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COOPERATIVE RESEARCH

CORRELATION STUDIES OF FUNDAMENTAL AGGREGATE PROPERTIES WITH FREEZE-THAW DURABILITY OF STRUCTURAL LIGHTWEIGHT CONCRETE

In cooperation with the
Department of Commerce
Bureau of Public Roads

RESEARCH REPORT 81-1
PROJECT 2-8-65-81
SYNTHETIC AGGREGATE RESEARCH

CORRELATION STUDIES OF FUNDAMENTAL AGGREGATE PROPERTIES WITH FREEZE-THAW DURABILITY OF STRUCTURAL LIGHTWEIGHT CONCRETE

by

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Research Report 81-1
Synthetic Aggregate Research
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PREFACE

This research was carried out in the Structural Research Department of the Texas Transportation Institute as part of the cooperative research program with the Texas Highway Department in cooperation with the U. S. Bureau of Public Roads. The following staff personnel were actively engaged in the project.

W. B. Ledbetter, Assistant Research Engineer and Principal Investigator.

Carl E. Buth, Research Assistant.

Horace R. Blank, Research Geologist.

Subodh K. Das, Graduate Student.

Chandrakant N. Kanabar, Graduate Student.

In addition, several undergraduate students were also employed on various phases.

The author is indebted to these people for their contribution to this research effort.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. *Introduction*

1.1 Purpose

Engineering knowledge of synthetic aggregates* in relation to their performance in structures applicable to the highway field has progressed to the point where these aggregates are being employed widely. It was the purpose of this project to extend the knowledge of structural lightweight synthetic aggregates by studying the relationship between selected fundamental synthetic aggregate properties and the freeze-thaw durability of lightweight concretes made with these aggregates.

1.2 Scope and Limitations

The scope of this phase of the research study was to extend the knowledge gained from previous studies on the durability of structural lightweight concrete,[1,2] and attempt to correlate (a) type of lightweight coarse aggregate, (b) cement factor, and (c) the freeze-thaw durability performance of selected concretes; utilizing the results obtained from prior research together with research carried out in this investigation. Also, investigations were begun to find out if the different types of lightweight aggregate could be described according to their fundamental properties.

The fundamental aggregate properties determined in this study include absorption, bulk specific gravity, dry unit weight, sieve analysis, petrographic analysis, x-ray diffraction pattern, and resistance to freeze-thaw.

Concrete specimens, made with selected aggregates, were subjected to freezing in air and thawing in water. Additional specimens were cast to determine compressive and splitting tensile strengths.

A total of five lightweight coarse aggregates and one regular weight coarse aggregate were selected for study. Three cement factors were selected for each aggregate type, and two concrete curing periods prior to initiation of the freeze-thaw tests were employed. This made a total of 36 separate combinations of aggregate type, cement factor, and curing period.

In order to isolate the effects of coarse aggregate type and cement factor from other factors affecting concrete freeze-thaw durability, the following variables were held as constant as possible throughout the study.

1. Fine Aggregate Type. All mixes used the same fine aggregate—a siliceous, river run, regular weight, fine aggregate.

2. Degree of Aggregate Saturation. All aggregates were immersed in water for 14 days prior to mixing the concrete.

3. Air—No air entraining admixtures were added.

4. Laboratory Procedure. See Section 5.1 for details.

5. Slump. All mixes were prepared with approximately 4-inch slump.

6. Cement. Type I cement from the same manufacturer was used throughout this investigation.

1.3 Conclusions

From the results obtained in this phase of investigation on the five synthetic lightweight aggregates and concrete, the following conclusions are suggested:

1. Wide differences in engineering properties have been found between the five lightweight aggregates (Tables 3-1 and 3-2).

2. All the synthetic lightweight aggregates are composed largely of porous glass, in amorphous form, with small traces of silt sized crystalline grains (Tables 3-3 and 3-4).

3. Wide variation in pore size, pore spacing, and extent of crystallinity exists between different samples of the same aggregate (Table 3-4). This presents one explanation for the difficulty in producing uniformly consistent concrete.

4. When these non-air entrained concretes, made with aggregate immersed in water for two weeks, are subjected to freezing in air and thawing in water, their durability is influenced to a marked degree by the type of synthetic coarse aggregate used; and to a lesser degree by the amount of cement employed (Figures 4-1 and 4-2). This is the first step toward the development of an "Aggregate Durability Factor," in which aggregates can be rated in terms of the durability of resulting concretes.

5. The data obtained do not indicate any correlation between coarse aggregate absorption and concrete durability (Figure 4-3). Nor is any correlation apparent between any of the aggregate properties determined and concrete durability.

1.4 Recommendations

From the findings of this study the following recommendations are suggested:

1. Continued attempts should be made to correlate fundamental synthetic aggregate properties with the durability of the resulting concrete. In addition, the differential thermal characteristics of each aggregate should be obtained.

2. A survey and diagnostic analysis should be made of concrete structures in service to attempt to correlate field performance with the laboratory results reported herein.

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*For the purposes of this report, synthetic aggregates are defined as structural quality aggregates produced by fusing raw shales or clays in a rotary kiln under intense heat into predominantly amorphous silicates. These aggregates can be broadly divided into two categories—(1) fused and bloated aggregates, generally termed structural lightweight aggregates, and (2) fused, but **not** bloated aggregates.

3. The laboratory freeze-thaw results obtained in this study should be correlated with ASTM Standard freeze-thaw results (ASTM C290).

4. Investigations should be initiated into the development of a simpler and quicker concrete durability evaluation than the freeze-thaw test. Such a test might be a fatigue test on small concrete specimens.

5. A recommended durability acceptance criteria for concretes using synthetic aggregates should be developed.

2. Background

2.1 General

The durability of concrete has been of importance to engineers ever since the introduction of concrete as a structural material. In this chapter, the "state of the art" concerning durability aspects of concrete will be very briefly reviewed to form a foundation for the experimental program presented in this report.

Durability, as currently defined by ACI committee 201,[3] is:

> "For present purposes, durability of concrete is defined as its resistance to deteriorating influences which may through inadvertence or ignorance reside in the concrete itself, or are inherent in the environment to which it is exposed."

There are three known basic mechanisms which cause deterioration of concrete when exposed to alternate freezing and thawing.[4] These are:

1. Build up of hydraulic pressure in the gel structure of the cement paste from free-water freezing.
2. Growth of capillary ice during sustained cold periods when the paste is relatively dense.
3. Deterioration caused by concrete aggregates.

2.2 Factors Affecting Durability of Concrete

According to Lyse[5] the following factors have an important effect on the resistance of concrete from freezing and thawing.

1. The materials which make up the concrete.
2. The proportioning of the materials used.
3. The length of time of effective curing of the concrete before it is exposed.
4. The amount of entrained air in the voids.

Concerning these four factors, let us concern ourselves with factors 1 and 2, and more specifically, with the aggregates and amount of cement used.

The following questions should be asked regarding aggregates before using them in concrete exposed to a freezing and thawing environment.

1. Is the aggregate itself durable, or does it contain dangerous voids?
2. Does it have a high coefficient of thermal expansion?
3. Does it change in volume appreciably due to wetting and drying?
4. What is its modulus of elasticity?
5. Does it necessitate the use of excessive amounts of mixing water in the concrete?

It is generally accepted that the pores in concretes need to be almost saturated before damage will result from water freezing. This is based upon the hydraulic pressure concept which in turn is founded on the fact that water increases in volume by some 9 percent when it changes from a liquid into a solid at 32°F. This means that concretes made with air dried aggregates should be more durable than concretes made with saturated aggregates.[4] In general, different people suggest different aggregate properties which affect durability, and there is wide disagreement. A good, quick, test procedure for evaluating in-place durability of concrete aggregate is yet to be developed.[6]

In examining the amount of cement used, it has been shown that—in most cases—the greater the strength of concrete, the greater will be its resistance to deterioration from freezing and thawing. However strength must not be used as the sole guide in selecting the mix for concrete which is to be exposed to the action of freezing and thawing. Each capillary must have an air void sufficiently close to prevent the build up of hydraulic pressures. Therefore, the use of adequate air entrainment to introduce millions of microscopic air bubbles into the concrete becomes very important where resistance to freezing and thawing is desired. In regular weight concrete, reducing the water-cement ratio and increasing the cement factor do not greatly increase concrete durability, unless air entrainment is employed.[7]

2.3 Durability of Concrete Made With Structural Lightweight Aggregate

In recent years the interest in structural lightweight concrete for use in structures exposed to the action of freezing and thawing has increased considerably. Accordingly, research programs have been initiated attempting to investigate the durability of lightweight concrete. In general the results have been encouraging. Sound, durable concretes have been produced in the laboratory, providing nonsaturated aggregates were used in conjunction with a suitable air entraining admixture.[8] In our research studies on durability of lightweight concrete we have, in the past, always employed the use of air entrainment.[2] By so doing, we generally produced durable concrete in the laboratory from all commercial sources of lightweight aggregate. However, the laboratory durability of these concretes may or may not be indicative of the field durability of these same concretes. Differences in concrete field performance have been noted and the question has been asked if the synthetic aggregates used had any effect on the concrete performance. This question can only be answered by subjecting concretes made with these different aggregates to freezing and thawing in such a manner as to insure their failure under test. This will indicate if there is any difference in the source of aggregate employed. One way to insure failure is by omitting the air entrainment and saturating the aggregate prior to batching the concrete. Therefore, this approach was utilized and will be presented in Chapter 3.

3. Experimental Program

3.1 *Aggregate Engineering Properties*

Synthetic lightweight aggregates from five sources, commercially available in Texas, were selected for investigation. All aggregates selected were structural lightweight aggregates manufactured by the rotary kiln process from shale. The engineering properties of these aggregates are summarized in Table 3-1. Notice that structural lightweight aggregates continue to absorb water for long periods of time while immersed in water. Complete absorption time curves for each aggregate are given in section 5.3.

3.2 *Aggregate Freeze-Thaw Tests*

Coarse aggregates from each source were sized into three groupings and placed in a shallow pan of distilled water, with the water level at about half the depth of the stone. The prepared sample was then cycled between a chest-type freezer and the laboratory atmosphere.[9] Results of this investigation obtained are given in Table 3-2. The data indicate that certain aggregates are more durable to this test than others.

3.3 *Petrographic Examinations*

The five synthetic aggregates were subjected to a complete petrographic examination under a polarizing light microscope.

Selected samples were pulverized and examined. The results are summarized in Table 3-3. Note the degree of inhomogeneity found in all aggregates examined.

As examinations of pulverized pieces yield only a portion of the information obtainable by petrographic means, several aggregate particles were impregnated with either balsam or an epoxy resin in a vacuum desiccator, then ground into extremely thin sections for examination under the microscope. All sections examined can be best described in terms of a "glass sponge." The aggregate has numerous, irregular pores in a matrix of predominately amorphous glass with only a few "specks" of silt-sized crystalline grains. Figs. 3-1 and 3-2 are photomicrographs of the "R" coarse aggregate and "S" coarse aggregate, respectively. The white areas are silt-sized crystalline grains, the light gray areas are pores, and the dark area is the amorphous glass matrix. The black specks in the pores of Fig. 3-2 are nonuniform regions in the mounting medium (epoxy resin in this case) and are not part of the aggregate. One observation stands out, and that is the extent of the pores in these aggre-

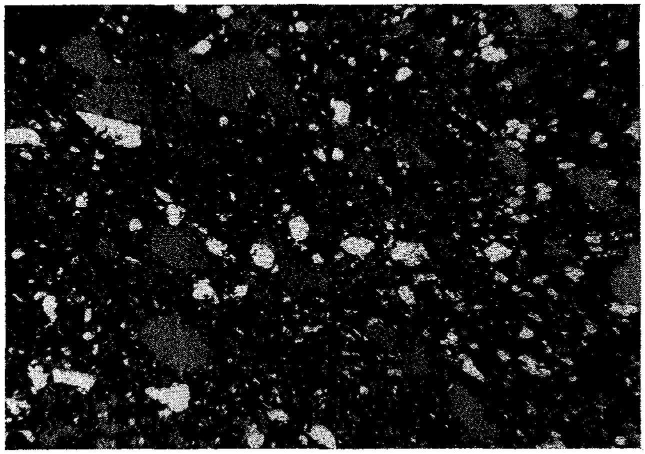

Fig. 3-1. Photomicrograph of Thin Section of "R" Coarse Aggregate (200x). Nicol prisms partly crossed.

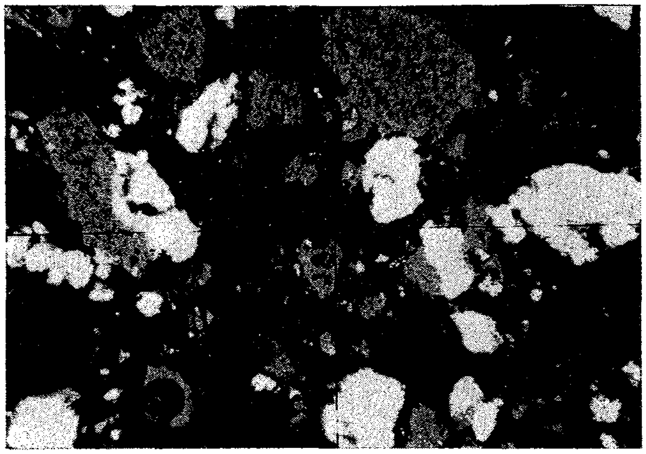

Fig. 3-2. Photomicrograph of Thin Section of "S" Coarse Aggregate (200x). The black specks in the pores (gray areas) are anisotropic portions of the mounting medium and should be disregarded. Nicol prisms partly crossed.

TABLE 3-1. SYNTHETIC COARSE AGGREGATE ENGINEERING PROPERTIES

Coarse Aggregate Designation	Absorption 3 Days[1] %	Absorption 14 Days[1] %	Bulk Specific Gravity (SSD) 3 Days[2]	Bulk Specific Gravity (SSD) 14 Days[2]	Dry Unit Wt (pcf)	Fineness Modulus[3]
R	4.7	8.0	1.47	1.50	46.8	7.0
C	8.0	12.1	1.37	1.41	38.1	6.7
E	5.5	8.6	1.42	1.46	43.8	6.5
S	10.9	16.6	1.78	1.85	48.5	6.9
D	22.5	28.0	1.35	1.42	34.4	6.7
H (Coarse)[4]	1.2		2.62		101	7.1
H (Fine)[4]	0.8		2.61		99	2.57

[1] Immersed in water for the period indicated.
[2] Immersed in water for the period indicated, then the aggregate surface was blotted dry.
[3] As defined in ASTM Designation: C125-58.
[4] Regular weight control aggregate.

TABLE 3-2. AGGREGATE FREEZE-THAW TESTS[1]

Coarse Aggregate Designation	Sieve Size	Percent Weight Loss After 50 Cycles	Percent Weight Loss After 100 Cycles
R	⅝ — ½ in. ½ — ⅜ in. ⅜ in. — No. 4	17.4 8.3 1.3	28.8 9.9 1.5
C	⅝ — ½ in. ½ — ⅜ in. ⅜ in. — No. 4	3.2 8.8 4.0	11.5 18.0 7.4
E	⅝ — ½ in. ½ — ⅜ in. ⅜ — No. 4	5.2 9.3 2.2	10.8 15.2 2.6
S	⅝ — ½ in. ½ — ⅜ in. ⅜ — No. 4	12.5 14.5 5.3	26.8 27.7 14.3
D	⅝ — ½ in. ½ — ⅜ in. ⅜ — No. 4	42.8 45.2 16.0	71.5 68.7 30.7

[1] Data obtained from Texas Transportation Institute Project 2-14-63-51 in progress. For details of the test procedure, see reference 8 in Section 5.4.

gates. Immediately it can be understood why some of these aggregates exhibited such a high absorption, and why it took so long to saturate these aggregates with water.

Measurements of pore size and abundance, together with crystalline silt size and abundance, were made and are summarized in Table 3-4. The range in values found is another indication of the large degree of nonuniformity in these aggregates. There seem to be no patterns exhibited in the sections examined. Note that in one section of the "R" aggregate, pores occupied approximately 10-15% of the section while in another section of the same aggregate, pores occupied around 35% of the section. Therefore, many sections would have to be examined before meaningful values could be obtained.

3.4 X-Ray Diffraction Examinations

Selected samples of each lightweight coarse aggregate were prepared and subjected to a beam of X-rays. As this beam passes into the prepared specimen, X-rays are scattered, or diffracted, in all directions. If there is any crystallinity (periodicity in the atomic structure), the X-rays are amplified in certain directions. This increase in X-ray intensity can be detected and the directions involved can be measured. From a study of crystallography, one can determine which crystalline patterns cause a given diffraction of the X-ray beam.

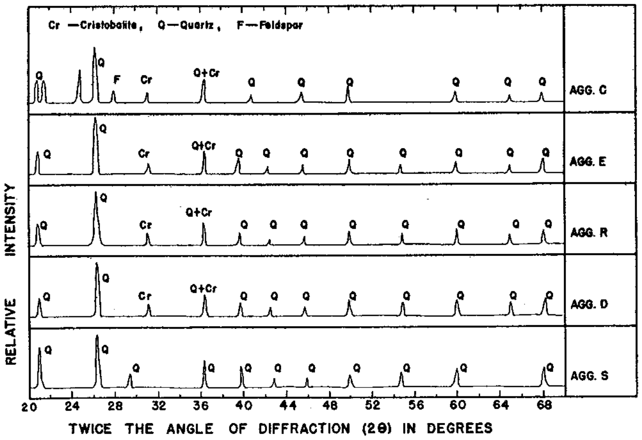

Fig. 3-3. X-Ray Diffraction Patterns on Synthetic Coarse Aggregate.

The X-ray diffraction patterns for each of the five lightweight coarse aggregates are given in Fig. 3-3, in terms of twice the angle of diffraction and relative intensities of the patterns. It is important to emphasize the X-ray diffraction differentiates *only* between crystalline portions of the aggregate and will react to very

TABLE 3-3. PETROGRAPHIC EXAMINATION OF PULVERIZED SYNTHETIC COARSE AGGREGATE

Coarse Aggregate Designation	Results
R	Mostly glass, minutely vesicular, with a few small birefringent grains. These grains are mostly cloudy-white and very ragged, and show an index of refraction slightly less than 1.539 but definitely greater than 1.535. While the material is not homogeneous, it appears to be the most homogeneous of the five aggregates examined.
C	Mostly glass, minutely vesicular, with fragments very ragged and sharp. A few anisotropic specks and grains, probably quartz silt. The glass pieces are clear, cloudy-white, red, and a few yellow. The clear and cloudy-white glass shows an index of refraction slightly less than 1.535. The red glass shows an index of refraction slightly greater than 1.535.
E	Mostly glass, but full of myriads of tiny dark inclusions, which may be mineral grains or bubbles. Numerous anisotropic specks (may be quartz). Many ragged fragments of different colored glass, mostly white and a few red. The index of refraction of the fragments is between 1.542 and 1.546. This aggregate, although far from homogeneous, is more nearly so and is more completely vitrified than either the "S" or the "D" aggregate.
S	Mostly glass fragments, many of which are gray to black in reflected light. They are very crowded with black, opaque grains. Very few areas of glass free from inclusions. The index of refraction of the different colored glass fragments varies slightly, with the colored glass around 1.544. The many birefringent grains and specks and the weakly birefringent areas in the glass fragments show that the material is not completely vitrified and is very inhomogeneous.
D	Mostly glass, ragged fragments, mostly opaque. Assorted colors by reflected light. Very difficult to obtain the index of refraction. Many inclusions. Two long prisms seen, apparently of gypsum. The brown, translucent, isotropic glass seems to have an index of refraction above 1.546 and possibly above 1.555. This material is incompletely vitrified and appears to be the least homogeneous of the aggregates investigated.

TABLE 3-4. SIZE AND ABUNDANCE OF PORES AND SILT SIZED GRAINS IN THIN SECTIONS OF SYNTHETIC AGGREGATE[1]

Coarse Aggregate Designation	Pores		Silt Sized Grains		Remarks
	Size (mm)	Abundance (%)	Size (mm)	Abundance (%)	
R (1)	.008 min to .238x.715 max	20	.004 min to .080 max	5	Pores mostly small
R (2)	.016 min to .557x2.381 max	10-15	.004 min to .040x.0795 max	5-8	Pores mostly small
R (3)	.004 min to .477x1.590 max	35	.004 min to .027 max	½	Pores mostly small
C (1)	.008 min to .318x.159 max	30-40	.008 min to .0557x.159 max	5	Red
C (2)	.008 min to .318x.477 max	50	.004 min to .111x.159 max	1-3	Composite colored
C (3)	.008 min to .318x.716 max	15	.004 min to .080x.239 max	2	Wide variation in pore size-black
C (4)	.008 min to .080x1.431 max	15	.004 min to .080x.120 max	<1	Wide variation in pore size-red
E (1)	.020 min to .238x.636 max	6	.004 min to .080x.120 max	3	Black
E (2)	.020 min to .080x5.168 max	9	.004 min to .040x.080 max	2	Red - pores elongated
S (1)	.020 min to .954x1.192 max	15	.004 min to .080x0.239 max	6	
D (1)	.008 min to .800x3.816 max	40	.004 min to .080 max	2	Black
D (2)	.020 min to .159x.239 max	<1	.008 min to .080x.239 max	1	Red - silt grains mostly small

[1] Thin sections of aggregate prepared and examined with micrometer-ocular grid at 60x magnification. Percentages of abundance are merely visual estimates from appearance of microscopic fields.

small amounts of crystalline matter. This is clearly the case here, because, according to the results of the petrographic examinations, the vast majority of the aggregates are noncrystalline. With this in mind we can see the marked similarity between the crystalline portions of all the aggregates. Therefore it appears safe to conclude that the differences between concretes made with these aggregates cannot be attributed to any differences in the crystalline portion of each aggregate. Although this is a negative conclusion, it is valuable information and narrows the several possible routes for further study.

3.5 Concrete Investigations

Structural quality concretes were made using each of the five selected synthetic coarse aggregates and one natural coarse aggregate. All mixes employed natural fine aggregate from the same source. Nominally, concretes with three cement factors were batched for each aggregate, which made a total of 18 different batches. Complete mix designs are given in Section 5.3.

Specimens were cast from these 18 concrete batches and subjected to the following types of tests:

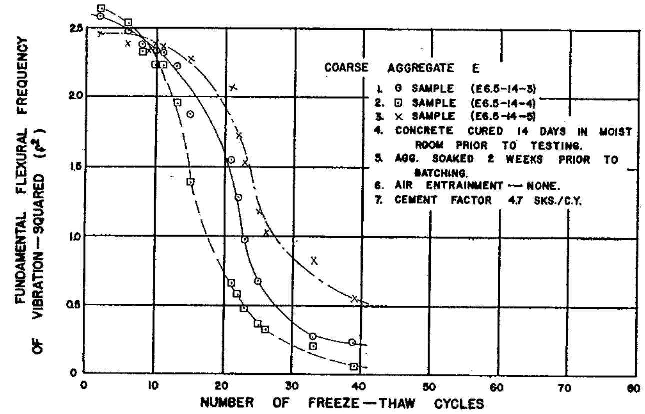

Fig. 3-4. Fundamental Flexural Frequency of Vibration-Squared (f^2) Versus Number of Freeze-Thaw Cycles for Lightweight Concrete Made with Coarse Aggregate E.

a. Freezing in Air and Thawing in Water. Standard 3" x 4" x 16" specimens were cured in the moist room at approximately 75°F and 100% R. H. Two specimens were cured for three days and three specimens were cured for 14 days. After curing, the specimens were subjected to freezing in air for approximately 10 hours followed by thawing in water for approximately two hours. Starting with an initial measurement prior to commencing the freeze-thaw tests, and continuing at the end of the thaw cycle, fundamental-flexural-frequency of vibration (f) measurements were taken.* These values were then squared. This f^2 value yields a non-destructive measure of the soundness of the concrete by measuring the specimen's fundamental frequencies of vibration. This value of f^2 can be converted directly into sonic modulus of elasticity. Thus, we have an indication of relative durability with time as the concrete undergoes cycles of freezing and thawing. A typical f^2 versus number of freeze-thaw cycles for one concrete is shown in Fig. 3-4. Note the rapid drop in f^2 values in a rela-

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*See ASTM Test Designation C215 for an explanation of this property.

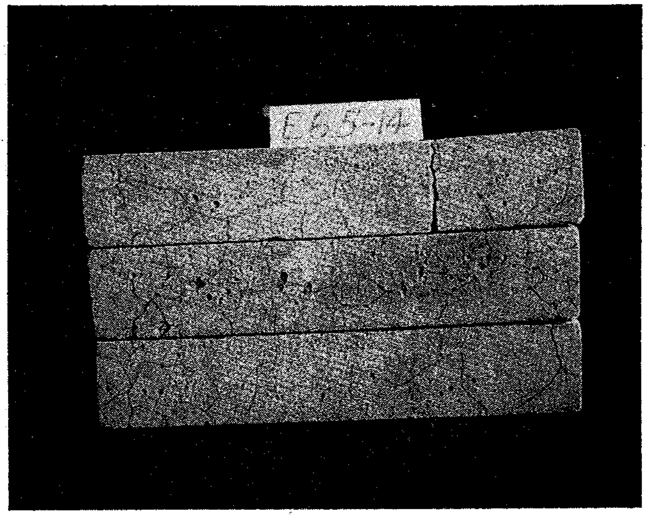


Fig. 3-5. Typical Concrete Specimens After Freezing and Thawing.

tively few cycles of freeze-thaw. Irregardless of when this drop occurred (5 cycles or 150 cycles of freeze-thaw), the drop was sudden and dramatic, resulting in the complete loss of specimen structural integrity. Thus it was relatively easy to determine the number-of-cycles-to-failure as that cycle which initiated the rapid drop in the f^2 value.

A photograph of a typical set of specimens which have been subjected to the freeze-thaw durability test to failure is shown in Fig. 3-5. Note the cracks which, in most uses, penetrate through the specimen. Note also the lack of surface spalling, so prevalent in tests where both freezing and thawing were conducted in an immersed condition.

These concretes did not contain any air entrainment, and furthermore the coarse aggregates were immersed in water for 14 days then drained for one day prior to batching (see Sec. 5.1). These were very severe conditions to place on concrete which was to undergo freezing and thawing. With such conditions imposed, the lightweight concrete was *not* expected to be durable. The purpose in utilizing such severe conditions was to ascertain if there were differences in durability as a direct result of either coarse aggregate type or amount of cement, and not to see if durable concrete could be produced.

b. Compressive Strength Tests. Standard 6 in. diameter x 12 in. long cylinders were molded and cured in accordance with ASTM C192. They were tested in accordance with ASTM C39.

c. Splitting Tensile Strength. Standard 6 in. diameter x 12 in. long cylinders were molded, cured, and tested in accordance with ASTM C496.

The results of the above three tests are given—for each parameter—in Table 3-5. Notice that in all cases structural quality concrete was made, with 28-day compressive strengths ranging from 3130 psi to 6380 psi, depending upon the cement content and type of coarse aggregate used.

The analysis and discussion of the results presented in this table are contained in Chapter 4 of this report.

TABLE 3-5. CONCRETE PROPERTIES AND FREEZE-THAW RESULTS

Coarse Aggregate Designation	Cement Factor (sks/cy)	Compressive Strength		Split Cylinder Strength 28 Days (psi)	Dynamic Modulus of Elasticity 28 Days (psi)	Number of Freeze-Thaw Cycles to Failure	
		14 Days (psi)	28 Days (psi)			Cured 3 Days Before Testing	Cured 14 Days Before Testing
R	4.1	3860	3730	409	3.79	15	125
	5.0	4500	4120	427	3.99	16	228
	6.4	5660	6380	460	3.95	†	†
C	3.7	3110	3130	348	3.58	11	53
	4.7	3770	3760	371	3.68	13	60
	6.5	5700	4810	446	4.12	55	155
E	4.0	2920	3340	369	3.61	10	12
	4.7	3750	4060	339	3.93	11	14
	6.4	5810	6370	517	4.28	36	20
S	3.9	2670	3150	324	3.08	10	18
	4.9	3790	4360	417	3.28	13	18
	6.5	5760	6230	537	3.79	33	25
D	4.1	2580	3130	371	3.07	5	11
	4.9	3330	3580	412	3.20	7	12
	6.5	4970	5150	418	3.64	13	29
H (control regular weight)	4.0	4190	4770	492	6.75	†	†
	4.9	4570	5430	559	6.63	†	†
	6.5	5140	5450	474	7.26	†	†

†This concrete was still sound after 300 cycles of freezing and thawing, at which time the test was terminated.

4. *Discussion and Analysis of Results*

4.1 Aggregate Properties

An examination of the aggregate engineering properties presented in Chapter 3 reveals (1) wide differences in the properties between different synthetic aggregate types and (2) marked inhomogeneity between samples of the same aggregate type. This could account for the difficulties experienced in obtaining uniformly consistent concrete. The water absorption versus time of these aggregates also indicates a possible reason for mix design difficulties, since the rate of water gain or loss in the aggregate as the concrete is mixed will vary markedly depending upon what aggregate moisture content is present. Much more rapid gain in water will occur with dry aggregates than with partially saturated aggregates. This is complicated by the hydration of the cement removing free water and sealing the aggregate. It is easy to see why nominal water-cement ratios are practically meaningless and also why effective, or true, water-cement ratios would be very difficult to accurately determine.

The aggregate freeze-thaw tests are still underway as of this writing so analysis of the data is difficult. However, the data do appear to be of value and will be briefly discussed in conjunction with the concrete freeze-thaw data.

It is interesting to note that the X-ray diffraction patterns of the "E" aggregate and "R" aggregate are very similar, indicating that the crystalline portions of their makeup are very similar. Thus, one might be tempted to conclude that concretes made with each of these two aggregates might be very similar. Unfortunately this is not the case, as will be discussed. As mentioned earlier X-ray analysis does not reveal anything concerning the amorphous (noncrystalline) portion of the material, and the large majority of all the synthetic aggregates consist of amorphous forms of glass which are not analyzed by X-ray patterns. I think it is safe to say that it is *not* the crystalline portion of the aggregates which accounts for their differences (not for their similarities for that matter).

The results of the petrographic examination under the polarizing light microscope reveal the wide variances between not only different aggregate types, but between different particles of the same type of aggregate. This again could account for some of the difficulty reported in obtaining concrete batches of similar consistency and in controlling mix design.

4.2 Concrete Studies

In an attempt to study the effect of aggregate type and cement factor on freeze-thaw durability of concrete, the results of the 14-day-cured-concrete freeze-thaw tests as a function of cement-factor are given in Fig. 4-1. The data were taken from Table 3-5. Here is one of the salient findings of this research to date. When subjected to this type of test, the durability of non-air entrained concrete is definitely influenced to a marked degree by the type of coarse aggregate used; and to a lesser degree by the amount of cement employed. This is the first step toward developing an "Aggregate Durability Factor" in which a given aggregate can be rated in terms of the durability of the resulting concrete. This is a severe test, and does not attempt to reproduce field conditions. But if a given concrete fails after only 12 cycles of freeze-thaw, how well will the concrete made with this same type of aggregate perform under the combined effect of erratic cycles of freeze-thaw coupled with heating and cooling, wetting and drying, fatiguing action of traffic, and repeated stress cycling from restrained volume changes due to reinforcement? When all these factors are considered, it is evident that concrete exposed to traffic and weather on a highway or bridge is also subjected to rather severe conditions.

The author of this report is not trying to defend the test by asserting that it represents a condition similar to that found in exposed locations. This remains to be investigated further. What is being said is that perhaps there is a correlation between the two conditions. What the test results do show clearly is the difference in performance of concretes made with different aggregates.

The question remains as to why there are these wide differences. As the concrete compressive strength is often more meaningful than the cement factor, the same data plotted in Fig. 4-1 were plotted in terms of concrete strength versus number of freeze-thaw cycles to failure (Fig. 4-2). The results here are practically the same as those shown on the preceding figure. It is interesting to note the different strengths exhibited between concretes made with different aggregates, and it is also interesting that those concretes exhibiting the highest strength were not the most resistant to this type of test.

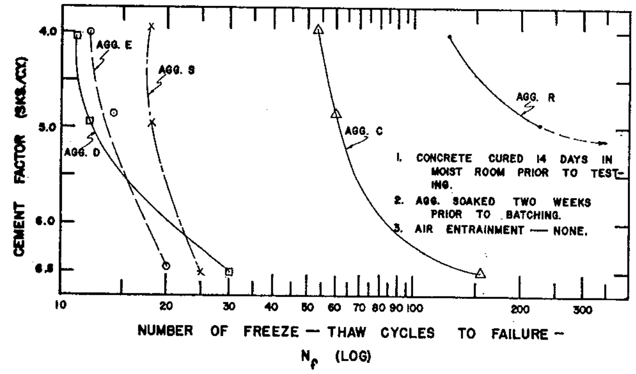


Fig. 4-1. Freeze-Thaw Durability as a Function of Cement Factor for Selected Lightweight Concretes.

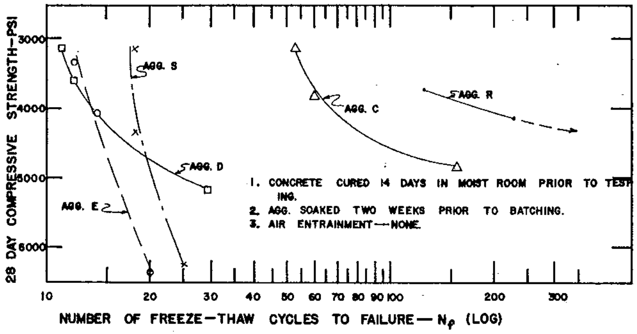
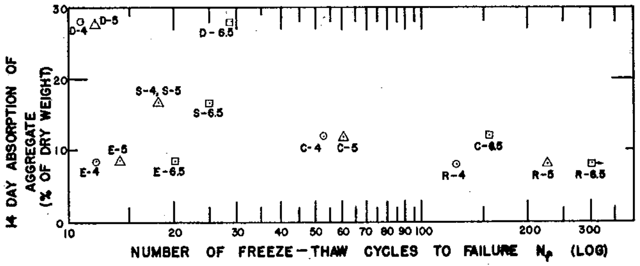


Fig. 4-2. Freeze-Thaw Durability as a Function of Concrete Strength for Selected Lightweight Concretes.



1. CONCRETE CURED 14 DAYS IN MOIST RM. PRIOR TO TESTING.
2. AGG. SOAKED TWO WEEKS PRIOR TO BATCHING.
3. AIR ENTRAINMENT — NONE.
4. C-5 MEANS AGG. C WITH 5 SKS. OF CEMENT PER CUBIC YARD OF CONCRETE.

Fig. 4-3. Freeze Thaw Durability as a Function of Aggregate Absorption and Cement Factor.

One possible correlation that has been suggested between synthetic aggregate properties and concrete durability is aggregate absorption. In order to test this hypothesis, 14-day aggregate absorption versus number of freeze-thaw cycles to failure of the resulting concrete was plotted in Fig. 4-3. It is obvious that no correlation exists. The E and R aggregates have very similar absorption characteristics as well as similar x-ray diffraction patterns, as discussed earlier. But here the similarity ends! The durability of the concrete made from these two aggregates is markedly different for each. One might be tempted to state that a correlation between concrete durability and aggregate absorption was found, with the E aggregate only a rare exception, but the data are entirely too limited to draw any such conclusion. If five other aggregates were investigated, they might exhibit *no* correlation. It would be premature to arrive at any other conclusion than that no correlation was found between durability and aggregate absorption. Knowing the different rates of absorption exhibited between different aggregates, it appears even more logical that no correlation between aggregate absorption and concrete durability should exist. And even if a correlation was found, as one might be tempted to assert has been found here, no cause-and-effect relationship can be proved. According to the hydraulic pressure concept of freeze-thaw durability discussed briefly in Chapter 2, almost complete saturation of the aggregate is required before significant internal stresses can be built up. And this is clearly a matter of rate-of-absorption rather than the value of total absorption in the aggregate.

One other point should be mentioned. An examination of the freeze-thaw results for the three-day cured specimens indicated that similar results were obtained with the disadvantage that considerably more data scatter occurred. This appears to be logical since at the age of three days concrete has completed only a portion of its hydration and continues to hydrate, changing its properties, during the thaw portion of the freeze-thaw test when the concrete is immersed in water. This in turn causes data scatter and makes analysis difficult. Therefore the 3-day cured concrete data were not considered further in this report.

As the aggregate freeze-thaw results are incomplete at this time it would be premature to draw any conclusions. The data thus far obtained indicate that perhaps some correlation exists between aggregate freeze-thaw durability and concrete freeze-thaw durability. At least the "D" aggregate shows poor resistance to freeze-thaw, which agrees with the laboratory performance exhibited by concrete made with "D" aggregate. Also, the "R" aggregate appears to be only slightly damaged by the freeze-thaw test which agrees with the concrete's freeze-thaw durability. Once again, these observations are tentative at this time and are subjected to modification or amplification as more test results are obtained.

5. *Appendix*

5.1 Laboratory Procedures

Procedure for Determining Aggregate Absorption. The absorption and absorption rate of the coarse aggregate were determined by a method developed at Texas A&M University and published in a thesis by Bryant.[10] An oven dry sample is placed in a pycnometer and water is then added to fill the pycnometer. As the aggregate absorbs water, additional water is added to refill the pycnometer and the filled pycnometer is weighed at specified time intervals. This method eliminates the need for obtaining a saturated surface dry condition which is very difficult to accurately determine for lightweight aggregates.

Mixing Procedure. The coarse aggregate, after being inundated for two weeks, was allowed to drain (while being covered) on the laboratory floor for 24 hours. The fine aggregate was stored in a bin in the laboratory. Immediately before batching, moisture contents of the aggregates were obtained by drying samples over a burner and adjustments in mixing water were made.

Ingredients for the batch were then weighed and mixed in the following sequence:

1. Introduce the coarse aggregate and approximately two-thirds of the mixing water.
    a. Mix for one minute
    b. Let stand for five minutes
    c. Mix for one minute

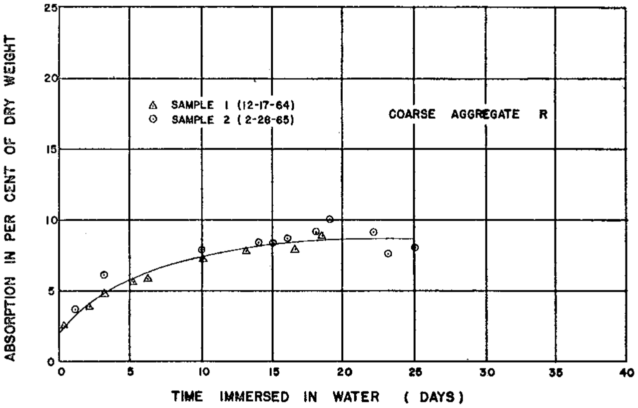


Fig. 5-1. Absorption-Time Curve for Aggregate R.

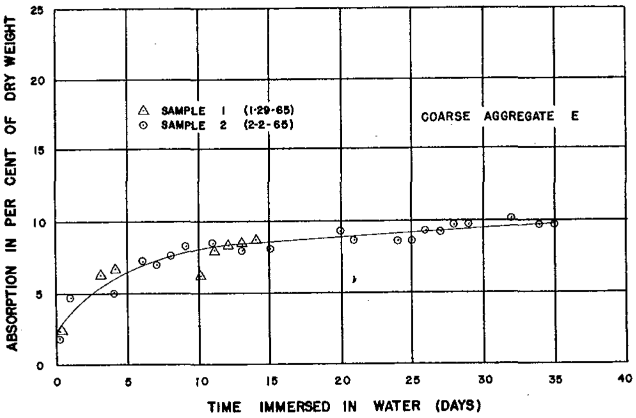


Fig. 5-2. Absorption-Time Curve for Aggregate E.

2. Add fine aggregate, cement, and one-sixth of the mixing water.
3. Mix for three to five minutes.
4. Add enough water to obtain desired slump.
5. Determine the air content (ASTM C231) and wet unit weight (ASTM C138).

The mix designs were based on trial mixes designed by the absolute volume method and only very slight corrections were required in the actual batches.

5.2 Aggregate Data

Coarse aggregate absorption-time curves are given in Figs. 5-1 through 5-5 for the aggregates investigated in this study. Several random samples of each aggregate were selected and their results are portrayed. In most cases the data scatter was not severe, indicating that the average absorption of the various aggregates is fairly consistent from sample to sample.

Aggregate sieve analyses for each aggregate investigated are given in Table 5-1.

5.3 Concrete Mix Design Data

The concrete mix designs are given, in terms of per cent absolute volume of the various constituents, in Table 5-2.

5.4 References

1. Hirsch, T. J., W. B. Ledbetter, and Don L. Ivey, "A Report on Durability Studies of Structural Lightweight Concrete," Research Report 35-1, Texas Transportation Institute, Texas A&M University, (to be published).
2. Ledbetter, W. B., T. J. Hirsch, and Don L. Ivey, "Selected Durability Studies of Structural Lightweight Concrete," Research Report 35-2, Texas Transportation Institute, Texas A&M University, (to be published).
3. ACI Committee 201, "Durability of Concrete in Service," JOURNAL OF THE ACI, December 1962, (Proceedings, Vol. 59, No. 12), P. 1771-1819.
4. Gordon, W. A., and D. Merill, "Requirements for Freeze-Thaw Durability for Concrete," ASTM Proceedings, Vol. 63, 1963, p. 1026-1036.

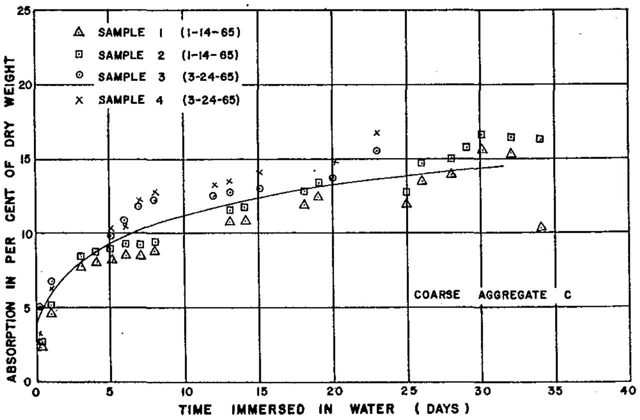


Fig. 5-3. Absorption-Time Curve for Aggregate C.

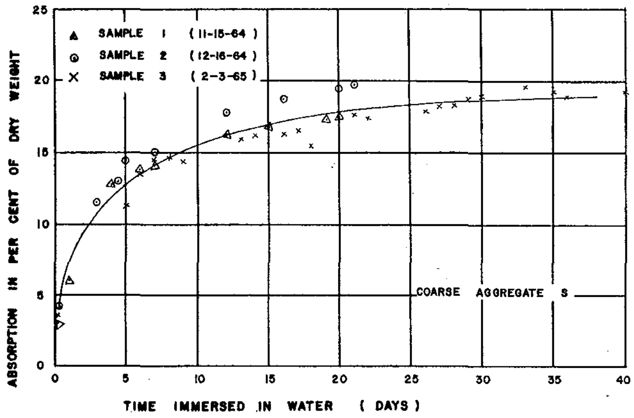


Fig. 5-4. Absorption-Time Curve for Aggregate S.

TABLE 5-1. AGGREGATE SIEVE ANALYSES DATA

Sieve Size	Cumulative Percent Retained						
	Coarse Agg. R	Coarse Agg. C	Coarse Agg. E	Coarse Agg. S	Coarse Agg. D	Coarse Agg. H	Fine Agg. H
¾ in.	2.4	3.8	0.2	0.6	0	12.1	
½ in.	30.5	22.8	12.3	29.6	15.2	39.4	
⅜ in.	54.3	57.1	46.8	63.0	61.8	65.3	
#4	93.0	92.1	100.0	93.2	98.5	95.8	0.4
#8	99.4	97.3	100.0	99.3	99.4	98.2	9.5
#16	100.0	100.0	100.0	100.0	100.0	100.0	23.4
#30							43.7
#50							83.5
#100							96.0

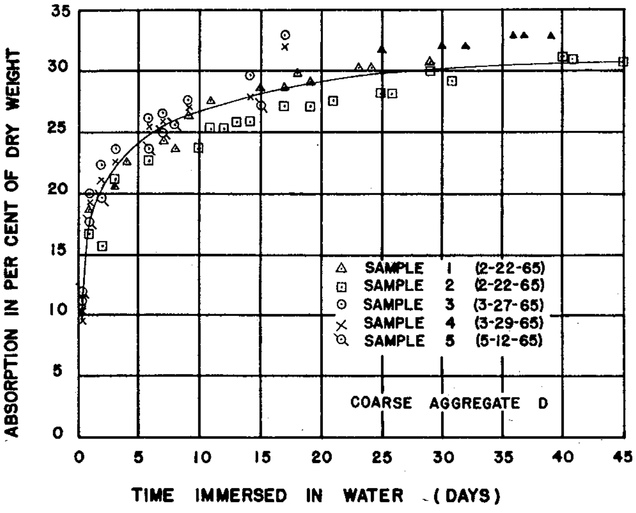


Fig. 5-5. Absorption-Time Curve for Aggregate D.

5. Lyse, Inge, "Durability of Concrete in Sea Water," Proceedings of the ACI, Vol. 57, 1960-61, p. 1575.

6. Larson, T., P. Cady, M. Franzen, and J. Reed, "A Critical Review of Literature Treating Methods of Identifying Aggregates Subject to Destructive Volume Change When Frozen in Concrete and a Proposed Program of Research," HRB Special Report 80, Highway Research Board, 1964, p. 81.

7. Klieger, Paul, "Effect of Entrained Air on Strength and Durability of Concrete Made With Various Sizes of Aggregate," BULLETIN NO. 128, Highway Research Board, 1956.

8. Hanson, T. A., and Paul Klieger, "Freezing and Thawing Tests of Lightweight Aggregate Concrete," Proceedings of the ACI, Vol. 57, 1960-61, p. 779.

9. Gallaway, Bob M., "Interim Report on the Use of Expanded Shale and Precoated Limestone as Coverstone for Seal Coats and Surface Treatments," Research Report 51-1, Texas Transportation Institute, Texas A&M University, August 1964.

10. Bryant, J. S., "The Determination of the Moisture Absorption Characteristics of Lightweight Concrete Aggregates," M. S. Thesis, Texas A&M University, January, 1959.

TABLE 5-2. CONCRETE MIX DESIGN DATA

Coarse Aggregate Designation	Cement Factor (sks/cy)	Per Cent Absolute Volume				Air Content[1] (%)	Slump (in.)	Initial Unit Weight (pcf)
		Cement	Water	F.A.	C.A.			
R	4.1	7.3	20.6	36.0	34.1	2.0	4	117.6
	5.0	8.7	20.4	34.7	33.7	2.5	3½	118.8
	6.4	11.3	23.2	30.5	32.9	2.0	3¾	120.4
C	3.7	6.6	23.1	36.9	30.9	2.5	3¾	119.3
	4.7	8.4	22.8	35.0	31.7	2.0	4½	115.7
	6.4	11.4	21.7	32.4	32.5	2.0	4½	120.7
E	4.0	7.0	21.2	37.0	32.4	2.4	4	121.6
	4.6	8.2	21.1	36.8	31.8	2.1	3¾	118.0
	6.4	11.3	19.7	34.5	32.4	2.1	3½	120.7
S	3.9	7.0	24.2	34.1	33.0	1.8	4	124.8
	4.9	8.6	23.6	32.7	33.2	1.9	4¼	126.8
	6.5	11.4	22.4	31.1	33.1	2.0	3½	128.0
D	4.1	7.2	20.7	38.4	31.6	2.1	3¾	118.0
	4.9	8.9	22.9	35.5	30.9	2.0	4¼	118.4
	6.5	11.6	22.7	32.5	31.2	2.0	4	119.2
H	4.1	7.2	15.2	30.5	45.1	2.0	3	146.9
	4.9	8.6	15.6	29.1	44.7	2.0	3	148.0
	6.6	11.6	14.5	26.4	45.6	1.9	3	150.0

[1] Determined in accordance with ASTM Test Designation C 231.