COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

HENRY WARD
COMMISSIONER OF HIGHWAYS

February 18, 1964

ADDRESS REPLY TO
DEPARTMENT OF HIGHWAYS
MATERIALS RESEARCH LABORATORY
132 GRAHAM AVENUE
LEXINGTON 29, KENTUCKY

D. 1. 7

MEMORANDUM

TO: W. B. Drake, Assistant State Highway Engineer
Chairman, Kentucky Highway Research Committee

FROM: Jas. H. Havens, Director
Division of Research

SUBJECT: "A Study of the Effects of Quick Freezing on Saturated Fragments of Rocks;" KYHPR-64-6, HPS-HPR-1(25)

The attached research report, entitled as above, by John W. Scott, and George R. Laughlin, covers a phase of study relating to our long-standing and continuing interest in aggregate durability and the mechanisms of freeze-thaw which cause damage. Whereas, the long-range objectives of this as well as prior studies encompass various aspects of aggregate quality criteria, the present study is concerned specifically with the resistance of aggregates to freeze-thaw when they are fully saturated. Complete saturation further implies that the study is concerned with the very worst condition ever expected to exist.

Heretofore, we have not been able to induce disruptive damage in aggregate particles in a single freeze. We realize now that complete saturation or re-saturation may not have been achieved in some of our earlier studies. Several years ago, a particular gravel performed rather badly in concrete; samples from the same source were obtained and brought into the laboratory for freeze-thaw testing in concrete. To the amazement of everyone, the performance of the aggregate far exceeded expectations.

After much deliberation, additional samples were obtained; and, in this case, care was taken to obtain stream-saturated gravel. It was kept covered with water until it was incorporated into concrete specimens. The performance of the aggregate in this condition in laboratory freeze-thaw was remarkably poor. Obviously the original sample had been at least partially air-dried and the usual re-soaking period preceding its incorporation into the concrete had not re-constituted the actual field condition of the aggregate. Although this experience illustrates the degree of improvements that may be derived from the drying of aggregate, it also emphasizes the significance of critical saturation.

The liklihood or probability that less-than-saturated aggregate will become critically saturated after being incorporated into concrete would depend upon the duration of wetting, temperature changes, proximity of aggregate particles to the surface, and many other conditions of exposure; however, if critical re-saturation is considered to be a significant probability, a meaningful, discriminative test is needed to indicate the susceptibility of aggregates to freeze-thaw damage.

In the past, freeze-thaw testing of composite samples of aggregates by soaking them in water and subjecting them to freezing conditions, such as prescribed by AASHO T 103-42, have not gained wide acceptance because the test has not proven to be sufficiently discriminative and involves a long period of time. Sulfate soundness tests remain a rather controversial recourse or alternative from actual freeze-thaw testing. Freezing and thawing concrete specimens (ASTM: C290, C291, C292, and C310) provide other alternatives for evaluating aggregates, but these procedures neglect the antecedent moisture condition in the same way that AASHO T 103 does.

The principal contention here is that, if an aggregate is fully saturated, fewer than five cycles of freezing will suffice to establish its inherent susceptibility to damage; whereas, if it is in a less-than-saturated condition, the number of cycles sustained merely reflect its susceptibility to re-saturation. Of course, the later case is meaningful in the sense that it reflects the time-probability idea previously mentioned whereas, the former case provides a straightforward approach to the evaluation of the inherent quality of an aggregate.

In this study, the prerequisite condition of saturation was fulfilled by the use of stream-saturated samples of gravel. Individual specimens or particles of the saturated gravel were subjected to a quick freeze by immersing them in chilled mercury - this procedure is remarkably unique and offers a means of testing which heretofore has been unachievable. By thus determining the damage-susceptibility of each particle, the relationships between the probability of failure and the measurable physical properties of the particles was established - and therein lies the significance of the study. Although additional confirming data will be sought, the relationships derived thus far provide helpful guidance toward the establishments of realistic soundness requirements for aggregates.

Realistic limits on absorption provide the most straightforward approach to a criteria of quality from the standpoint of enforcement; however, this implies that each particle of a aggregate should be so limited. Absorption tests performed on composite samples are meaningful only in the statistical sense of a mean or average value -- half of the particles comprising the sample could have no absorption while the other half could exceed the limit by a factor of two. Actually, it is the percentage of offensive aggregate in the sample that we are concerned about; and, from this point of view, it is imperative that a means be provided for isolating and measuring the offensive portion of a sample from the sound portion. Inasmuch as absorption is intimately related to specific gravity, a heavy medium separation, at a meaningful level of specific gravity, would implement the enforcement of a satisfactory quality criterion. Some of these concepts have already been incorporated into the Department's specifications.

This report is furnished for information and future reference. It is largely a report of progress and achievement. Although no specific action is required, suggestions and comments are invited. Inasmuch as our work in this area of study became identified with the Department's planning and research program, HPS-HPR-1(25), July 1, 1963, copies of this report are being transmitted to the Bureau of Public Roads in accordance with PPM 50-1.1.

Mr. Scott has been accorded principal authorship of the report inasmuch as he was assigned to the project as a graduate student pursuing a thesis. Mr. Laughlin served as his project supervisor and contributed in a major way to the conduct of the project and to the report.

In addition to my duties as Director of Research, I served as the director of Mr. Scott's thesis. Mr. Scott was a recipient of a Highway Department Scholarship in 1956.

Respectfully submitted,

Jas. H. Havens
Director of Research
and Secretary, Kentucky Highway
Research Committee

JHH:ajj

Attachment

cc: Research Committee
R. O. Beauchamp
R. L. Campbell
T. J. Hopgood
A. O. Neiser
J. C. Moore
D. V. Terrell
File D.1.7

Research Report

A STUDY OF THE EFFECTS OF QUICK FREEZING ON SATURATED FRAGMENTS OF ROCKS
KYHPR-64-6; HPS-HPR-1(25)

by

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and
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DEPARTMENT OF HIGHWAYS
Commonwealth of Kentucky

in cooperation with the
BUREAU OF PUBLIC ROADS
U.S. Department of Commerce

132 Graham Avenue
Lexington, Kentucky

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CHAPTER I

INTRODUCTION

Quick freezing of a fragment of rock which is fully saturated with water is, perhaps, the most rigorous of all tests for soundness, durability, or resistance to weathering. So-called soundness or quality tests employed currently, or heretofore, for evaluating concrete aggregates are usually less rigorous inasmuch as the state of saturation at the outset of freezing is not at a critical level. Hence, the number of freeze-thaw cycles endured by a rock specimen undergoing freezing and thawing in the presence of available water may merely reflect the duration of the exposure before the rock becomes vulnerable to damage -- i.e., time required for critical saturation. Damage arises wholly from the combined effects of the volume dilation accompanying the freezing of absorbed water, the dilation pressure induced, and the inherent restraining strength of the aggregate particle. Thus, the severest freezing condition, to which rock or concrete may be exposed, occurs after long periods of sustained wetting -- when the degree of saturation is the highest.

The purpose of this study was to investigate the feasibility of a quick freeze-and-thaw test and to determine the effects of such a test on saturated gravel. This investigation was unique inasmuch as stream-saturated gravel particles of varying sizes and properties were individually subjected to a rapid freeze in chilled mercury ($-30^{o}C$ to $-38^{o}C$). Only the mechanical aspects of freeze-and-thaw were considered. Deteriorations caused by chemical reactions of aggregate do not fall within the scope of this study.

ASTM C 290-61T (Resistance of Concrete Specimens to Rapid Freezing and Thawing in Water), C 291-61T (Resistance of Concrete Specimens to Rapid Freezing in Air and Thawing in Water), C 292-61T (Resistance of Concrete Specimens to Slow Freezing and Thawing in Water or Brine), and C 310-61T (Resistance of Concrete Specimens to Slow Freezing in Air and Thawing in Water) entrust the discernment of soundness and quality of aggregate almost wholly to the comparison of durability factors between specimens of concrete containing the aggregate in question and specimens of concrete containing a reference aggregate. These factors, at best, are only relative and are greatly affected by such variables as the cement factor, air content, water-cement ratio, curing conditions, and type of freeze-and-thaw test employed. Although field-exposure conditions are supposedly replicated to some degree by the four different freeze-and-thaw test procedures, sufficient consideration is not given to the state of saturation of the aggregate at the beginning of the freezing routine. Different antecedent moisture conditions of the aggregate often produce misleading results -- viz., a disparity between actual field performance and results of laboratory freeze-and-thaw tests. Some gravels which exhibit poor field performance stand up relatively well in laboratory freeze-and-thaw tests. The fact that stream-saturated samples of gravel incorporated directly into concrete generally exhibit poor laboratory performance suggests that the disparity between field performance and laboratory performance may be due to partial air drying of the gravel to a less-than-saturated condition before it is incorporated into concrete.

ASTM C 88-61T and AASHO T 104-57 (Soundness of Aggregates by Use of Sodium Sulfate or Magnesium Sulfate) describe different methods which are intended to assess soundness of aggregate but which utilize a somewhat different mechanism to create the disruptive forces within the aggregate particles. This action is provided by the growth of sulfate salt crystals within the pores of the aggregate. The dry sample is immersed in a saturated solution of the salt and is then removed and dried. As the cycle is repeated, more solution is absorbed; and salt accumulates in the pores. Crystal growth presumably accompanies the drying process. Aggregate particles which are highly absorptive fracture more readily than less-absorbent particles, and the amount of degradation incurred by this process generally correlates with the field performance of the aggregate and with the various freeze-thaw tests.

AASHO T 103-42 (Soundness of Aggregates by Freezing and Thawing) is not used as frequently as are the previously mentioned methods because it requires more equipment and time than the sulfate soundness test -- and the results are not any better than those obtained by other methods. In some cases, results obtained from this test do not correlate reliably with actual field performance. These disparities can be attributed, in part, if not wholly, to the fact that the antecedent moisture condition of the sample is not completely defined or required to be at a critical level (22)*. The aggregate is oven-dried, soaked in water for 24 hours, and exposed to freezing. When oven-dried and allowed to soak for 24 hours as specified, aggregate, which has been previously saturated, will regain only 70 per cent of its original moisture (18) (22). This test method, therefore, is indicative of the number of cycles -- which may be 100 to 200 -- accumulated before the sample became critically saturated. It does not necessarily reflect the damage that the sample might have sustained if the sample had been fully saturated at the outset of freezing.

Ideally, a soundness or durability test for aggregate should provide information with respect to: 1) the duration of exposure, from a given antecedent moisture condition, which will produce a critical degree of saturation; and 2) the ability of the aggregate, when fully saturated, to withstand the dilating pressures induced. These two factors are not isolated in the previously mentioned test methods; however, the latter factor can be evaluated by further treatment of the sample to insure complete saturation before the first onset of freezing.

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* Number in parentheses refer to bibliographical references at the back of this report.

If distress is likely to occur in a rock fragment which is repeatedly stressed by the dilating pressures of freezing, fractures, either internally or externally, should appear after the first cycle. Although internal distress would not, perhaps, be detected by a visual examination of the surface of the particle at the end of the first freeze-and-thaw cycle, external evidences of damage should appear after a few cycles. The ability of an aggregate particle to withstand a relatively few cycles of freezing depends upon the magnitude of the induced dilating pressures -- which are governed by the absorption and degree of saturation of the fragment at the outset of freezing and by the severity of the freezing cycle. Of course, the condition for the conducive development of maximum pressures is one of 100 per cent saturation. A rapid rate of freezing is desired inasmuch as any extrusion or outward flow of water through the pores would be blocked or hindered by the expeditious and instantaneous formation of an ice crust or shell encasing the particle.

Mercury was selected for the cooling medium because it has a low freezing-point, is insoluble in water, and has a high thermal conductivity (5). Inasmuch as mercury is not soluble, the freezing point of water within the aggregate pores is not lowered; whereas, this possibility exists with freezing media such as brine or water-alcohol mixtures.

This test proved to be very rigorous from the standpoint of number of cycles required for failures to occur. Failures were the direct result of excessive dilating pressures rather than thermal stresses. As expected, the correlations indicate that the resistance of the test specimens to a rapid freeze-and-thaw was dependent upon porosity, absorption, and degree of saturation. The correlation between bulk specific gravity (saturated surface-dry) and freeze-and-thaw resistance was somewhat erratic, but this may have been due to the fact that some of the particles tested consisted of dolomites which are inherently heavier than limestones and siliceous gravels. It was also ascertained that the size of the particle bears no relationship with the soundness of the specimens tested.

CHAPTER II

MATERIALS AND PROCEDURES

Preliminary Investigations

Specimens of porous chert having poor field performance records were saturated with water and immersed in cold mercury. Within a period of 30 to 45 seconds, these specimens broke into several pieces. Specimens of a similar nature were also oven-dried (110°C) to a constant weight and allowed to cool to room temperature; and, when subjected to the same freezing conditions, no distress was noted -- indicating that failure was caused by dilating pressures and not from thermal shock.

Selection and Testing of Specimens

The following two requirements were placed upon the aggregate used in testing: 1) both sound and unsound particles should be represented in the sample, and 2) the aggregate should be totally saturated or in a stream-saturated condition. Obviously, the first requirement was necessary to facilitate correlation studies of the relationships between the physical properties of aggregates and their resistance to freeze-and-thaw. The purpose of the second requirement was twofold. First, by insuring that the degree of saturation was constant for all cases, one of the confounding variables was eliminated. Second, the use of totally saturated aggregate, in this case stream-saturated aggregate, insured the development of maximum dilating pressures and, thus, a reduction of the number of cycles required for testing.

Samples of stream-saturated gravel were obtained from a commercial dredge operating at mid-stream in the Ohio River approximately 12 miles upstream from Louisville. The primary constituents of this gravel were dolomites, cherts, limestones, sandstones, siltstones, and various non-sedimentary rocks such as granite. Although usually acceptable for concrete, this gravel contained both sound and unsound particles and, thereby, provided an assortment of particles needed for the study.

The requirement that the aggregate be totally saturated was satisfied by the fact that it was obtained from the river bottom where it had been underwater for a period of perhaps several thousand years. The samples were immediately immersed in water upon removal from the river bottom and were maintained so until tested.

Since the sample contained both sound and unsound particles, tests performed on the whole sample would yield only an average value for the sample -- which would not be meaningful to the study. It was desired to study the behavior of the particles individually; and, with this in mind, 25 particles of each of the following five sieve sizes were selected:

passing 1-1/2-inch and retained on 1-inch,
passing 1-inch and retained on 3/4-inch,
passing 3/4-inch and retained on 1/2-inch,
passing 1/2-inch and retained on 3/8-inch, and
passing 3/8-inch and retained on No. 4.

These particles were immersed in water in individual glass jars where they remained at all times except while testing was in progress. The jars were sealed and labeled according to the specimen number. It was possible, therefore, to keep detailed records of the various physical properties measured as well as the behavior of each specimen when subjected to freezing and thawing.

<u>Bulk Specific Gravity (Saturated Surface-Dry Basis).</u> The saturated surface-dry weight and bulk volume were obtained for each particle prior to the freeze-and-thaw tests. The weight was obtained by weighing each surface-dry specimen in a capsule, and the volume was obtained by weighing the amount of mercury displaced by the specimen. These weighings were performed on an analytical balance to the nearest 0.0001 gram.

Calculations for the bulk specific gravity were made for each particle by the use of the following expression:

$$G_{SSD} = \frac{W_T}{W_M} \frac{\gamma_M}{\gamma_W}$$

where:

G_{SSD} = bulk specific gravity (saturated surface-dry),

W_T = saturated surface-dry weight of specimen,

γ_M = density of mercury at temperature of test,

W_M = weight of mercury displaced by specimen, and

γ_W = density of water at temperature of test.

Freeze-and-Thaw Tests. The freezing of the aggregate was accomplished by submerging the specimens in cold mercury (-30°C to -38°C) for a period of five minutes. The freezing apparatus is shown in Figure 1. The mercury was contained in a glass cylinder enclosed in an insulated container of dry ice (solid CO_2). A low-temperature thermometer was used to observe the temperature of the mercury. The temperature was maintained within limits by adding dry ice and by removing the cylinder of mercury from the container of dry ice and allowing it to warm in air. Occasionally, the mercury froze and had to be warmed in this way.

A plunger, mounted on a ring-stand, was used to submerge the specimens in the cold mercury. The plunger was constructed of No. 4 wire screen attached to a brass rod. The volume of the plunger was held to a minimum by the use of the wire screen; and, as a result, the temperature of the mercury was not raised appreciably by the absorption of a large quantity of heat from the plunger.

At the end of the freezing cycle, the specimen was removed from the freezing medium and returned to its container of water and allowed to thaw. At the end of each thawing cycle, a visual examination was made of each particle

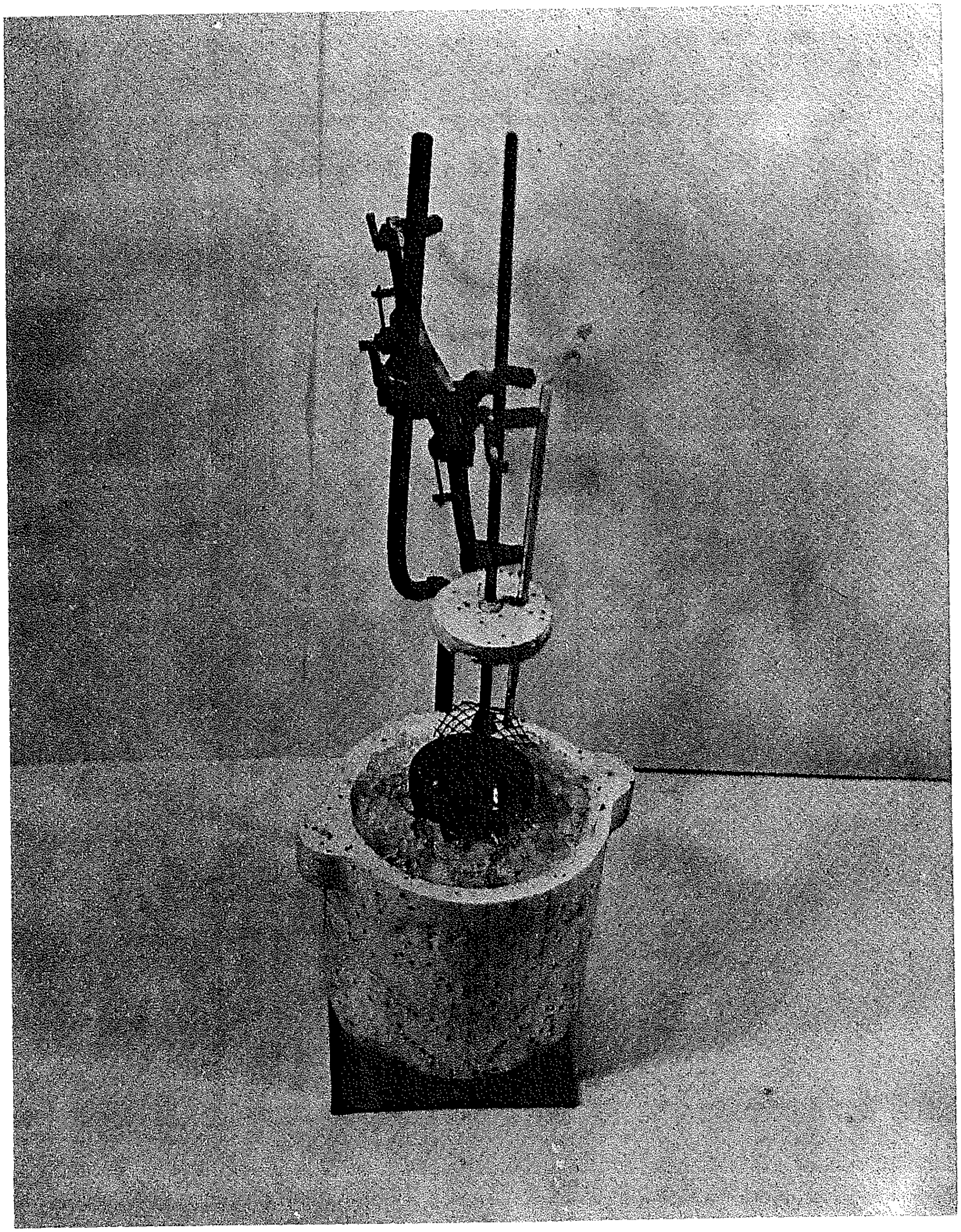

Figure 1: Freezing Apparatus.

by means of a binocular microscope; and any distress resulting from the freezing and thawing cycle was recorded. Four classifications were used to denote the condition of the particle:

1) no visible fractures,
2) hairline, or closed fractures,
3) opened fractures, and
4) fractures, where particle separated into two or more pieces.

Absorption. For obvious reasons, the absorptive values for each specimen were not determined until the conclusion of freeze-and-thaw testing. Also, since any losses due to chipping and spalling would vary the weight of the specimen, the saturated surface-dry weight of each specimen (or major pieces thereof) was determined for the second time. Each specimen (or major piece) was then dried (110°C) to a constant weight. These weighings were performed on an analytical balance to the nearest 0.0001 gram.

Calculations for the absorption of each specimen were made by the use of the following expression:

$$\omega = \frac{W_T - W_S}{W_S} \times 100$$

where:

ω = absorption expressed as a per cent,

W_T = saturated surface-dry weight of particle (or major pieces), and

W_S = oven-dry weight of particle (or major pieces).

Porosity. Porosity calculations were made by the use of the following expression for saturated aggregate:

$$n = \frac{\omega}{100+\omega} G_{SSD} \times 100$$

where:

n = porosity expressed as a per cent,

ω = absorption expressed as a per cent, and

G_{SSD} = bulk specific gravity (saturated surface-dry).

It should be emphasized that the above equation applies only for saturated aggregate.

Petrographic Examination. After all other testing was completed, a fresh surface of each particle was examined by use of binocular and petrographic microscopes.

Where necessary, the petrographic examination was supplemented by chemical tests. Mineralogical and textural features were recorded.

CHAPTER III

DATA AND RESULTS

The results of the various tests performed on the 125 test specimens are summarized in Tables 1 through 5. The tabulations show the bulk specific gravity (saturated surface-dry), absorption, porosity, petrographic description, and condition of each test specimen at the end of each freeze-and-thaw cycle. All values are self-explanatory except where symbols were used to denote the conditions of the particles at the end of each freeze-and-thaw cycle. The four symbols used and their explanations are as follows:

A - no visible fractures,

B - hairline, or closed fractures,

C - opened fractures, and

D - fractures, where particle separated into two or more pieces.

Typical fractures are shown in Figures 2 and 3. The symbol C was used to denote the condition of the specimen in Figure 2 because the distress was in the form of opened

TABLE 1

RESULTS OF TESTS PERFORMED ON 1-INCH AGGREGATE SPECIMENS

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
1	2.34	8.65	18.63	D	-	-	-	White, porous chert
2	2.43	5.93	13.62	C	C	C	D	Brown, porous chert
3	2.66	4.18	10.67	D	-	-	-	Brown, porous, limonitic quartz siltstone
4	2.69	0.62	1.65	A	A	A	A	Gray, dense, fine-grained, crystalline limestone
5	2.61	5.54	13.71	C	D	-	-	Tan, porous, aphanitic dolomite
6	2.63	0.76	1.99	A	A	A	A	Brown, dense, limonitic quartz siltstone
7	2.55	1.71	4.28	B	B	C	C	White, porous, fine-grained quartzite
8	2.63	0.69	1.79	A	A	A	A	Brown, dense, medium-grained quartz monzonite
9	2.55	3.17	7.83	B	C	D	-	Tan, porous, fine-grained dolomite
10	2.71	0.36	0.96	A	A	A	A	Gray, dense, fine-grained, crystalline limestone

TABLE 1 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
11	2.22	12.52	24.70	B	C	D	-	Tan, porous claystone
12	2.65	0.21	0.55	A	A	A	A	Gray, dense, fine-grained diorite
13	2.65	0.15	0.39	A	A	A	A	Tan, dense, fine-grained quartzite
14	2.61	1.04	2.69	B	B	B	B	Brown, porous, medium-grained, weathered granite
15	2.54	2.66	6.58	A	A	A	A	Brown, locally porous chert
16	2.66	0.68	1.80	B	C	C	D	Tan, vugular, medium-grained, crystalline limestone
17	2.62	0.65	1.68	A	A	A	A	Tan, dense chert
18	2.64	0.44	1.16	A	A	A	A	Brown, dense, medium-grained granite
19	2.71	3.05	8.02	D	-	-	-	Gray, porous dolomite
20	2.61	1.26	3.25	A	A	A	A	Gray, locally porous chert
21	2.66	1.23	3.23	A	A	A	A	Brown, dense, calcareous claystone

TABLE 1 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
22	2.80	0.75	2.07	A	A	A	A	Gray, dense, aphanitic dolomite
23	2.61	1.02	2.62	A	A	A	A	Brown, dense, fine-grained quartz monzonite
24	2.52	3.58	8.72	B	C	C	D	Brown, porous, fine-grained, limonitic quartz sandstone
25	2.82	0.43	1.21	A	A	A	A	Gray, dense andesite

TABLE 2

RESULTS OF TESTS PERFORMED ON 3/4-INCH AGGREGATE SPECIMENS

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
26	2.65	0.66	1.75	A	A	A	A	Brown, dense, fine-grained granite
27	2.70	2.64	6.96	D	-	-	-	Gray, vugular, fine-grained dolomite
28	2.68	3.61	9.33	D	-	-	-	Gray, porous, fine-grained dolomite
29	2.45	3.06	7.27	B	C	D	-	Tan, porous, aphanitic dolomite
30	2.70	1.11	2.95	A	A	B	B	Tan, dense, medium-grained, crystalline limestone
31	2.62	0.90	2.33	A	A	A	A	Brown, dense, fine-grained monzonite
32	2.47	4.60	10.86	B	C	C	D	Brown, porous, fine-grained, limonitic quartz sandstone
33	2.64	4.50	11.39	A	A	B	B	Brown, porous, fine-grained dolomite
34	2.60	4.12	10.28	C	D	-	-	Tan, porous, aphanitic dolomite
35	2.59	1.35	3.45	A	A	A	A	Gray, dense, fine-grained, crystalline limestone

TABLE 2 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
36	2.61	5.85	14.43	B	C	C	D	Brown, porous, coarse-grained, weathered granite
37	2.42	5.39	12.36	C	C	C	D	White, porous chert
38	2.51	6.98	16.36	D	-	-	-	Brown, porous, fine-grained dolomite
39	2.72	1.43	3.83	A	A	A	A	Gray, dense, calcareous siltstone
40	2.72	1.62	4.34	A	A	A	A	Gray, porous, fine-grained dolomite
41	2.72	2.31	6.12	A	A	A	A	Tan, porous, fine-grained dolomite
42	2.60	0.61	1.58	A	A	A	A	Gray, dense, aphanitic, crystalline limestone
43	2.69	0.64	1.72	A	A	A	A	Tan, dense, medium-grained, crystalline limestone
44	2.67	3.51	9.04	C	D	-	-	Gray, porous, medium-grained dolomite
45	2.68	0.27	0.73	B	B	B	B	Gray, dense, fine-grained, crystalline limestone
46	2.71	2.72	7.18	B	B	C	C	Gray, porous, aphanitic dolomite

TABLE 2 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
47	2.63	4.24	10.71	C	D	-	-	Brown, porous, aphanitic dolomite
48	2.62	0.45	1.18	A	A	A	A	Gray, dense, fine-grained nepheline syenite
49	2.54	2.18	5.42	A	A	A	A	Tan, porous, fine-grained, crystalline limestone
50	2.58	0.70	1.80	A	A	A	A	Gray, dense, aphanitic, dolomitic limestone

TABLE 3

RESULTS OF TESTS PERFORMED ON 1/2-INCH AGGREGATE SPECIMENS

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
51	2.65	2.23	5.78	A	A	C	D	Tan, porous, fine-grained dolomite
52	2.81	0.15	0.41	A	A	A	A	Tan, dense, medium-grained dolomite
53	2.72	2.39	6.35	A	B	C	D	Gray, porous, aphanitic dolomite
54	2.69	2.68	7.00	B	C	C	D	Tan, porous, aphanitic dolomite
55	2.73	2.04	5.45	C	D	-	-	Tan, porous, fine-grained dolomite
56	2.71	2.23	5.93	C	D	-	-	Tan, porous, fine-grained dolomite
57	2.56	6.20	14.92	D	-	-	-	Tan, porous, aphanitic dolomite
58	2.40	5.84	13.22	B	C	C	D	Gray, porous chert
59	2.50	3.59	8.64	A	A	A	B	Gray, porous, calcareous siltstone
60	2.62	0.10	0.25	A	A	A	A	Black, dense, aphanitic basalt

TABLE 3 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
61	2.39	6.76	15.14	D	-	-	-	Brown, porous chert
62	2.62	3.65	9.22	C	D	-	-	Tan, porous, fine-grained dolomite
63	2.68	3.05	7.95	D	-	-	-	Tan, porous, aphanitic dolomite
64	2.69	2.01	5.31	A	A	A	A	Tan, porous, aphanitic dolomite
65	2.84	2.23	6.20	A	A	A	C	Brown, porous, medium-grained, weathered granite
66	2.52	1.75	4.33	A	A	B	B	Tan, porous, aphanitic dolomite
67	2.60	0.86	2.21	A	A	A	A	Gray, dense, fine-grained, crystalline limestone
68	2.62	1.08	2.80	A	A	A	A	Gray, dense, fine-grained, crystalline limestone
69	2.31	8.38	17.88	A	A	B	B	White, porous chert
70	2.69	1.55	4.11	A	A	B	B	Gray, porous, fine-grained dolomite
71	2.58	4.12	10.22	B	D	-	-	Gray, porous, aphanitic dolomite

TABLE 3 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
72	2.73	1.56	4.18	B	B	B	C	Gray, porous, aphanitic dolomite
73	2.56	1.16	2.94	A	A	A	A	Gray, dense chert
74	2.61	0.82	2.12	A	A	A	A	Gray, dense, aphanitic, crystalline limestone
75	2.61	0.22	0.57	A	A	A	A	Tan, dense, fine-grained quartzite

TABLE 4

RESULTS OF TESTS PERFORMED ON 3/8-INCH AGGREGATE SPECIMENS

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
76	2.78	0.35	0.96	A	A	A	A	Gray, dense, fine-grained dolomite
77	2.53	3.08	7.56	B	C	D	-	Tan, porous siltstone
78	2.59	1.79	4.57	A	A	A	A	Tan, porous, aphanitic, crystalline limestone
79	2.53	4.18	10.14	B	B	C	C	Gray, porous, fine-grained, crystalline limestone
80	2.77	1.82	4.95	A	A	B	B	Gray, porous, fine-grained dolomite
81	2.74	0.51	1.39	A	A	A	A	Pink, dense, fine-grained granite
82	2.53	2.82	6.94	A	B	C	C	Tan, porous chert
83	2.62	1.52	3.92	A	B	C	D	Tan, porous, fine-grained quartzite
84	2.65	4.18	10.60	C	C	C	D	Tan, porous, calcareous claystone
85	2.39	6.94	15.49	B	B	D	-	Brown, porous chert
86	2.76	1.97	5.33	B	B	C	D	Tan, porous, fine-grained, dolomitic limestone

TABLE 4 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
87	2.36	7.05	15.54	B	C	C	D	White, porous chert
88	2.62	0.26	0.68	A	A	A	A	Brown, dense, fine-grained granite
89	2.62	1.67	4.29	A	A	B	B	Brown, porous, fine-grained, weathered granite
90	2.65	2.72	7.01	B	B	B	C	Tan, porous, fine-grained dolomite
91	2.69	0.08	0.22	A	A	A	A	Red, dense, fine-grained monzonite
92	2.79	0.86	2.37	A	B	B	B	Tan, dense, aphanitic dolomite
93	2.79	0.91	2.53	A	A	A	A	Tan, dense, aphanitic dolomite
94	2.68	1.02	2.71	A	A	A	A	Black, dense, aphanitic basalt
95	2.67	0.28	0.74	A	A	A	A	Brown, dense, fine-grained granite
96	2.60	0.28	0.73	A	A	A	A	Gray, dense, coarse-grained vein quartz
97	2.77	0.95	2.61	B	D	-	-	Tan, locally porous, aphanitic dolomite

TABLE 4 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorp-tion (%)	Poros-ity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
98	2.62	0.27	0.70	A	A	A	A	White, dense, coarse-grained vein quartz
99	2.30	7.25	15.55	A	B	B	D	Tan, porous chert
100	2.64	0.49	1.29	A	A	A	A	Gray, dense, fine-grained, crystalline limestone

TABLE 5

RESULTS OF TESTS PERFORMED ON NO. 4 SIEVE SIZE AGGREGATE SPECIMENS

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
101	2.49	7.02	16.34	A	B	B	B	Brown, porous, fine-grained sandstone
102	2.76	0.04	0.10	A	A	A	A	Gray, dense, aphanitic andesite
103	2.70	2.56	6.72	B	C	C	C	Tan, porous, fine-grained dolomite
104	2.72	1.52	4.07	A	B	C	D	Gray, porous, aphanitic dolomite
105	2.47	3.57	8.52	A	A	A	A	Brown, porous chert
106	2.77	0.12	0.32	A	A	A	A	Gray, dense, aphanitic dolomite
107	2.42	4.37	10.13	A	A	B	C	Gray, porous, aphanitic dolomite
108	2.45	3.11	7.38	A	A	A	B	Tan, porous, fine-grained dolomite
109	2.31	8.33	17.77	B	C	C	D	Gray, porous siltstone
110	2.51	2.53	6.18	A	A	A	A	Brown, porous, limonitic chert

TABLE 5 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
111	2.71	0.13	0.34	A	A	A	A	Black, dense, aphanitic basalt
112	2.65	3.71	9.46	A	B	B	C	Tan, porous, aphanitic dolomite
113	2.36	9.31	20.10	B	B	B	C	Gray, porous, fine-grained syenite
114	2.47	0.47	1.16	A	A	A	A	Black, dense, fine-grained diorite
115	2.62	0.84	2.18	A	A	A	A	Black, dense, fine-grained diorite
116	2.64	1.12	2.94	A	A	A	A	Pink, dense, medium-grained monzonite
117	2.41	3.22	7.52	A	A	A	A	Brown, porous, fine-grained, limonitic quartz sandstone
118	2.63	0.47	1.23	A	A	A	A	Brown, dense, fine-grained syenite
119	2.40	6.90	15.50	B	B	C	D	Tan, porous, aphanitic, crystalline limestone
120	2.58	0.13	0.34	A	A	A	A	Gray, dense, fine-grained granite
121	2.59	0.29	0.74	A	A	A	A	Pink, dense, medium-grained syenite

TABLE 5 - Continued

Spec. No.	Bulk Sp.Gr. (SSD)	Absorption (%)	Porosity (%)	Condition of Particle at End of Freeze-and-Thaw Cycle Indicated				Petrographic Description
				1	2	3	4	
122	2.64	0.42	1.11	A	A	A	B	Gray, dense, fine-grained, crystalline limestone
123	2.73	0.11	0.29	A	A	A	A	Gray, dense, aphanitic, calcitic dolomite
124	2.60	0.20	0.52	A	A	A	A	Pink, dense, fine-grained monzonite
125	2.57	3.53	8.78	C	D	-	-	Brown, porous, fine-grained, weathered granite

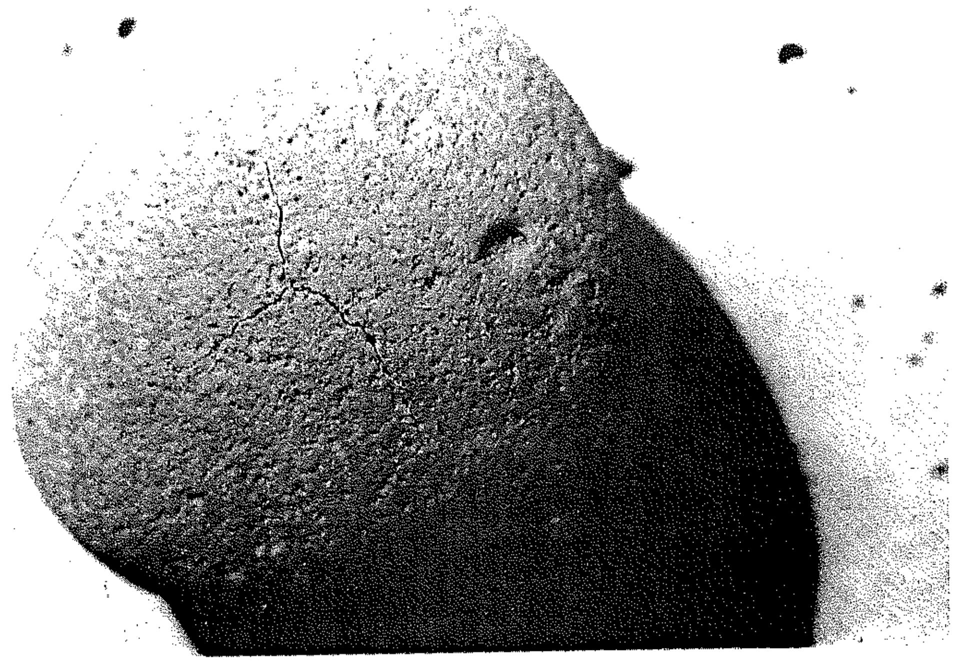

Figure 2: Distress in the Form of Opened Fractures.

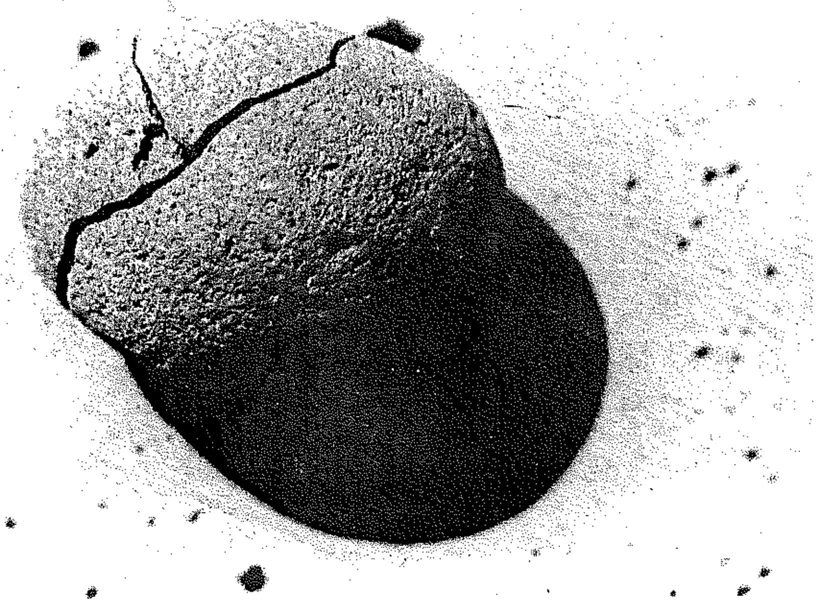

Figure 3: Fracture, Where the Specimen Broke into Three Pieces.

fractures. The symbol D was used to denote the condition of the particle in Figure 3 because it separated into three pieces (the pieces were held together with mastic while photographing them).

The accumulated number of fractured specimens at the end of each cycle of freeze-and-thaw, expressed as a percentage of the total number of specimens, is presented graphically in Figure 4. The slope of the curve in Figure 4 indicates the increase in the percentage of fractured particles at the end of each cycle; and, as would be expected, the largest increase occurred at the end of the first cycle. Of the total number of fractured specimens, approximately 70 per cent fractured at the end of the first freezing cycle. The small increases in the accumulated percentage of fractured specimens which occurred with succeeding cycles are probably due to the fact that many of the specimens had undetected fractures at the end of the first freezing cycle and additional cycles were needed before the fractures became visible. The condition of the particle at the end of the fourth cycle of freeze-and-thaw will, therefore, be the criterion for the correlation studies.

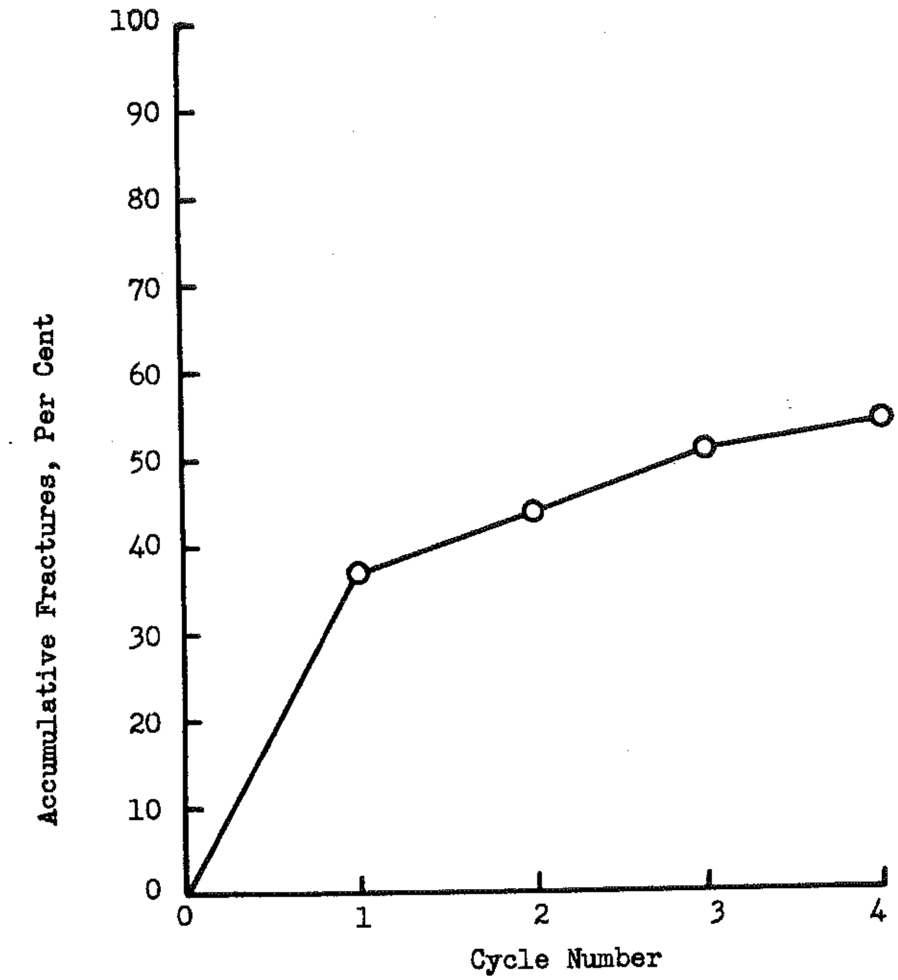

Figure 4: Accumulative Percentage of Fractured Specimens for Each Cycle of Freeze-and-Thaw.

Particle Size. The percentage of fractured specimens at the end of the fourth cycle of freeze-and-thaw, for each particle size tested, is given in Figure 5. The largest percentage of fractured specimens occurred in the 1/2-inch size; whereas the smallest percentage of fractured specimens occurred in the 1-inch and No. 4 sizes. The average percentage of fractured specimens in all sizes combined is indicated by the dashed line, at 53.6 per cent. The slight deviations from the average are probably due to variations in physical properties of particles within each size group. For example, it was observed that a greater number of porous or unsound particles occurred in the 1/2-inch group than in any of the other size groups.

Bulk Specific Gravity (Saturated Surface-Dry). The percentage of fractured specimens at the end of 4 cycles of freeze-and-thaw for different bulk specific gravity values is shown in Figure 6. A definite trend is established, indicating that aggregate in the lower specific gravity ranges has lower resistance to freezing and thawing than aggregate of the higher specific gravity ranges. However, no specific gravity level can be classed as critical --

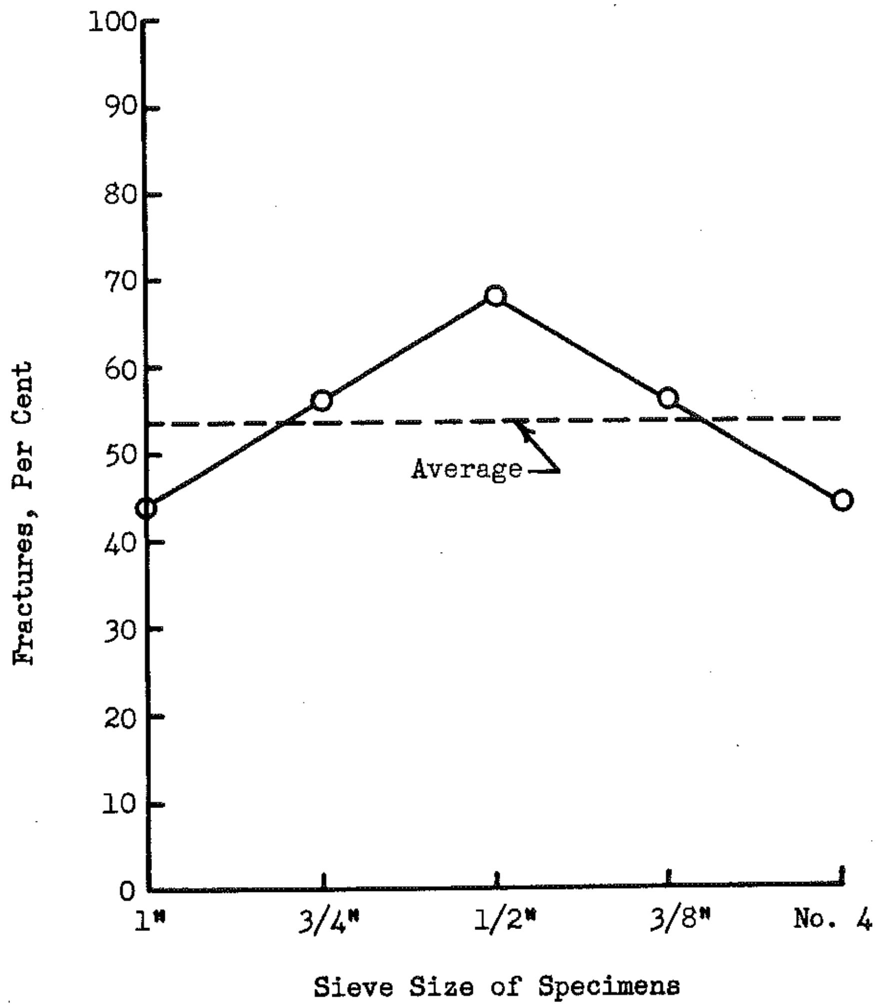

Figure 5: Relationship between Particle Size and Percentage of Fractured Specimens after Exposure to 4 Cycles of Freeze-and-Thaw.

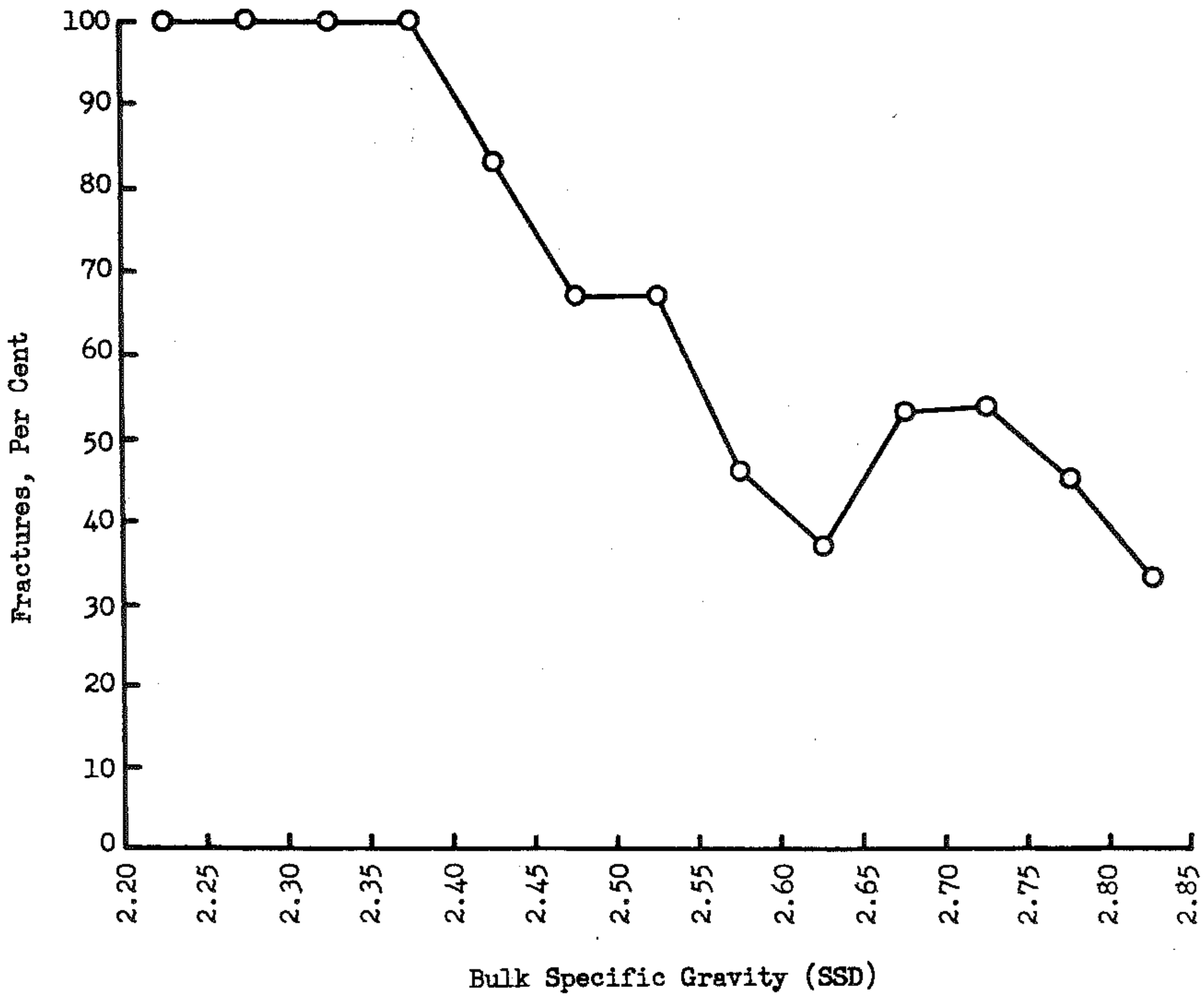

Figure 6: Relationship between Bulk Specific Gravity (Saturated Surface-Dry) and Percentage of Fractured Specimens after Exposure to 4 Cycles of Freeze-and-Thaw.

except the level below 2.40. It should also be noted that the curve in Figure 6 does not necessarily approach zero as the specific gravity continues to increase -- this indicates that heavier minerals lie farther to the right in the graph and that a family of curves would better describe the relationship.

Absorption (100 Per Cent Saturation). A graph depicting the relationship between the percentage of fractured specimens and the absorption values of the test specimens is shown in Figure 7. All particles having absorptions of 4 per cent or greater failed when subjected to freezing and thawing. However, very few specimens having absorptions of less than 1 per cent failed. Between these extremes, the percentage of specimens with failures increased as the absorption increased. From comparison of Figures 6 and 7, it is obvious that absorption provides a more direct basis for judging soundness than does bulk specific gravity.

Porosity (100 Per Cent Saturation). The relationship between the soundness of the test specimens and their

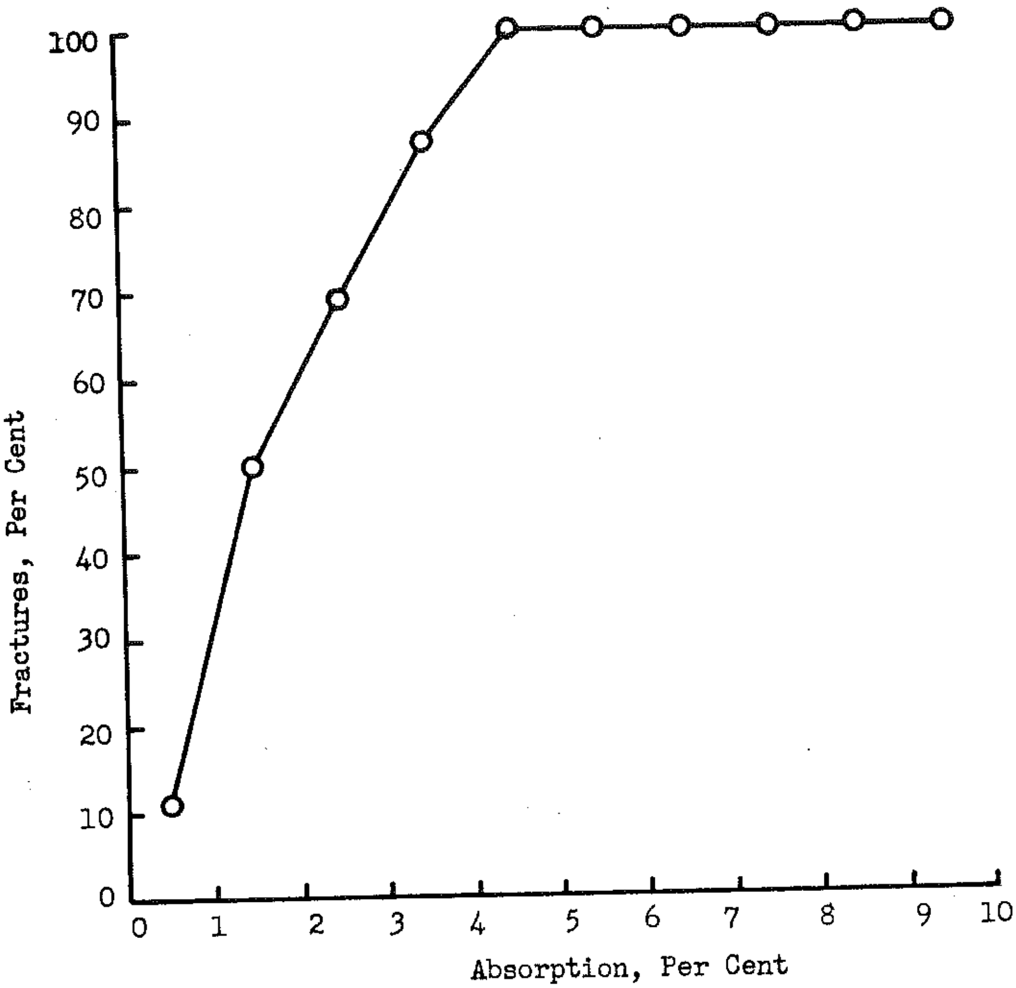

Figure 7: Relationship between Absorption and Percentage of Fractured Specimens after Exposure to 4 Cycles of Freeze-and-Thaw.

porosity values is shown in Figure 8. As expected, particles in the higher porosity range were less durable than particles of the lower range. All particles having a porosity of more than 10 per cent fractured; whereas only 10 to 25 per cent of the particles having a porosity of less than 4 per cent fractured.

Classification. The durability of the various types of aggregate particles is presented in Table 6. Sedimentary rock particles contained a much larger percentage of specimens which fractured than igneous and metamorphic particles. Within the sedimentary classification, limestone contained the least percentage of fractured particles, whereas dolomite contained the greatest.

It is interesting to note that chert, which is usually thought of as being very unsound under freeze-and-thaw action, did not have the greatest percentage of fractured particles. Since weathered (porous) chert and dolomite are frequently similar in appearance, it is possible that, in the past, some pavement deteriorations which were thought to be due to unsound chert were, in reality, due to unsound dolomite.

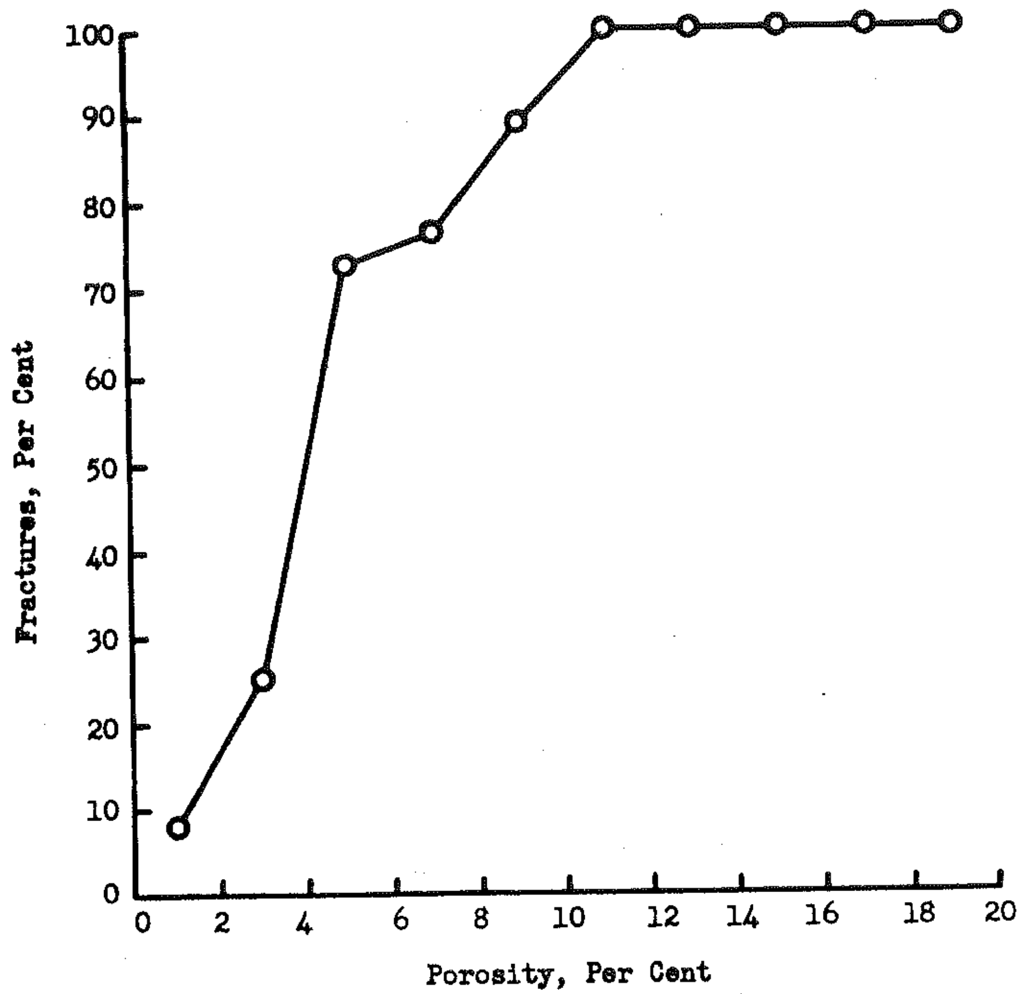

Figure 8: Relationship between Porosity and Percentage of Fractured Specimens after Exposure to 4 Cycles of Freeze-and-Thaw.

TABLE 6

DURABILITY OF AGGREGATE ACCORDING TO CLASSIFICATION

Classification	Per Cent Fractured Specimens at End of 4 Cycles of Freeze-and-Thaw
1) Sedimentary	66
a) Dolomite	77
b) Chert	59
c) Limestone	41
d) Sandstone & Siltstone	69
2) Igneous and Metamorphic	23

CHAPTER IV

DISCUSSION

Practical Applications of Quick-Freeze Test

An expeditious test for the quality and soundness of aggregate could be developed from the freezing technique utilized in this study. For practical application, however, some adaptations would have to be made. For example, field testing of individual particles would be impractical from the standpoint of time and equipment, so freeze-thaw testing would have to be performed on samples as a whole. Problems would also be encountered with samples of crushed stone composed of several particle sizes because fracturing or disintegration resulting from freeze-thaw would be nearly impossible to distinguish from fracturing produced in the process of crushing. This difficulty might be obviated by sizing the material with suitable sieves before testing. After obtaining the initial weight, each size group could be subjected to a rapid freeze in cold mercury and allowed to thaw in water. At the conclusion of the freeze-and-thaw testing, the sieve group could be re-sieved over the appropriate sieve and a second weight obtained. The percentage of fractures for each group could be computed by expressing the difference between the original weight and the final weight as a percentage of the original weight.

Theoretical Considerations of Freezing Effects

The ability of a rock fragment to withstand internal pressures accompanying freezing is controlled by certain inherent properties of the fragment. Insight into these properties might be gained if Timoshenko's (20) explanation of Lamé's solution for the radial and tangential normal stresses in a thick-walled, spherical container under internal and external pressures is considered (Figure 9). According to Timoshenko (20), the radial normal stress is given by the expression:

$$\sigma_R = \frac{P_o\, b^3\, (R^3 - a^3)}{R^3\, (a^3 - b^3)} + \frac{P_i\, a^3\, (b^3 - R^3)}{R^3\, (a^3 - b^3)}$$

and the tangential normal stress is obtained by the equation:

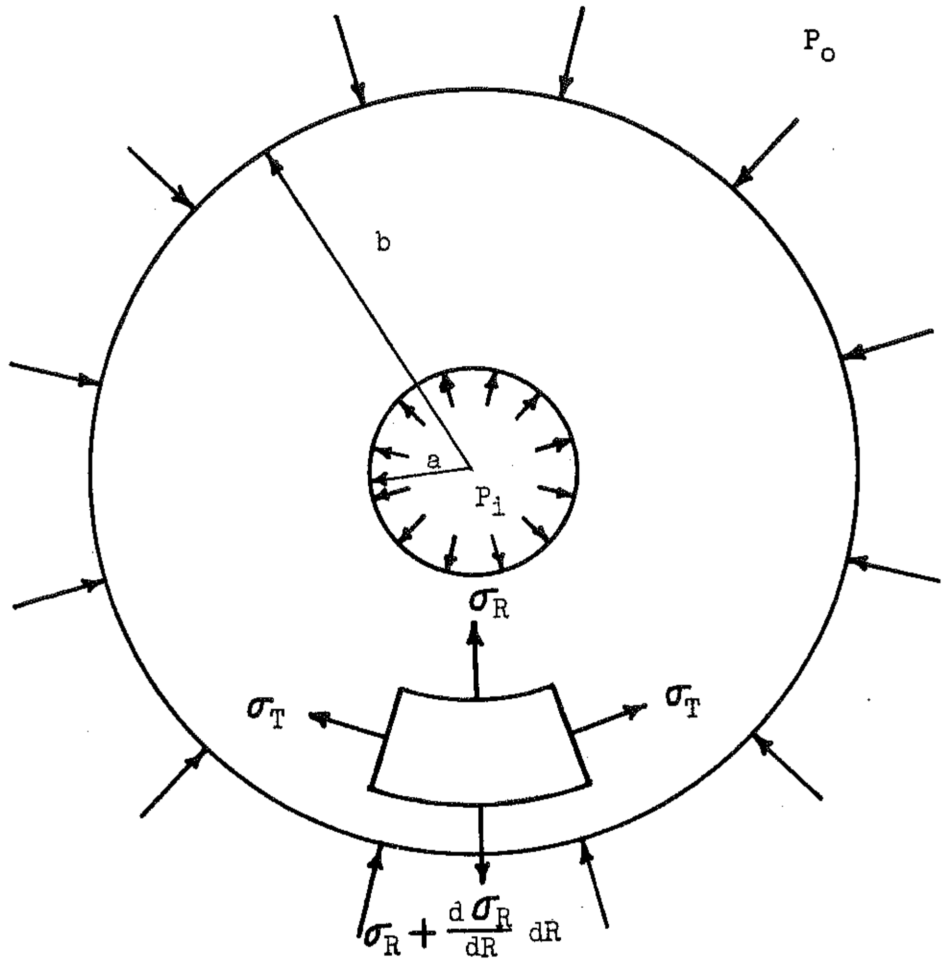

Figure 9: Thick-Walled Sphere under Internal and External Pressures (cf. Reference 20, Page 325).

$$\sigma_T = \frac{P_o\, b^3\, (2R^3 + a^3)}{2R^3\, (a^3 - b^3)} - \frac{P_i\, a^3\, (2R^3 + b^3)}{2R^3\, (a^3 - b^3)}$$

where:

a = inner radius of the sphere,

b = outer radius of the sphere,

P_i = the internal pressure, and

P_o = the external pressure.

If the exterior confining pressure (P_o) is zero, the equations for the normal stresses at the extreme outer fiber are as follows:

$$\sigma_R = 0$$

$$\sigma_T = - \frac{3P_i\, a^3}{2\, (a^3 - b^3)}$$

and by multiplying and dividing the latter equation by $4/3\ \pi$ and substituting:

$V_v = 4/3\ \pi\ a^3$,

$V_t = 4/3\ \pi\ b^3$, and

$V_v = \eta\ V_t$

where:

V_v = volume of voids,

V_t = volume of sphere, and

n = porosity as defined above,

the equation reduces to

$$\sigma_T = 3/2\ P_i\ \frac{n}{1 - n}$$

The radial normal stress, σ_R, along the outer edge of the spherical container is zero and the tangential normal stress, σ_T, at the same point, which is a tensile stress, is dependent upon the porosity and the internal pressure created. Conversely, the ability of a spherical container to withstand a given internal pressure is dependent upon the porosity and tensile strength of the container and is independent of size or total volume.

If the tensile strength, σ_u, is inserted in the above equation for σ_T, the equation becomes

$$P_u = 2/3\ \sigma_u\ \frac{(1 - n)}{n}$$

where:

P_u = maximum allowable internal pressure, and

σ_u = tensile strength.

Tensile strengths of the gravel particles were not determined but similar materials have tensile strengths ranging from 100 to 1000 psi (8). With a known tensile strength, the maximum allowable internal pressure for various porosity values may be calculated. Three porosity-pressure curves for tensile strengths of 300, 600, and 900 psi are shown in Figure 10.

The determination of the internal pressure accompanying freezing of water within a hollow sphere may, likewise, be approached from a theoretical standpoint. If the temperature-volume changes of the sphere, water, and ice are neglected, the volume of ice within the cavity, assuming all the water freezes, is as follows:

$$V_i = 4/3 \; \pi \; a^3 \; S \; (1 + \beta) \; (1 - \frac{P_a}{K})$$

where:

V_i = volume of ice,

S = degree of saturation,

β = volume increase accompanying freezing of water,

P_a = available internal pressure, and

K = bulk modulus of ice.

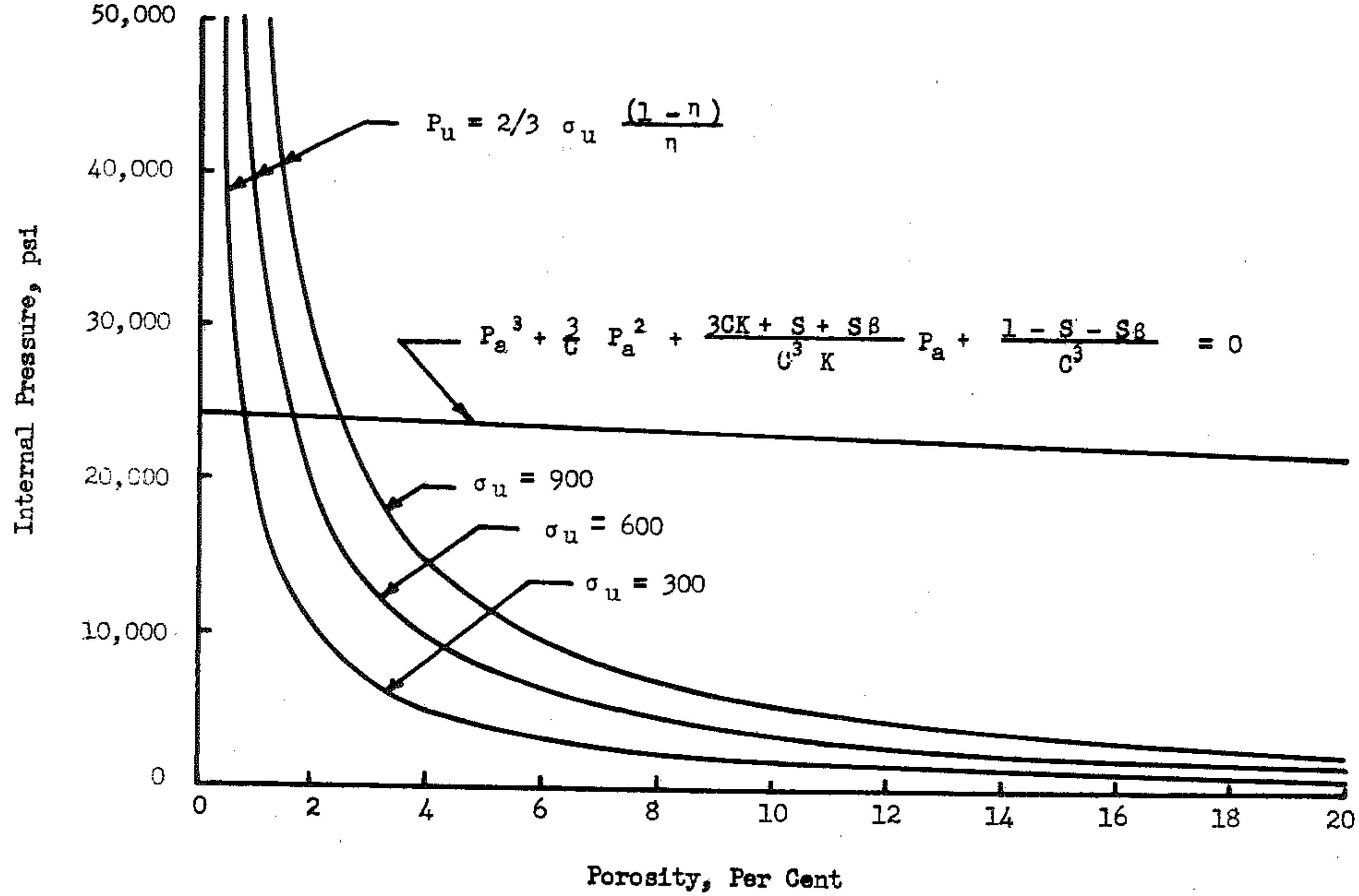

Figure 10: Suggested, Theoretical Relationship between Allowable Internal Pressure, P_u, and Available Internal Pressure, P_a, for Varying Porosities and Tensile Strengths.

The tangential strain at any point within the sphere is given by the expression:

$$\epsilon_T = \frac{\delta}{R} = \frac{\sigma_T}{E} - \mu \frac{\sigma_T}{E} - \mu \frac{\sigma_R}{E}$$

where:

ϵ_T = tangential strain,

δ = radial displacement,

E = Young's modulus of elasticity, and

μ = Poisson's ratio.

Assuming $P_o = 0$, the increase in the radius of the internal cavity or void due to an internal pressure, P_a, is

$$\delta_a = \frac{(4\mu - 2)\, a^3 - (1 + \mu)\, b^3}{2E\,(a^3 - b^3)} \cdot aP_a$$

and, by multiplying and dividing the latter equation by $4/3\,\pi$ and substituting,

$V_v = 4/3\,\pi\, a^3 = \eta\, V_t$, and

$V_t = 4/3\,\pi\, b^3$,

the equation reduces to

$$\delta_a = \frac{1 + \mu + 2\eta - 4\mu\eta}{2E\,(1 - \eta)} \cdot aP_a$$

The volume of the cavity, V_c, under internal pressure will, thus, be

$$V_c = 4/3\,\pi\,(a + \delta_a)^3$$

or

$$V_c = 4/3\,\pi\,a^3(C^3 P_a^{\,3} + 3C^2 P_a^{\,2} + 3C\,P_a + 1)$$

where:

$$C = \frac{1 + \mu + 2\eta - 4\mu\eta}{2E\,(1 - \eta)}$$

The volume of the ice within the cavity must be equal to the volume of the cavity and by equating the two, it follows that:

$$4/3\,\pi a^3\,S\,(1 + \beta)(1 - \frac{Pa}{K}) = 4/3\,\pi a^3\,(C^3 P_a^{\,3} + 3C^2 P_a^{\,2} + 3C\,Pa + 1)$$

or

$$P_a^{\,3} + \frac{3}{C} Pa^2 + \frac{3CK + S + S\beta}{C^3 K} P_a + \frac{1 - S - S\beta}{C^3} = 0$$

From the above relationship, it is seen that the respective dimensions disappear and that the internal pressure created by the freezing of water within a closed, spherical container is dependent upon the volume increase accompanying freezing of water, the bulk modulus of ice, and the porosity, degree of saturation, Poisson's ratio, and modulus of elasticity of the sphere.

The available internal pressure, P_a, was calculated for various porosity values by selecting, from the indicated references, the following values:

$\mu = 0.25$ (8),

$E = 2 \times 10^6$ psi (8),

$K = 0.392 \times 10^6$ psi (3),

$S = 1.00$, and

$\beta = 0.09$ (3).

This plot is superimposed on the maximum allowable internal pressure curves in Figure 10.

The intercept between the available pressure curve and the appropriate allowable pressure curve is the maximum allowable porosity value. For porosity values greater than this, the available pressure is greater than the allowable pressure and the container will rupture. Conversely, for porosity values less than this, the available pressure is less than the allowable pressure, and the container will withstand the pressure.

Although the pore structure within a rock fragment is complicated and variable in nature, a comparison between the theoretical approach and the test results is possible. According to Figure 10, the porosity at which failure is to be expected ranges from 1.0 to 2.5 per cent. Figure 8 shows that at a porosity of 3 per cent, approximately 25 per cent of the specimens had failed. At a porosity of 5 per cent, the same figure shows that approximately 75 per cent of the specimens had failed.

By investigating the mechanism of freezing-point depression, Havens (4) demonstrated the measurement of the internal hydrostatic pressure attending freezing of concrete. These pressures, which were in the magnitude of the compressive strength of concrete, are attributed to the freezing of water within the concrete and the dilation of aggregate particles. As dilation of aggregate particles occurs, pressures are induced into the surrounding layers of concrete and the damage, if any, caused by such action is dependent upon the magnitude of these pressures and the area over which they act. Whereas particles of all sizes are capable of inducing the same amount of pressure, particles of the larger sizes have a larger surface area over which to impart these pressures to the surrounding concrete and are individually capable of causing the most damage. On the other hand, volume for volume, the smaller particles have more surface area and a large concentration of these particles could cause severe damage.

The form of concrete disintegration called "pop-outs", is due to the occurrence of absorptive particles near the surface of concrete. A "pop-out" can occur even though the induced dilating pressure of an aggregate particle is relatively low because the surrounding shell of concrete offers little restraint. "Pop-outs" can thus be caused by any size of aggregate, including the fine sizes.

Concrete disintegration due to deep internal damage is likewise due to absorptive particles; but, because these particles are more highly restrained, large dilating pressures are required to cause damage. Most deep-seated deterioration, therefore, is produced by particles of the larger sizes which are capable of inducing this pressure over a larger area.

CHAPTER V

CONCLUSIONS

The following conclusions were drawn from the results of this investigation:

1. The subjection of stream-saturated gravel to a quick-freeze produces dilating pressures which are damaging and can lead to failure in a single freeze-thaw cycle.

2. Particle size of aggregate tested in an unconfined state is not related to freeze-and-thaw durability.

3. Although most failures occur in the lower specific gravity ranges, specific gravity is not the sole indicator of aggregate durability.

4. For saturated aggregate, absorption, or its counterpart, porosity, could be used for the discernment of aggregate durability.

5. Gravel particles derived from igneous and metamorphic rocks are less absorptive and more resistant to freeze-and-thaw than gravel particles derived from sedimentary rocks.

6. According to theoretical analysis, the porosity at which failure of aggregate particles can be expected occurs from 1.0 to 2.5 per cent.

7. The porosity at which failure actually occurs under freezing closely approximates the theoretical.

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