EFFECT OF DEGREE OF SYNTHETIC LIGHTWEIGHT AGGREGATE PRE-WETTING ON THE FREEZE-THAW DURABILITY OF LIGHTWEIGHT CONCRETE

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PREFACE

This is the second report of a research study 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 first report is titled:

"Correlation Studies of Fundamental
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In addition, several undergraduate students from Texas A&M University were employed on various phases.

The authors are indebted to these people for their contribution to this research effort.

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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ABSTRACT

The scope of this research study was to extend the knowledge gained from previous studies on the durability of structural lightweight concrete, and to attempt to correlate (a) degree of pre-wetting of the synthetic lightweight coarse aggregate, (b) type of synthetic lightweight coarse aggregate, (c) compressive strength of lightweight concrete and (d) the freezer-thaw durability of lightweight concretes made with these aggregates; utilizing the results obtained from prior research, together with research carried out in this investigation. Concrete specimens made with selected synthetic coarse lightweight aggregates were subjected to freezing in air and thawing in water. An analysis of the data indicates that results were obtained on the effects of all the variables included in this investigation, and although the number of tests was not sufficient to draw final conclusions the following tentative conclusions were suggested:

1. The degree of aggregate pre-wetting has a definite effect on the freeze-thaw durability of the concretes tested. Excessive aggregate pre-wetting is extremely detrimental to the freeze-thaw durability of the concretes tested and, for the aggregates investigated herein, should be avoided in exposed conditions.

2. All the three aggregates tested have more or less similar effects on the freeze-thaw durability of the resulting concretes.

3. A trend is revealed indicating that when the total water absorbed in the aggregate in terms of per cent absolute void volume exceeds around 85 to 90 per cent, the resulting concrete fails rapidly under the type of freeze-thaw tests employed in this study.

4. The hydraulic pressure concept may not always provide the full explanation for disruptive action from freezing and thawing.

These conclusions are entirely dependent upon the conditions under which this research was conducted and should not be further generalized.

CHAPTER I

Introduction

1.1 General

In recent years, interest in structural lightweight concrete[1] has become widespread, not only on account of its light weight, but also because of its high thermal and sound insulation properties.

To date, the production of lightweight concrete in this country has been achieved primarily through the use of synthetic lightweight aggregates.[2] Synthetic lightweight aggregate suitable for use in structural concrete were first introduced in 1917, and the first synthetic lightweight aggregate plant was installed in Birmingham, Alabama in 1918 (1).[3] In recent years, a large variety of inorganic lightweight materials has become commercially available. Since about 1950, the potentialities of this synthetic material for lightweight concrete have become widely recognized and economically attainable. At present, lightweight concrete is being extensively used by engineers, architects and contractors in the construction industry. The majority of the structures built with this lightweight concrete in the past are still sound and safe, and have performed well in service. However, a few structures built with this lightweight concrete did not come up to standards of in-service performance and showed severe deterioration within short periods. For these early durability problems, the blame has often been placed on this relatively new synthetic lightweight aggregate, without any further investigations of either the concrete or the aggregate used, or of the circumstances in which the concrete deteriorated. These reported durability problems have been with concrete which designed compressive strengths specified by engineers and architects. Since these structures were constructed with adequate strength lightweight concretes, this suggests that concrete strength in itself does not always guarantee required service. For satisfactory performance in the field, concrete must be capable of withstanding deteriorating influences of weather and other aspects of environment. In other words, the concrete must be durable, and to insure this durability, every ingredient which goes into the concrete must be durable. More often than not, adequate durability will provide ample strength, while the converse is not always true.

Next to density, which ranges from 30 lbs./cft to 70 lbs./cft, the most significant property of these synthetic lightweight aggregates is their high absorption value. Absorption values range from about 7 per cent by weight for the expanded shales to as high as 30 per cent for some of the expanded clays. In order to minimize the effect of high absorption of these aggregates in obtaining a good workable concrete, pre-wetting of the aggregate is a well accepted practice and is desirable for the following reasons:

(a) Segregation of the aggregate is reduced or eliminated.

(b) Tendency to dust is reduced, thus preventing loss of valuable fines.

(c) Mixing time can be reduced somewhat.

(d) To obtain better uniformity between various batches of concrete.

(e) To eliminate premature stiffening.

The effect of synthetic lightweight aggregate pre-wetting on the freeze-thaw durability of resulting concrete is not very well known. This research was initiated to study the effect of degree of synthetic lightweight aggregate pre-wetting on the freeze-thaw durability of lightweight concrete.

1.2 Purpose

The durability of concrete has been of importance to engineers ever since the introduction of concrete as a structural material. The engineering knowledge of synthetic lightweight aggregates in relation to their performance in structures has progressed to the point where these aggregates are being employed widely. This study was initiated to extend the knowledge concerning synthetic lightweight aggregates by studying the relationship between degree of pre-wetting of these aggregates and the freeze-thaw durability[4] of unreinforced lightweight concretes made with these aggregates. It was anticipated that improved criteria concerning degree of pre-wetting could be developed for synthetic lightweight aggregates used in structural concrete.

1.3 Scope and Limitations

The scope of this research study was to extend the knowledge gained from previous studies on the durability of lightweight concrete (2, 3) and to attempt to correlate (a) degree of pre-wetting of synthetic lightweight coarse aggregate, (b) type of synthetic lightweight coarse aggregate, (c) compressive strength of lightweight concrete, and (d) the freeze-thaw durability of lightweight concretes made with these aggregates; utilizing the results obtained from prior research (3), together with research carried out in this investigation.

Concrete specimens, made with selected synthetic coarse lightweight aggregates, were subjected to freezing in air and thawing in water.[5] Additional specimens were cast to determine compressive strengths.

Synthetic lightweight aggregates from three sources, commercially available in Texas, were selected for in-

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[1] Structural lightweight concrete is one type of synthetic aggregate concrete; and, hereafter, it will be referred to as lightweight concrete in this report.

[2] For the purpose 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: (a) fused and bloated aggregates (less than 55 pcf dry unit weight), generally termed structural lightweight aggregates, and (b) fused but not bloated aggregates (greater than 55 pcf dry unit weight).

[3] Numbers in parentheses refer to references contained in Section 6.4.

[4] Refer to Section 2.1 for definition and explanation of freeze-thaw durability.

[5] For laboratory procedure, see Section 3.2.

vestigation. All three aggregates selected were structural lightweight aggregates manufactured by the rotary kiln process from shale. The physical properties of the three synthetic lightweight coarse aggregates, together with the one natural sand employed in this study as fine aggregate, are given in Table 1-1. Table 1-2 contains the list of parameters, together with the variables studied.

In research studies on durability of lightweight concrete in the past, researchers have almost always employed the use of air-entrainment and have generally produced durable concrete in the laboratory from most commercial sources of synthetic lightweight aggregate (2, 5, 6). Thus, the researchers have not been able to evaluate any effect of the type of synthetic lightweight aggregate used on the concrete's durability performance, because all the concretes tested were found to be durable. The effect of the synthetic lightweight aggregates used on lightweight concrete performance can best be studied by subjecting lightweight concretes made with these different aggregates to freezing and thawing in such a manner as to insure their failure under test. Thus, by holding all factors, insofar as practical, constant with the exception of coarse aggregate type, such a test will indicate if there are any differences in concrete durability as a result of aggregate employed. One such way to insure failure is by omitting the air-entrainment and saturating the aggregate prior to batching the concrete. This approach was used previously; and out of five synthetic lightweight aggregates used, three resulted in poor lightweight concrete durability irrespective of cement content or strength. The same approach was utilized in this phase of the study for determining the effect of degree of pre-wetting of three synthetic lightweight coarse aggregates which gave poor results previously on the freeze-thaw durability of resulting concrete (3). In order to isolate the effects of synthetic lightweight coarse aggregate pre-wetting and synthetic lightweight coarse aggregate types from other factors affecting concrete freeze-thaw durability, the following factors were held as nearly constant as possible throughout the study:

1. Cement Factor. Five sacks per cubic yard.
2. Cement Type. Type 1 cement from the same manufacturer was used throughout the study.
3. Fine Aggregate Type. All mixes used the same fine aggregate—a siliceous, river-run, regular weight fine aggregate (Agg. H).
4. Air. No air-entrainment admixtures were used.
5. Laboratory Procedure. See Section 6.1 for details.
6. Slump. All mixes were prepared with approximately 3 to 4 in. slump.
7. Curing Procedure. All specimens were kept for one day in molds and then for 13 days in a moist room at approximately 100% relative humidity and 73°F.

TABLE 1-2. VARIABLES INVOLVED IN THIS STUDY

Parameters	Variation in Parameters (Variables)
Coarse Aggregate Type	Three — Aggregate S Aggregate D Aggregate E
Degree of Aggregate Saturation Prior to Mixing	Four — Oven Dry Immersed in water for 3 days. Immersed in water for 14 days. Immersed in water for 21 days.

TABLE 1-1. SYNTHETIC COARSE AGGREGATE ENGINEERING PROPERTIES

Coarse Aggregate Type	Dry Unit Wt. (pcf)	ABSORPTION* PER CENT (of Dry Weight)				Bulk Specific Gravity**				Fineness Modulus***
		Oven Dry†	3 Day	14 Day	21 Day	Oven Dry	3 Day	14 Day	21 Day	
S	48.5	5.0	10.9	16.6	18.0	1.70	1.78	1.85	1.90	6.90
D	34.4	12.0	22.5	28.0	30.0	1.30	1.35	1.42	1.45	6.70
E	43.8	2.5	5.3	8.6	9.0	1.40	1.41	1.46	1.46	6.50
H (Fine)††	99.0		0.8				2.61			2.57

*Immersed in water for the period indicated.

**As determined according to Bryant's method (4).

***As defined in ASTM Designation C125-58.

†The amount of water absorbed by oven-dried aggregates, when immersed in water for 100 minutes. This immersion period was selected to estimate the amount of water absorbed by the aggregate while the concrete was in a fluid state.

††Regular weight fine aggregate.

CHAPTER II

Literature Review

2.1 General

The durability of concrete is not only a matter of concern with lightweight concrete. Exposed concrete—either lightweight or normal weight—is subjected to the potential deteriorating influences of weather, and other aspects of environment and durability of such exposed concrete are of prime importance. Freeze-thaw durability of concrete is perhaps given the most attention in durability studies of concrete undertaken to find out what constitutes good and poor durability. In this Chapter, a brief review of literature concerning durability aspects of concrete is presented.

2.2 Fundamental Mechanisms

There are three basic mechanisms which cause deterioration of concrete when exposed to alternate freezing and thawing (7). These are:

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

Hydraulic Pressure Concept. It is believed that the principal force responsible for frost damage in ordinary wet concretes exposed to alternately repeated cycles of freezing and thawing is internal hydraulic pressure created by an expanding ice-water system during freezing (8).

When concrete dries during thawing, capillary cavities in the cement paste fraction of concrete are left by the evaporating water. These cavities are occupied by deposits of the cement gel produced by hydration of the cement. Thus, there exists in concrete, a system of capillary cavities, most of which are surrounded by an unfreezable gel system of low permeability.

Now, when water in a saturated cavity freezes, the expansion produced in the ice-water system requires a dilation[6] of the cavity of some nine per cent of the volume of frozen water, or the forcing of that volume of water out of the cavity into the surrounding paste, or a combination of both. The pressure required to effect the transfer of the excess volume of water resulting from progressive freezing is known as hydraulic pressure. If the magnitude of the pressure required is too high the paste will be damaged.

Growth of Capillary Ice. If the concrete body contains relatively few capillaries, the resulting hydraulic pressure will be too low to cause significant dilation. But, once ice is formed in a cavity that ice acquires the ability to draw water from the surrounding unfrozen region as soon as temperature drops below the melting point of ice in the cavity. While water is being drawn from regions surrounding a body of capillary ice, paste tends to shrink, but this tendency may be more than overcome by growth of ice crystals, the overall result being dilation. Since crystal growth follows after temperature begins to fall, dilation may not be apparent the same instant that freezing occurs. Also, it does not stop as soon as freezing ceases (9).

Deterioration Caused by Concrete Aggregates. Refer to Section 2.4 for a review on deterioration caused by concrete aggregates.

2.3 Factors Affecting Durability of Concrete

There are four basic factors having an important effect on the resistance of concrete from frost action (10). They are:

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, and
4. The amount of air entrained in the voids.

Materials. Use of suitable materials is of primary importance in producing durable concrete structures.

Grieb, Werner, and others have undertaken extensive studies to determine whether durability of concrete was related to certain properties of the cements such as chemical composition or fineness (11). They concluded:

1. Concretes prepared with Type III cements gave the poorest resistance to natural weathering.
2. Concretes containing Type I cement showed next poorest resistance.
3. Concretes prepared with cement Types II, IV, V, and with air-entraining cement, showed no appreciable difference in overall durability—showed (good durability).

Russian investigators have found that where pozzolans are used to replace a portion of the cement, the resistance of concrete to freezing and thawing is reduced (12).

Tests indicate that neither color nor odor furnishes a satisfactory criterion on the suitability of water for mixing concrete. Water for durable concrete shall be clean and free from injurious amounts of oil, acid, alkali, organic matter or other deleterious substances (13).

Air-entraining admixtures, like vinsol resin, when added to concrete, increases freeze-thaw durability considerably (14). When it is desired to improve early strengths (1 to 3 days) as well as resistance to freezing and thawing, vinsol resin and calcium chloride may be used in the same mix provided the amount of calcium chloride is limited to 2 per cent by weight of cement (15). When high percentages of calcium chloride and/or sodium chloride are added to concrete for construction at 0° weather, the durability is considerably decreased (12).

Proportioning of the Materials Used. The greater the strength of a concrete, in most cases, the greater will be its resistance to freezing and thawing; but 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. In order to resist decomposition, concrete should be as dense and impermeable as possible. Permeability, rather than porosity (or density), is the more valuable criterion of resistance, and the aim should be to produce impermeability rather than low porosity or absorption (16). The more impervious the paste, the greater will be the restriction on movement of water into and out of the aggregate. Richer mixes, therefore, produce concrete that is more resistant to freezing and thawing under natural exposure.

Cordon and Merrill (7) conclude that portland cement pastes of low water-cement ratios are more resistant to the build-up of hydraulic pressures and the growth of capillary ice simply because there are fewer capillaries in such pastes. Durable concrete cannot be produced by only restricting water-cement ratio because even when there are fewer capillaries in the paste, these capillaries must be protected by air voids (7). If this protection is not provided, the development of hydraulic pressures in the capillaries, although not as extensive as in paste of higher water-cement ratios, would be sufficient to cause deterioration.

Concrete which will be exposed to a combination of moisture and freezing should be made with entrained

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[6] Dilation. When highly saturated concrete is cooled to low temperatures the formation of ice results in expansion which may exceed the contraction due to cooling. This expansion is called the "dilation."

air. When non-air-entrained concrete is used, the water-cement ratio should be held as low as practical—0.4 or less by weight (8).

Curing and Finishing. The length of time of effective curing of the concrete before it is exposed plays an important role in frost resistance of concrete. The moist curing period of the concrete has been found to be of significant importance to achieve frost resistance in fresh water. But in sea water, the moist curing period has only a small effect on freeze-thaw durability of concrete (10). However, durability of air-entrained concrete against freezing and thawing is affected only to a small extent by curing period and sometimes prolonged curing has even an adverse effect on freeze-thaw durability of air-entrained concrete (17).

Application of curing water before the beginning of initial set is harmful for concrete. The addition of curing water after the concrete has reached initial set reduces shrinkage, helps in continuation of hydration until the permanent hydration structure is well developed and thus is helpful in improving concrete durability (18).

The durability of concrete against freezing and thawing is significantly improved if freezing and thawing starts after the concrete has had a chance to dry after curing (19).

Air-Entrainment. The higher the hydraulic pressure developed inside the concrete, the greater the damage and poorer the durability. The magnitude of the hydraulic pressure developed depends on "the distance from the cavity in a cement paste to a point of pressure relief" (8). In order to reduce the pressure developed, it becomes necessary to provide pressure relief points at short distances from the cavity. This can be effectively done through incorporation in the paste of a system of small air voids (entrained air bubbles). Experience has shown that disruptive hydraulic pressure will not develop in the paste fraction of normal concretes if enough entrained voids are present so that the distance between capillary voids and entrained air voids do not exceed around .007 in. (8). This leads to the conclusion that air-entrainment in concrete is one of the best ways to reduce hydraulic pressure and thereby increase durability of concrete against freezing and thawing.

Concrete with air contents of about 3 to 5 per cent (an increase of about 2 to 4 per cent points over the air content of non-entrained concrete) shows as good a resistance to freezing and thawing as those with higher air contents (15). Air contents in excess of about five per cent generally cause a considerable loss in strength without any appreciable gain in resistance to freezing and thawing and, in general, should be avoided (15). More air-entrainment is required in concrete mixes of low and high cement content than in mixes of medium cement content. Also, where concrete is exposed to freezing and thawing in a saturated condition, it should contain a minimum of 5 per cent entrained air for concrete containing 1½ in. maximum size aggregate (7).

2.4 Effect of Aggregates Used on Freeze-Thaw Durability of Concrete

The physical and chemical properties of aggregates —both coarse and fine—used in concrete play an important role in the durability of concrete against the disruptive action of freezing and thawing. The deleterious influence of aggregates on concrete durability results from chemical deposition, freezing of water in the aggregate pores, differential expansion between mortar and aggregate, and reaction between the cement and aggregate (20). In many cases, it appears that this disruptive action is accompanied by abnormal expansion of concrete.

According to Carlson (21), some of the questions to be asked regarding the aggregates before accepting them for use in concrete exposed to a freezing and thawing environment are:

1. Is the aggregate itself durable or does it contain dangerous voids?
2. Does it have a high 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 an excessive amount of mixing water in the concrete?

Soundness is an important characteristic of concrete aggregates. Unsound aggregates cause deterioration of concretes regardless of quality mix or construction practices (7). The resistance to frost action of concrete depends not only on the amount of water absorbed after a certain period or after having been saturated more or less completely, but also on the speed of absorption (22). While most, if not all, non-durable aggregate types have a relatively high absorption, say greater than 2 per cent for natural aggregate, many durable aggregates also have a high absorption. The size and character of the voids, particularly as they affect the degree of saturation, have a notable influence (20).

Committees and individuals attempting to list the factors which affect the durability of concrete have frequently mentioned thermal coefficient of expansion of the aggregate as one of the factors to be considered (23). It is evident that if the thermal coefficient of the aggregate is significantly different than that of the cement paste, whether higher or lower, it would tend to set up destructive stresses in the concrete as extreme changes in temperature occur (24). Where the difference between coefficients of expansion of coarse aggregate and mortar is large, the durability of the concrete may be considerably lower than would be expected from the quality of the aggregates as determined by the usual aggregate tests (25).

The greater the saturation of concrete and/or aggregates, the greater will be the hydraulic pressure developed in the concrete as a result of alternate freezing and thawing (8). This suggests that the greater the amount of mixing water required for proper placing and finishing, the poorer will be the freeze-thaw durability of exposed concrete.

According to Carlson (21), neither very large aggregate nor very small aggregate is best for use in exposed concrete. Not only are the harmful effects of bleeding magnified where aggregates are large, but internal cracks due to volume change are also intensified. A lesser overall volume change is obtained with the use of large aggregates, but at the expense of greater internal stresses and cracking.

According to Sweet and Woods (20), the grading, particle shape and surface characteristics of fine aggregate have a marked influence on durability of concrete pavements through their effect on the water required for proper placing and finishing and the water retaining characteristics of the concrete.

Alternate freezing and thawing of concrete is a contributory rather than a fundamental cause for its deterioration (26). The fact that the temperature of concrete drops below 32°F has no significance in itself, for dry concrete may be frozen and thawed repeatedly with negligible damage. According to ACI Committee 201 (8), there must be water in concrete pores before harm can result from freezing, and it must be present in such an amount that when it increases in volume by some nine per cent as it changes state because of freezing, the ice formed will more than fill the pores containing it and so develop disruptive pressure. In other words, the pores in concretes need to be almost saturated before damage will result by hydraulic pressure developed from freezing. Price and Cordon (5) state that if the aggregate pores are not fully saturated when the freezing starts, less water (or none at all) would need to be expelled during freezing; and as a result, lower or negligible hydraulic pressure will be developed. This means that concretes made with air dried aggregates should be more durable than concretes made with saturated or soaked aggregates. This has been confirmed by Hanson and Klieger (27), ACI Committee 201 (8) and Ledbetter, Hirsch and Ivey (2).

In general, different people suggest different aggregate properties which affect durability of concrete. Unsound aggregates cause deterioration of concretes regardless of quality of mix or construction practices. It has been shown by experiments that entrained air in the cement paste could not be expected to subdue the effects of bad aggregates in concrete.

Price and Cordon (5) report that lightweight concrete in general displays good resistance against the disruptive action of freezing and thawing. Durability of synthetic lightweight aggregate concrete, in general, compares favorably with regular weight aggregate concrete, and the spread in durability among the concretes made with the different synthetic lightweight aggregates appears no greater than might be encountered with normal weight concrete (27). Sound, durable concretes have been produced in the laboratory, providing nonsaturated synthetic lightweight aggregates were used in conjunction with a suitable air-entraining admixture (2, 27). The use of intentionally entrained air results in a marked increase in resistance to freezing and thawing of concretes made with synthetic lightweight aggregates (27). The percentage of entrained air required for adequate durability of synthetic lightweight aggregate concrete is similar to that required for regular normal weight aggregate concrete.

CHAPTER III

Concrete Investigations

3.1 General

Three synthetic lightweight coarse aggregates which yielded low freeze-thaw durability in the previous phase of this study (2) were selected for further studies with different aggregate pre-soaking conditions.

Structural quality concretes were batched using each of the three selected synthetic lightweight coarse aggregates—aggregates S, D, and E—in each of four selected aggregate pre-soaking conditions[7] (oven-dried, three-day pre-soaked, 14-day pre-soaked, and 21-day pre-soaked). This made a total of 12 different batches. For the purpose of verification, two batches of aggregate D and two batches of aggregate E, using 14-day and 21-day soaking periods were rebatched. Complete mix designs are given in Section 6.2. The nomenclature adopted to identify the various mixes and specimens was as follows: The first letter (S, D, E, or H) indicated the coarse aggregate type used, the number immediately following indicated the aggregate pre-soaking period prior to batching for the coarse aggregate used, the terminal numbers (whenever used) indicated specimen numbers from the mix. As an example, S-21-1 indicated specimen 1 from the mix prepared with aggregate S pre-soaked for 21 days prior to batching.

3.2 Concrete Durability Test

The specimens for the freezing and thawing tests were 3 in. x 4 in. x 16 in. concrete prisms. Immediately after the completion of mixing, the concrete was placed, with the 4-in. side vertical, in steel molds in two equal layers, each layer being tamped 25 times with a standard ⅝ in. round, bullet-nosed tamping rod. After each sample mold was filled and tamped, the top was struck and smoothed with a trowel and the concrete was allowed to stand for approximately 24 hours before removal from the molds. A total of four freezer-thaw specimens were cast from each batch.

The prisms were cured for 13 days (after removal from molds) in the moist room at approximately 73°F and 100 percent relative humidity. At the end of the curing period, the test prisms were weighed and, with a portable type soniscope, initial measurements were taken and converted to fundamental-flexural-frequency of vibration squared (f^2)[8].

After taking the initial readings, three prisms from each batch were subjected to freeze-thaw cycles and the fourth prism was returned to the moist room as a control specimen. The prisms were frozen in air in a deep freezer for approximately ten hours and thawed in water for approximately two hours. Thus, two cycles of freezing and thawing were obtained every 24 hours, seven days per week. The minimum specimen temperature obtained was approximately 0°F. The maximum specimen temperature attained was approximately 70°F. The test prisms were tested periodically, at the end of a thaw cycle, with the soniscope and, again, values of fundamental-flexural-frequency of vibration squared (f^2) were determined. This f^2 value yields a non-destructive measure of the soundness of concrete. This value of f^2 can be converted directly into dynamic modulus of elasticity

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[7] Refer to Section 6.1 for details of the laboratory procedure.

[8] See ASTM Test Designation C215 for an explanation of this property.

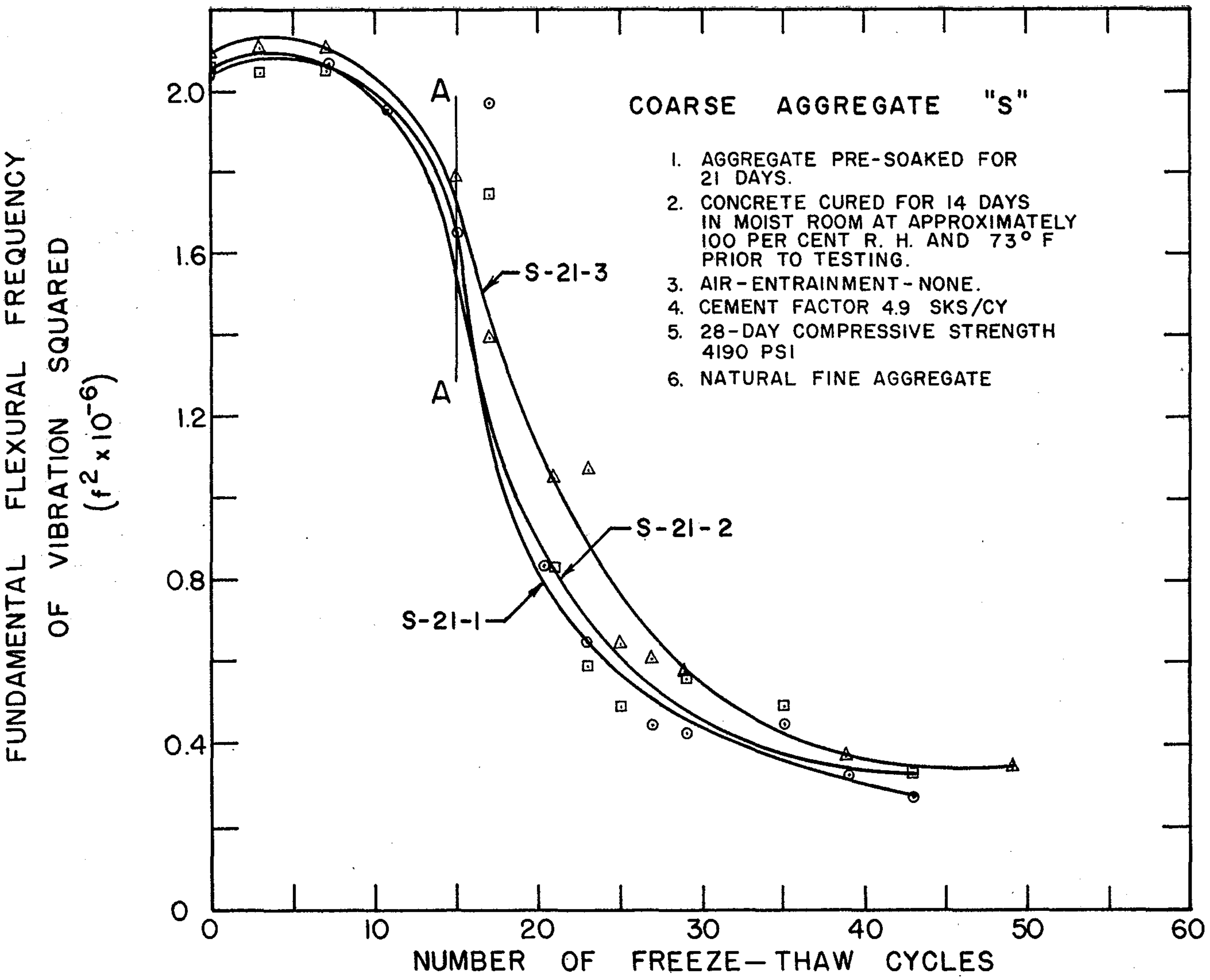

Fig. 3-1. Typical Freeze-Thaw Durability Curve for Lightweight Concrete.

(E) (28). Thus, the periodical testing of the prisms with the soniscope for measuring fundamental-flexural-frequency of vibration squared yields 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 Figure 3-1. As shown in the Figure by the vertical line A-A, which represents the point where a sudden drop in the value of f^2 occurred, the number of freeze-thaw cycles to failure (N_f) was determined for each concrete batch. Specimens which did not show any appreciable drop in f^2 value after 200 freeze-thaw cycles, were removed from the test.

3.3 Compressive Strength Tests

The primary purpose of this investigation was to obtain freeze-thaw durability data; however, in order to properly identify the concrete mixes, tests were also performed to establish the compressive strengths of specimens prepared from the various mixes. A total of six standard 6 in. diameter x 12 in. long cylinders from each batch of concrete were molded and cured in accordance with ASTM C192. Watertight steel molds were used throughout. The cylinders were tested in a Forney compression testing machine in accordance with ASTM C39. Three cylinders were tested after 14 days of curing, and the remaining three were tested after 28 days of curing.

Concrete properties and freeze-thaw results are given, for each parameter, in Table 3.1. The reported values represent the average of three individual tests in each case. Note that in all cases, structural quality concrete was achieved with 28 day compressive strengths ranging from 3380 psi to 5600 psi.

For all mixes except those containing oven-dried coarse aggregates, the theoretical water-cement ratio was obtained by assuming the net water in the mix was equal to the total water minus that water absorbed in the coarse aggregate prior to mixing; as obtained from the aggregate absorption-time curve. (The fine aggregate was converted to an SSD condition.) For those mixes containing oven-dried aggregates, the net water in the mix was arbitrarily assumed to be equal to the total water minus that water absorbed in the coarse aggregates after 100 minutes of immersion in water.

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

TABLE 3-1. CONCRETE PROPERTIES AND FREEZE-THAW RESULTS

Coarse Aggregate Designation	Coarse Aggregate Degree of Saturation	Cement Factor (sks/cy)	Theoretical W/C Ratio by Weight***	Compressive Strength		Fundamental Flexural Frequency of Vibration Squared 14 Day ($f^2 x 10^{-6}$)	Dynamic Modulus of Elasticity E 14 Day (psi) ($psi x 10^{-6}$)	Number of Freeze-Thaw Cycles to Failure (N_f)
				14 Day (psi)	28 Day (psi)			
S	Oven Dry	4.79	0.90	3970	4490	2.103	3.21	**
	3 Day Soaked	4.96	0.78	4020	4530	2.179	3.36	**
	14 Day Soaked	4.9	0.88	3790	4360	1.452	2.36	18*
	21 Day Soaked	4.93	0.82	3790	4190	2.055	3.26	15
D	Oven Dry	4.98	0.76	3950	4540	2.268	3.37	**
	3 Day Soaked	5.02	0.74	3400	3550	2.100	3.16	**
	14 Day Soaked-1	4.9	0.84	3330	3580	2.146	3.36	12*
	14 Day Soaked-2	4.90	0.82	3140	3630	2.047	3.18	16
	21 Day Soaked-1	4.86	0.87	3290	3830	2.082	3.24	195
	21 Day Soaked-2	4.92	0.82	3640	4220	1.991	3.15	9
E	Oven Dry	5.08	0.72	5090	5530	2.733	4.41	**
	3 Day Soaked	4.95	0.79	4290	4910	2.639	4.36	**
	14 Day Soaked-1	4.70	0.82	3750	4070	2.273	3.57	14*
	14 Day Soaked-2	4.70	0.81	2910	3380	2.288	3.80	8
	21 Day Soaked-1	4.92	0.80	4980	5600	2.664	4.40	**
	21 Day Soaked-2	4.70	0.77	3640	4280	2.481	4.12	

*Data obtained from reference (3).
**Removed from freeze-thaw cycle after 200 cycles.
***See explanation in text.

CHAPTER IV

Discussion and Analysis of Results

4.1 General

In this chapter, results obtained (Table 3-1) were analyzed for the relationships between (a) the degree of aggregate pre-wetting (b) the aggregate absorption, and (c) the freeze-thaw durability of the concrete.

4.2 Effect of Aggregates Pre-Wetting on the Freeze-Thaw Durability of Concrete

Figures 4-1 through 4-3 reveal that aggregate pre-wetting has a definite effect on the freeze-thaw durability of the concretes tested in this research program. The concretes made with the 3-day pre-soaked aggregates, as well as those made with oven dried aggregates, did not fail after 200 cycles of freeze-thaw. Almost all the concretes, except 'D-21', 'E-21' and '2E-21', prepared with either 14-day pre-soaked or 21-day pre-soaked aggregates, failed within 20 freeze-thaw cycles indicating poor freeze-thaw durability in this test. This suggests that the extent of aggregate pre-wetting influences to a marked degree the freeze-thaw durability of this concrete.

The first batch of concrete prepared with 21-day pre-soaked aggregate E did not fail even after 200 freeze-thaw cycles, but a second batch of concrete prepared with the same 21-day pre-soaked aggregate E failed after 105 cycles. In contrast, four concrete batches prepared with 14-day pre-soaked aggregate E failed within 20 cycles of freezing and thawing. The first batch of concrete mixed with 21-day pre-soaked aggregate D failed after 195 freeze-thaw cycles, whereas the second batch failed after only nine freeze-thaw cycles. At this time, no definite reasons for the erratic behavior of 'D-21', 'E-21' and '2E-21' concretes can be given. One possible explanation is the marked inhomogeneity between samples of the same aggregate type as reported in report 81-1 of this investigation (3):

> "The results of the petrographic examination of these aggregates under polarizing light microscope reveal the wide variances between not only different aggregate types, but between different particles of the same type of aggregate."

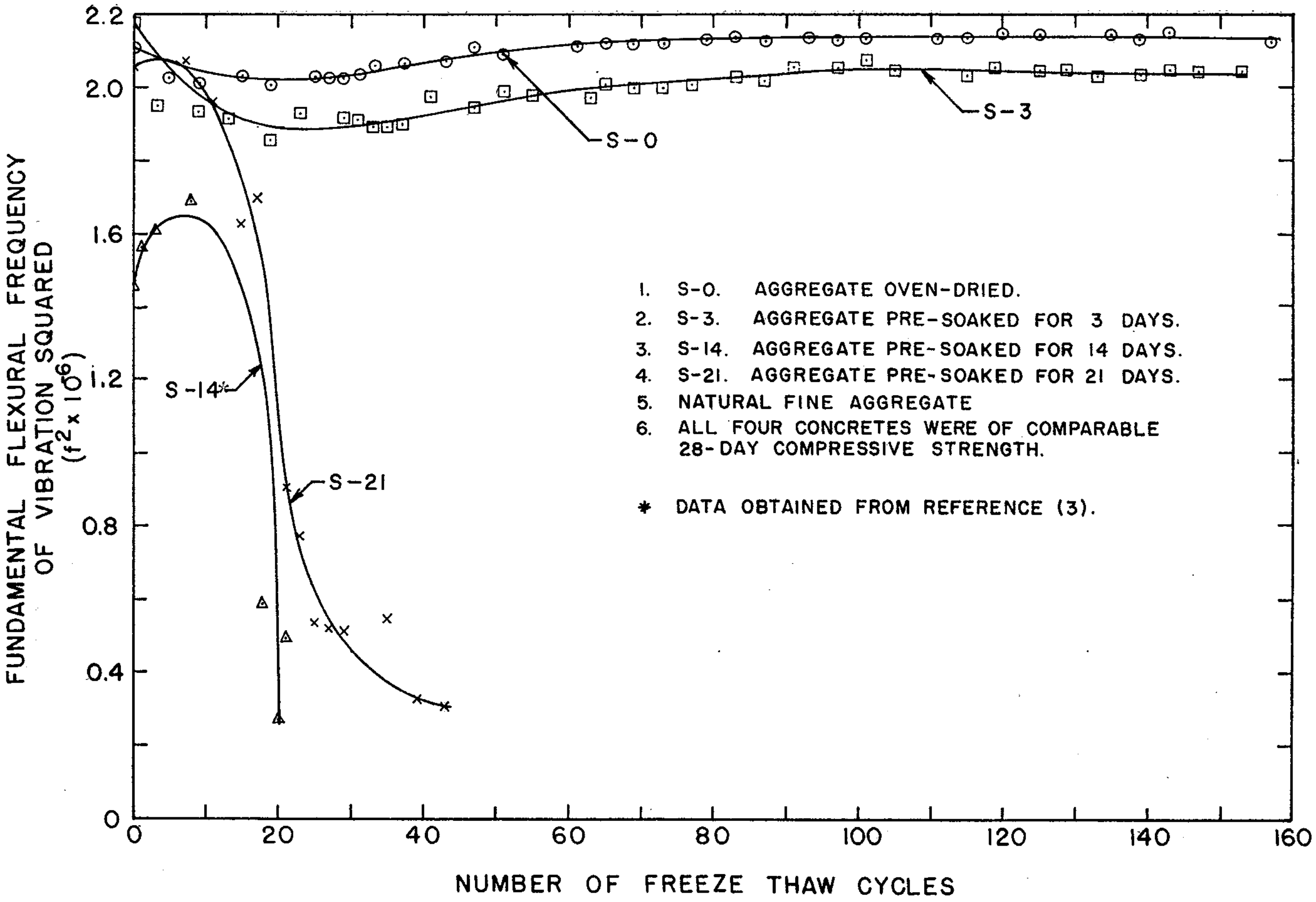

Fig. 4-1. Effect of Aggregate Pre-Wetting on the Freeze-Thaw Durability of Lightweight Concrete Made with Aggregate S.

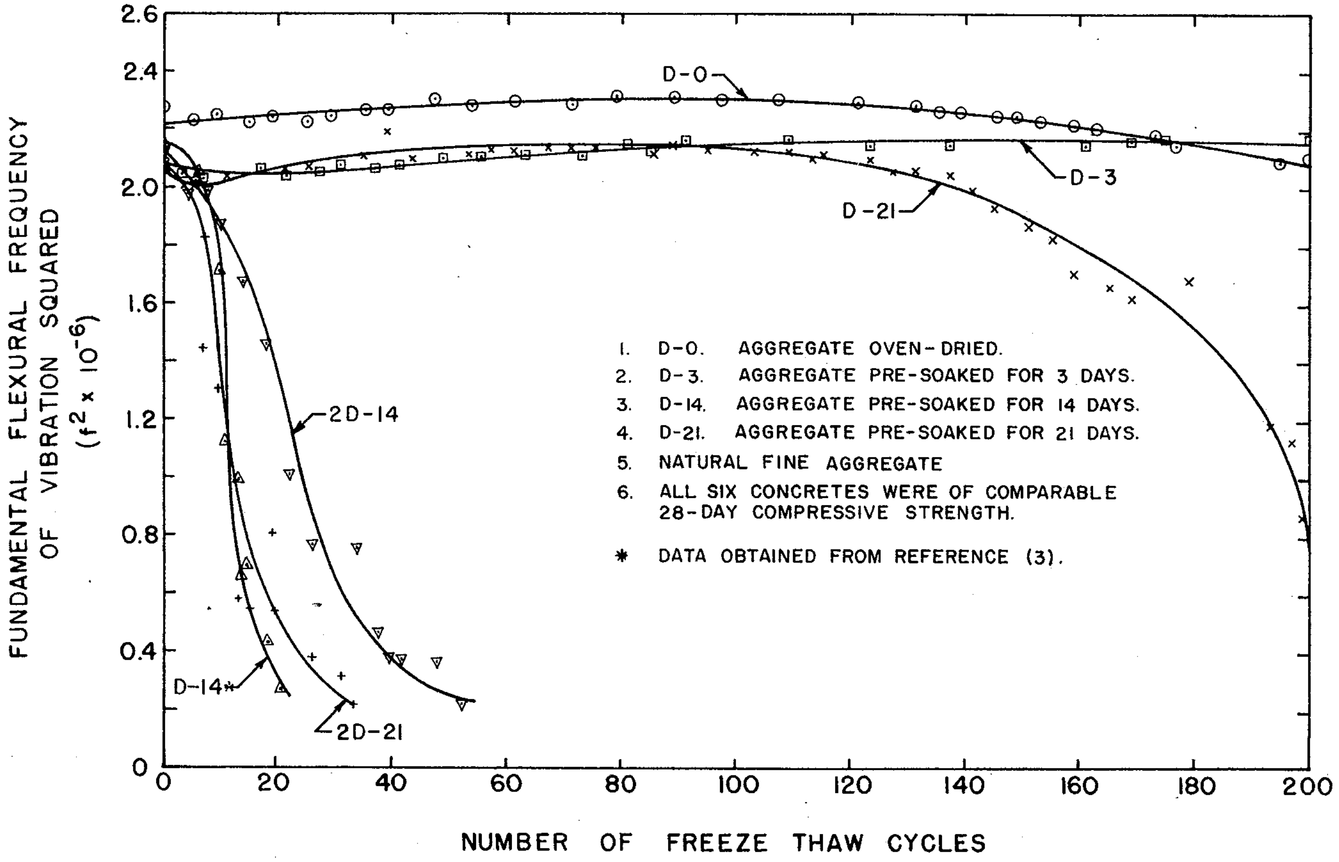

Fig. 4-2. Effect of Aggregate Pre-Wetting on the Freeze-Thaw Durability of Lightweight Concrete Made with Aggregate D.

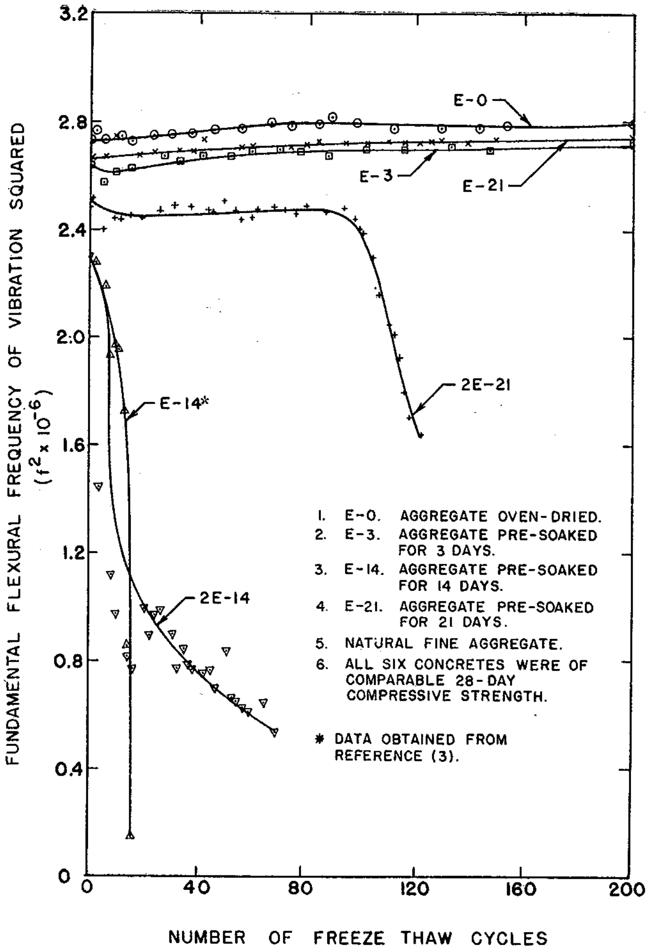

Fig. 4-3. Effect of Aggregate Pre-Wetting on the Freeze-Thaw Durability of Lightweight Concrete Made with Aggregate E.

Carlton (29) reports in his thesis,

"The porosity of lightweight aggregate has been noted to vary even within the same day's production. A change in the moisture content or physical characteristics of the unburned clay or shale, or a change in the temperature of the rotary kiln in which the clay or shale is burned can cause a variation in the porosity of the aggregate produced. Many of the pores in the lightweight aggregate are sealed where water cannot enter, and the general arrangement of the pores varies considerably from batch to batch."

Taking all these factors into consideration along with the early failures exhibited by the majority of the concretes prepared with saturated aggregates, it is concluded that the batches 'D-21', 'E-21' and '2E-21' are unusual and not representative of typical results. It can be said, therefore, that the degree of aggregate pre-wetting has a definite effect on the freeze-thaw durability of the concretes tested. It can also be said that excessive aggregate pre-wetting can be extremely detrimental to the freeze-thaw durability of the concrete.

As explained in Section 2.2, these early failures of the concretes made with 14-day and 21-day pre-soaked aggregates can be attributed to the development of excessive hydraulic pressures during concrete freezing. Non-availability of pressure relief points in the form of uniformly distributed air bubbles adds to the severity of this test and expedites the failure of the specimens from cycles of freezing and thawing.

4.3 Effect of Aggregates Absorption on the Freeze-Thaw Durability of Concrete

The total water absorbed in the aggregate in terms of per cent dry weight and also per cent absolute volume was calculated for each aggregate. These values, along with the number of freeze-thaw cycles to failure, are reported in Table 4-1.

TABLE 4-1. TOTAL WATER ABSORBED BY THE COARSE AGGREGATES AND THE NUMBER OF CONCRETE FREEZE-THAW CYCLES TO FAILURE

Coarse Aggregate Designation	Coarse Aggregate Saturation Condition	Coarse Aggregate Absorption in Percentage of Dry Weight	Total Water Absorbed in the Aggregate Percentage Absolute Volume	Number of Concrete Freeze-Thaw Cycles to Failure-N_f.
S	Oven Dry	5 ***	26.3	**
	3 Day Soaked	10.8	56.8	**
	14 Day Soaked	16.6	87.4	18*
	21 Day Soaked	18.0	94.7	15
D	Oven Dry	12 ***	38.7	**
	3 Day Soaked	22.5	72.6	**
	14 Day Soaked	28.2	91.0	12*
	14 Day Soaked	28.2	91.0	16
	21 Day Soaked	30.0	96.8	195
	21 Day Soaked	30.0	96.8	9
E	Oven Dry	2.5***	25.5	**
	3 Day Soaked	5.3	54.1	**
	14 Day Soaked	8.9	90.8	14*
	14 Day Soaked	8.9	90.8	8
	21 Day Soaked	9.0	91.8	**
	21 Day Soaked	9.0	91.8	105

*Data obtained from Reference (3).
**Removed from freeze-thaw cycles after 200 cycles.
***The amount of water absorbed by oven-dried aggregates, when immersed in water for 100 minutes.

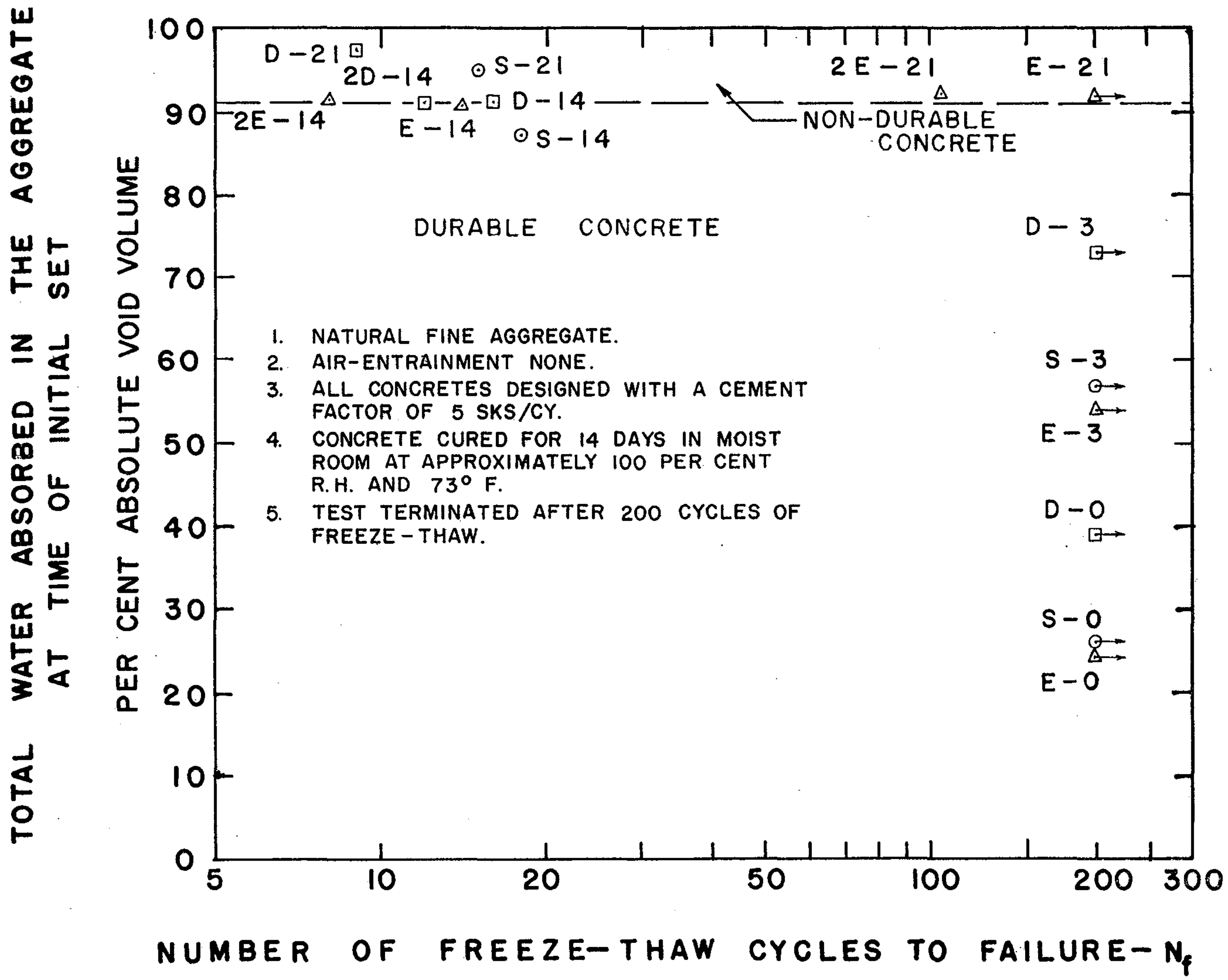

Fig. 4-4. Effect of Total Water Absorbed in the Aggregate on the Freeze-Thaw Durability of Selected Lightweight Concretes.

One possible correlation that has been suggested between synthetic aggregate properties and concrete durability is aggregate absorption. From earlier results, it was found that no correlation existed between the aggregate absorption in per cent of dry weight and the freeze-thaw durability of concrete made from these aggregates (2). However, when absorption is expressed in terms of per cent absolute void volume, an interesting trend is found. The freeze-thaw durability of concrete as a function of total water absorbed in the aggregate (at approximate time of initial set[9]) in terms of per cent absolute void volume is given in Figure 4-4. A trend is revealed indicating that the total water absorbed in the aggregate in terms of per cent absolute void volume has a marked influence on the freeze-thaw durability of concrete. Almost all the concretes prepared with the aggregates with more than 90 per cent total water absorbed in the aggregate in terms of per cent absolute void volume failed rapidly in this test. These rapid failures of the concretes made with more or less completely saturated aggregates are in accordance with the hydraulic pressure theory discussed in Section 2.2. According to that theory, concretes made with aggregates whose voids contain 91 per cent or more absorbed water, should exhibit poor freeze-thaw durability, and such was the case as seen in the Figure. However, there were a few exceptions to this theory which indicate that the hydraulic pressure concept may not provide the full explanations for disruptive actions from freezing and thawing. Further research is necessary in this area.

4.4 *Comparison of Results with Previous Research*

The results obtained from this study for the most part, agree with those obtained in previous research.

ACI Committee 201 (8) reports:

> "If the aggregate pores are not fully saturated when the freezing starts, less water, or none at all, would need to be expelled during freezing and lower or negligible hydraulic pressures would result. The vulnerability of the aggregate to frost damage, therefore, depends importantly on its moisture content."

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[9] For oven-dried aggregates, assumed to be that water which is absorbed by the aggregate when immersed in water for 100 minutes.

Sweet and Woods (20) report:

"The deleterious influence of aggregates on concrete durability results from freezing of water in the aggregate pores."

Klieger and Hanson (27) conclude:

"The moisture condition of the aggregate has a significant influence on the resistance to freezing and thawing of the concrete. This is particularly so for the non-air entrained concretes."

Price and Cordon (5) reported higher freeze-thaw durability of concrete made with air-dried aggregates than that made with saturated aggregates. The results reported herein agree with the findings reported above in that the concretes made with saturated aggregates showed poorer freeze-thaw durability than that made with air-dried or partially saturated aggregates.

CHAPTER V

Conclusions and Recommendations

5.1 Conclusions

An analysis of the data gathered in this research program has been summarized herein. These results reflected the effects of all the variables included in this investigation, and although the number of tests was not sufficient to draw final conclusions, the following tentative conclusions are suggested:

1. The degree of aggregate pre-wetting has a definite effect on the freeze-thaw durability of the concretes tested. Excessive aggregate pre-wetting is extremely detrimental to the freeze-thaw durability of the concretes tested (Figures 4-1 through 4-3) and for the aggregates investigated herein, should be avoided in exposed concretes.
2. All the three aggregates tested have more or less similar effect on the freeze-thaw durability of the resulting concretes.
3. A trend is revealed indicating that when the total water absorbed in the aggregate in terms of percent absolute void volume exceeds around 85 to 90 percent, the resulting concrete fails rapidly under the type of test (Figure 4-4).
4. The hydraulic pressure concept may not always provide the full explanation for disruptive action from freezing and thawing.

These conclusions are entirely dependent upon the conditions under which this research was conducted and should not be further generalized.

5.2 Recommendations

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

1. Attempts should be made to continue to find the effect of different pre-wetting conditions of the synthetic lightweight aggregates on the freeze-thaw durability of the resulting concretes. Effect of pre-wetting the aggregates for periods between three days and 14 days on the freeze-thaw durability should be studied.
2. An effort should be made to study the effect of aggregate pre-wetting on the freeze-thaw durability of air-entrained concrete.
3. An attempt should be made to relate the laboratory results reported herein with field performance of similar concretes.
4. Freeze-thaw data should be obtained in accordance with ASTM Test Designation C290 (rapid freezing and thawing in water) and compared with the data obtained in this report.

CHAPTER VI

Appendix

6.1 Laboratory Procedure

For each selected synthetic lightweight coarse aggregate type, concretes were prepared using the aggregate in four different moisture conditions:

1. Dried in oven at 240°F for 48 hours,
2. Pre-soaked in water for 3 days and allowed to drain for one hour, or
3. Pre-soaked in water for 14 days and allowed to drain for 24 hours, or
4. Pre-soaked in water for 21 days and allowed to drain for 24 hours.[10]

At the end of draining period—prior to batching—moisture contents of the aggregates were obtained by drying samples over a burner.

The fine aggregate was stored in a bin in the laboratory. Moisture content of the fine aggregate was also obtained immediately before batching, using the above method. The necessary adjustments in mixing water were made, depending on the moisture contents of the coarse and fine aggregates.

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[10] Draining Procedure. The aggregates were spread on laboratory floor in about 5 to 6 in. thick layers after being removed from water at the end of soaking period. The aggregate layer was covered with burlap sacks during the draining period.

TABLE 6.1. CONCRETE MIX DESIGN DATA

Concrete Mix Designation	Cement Factor (sks/cy)	Percent Absolute Volume				Air Content Per Cent	Slump In.	Initial Unit Weight pcf
		Cement	Water	F.A.	C.A.			
S-0	4.8	8.5	24.2	32.4	32.6	2.3	3 ¾	114.8
S-3	5.0	8.8	21.5	33.6	33.8	2.3	3	118.8
S-14	4.9	8.6	23.6	32.7	33.2	1.9	4 ¼	126.8
S-21	4.9	8.7	22.6	33.4	33.6	1.7	3 ½	119.6
D-0	5.0	8.8	21.0	35.4	32.2	2.6	3	108.4
D-3	5.0	8.9	20.7	35.8	32.5	2.1	3 ½	114.8
D-14	4.9	8.9	22.9	35.5	30.9	2.0	4 ¼	118.4
2D-14	4.9	8.7	22.9	35.5	30.9	2.0	4	119.2
D-21	4.9	8.6	23.4	34.6	31.5	1.9	4	114.8
2D-21	4.9	8.7	22.3	35.7	31.8	1.5	2	118.4
E-0	5.1	9.0	20.4	34.8	34.7	1.1	3 ¼	120.9
E-3	5.0	8.8	21.7	34.0	33.7	1.8	3 ½	123.6
E-14	4.60	8.2	21.1	36.8	31.8	2.1	3 ¾	118.0
2E-14	4.7	8.2	21.0	36.7	31.8	2.3	3	127.6
E-21	4.9	8.7	22.0	33.7	33.5	2.1	3	118.2
2E-21	4.7	8.3	20.2	37.2	32.3	2.0	4 ½	128.0

Ingredients for the batch were then weighed and mixed in a 6.0 cu. ft. mixer 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.
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 wet unit weight (ASTM C138) and the air content (ASTM C231).

The mixes were designed by the absolute volume method and very minor changes were required for holding the concrete slumps in the range of 3 to 4 in.

6.2 Concrete Mix Design Data

The concrete mix designs—actual—in terms of percent absolute volume of the various constituents are given in Table 6.1.

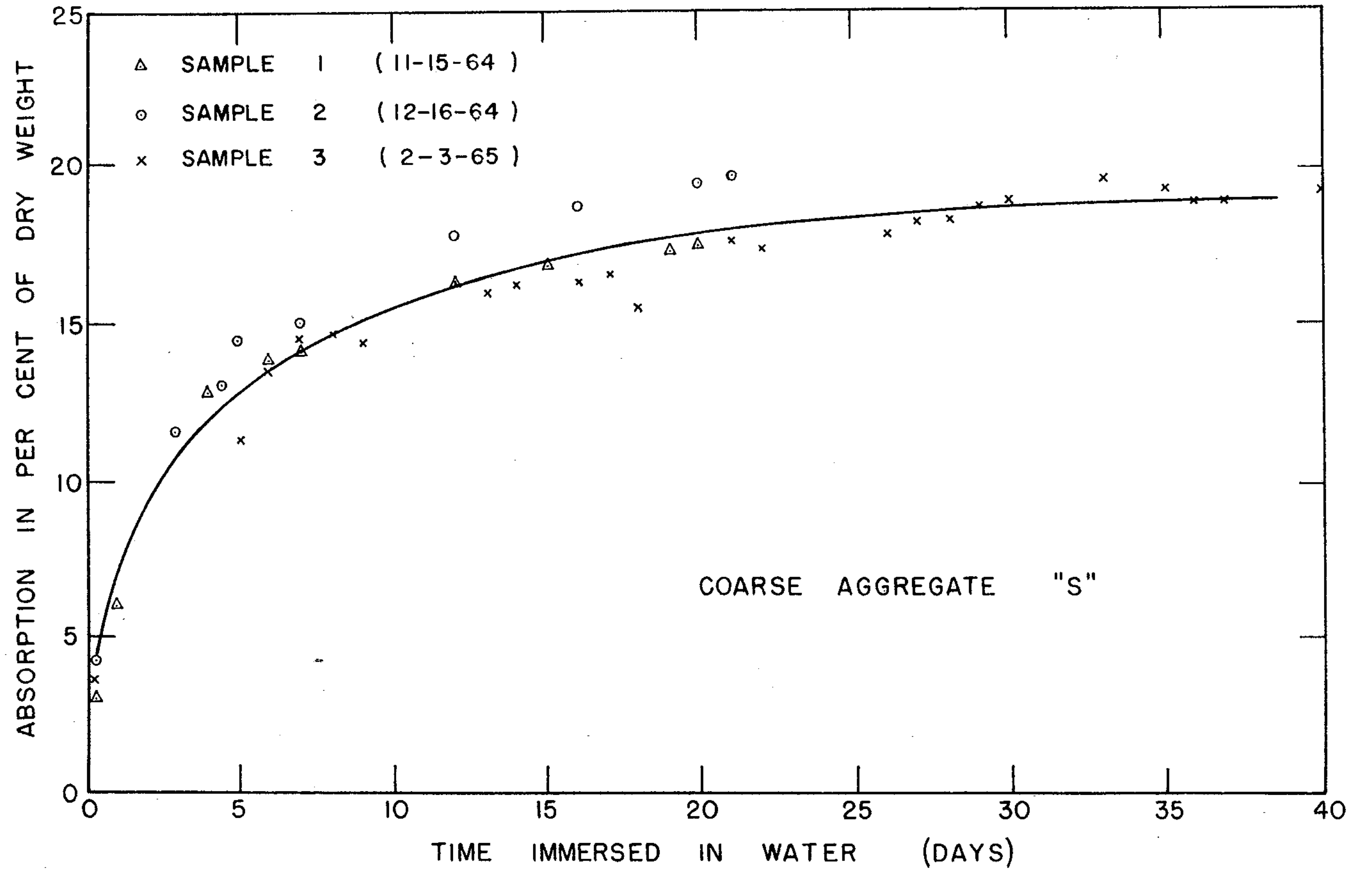

Fig. 6-1. Absorption-Time Curve for Aggregate S.

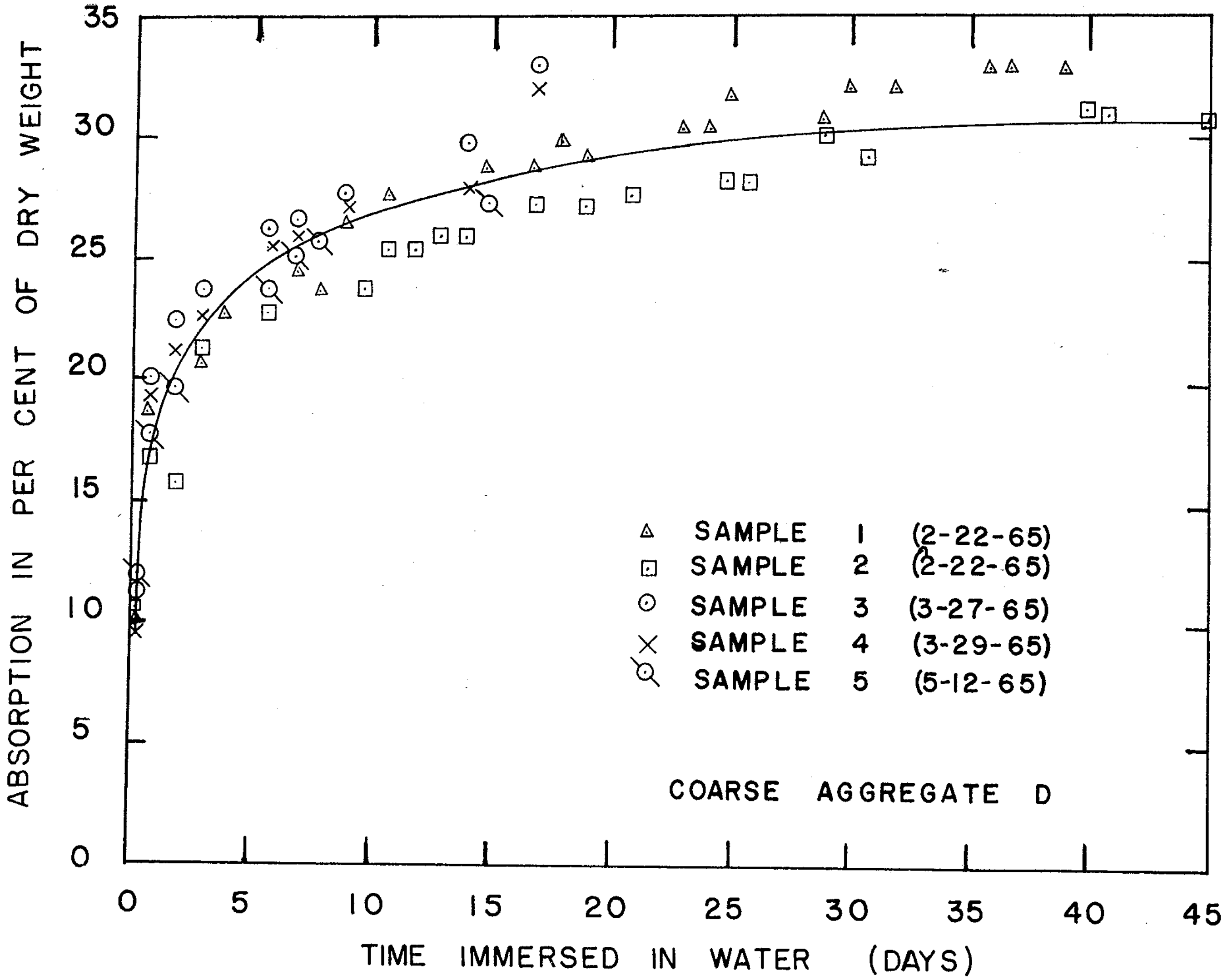

Fig. 6-2. Absorption-Time Curve for Aggregate D.

6.3 Results From Prior Research

Research conducted during the first year of this study is reported in Report 81-1 (3). In order to make this report more complete, aggregate absorption data previously obtained and reported in Report 81-1 are repeated here in Figures 6-1, 6-2, and 6-3. Also, the aggregate sieve analysis data are given in Table 6-2.

6.4 References

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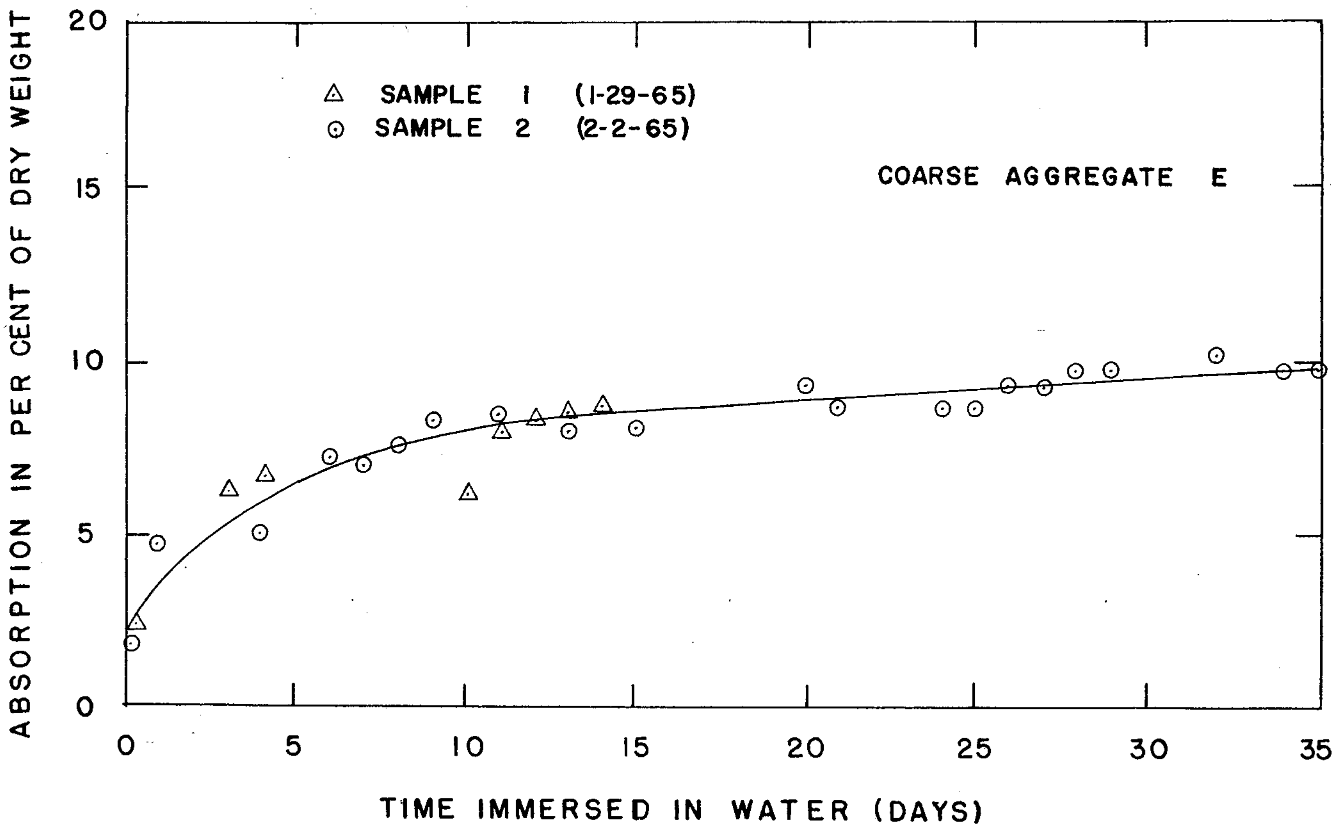

Fig. 6-3. Absorption-Time Curve for Aggregate E.

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TABLE 6.2. AGGREGATE SIEVE ANALYSIS DATA

	Cumulative Per Cent Retained				
Sieze Size	Coarse Agg. S	Coarse Agg. D	Coarse Agg. E	Coarse Agg. H	Fine Agg. H
¾ in.	0.6	0.0	0.2	12.1	
½ in.	29.6	15.2	12.3	39.4	
⅜ in.	63.0	61.8	46.8	65.3	
#4	93.2	98.5	100.0	95.8	0.4
#8	99.3	99.4	100.0	98.2	9.5
#16	100.0	100.0	100.0	100.0	23.4
#30					43.7
#50					83.5
#100					96.0

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