges. It was found that beams containing chert from the 2.45 minus specific gravity group had significantly lower durability than those containing chert from the 2.55 plus and 2.45-2.55 specific gravity ranges. This is in accord with the work of Sweet and Woods (3) which indicated low specific gravity chert to be the most susceptible to freeze-thaw deterioration.

The percentage of chert used also had a significant effect on the durability factors, but only at the 2.45 minus specific gravity level. At the 2.55 plus and 2.45-2.55 specific gravity levels, there was no significant difference among the durability factors of the beams containing different percentages of chert. Even 10 percent of chert from these specific gravity groups caused no deep-seated failure of beams in which it was included.

In the 2.45 minus specific gravity level the percentage of chert had a strong effect on durability of the concrete. Without exception, beams containing 10 percent of 2.45 minus chert suffered severe deep-seated deterioration. Every beam was intersected by at least one deep-seated crack caused by failure of the chert. The lowest durability factors recorded in the freeze-thaw testing occurred for this combination.

At the 6 percent level of the 2.45 minus specific gravity group, no deep-seated cracks occurred and the durability factors were found to be not significantly lower than those of the 2 and 4 percent levels of this gravity range. However, more variability in the data occurred at this level than at the 2 and 4 percent levels, that is, individual beams containing 6 percent of 2.45 minus chert had durability factors as low as 68.9 and 78.1 while others were as high as 97.2. The few low durability factors at the 6 percent level, while not nearly as low as those at the 10 percent level and not low enough to cause significant differences in the cell means, were low enough to suggest

TABLE 1
SUMMARY OF INDIVIDUAL DURABILITY FACTORS FOR FREEZE-THAW TESTING PROGRAM OF CONCRETE BEAMS
CONTAINING SMALL PERCENTAGES OF CHERT COARSE AGGREGATE

| Chert in Coarse Aggregate, (%) | Sp Gr Range, 2063 Chert | | | Sp Gr Range, 2064 Chert | | | Sp Gr Range, 2066 Chert | | | Sp Gr Range, 2067 Chert | | | Sp Gr Range, 2072 Chert | | | Sp Gr Range, 2077 Chert | | |
|--------------------------------------|----------------------------|---------------|---------------|----------------------------|---------------|---------------|----------------------------|---------------|---------------|----------------------------|---------------|---------------|----------------------------|---------------|---------------|----------------------------|---------------|---------------|
| | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus |
| 2 | 97 5 | 98 2 | 94 1 | 98 2 | 98 2 | 96 4 | 98 8 | 97 3 | 89 1 | 97 9 | 96 9 | 96 1 | 98 2 | 97 0 | 93 8 | 98 2 | 98 2 | 94 4 |
| | 98 3 | 99 7 | 92 0 | 98 1 | 97 4 | 93 6 | 97 9 | 97 3 | 96 7 | 98 9 | 98 0 | 98 2 | 99 0 | 97 0 | 97 2 | 97 8 | 96 5 | 95 5 |
| | 97 9 | 99 0 | 93 1 | 98 2 | 97 8 | 95 0 | 98 4 | 97 3 | 92 9 | 98 4 | 97 5 | 97 2 | 98 6 | 97 0 | 95 5 | 98 0 | 97 4 | 95 0 |
| 4 | 99 8 | 98 3 | 88 9 | 98 2 | 97 3 | 95 5 | 98 0 | 96 5 | 95 5 | 97 7 | 96 4 | 95 5 | 99 0 | 94 6 | 96 5 | 97 2 | 97 3 | 90 3 |
| | 96 6 | 97 2 | 96 4 | 99 0 | 96 4 | 98 0 | 98 0 | 94 7 | 95 6 | 97 7 | 95 4 | 95 5 | 97 0 | 97 3 | 94 9 | 97 0 | 97 4 | 96 5 |
| | 98 2 | 97 8 | 92 7 | 98 6 | 96 9 | 96 8 | 98 0 | 95 6 | 95 6 | 97 7 | 95 9 | 95 5 | 98 0 | 96 0 | 95 7 | 97 1 | 97 4 | 93 4 |
| 6 | | | 96 3 | | | 94 7 | | | 88 7 | | | 84 5 | | | 92 1 | | | 87 8 |
| | | | 78 1 | | | 97 2 | | | 89 7 | | | 95 6 | | | 90 0 | | | 68 9 |
| | | | 87 2 | | | 96 0 | | | 89 2 | | | 90 1 | | | 91 1 | | | 78 4 |
| 10 | 98 2 | 71 0 | 24 4 | 99 1 | 82 5 | 11 2 | 97 0 | 93 5 | 29 6 | 99 1 | 83 2 | 57 3 | 98 9 | 92 0 | 64 7 | 97 9 | 96 3 | 30 0 |
| | 98 2 | 94 7 | 29 5 | 96 4 | 98 0 | 25 0 | 98 0 | 95 5 | 46 5 | 97 3 | 94 6 | 38 4 | 98 9 | 91 9 | 36 3 | 97 2 | 92 9 | 26 4 |
| | 98 2 | 82 9 | 27 0 | 97 8 | 90 3 | 18 1 | 97 5 | 94 5 | 38 1 | 98 2 | 88 9 | 47 9 | 98 9 | 92 0 | 51 5 | 97 6 | 94 6 | 28 2 |

that some deterioration can occur in concrete containing as little as 6 percent chert with a bulk specific gravity of less than 2.45.

Durability factors for beams containing 2 and 4 percent of 2.45 minus chert were shown by analysis of variance to be significantly lower than durability factors for beams containing the same percentages of chert from the two heavier specific gravity ranges. However, all the durability factors for these beams are high enough to indicate little deep-seated deterioration (Table 1). For example, the lowest durability factor computed for the 4 percent level of the 2.45 minus specific gravity range was 88.9 and the lowest cell mean was 92.7. These values are high enough to be considered indicative of sound concrete.

In summary, it appears that otherwise sound concrete containing up to 4 percent chert with a bulk specific gravity (saturated surface-dry basis) of 2.45 or less, or as much as 10 percent chert with a specific gravity greater than 2.45, can successfully withstand laboratory freeze-thaw exposure without undergoing deep-seated deterioration.

The effect of size of the individual chert particles on their freeze-thaw durability in concrete is of interest. Previous studies of deleterious substances have indicated a relationship between size of unconfined particle and lack of freeze-thaw durability. Wray and Lichtefeld (4) found in their study of Missouri cherts that saturated 1- to $\frac{1}{2}$ -in. particles had less resistance to freezing and thawing failure than saturated $\frac{3}{4}$ - to 1-in. particles. Thomas (5) saturated prisms of different sizes from the same rock and found that damage was greater the larger the specimen.

The effect of size on the durability of particles of deleterious materials in concrete is not so clear, however. Sweet and Woods (3) embedded saturated chert pieces of three sizes, $\frac{3}{4}$ to 1 in., $\frac{1}{2}$ to $\frac{3}{4}$ in., and $\frac{3}{8}$ to $\frac{1}{2}$ in., in 1-in. mortar cubes and subjected these cubes to up to 309 cycles of freezing and thawing. They found that the cubes failed at an earlier cycle for the $\frac{3}{4}$ - to 1-in. pieces than for the $\frac{1}{2}$ - to $\frac{3}{4}$ -in. pieces, and that no failure occurred in the cubes containing the $\frac{3}{8}$ - to $\frac{1}{2}$ -in. pieces. Klieger (6), however, found no apparent relationship between size of unsound aggregate particles and durability as long as the air content of the mortar was held constant. Walker and McLaughlin (7) demonstrated that lightweight chert less than $\frac{3}{8}$ in. in size would not cause deep-seated freeze-thaw deterioration in concrete, but their method of test did not distinguish between the degrees of resistance to freeze-thaw deterioration exhibited by different sizes of chert larger than $\frac{3}{8}$ in.

In this study no attempt was made to determine the effect of size on durability. However, for those beams that had suffered deep-seated cracking as a result of freezing and thawing, a qualitative study was conducted to determine the sizes of the pieces of chert intersected by each crack. In each case it appeared that the $\frac{3}{4}$ - to 1-in. piece had provided most of the disruptive force. In no case was a crack caused by $\frac{1}{2}$ - to $\frac{3}{4}$ - or $\frac{3}{8}$ - to $\frac{1}{2}$ -in. pieces alone. This does not mean that $\frac{1}{2}$ - to $\frac{3}{4}$ - or $\frac{3}{8}$ - to $\frac{1}{2}$ -in. pieces could not cause deep-seated failure of concrete, but does show that they are not as harmful as the larger pieces. Larger chert particles in concrete appear to have less resistance to freeze-thaw deterioration than smaller ones.

Although freeze-thaw testing of concrete specimens is primarily intended to cause deep-seated failure and subsequent loss of strength of concrete specimens containing unsound aggregates, surface deterioration of the concrete, which in some cases is equally as important as deep-seated failure, often occurs in these tests. A part of this study was to determine how surface deterioration is influenced by each of the variables introduced into the freeze-thaw study.

Surface deterioration factors for the chert beams are given in Table 2. These data indicate no significant difference in severity of popout damage among the six chert sources. The major differences in severity of surface deterioration apparently were caused by material from different bulk specific gravity ranges. For all six cherts a negligible amount of surface deterioration occurred in beams containing material from the 2.55 plus and 2.45-2.55 specific gravity ranges. Material from the 2.45 minus gravity range, however, resulted in a significant amount of popout damage in beams made from each of the six cherts. In general, the 6 to 10 percent levels within

TABLE 3
SUMMARY OF SURFACE DETERIORATION FACTORS FOR FREEZE-THAW TESTING PROGRAM OF CONCRETE
BEAMS CONTAINING SMALL PERCENTAGES OF CHERT COARSE AGGREGATE

| Chert in Coarse Aggregate, (%) | Sp Gr Range, 2063 Chert | | | Sp Gr Range, 2064 Chert | | | Sp Gr Range, 2066 Chert | | | Sp Gr Range, 2067 Chert | | | Sp Gr Range, 2072 Chert | | | Sp Gr Range, 2077 Chert | | |
|--------------------------------------|----------------------------|---------------|------------------|----------------------------|---------------|------------------|----------------------------|---------------|------------------|----------------------------|---------------|------------------|----------------------------|---------------|------------------|----------------------------|---------------|------------------|
| | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus | 2 55 Plus | 2 45- 2 55 | 2 45 Minus |
| 2 | 0 0 | 0 0 | 0 6 | 0 0 | 0 6 | 0 0 | 0 0 | 0 0 | 3 0 | 0 0 | 0 0 | 1 0 | 0 0 | 1 0 | 0 0 | 0 0 | 0 0 | 0 0 |
| | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 3 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 |
| | 0 0 | 0 0 | 0 3 | 0 0 | 0 3 | 0 2 | 0 0 | 0 0 | 1 5 | 0 0 | 0 0 | 0 5 | 0 0 | 0 5 | 0 0 | 0 0 | 0 0 | 0 0 |
| 4 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 6 | 0 0 | 0 0 | 0 0 | 1 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 1 7 |
| | 0 0 | 0 0 | 1 3 | 0 0 | 0 3 | 1 0 | 0 0 | 0 0 | 1 2 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 2 0 |
| | 0 0 | 0 0 | 0 7 | 0 0 | 0 2 | 0 5 | 0 0 | 0 3 | 0 6 | 0 0 | 0 0 | 0 5 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 1 9 |
| 6 | | | 1 0 | | | 2 6 | | | 1 7 | | | 0 3 | | | 1 7 | | | 0 3 |
| | | | 0 5 | | | 4 3 | | | 1 3 | | | 0 0 | | | 0 0 | | | 0 0 |
| | | | 0 8 | | | 3 5 | | | 1 5 | | | 0 2 | | | 0 9 | | | 0 2 |
| 10 | 0 0 | 0 0 | 0 0 ¹ | 0 0 | 0 0 | 0 0 ¹ | 0 0 | 0 0 | 2 5 ¹ | 0 0 | 0 0 | 0 3 | 0 0 | 0 0 | 3 0 | 0 0 | 0 0 | 1 5 ¹ |
| | 0 0 | 0 6 | 0 3 ¹ | 0 0 | 0 0 | 0 0 ¹ | 0 0 | 0 0 | 2 5 ¹ | 0 0 | 0 0 | 0 0 ¹ | 0 0 | 0 3 | 1 7 ¹ | 0 0 | 0 0 | 0 0 ¹ |
| | 0 0 | 0 3 | 0 2 | 0 0 | 0 0 | 0 0 | 0 0 | 0 0 | 2 5 | 0 0 | 0 0 | 0 2 | 0 0 | 0 2 | 2 4 | 0 0 | 0 0 | 0 8 |

¹Removed from freeze-thaw test at less than 300 cycles

the 2.45 minus specific gravity range had higher surface deterioration factors than the 2 and 4 percent levels, but this was not true for all six cherts. For example, in the 2.45 minus specific gravity range for chert 2077, the 4 percent level had an average surface deterioration factor of 1.9, while the 6 percent level had an average factor of only 0.2. This seeming anomaly is probably due more to random positioning of the pieces of chert than to any error in procedure or real differences in the material.

It also should be noted that, in most cases, larger factors were obtained for beams in the 6 percent level of the 2.45 minus specific gravity range than in the 10 percent level. This was primarily due to failure of most of the 10 percent beams to complete a full 300 cycles of freezing and thawing while all the 6 percent beams lasted the full 300 cycles. Thus the 10 percent specimens were not exposed to as many cycles of freezing and thawing as those containing 6 percent chert.

In summary, surface deterioration in the beams containing chert paralleled the deep-seated failure of these beams. In both cases the different sources had little, if any, effect. For all sources failure occurred primarily in the 6 and 10 percent levels of the 2.45 minus specific gravity range.

SHALE STUDIES

An experimental outline was formulated in which two variables were introduced into design of the concrete beams containing shale with all controlled factors remaining constant. This experimental design differed from that of the chert study in that no specific gravity separation of the shale was made. It was set up as a two-way crossed classification. The two variables in the design were as follows:

1. Source of shale—material from each of the sources was blended with the crushed stone coarse aggregate in different beams.
2. Percentage of shale—shale from each of the sources was combined with the crushed stone coarse aggregate in blends of 2, 4, 6, and 10 percent.

Study of the durability factors for concrete beams containing shale (Table 3) indicates that no combination of sources and percentages (up to 10 percent) of shale resulted in deep-seated failure of the beams. Only a few beams were found to have durability factors below 90, and these few values appear to be well distributed throughout the data. Only one cell mean is below 90 and this is at the 4 percent level, while the durability factors at the 6 and 10 percent levels for this same shale (2066) are well above 90. This indicates that the low mean for the 4 percent level is probably due to random error.

TABLE 3

**SUMMARY OF INDIVIDUAL DURABILITY FACTORS FOR FREEZE-THAW
TESTING PROGRAM OF CONCRETE BEAMS CONTAINING SMALL
PERCENTAGES OF SHALE COARSE AGGREGATE**

| Shale in Coarse Aggregate (%) | Shale Source | | | | |
|-------------------------------------|--------------|------|------|------|-------|
| | 2063 | 2066 | 2068 | 2075 | 2076 |
| 2 | 100.0 | 97.8 | 99.5 | 96.5 | 96.0 |
| | 98.8 | 96.0 | 85.5 | - | 96.5 |
| | 92.0 | 92.8 | 94.0 | 88.5 | 96.0 |
| | - | 94.5 | - | 97.2 | 95.4 |
| | - | 95.3 | - | 97.2 | 95.8 |
| | - | - | - | 98.2 | 96.3 |
| | 97.0 | 95.3 | 93.0 | 95.5 | 96.0 |
| | 96.3 | 96.5 | 94.3 | 96.4 | 96.3 |
| | 85.3 | - | - | 96.4 | 94.0 |
| | 97.1 | 90.8 | - | 97.2 | 97.2 |
| 4 | - | 80.5 | 97.1 | - | 93.0 |
| | - | - | 96.5 | - | 96.0 |
| | - | 87.2 | 95.3 | - | 99.5 |
| | 92.9 | 88.8 | 95.8 | 96.7 | 96.0 |
| | 99.0 | 97.4 | - | 98.5 | 99.8 |
| | 98.2 | 92.5 | 98.4 | 87.0 | 89.0 |
| | 96.0 | 98.2 | - | 96.5 | 100.0 |
| | 99.0 | 96.3 | 87.9 | - | 97.0 |
| | 98.7 | 87.6 | 85.1 | - | 89.0 |
| | 100.0 | 96.5 | - | - | 88.4 |
| 6 | 98.5 | 94.8 | 90.5 | 94.0 | 93.9 |
| | 95.5 | 87.0 | - | - | 90.8 |
| | 86.5 | 96.5 | 83.0 | 98.0 | 95.4 |
| | 95.0 | - | - | 96.2 | 95.5 |
| | - | 97.0 | 95.3 | 96.4 | - |
| | - | 96.0 | 93.5 | 98.2 | - |
| | - | 96.2 | 91.6 | 96.4 | - |
| | 92.3 | 94.5 | 90.9 | 97.0 | 93.9 |
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Thus it appears from these data that in amounts of up to 10 percent, little difference in resistance of the concrete to deep-seated deterioration was caused by the different shales even though they were from widely separated areas throughout the state and had significantly different basic properties. This is in accord with the findings of Lang (8) who noted that for pavement concrete containing small percentages of shale, the only harmful effect of the shale due to freezing and thawing consisted of surface deterioration of the concrete.

A comparison of durability factor data for the cherts and shales shows that the only deep-seated deterioration caused by either of these materials was due to chert with a bulk specific gravity (saturated surface-dry basis) of less than 2.45. Since some of the shale samples contained a considerable quantity of material which is of low bulk specific gravity even for shale (2.15 minus or 2.25 minus), and since none of these shales produced any deep-seated failure, specific gravity apparently does not have the same relationship to resistance to deep-seated failure for shales as it does for cherts.

Surface deterioration factors for the shale beams are given in Table 4. It is evident

TABLE 4

**SUMMARY OF SURFACE DETERIORATION FACTORS FOR FREEZE-THAW
TESTING PROGRAM OF CONCRETE BEAMS CONTAINING SMALL
PERCENTAGES OF SHALE COARSE AGGREGATE**

| Shale in Coarse Aggregate (%) | Shale Source | | | | |
|-------------------------------------|--------------|------|------|------|------|
| | 2063 | 2066 | 2068 | 2075 | 2076 |
| 2 | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 |
| | 0.0 | 0.0 | 2.0 | - | 0.0 |
| | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 |
| | - | 0.0 | - | 0.0 | 0.0 |
| | - | 0.0 | - | 0.0 | 0.0 |
| | - | - | - | 0.0 | 0.0 |
| | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 |
| 4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | 0.0 | - | - | 0.0 | 0.0 |
| | 0.0 | 0.0 | - | 0.0 | 0.0 |
| | - | 0.0 | 6.0 | - | 0.0 |
| | - | - | 0.3 | - | 0.0 |
| | - | 0.0 | 1.7 | - | 0.0 |
| | 0.0 | 0.0 | 2.0 | 0.0 | 0.0 |
| 6 | 0.0 | 0.0 | - | 0.0 | 1.0 |
| | 0.0 | 0.5 | 4.2 | 0.0 | 0.0 |
| | 0.0 | 0.3 | - | 1.0 | 1.0 |
| | 2.0 | 2.0 | 0.3 | - | 0.0 |
| | 0.0 | 0.0 | 2.5 | - | 0.0 |
| | 2.0 | 0.0 | - | - | 1.0 |
| | 0.7 | 0.5 | 2.3 | 0.3 | 0.5 |
| 10 | 0.0 | 0.5 | - | - | 4.0 |
| | 0.0 | 1.0 | 1.2 | 0.0 | 3.3 |
| | 0.0 | - | - | 1.0 | 0.3 |
| | - | 0.0 | 5.9 | 0.0 | - |
| | - | 0.0 | 3.0 | 1.0 | - |
| | - | 0.0 | 8.5 | 0.0 | - |
| | 0.0 | 0.3 | 4.7 | 0.4 | 2.5 |

from these data that shale 2068 caused considerably more popout damage than any of the other shales. Beams containing shale 2068 had higher surface deterioration factors than beams containing the other shales at every percentage level, and shale 2068 was the only shale to cause even a single popout in beams containing 2 to 4 percent of this material.

Only a small difference in performance relative to popout damage could be detected among the other four shales. No surface deterioration occurred for any of these shales when used in amounts up to and including 4 percent. At the 6 to 10 percent levels, shales 2066 and 2076 caused little more popout damage than shales 2063 and 2075, but the difference is slight.

Comparison of surface deterioration factors for the cherts and shales indicates that, except for sample 2068, the shales caused about the same amount of surface deterioration as cherts of the 2.45-2.55 specific gravity range. In general, the shales

caused greater popout damage than cherts of the 2.55 plus specific gravity range and lesser damage than cherts of the 2.45 minus gravity range. Shale 2068, however, resulted in more severe surface deterioration than any of the cherts of any specific gravity range.

COMPARISON OF AIR VOID PARAMETERS AND DURABILITY OF CONCRETE MIXED BY HAND AND MACHINE

During the early stages of the freeze-thaw study of concrete beams containing shales, a few beams were prepared from hand-mixed concrete to see how their durabilities would compare with those of the regular beams from machine-mixed concrete used in the freeze-thaw testing program. It was found that in nearly all cases the hand-mixed concrete had lower durability factors than machine-mixed concrete of identical composition. It was felt that this presented an opportunity to study the air-void parameters of these two classes of concrete in an attempt to explain the observed differences.

By means of the linear traverse technique outlined by Fears (9), the total percentage of entrained and entrapped air was determined for each beam. Using the values obtained for total percentage of air and voids per inch of traverse, it was possible to compute specific surface areas and bubble spacing factors for the beams using Powers method (10). Powers theorized that the increase in durability afforded concrete by means of air entrainment is largely a function of the spacing of the air voids in the concrete. He suggested that a concrete containing air voids with high specific surface area, and thus with a low void spacing factor, would receive more protection from the air voids than one containing air bubbles having a low specific surface area and a high spacing factor. He considered a void spacing of about 0.01 in. to be critical; those concretes with spacing factors lower than 0.01 in. were thought to be well protected from freezing and thawing deterioration; those with spacing factors greater than 0.01 in. were thought to be poorly protected.

This theory is supported by the results of the linear traverse studies (Table 4A and Figure 2). For the 14 beams studied, it was found that those having high durability factors (83 and above) all had spacing factors below 0.01 and those with low durability factors (21 and below) had spacing factors above 0.01. Also, the specific surface areas of the beams with high durability factors were all higher than those with low durability factors.

INFLUENCE OF BASIC PROPERTIES OF THE CHERTS AND SHALES ON FREEZE-THAW DURABILITY

The primary objective of this portion of the study was to study the basic properties of cherts and shales in Indiana's gravel aggregates and to determine how these properties

TABLE 4A
RESULTS OF AIR VOID STUDIES OF CERTAIN CONCRETE BEAMS BY MEANS
OF THE LINEAR TRAVERSE TECHNIQUE

| Beam | | Durability Factor | % Air | Voids per In | Calculated Specific Surface Area of Voids (sq in / cu in) | Calculated Void Spacing Factor (in) |
|-------|-----------------------------------|----------------------|----------|--------------------|--|--|
| No | Description | | | | | |
| S6-3 | 4% shale No 2063, machine mixed | 97 1 | 3 3 | 4.2 | 506 | 0 0080 |
| S6-6 | 4% shale No 2063, hand mixed | 21 1 | 4 1 | 2.9 | 287 | 0.0131 |
| S8-6 | 10% shale No 2063, machine mixed | 95 0 | 3 8 | 4 8 | 512 | 0 0075 |
| S8-1 | 10% shale No 2063, hand mixed | 6 0 | 3.8 | 2.0 | 208 | 0 0185 |
| S9-5 | 10% shale No. 2068, machine mixed | 83 0 | 2.7 | 3 5 | 523 | 0 0088 |
| S9-1 | 10% shale No 2068, hand mixed | 8 3 | 3 3 | 2 7 | 324 | 0 0126 |
| S20-2 | 10% shale No 2066, machine mixed | 96 5 | 3.5 | 3 8 | 441 | 0 0091 |
| S20-5 | 10% shale No 2066, hand mixed | 14 2 | 3.0 | 2.0 | 269 | 0 0185 |
| S21-2 | 6% shale No 2075, machine mixed | 72 4 | 3 0 | 3.8 | 512 | 0.0083 |
| S21-6 | 6% shale No. 2075, hand mixed | 10 6 | 3 1 | 2 1 | 273 | 0 0154 |
| S22-1 | 10% shale No 2076, machine mixed | 90 8 | 2 8 | 3 2 | 451 | 0 0098 |
| S22-4 | 10% shale No 2076, hand mixed | 30.1 | 2 7 | 2 2 | 326 | 0.0139 |
| S23-3 | 10% shale No 2075, machine mixed | 96 2 | 3 1 | 5 0 | 637 | 0 0066 |
| S23-4 | 10% shale No 2075, hand mixed | 5 3 | 3 8 | 3 0 | 316 | 0 0121 |

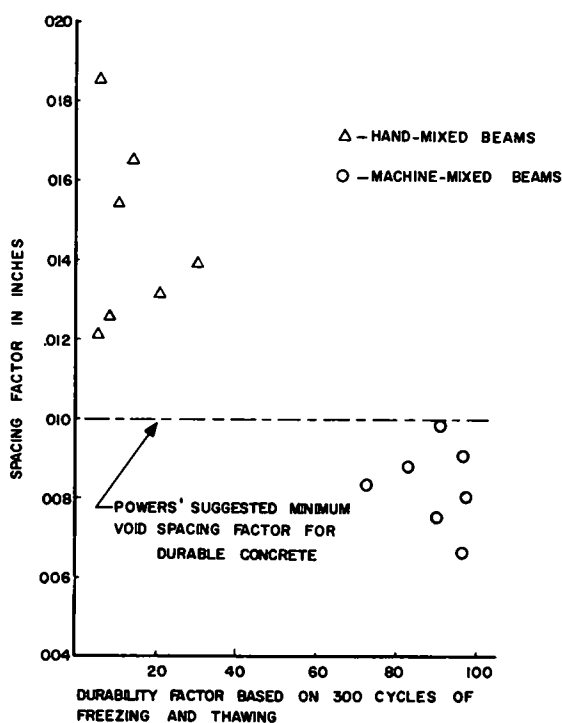


Figure 2. Relationship of durability factors to void spacing factors for air-entrained concrete.

of voids and volume of voids less than and greater than 5 microns in diameter were determined for the three specific gravity groups of cherts 2067 and 2077, and total porosity was determined for the five shale samples.

Total Porosity

Total porosity was calculated by means of the following relationship between bulk and true specific gravity:

$$n = \frac{V_v}{V} = 1 - \frac{S_b}{S_t}$$

in which

- n = porosity,
- V = total volume,
- V_v = volume of voids,
- S_t = true specific gravity, and
- S_b = bulk specific gravity.

The total porosity of chert is inversely related to its bulk specific gravity (a more easily measured characteristic than porosity) for materials of the same true specific gravity, and as such is generally reflected in specifications for chert in concrete aggregate. It has been found that the most porous cherts (those with the lowest bulk specific gravities) cause the most severe freeze-thaw deterioration.

Freeze-thaw studies of concrete beams containing chert showed that significant deep-seated and surface deterioration took place only in beams containing 6 to 10 percent of material from the 2.45 minus specific gravity group. For the samples tested, the

affect the freeze-thaw durability of these materials. The properties discussed are porosity, absorption, mineralogy, texture and microstructure.

Porosity

Much work relating porosity and durability of crushed limestone aggregates has been done by Sweet (11) and Fears (12). Early studies by Cantrill and Campbell (13), Wuerpel and Rexford (14), and Sweet and Woods (3) correlated porosity and durability for cherts. However, little correlation of this type has been attempted for shales, and the chert studies mentioned were made before air-entrained concrete had come into use and before freeze-thaw testing had reached its present state of development. In addition, little was done in a quantitative sense in these previous studies. For example, it was determined in a qualitative way that lightweight chert causes deterioration when used in concrete exposed to freezing and thawing, but nothing has been done to determine the quantity of this material required to cause deterioration.

Since porosity is so important in the freezing and thawing durability of concrete aggregates, several studies of voids in the cherts and shales were made. Total volume

TABLE 5
TOTAL POROSITIES OF CHERT SAMPLES

| Source | Gravity Group (by heavy liquid separation) | Bulk Sp Gr | True Sp Gr | $\frac{S_b}{S_t}^*$ | Porosity, n (%) |
|--------|---|---------------|---------------|---------------------|--------------------|
| 2067 | 2.55 plus | 2.56 | 2.64 | 0.970 | 3.0 |
| | 2.45-2.55 | 2.44 | 2.64 | 0.924 | 7.6 |
| | 2.45 minus | 2.30 | 2.64 | 0.871 | 12.9 |
| 2077 | 2.55 plus | 2.56 | 2.64 | 0.970 | 3.0 |
| | 2.45-2.55 | 2.47 | 2.64 | 0.936 | 6.4 |
| | 2.45 minus | 2.31 | 2.65 | 0.872 | 12.8 |

$$* n = \left(1 - \frac{S_b}{S_t}\right) 100$$

porosity of chert in this specific gravity group was nearly 13 percent (Table 5). Chert from the 2.45-2.55 and 2.55 plus specific gravity groups, which caused little freeze-thaw deterioration, had porosities of only about 7 and 3 percent, respectively. This relationship definitely supports the ideas of Wuerpel and Rexford (14) and Sweet and Woods (3) that cherts with high porosity are more susceptible to freeze-thaw deterioration than those with low porosity, and further demonstrates that this concept holds for air-entrained concrete as well as concrete with no entrained air. It also suggests that the 2.45 bulk specific gravity level (saturated surface-dry basis) suggested by Sweet and Woods as the critical level of separation of unsound chert and durable chert is realistic even for air-entrained concrete.

The lack of protection afforded porous aggregates such as these lightweight cherts by air-entrained cement paste has been explained in general terms by Powers (15). When saturated aggregate particles surrounded by air-entrained cement paste are subjected to freezing, the water in the paste is able to move to the "escape boundaries" provided by entrained bubbles in the paste, and no excess hydraulic pressures are able to develop. Thus the paste itself is protected from dilation. However, saturated porous rock particles enclosed by the paste still perform as virtually enclosed containers and are only a little better off than if the paste were not air-entrained. Probably the paste bubbles near the contact between aggregate particle and paste do accept a small amount of the excess water produced by freezing the saturated aggregate, but for saturated aggregates of high porosity, the amount of excess water is too large to be taken on by the bubbles in the paste immediately adjacent to the aggregate. For this reason, protecting the paste by air entrainment, while possibly successful for aggregates of low porosity, fails to protect saturated highly porous aggregate particles. This concept helps to explain the findings of Axon, Willis, and Reagel (16) who noted that the entrainment of air resulted in a definite improvement in durability of concrete containing limestones with good service records, but only caused a slight increase in durability for concrete made with chert-rich aggregate with a fair service record, and affected no appreciable improvement in durability of concrete made with chert-rich aggregate with a poor service record.

As given in Table 6, the porosities of the different shales varied widely. For example, shale 2068, which was the softest and weakest of the shales, was nearly twice as porous as any of the other shales, and over five times as porous as shale 2063, the least porous and the most-indurated of the samples. The widely varying porosities of the shales had no effect on the amount of deep-seated freeze-thaw deterioration caused by these materials, however. In amounts up to 10 percent, none of the shales caused any deep-seated damage to the concrete in which they were used. This lack of deep-seated deterioration of concrete containing shales of relatively high porosity was due

TABLE 6
TOTAL POROSITIES OF SHALE SAMPLES

| Source | Bulk Sp Gr | True Sp Gr | $\frac{S_b^*}{S_t}$ | Porosity, n (%) |
|--------|---------------|---------------|---------------------|--------------------|
| 2063 | 2.28 | 2.38 | 0.958 | 4.2 |
| 2066 | 2.06 | 2.39 | 0.862 | 13.8 |
| 2068 | 2.00 | 2.58 | 0.775 | 22.5 |
| 2075 | 2.24 | 2.45 | 0.914 | 8.6 |
| 2076 | 2.08 | 2.47 | 0.842 | 15.8 |

$$*n = (1 - \frac{S_b}{S_t}) 100$$

to the inherent structural weakness of these materials. Since the shale is considerably weaker than the surrounding mortar, it will fail internally due to the pressures developed in freezing rather than disrupt the mortar. This was demonstrated by comparison between pieces of chert and shale that had failed in the freeze-thaw test and subsequently had been removed from the beams. The chert pieces, which had caused deep-seated deterioration had broken into many pieces, but the individual pieces were still relatively hard and firm. The shales, on the other hand, had disintegrated into weak crumbly masses although they had caused no deep-seated deterioration. From all appearances these shales had failed internally before the pressures due to freezing could develop enough to break the surrounding mortar.

Where an individual shale particle occurred close to the surface of a beam, the enclosing mortar layer was often not strong enough to resist the hydrostatic pressures developed by freezing the saturated particle. In this case the mortar was disrupted, resulting in surface deterioration in the form of a popout or pit. The relative porosities of the shales had a marked relationship to severity of surface deterioration. Shale 2068, the material having the highest porosity of the group (Table 6), caused considerably more popout damage than any of the other shales or any of the cherts. It appears that this larger amount of deterioration is related to the greater porosity of shale 2068, but, as will be discussed later, other factors such as the size of the pores and the amount of absorption of the shale probably have a greater effect on the durability of the aggregate than the total porosity.

It should be noted that among the other four shales the relationship between porosity and surface deterioration is not so clear. Shales 2076 and 2066 are considerably more porous and more absorptive than 2063 and 2075, yet caused only a little more popout damage than 2063 and 2075.

In summary of the relationship of total porosity to freeze-thaw deterioration of concrete containing cherts and shales, the following points should be brought out:

1. Although other pore characteristics such as pore size and absorptivity may have a strong influence on the resistance of the cherts tested to both deep-seated and surface deterioration, there is a definite relationship between total porosity and the freeze-thaw resistance of these materials. The more porous fractions from all six chert groups caused more freeze-thaw deterioration than the less porous material.

2. Total porosity of shales was related to severity of surface deterioration of concrete in which the shales were used, but in spite of widely varying porosities, none of the shales resulted in deep-seated deterioration of concrete in which they were used in amounts up to ten percent. Shale 2068, which was considerably more porous than the other shales, caused much more surface deterioration than the others but caused no deep-seated deterioration.

Size of Pores

Although recognizing a relationship between total porosity and freeze-thaw durability

of aggregates, Sweet (1) and Fears (12) have contended that the durability of aggregates is dependent more on the size and continuity of aggregate pores than on total porosity. Lewis and Dolch (17) maintained that the harmful pore size is that large enough to permit water readily to enter much of the pore space but not large enough to permit easy drainage. Studies by Sweet (1), and Fears (12) have indicated that critical pore size for freezing and thawing durability of limestone aggregates is about 5 microns. Blanks (18) has shown that, under natural conditions of freezing and thawing, voids less than 5 microns in diameter, and particularly those less than 4 microns in diameter, will drain effectively only at hydrostatic pressures that exceed the tensile strengths of some rocks and concrete.

These previous investigations indicate the importance of microvoids (pores less than 5 microns in diameter) in the durability of aggregates. Therefore, part of the present study was devoted to determining if this relationship between pore size and durability holds for Indiana cherts. For cherts 2067 and 2077, the percentage of total volume of aggregate occupied by voids greater than 5 microns in diameter was determined by a linear traverse study of polished surfaces and this percentage was subtracted from the total porosity to obtain the percentage of total aggregate volume occupied by microvoids. (As used here, the term "microvoids" refers to voids less than 5 microns in diameter.) The linear traverse technique used was similar to that reported by Fears (9) for study of air-voids in hardened concrete. Recording of traverse lengths was accomplished by means of a Hunt-Wentworth recording micrometer of the type commonly used for micrometric mineralogical analyses.

The results of the pore size studies are given in Table 7. It was found that the volume of microvoids was somewhat less than expected. Sweet (1) had noted that in Indiana limestone aggregates the volume of microvoids, expressed as a ratio of the total volume, was less than 0.057 for aggregates with good field performance records and greater than 0.091 for aggregates with poor service records. If Sweet's criteria were to be applied to the chert fractions whose void ratios are given in Table 7, it would seem that none of the material in these fractions would be susceptible to freeze-thaw deterioration since none of this material has microvoid ratios (as used here the term "microvoid ratio" refers to the ratio of volume of voids less than five microns in diameter to the bulk volume of the aggregate) as high as 0.091. The highest ratio, 0.064 for the 2.45 minus specific gravity group of chert 2067, is only slightly higher than the 0.057 ratio designated as the upper limit for aggregates with good service records. In spite of these relatively low microvoid ratios, the 2.45 minus specific gravity chert from sources 2067 and 2077 caused serious freeze-thaw deterioration in concrete in which it comprised 10 percent of the coarse aggregate.

It also should be noted that practically no freeze-thaw deterioration occurred in concrete containing chert from the 2.45-2.55 specific gravity range even though this material contained nearly as large a ratio of microvoids as did chert from the 2.45 minus specific gravity group. In spite of the lack of difference in volume of microvoids between the 2.45-2.55 and 2.45 minus specific gravity ranges, there is considerable difference in total porosity between these ranges. As given in Table 7, the high total porosity of the 2.45 minus chert as compared to the 2.45-2.55 material is primarily

TABLE 7
RELATION OF PORE SIZE TO DEGREE OF SATURATION FOR CHERTS 2067 AND 2077

| Source | Sp Gr Range | Total Porosity (%) | % of Bulk Volume Consisting of Voids >5 Microns in Diameter | % of Voids Volume Consisting of Voids >5 Microns in Diameter | % of Bulk Volume Consisting of Voids <5 Microns in Diameter | % of Voids Volume Consisting of Voids <5 Microns in Diameter | Degree of Saturation (%) |
|--------|-------------|--------------------|---|--|---|--|--------------------------|
| 2067 | 2 55 plus | 3 0 | 0 6 | 20.0 | 2 4 | 80 0 | 82 3 |
| | 2 45-2 55 | 7 6 | 1.9 | 25 0 | 5 7 | 75 0 | 92 5 |
| | 2 45 minus | 12 9 | 6 5 | 50 4 | 6.4 | 49 6 | 100 0 |
| 2077 | 2.55 plus | 3 0 | 0.4 | 13 3 | 2 6 | 86 7 | 78.3 |
| | 2.45-2.55 | 6.4 | 2 3 | 35 9 | 4 1 | 64.1 | 87 7 |
| | 2 45 minus | 12.8 | 7 9 | 61.7 | 4 9 | 38 3 | 90 5 |

due to the increase in voids larger than 5 microns in diameter in the 2.45 minus material. As the total porosity of the chert increases in going from material of high to low bulk specific gravity, the voids larger than 5 microns in diameter constitute an increasingly larger percentage of the total pore space, and conversely, the microvoids make up an increasingly smaller percentage of the pore space (Table 7). For example, for chert 2067, the microvoids constitute 80 percent of the total pore space in the 2.55 plus chert, 75 percent in the 2.45-2.55 material, and only 50 percent in the 2.45 minus range.

On the basis of this study, it appears the microvoids ratio is not as reliable an indicator of freeze-thaw durability of chert aggregate as Sweet (1) and Fears (12) found it to be for limestone aggregate. The results of this study indicate that some other pore characteristic or, more probably, a combination of characteristics (perhaps including volume of microvoids) is probably the main factor in determining chert durability.

As given in Table 7, the degree of saturation of the cherts increases with increasing total porosity and decreasing bulk specific gravity. This increase is probably caused by the larger percentage of voids larger than 5 microns in diameter in the more porous material. Under conditions of vacuum saturation and frequently repeated immersion as used in these tests, a piece of aggregate containing numerous large voids as well as microvoids would probably reach a high degree of saturation more readily than a particle containing only microvoids, because of the greater ease of flow through the larger voids. In this way it is thought that 2.45 minus chert reaches a higher degree of saturation than heavier less porous fractions, and that this high degree of saturation is a prime factor in the lack of durability of the 2.45 minus material.

Besides being a factor in the permeability of the chert, the size of the pores undoubtedly determines whether dilation occurs. Pores or bulges in pores that are large enough to act as escape boundaries for the water under hydrostatic pressure (15) will cause no dilation. Obviously some of the large pores in the 2.45 minus material are in this category. The critical size between pores which will cause dilation and those which will act as escape boundaries depends on the length and tortuosity of the pores. It is possible that dilation in lightweight cherts occurs entirely within voids less than 5 microns in diameter which are supplied with water by the larger voids, but it is quite probable that some of the voids larger than 5 microns are too small to serve as escape boundaries and thus contribute to dilation of the particle.

In summary, the microvoids ratio does not provide a satisfactory indication of the freeze-thaw durability of chert. Instead chert durability is probably more closely related to the degree of saturation of these small voids (and larger voids that are too small to act as escape boundaries) which is strongly influenced by the presence of voids greater than 5 microns in diameter. Based on this concept and the results of the freeze-thaw tests, it appears that total porosity, as reflected in bulk specific gravity, serves as a satisfactory criterion for predicting the freeze-thaw durability of chert.

ABSORPTION

Lewis and Dolch (17) have stated that, "The lack of durability of an aggregate in freezing and thawing is primarily dependent on its ability to become and stay highly saturated under the given conditions of moisture." Thus besides being porous, an aggregate must be absorptive in order to be susceptible to freeze-thaw deterioration. This section discusses the relationship between (a) vacuum-saturated absorption, and (b) rate of absorption of cherts and shales, and the resistance of these materials to freeze-thaw deterioration.

Vacuum-Saturated Absorption

Comparison of the results of the vacuum-saturated absorption tests of the chert groups (Table 8) to the results of freeze-thaw tests of concrete containing the cherts indicates a direct relationship between percentage of absorption and lack of freeze-thaw durability for chert. Cherts of the 2.45 minus specific gravity ranges for all six

sources had absorption percentages about twice as great at those for the 2.45-2.55 groups and five times as great as the 2.55 plus groups. The absorptions of these materials are directly related to their porosities. As given in Table 7, the higher percentage of pores larger than 5 microns in diameter found in the highly porous 2.45 minus material as compared to that in the 2.45-2.55 and 2.55 plus fractions apparently facilitated absorption in the lightweight chert with a resulting higher degree of saturation than could be obtained in the heavier materials.

As has been shown previously, chert with a specific gravity of less than 2.45 caused the only deterioration in the freeze-thaw test. From the data it appears that cherts with vacuum-saturated adsorptions of less than about 3 percent will not cause significant freeze-thaw deterioration when included in concrete in amounts up to 10 percent of the coarse aggregate for the size groups studied. Apparently chert with absorptions of about 4 percent or greater will cause freeze-thaw failure when used in amounts as low as 6 percent of the coarse aggregate.

The vacuum-saturated absorption values for the shales (Table 9) varied considerably—the percentages of absorption roughly paralleling the porosities of the shale samples. As was the case for porosity, the absorption of the shales had no apparent influence on the resistance of concrete containing these materials to deep-seated deterioration. This is shown by the fact that none of the shales, including the most absorptive samples, caused any deep-seated freeze-thaw failure when used in concrete in amounts up to 10 percent of the coarse aggregate.

There does appear to be a relationship between absorption and severity of surface deterioration, however. Shale 2068, which has the greatest absorption, caused by far the greatest amount of popout damage. As was the case for porosity, the influence of absorption on surface deterioration is not so distinct among the other four shales. Shales 2066 and 2076 had considerably greater absorptions than shales 2063 and 2075 (Table 9), but there was little difference in the amount of surface deterioration caused by these four shales. Although the popout damage caused by shales 2066 and 2076 was slightly

TABLE 8
VACUUM-SATURATED ABSORPTION VALUES
FOR CHERT SAMPLES

| Source | Saturated Surface-Dry Bulk Specific Gravity Group | Size Range (in.) | Absorption (%) |
|--------|---|-------------------------------|----------------|
| 2063 | 2 55 plus | $\frac{3}{4}$ -1 | 1 26 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 1 21 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 1 12 |
| | | | 1 20 |
| | 2 45-2 55 | $\frac{3}{4}$ -1 | 3 02 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 2 84 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 3 30 |
| | | | 3 05 |
| | 2 45 minus | $\frac{3}{4}$ -1 | 6 26 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 6 13 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 6 88 |
| | | | 6 42 |
| 2064 | 2 55 plus | $\frac{3}{4}$ -1 | 0 82 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 0 93 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 1 00 |
| | | | 0 92 |
| | 2 45-2 55 | $\frac{3}{4}$ -1 | 2 86 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 2 78 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 2 90 |
| | | | 2 85 |
| | 2 45 minus | $\frac{3}{4}$ -1 | 5 71 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 5 56 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 5 82 |
| | | | 5 63 |
| 2066 | 2 55 plus | $\frac{3}{4}$ -1 | 1 14 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 1 30 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 1 09 |
| | | | 1 18 |
| | 2 45-2 55 | $\frac{3}{4}$ -1 | 2 76 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 3 12 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 2 86 |
| | | | 2 91 |
| | 2 45 minus | $\frac{3}{4}$ -1 | 6 12 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 6 36 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 6 11 |
| | | | 6 20 |
| 2067 | 2 55 plus | $\frac{3}{4}$ -1 | 1 09 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 1 05 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 1 19 |
| | | | 1 11 |
| | 2 45-2 55 | $\frac{3}{4}$ -1 | 2 96 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 2 84 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 2 67 |
| | | | 2 82 |
| | 2 45 minus | $\frac{3}{4}$ -1 | 5 58 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 5 59 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 5 82 |
| | | | 5 60 |
| 2072 | 2 55 plus | $\frac{3}{4}$ -1 | 1 02 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 1 11 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 1 11 |
| | | | 1 08 |
| | 2 45-2 55 | $\frac{3}{4}$ -1 | 2 55 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 2 60 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 2 98 |
| | | | 2 77 |
| | 2 45 minus | $\frac{3}{4}$ -1 | 5 28 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 5 39 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 5 91 |
| | | | 5 52 |
| 2077 | 2 55 plus | $\frac{3}{4}$ -1 | 1 06 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 0 92 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 1 04 |
| | | | 1 01 |
| | 2 45-2 55 | $\frac{3}{4}$ -1 | 2 31 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 2 69 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 2 27 |
| | | | 2 42 |
| | 2 45 minus | $\frac{3}{4}$ -1 | 4 77 |
| | | $\frac{1}{2}$ - $\frac{3}{4}$ | 4 20 |
| | | $\frac{1}{4}$ - $\frac{1}{2}$ | 4 51 |
| | | | 4 49 |

TABLE 9
VACUUM-SATURATED ABSORPTION VALUES
FOR SHALE SAMPLES

| Source | Size Range (in) | Absorption (%) |
|--------|-------------------------------|-------------------|
| 2063 | $\frac{3}{4}$ -1 | 1 54 |
| | $\frac{1}{2}$ - $\frac{3}{4}$ | 1 60 |
| | $\frac{3}{8}$ - $\frac{1}{2}$ | 2 17 |
| | | 1 77 |
| 2066 | $\frac{3}{4}$ -1 | 7 07 |
| | $\frac{1}{2}$ - $\frac{3}{4}$ | 7 05 |
| | $\frac{3}{8}$ - $\frac{1}{2}$ | 7 04 |
| | | 7 05 |
| 2068 | $\frac{3}{4}$ -1 | 12 83 |
| | $\frac{1}{2}$ - $\frac{3}{4}$ | 12 23 |
| | $\frac{3}{8}$ - $\frac{1}{2}$ | 12 63 |
| | | 12 56 |
| 2075 | $\frac{3}{4}$ -1 | 3 64 |
| | $\frac{1}{2}$ - $\frac{3}{4}$ | 4 06 |
| | $\frac{3}{8}$ - $\frac{1}{2}$ | 4 68 |
| | | 4 13 |
| 2076 | $\frac{3}{4}$ -1 | 7 82 |
| | $\frac{1}{2}$ - $\frac{3}{4}$ | 8 61 |
| | $\frac{3}{8}$ - $\frac{1}{2}$ | 7 91 |
| | | 8 11 |

of absorption indicate the two materials have considerably different pore systems. Chert 2067 is obviously more permeable than chert 2077. This difference in permeability between cherts 2067 and 2077 is reflected in degrees of saturation obtained by vacuum-saturating these two aggregates (Table 7). At all specific gravity levels chert 2067 had higher saturation coefficients than chert 2077. In spite of this difference in permeability and its resulting difference in degree of saturation, these two cherts resulted in similar deterioration in the freeze-thaw test at all specific gravity levels.

It should be noted that the freeze-thaw tests were conducted under rather severe saturation conditions. The aggregate was vacuum-saturated before mixing the concrete, and the beams were immersed in water for 13 days prior to being subjected to freezing and thawing. They were, of course, reimmersed during each thaw cycle. Under such conditions both cherts maintained a high degree of saturation (Table 7). Under actual service conditions, however, the amount of available water would not always be as great as in these laboratory tests and permeability could have a greater influence on freeze-thaw durability.

The rates of absorption of the shales (Fig. 4) are directly related to the total absorptions of these materials. Those shales with high total absorptions absorbed water rapidly during the first few minutes of the test, following which, water was absorbed at a slowly decreasing rate for the rest of the test. The shales with low total absorptions exhibited a fairly constant increase in absorption throughout the test. As was the case with porosity and total absorption, this greater permeability of certain shales had no influence on the resistance of the shales to deep-seated deterioration. It probably is a factor in surface deterioration, however, since shale 2068 which caused the most popout damage also had the fastest rate of absorption.

greater than that caused by shales 2063 and 2075, it was not as great as might be expected in light of the severe damage to concrete containing shale 2068. It is probable that the great difference in surface deterioration between shale 2068 and shales 2066 and 2076 is not entirely due to the greater porosity and absorption of sample 2068, but was at least partially a result of the relative lack of induration of this shale as compared to the others.

Rate of Absorption

The rates of absorption of cherts 2067 and 2077 (Fig. 3) apparently had little influence on freeze-thaw durability of these materials. Material in all three specific gravity groups of chert 2067 attained nearly maximum absorption for the test in only five minutes, while the absorption of chert 2077 for the same specific gravity groups for the first five minutes was only about 25 percent of its total absorption. Although the total porosities and absorptions of these two cherts were similar, the rates

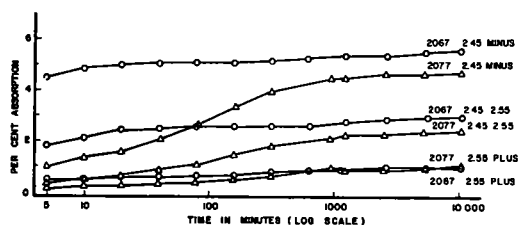


Figure 3. Rates of absorption for different specific gravity fractions of cherts 2067 and 2077.

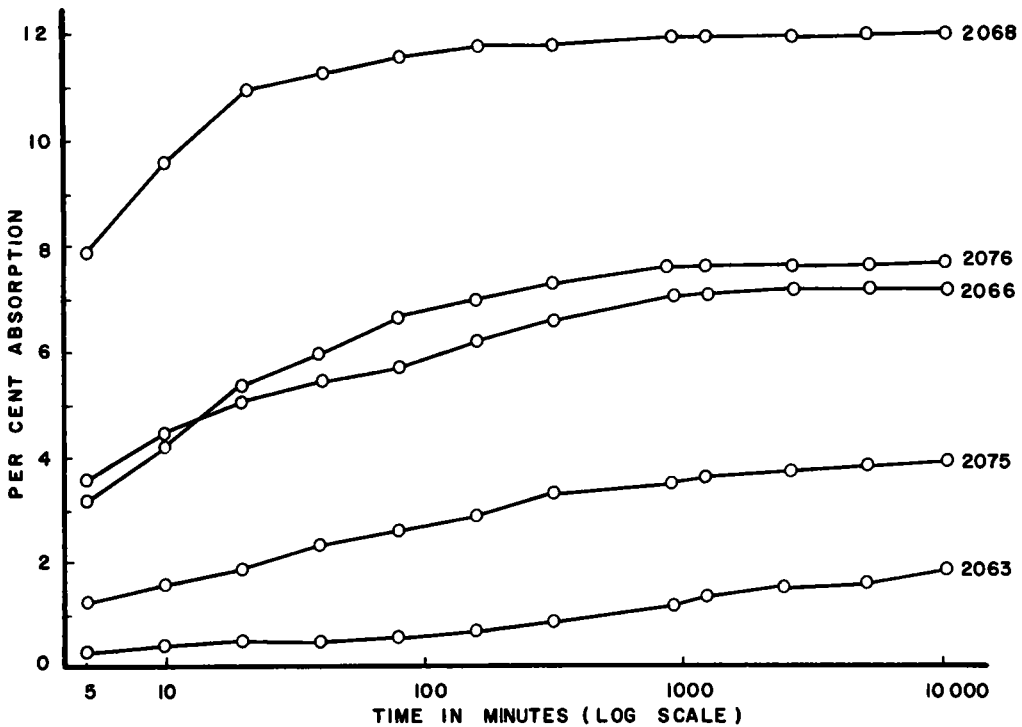


Figure 4. Rates of absorption for shale samples.

MINERALOGY, TEXTURE AND MICROSTRUCTURE

The properties of mineralogy, texture, and microstructure have been grouped together because they were all included in studies utilizing the petrographic microscope. Microscopic petrography has long been a valuable tool in study of the characteristics of rocks. Runner (19) was one of the first to apply petrography to the study of deleterious substances in aggregates. His petrographic investigations were followed by reports of similar studies and description of techniques by Mielenz (20, 21), Rhoades and Mielenz (22, 23), and Mather and Mather (24). In the present study an attempt was made to find a relationship between the results of petrographic studies of deleterious materials and the laboratory freeze-thaw durability of these materials.

Petrographic study was carried out using a Leitz Ortholux petrographic microscope with binocular attachments. Thin sections were made from each of the five shale samples and six chert samples. These sections were studied under transmitted light at magnifications of approximately 100 X to 400X. Since the complete mineral composition of shales is not easily determined by microscopic analysis, X-ray diffraction and differential thermal analysis supplemented microscopic petrography in study of shale mineralogy.

Petrographic analysis of thin sections showed the cherts to be of generally similar mineralogical character. They are composed primarily of microcrystalline quartz and radial chalcedony. Small amounts of coarser-grained secondary quartz, some calcite, and limonite and carbonate rhombs are also present.

Each of the cherts consists primarily of microcrystalline aggregates of quartz grains usually less than 0.01 mm in diameter. The secondary quartz occurs as granular masses which apparently replaced carbonate minerals. The individual quartz grains in these secondary masses range in size from less than 0.01 mm to as large as 0.2 mm. Radiating chalcedony in the chert samples occurs as spherulites, often as much as 0.25 mm wide.

The carbonate and limonite rhombs range in size from less than 0.01 mm to as much as 0.1 mm. Although most of the rhombs consisted of carbonate or limonite, some appeared to have a translucent carbonate mineral in the center surrounded by a rim of opaque limonite. The carbonate rhombs probably formed by replacement of crystal-line quartz in the original chert (25), and in turn these rhombs are being replaced by limonite. Limonite also occurs as finely disseminated masses scattered throughout the chert.

One chief mineralogical difference was noted among the chert gravels. Cherts from the southern part of Indiana (especially material from the Ohio River) contain considerably more limonite than those from the northern part of the state. This difference in limonite content apparently had no influence on freeze-thaw durability, however, since all six cherts reacted similarly to the freeze-thaw tests.

It is also of interest to note that little difference in mineralogy was found among the different specific gravity groups for each chert source in spite of the fact that the materials in the different specific gravity groups had considerably different freeze-thaw durabilities. Apparently there is little direct relationship between mineralogy and freeze-thaw durability of Indiana cherts.

An important microstructural feature in chert samples from all six sources is the numerous voids observed in thin sections from material in the 2.45 minus specific gravity range (Figs. 5 and 6). No voids were noted in the 2.45-2.55 and the 2.55 plus ranges. The voids are all fairly large, since voids less than about 30 microns in

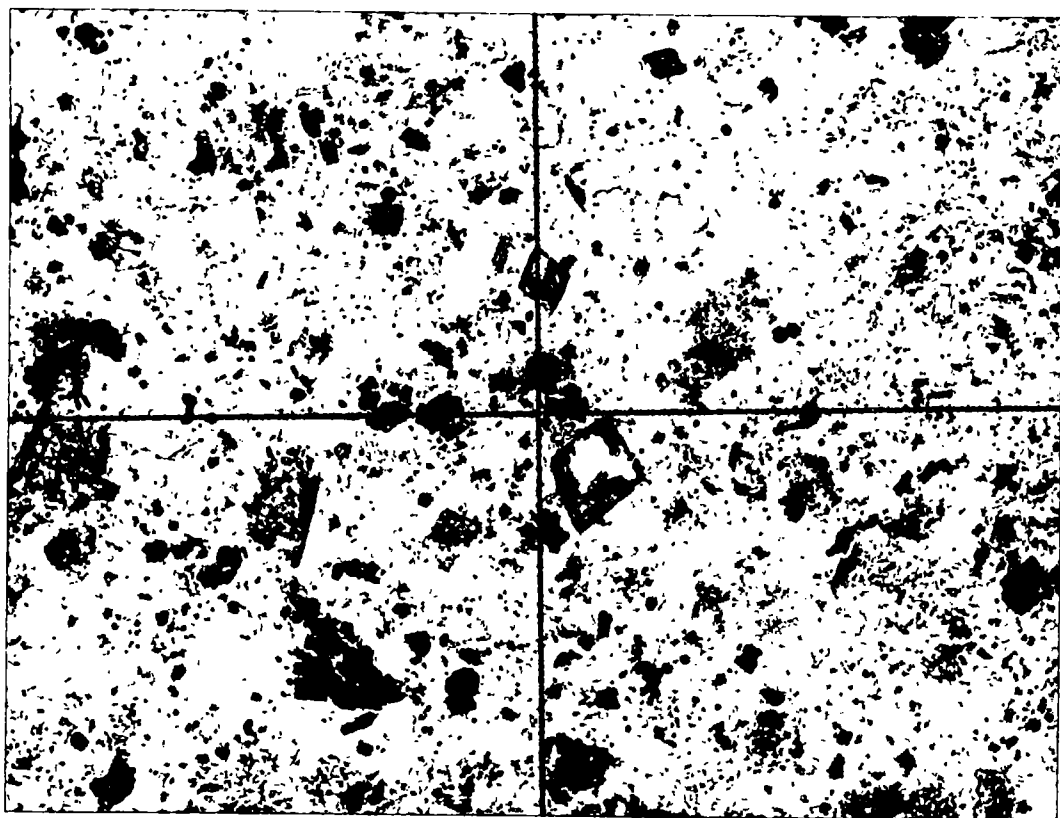


Figure 5. Chert 2077 (s.g. 2.45 minus) in plain light. Limonite (opaque) and carbonate (translucent rhombs in fine-grained quartz matrix. Note void in process of formation by solution of carbonate from large rhomb near intersection of cross-hairs.

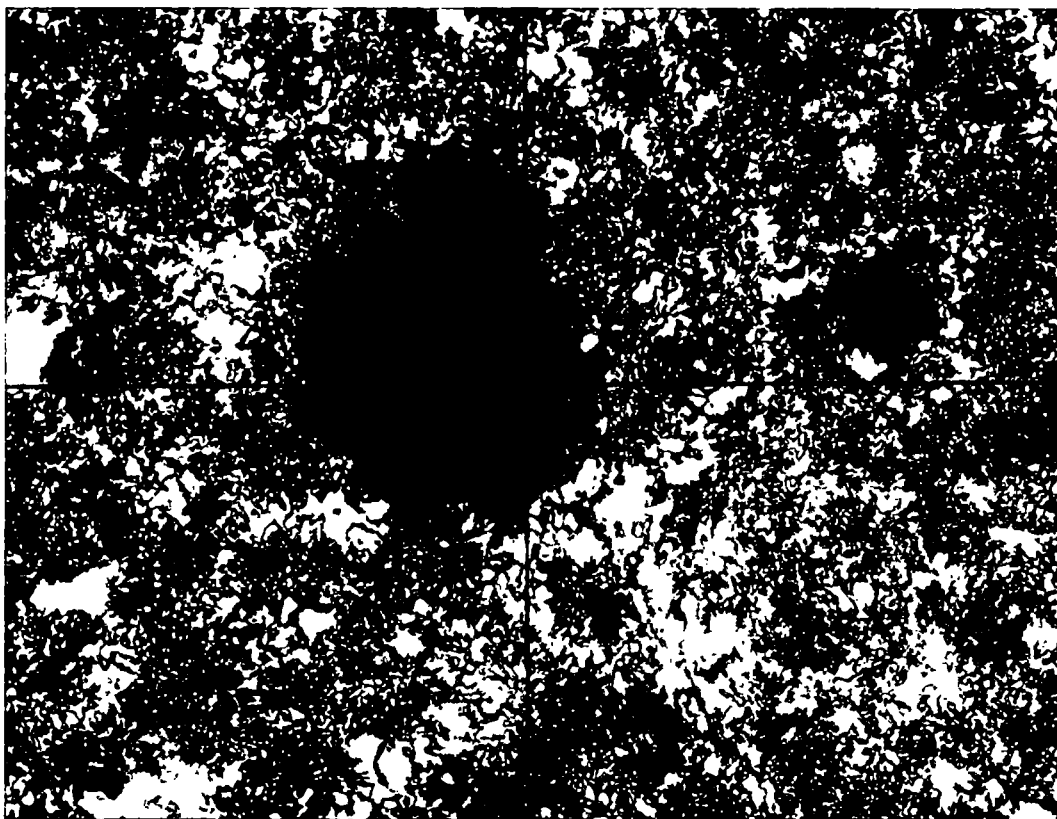


Figure 6. Chert 2063 (s.g. 2.45 minus) between crossed nicols. Large voids surrounded by radial chalcidony and fine-grained quartz matrix.

diameter cannot be detected easily in thin-section study. They range in size up to 0.4-0.5 mm in diameter, but most are less than 0.1 mm in diameter. As noted in the previous section on porosity, the concentration of these voids in the chert with specific gravity less than 2.45 resulted in the relatively high porosity of this lightweight chert, and the high degree of saturation achieved in the lightweight chert fractions is probably also related to the presence of these voids. Voids of this size had previously been recognized in thin sections of lightweight cherts from other states by Wuerpel and Rexford (14) who noted that these voids were related to the lack of durability of the cherts.

The 2.45-2.55 and 2.55 plus specific gravity groups contained practically no voids large enough to be recognized in thin section. Since lack of freeze-thaw durability was found only in the 2.45 minus chert, there is a direct correlation between the presence of these voids and the lack of durability of the lightweight chert. Although this contradicts the theories of Blanks (18) and others, that freeze-thaw deterioration occurs primarily in voids less than 5 microns in diameter, there is a strong possibility (as demonstrated previously in the section on porosity) that the larger voids are prime factors in the freeze-thaw breakdown of lightweight cherts due to the higher degree of saturation afforded the chert by the larger voids.

Other textural properties such as grain size, and presence of rhombic-shaped grains and replaced fossils, apparently had no influence on the freeze-thaw durability of the chert. These characteristics are similar in cherts of all three specific gravity ranges.

Petrographic, X-ray, and differential thermal analyses of the shales indicate a similarity in their general mineralogic composition, but there is considerable variation

in certain characteristics. All the shales consist of detrital mineral grains, primarily quartz, in a fine-grained matrix of clay minerals or hydromicas. The chief differences shown by the shales are the relative size and abundance of the detrital minerals and the relative amounts of clay minerals and organic material in the samples.

In order to satisfactorily describe the shales and to point out differences in their petrographic characteristics, and yet avoid repetition, a brief petrographic description of a shale with "average" characteristics will be given, and the mineralogies, textures, and microstructures of the strongest, least porous shale (2063) and the weakest, most porous shale (2068) will be compared with those of the average sample.

The average shale is composed primarily of a fine-grained illite matrix enclosing detrital quartz grains up to 0.04 mm in diameter (0.01-0.02 mm average). It contains considerable organic matter and disseminated limonite and a small amount of chlorite. Loss on ignition for this shale is approximately 12 percent. This description fits shales 2066, 2075, and 2076 fairly well.

Shale 2063, the most indurated and least porous of the shales, contained more detrital quartz and less clay mineral than the average shale. Besides being more abundant, the detrital quartz grains are larger than in the other shales, ranging in size up to 0.07 mm in diameter (0.02-0.03 mm average). The abundance and size of the detrital quartz is sufficient to classify sample 2063 as a silty shale or possibly even a siltstone. This sample also contained more organic material than the other shales as was shown by the 16.7 percent loss on ignition, the highest of all the shales.

Shale 2068, the softest and most porous of the shales, contains more clay mineral and less detrital quartz than the other shales. The size of the detrital quartz grains is about the same as that of the average shale, but the lower percentage of these grains means that the average grain size of shale 2068 is considerably smaller than that of the average shale. The relatively high percentage of illite accounts for the high porosity of this shale, and the combination of high clay and low quartz content accounts for its lack of induration.

Although the differences in relative percentages of clay minerals and quartz apparently have no effect on the tendency of the shales to resist deep-seated deterioration, these mineralogic differences, which influence the textures and microstructures, apparently do affect the amount of surface deterioration caused by the shales. This is especially true for shale 2068. Its high clay mineral content renders it weaker and more porous than the other shales, and thus it is more susceptible to freeze-thaw deterioration.

SUMMARY OF RESULTS

The following is a brief recapitulation of major findings of the study:

1. Freezing and thawing tests of concrete beams containing chert indicated the following:
 - (a) The source of chert had no effect on freeze-thaw durability.
 - (b) The only combination of variables resulting in severe deep-seated deterioration was 10 percent of 2.45 minus chert. This combination resulted in deep-seated failure of all beams containing chert from each of the six sources. In addition, 6 percent of 2.45 minus chert caused moderate deep-seated damage in a few cases.
2. Durability factors for the shale beams indicated that no deep-seated deterioration occurred in beams containing 2 to 10 percent of any of the five shales studied. The data included no extremely low durability factors as were found for beams containing 10 percent of 2.45 minus specific gravity chert. Only a few had durability factors below 90, and these few values were seemingly randomly distributed throughout the data.
3. Study of surface deterioration of concrete beams containing chert showed that freezing and thawing caused significant popout damage in beams containing 2.45 minus specific gravity chert. Few popouts were caused by chert having specific gravities of 2.45-2.55 and 2.55 plus.
4. The greatest amount of surface deterioration of the beams containing shale was caused by shale 2068, the most porous and most absorbent of the shales. Shale 2068

caused considerable popout and pitting damage at all four percentage levels, but, as would be expected, the amount of deterioration increased with increasing percentage of shale. The other four shales tested caused no surface deterioration when included in concrete in amounts up to and including 4 percent. At the 6 and 10 percent levels, shales 2066 and 2076, which were more porous and absorbent than shales 2063 and 2075, caused slightly more surface deterioration than the latter.

5. The study of air voids in concrete by means of the linear traverse technique demonstrated that machine-mixed concrete beams with high durability factors had air-void spacing factors lower than 0.01 in., and hand-mixed beams with low durability factors had spacing factors higher than 0.01 in. These results support Powers theory that concretes with spacing factors lower than 0.01 in. are well protected from freezing and thawing deterioration, while those with spacing factors greater than 0.01 in. are poorly protected.

6. Study of the size distributions of pores for cherts 2067 and 2077 indicated a marked increase in percentage of total voids volume consisting of pores larger than 5 microns in diameter with decreasing bulk specific gravity of the chert. For example, in the case of chert 2067, the voids larger than 5 microns in diameter constituted only 20 percent of the total pore space in the 2.55 plus chert, 25 percent in the 2.45-2.55 material, and 50 percent in the 2.45 minus range. Conversely, the voids less than 5 microns in diameter constituted a decreasing percentage of total voids volume with increase in total porosity and resulting decrease in bulk specific gravity.

7. Although the total porosities and absorptions of cherts 2067 and 2077 were similar, their rates of absorption indicate that these two cherts have considerably different pore systems. Chert 2067 was more permeable than chert 2077. Material in all three specific gravity groups of chert 2067 attained nearly maximum absorption after only five minutes of immersion, while the absorption of the same specific gravity groups of chert 2077 for the first five minutes was only about 25 percent of its total absorption.

The rates of absorption of the shales were directly related to the total absorptions. Those shales with high total absorptions absorbed water rapidly during the first few minutes of immersion, following which water was absorbed at a slowly decreasing rate for the rest of the test. The shales with low total absorptions exhibited a fairly constant increase in absorption throughout the test.

8. Petrographic analysis of thin sections showed the cherts to be of generally similar mineralogical character. They were composed primarily of microcrystalline quartz and radial chalcedony. Small amounts of coarse-grained secondary quartz, some calcite, and limonite were also present. One chief mineralogical difference was noted. Cherts from the southern part of Indiana (especially from the Ohio River) contained more limonite than those from the northern part of the state. This limonite occurred both as rhombs and in amorphous form. No differences in mineralogy were noted among the three specific gravity groups for the chert samples.

The shales also presented a similarity in their general mineralogic compositions, but showed considerable variability in certain characteristics. All the shales consisted of detrital mineral grains, primarily quartz, in a fine-grained matrix of clay minerals or hydromicas. The chief differences shown by the shales were the relative size and abundance of the detrital mineral grains and the relative amounts of clay minerals and organic material in the samples.

9. The textures and microstructures of the cherts were all similar. Each chert consisted primarily of microcrystalline aggregates of quartz grains usually less than 0.01 mm in diameter with granular masses of secondary quartz, radiating masses of chalcedony, and carbonate and limonite rhombs. The only notable structural difference in the cherts was that the 2.45 minus fraction of each sample contained numerous voids large enough to be identified in thin sections between crossed nicols. These voids, which averaged less than 0.01 mm in size, but ranged in size up to 0.4-0.5 mm, did not occur in the 2.55 plus and 2.45-2.55 specific gravity groups.

The textures and microstructures of the shales varied considerably. Although all the shales consisted of a fine-grained matrix enclosing detrital quartz grains, the

relative amounts of these materials and the sizes of the detrital particles varied enough to influence strongly the strength and hardness of the different shales. All the shales showed preferred orientation of grains.

CONCLUSIONS

Since this study was restricted to certain Indiana cherts and shales subjected to specific methods of test, the conclusions can logically be applied only to similar cherts and shales under similar conditions. However, in some cases, field behavior of the cherts and shales may be inferred from the following conclusions:

1. For a wide variety of cherts, the source of the chert has no effect on its freeze-thaw durability in concrete. Chert does, however, exhibit a definite relationship between its bulk specific gravity and durability in concrete exposed to freezing and thawing. The use of chert having a bulk specific gravity of less than 2.45 (saturated surface-dry basis) in concrete exposed to freezing and thawing should be avoided.

2. The freeze-thaw durability of concrete containing chert apparently is not as dependent on pores in the chert less than 5 microns in diameter as has been postulated by Sweet (1). Instead chert durability is apparently based on a more complicated interrelationship between total porosity, size of pores, absorption, and degree of saturation. Pores larger than the 5-micron size specified by Sweet permit easier passage of water into immersed aggregates, result in relatively high degrees of saturation, and contribute to freeze-thaw deterioration of lightweight chert. Microscopic studies of polished sections show that these larger pores make up about half the void volume in 2.45 minus specific gravity chert.

3. The petrographic characteristics of the cherts influence the freeze-thaw durability of these materials only in the relationship of these characteristics to porosity of the cherts. For example, although mineralogy of the cherts has no direct effect on their freeze-thaw durability, the presence of carbonate rhombs, which have weathered out to form voids, has lessened the durability of some chert particles.

4. Many shales will not cause deep-seated deterioration of air-entrained concrete beams subjected to laboratory freezing and thawing when included in these beams in amounts up to 10 percent. The inherent structural weakness of these materials may account for this.

5. Different shales cause considerably different degrees of surface deterioration of air-entrained concrete exposed to freezing and thawing. Some shales cause considerable popout damage when included in concrete in amounts as low as 2 percent of the coarse aggregate. Other shales cause little damage when used in amounts up to 10 percent.

6. The durability of the shales studied apparently is related primarily to the porosities and absorptions of these materials; the most porous and most absorbent causing the greatest amount of surface deterioration of concrete in which these materials are used. However, the strength and induration of the shales, as determined by relative amounts of clay minerals and detrital quartz present, also influence the ability of these materials to cause surface deterioration, the softer, weaker materials being less resistant than the harder, stronger ones.

7. As theorized by Powers (10), concretes with air-void spacing factors lower than 0.01 in. are well-protected from freezing and thawing deterioration, while those with spacing factors greater than 0.01 in. are poorly protected.

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Discussion

F. E. LEGG, JR., Associate Professor of Construction Materials, University of Michigan, and Materials Consultant, Michigan State Highway Department—The authors of this study are to be congratulated on making such an intensive effort to determine the behavior of chert and shale in concrete when exposed to freezing and thawing and, even more important, to discover the fundamental properties of these rock types which caused their deleterious action.

The remarkable increase in commercial heavy media beneficiation in recent years now gives opportunity to study the behavior of the heavier gravel constituents under actual service conditions thus permitting comment on the validity of the authors' laboratory findings. The low specific gravity types are quite effectively discarded by the media process and deleterious action in concrete made with the beneficiated gravel is presumably confined to the higher gravity particles. Observations of concrete in service containing such gravel led to the conclusion that even the high gravity cherts will cause popouts although the action may be delayed a few years.

Brief survey was recently made of chert popouts in two air-entrained concretes made with beneficiated gravel from the same southern Michigan source—a pavement 2 yr old and the top deck of an open parking structure 4 yr old. Where they could be found, the fragments of chert remaining in the bottom of the popouts were removed and their saturated surface dry gravities determined in heavy liquids. Table 10 gives the gravity range of the chert extracted from the bottom of each popout. It is observed that the majority of chert popouts in the younger pavement are in the range of 2.40 to 2.50 specific gravity whereas in the older parking structure they are in the range of 2.50 to 2.60. In both there are a substantial number having gravities above 2.45 which is contrary to that which might be anticipated from the laboratory findings of the present authors whose second conclusion is, in part, "Apparently only chert with a bulk specific gravity of less than 2.45 (saturated surface dry basis) will cause either deep-seated or surface deterioration of air-entrained concrete in which it is used."

Laboratory data leading to a prediction of deleterious action from even the heavier cherts were presented to the Highway Research Board in 1956 (1). Gravel having an average durability factor of 87 was diluted with 10 percent chert of four specific gravity ranges—minus 2.45, 2.45 to 2.50, 2.50-2.55 and 2.55 plus. Six test beams, two each from three batches of air-entrained concrete, were freeze-thaw tested using the rapid air method, ASTM C-291. Figure 7 shows the results of these tests, with the 95 percent confidence interval designated by shaded areas. Where overlapping of confidence limits occurs, it indicates that chance plays such a part that discrimination between the concrete may not be justified. The data on this basis indicate superior performance for the undiluted gravel over that diluted with 10 percent chert having a specific gravity of 2.55 or lower. Also, the undiluted gravel or that containing 10 percent chert of 2.55 plus gravity exhibits superior performance to that containing chert of 2.50 gravity or lower. The data thus indicate a scale of durability of chert—with diminishing durability as the gravity goes down, rather than the abrupt change exhibited in the Purdue studies.

The disparity in results between the Indiana and Michigan studies indicates the likelihood of subtle differences in conduct of freeze-thaw tests, the influence of which are not now well understood. The possibility of actual differences between the cherts from the two areas cannot be positively ruled out, but in view of the recent report of Cook (2) and the HRB Report of Cooperative Freezing-and-Thawing Tests of Concrete (3), it seems more likely that minor differences in technique may be the reason for lack of concordance.

TABLE 10
SPECIFIC GRAVITY OF CHERT FRAGMENTS
EXTRACTED FROM POPOUTS

| Bulk Specific Gravity, Saturated Surface Dry | Number of Chert Popouts | |
|---|-------------------------|-------------------------------|
| | Pavement 2 Yr Old | Parking Structure 4 Yr Old |
| 2 30 - 2 35 | 1 | - |
| 2 35 - 2 40 | 0 | - |
| 2 40 - 2 45 | 2 | 1 |
| 2 45 - 2 50 | 4 | 1 |
| 2 50 - 2 55 | 1 | 6 |
| 2 55 - 2 60 | - | 5 |
| 2 60 - 2 65 | - | 1 |
| Total | 8 | 14 |

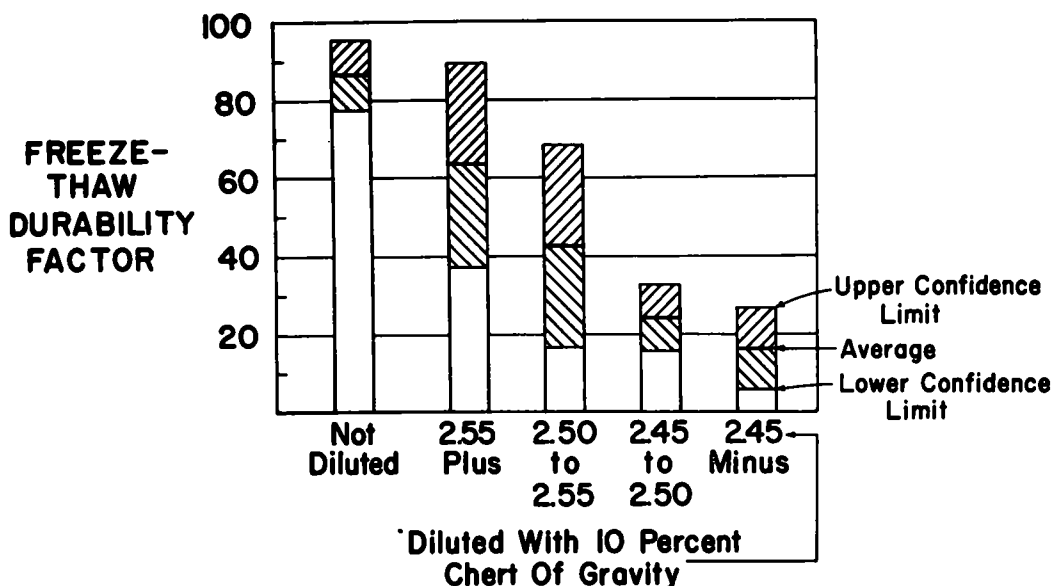


Figure 7. Freeze-thaw durability factors of a Michigan gravel diluted with 10 percent chert of different specific gravities.

Briefly, caution is suggested with respect to the authors' observations regarding lack of popouts of chert having a gravity greater than 2.45. Severity of exposure, or differing quality of chert, apparently influence chert behavior in exposed concrete. The writer's experience leads to the conclusion that much heavier cherts will actually cause popouts, but it is agreed that the lighter cherts are more active.

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J. F. McLAUGHLIN and R. L. SCHUSTER, Closure—The authors agree that the properties of chert giving rise to deterioration, either popouts or deep-seated failure, do not change dramatically at any given specific gravity level. Studies have shown, however, that when this chert is in concrete wherein the remainder of the aggregate is uniformly of excellent quality, the effect of these properties on the concrete is practically nil unless the chert has a gravity of 2.45 or less. Professor Legg justifiably points out that this may not be the case when the chert is in more heterogeneous surroundings. The authors were attempting in this study to quantify the effects of chert on an otherwise uniform, highly durable concrete and conclusions, as stated in the paper, must necessarily be limited by these conditions.