FUNDAMENTAL FACTORS INVOLVED IN THE USE OF SYNTHETIC AGGREGATE PORTLAND CEMENT CONCRETE

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

PREFACE

The primary objective of the synthetic aggregate research being conducted by the Texas Transportation Institute is to develop a recommended acceptance criterion for synthetic aggregates for use in all phases of highway construction.

This is the seventh report issued under Research Study 2-8-65-81, one of the synthetic aggregate research studies being conducted at the Texas Transportation Institute in the cooperative research program with the Texas Highway Department and U. S. Bureau of Public Roads. The first six reports are:

"Correlation Studies of Fundamental Aggregate Properties with Freeze-Thaw Durability of Structural Lightweight Concrete," by W. B. Ledbetter, *Research Report 81-1,* Texas Transportation Institute, August, 1965.

"Effect of Degree of Synthetic Lightweight Aggregate Pre-Wetting on the Freeze-Thaw Durability of Lightweight Concrete," by C. N. Kanabar and W. B. Ledbetter, *Research Report 81-2,* Texas Transportation Institute, December, 1966.

"Aggregate Absorption Factor as an Indicator of the Freeze-Thaw Durability of Structural Lightweight Concrete," by W. B. Ledbetter and Eugene Buth, *Research Report 81-3,* Texas Transportation Institute, February, 1967.

"Flexural Fatigue Durability of Selected Unreinforced Structural Lightweight Concretes," by J. C. Chakabarti and W. B. Ledbetter, *Research Report 81-4,* Texas Transportation Institute, July, 1967.

"Suitability of Synthetic Aggregates Made from Clay-Type Soils for Use in Flexible Base," by W. M. Moore, Richard S. van Pelt, F. H. Scrivner, and George W. Kunze, *Research Report 81-5,* Texas Transportation Institute, February, 1968.

"Performance Studies of Synthetic Aggregate Concrete," by C. E. Buth, H. R. Blank, R. G. McKeen, *Research Report 81-6,* Texas Transportation Institute, September, 1968.

ABSTRACT

This is an outline of practice in the use of structural lightweight aggregate concrete. A brief description of the types of lightweight aggregate is given. Properties of the aggregates which must be considered in selecting an aggregate, mix proportioning, and methods of achieving good workability and finishability of the concrete are considered. Placing and curing guides are discussed briefly.

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1. Introduction

1.1 Purpose

It has been said that "There is nothing in the world so constant as change." This most surely applies to lightweight aggregate concrete practices. In the past few years, as a result of research and experience, many changes have been made in the acceptance, design, mixing, placing, and quality control of synthetic lightweight aggregate concrete.

The objective of this report is to present a review of the state-of-the-art in the use of structural quality, synthetic lightweight aggregate, portland cement concrete as it applies to the highway system. Furthermore, this report is prepared from the viewpoint of interpreting the latest research results (both from TTI and others) in light of their application to the concrete mix designer and concrete inspector. This objective is in keeping with one of the phases of the over-all study involving synthetic aggregates which is titled "Preliminary Recommended Mix Design, Handling and Field Control Practices for Synthetic Aggregate Concrete."

1.2 Scope and Limitations

As this report is aimed primarily at field practices for the Texas Highway Department concrete mix designer and concrete inspector, it will be limited to the use of synthetic aggregate concrete for pavement and bridge structures. The materials involved include lightweight coarse aggregates (produced in Texas by the rotary kiln process) which are combined with naturally occurring fine aggregates, portland cement, and water to form portland cement concrete.

There are many reports, guides, and manuals in publication covering various facets of the use of synthetic aggregate concrete, including some manuals published by the Texas Highway Department (THD). This report will amplify these manuals and cover some of the areas not mentioned. Whenever possible and appropriate, THD manuals will be referred to in the text of this report.

1.3 Implementation Statement

It is recommended that implementation of this report be considered in the following manner:

1. A special summary report be prepared for distribution to THD field personnel responsible for the design, supervision of construction, evaluation of materials and the inspection of lightweight concrete structures.

2. Short courses should be held to acquaint field personnel with the characteristics of lightweight aggregates and the structures produced by them.

3. A slide and tape presentation or a sound film presentation should be prepared to cover the highlights of the report.

The above statements represent the combined opinions of the Study Contact Representatives and the authors and should not be construed as Departmental policy.

2. Materials

2.1 Portland Cement

Portland Cement is the binder that holds this composite construction material called concrete together. Lightweight synthetic aggregates can be used with all common types of cement. Type I cement is generally used for most structural purposes. Type II cement can be used when moderate heat of hydration is desired, such as a massive pour of a large footing or exceptionally thick slab. When high early strength is desired, such as precast prestressed applications, or when the ambient temperature is expected to be low then Type III cement may be used. Cement Types IV and V are generally available only on special order and are not considered in this report. Applicable specifications for the cement include the 300-D series (Hydraulic Cement),[1]* ASTM C150 (Portland Cement),[2] and ASTM C175 (air-entrained Portland Cement). Where close control of the air content is required, the use of air-entraining agents rather than air-entraining cement is recommended.[3]

2.2 Lightweight Synthetic Aggregate

General

There are many types of lightweight synthetic aggregate. These produce Portland Cement Concrete which may be divided into three broad categories[2]:

a. Low Density Concrete—unit weight between 20 and 50 pcf.

b. Intermediate Density Concrete—unit weight between 50 and 100 pcf.

c. Structural Lightweight Concrete—unit weight between 90 and 115 pcf.

The compressive strengths of these concretes range all the way from a few hundred psi for the low density concretes (used principally for insulation purposes) to in excess of 5000 psi for the structural lightweight concretes. This report is concerned only with this third class-structural lightweight concrete. According to ACI Committee 213[3] this concrete is defined as:

> Structural lightweight aggregate concretes are defined as concretes having a 28-day compressive strength in excess of 2500 psi (175 kgf/cm^2) and a 28-day, air-dry unit weight not exceeding 115 pcf (1850 kg/cm^3).

The aggregates which will produce concretes with these properties come from many processes. A partial list of synthetic aggregates found suitable includes:

Cinders
Expanded Slab
Expanded Shale
Expanded Clay
Expanded Slate
Sintered Aggregates

These aggregates vary widely in their properties, and the concrete produced from them may have different strengths and other properties.

*References are contained in Section 7.1 of this report.

National specifications governing the quality of these aggregates are, in the opinion of the authors, at best incomplete, although they do provide some significant guidelines. These specifications are given in ASTM C330.[2]

In Texas, to date, the only types of lightweight aggregates used in structural concrete for the Highway Department have been expanded clays and shales produced by the rotary kiln process.[4] Therefore, the remainder of this report will be concerned only with these types of lightweight aggregates.

Texas Highway Department Item 423,[5] which is the THD Specifications for lightweight aggregates for concrete structures, is updated regularly by means of special provisions. One of the latest of these special provisions is 423 . . . 008 in June of 1969. If a lightweight synthetic aggregate were tested under this provision, the following determinations will have been made:

		Texas	ASTM
(a)	Gradation (sieve analysis)	Tex-401-A	C136
(b)	Los Angeles Abrasion	Tex-410-A	C131
(c)	Freeze-thaw Test for Aggregates	Tex-432-A	
(d)	Potential Reactivity		C289
(e)	Friable Particles		C142
(f)	Loss on Ignition		C114
(g)	Compressive Strength	Tex-418-A	C39
(h)	Splitting Tensile Strength		C496
(i)	Drying Shrinkage	Tex-422-A	C157
(j)	Popout Materials		C151
(k)	Freeze-thaw Test for Concrete	Tex-433-A	C290 or C291
(l)	Absorption and Specific Gravity	Tex-433-A	C127
(m)	Unit Weight	Tex-404-A	C29
(n)	Pressure Slaking Test	Tex-431-A	

Tests (a) through (f) are acceptance tests for source qualification and should be performed in a random manner on at least each shipment of lightweight aggregate. Tests (l), (m), and (n) are field control tests and should be performed in a random manner but more frequently than the source acceptance tests. Tests (g) through (k) are to determine concrete performance using the particular mix design and aggregate.

In the following paragraphs some of the more important of the above aggregate properties are discussed.

Sieve Analysis

This, strictly speaking, is not a unique property as it can be easily altered. Yet it should be pointed out that proper gradation is important to the making of quality concrete, no matter what kind of aggregate is used. When making a sieve analysis remember that the aggregate pieces are light and often very dusty, which does influence the test. As pointed out in THD Bulletin C-11,[6] care should be exercised in running this test.

Los Angeles Abrasion

This test (Tex-410-A or ASTM C131[2]), designed to measure the aggregate resistance to impact, has been in use for a long time. Strictly speaking, the test does *not* measure abrasion resistance of the aggregate. Instead, it measures the aggregate's ability to withstand impact blows imported by several steel balls in a rolling cylinder. Such a measure is often referred to as "toughness." Thus it has been questioned in terms of its meaning and validity,[14] especially with lightweight aggregates.[15] In an attempt to obtain more meaningful test results on lightweight aggregates, the Texas Highway Department modified the tests (Test Method Tex-410-B[1]), but research results indicate that the modified test is no better in delineating quality than is ASTM C131.[16] However, the importance of having some means to assess an aggregate's abrasion resistance, hardness, and toughness is well established so until such time as other tests are developed, the Los Angeles abrasion test should continue to be used.

Freeze-thaw Tests for Aggregates

The mechanical action of expanding water by freezing in a restricted volume has long been a source of potential trouble in concrete. The ability of a given lightweight aggregate to accommodate this expansion is very important because the many pores or voids (see Section 2.6) in the lightweight aggregate often become wholly (or partially) filled with water. In an attempt to measure an aggregate's ability to withstand these forces, an aggregate freeze-thaw test was developed and recommended by TTI.[8] However, in those areas where concrete will not be subjected to freezing temperatures, there is no need to be concerned with this property and any aggregate freeze-thaw requirements could be logically waived.[8]

Absorption

This is a property which has only recently been given the attention it deserves. The amount of absorption of these aggregates is often many fold that of normal weight aggregates and thus the rate of absorption and degree of aggregate saturation become very important. The very fact that these aggregates are lightweight indicates that they must be full of tiny bubbles and pores (termed "blebs"). This bleb structure offers a path for water to slowly enter the aggregate over long periods of time (Figure 2-1). Note that the aggregates (shown in Figure 2-1, all of which were commercially produced in Texas) continue to absorb water for as long as a

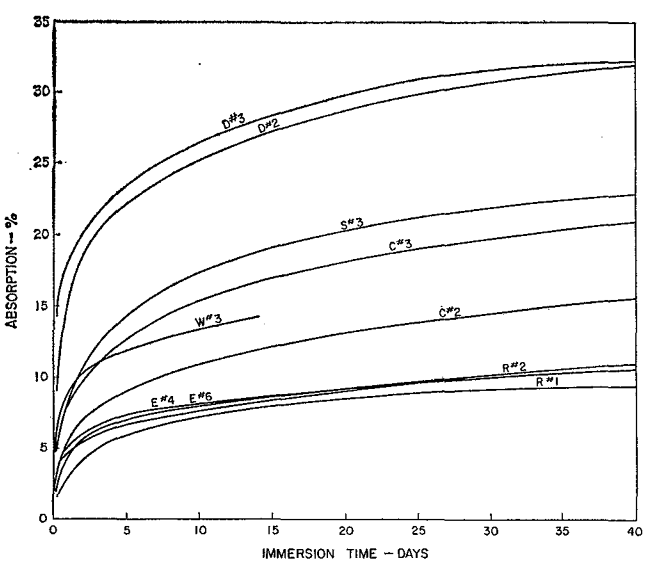

Figure 2-1. Absorption-time relationships for commercially produced lightweight aggregates.

month or more. *This fact cannot be over-emphasized!* It is this property that makes realistic determinations of net water-cement ratio almost impossible.

Due to the high total absorption of lightweight aggregates, the authors have found, as have others,[3] that it is often extremely difficult to accurately and repeatably determine the Saturated-Surface-Dry (SSD) absorption and SSD specific gravity, in accordance with THD Test Method Tex-403-A.[1] As a partial solution to this problem, the Bryant Method[7] of determining absorption-time curves for lightweight aggregates, as depicted in Figure 2-1, is recommended.

Absorption also influences the ability of lightweight concrete to resist freezing and thawing.[9] Two conclusions drawn by Buth and Ledbetter[9] were:

1. When tested under the prescribed conditions, wide differences exist between the freeze-thaw resistance of concretes made with the lightweight aggregates studied.

2. Under the conditions of prewetting imposed by the tests, those concretes whose aggregates had high absorption values and/or absorption rates were less durable.

Since publication of the above report, it has been found that the absorption per se does not actually influence the resistance of lightweight concrete to freeze-thaw. In a later report[10] it is shown that resistance to freeze-thaw is strongly influenced by the degree of saturation of the coarse aggregate (other factors held constant). Furthermore, the degree of saturation is a function of the rate of absorption of the aggregate and the length of time that water is available to the aggregate pores.

Present Texas Highway Department procedures call for prewetting the lightweight aggregate before use.[5] This is necessary as many of the particles, when dry, will pull excessive amounts of water out of the concrete mixture causing loss of slump and making it difficult to control the uniformity of the mixture. However, as can be seen by the foregoing, prewetting can be overdone. If the aggregates become too highly saturated with water prior to mixing, the resulting concrete, if exposed to freezing, may be nondurable (see Section 3.3 for further discussion). Therefore, lightweight aggregate prewetting should be carefully controlled and only the minimum amount of prewetting necessary for control of uniformity of the mixture should be permitted.

Unit Weight

According to ASTM C330[1] and THD Item 423,[5] the dry unit weight of the coarse fraction of lightweight aggregate shall not exceed 55 pcf. This maximum weight is placed in the specification, not as a quality control, but rather to insure that the dry unit weight of the concrete does not exceed 115 pcf for class Y concrete.* When using normal weight fine aggregate, it may be difficult to stay below 115 pcf concrete unless the dry unit weight of the coarse aggregate is less than 45 pcf.[11] Of course, the concrete unit weight is significantly influenced by the amount of cement, the moisture condition of the aggregate, and the amount of air entrainment. These factors are discussed in more detail in Section 3.1.

*See THD Special Provision 423 . . . 008.

Bulk Specific Gravity

Like the absorption, the specific gravity of lightweight synthetic aggregate is significantly influenced by its bleb structure. Therefore, it is extremely difficult, if not impossible, to accurately ascertain exactly when the pores are filled with water and the surface of the aggregate is dry (the condition known as saturated-surface-dry). As the pores in the aggregate vary in size from those readily discernible to the naked eye down to microscopic size, and as the aggregate contains closed pores as well as pores open to the surface, the bulk specific gravity is a function of the amount of water which has been able to penetrate into the pores in the time during which water and aggregate have been in contact. Quite often upon immersing a sample of lightweight synthetic aggregate into water some of the particles will actually float. As they soak up water, they then often sink. This indicates that the bulk specific gravity is less than one to start with and gradually increases as the pores become filled with water. Another factor complicating this property is that lightweight aggregate from each individual source is unique and often not at all similar to that from another source. However, some generalizations can be made.

According to ACI Committee 213[3]:

> The practical range of bulk specific gravities of coarse lightweight aggregates, corrected to the dry condition, is about ⅓ to ⅔ of that for normal weight aggregates.

All the lightweight aggregates commercially produced in Texas have dry bulk specific gravities within this range.[7]

Pressure Slaking Test

This test has been recently developed.[8] It is designed to indicate the amount of thermal transformation that has occurred during the burning process in the production of synthetic aggregates from raw clay or shale.

2.3 Normal Weight Aggregates

Present Texas Highway Department specifications require the use of natural sand fine aggregate and do not permit the use of lightweight fine aggregates.[12] The requirement for the use of natural sand fine aggregate accomplishes two desirable features in the construction of lightweight concrete. First, it increases the density of the mixture as the specific gravity of the fine aggregate is around 2.6. As a result, the mix becomes more viscous, and the lighter pieces of coarse aggregate are prevented from floating to the surface of the mix and interfering with finishing operations. Second, the use of the natural sand fine aggregate reduces the variability in workability and consistency of the mixture which would be caused by using lightweight fine aggregate of variable moisture content. This increases the ease of construction and the ease in which uniformity and consistency are maintained. The primary disadvantage to the use of natural sand fine aggregate is the increase in unit weight of the concrete. However, this does not appear to be a major disadvantage, and, according to personnel who have used lightweight concrete, the advantages far outweigh the disadvantage.

Current applicable specifications for natural sand fine aggregate for normal weight portland cement concrete are suitable in specifying the natural sand fine aggregate for lightweight concrete. These are Item 421[5] (latest provision) or ASTM C33.[2]

2.4 Admixtures

A complete discussion of the use of admixtures in lightweight concrete would require many, many pages. Admixtures are a complex subject, and one in which there is need for further information.

In general, the accepted procedure for admixtures in lightweight concrete is to require the use of air-entraining and cement dispersing agents. Current Texas Highway Department specifications require a total air content of 6 percent.[5]

The use of air-entrainment in lightweight concrete is almost mandatory. *Without the air-entrainment, due to the lightness of the coarse aggregate, difficulty in keeping the mixture from becoming segregated and in finishing operations is often encountered.* However, with air introduced, the workability of the mixture is increased; finishing is made easier; and the problem of segregation is reduced. This will be discussed in more detail later in this report. According to ACI Committee 213:[3]

> 3.2.1.5 Entrainment air content. Air entrainment in lightweight concrete, as in normal weight concrete, improves durability. Moreover, in concretes made with some lightweight aggregates, it is a particularly effective means of improving workability of otherwise harsh mixtures. The mixing water requirement is then lowered while maintaining the same slump, thereby reducing bleeding and segregation.

Recommended ranges of total air contents for lightweight concrete are:

Maximum Size of Aggregate	Air Content Percent by Volume
¾ in. (19 mm)	4 to 8
⅜ in. (10 mm)	5 to 9

At times there is a temptation to use a large proportion of natural sand in lightweight concrete to reduce costs, and then to use a high air content to meet weight requirements. Such a practice usually becomes self-defeating because compressive strength is thereby lowered 150 psi (10 kgf/cm^2) or more for each increment of one percent of air beyond the recommended ranges. The cement content must then be increased to meet strength requirements. Although the percentages of entrained air required for workability and frost resistance reduce the unit weight of the concrete, it is not recommended that air contents be increased beyond the upper limits given above, simply to meet unit weight requirements. Adjustment of proportions of aggregates, principally by limiting the normal weight aggregate constituent, is the safer, and usually the more economical way to meet specified unit weight requirements.

Concerning the recommended types of air-entrainment, the same general comments and specifications covering normal weight concrete should be followed when dealing with lightweight concrete. (See Item 437[5] and ASTM C260.[2])

The use of a cement dispersing agent is recommended. These agents will improve the workability, decrease the mixing water requirement, decrease the temperature rise during hydration of the cement, and act as a set retarder to maintain the mix in a plastic condition throughout placement operations.

A variety of cement dispersing or wetting agents, most of which are patented preparations sold under trade names, are commercially available. Generally, those admixtures produced from lignosulfonates are more difficult to control and to obtain desired results than the organic acid or polymer types of cement dispersing agents.[13] The manufacturers' recommended procedures and quantities should be used when incorporating one of these admixtures into a lightweight concrete mix. (See Item 437.[5])

3. Mixture Proportioning Criteria

3.1 Physical Properties

In general, the desired physical properties of any portland cement concrete include adequate strength and durability, proper workability, and finishability to permit economical construction, and a pleasing, functional appearance.

The physical property of strength has long been recognized as extremely important. Many studies have been made relating the strength of the concrete to the types of proportions of the various ingredients.[17, 18, 19, 20] In general, the achievement of design strengths of synthetic lightweight concrete presents no problem in Texas.[21] In fact, due to the pozzolanic nature of some of the synthetic aggregates, extremely high strengths have been achieved with nominal amounts of cement.[21]

Currently the Texas Highway Department requires that concrete used in structures achieve a certain 28-day compressive strength (5000 psi for class "Y" concrete[5]), and that concrete used in pavements achieve a certain minimum average flexural strength at an age of 7 days (650 psi, center-point loading).[22]

Should a design engineer wish to use synthetic aggregates for pavements, he should be cautioned concerning the use of the flexural test to control concrete strength. It has been reported:[23]

> The correlation of flexural strengths with either compressive strengths or split-cylinder strengths was poor, which further indicated the difficulty of using flexure as an index of strength and more particularly of tensile

strength. A comparison of bag-cured lightweight concrete with the bag-cured regular weight concrete showed that their compressive, direct tensile, and split-cylinder strengths were practically identical; but the flexural strength of the lightweight concrete was often 20 to 25 percent lower than the flexural strength of the regular-weight concrete. The obvious conclusion is that the flexural strength test is a poor indicator, often unduly restrictive and incorrect, of lightweight concrete strength and quality.

Thus, ACI Committee 213 states:[3]

> A number of studies have indicated that modulus of rupture tests of concretes undergoing drying are extremely sensitive to the transient moisture content, and under these conditions may not furnish data that is satisfactorily reproducible.

If the foregoing statements are accepted, where does this leave the concrete designer in terms of quality control of a pavement? In the authors' opinion, quality control of strength should be based either on compressive strength or on the more recent splitting-tensile strength in accordance with ASTM C496.[2] This test is less sensitive to transient moisture changes and yields valid and reproducible tensile strength data.[23] The test can be performed, using standard 6 in. × 12 in. cylinders, on a 100-kip capacity test machine, which in turn is small enough to be placed at the job site or in the residency laboratory.

3.2 *Workability and Finishability*

The workability of fresh concrete is one of its most important properties. Without proper workability it may be extremely difficult, if not impossible, to achieve all of the desired properties of hardened concrete.[3] An excellent discussion of the workability of concrete is given by Troxell et al.[24] and is repeated here:

> It is desirable that freshly mixed concrete be relatively easy to transport, deposit, consolidate, and finish and that it remain free from segregation during these operations. The composite quality sought, involving ease of placement and resistance to segregation, is termed 'workability.' The workability of concrete depends on a number of properties which cannot be satisfactorily measured; there is, in fact, no general agreement what all these properties are. Further, workability is a *relative* property; a concrete that is workable under some conditions may not be workable under some other conditions. The necessary workability may vary with the equipment for mixing, transporting, or consolidating or with the size and shape of the mass to be formed. For example, a rather stiff concrete suitable for massive construction could not be placed in narrow, deep forms filled with intricate reinforcement. Usually a workable concrete is plastic although under certain conditions of placement stiff concretes are usable and are therefore considered 'workable.'

The engineer should keep in mind that the specific gravities of the ingredients in lightweight concrete differ widely (1.00 for water, around 1.4 for the lightweight coarse aggregate, and around 3.15 for the portland cement), which promotes segregation, poor workability, and poor finishability. Thus, more fine aggregates and more air entrainment than generally required for normal weight concrete are recommended. Bulletin C-11[6] states:

> The amount of coarse aggregate will usually vary from 55 to 60 percent of the total amount of aggregates loose volume.

And another good rule of thumb is that workable mixes of lightweight concrete require 45 to 60 percent of fines by bulk volume.[25]

These amounts may be reduced slightly if normal weight fines are used. With its specific gravity of around 2.6, normal weight fine aggregate tends to hold the lighter coarse aggregates suspended in the mix, thereby improving workability and finishability. For this reason, the use of normal weight fines is recommended in all cases.

The main measure of consistency is slump. For most lightweight concretes, in order to control segregation, the slump should not exceed 3 in.[24]

For general guidance the *THD Bulletin C-11*[6] and the *THD Construction Manual*[26] offer excellent information and should be carefully read.

3.3 *Durability (Performance)*

Durability, as defined by ACI Committee 203,[27] 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.

This definition implies time. To be durable, the concrete must be able to perform satisfactorily in service throughout its design life.

As portland cement concrete has performed excellently for many years, engineers, rightly, have confidence in its durability, provided they use proven materials in the concrete. With the recent advent of synthetic, lightweight aggregates on the construction scene, the question of durability arises. In Texas, the first commercial use of lightweight aggregates by the Texas Highway Department was only around 15 years ago. And new synthetic aggregate plants have only recently been completed. What about the durability of concretes made from these new aggregates? Are there quality control tests to insure that the concrete will perform satisfactorily in service throughout its design life?

The answer is a qualified "yes." If the main environmental factor the concrete encounters — besides carrying loads — is alternate freezing and thawing, then there is a laboratory test for concrete freezing and thawing (ASTM C290[2]). If the main environmental factor involves surface abrasion, then there is no generally accepted standard test.

Without going into too much detail, it is the authors' opinion that there are four, interrelated, facets of this durability problem. They are:

1. Physical Durability. This is defined as the concrete's resistance to repeated internal stressing from cycles of freezing and thawing or external fatigue loading.

2. Chemical Durability. This is defined as the concrete's resistance to the various chemical actions occurring on, or in, the concrete during its service life.

3. Mechanical Durability. This is defined as the concrete's resistance to surface abrasion and wear.

4. Volume Change Durability. This is defined as the concrete's resistance to the detrimental effects of internal volume changes due to shrinkage and creep.

As mentioned above, all four of these facets are interrelated, and all should be considered when evaluating a particular concrete. Concerning the physical durability, it has been shown that quality, air-entrained concrete made with any commercially produced synthetic aggregate in Texas can be destroyed through freeze-thaw, provided the synthetic aggregate is nearly saturated with water prior to mixing.[10] Conversely, if the aggregate is dry enough prior to mixing the concrete, durable concrete can be produced from any commercially available synthetic aggregate in Texas today.[10] Compounding the problem is the fact that critical saturation (saturation sufficient to cause concrete freeze-thaw failure) can take from as little as one hour of aggregate sprinkling to as long as several months of aggregate innundation, depending upon the aggregate used.[10] This aspect is currently under investigation at the Texas Transportation Institute (as well as the effects of the degree of saturation at the time of freezing). Based on current reports, it is recommended that prewetting synthetic aggregate prior to concrete batching be held to a minimum, because prewetting can be overdone (see Section 2.2) where freezing temperatures are common.

Chemical durability and mechanical durability facets of the problem have not been studied in detail. Therefore, no over-all recommendations can be made at this time. However, no deleterious chemical effects and no detrimental mechanical effects have been noticed in lightweight concretes in service for several years. Thus, it may well be that these aspects are not significant if the concrete is sufficiently strong and durable against freezing and thawing. Further research is needed in these areas.

The fourth durability aspect—that of volume change durability—has received some attention by researchers. ASTM C 330[2] requires lightweight concrete of a specified mixture to have less than 0.10 percent drying shrinkage. This may not be adequate control and further study is definitely needed to establish shrinkage limits which will insure a durable concrete. Along this line, the drying shrinkage of any concrete is strongly a function of the curing practice followed, and as lightweight concrete often exhibits greater drying shrinkage than normal weight concrete,[3, 21] proper curing procedures should be carefully followed (see Section 6.2).

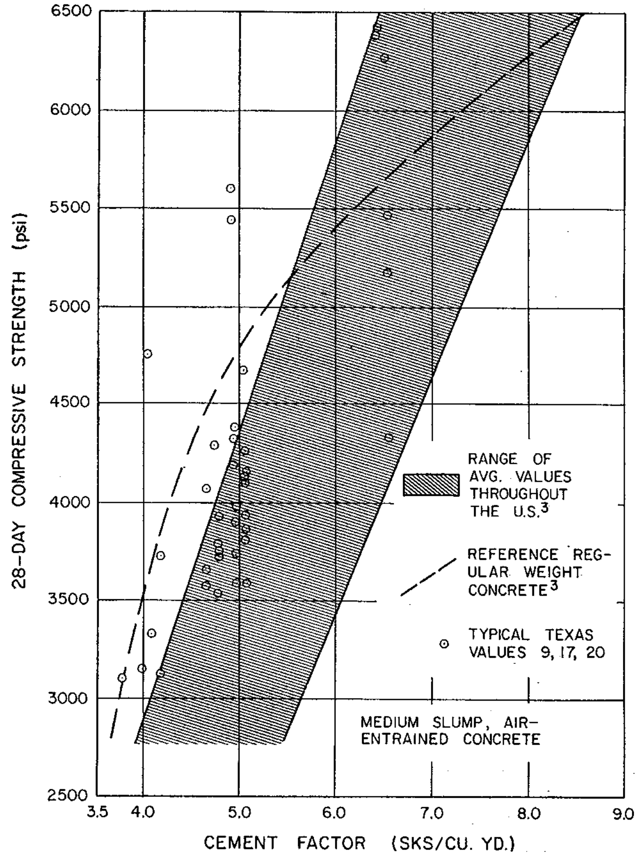

Figure 3-1. Relationship between 28-day compressive strength and cement factor for structural lightweight concrete.

3.4 Relationship Between Water and Cement

As mentioned in Section 2.2, the relatively high and variable absorption-time properties of lightweight aggregate make meaningful determinations of net water-cement ratio almost impossible to obtain. Thus, the designer is faced with the problem of how to proportion the concrete mixture to achieve the desired concrete strength and durability. To do this, there are many ways recommended by individuals and agencies. The one currently receiving the greatest acceptance is to compare cement factor (sks/c.y.) to compressive or splitting tensile strength.[3] Figure 3-1 shows the range of average compressive strength values vs. cement factor found throughout the United States,[3] together with some typical values reported for Texas concretes.[7,23,28] From these curves the designer can obtain some idea of required cement, although verification through trial batching is strongly recommended (see Section 4.1).

4. Proportioning and Adjusting Mixes

4.1 General Remarks

In the final analysis proportioning and adjusting lightweight aggregate concrete is a trial and error procedure. The best place to begin is the synthetic aggregate manufacturer's files. The manufacturer should be able to supply mix designs for various applications and these then can be adjusted to suit particular needs. If this information is not available, then a first trial must be made using what experience is available to determine proportions.

Several references are available to give guidance on a first trial batch design. The Texas Highway Department Construction Bulletin C-11 provides good guidance, as does the published "Recommended Practice for Selecting Proportions for Structural Lightweight Concrete," American Concrete Institute Standard 211.2-69. Either of these references are recommended for use.

4.2 Field Control

The air content, unit weight, and slump tests, as well as cylinders for quality control, should be taken at the beginning of each job's placement or each day's placement, as the case may be, and continued to be taken at regular intervals or when problems occur. This allows for immediate adjustments in mixes and reduces the chance of placing unsuitable concrete.

The air content should be determined by the volumetric method Tex-416-A Part B (ASTM C173), as this method gives the most reliable results.[3] If air content exceeds prescribed limits, strength test cylinders should be taken to insure quality.

Unit weight determinations may be made using Tex-417-A or ASTM C567.

Tex-415-A or ASTM C143 may be used to measure slump. Slump for most lightweight concrete applications should not exceed 3 inches. If the concrete is too wet (slump exceeds prescribed maximum value) the material should be rejected rather than allowed to dry up to meet specifications.

Cylinders for strength tests should be made in accordance with Tex-418-A (ASTM C192).

5. Mixing and Delivery

The standard procedures for mixing normal weight portland cement concrete are recommended when using lightweight concrete. ASTM C94[1] offers excellent guidelines for the use of ready-mixed concrete. In addition to C-94 for truck mixers, it is generally recommended that the mixers should be charged with about ⅔ of the total mixing water and with all of the lightweight coarse aggregates.[5] These ingredients should then be mixed for 60 seconds or until the initial water demand of the aggregate is reached. The cement, sand, air entraining admixture, and remaining water should then be added and mixed for an additional 3 minutes (approximately 100 revolutions). If desirable, the initial material charged into the mixer can include the sand. The change and sequence of the aggregates will not appreciably affect the end product. Prior to discharge, it is recommended that the mixer be rotated approximately 30 seconds at mixing speed to minimize segregation.

Also, for stationary mixers, the mix should be charged with ⅔ of the total mixing water and with all of the aggregates.[25] Mixing for 30 seconds or until initial water demand is satisfied is recommended. After the cement, air entrainment admixture, and remaining water is added, mixing should be continued for at least one minute in mixers of one cubic yard or less. Mixing time for larger mixtures should be increased 15 seconds for each additional cubic yard, or fraction thereof, of additional capacity.[23]

The amount of mixing prior to the introduction of portland cement is strongly dependent upon the absorptive characteristics of the aggregate (see Section 2.2). As various lightweight aggregates exhibit different absorptive characteristics, it is recommended that trial batches be made to determine the "feel" for the water requirements of the aggregate while in the mixer, to preclude a drastic change in slump or consistency of the concrete during mixing and placing operations.

6. Placing, Finishing and Curing

6.1 Placing and Finishing

This phase of the construction process of any type of portland cement concrete is extremely important, and there are many excellent references covering guidelines for the proper placing and finishing of concrete. The Texas Highway Department's *Construction Manual*[26] contains a complete chapter (Chapter 12) involving the placing of concrete including operation of the plant, inspection of materials and the plant site, the mix design, stockpiling, storage, equipment inspection, batching operations, spreading, placing, and finishing.

Problems relating to placing the concrete on hot dry days have been observed in many areas and should be recognized. Concrete temperature at the time of placement should not exceed certain specified values depending upon the type of structure. When constructing bridge structures the latest special provisions to Item 420 give specific instructions. When constructing concrete pavements every effort should be made to keep the concrete placement temperature below 90°F.

One general comment, or caution, is in order when discussing the finishing operations of structural lightweight concrete. As mentioned earlier in this report, the lightweight aggregate particles, being light, tend to float to the surface of the concrete and therefore sometimes hamper proper finishing operations. The impulse to increase the slump or to over-sand the mix should be avoided. The use of normal weight fines reduces this problem as does the use of air entrainment. It should be pointed out that structural lightweight concretes, properly designed, and containing adequate amounts of air entrainment and regular weight fines, present no additional difficulties over normal weight concrete to proper finishing.[3]

6.2 Curing

Upon completion of the finishing operations, any portland cement concrete should be adequately protected as soon as possible from loss of surface moisture. There is no substitute for good curing practice. In curing of structural lightweight concretes, one important facet of this material should be pointed out. According to Jones, et al.:[21]

> These curves indicate that the lightweight aggregate concretes shrink almost twice as much as the sand and gravel. The phenomena of shrinkage in concrete is for the most part caused by contractions of the cement paste due to drying.

From the foregoing, it is obvious that lightweight concretes may shrink significantly more than normal weight concretes, if the surface moisture is allowed to dry out. For this reason, it becomes extremely important to closely follow prescribed curing conditions, if not to increase the required curing time for lightweight concrete. To insure against the development of a "map-crack" surface, it is strongly recommended that longer curing times be used with lightweight concrete.

7. Appendix

7.1 References

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