EVALUATION OF SHRINKAGE-CRACKING CHARACTERISTICS OF STRUCTURAL LIGHTWEIGHT CONCRETE

by
R. G. McKeen
Research Assistant
Texas Transportation Institute
and
W. B. Ledbetter
Associate Research Engineer
Texas Transportation Institute

Research Report 81-11

Synthetic Aggregate Research
Research Study 2-8-65-81

Sponsored by
The Texas Highway Department
in cooperation with the
U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

October, 1969

TEXAS TRANSPORTATION INSTITUTE
Texas A&M University
College Station, Texas

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 eleventh 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 the U. S. Bureau of Public Roads. The first ten 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, and R. G. McKeen, *Research Report 81-6,* Texas Transportation Institute, March, 1969.
>
> "Fundamental Factors Involved in the Use of Synthetic Aggregate Portland Cement Concrete," by W. B. Ledbetter, C. E. Sandstedt, and A. H. Meyer, *Research Report 81-7,* Texas Transportation Institute, November, 1969.
>
> "A Sandblast Abrasion Test for Synthetic Aggregate Evaluation," by James T. Houston and W. B. Ledbetter, *Research Report 81-8,* Texas Transportation Institute, October, 1969.
>
> "Studies of the Thermal Transformation of Synthetic Aggregates Produced in a Rotary Kiln," by James T. Houston, H. R. Blank and G. W. Kunze, *Research Report 81-9,* Texas Transportation Institute, November, 1969.
>
> "Effect of Synthetic Aggregate Thermal Transformation on Performance of Concrete," by James T. Houston and W. B. Ledbetter, *Research Report 81-10,* Texas Transportation Institute, November, 1969.

In addition, a special report has been published under this research study. The report is:

> "A Recommended Synthetic Coarse Aggregate Classification System (Revised August, 1969)," by W. B. Ledbetter, B. M. Gallaway, W. M. Moore, and Eugene Buth, *Special Report,* Texas Transportation Institute, August, 1969.

The authors wish to thank all members of the Institute who assisted in this research.

The authors wish to acknowledge the guidance and assistance given by the advisory committee for this study. The members are as follows: (a) Texas Highway Department Personnel—Mr. Kenneth D. Hankins, Study Contact Representative and Research Area Representative; Mr. H. A. Sandberg, Jr., Materials and Tests Division Representative; and Mr. Louis White, Bridge Division Representative; (b) Bureau of Public Roads Personnel—Mr. Edward V. Kristaponis, Division Representative, and Mr. W. J. Lindsay, Regional Representative.

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

ABSTRACT

Shrinkage-Cracking Characteristics of Structural Lightweight Concrete

Tests were conducted to determine the effect of coarse aggregate type, cement content and curing environment on unrestrained volume changes and restrained shrinkage cracking behavior. Measurements of restrained shrinkage stress and ultimate tensile strength were made for purposes of comparing these properties with the above characteristics. Two synthetic lightweight aggregates, commercially produced in Texas and having widely different saturation characteristics were used along with a natural siliceous river gravel as coarse aggregates. After a five-day initial moist curing period, the specimens were placed in four different curing environments, a) 140°F 25 percent R.H., b) 73°F 50 percent R.H., c) 73°F 95 percent R.H., and d) 40°F 92 percent R.H. Cement contents of 5.0, 6.0 and 6.5 sacks/cubic yard were used. Unrestrained volume changes were measured on standard type specimens (3 x 3 x 11.25 in.). Cracking was evaluated as the number of cracks occurring on a specimen 4 x 4 x 48 in. with a No. 8 reinforcing bar through the center.

Using concrete made with one of the lightweight coarse aggregates, specimens were cast for measurement of restrained shrinkage stress. After 60 days, these specimens were loaded to concrete failure in tension and ultimate tensile strength was determined. The effective or usable tensile strength was greatly affected by the curing environment. Results indicated that both unrestrained shrinkage and concrete water loss relate to restrained shrinkage stress. Unrestrained shrinkage did not indicate cracking tendency while water loss provided an indication of cracking tendency.

TABLE OF CONTENTS

Page

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

1.1 General Remarks

The concrete construction industry today is consuming an ever increasing quantity of high quality aggregates in order to meet the growing demands of our modern society. As conventional natural materials have been depleted, the industry has made increased use of structural lightweight concrete. This has led to the development of many more sources of synthetic lightweight aggregates. Synthetic lightweight aggregates offer certain advantages, such as reduction of structural dead load, lower shipping costs and improved insulation, while in most cases developing conventional strength.

The use of synthetic lightweight aggregates has created a need for knowledge concerning fundamental and performance characteristics of concrete made with these materials. In all types of construction it is essential to produce a product that is durable. The materials used must perform the required function under all conditions to which they are exposed. The acceptance of new materials then depends on their ability to perform as designed under the conditions they encounter. In the past two decades a large amount of research has been devoted to characterizing synthetic aggregates. Generally, research work has consisted of relating fundamental parameters of the material to performance characteristics. For the last five years a research study at Texas A&M University, conducted by the Texas Transportation Institute, has been devoted to classifying synthetic aggregates in terms of expected service performance. As a portion of the study, work for this report has been devoted to evaluating these materials in terms of their volume change durability.

Volume changes of portland cement concrete are generally classified into three categories: thermal, creep, and shrinkage. The first group includes those dimensional changes resulting from variations in the ambient temperature. Creep as defined by ACI-ASCE Committee 323 is inelastic deformation dependent on time and resulting solely from the presence of stress and a function thereof (1*). The same committee defined shrinkage as contraction of concrete due to drying and chemical changes, dependent on time but not on stresses induced by external loading. This investigation is primarily concerned with the shrinkage of certain concrete materials and its relationship to their cracking characteristics.

Shrinkage is an inherent property of portland cement concrete made with Type I cement. It is a well-known fact that hardened portland cement paste occupies less volume than the individual components before mixing (2). If a thick specimen of hardened paste, saturated with water, is exposed to dry air, it becomes severely cracked from temporary stresses arising from inequality of shrinkage between inner and outer parts of the specimen during the course of drying (3). This fundamental characteristic renders portland cement paste useless as a construction material. In order to restrict the shrinkage of cement paste, particles of relatively inert material are added to it, thus reducing shrinkage to a point that concrete becomes a practical construction material. Since the inert material, or aggregate, exhibits little or no shrinkage, the shrinkage of concrete is primarily a property of the cement paste and must be considered in the design of concrete structures.

Although the presence of aggregate limits the shrinkage of cement paste, cracking may still occur. Cracking is the real problem involved in shrinkage of concrete, due to the development of tensile stress in the material. The durability is affected by the entry of water through cracks, which corrodes reinforcing steel, leaches out soluble components, and accelerates deterioration due to freezing and thawing (4). Other shrinkage related problems are warping, prestress loss, reduced effective tensile strength (5), and excessive deflections in unsymmetrically reinforced members (6).

1.2 Purpose of the Investigation

There is a great deal of work reported in the literature concerning the shrinkage of concrete as influenced by various parameters (summarized in Chapter II). The problem being considered in this report is the relationship between the unrestrained and restrained shrinkage characteristics and the cracking characteristics of the particular materials under study. The purpose of the work is to develop a means of rating or classifying these materials in terms of their performance by values obtained in standard tests already available. In this investigation the performance is being measured as the resistance to cracking when restrained. Once this information is available, it may be determined if the present methods of evaluating shrinkage of concrete are adequate and which types of failure, taking the form of cracking, may feasibly be attributed to the shrinkage of the concrete.

1.3 Objectives

The objectives of this research were:

1. To determine the effects of coarse aggregate type, cement content and curing environment on unrestrained volume changes and restrained shrinkage cracking behavior in structural lightweight concrete.
2. To measure the stress development due to restrained shrinkage, determine tensile strength characteristics, and relate them to results of objective 1.
3. To compare the results of objectives 1 and 2 and develop methods of predicting cracking characteristics of the materials studied.

1.4 Conclusions

The following conclusions were reached based on the test results presented in Chapter IV.

1. For the conditions studied, coarse aggregate type and cement content did not appear to significantly influence unrestrained volume changes.

---

*Numbers in parentheses throughout this report refer to corresponding items in the list of references.

2. Curing conditions into which concrete was placed after initial moist curing significantly influenced the unrestrained volume changes (Figure 4-3).
3. A relationship was found between unrestrained shrinkage measured on standard type specimens, and restrained concrete shrinkage stress. The environment appeared to have only a small influence on this relationship (Figure 4-7).
4. The unrestrained shrinkage-water loss data indicated changes in coarse aggregate type caused significant differences in unrestrained shrinkage per unit of water lost (Figure 4-5). This may be explained by differences in the capillary water content of the cement paste as the aggregate is varied while the gel water content of the paste was not affected by changes in aggregate characteristics.
5. The unrestrained shrinkage-water loss data indicated that increases in cement content reduced the capillary water content of the concrete (Figure 4-6).
6. For specimens drying in the mild (73°F, 50 percent) and hot (140°F, 25 percent) environments, increased temperature resulted in lower unrestrained shrinkage for a given amount of water loss. This could be due to the reduction in surface tension of water associated with temperature increases (Figure 4-6).
7. Concrete water loss related well to restrained shrinkage stress for aggregate R concrete. This relationship was influenced significantly by curing environment (Figure 4-8).
8. The ultimate tensile strength of aggregate R concrete at 60 days of age did not appear to be significantly influenced by the curing environments studied (Figure 4-9).
9. The effective tensile strength was controlled by the curing environment and the ultimate tensile strength (Figure 4-9).
10. Concrete restrained shrinkage cracking varied with coarse aggregate type, curing environment and cement content (Figures 4-10 and 4-11).
11. Restrained shrinkage stress and concrete cracking continued to increase after shrinkage was constant due to the continued hydration and therefore increased strength of the cement paste (Figure 4-13 and Section 4.2.1).
12. Concrete water loss provided an indication of restrained shrinkage cracking behavior (Figure 4-14) for the materials studied, while unrestrained shrinkage did not.
13. It may be tentatively concluded that higher coarse aggregate porosity and rate of saturation characteristics are associated with a greater tendency of concrete to crack.

1.5 Recommendations

It is recommended that future investigations attempt to:

1. Verify unrestrained shrinkage and water loss as indicators of restrained shrinkage stress for other proportions and materials than those used in this study.
2. Verify crack prediction by use of concrete water loss for other proportions and materials.
3. Predict reductions in tensile strength due to restrained shrinkage in structural members using data in Figures 4-7 and 4-8.
4. Study the unrestrained and restrained volume change and cracking behavior under alternating climatic conditions in order to evaluate the influence of more realistic environments.
5. Investigate the influence of sudden temperature drops and the tensile stresses that would be superimposed on restrained shrinkage stresses in order to develop truly meaningful design parameters.
6. Summarize the state-of-the-art with regard to concrete shrinkage and shrinkage related cracking.

1.6 Implementation Statement

As this phase of the study is continuing, no immediate implementation is proposed at this time. However, as the results are promising, this study should be continued with the goal of determining if a shrinkage requirement should be recommended for concrete pavement.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to present and discuss the present state of knowledge concerning the shrinkage and cracking of concrete. Due to the volume of literature in the field of concrete in general and in the study of shrinkage and cracking in particular, only certain references have been included. It is felt the material cited provides a foundation from which to develop a study of the shrinkage-cracking behavior of concrete. For purposes of discussion and investigation, the numerous investigators have defined shrinkage in terms of various types of shrinkage. Although there is some variation found in the literature, the following discussion generally agrees with the current nomenclature.

2.2 *Types of Volume Changes Involved in Shrinkage*

2.2.1 Plastic Shrinkage

The term plastic shrinkage has been rather loosely used but generally refers to shrinkage or cracking occurring within the first few hours after placing. Two schools of thought have developed to explain the causes of plastic shrinkage. One explanation is that it stems from contraction of the fresh concrete mass resulting from rapid drying. Reduction in volume caused by differential settlement of fresh concrete is the other explanation. It has been suggested (7) that the two types of plastic shrinkage often resulting in plastic shrinkage cracking be separated for clarity. The first type mentioned involves tensile stresses while in the second case shear stresses produce cracking (7).

Cracks resulting from rapid drying are a common problem where climatic conditions cause heavy evaporation loss of mixing water. Lerch (8) assumes that cracks are likely if the rate of evaporation exceeds the rate at which bleeding water rises to the surface. Ravina and Shalon (7) found that complete prevention of evaporation immediately on casting eliminates cracking, although cracking is not a direct function of water loss, evaporation rate, or shrinkage. These results have been confirmed by other investigators (9). The other school of thought attributes plastic shrinkage cracking to differential settlement of the fresh concrete caused by obstacles such as large aggregate particles or reinforcement (10, 11). Tuthill (12) reported plastic shrinkage cracking on the surface of concrete footings even when flooding was applied almost as soon as the concrete was in place. On the basis of field experience, he suggested this cracking may result from a false set or some other cement characteristic as the principal factor.

Plastic shrinkage cracks (sometimes extending through slabs) may severely damage structural concrete. Although this problem is not confined to high air temperature regions, close attention should be given to curing methods when a high evaporation rate is likely. The problem of settlement in the fresh mass might be minimized by close control of placing procedures such as vibration, tamping, etc., which has not been studied to date. There is still much room for investigating the plastic shrinkage characteristics of concrete and mortars. No significant agreement as to its causes has been reached by investigators.

2.2.2 Autogenous Volume Changes

Volume changes due to causes other than loss or gain of water, rise or fall of temperature and external load or restraint are termed autogenous (4), preset or setting volume changes since they are self-produced by the hydration of the cement. Troxell and Davis (4) pointed out the following major variables as important: (a) composition of the cement (affecting the rate and nature of chemical reactions and type of reaction products), (b) amount of original mixing water (affecting the rate of early reactions, porosity of the paste, and the availability of free pore water), (c) temperature conditions (affecting the rate of reaction), and (d) time (affecting the extent of reaction).

Neville (13) indicates there are two simultaneous phenomena causing autogenous volume changes. First the combination, cement plus water, results in a reduction in the volume of the system. This contraction is of the order of one percent of the absolute volume of the dry cement. At early ages this contraction may be offset since the solids form a structure and free water is utilized in the formation of new solid hydration products as well as in causing expansion of the gel. Continued hydration uses all free water and begins to remove loosely held water from the gel, causing it to collapse. When the expansion is greater than the contraction a net increase in volume will be observed. At later ages the contraction becomes the dominant factor as the free water is depleted. This explanation of expansion at early ages is generally accepted (2,4,13,14). Specimens stored in water may continue expanding for several years since the pore or free water is constantly replaced (2). In a situation where the free water is limited to the excess mixing water expansion ordinarily ceases soon after placing as more and more water is bound chemically in the hydration process.

2.2.3 Carbonation Shrinkage

The term carbonation shrinkage designates a decrease in volume of a specimen of cement paste or concrete that occurs during or after a period of drying as a result of chemical reaction between the hydration products of portland cement and carbon dioxide (15). Although the carbonation of hydrated cement has been studied for some time (16-21), its connection with shrinkage has been hypothesized only rather recently.

There are primarily two reactions that take place involving carbon dioxide (2):

$$(1)\quad Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

and

$$(2)\quad 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 3H_2O$$

The first reaction results in a small change in volume. The second reaction exhibits some significant volume reduction under certain conditions. The mechanism is not fully understood at this time. Powers (15) has presented a hypothesis to explain carbonation shrinkage. He attributes the reduction of volume to the dissolution of calcium hydroxide crystals while the crystals are under pressure, and deposition of calcium carbonate in places where carbonate is not under pressure. This theory does not offer water loss as a causative factor in carbonation shrinkage.

Shrinkage due to carbonation does not occur at 100 percent relative humidity or below some minimum value. It reaches a maximum in the region of 55 percent. As shown by Verbeck (21), when a specimen is dried to a definite internal humidity in the absence of carbon dioxide, a certain reduction of volume, or of length, is observed. If the specimen is then transferred to an atmosphere of CO_2 having the same humidity, further shrinkage occurs provided the internal humidity is less than 100 percent. The amount of shrinkage due to extensive carbonation after drying is about equal to that produced by drying and thus the total of the two consecutive shrinkages is about double that of the drying shrinkage alone (15). Carbonation usually does not penetrate far into a concrete mass, and therefore its effects are limited to the surface. In masonry walls and thin slab construction, however, it may be a significant factor. These structures are particularly vulnerable to carbonation shrinkage when they are on the interior of buildings in which the relative humidity is in the middle range.

2.2.4 Drying Shrinkage

Drying shrinkage is the term applied to the dimensional changes taking place in cement paste or concrete when it is exposed to the normal atmosphere. It is generally associated with loss of water from the specimen and hence a reduction in weight. According to Powers (22) there are three mechanisms which are accompanied by shrinkage:

(1) change in surface tension of the colloidal gel particles,

(2) change in pressure between gel particles, and

(3) change in capillary tension.

Powers has solved the equation representing the total volume change resulting from the above three causes for real cement gel. He found that change in surface tension accounts for 10 to 20 percent of the total drying shrinkage. Change in capillary tension may produce no more than 20 to 30 percent, occurring only for water-cement ratios greater than about 0.40. The major portion of drying shrinkage is the result of change in the pressure between gel particles. The distance between gel particles is dependent upon the forces acting on them. The amount and nature of the water between layers largely controls the spacing and therefore the volume.

Ordinarily, the drying shrinkage of concrete is taken to be all of the contraction of the material when exposed to the normal atmosphere. It is important to recognize that volume changes occur due to causes other than drying, as discussed previously. Naturally the total volume change of the material is the only practical way to consider shrinkage in design work. In most cases the values of shrinkage reported include the drying and carbonation shrinkage. Current laboratory procedures for evaluating shrinkage usually provide for the first measurement to be made after a specified curing period. Most of the effects of plastic shrinkage and autogenous volume changes are thus practically eliminated. The comparison of data from several sources should not be made without information to clarify which types of shrinkage and volume change were measured. From a practical point of view it seems that the net overall volume change is the most important design consideration. From this statement then it seems obvious that most methods used for evaluation of shrinkage should attempt to measure the net shrinkage. Net shrinkage is usually approximated by moist curing the material (which effectively prevents all shrinkage) and beginning measurements at the end of the curing period.

2.3 Factors Affecting Shrinkage

2.3.1 Materials

Cement—Primary cement characteristics influencing shrinkage are fineness of grinding and gypsum content in relation to chemical composition (3). The fineness of cement is important since the presence of coarse particles results in incomplete hydration of the cement. Any unhydrated cement in the gel structure tends to reduce shrinkage by restraining the contraction of the gel structure surrounding it. Lerch (23) demonstrated that shrinkage of pastes made with a given cement varied with the gypsum content. His results indicated that it was possible to find an optimum proportion producing the least shrinkage. This proportion varied with the chemical composition of the cement. Lerch and others have shown that mortars deficient in gypsum may shrink 50 percent more than ones made with the same cement having the optimum proportion of gypsum. Gypsum is added to retard quick setting of cement due to formation of calcium aluminate hydrates. In the process, a calcium sulphoaluminate hydrate, $3CaO \cdot Al_2O_2 \cdot 3CaSO_4 \cdot 32H_2O$, is formed (24). Under appropriate conditions this reaction is accompanied by expansion and therefore leads to limited shrinkage compensation.

Since shrinkage in concrete is primarily a property of the cement paste it follows that an increase in cement content increases shrinkage. Several investigators have studied the influence of cement type on shrinkage with conflicting results. These workers have found the effect of cement type diminishes in practical concrete mixes.

Water—The total quantity of water in a concrete mix seems to be the major factor affecting shrinkage (25). The relationship between water loss and shrinkage depends on the capillary porosity of the material. Water loss from the capillary pores is not accompanied by shrinkage. Thus the initial water loss (capillary water) occurs without contraction. Once the capillary water is evaporated and adsorbed water begins evaporating shrinkage is observed. This is illustrated in Figure 2-1, which was first published by Menzel (26).

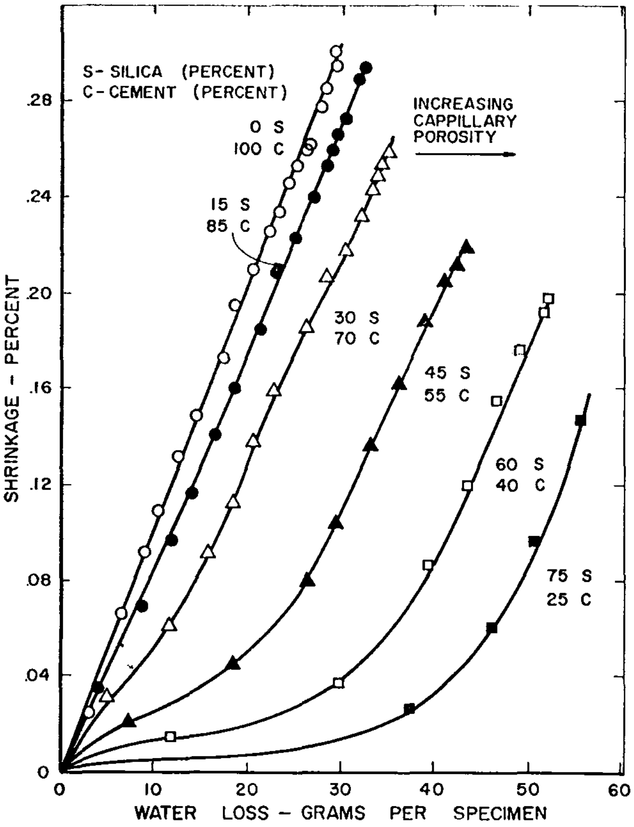


Figure 2-1. Relationships between water loss and shrinkage (Menzel, Ref. 26).

These curves show the relationship between shrinkage and water loss for a series of specimens ranging from neat cement to a mixture composed of 25 percent cement and 75 percent pulverized silica. The specimens had been cured seven days at 70°F.

Powers (3) concludes that the shrinking and swelling of cement is controlled by those water molecules within the range of the force field of solid surfaces, i.e. adsorbed water. Therefore, shrinkage from water loss depends on how much of the loss is capillary water and how much is adsorbed water. In the case of concrete the water in the pores of aggregate particles does not affect shrinkage since it is not wthin the influence of the gel surfaces.

Aggregates—As previously stated, one of the principle functions of aggregates (particles of rock or other reasonably inert material embedded in cement paste) is to restrain the shrinkage of portland cement paste to a point that the concrete becomes a practical material. Carlson (27) hypothesized and Pickett (28) later confirmed the importance of the restraining effect of aggregate. Pickett showed theoretically and experimentally that the quantity of aggregate rather than size and gradation is the important parameter with respect to shrinkage. This is illustrated in Figure 2-2 by Powers using Pickett's data (3). The conclusions reached were, (a) first shrinkage is greater than any subsequent expansion or contraction resulting from moisture change; (b) at a given aggregate content the shrinkage is approximately proportional to water-cement ratio; (c) after first shrinkage, subsequent volume changes are approximately independent of water-cement ratio. The restraining effect of a particular aggregate is also dependent on its elastic properties. The less compressible the particles, the more the shrinkage is restrained. Powers (3) has pointed out that maximum size of aggregate influences shrinkage since aggregate volume may vary with maximum size.

The use of lightweight aggregates in concrete generally increases the shrinkage. Shideler (29) found that shrinkage was as much as 30 percent higher for some lightweight aggregate concretes as compared to natural gravel concrete, in relatively low strength ranges (3000 psi). In the higher strength range (4500 psi) studied, he found the values were not significantly different. Similar results were obtained on concrete made with Texas lightweight aggregates (30). The replacement of lightweight fine aggregate with natural sand results in a reduction of shrinkage (31,32).

Shrinking aggregates are one of the most detrimental situations that may arise in structural concrete. Usually the effects cannot be controlled by adjusting mix proportions (33). Shrinking aggregates encountered in South Africa led to rapid deterioration of the concrete (34). Certain rock types have been identified as shrinking aggregates but the mechanism remains to be explained. Although shrinking aggregates are apparently not a widespread problem, they have been found around the world.

The presence of clay in commercial aggregates may have a significant influence on the shrinkage of concrete made with the aggregate. Most likely the clay material is distributed as flocs throughout the cement paste (3). Due to the characteristic shrinkage of the clay material upon drying and the volume reduction of rigid aggregate particles, the shrinkage may be greatly increased. Hveem and Tremper (35) reported that concrete made with dirty sand may shrink twice as much as concrete made with the same sand washed clean. They found that unwashed coarse aggregate gave as much as 70 percent more shrinkage than when thoroughly washed. A good correlation between shrinkage and sand equivalent value for the fine aggregate used in the concrete has been reported (36), thus supporting previous conclusions concerning the effect of clay.

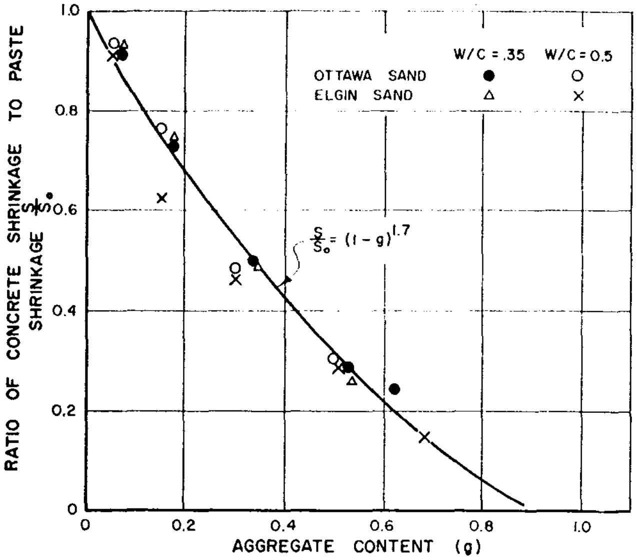


Figure 2-2. Influence of aggregate content on shrinkage ratio (Power, Ref. 3).

Houston (37) recently completed an investigation of the effect of the degree of thermal transformation on selected properties of synthetic aggregates. This study was based on six aggregates made under various conditions in a rotary kiln for each of two raw materials. For the materials tested and the processing parameters used the shrinkage of the concrete was not significantly affected.

Admixtures—With the widely accepted use of chemical admixtures in concrete and the knowledge of their beneficial effects, it is imperative to also consider the side effects. Chemical admixtures are generally thought of as materials other than water, aggregates and portland cement (including special types) that are used in concrete, and are added at some point in the mixing process. It has been reported that a given admixture used in concrete made with a particular aggregate type may result in an increase of 50 percent or more in shrinkage over another concrete containing the same admixture but made with a different aggregate type (38). This particular problem has not been widely studied and there is little information available in the literature. With respect to shrinkage, the statement above indicates that some degree of caution should be exercised in the use of chemical admixtures in concrete.

2.3.2 *Curing*

The conditions under which cement pastes and concrete are allowed to cure are important considerations in the study of shrinkage. A prolonged moist curing period would allow more complete hydration of the cement. More complete hydration of cement results in fewer unhydrated cement grains and therefore increased volume changes since they provide restraint when present. However, at the same time more structure will have developed in the cement paste increasing its strength and stiffness. These results lead to a lowering of the rate of creep or relief of stresses. The overall result is generally thought to be a material more likely to crack if restrained although conflicting results have been reported. In practice the prolonging of moist curing is rather unimportant from shrinkage considerations.

Use of steam curing provides a material that shows practically no volume change with variations in moisture content while severely reducing strength (3). Menzel (26) reported that blending silica powder with cement yields a steam cured product with normal strength and about half the shrinkage of similar concrete normally cured without the addition of silica.

2.3.3 *Environment*

Temperature and Humidity—The mechanisms controlling volume changes due to variations in moisture content depend on the amount and nature of water in the specimen. Although the total quantity of water at the time of mixing is easily controlled, that which remains is a function of the rate of evaporation. It is known that the shrinkage is greater for concrete having the greater water loss. Concrete cured in water or around 100 percent relative humidity shows no contraction and often expands. At lower humidities the shrinkage increases as relative humidity decreases. It also should be recalled that carbonation shrinkage reaches a maximum value in the humidity range around 55 percent. The major effect of temperature is its effect on rate of evaporation with regard to shrinkage.

Wind—Hansen (39) studied the influence of wind on creep and drying shrinkage. These tests were conducted on small specimens of cement mortar having a large ratio of exposed surface to volume. In this way any effect of differences in drying should be more pronounced than it would be in structural concrete members. The results show that there is little difference in weight change, shrinkage and creep of cement mortar specimens exposed to wind (5 meters/sec.), and specimens stored in calm air. Therefore it may be concluded from these tests that the effect of wind velocity on creep and drying shrinkage of structural concrete members is insignificant.

2.3.4 *Size and Shape*

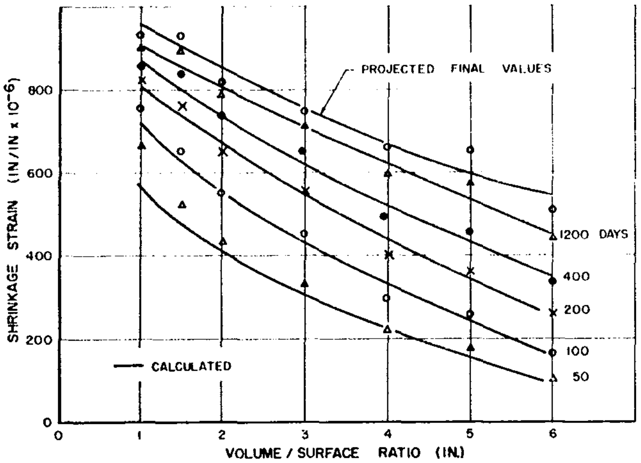


Figure 2-3. Variation of shrinkage with volume/surface ratio (Hansen and Mattock, Ref. 40).

The major portion of the shrinkage of concrete is associated with the movement of internal water out of the specimen. The moisture is attracted by the gel surfaces within the specimen and is therefore highly viscous with respect to movement to the surface. Internal moisture moves toward the surface very slowly. If the distance the moisture is required to move is increased, it follows that the movement takes longer and so does the associated contraction. Significant differences may be obtained if only a portion of the surface area is exposed to drying (27). Results reported by Hansen and Mattock (40) indicate the degree of correlation between shrinkage and volume-to-surface ratio is sufficient to warrant its use in practical design work. Both the rate and final values of shrinkage decrease as the member becomes larger. Figure 2-3 shows some of the data presented by Hansen and Mattock. The investigators pointed out that the conclusions should not be extended to other materials and testing conditions without confirming that they are valid by testing.

2.3.5 *Restraint*

When mortar or concrete is in some way restrained (such as introduction of reinforcing steel) the shrinkage is reduced. Restraint of shrinkage results in higher tensile stresses than would otherwise be encountered. If the increase in stresses exceeds the tensile strength of the mortar or concrete, cracking will occur. All materials do not respond to restraint to the same extent. Richie (41) presented results that indicated the response of masonry mortars to restraint is influenced by strength. The introduction of restraint will result in a material more prone to cracking since it is accompanied by increased tensile stresses.

2.3.6 *Consolidation*

The influence of consolidation on the shrinkage of concrete was studied and reported by Heaton (42). The results indicated that no significant difference in shrinkage occurred due to various degrees of consolidation. Although the results show shrinkage is not significantly affected, the compaction does significantly influence strength and durability of the concrete.

2.3.7 *Mixing and Retempering*

In tests reported by Polivka (43) the influence of continued mixing and retempering were studied for concretes made with several California aggregates. Retempering refers to the addition of additional mix water necessary to attain proper workability after prolonged mixing. For the tests reported, significant increases in shrinkage accompanied continued mixing and retempering.

2.3.8 *Summary*

The following is a listing of the parameters that are generally considered to be the major factors influencing the shrinkage behavior of concrete.

(a) cement composition, in particular the gypsum content

(b) amount and pore structure of cement paste

(c) amount (volume) and maximum size of aggregate

(d) compressibility of the aggregate

(e) cleanliness of aggregates with regard to clay

(f) exposure conditions, such as humidity, volume to exposed surface ratio, and time of exposure

(g) physical restraint of the material, such as reinforcement and external friction

(h) chemical admixtures employed

(i) unit water content

2.4 Cracking of Concrete

2.4.1 *General*

The cracking of concrete has been a subject of interest to designers for many years. In many applications cracking may not be detrimental. However, in concrete pavements, bridge decks, and many other structural applications, cracking may lead to extensive deterioration and failure of the structure to perform as designed. Fundamental material characteristics related to cracking as well as means for their evaluation are necessary to provide designers with the tools for crack prevention or control.

2.4.2 *Unrestrained Shrinkage-Cracking of Concrete*

The microcracking of concrete has been the subject of several publications in recent years (44-48). Hsu, et al, have reported that shrinkage of concrete induced cracking at the coarse aggregate mortar interface (44). These results have been confirmed (48) and the extent of cracking found to increase with shrinkage. This work is in agreement with that reported by Pickett some time ago (50). Hansen investigated the subject and found no cracks after several years of exposure to a dry atmosphere (49). It should be pointed out, however, that Hansen's work involved a high quality granite aggregate while Hsu, et al, used a mixed gravel. From these investigations it may be concluded that in many situations microcracking of concrete results solely from shrinkage stresses in the material, although not in every case.

The importance of microcracking of concrete is primarily due to its influence on strength properties of the material. The mechanism of fracture in concrete under uniaxial tensile or compressive stress begins with the spreading of microcracks (51,52). The importance of microcracking is not considered in the design procedures presently used. The reloading tests reported by Isenberg (52) indicate that in design work, neglect of short term preloadings may be unsafe due to microcracking. There is no practical method for predicting the microcracking of concrete under various situations at this time.

The above discussion is concerned with the internal cracking of concrete due to shrinkage. In some cases the microcracking continues to such an extent that macrocracks occur in the material. In unrestrained concrete (one without reinforcement or fixed ends) macrocracking can only result from differential volume changes of the material. Shrinkage depends primarily on the movement of internally held water to the surface and its loss by evaporation. As pointed out by many investigators this movement is a slow process. After years of exposure shrinkage will penetrate only a short distance into a concrete mass. For this reason differential tensile stresses may develop as the center portion restrains the shrinkage at the surface. This type of cracking may also occur in thin slab construction where only one side of the slab is exposed to drying. Sudden changes in temperature or temperature gradients produce cracking very similar to shrinkage cracking in concrete. Like shrinkage, exterior temperature changes are transferred to the interior slowly. A rapid drop in temperature of only 20°F would result in a tensile stress in the skin of about 400 psi (53). Considering the skin of concrete is under tension due to shrinkage, the addition of only moderate temperature stresses may contribute to cracking.

2.4.3 *Environmentally Induced Cracking*

Cracking that results from the interaction of concrete with its environment is seldom desirable. There is no dependable method of predicting the extent of the material-environment interaction. Several of the mechanisms are understood and means of avoiding cracking are readily available. Mather (54) listed six causes of environmentally induced cracking as follows: (a) unsound cement, (b) frost suspectibility of cement paste, (c) alkali-aggregate reaction, (d) plastic shrinkage, (e) corrosion of embedded metal and, (f) sulfate attack. Only plastic shrinkage is to be considered in this study. It is normally associated with areas exhibiting a high rate of evaporation as discussed in section 2.2.1. Although plastic shrinkage cracking can usually be eliminated by flooding soon after placing, it has been known to occur even when evaporation was prevented (12). This observation suggests that perhaps the rate of evaporation is not the only cause of plastic shrinkage.

The influence of the environment may be extended to include cracking of concrete due to restrained shrinkage. Since the temperature and humidity largely control the amount of shrinkage that may be realized in the field, they must also relate to stress developed due to restrained shrinkage. When a concrete mass undergoes drying and is prevented from deforming, stresses develop in the material. These stresses will result in cracking of the material if they exceed its tensile strength or if, when superimposed on the working loads, the tensile strength is exceeded. The influence of a normal field environment is very difficult to evaluate. It is known concrete takes up water much more easily than it looses water making average conditions meaningless with respect to shrinkage considerations. At this time there is no reliable method of evaluating the influence of a normal environment on concrete due to its characteristic wet-dry cycling.

2.4.4 *Summary of Factors Influencing Cracking*

The following list of factors were taken from the references indicated. They refer to cracking due to causes other than externally applied loads and are based on tests of conventional natural aggregate concrete. Main factors influencing cracking were listed by Carlson (55) as a) extent of shrinkage, b) degree of restraint, c) concrete tensile strength, d) extensibility or the concrete flow under sustained load, and e) time or the rate of shrinkage. Concrete mix parameters that influence cracking and their effect are listed below.

(a) Prolonged moist curing is believed to result in concrete that is more prone to cracking (3) although conflicting results have been reported (55).

(b) Aggregate type influences cracking through its effect on the shrinkage strain and tensile strength.

(c) Increases in cement content are associated with a greater cracking tendency, believed to result from reduced creep (4).

(d) Up to ¾ in. greater maximum size aggregate reduces cracking; beyond this size the differences are small.

(e) Air entrainment may result in increased cracking where it is accompanied by higher shrinkage and lower ultimate tensile strength.

CHAPTER III

EXPERIMENTAL METHODS

3.1 Strength Tests

Compressive strength tests were made on two six by twelve in. cylinders from each batch of concrete for purposes of control. The specimens were moist cured 14 days prior to testing. Testing was performed in accordance with ASTM C39-64. The data were taken to provide an indicator of different properties of the material from those normally observed.

3.2 Variables

3.2.1 Coarse Aggregates

The concrete specimens used for unrestrained shrinkage and restrained cracking were made using three coarse aggregates each combined with the same fine aggregate. Specimen descriptions are in section 3.3. Two synthetic lightweight aggregates were used. Aggregate R is a semicoated expanded shale that has low water absorption characteristics. Aggregate D is an uncoated expanded shale that has high water absorption characteristics. Aggregate H is a natural siliceous gravel known to have a good service record, included primarily as a reference. Pertinent aggregate data are presented in section 5.1. The synthetic lightweight aggregates were saturated prior to batching for a period of time sufficient to allow 25 percent of the internal voids to become saturated (56).

3.2.2 Cement Content

Unrestrained shrinkage and restrained cracking characteristics were observed on specimens made with three different cement contents. It has been reported in the literature that the cement concrete does not significantly influence shrinkage of practical concrete mixes. This parameter was varied primarily to establish the relationship of cement content to the cracking characteristics for the material tested. The variation of cement was studied under only one environment. Cement contents of 5.0, 6.0 and 6.5 sacks/cubic yard were used.

3.2.3 Environmental Conditions

The atmospherically controlled rooms in the McNew Laboratory at Texas A&M University were used to provide four conditions of temperature and humidity for this investigation. The facilities include a constant readout chart that enables researchers to monitor environmental conditions throughout a long time test. Further description of the facilities is given in section 5.2. The four conditions used in the study are given in Table 3-1.

TABLE 3-1. ENVIRONMENTS

Environment Designation	Temperature (°F)	Relative Humidity (percent)
mild	73	50
wet	73	95
cold	40	92
hot	140	25

The relative humidity of the cold room was measured throughout the tests with a wet bulb-dry bulb sling psychrometer since that room has no humidity control. There was no variation from the measured relative humidity throughout the test.

3.3 Test Descriptions

3.3.1 Organization

The data taken for this investigation were obtained primarily from three methods using three different specimen types. Unrestrained volume changes and restrained shrinkage cracking were evaluated for all variables under study as shown in Table 3-2, giving batch designations. The batch designations reflect the curing environment (M, H, C, W), coarse aggregate type (D, R, H) and cement content of the mixture (5.0, 6.0, 6.5) in sacks/cubic yard. Concrete weight loss due to evaporation of water was measured on all batches in the mild environment and on aggregate R concrete in the hot environment using the unrestrained shrinkage specimens.

TABLE 3-2. TESTING PROGRAM

Environment	Aggregate		
	D	R	H
mild (M)	MD6.5	MR6.5	MH6.5
	MD6.0	MR6.0	MH6.0
	MD5.0	MR5.0	MH5.0
hot (H)	HD5.0	HR5.0	HH5.0
cold (C)	CD5.0	CR5.0	CH5.0
wet (W)	WD5.0	WR5.0	WH5.0

3.3.2 *Unrestrained Shrinkage Specimens*

Specimens used for the measurement of unrestrained shrinkage were 3 x 3 x 11.25 in. having a 10-in. gage length between stainless steel gage points mounted in the ends in accordance with ASTM Method C157-67T. The method of measuring length changes and equipment used are those suggested by the above mentioned standard method.

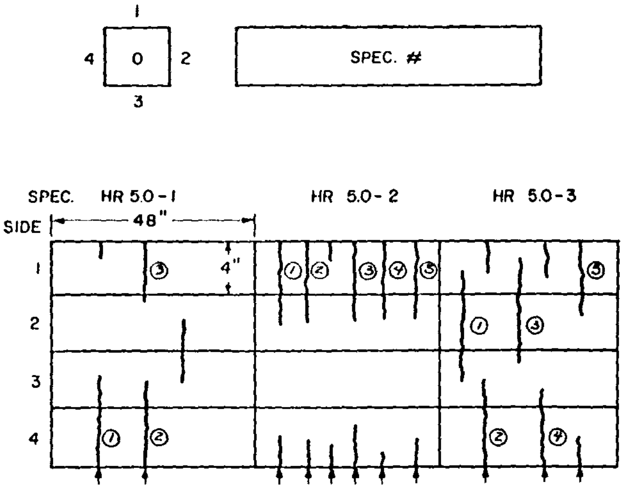
3.3.3 *Restrained Cracking Specimens*

The specimens used to evaluate the cracking characteristics of the materials were 4 x 4 x 48 in. with a one-in. diameter deformed reinforcing bar mounted along the specimen centerline. This type specimen was developed in a pilot study for the purpose of comparing structural lightweight concretes on the basis of their cracking behavior when restrained. The specimens were placed in the molds in accordance with ASTM Method C192. The cracking behavior reported as the number of transverse cracks, was recorded through visual inspection of the specimens periodically. Both transverse and longitudinal cracking patterns were recorded for each specimen. Figure 3-1 is a typical data sheet for crack evaluation, illustrating the method of counting cracks.

3.3.4 *Direct Tensile Specimen*

The direct tensile test specimen reported by Ledbetter and Thompson (57) was used to measure stress development with age due to restrained shrinkage. After 60 days of drying the specimens were loaded in uniaxial tension to concrete failure in order to determine the total tensile strength of the material. The test specimen consist of a thick-walled steel tube upon which electrical strain gages are mounted and protected by a brass sleeve around the tube; and the tube is encased in a specimen of concrete. The brass sleeve in addition to moisture proofing the gages, serves to reduce the cross-sectional area of the concrete, and thereby insures concrete failure at the point where the gages are mounted (57). For a complete description of the technique the reader is referred to Reference (57).

Concrete was cast around six of the instrumented bars from one batch of concrete prepared as discussed in section 5.3. Six specimens for unrestrained shrinkage determination were also made. Three specimens were placed in the hot and three in the mild environments. Strain measurements were taken periodically on the specimens beginning immediately after placement.



DATE 5/28/69 AGE 212 DAYS

NUMBER OF CRACKS ACROSS FULL WIDTH OF ONE SPECIMEN FACE = 3+5+5

AVERAGE 4.3

Figure 3-1. Crack evaluation sheet.

3.4 Constants

Throughout the preparation and testing certain parameters were maintained as constant as practicable. The mixing sequence and procedures for testing the fresh concrete were constant throughout. Mix data are shown in section 5.5 for each batch of concrete. One shipment of Type I portland cement was used in all mixes. The volume of coarse and fine aggregates was held constant. Each of the aggregates used required a different amount of mix water to provide a given workability. Therefore, a relatively wide range of slump (2-5 in.) was allowed in the concrete batches in order to achieve about the same water content for each mix.

The air content of the fresh concrete was maintained between 5.0 and 6.0 percent for all batches, determined by the pressure method. Specimens for unrestrained shrinkage, restrained cracking and direct tension measurements were all cured 24 ± 2 hours in the molds covered with plastic sheets. At approximately one day of age they were removed from the molds and placed in a moist curing environment (73°, 95-100 percent) for four additional days of curing. After the total of five days initial curing the specimens were placed in the environments discussed previously.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Results

4.1.1 *General*

The data to be presented were obtained primarily from three test methods. They were a) an unrestrained volume change test similar to the ASTM Method C157-67T, b) a restrained cracking test, and c) a direct tensile test, all described in Chapter III. The cement content, coarse aggregate type and environment were deliberately varied while other parameters were maintained as constant as practicable.

4.1.2 *Statistical Considerations*

Since it is physically impossible to hold the constants truly invarient, some measure of their variability must be provided before one can safely consider them

TABLE 4-1. STATISTICAL DATA

Parameter	n	x	σ	CV
Specimen gage length (in.)	54	10.1584	0.063	0.62%
Unit water content (lbs./cubic yard)	19	290.5	21.4	7.4 %
Total aggregate content (percent absolute volume)	19	67.6	1.8	2.7 %
Air content (percent absolute volume)	19	5.5	0.27	4.9 %

constant in an analysis. The statistical measures of standard deviation and coefficient of variation are shown in Table 4-1 for several of the constants of this study.

The values shown in the table were arrived at by using the following equations:

$$\bar{x} = \frac{\Sigma x_i}{n} \quad \ldots \ldots \ldots \ldots \quad (4\text{-}1)$$

$\bar{x}$ = mean of observation x_i, where $i = 1,2,3 \ldots n$

n = number of observations

$$\sigma^2 = \frac{\Sigma(x_i^2) - (\Sigma x_i)^2/n}{(n-1)} \quad \ldots \ldots \quad (4\text{-}2)$$

$$\sigma = (\sigma^2)^{1/2} \quad \ldots \ldots \ldots \ldots \quad (4\text{-}3)$$

σ = standard deviation

$$CV = \frac{\sigma}{\bar{x}}\,(100\%) \quad \ldots \ldots \ldots \quad (4\text{-}4)$$

CV = coefficient of variation

It is assumed the parameters presented in Table 4-1 may for practical purposes be represented by some form of normal distribution curve from which the statistical values are determined. The standard deviation expresses the degree of uniformity or scatter about the mean value for all measurements. The coefficient of variation is simply the standard deviation expressed as a percent of the mean value.

The variation as indicated by the parameters is not considered large enough to warrant further consideration in analyzing results. Other constant parameters not shown in Table 4-1 were determined to have such low variation that it was not necessary to analyze them statistically.

4.1.3 *Control Tests*

In order to provide a means of detecting irregularities in the materials prepared for this investigation, 14 day compressive strength determinations were made on two six-by-twelve in. cylinders from each batch (Figure 4-1). The bars for the 5.0 sack/cubic yard concrete represent the average of eight specimens from four batches while those for the 6.0 and 6.5 sack/cubic yard batches represent the average of two specimens from one batch. The shaded portion indicates the range of values.

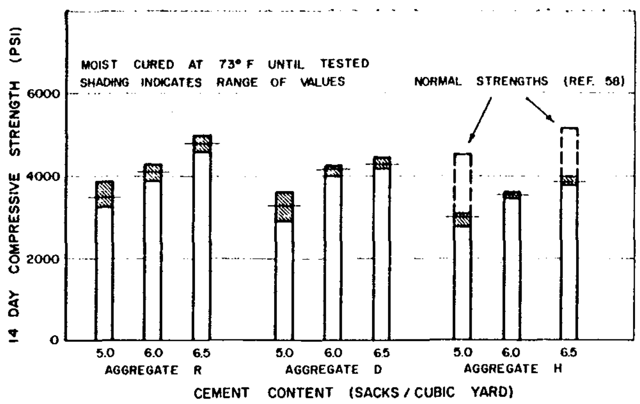


Figure 4-1. Concrete compressive strength data.

All compressive strengths are considered as "representative" with the exception of the following.

The compressive strength for the aggregate H concrete was lower than values normally observed (58). Inspection of the material revealed that most of the coarse aggregate was coated with fine material. Mechanical analyses, when washed, indicated that the fine material amounted to only about one percent by weight. It was concluded that the fine material coated the coarse aggregate particles and caused a reduction in strength by hampering the development of paste aggregate bond. While the amount of fine material was sufficiently large to cause a significant strength reduction, on the basis of previous investigations (36), it was not believed to have influenced unrestrained shrinkage behavior.

The compressive strength shown for the aggregate D concrete at 6.5 sacks/cubic yard is not believed to be representative of the material in the other specimens made from that batch. Due to a malfunction of the moist curing facilities, the compressive strength specimens were placed at 50°F 95 percent for a significant portion of their curing period and thus exhibited reduced strength at 14 days of age. All other specimens from the batch were removed to the appropriate curing environment during the malfunction period.

4.1.4 *Unrestrained Volume Changes*

The unrestrained shrinkage values measured in this study as a function of curing environment are given in

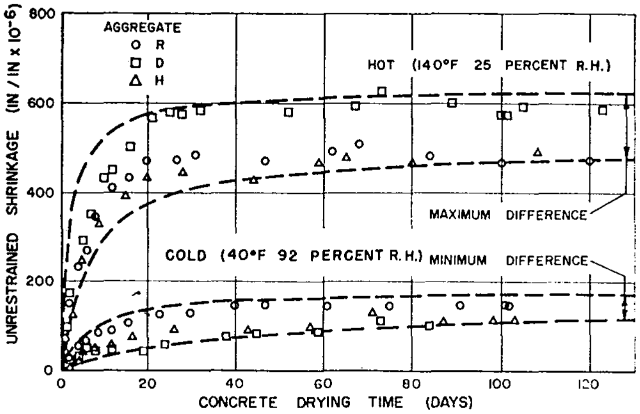


Figure 4-2. Limits of volume change for the environments studied.

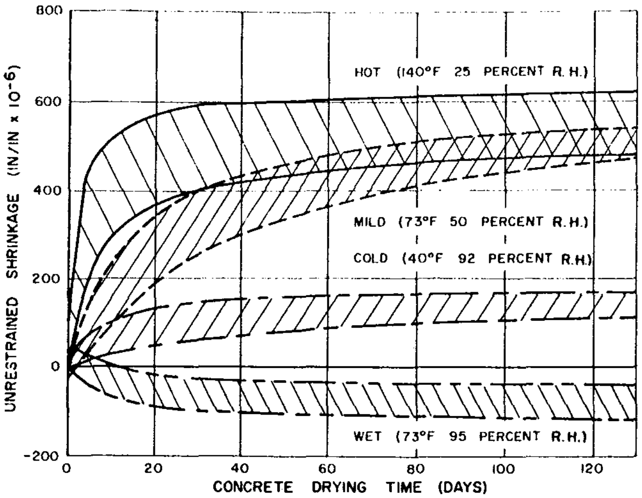


Figure 4-3. Unrestrained shrinkage data.

Figues 4-2 and 4-3. The data shown were corrected for thermal volume changes which were encountered in moving the specimens from moist curing to the cold and hot environments. Methods used and thermal properties recorded are shown in section 5.4. The environment into which the specimens were placed produced significant differences, as well as influencing the aggregate-to-aggregate differences as shown in Figure 4-2. The cold environment resulted in the least aggregate-to-aggregate difference while the hot environment produced the largest. However, for the methods and equipment used in this work, greater than approximately 100 in./in. x 10^{-6} may be regarded as a significant difference.

Three different lightweight coarse aggregates were investigated in each environment. Cement contents of 5.0, 6.0 and 6.5 sacks/cubic yard were used in the mild environment while 5.0 sacks/cubic yard only was used in the other curing environments. Thus it is concluded from these test results that the values were not significantly influenced by either the coarse aggregate type nor by the cement factor used (although in the hot environment there was an apparent aggregate effect). The only variable investigated that produced significant differences in unrestrained shrinkage was the curing environment, as illustrated in Figure 4-3. All data points fall between the curves plotted by selecting the proper constants for the equation,

$$\epsilon_s = \frac{\epsilon_{s_\infty} t}{N_s + t}$$

where,

ϵ_s = unrestrained shrinkage strain (in./in. x 10^{-6})

ϵ_{s_∞} = ultimate shrinkage strain (in./in. x 10^{-6})

N_s = age at which $\epsilon_s = 1/2\ \epsilon_{s_\infty}$, (days)

t = any time after drying begins, (days),

which has been used by Hansen and Mattock (40). In order to achieve a better fit to the data, a constant was added to the equation for the lower limit of the mild environment data and the upper limit of the moist environment data.

From the bands shown in Figure 4-3 it is clear that the environmental conditions are vital factors in controlling the rate of volume change as well as the final value. The possibility of the ultimate shrinkage strain in the mild environment being greater than that in the hot environment exists for the bands of data shown. It is apparent from this information and other data presented in section 4.1.5 that in some cases, if not all, the ultimate shrinkage strain in the mild environment exceeds that in the hot environment. This point is primarily of fundamental interest and is discussed further in the next section.

As mentioned above the rate at which volume changes occur is controlled by environmental conditions. When concrete is restrained from shrinking by the presence of reinforcing steel, the rate of shrinkage is very important as it relates to the amount of stress relief through creep. This importance is illustrated in sections 4.1.6 and 4.1.8.

4.1.5 Concrete Water Loss on Drying

Water loss determinations were made on specimens of each coarse aggregate in the mild environment at cement contents of 5.0, 6.0 and 6.5 sacks/cubic yard and on one batch of aggregate R concrete at 5.0 sacks/cubic yard in the hot environment. Data shown in Figure 4-4 illustrate that water loss varied from about 2.2 to 7.5 percent of the specimen weight after initial moist curing. The water loss that occurred was influenced by both coarse aggregate type and cement content. For the methods used the differences shown in Figure 4-4 can be regarded as significant. Accuracy was to the nearest gram in something over 3000 grams of total weight for the specimens used.

Data shown in Figure 4-5 illustrate the influence of coarse aggregate type on the shrinkage-water loss relationship. The influence is believed to result from changes in the amount of water not associated with shrinkage (capillary water), represented by the initial flat portion of the curves in Figure 4-5. Examination of the curves reveals that nearly all of the differences between the curves occurs during the first 100 in./in. x 10^{-6} of shrinkage. Thus the amount of water loss associated with early shrinkage was greatly influenced by the type of coarse aggregate, while the later water losses associated with continued shrinkage were

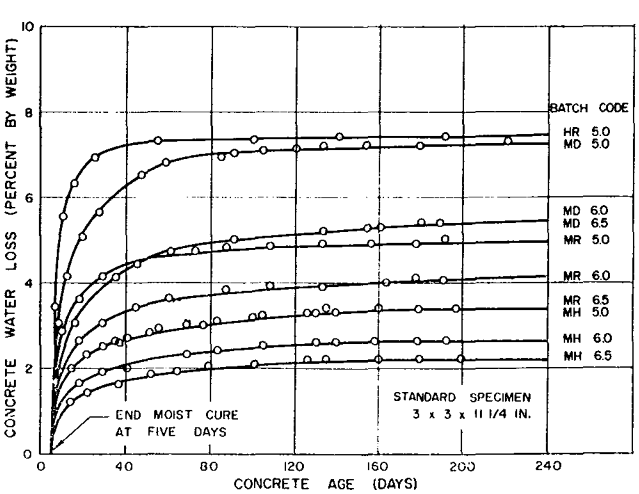


Figure 4-4. Concrete water loss on drying.

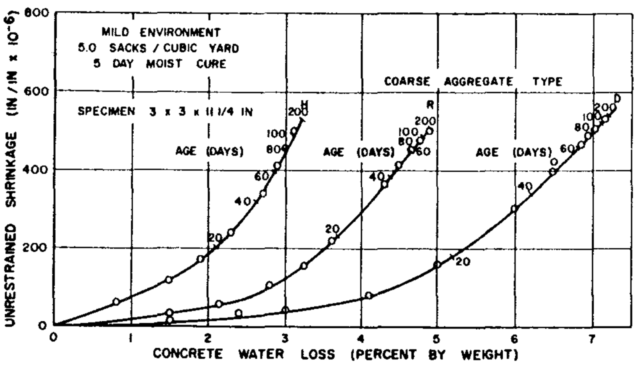


Figure 4-5. Influence of the coarse aggregate on the shrinkage-water loss relationship.

not significantly different for the different aggregates. An interesting comparison arises with 100-minute degree of saturation (56) and data shown in Figure 4-5. The 100-minute degree of saturation values are 0.29, 0.08 and $\simeq$ 0 for aggregates D, R, and H respectively. The differences in water loss associated with coarse aggregate type were due to saturation characteristics of the coarse aggregate (see section 4.2.3) and the cement gel structure was not significantly altered with respect to its water content and distribution, although the capillary porosity was affected. The fact that the unrestrained shrinkage for all specimens used in Figure 4-5 lies in the narrow band of the mild environment (Figure 4-3) supports this conclusion.

The shrinkage-water loss relationship as affected by cement content and drying conditions is shown in Figure 4-6 for aggregate R concrete. Again, due to the accuracy of the measurements, all differences can be regarded as significant. An important point is the difference in unrestrained shrinkage for the same cement factor for a given amount of water loss as influenced by the curing environment. For instance, at a water loss of 4.5 percent, unrestrained shrinkage values for the 5.0 sack/cubic yard concretes are 170 and 410 in./in. x 10^{-6} for the hot and mild environments respectively. It is believed the reason for such a significant difference is the reduction in surface tension of water as temperature increases (59). The water is evaporated more easily and involves much less surface tension at the internal surfaces of the material, resulting in less shrinkage per unit of water evaporated. Hansen illustrated that the reduction of relative humidity (50 to 25 percent) would not increase shrinkage (2). Thus if over a period of time the same quantity of water is lost from two specimens of concrete, that in the higher temperature environment should exhibit the least shrinkage. However, it should be pointed out clearly that when concrete is restrained, as it invariably is in reinforced concrete structures, the rate of shrinkage becomes much more important than the absolute volume change (age is indicated on the curves).

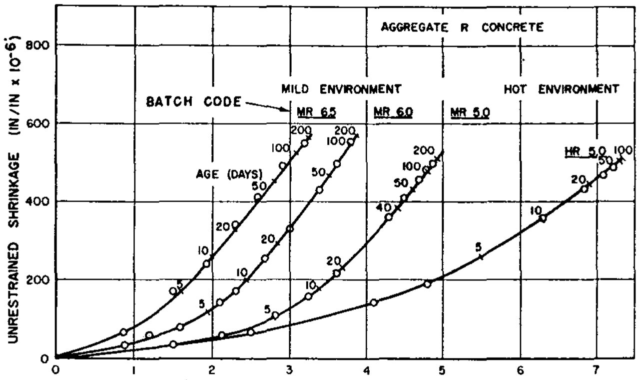


Figure 4-6. Influence of cement and environment on shrinkage-water loss relationship.

As a result, even though the total shrinkage is less in the above example for the concrete exposed to the hot environment, the rate of change is higher and hence cracking of restrained concrete would tend to be greater. This in fact was shown to be the case. Concrete under mild conditions may never lose as much water to evaporation as that in hot conditions which certainly could result in greater volume changes in the hot environment. The influence of cement content on the shrinkage-water loss relation can be discussed as before in terms of the shrinkage per unit of water evaporated. Lower water loss with increased cement was due to a decreased volume of capillary pores in the cement paste structure associated with the increased cement content or lower water-cement ratio. Influence of capillary porosity was illustrated by Menzel, as shown in Figure 2-1. The decreasing shrinkage per unit water loss is due to a decreasing percentage of the total water intimately associated with the gel surface area, as capillary porosity increases. Although these differences existed, the amount of shrinkage at a given age was not greatly affected.

4.1.6 Restrained Shrinkage

The direct tensile specimen was used to measure the development of concrete tensile stress due to restrained shrinkage in the hot and mild environments for aggregate R concrete. A detailed description of the test appears in Reference (57). Concrete tensile stress due to restrained shrinkage is shown in Figure 4-7 plotted against unrestrained shrinkage measured on accompanying standard type specimens. Data shown for the two environmental conditions indicate that the environmental parameter had little influence on the relationship shown.

The type of information shown in Figure 4-7 appears to have considerable practical significance. If it is assumed that the manner of restraint involved in the

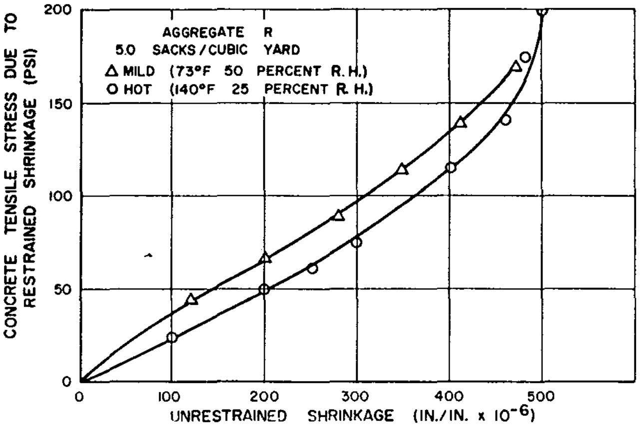


Figure 4-7. Restrained shrinkage stress related to unrestrained shrinkage.

direct tensile specimen simulates that in reinforced concrete structures, then the unrestrained shrinkage obtained by means of the standard specimens could be used to predict restrained shrinkage stress for a wide range of curing environments (Figure 4-7). In Figure 4-8 the relationship of water loss to restrained shrinkage stress presents another promising possibility for use in practical situations. For a given environment a certain water loss could be related to restrained tensile stress in reinforced concrete with the result that cracking could be reliably predicted. Since the water loss determinations would most likely be easier to accurately obtain than length changes, it is believed that both should be further investigated for different materials, mix proportions, and environments. Such an investigation would determine the feasibility of such an approach to crack prediction of restrained concrete.

4.1.7 *Direct Tensile Test*

After restrained shrinkage was measured up to an age of 60 days, the direct tensile specimens were placed in an Instron testing machine and loaded to concrete failure in tension. A detailed discussion of the test appears in Reference 57. Figure 4-9 illustrates the total stress-strain curves obtained using the restrained shrinkage and direct tensile test data. Specimen 1 could not be included due to electrical malfunctions during the restrained shrinkage test. In Figure 4-9 the dashed portion of the curves represents behavior during restrained shrinkage. The curve is drawn as a dashed line since the actual stress-strain relationship during restrained shrinkage is not known. As stated in Reference 57,

> ... the strains in the steel specimen were measured during the hydration period, from which the concrete restrained volume change stresses can be calculated. However, the concrete strains during this period are not known until the time of test. When the specimen is tested, the relationship between concrete stress and strain is determined and, therefore, the strain existent in the concrete prior to testing can be calculated. Thus the solid portion of the tensile stress-strain curve is positioned correctly on the graph and portrays the influence of restrained volume changes on concrete tensile properties.

Comparing the percent of the ultimate tensile strength lost to shrinkage reveals the influence of the total amount of shrinkage in the hot environment at 60 days (Table 4-2).

The higher loss of effective tensile strength in the hot environment is not only due to higher shrinkage (as can be deduced from Figure 4-3) but also due to a much greater rate of shrinkage. Since both shrinkage and creep are time dependent, the faster a stress is applied, the lower the amount of stress that is relieved through creep. In the design of reinforced concrete structures, the effective tensile strength is of interest rather than the total tensile strength, and reductions due to restrained shrinkage stress must be taken into account if cracking is to be reduced or avoided.

TABLE 4-2. DIRECT TENSILE SPECIMEN DATA

Specimen	Environment	Tensile Strength (psi)	Percent Reduction Due to Restrained Shrinkage	Restrained Shrinkage Stress (psi)
2	hot	470	55	260
3		430	69	245
6		315	78	290
1	mild			
4		375	46	172
5		400	43	172

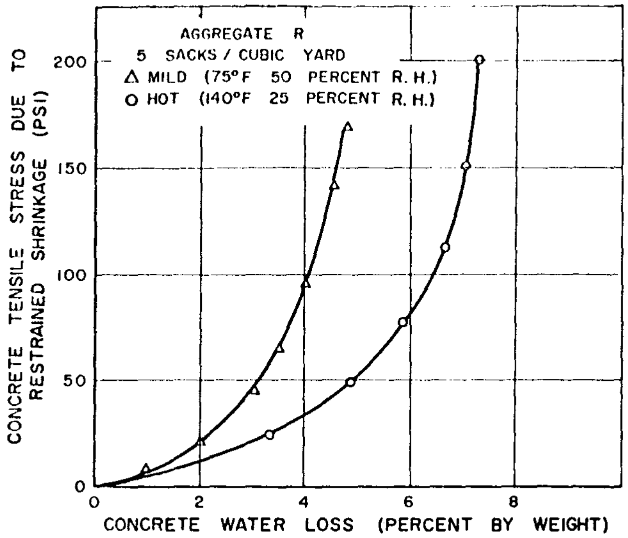


Figure 4-8. Restrained shrinkage stress related to water loss.

In Figure 4-9 there appears to be no relation between ultimate tensile strength or modulus of elasticity and the curing environment. It should be pointed out

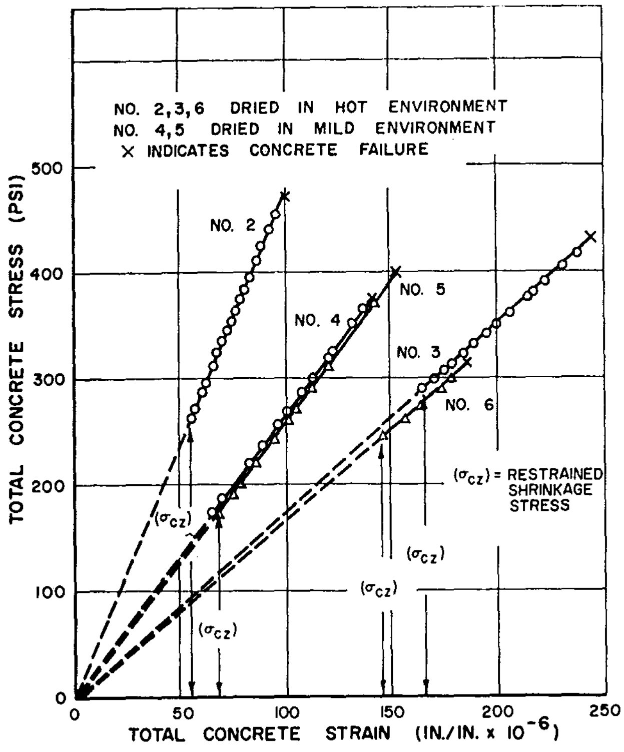


Figure 4-9. Concrete total stress-strain curve in tension.

that in every case lower ultimate tensile strength may be associated with a greater percent reduction due to restrained shrinkage. This observation suggests that the shrinkage and therefore the restrained shrinkage stress remained about the same for all specimens in a particular curing environment while the ultimate tensile strength varied from specimen to specimen. Values of restrained shrinkage stress in Table 4-2 substantiate this concept.

4.1.8 Concrete Cracking

Concrete cracking was evaluated as the number of cracks occurring on a specimen 4 x 4 x 48 in. having a one in. diameter deformed reinforcing bar through the center. Three specimens were made from each aggregate type at 5.0 sacks/cubic yard cement content for each curing environment. In addition specimens at 6.0 and 6.5 sacks/cubic yard were made for each aggregate type and placed in the mild environment. All specimens in the cold and wet environments remained crack free. Data from 5.0 sack/cubic yard concrete in the hot and mild environments are shown in Figure 4-10. These data emphasize the role of the rate of shrinkage as mentioned earlier. In all cases specimens in the hot environment cracked significantly more than similar specimens in the other environments. Specimens for the 5.0 sack/cubic yard aggregate H concrete were damaged after the data point at about 100 days of age and therefore the data beyond that point were not considered. In Figure 4-11 the influence of variations in the cement content is illustrated for the three coarse aggregate types in the mild environment. A concrete containing more cement was more prone to cracking in most instances. This behavior has been reported in the literature and is generally believed to result from increased stiffness of the cement paste structure and therefore a reduced creep capacity (4,43,55).

The cracking behavior of the specimens up to about 40 days of age is not clear from the data presented. The specimens were observed about once a week for cracks until the first ones were found, then a thorough inspection of the specimens was made. It seems unreasonable that several cracks would occur simultaneously since the distribution of stress along the length of the specimen is not uniform. Therefore, it is believed the cracking occurred as indicated by the dashed lines in Figure 4-10 and the visual inspection of the specimens did not detect these early cracks. On later batches closer attention was given to inspection prior to cracking, as in the case of aggregate R concrete in the mild environment.

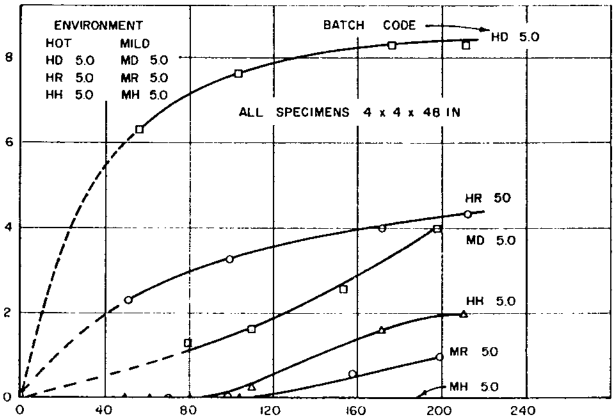


Figure 4-10. Cracking related to age, environment, and coarse aggregate.

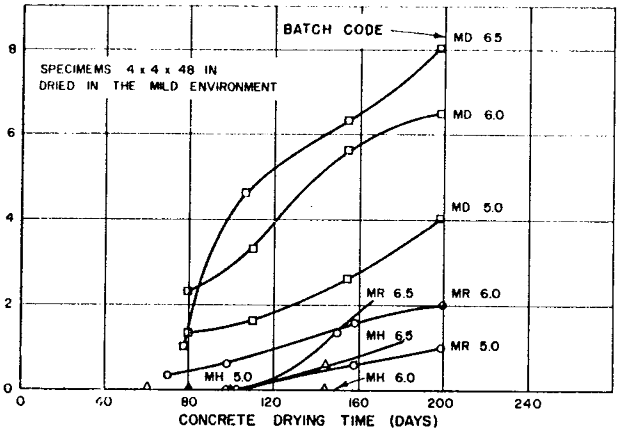


Figure 4-11. Cracking related to cement content.

In every situation included in this investigation, the aggregate D concrete cracked more readily than the aggregate R concrete. This resulted from one or a combination of a) greater volume change for aggregate D concrete and therefore higher restrained shrinkage stress, b) greater rate of strength development, therefore higher restrained shrinkage stress, c) lower ultimate tensile strength, therefore less stress required to form a crack or d) a lower rate of creep and therefore less stress relief. Since unrestrained volume changes were not significantly different, it is concluded that the applied restrained shrinkage stresses are about the same. Previous workers have demonstrated that no significant difference exists regarding rate of strength development (30). The significant differences are thus a function of the creep and tensile strength properties of the materials under study.

On almost all restrained cracking specimens longitudinal cracking (parallel to the reinforcing bar) was observed near the ends. It has been shown that such cracking is likely to occur near a transverse crack in which the faces of the crack are separated (60). The concrete near the end of the specimen behaves as if the end of the specimen were a transverse crack. The concrete and steel tend to separate as the concrete "peels" away from the bar. This situation imposes a circumferential stress on the concrete at the end, resulting in longitudinal cracking in the specimens in this study.

4.2 Discussion of Interrelationships

4.2.1 Concrete Strength and Restrained Shrinkage Cracking

The strength of concrete has an important role in the development of cracking due to restrained shrinkage. First, a stronger material exhibits less deformation for a given applied load due to a stiffer structure. Secondly, the stiffer structure also exhibits less creep strain under a sustained load and therefore retains a greater percentage of the applied stress. Results of restrained cracking

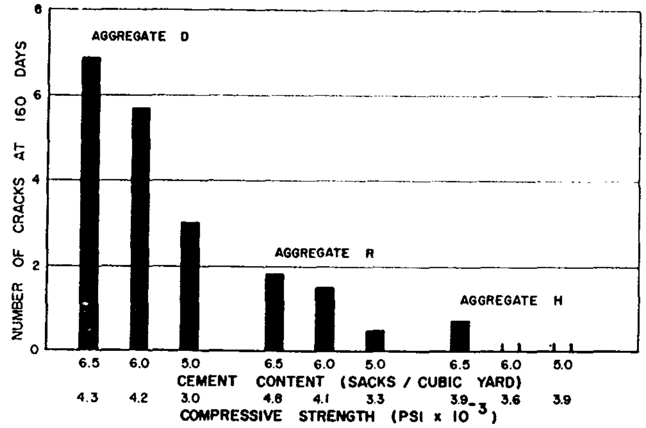


Figure 4-12. Relationship of cracking to strength properties.

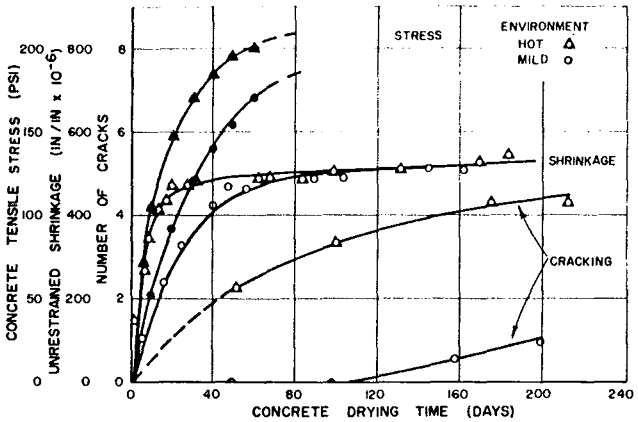


Figure 4-13. Shrinkage, stress, and cracking in the hot and mild environments.

at 160 days of age are shown in Figure 4-12 related to strength properties indicating increased cracking for higher cement factors and related strength characteristics. It was noted that the concrete stress and cracking continued to increase after unrestrained volume changes were almost constant as shown in Figure 4-13. Computations based on volume-to-surface area ratio as presented by Hansen and Mattock (40) indicated there should be no great difference attributable to specimen size differences. Thus it was concluded that increased stress and therefore cracking was caused by the continuing strength development under a constant deformation. This can be explained by assuming the material to behave, at any given age, in accordance with Hooke's Law, which is,

$$\Delta = \frac{PL}{AE}$$

Δ = deformation

P = applied load

L = length under consideration

A = cross-sectional area

E = modulus of elasticity

In a situation where shrinkage is constant and the material is gaining strength, as pointed out above; Δ, L, and A are constant while E changes. Thus,

$$P = \frac{\Delta AE}{L} = KE$$

where $\frac{\Delta A}{L} = K$ is a constant for the given conditions, for E to increase P must increase, causing the greater restrained shrinkage stress observed in Figure 4-13.

The above discussion may be used to point out and explain differences in behavior of concrete under different environmental conditions. Cracking can be expected to occur earlier in an elevated temperature due to the rapid rate of strength development occurring simultaneously with the rapid development of shrinkage strain.

4.2.2 Concrete Water Loss and Cracking

The data presented indicated that concrete water loss and concrete cracking were both influenced by all parameters under investigation. This observation led to the relationship shown in Figure 4-14. Although the data are somewhat limited, the relationship appears to be worth further consideration. One goal of this study was to determine an indicator for cracking behavior of the materials under study. For the materials and test conditions investigated unrestrained shrinkage was not significantly different for concretes exhibiting quite different cracking behavior. Water loss for the same materials and conditions did provide an indication of cracking for a particular aggregate, and could be used to compare these materials at constant cement content. Variations in cement content influenced water loss since the nature of the cement paste structure controlled the quantity of water and its availability for evaporation into the atmosphere.

4.2.3 Coarse Aggregate Properties and Cracking

In order to determine a means of quality control for synthetic coarse aggregates with respect to restrained shrinkage cracking several properties were compared

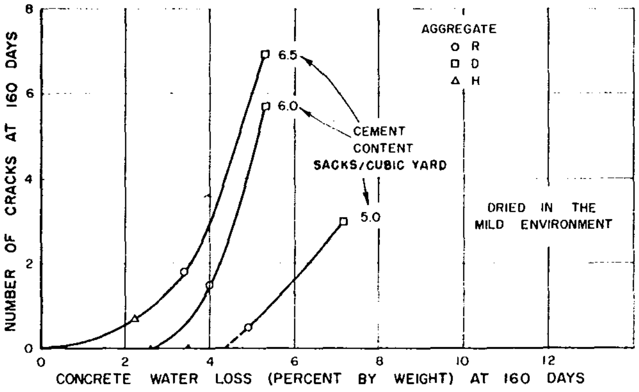


Figure 4-14. Cracking as indicated by water loss.

with cracking data. The properties of porosity and degree of saturation after 100 minutes immersion in water are shown in Table 4-3 for the coarse aggregates used.

TABLE 4-3. COMPARISON OF SELECTED COARSE AGGREGATE PROPERTIES AND CRACKING

Aggregate	Cement (sacks/ cubic yard)	Cracks After 160 Days Drying	Porosity (percent)	Deg. Sat. After 100 Minute Immersion
D	5.0 6.0 6.5	3.0 5.7 6.9	57	0.293
R	5.0 6.0 6.5	0.5 1.5 1.8	42	0.083
H	5.0 6.0 6.5	0* 0 0.7	0.56	low ≃0

*This value inferred from other aggregate H data, since the specimens at 5.0 sacks/cubic yard were damaged after 100 days drying.

The aggregate porosity and saturation characteristics directly related to the resulting concrete's cracking behavior. While it was concluded that there were not enough different aggregates to develop any firm conclusions at this time, the trend established is that poorer performance is exhibited with increased aggregate porosity and rate of saturation characteristics.

CHAPTER V

APPENDIX

5.1 Aggregate Data

TABLE 5-1. AGGREGATE PROPERTIES

Aggregate	Dry Unit Wt. (pcf)	Absorption* (percent dry wt.)	Porosity** (percent)	100 min. Degree of Saturation (percent)
D	39.4	21.6	57.0	29.3
R	47.5	5.3	42.0	8.3
H	101.0	1.2	0.6	0
B (fine)	99.0	0.8		

*After 3 days immersion in water.

**Based on absorption in a pressure pycnometer at 1200 psi (56).

TABLE 5-2. AGGREGATE GRADATIONS

Sieve Size	Cumulative Percent Retained Agg. D	Agg. R	Agg. H	Agg. B
¾ in.	4.6	1.5	2.3	
½ in.	42.4	35.4	8.4	
⅜ in.	94.3	75.0	51.1	
# 4	98.9	99.4	96.8	
# 8	99.7	99.6	98.9	
# 16	100.0	100.0	99.0	19.8
# 30				34.6
# 50				73.6
# 100				95.1

5.2 Environmental Control Facilities

5.2.1 General

The recently completed facilities in the McNew Laboratory at Texas A&M University provided the atmospheric control necessary for the testing conducted. Twelve rooms, each approximately 8 x 11 x 16 feet, with a wide variety of conditions ranging from —20°F to 140°F offer the capability to simulate almost any condition desired. Only four of the rooms were used as discussed previously in Chapter III. These conditions were maintained quite accurately throughout the tests conducted. The normal variation experienced during the conduct of the reported tests are shown in Table 5-3, exceptions to these limits are discussed in the next paragraph.

5.2.2 Discussion of Variations

Due to the fact that the above discussed facilities were recently completed there were several occasions on which variations beyond those shown in Table 5-3 occurred. On one occasion the hot room temperature was dropped to 120°F which was accompanied by a rise in humidity to 35 percent. This temporary variation was necessary for work done on the control instrumentation and lasted for about three hours. Specimens in the room were approximately 30 days of age at the time. Several times during the tests the relative humidity in the hot room varied outside of that shown. The tests results did not appear to be affected, although no measurements taken during these times have been retained in the analysis of the results. In the cold environment on one occasion the temperature dropped below 40°F.

TABLE-5-3. ENVIRONMENTAL VARIATIONS

Environmental Designation	Temperature Range (°F)	Humidity Range (percent)	Nominal Conditions
mild	72 - 75	50 - 53	73° 50%
moist	69 - 73	+95	73° > 95%
cold	39 - 41	92	40° 92%
hot	138 - 141	23 - 27	140° 25%

The drop lasted for about eight hours and was then corrected. Data taken indicated the only influence on the specimens was the thermal contraction since the relative humidity remained at 92 percent.

5.3 *Laboratory Procedures*

All concrete was mixed in a three and one-half cubic foot rotary drum mixer. Materials were allowed at least 24 hours to stabilize in the batching room prior to mixing. Preceding each batch a small charge of materials were used to "butter" the mixer. Batching was begun by placing the coarse aggregate and a portion of the mixing water containing the air entraining agent into the mixer. After ten minutes, the fine aggregate and cement were added with the remaining mix water used for slump control. The ingredients were mixed about ten minutes after the addition of cement. After the ingredients were mixed, tests for slump (ASTM C143-66) and air content (ASTM C231-68) were run. Once these control tests were completed the batch was discharged and placed in the molds.

As soon as the concrete was placed, the specimens were covered with polyethylene plastic sheets in order to prevent excessive water loss during initial curing. Between 22 and 26 hours after placing, the specimens were removed from the molds, labeled and placed in the moist curing environment (73°F, 95% R.H.). At the age of five days the specimens were removed from moist curing and placed in the various prescribed environments.

5.4 *Thermal Volume Changes*

It is important in the testing of materials under various environmental conditions to take into account the influence of temperature. In the tests conducted for this study two of the environmental conditions used involved a change in temperature. For purposes of comparing the results of shrinkage tests it was necessary to make corrections for the thermal volume changes that occurred. Since the thermal coefficient of expansion of the material under study is highly variable depending on the constituents used, age and moisture condition, it was decided to make corrections for thermal volume changes by data extrapolation. This involved recording a considerable amount of data at early ages in order to establish the volume change-time relationship and determine the point at which thermal volume changes ceased. It is important to realize that thermal and shrinkage volume changes occur simultaneously. Thermal properties of the concrete studied are shown in Table 5-4. Each value is the average of three specimens.

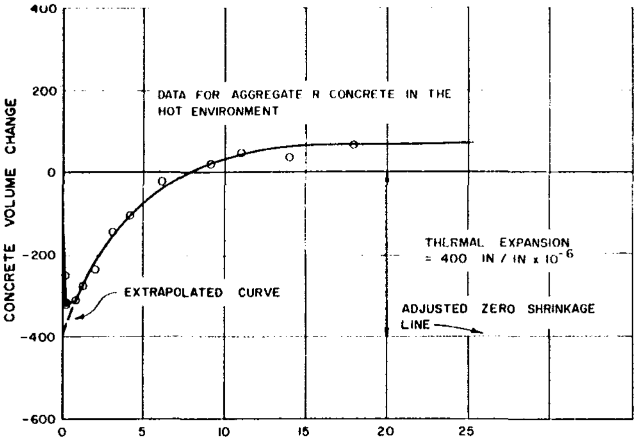


Figure 5-1. Thermal expansion correction by extrapolation.

The data shown at age five days were obtained by extrapolation of the shrinkage-time curves for specimens when moved from moist curing to the designated environment (Figure 5-1). Values of coefficient of thermal expansion (α) were computed from these data (Table 5-4). At the age of about 145 days specimens were placed in plastic bags and moved to 73°F, the moisture condition of the specimen remaining essentially the same. After 24 hours, length measurements were made yielding the results shown in the table. Upon return to their respective environments, the measurements were verified. Specimen weights were recorded throughout this test and indicated that no significant weight change occurred.

It can be concluded from the above presented data that the thermal properties of the materials studied vary with environment, age and moisture condition. The H(140°F and 25 percent) specimens showed no significant change of thermal properties with age, even though the thermal coefficient of expansion did increase slightly with age. This result seems likely since the stiffness of the material had increased somewhat. In the cold environment the thermal properties for the aggregate R and H concretes were considerably different from those for the aggregate D concrete at five days of age. The low thermal coefficient of expansion recorded for aggregate D concrete is believed directly related to the coarse

TABLE 5-4. CONCRETE THERMAL PROPERTIES

Batch Code	Temp. Change	Age 5 Days		Temp. Change	Age 145 Days	
	°F	ΔL in./in. x 10^{-6}	α in./in. x 10^{-6}/°F	°F	ΔL in./in. x 10^{-6}	α in./in. x 10^{-6}/°F
HR5.0	+69	400	5.8	±67	420	5.2
CR5.0	−29	230	7.9	±30	300	9.9
HD5.0	+71	400	5.6	±67	400	6.0
CD5.0	−29	140	4.8	±30	310	10.4
HH5.0	+79	410	5.8	±67	400	6.0
CH5.0	−29	216	7.4	±30	260	8.6

α = thermal coefficient of linear expansion

TABLE 5-5. CONCRETE MIX DATA

Batch Code	Cement Factor sk./c.y.	Percent Absolute Volume Cement	Water	F.A.	C.A.	Air	Slump in.	Initial Unit Weight lbs./ft.^{3}	Compressive Strength psi
4RS	4.98	8.8	16.4	36.0	32.8	6.0	2.5	116.0	3620
HR5.0	4.96	8.8	17.0	35.8	32.8	5.5	3.0	115.6	3810
CR5.0	4.97	8.8	16.5	36.5	32.8	5.4	2.5	113.6	3500
WR5.0	4.99	8.8	16.1	36.2	33.1	5.8	3.5	114.4	3370
MR5.0	5.00	8.8	16.5	36.2	33.0	5.5	3.5	116.4	3300
MR6.0	6.18	10.9	16.6	33.3	34.0	5.2	5.0	117.6	4100
MR6.5	6.52	11.6	17.1	33.1	33.1	5.1	2.75	119.6	4800
HD5.0	4.96	8.8	19.4	33.3	32.8	5.7	2.5	112.0	3440
CD5.0	4.94	8.7	19.4	33.3	32.6	6.0	2.5	111.6	3390
WD5.0	4.96	8.8	19.4	33.4	32.8	5.6	2.0	112.8	3480
MD5.0	5.01	8.9	18.4	33.7	33.1	5.9	3.5	109.6	3000
MD6.0	5.85	10.8	18.0	32.2	33.5	5.5	4.25	112.4	4190
MD6.5	6.50	11.6	19.0	31.1	33.0	5.3	4.25	111.6	4280
HH5.0	4.94	8.8	16.3	36.8	32.7	5.5	2.0	141.6	3050
CH5.0	4.97	8.8	15.8	37.0	32.9	5.5	3.5	144.9	3080
WH5.0	4.95	8.7	16.1	37.4	32.7	5.1	2.0	139.6	3050
MH5.0	4.88	8.7	16.4	36.8	32.8	5.8	3.25	139.2	2880
MH6.0	6.00	10.6	15.9	32.1	33.0	5.3	3.5	141.6	3590
MH6.5	6.48	11.5	16.3	33.8	32.8	5.6	4.25	142.8	3900

aggregate since it is the only significant variable. As with the specimens in the hot room the thermal coefficient of expansion is increased with age. In the cold room the increase is greater probably due to the presence of more water resulting in more complete hydration of the cement. At 145 days of age the data for aggregate D concrete in the cold environment seem to agree more closely with that for the other concretes tested.

Like shrinkage, thermal volume changes are not particularly important unless they threaten the durability of the material. When restrained, thermal volume changes may produce significant stresses in concrete. The situation caused by a rapid temperature drop is particularly detrimental. In this case tensile stresses are produced at the surface due to a temperature gradient as well as restraint. When thermal stresses are superimposed on those resulting from restrained and differential shrinkage, the tensile strength of the material may be exceeded. Thus it is important to consider both sources of tensile stress when evaluating the cracking characteristics of such a material in the field.

5.5 Tabulated Test Data

Tables 5-5 and 5-6 present the concrete mix data and unrestrained shrinkage data. All other data were presented as points on the various figures presented.

TABLE 5-6. UNRESTRAINED SHRINKAGE DATA

Drying Time (days)	Shrinkage (in./in. x 10^{-6}) MR5.0	MR6.0	MR6.5	WR5.0	Drying Time (days)	Shrinkage (in./in. x 10^{-6}) MD5.0	MD6.0	MD6.5	WD5.0	Drying Time (days)	Shrinkage (in./in. x 10^{-6}) MH5.0	MH6.0	MH6.5	WH5.0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	40	60	100	0	1	20	10	10	0	1	60	60	47	10
3	60	80	110	10	7	80	70	70	−20	4	130	130	120	0
4	100	100	130	20	11	130	100	100	−30	6	170	180	150	−10
5	100	120	140	30	17	200	170	170	−20	8	200	200	170	−20
9	150	170	190	10	22	260	220	210	−20	13	250	250	210	−30
16	240	220	280	0	38	390	340	340	−60	24	350	330	290	−70
19	280	290	300	−10	54	470	410	420	−90	36	370	360	350	−70
24	330	350	320	−30	66	490	460	480	−100	51	400	420	400	−80
40	420	450	420	−50	81	500	460	480	−90	64	460	470	430	−90
56	460	510	470	−50	86	490	430	500	−100	78	510	490	460	−80
68	490	540	500	−50	101	520	470	520	−100	105	460	500	490	−90
82	480	500	520	−60	114	540	510	530	−110	125	490	500	500	−90
89	480	510	540	−60	128	570	540	570	−110					
104	490	490	530	−60										
139	460	500	540	−60										

REFERENCES

1. ACI-ASCE Committee 323, "Proposed Definitions and Notations for Prestressed Concrete," ACI Journal, *Proceedings*, Vol. 49, No. 2, October 1952, pp. 85-88.
2. Hansen, T. C., "Notes From A Seminar on Structure and Properties of Concrete," *Technical Report*, No. 71, Stanford University, September 1966.
3. Powers, T. C., "Causes and Control of Volume Change," *Journal*, PCA Research and Development Laboratories, Vol. 1, No. 1, January 1959, pp. 29-39.
4. Troxell, G. E., and Davis, H. E., *Composition and Properties of Concrete*, McGraw-Hill Book Co., Inc., New York, 1956.
5. "Guide for Structural Lightweight Aggregate Concrete," Reported by ACI Committee 213, ACI Journal, *Proceedings*, Vol. 64, No. 8, August 1967, pp. 433-467.
6. Ferguson, Phil M., *Reinforced Concrete Fundamentals*, John Wiley & Sons, Inc., New York, 1965.
7. Ravina, Dan, and Shalon, Rahel, "Plastic Shrinkage Cracking," ACI Journal, *Proceedings*, Vol. 65, No. 4, April 1968, pp. 282-291.
8. Lerch, W., "Plastic Shrinkage," ACI Journal, *Proceedings*, Vol. 53, No. 8, February 1957, pp. 797-802.
9. Howard, E. L., Ravina, Dan, and Shalon, Rahel, Discussion of "Plastic Shrinkage Cracking," by Dan Ravina and Rahel Shalon, ACI Journal, *Proceedings*, Vol. 65, No. 10, October 1968, pp. 889-892.
10. Blakey, B. E., and Beresford, F. D., "Cracking of Concrete," *Constructional Review* (Sydney), Vol. 32, No. 2, February 1959, pp. 24-28.
11. Beresford, F. D., and Mattison, E. N., "Presetting Cracks in Fluid Concrete," *Constructional Review* (Sydney), Vol. 31, No. 9, September 1958, pp. 23-26, 33-36.
12. Abdun-Nur, E. A., Beresford, F. D., Blakey, F. A., Spinel, M., and Tuthill, L. H., Discussion of "Plastic Shrinkage" by William Lerch, ACI Journal, *Proceedings*, Vol. 53, No. 6, December 1957, pp. 1341-1346.
13. Neville, A. M., *Properties of Concrete*, John Wiley & Sons, Inc., New York, 1963.
14. McKee, Dean C., and Turner, Humphreys T., "Investigation of Properties of Lightweight Concrete Statewide," *Engineering Research Bulletin*, No. 74, Division of Engineering, Louisiana State University, 1964, 105 pp.
15. Powers, T. C., "A Hypothesis on Carbonation Shrinkage," *Journal*, PCA Research and Development Laboratories, Vol. 4, No. 2, May 1962, pp. 40-50.
16. Brady, F. L., "Modification of the Physical Properties of Cement Produced by Carbonation," *Cement and Cement Manufacture*, (London), Vol. 4, 1931, pp. 1101-1105.
17. Yoshida, Yashichi, "Length Changes of Cement Paste in Relation to Combined Water," ACI Journal, *Proceedings*, Vol. 34, No. 1, September-October 1937, pp. 24-41.
18. Lea, F. M., and Desch, C. H., *The Chemistry of Cement and Concrete*, E. Arnold, London, 1956, p. 473.
19. Meyers, S. L., "Effects of Carbon Dioxide on Hydrated Cement and Concrete," *Rock Products*, Vol. 52, No. 1, January 1949, pp. 96-98.
20. Leber, I., and Blakey, F. A., "Some Effects of Carbon Dioxide on Mortars and Concrete," ACI Journal, *Proceedings*, Vol. 53, No. 3, September 1956, pp. 295-308.
21. Verbeck, G. J., "Carbonation of Hydrated Portland Cement," *Special Technical Publication*, No. 205, ASTM, 1958.
22. Powers, T. C., "Mechanism of Shrinkage and Reversible Creep of Hardened Cement Paste," *Proceedings International Conference on the Structure of Concrete*, London, 1965.
23. Lerch, William, "The Influence of Gypsum on the Hydration and Properties of Portland Cement Pastes," ASTM, *Proceedings*, Vol. 46, 1946, pp. 1252-1292. (Also PCA Research Bulletin No. 12.)
24. Aroni, Samuel, and Mehta, Povindar K., "Fundamentals Underlying Shrinkage in Concrete—A Review," *Indian Concrete Journal*, Vol. 39, No. 12, December 1965, pp. 485-492.
25. *Concrete Manual*, U. S. Department of Interior, p. 17.
26. Menzel, Carl A., "Strength and Volume Change of Steam Cured Portland Cement Mortar and Concrete," ACI Journal, *Proceedings*, Vol. 31, No. 2, November-December 1934, pp. 125-148.
27. Carlson, R. W., "The Chemistry and Physics of Concrete Shrinkage," ASTM, *Proceedings*, Vol. 35, Part II, 1935, pp. 370-379.
28. Pickett, Gerald, "Effect of Aggregate on Shrinkage of Concrete and a Hypothesis Concerning Shrinkage," ACI Journal, *Proceedings*, Vol. 52, No. 5, January 1956, pp. 581-590.
29. Shideler, J. J., "Lightweight Aggregate Concrete for Structural Use," ACI Journal, *Proceedings*, Vol. 54, No. 4, October 1957, pp. 299-328.
30. Jones, T. R., Hirsch, T. J., and Stephenson, H. K., "The Physical Properties of Structural Quality Lightweight Aggregate Concrete," *Research Report*, Texas Transportation Institute, Texas A&M College System, August 1959, 46 pp.
31. Pfeifer, Donald W., "Sand Replacement in Structural Lightweight Concrete—Creep and Shrinkage Studies," ACI Journal, *Proceedings*, Vol. 65, No. 2, February 1968, pp. 131-140.
32. Hanson, J. A., "Replacement of Lightweight Aggregate Fines with Natural Sand in Structural Concrete," ACI Journal, *Proceedings*, Vol. 61, No. 7, July 1964, pp. 779-794. (Also PCA Development Department Bulletin D80.)
33. Hansen, T. C., and Nielson, Knud. E. C., "Influence of Aggregate Properties on Concrete Shrinkage," ACI Journal, *Proceedings*, Vol. 62, No. 7, July 1965, pp. 785-794.

34. Roper, Harold, "Volume Changes of Concrete Affected by Aggregate Type," *Journal,* PCA Research and Development Laboratories, Vol. 2, No. 3, September 1960, pp. 13-19.

35. Hveem, F. N., and Tremper, B., "Some Factors Influencing Shrinkage of Concrete Pavements, ACI Journal, *Proceedings,* Vol. 53, No. 8, February 1957, pp. 781-789.

36. Buth, C. E., Ivey, D. L., and Hirsch, T. J., "Clay, Aggregate and Concrete," *Research Report 71-3,* (Final), Texas Transportation Institute, Texas A&M University, College Station, Texas, March 1967, 17 pp.

37. Houston, J. T., and Ledbetter, W. B., "The Effect of Synthetic Aggregate Thermal Transformation on Performance of Concrete," *Research Report 81-10,* Texas Transportation Institute, Texas A&M University, College Station, Texas, November, 1969.

38. Torrans, P. H., Ivey, D. L., and Hirsch, T. J., "The Effect of Chemical Admixtures on the Drying Shrinkage of Concrete and the Control of Chemical Uniformity of Admixtures," *Research Report 70-1,* Texas Transportation Institute, Texas A&M University, College Station, Texas, August 1964, 34 pp.

39. Hansen, T. C., "Effect of Wind on Creep and Drying Shrinkage of Hardened Cement Mortar and Concrete," *Materials Research and Standards,* Vol. 6, No. 1, January 1966, pp. 16-19.

40. Hansen, T. C., and Mattock, Alan H., "Influence of Size and Shape of Member on the Shrinkage and Creep of Concrete," ACI Journal, *Proceedings,* Vol. 63, No. 2, February 1966, pp. 267-290.

41. Richie, T., "Effect of Restraint on the Shrinkage of Masonry Mortars," *Materials Research and Standards,* Vol. 6, No. 1, January 1966, pp. 13-16.

42. Heaton, B. S., "Strength, Durability and Shrinkage of Incompletely Compacted Concrete," ACI Journal, *Proceedings,* Vol. 65, No. 10, October 1968, pp. 846-850.

43. Polivka, Milos, "Effect of Type of Aggregate on Shrinkage and Cracking Characteristics of Concrete," *Report to Division of Architecture,* Department of Public Works, State of California, Series 100, Issue 17, February 1962, 37 pp.

44. Hsu, Thomas T. C., Slate, Floyd O., Sturman, Gerald M., and Winter, George, "Microcracking of Plain Concrete and the Shape of the Stress-Strain Curve," ACI Journal, *Proceedings,* Vol. 60, No. 2, February 1963, pp. 209-223.

45. Slate, Floyd O., and Olsefski, Stanley, "X-rays for Study of Internal Structure and Microcracking of Concretes," ACI Journal, *Proceedings,* Vol. 60, No. 5, May 1963, pp. 575-588.

46. Hsu, Thomas T. C., "Mathematical Analysis of Shrinkage Stresses in a Model of Hardened Concrete," ACI Journal, *Proceedings,* Vol. 60, No. 3, March 1963, pp. 371-389.

47. Hsu, Thomas T. C., and Slate, F. O., "Tensile Bond Strength Between Coarse Aggregate and Cement Paste or Mortar," ACI Journal, *Proceedings,* Vol. 60, No. 4, April 1963, pp. 465-486.

48. Meyers, Bernard L., Slate, F. O., and Winter, George, "Relationship Between Time-Dependent Deformation and Microcracking of Plain Concrete," ACI Journal, *Proceedings,* Vol. 66, No. 1, January 1969, pp. 60-68.

49. Hansen, Torben C., "Cracking and Fracture of Concrete and Cement Paste," in *Causes, Mechanism and Control of Cracking in Concrete,* ACI Publication SP-20, Detroit, Michigan, 1968, pp. 43-66.

50. Pickett, Gerald, "Shrinkage Stresses in Concrete," ACI Journal, *Proceedings,* Vol. 42, January-February 1946, pp. 165-204 and 361-400.

51. Jones, R., "A Method of Studying the Formation of Cracks in a Material Subjected to Stress," *British Journal of Applied Physics,* Vol. 3, July 1952, pp. 229-232.

52. Isenberg, J., "Properties of Concrete Change When Microcracking Occurs," in *Causes, Mechanism, and Control of Cracking in Concrete,* ACI Publication SP-20, Detroit, Michigan, 1968, pp. 29-41.

53. "Drying Shrinkage of Concrete," California Producers Committee on Volume Change and Affiliated Technical Organizations, Oakland, California, March 1966, 51 pp.

54. Mather, Bryant, "Cracking Induced by Environmental Effects," in *Causes, Mechanism and Control of Cracking in Concrete,"* ACI Publication SP-20, Detroit, Michigan, 1968, pp. 67-72.

55. Carlson, R. W., "Attempts to Measure the Cracking Tendency of Concrete," ACI Journal, *Proceedings,* Vol. 36, No. 6, June 1940, pp. 533-537.

56. Buth, Eugene, Blank, H. R., and McKeen, R. G., "Performance Studies of Synthetic Aggregate Concrete," *Research Report 81-6,* Texas Transportation Institute, Texas A&M University, College Station, Texas, September 1968.

57. Ledbetter, W. B., and Thompson, J. Neils, "A Technique for Evaluation of Tensile and Volume Change Characteristics of Structural Lightweight Concrete," ASTM, *Proceedings,* Vol. 65, 1965, pp. 712-728.

58. Ledbetter, W. B., "Correlation Studies of Fundamental Properties With Freeze-Thaw Durability of Structural Lightweight Concrete," *Research Report 81-1,* Texas Transportation Institute, Texas A&M University, College Station, Texas, August 1965, 14 pp.

59. *Handbook of Physics and Chemistry,* Chemical Rubber Publishing Company, Cleveland, Ohio, 37th Edition, 1955-56.

60. Lutz, LeRoy A., "The Mechanics of Bond and Slip of Deformed Reinforcing Bars in Concrete," *Report No. 324,* Department of Structural Engineering, Cornell University, August 1966.