AN EXPERIMENTAL STUDY OF CREEP AND SHRINKAGE
OF EXPOSED LIMESTONE AGGREGATE CONCRETE

by

Darwin Fay Alt

Thesis submitted to the Graduate Faculty of the
Virginia Polytechnic Institute
in candidacy for the degree of

MASTER OF SCIENCE
in
Civil Engineering

May, 1961
Blacksburg, Virginia
II. TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. TITLE PAGE</td>
<td>1</td>
</tr>
<tr>
<td>II. TABLE OF CONTENTS</td>
<td>2</td>
</tr>
<tr>
<td>III. LIST OF SYMBOLS</td>
<td>4</td>
</tr>
<tr>
<td>IV. LIST OF TABLES AND FIGURES</td>
<td>5</td>
</tr>
<tr>
<td>V. INTRODUCTION</td>
<td>6</td>
</tr>
<tr>
<td>VI. SIGNIFICANCE OF CREEP AND SHRINKAGE STUDIES</td>
<td>9</td>
</tr>
<tr>
<td>VII. DEFINITION OF SHRINKAGE</td>
<td>11</td>
</tr>
<tr>
<td>VIII. THEORY OF SHRINKAGE</td>
<td>12</td>
</tr>
<tr>
<td>IX. DEFINITION OF CREEP</td>
<td>14</td>
</tr>
<tr>
<td>X. THEORIES OF CREEP</td>
<td>15</td>
</tr>
<tr>
<td>A. Plastic Theory</td>
<td>15</td>
</tr>
<tr>
<td>B. Viscous Theory</td>
<td>15</td>
</tr>
<tr>
<td>C. Elastic After Effect Theory</td>
<td>16</td>
</tr>
<tr>
<td>D. Seepage Theory</td>
<td>18</td>
</tr>
<tr>
<td>XI. THE EXPERIMENT</td>
<td>20</td>
</tr>
<tr>
<td>A. Object of Tests</td>
<td>20</td>
</tr>
<tr>
<td>B. Outline of Tests</td>
<td>20</td>
</tr>
<tr>
<td>C. Materials</td>
<td>22</td>
</tr>
<tr>
<td>D. Preparation of Specimens</td>
<td>24</td>
</tr>
<tr>
<td>E. Properties of the Concrete</td>
<td>25</td>
</tr>
<tr>
<td>F. Testing Apparatuses and Methods</td>
<td>26</td>
</tr>
<tr>
<td>XII. TEST RESULTS</td>
<td>31</td>
</tr>
<tr>
<td>Section</td>
<td>Page</td>
</tr>
<tr>
<td>------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>XIII. DISCUSSION OF RESULTS</td>
<td>45</td>
</tr>
<tr>
<td>XIV. SUMMARY OF RESULTS</td>
<td>52</td>
</tr>
<tr>
<td>XV. APPENDIX</td>
<td>55</td>
</tr>
<tr>
<td>A. Problems Encountered</td>
<td>55</td>
</tr>
<tr>
<td>B. Errors Encountered</td>
<td>59</td>
</tr>
<tr>
<td>XVI. ACKNOWLEDGMENTS</td>
<td>61</td>
</tr>
<tr>
<td>XVII. BIBLIOGRAPHY</td>
<td>62</td>
</tr>
<tr>
<td>XVIII. VITA</td>
<td>65</td>
</tr>
</tbody>
</table>
III. LIST OF SYMBOLS

1. $\Sigma_e$  \hspace{1cm} Elastic or instantaneous strain
2. $\Sigma_u$  \hspace{1cm} Ultimate creep strain
3. $\Sigma(c-1000)$  \hspace{1cm} Creep strain for 1000 psi constant stress specimens
4. $\Sigma(v-1000)$  \hspace{1cm} Creep strain for 1000 psi variable stress specimens
5. $\Sigma(c-500)$  \hspace{1cm} Creep strain for 500 psi constant stress specimens
6. $\Sigma(v-500)$  \hspace{1cm} Creep strain for 500 psi variable stress specimens
7. $C_c$  \hspace{1cm} Creep coefficient
8. $t$  \hspace{1cm} Time in days
9. $f'_c$  \hspace{1cm} Ultimate compressive strength
IV. LIST OF TABLES AND FIGURES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table I</td>
<td>Disposition of Specimens</td>
<td>21</td>
</tr>
<tr>
<td>Table II</td>
<td>Sieve Analysis for Crushed Stone Sand</td>
<td>23</td>
</tr>
<tr>
<td>Table III</td>
<td>Sieve Analysis for Crushed Stone Aggregate</td>
<td>23</td>
</tr>
<tr>
<td>Figure 1</td>
<td>Whittemore Strain Gage</td>
<td>27</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Creep Apparatus</td>
<td>27</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Creep Plus Shrinkage and Shrinkage Curves</td>
<td>35</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Creep Curve for 1000 psi Constant Stress</td>
<td>36</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Creep Curve for 1000 psi Variable Stress</td>
<td>36</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Creep Curve for 500 psi Constant Stress</td>
<td>37</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Creep Curve for 500 psi Variable Stress</td>
<td>37</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Creep Rate Curve for 1000 psi Constant Stress</td>
<td>38</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Average Daily Temperature Curve</td>
<td>39</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Average Daily Relative Humidity Curve</td>
<td>40</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Stress-Strain Curve at 4 Days</td>
<td>41</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Stress-Strain Curve at 7 Days</td>
<td>42</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Stress-Strain Curve at 28 Days</td>
<td>43</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Stress-Strain Curve at 90 Days</td>
<td>44</td>
</tr>
<tr>
<td>Figure 1-A</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>Figure 2-A</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>Figure 3-A</td>
<td></td>
<td>58</td>
</tr>
<tr>
<td>Figure 4-A</td>
<td></td>
<td>58</td>
</tr>
</tbody>
</table>
V. INTRODUCTION

Since the turn of the century, increased interest has been given to the phenomena of creep and shrinkage of concrete. These phenomena represent two of the principal volume changes occurring in concrete and for which allowances are usually made in the design of concrete structures.

The first reference to creep of concrete is believed to be that of I. H. Woolson in 1905. Following the experiments of Woolson, other researchers in the late 1920s began studies on creep as well as on shrinkage. Maney and Lagaard express the opinion that the results of many of these early experiments were probably somewhat misinterpreted. They felt that creep was accredited with volume changes that were probably due to shrinkage. Thus, according to Maney and Lagaard, creep and shrinkage were probably terms used more as synonyms prior to 1930 rather than independent factors controlling volume changes. Since 1930, however, creep and shrinkage have been investigated quite extensively and have been given almost equal consideration.

After the introduction of prestressed concrete into this country in about 1949, Keeton points out that renewed interest was given to volume changes in general and to creep and shrinkage in particular. Prestressing losses in excess of those predicted in design allowances caused justifiable alarm since the stability of prestressed members depends upon calculable residual compressive stresses. Earlier studies

* The number in parenthesis refers to the bibliography at the end of this thesis.
had been mainly concerned with determining factors affecting creep and shrinkage and the relative importance of these factors. But with the increasing use of prestressed concrete, more attention was given to extrapolating creep quantities and coefficients from empirical data in efforts to provide more realistic values to be used in design.

Although extensive studies have been conducted on creep and shrinkage since the turn of the century, Neville(5) states that no conclusive evidence has been found to explain the exact mechanism of creep. Results of many of these investigations have revealed that the type of aggregate used and the temperature and the relative humidity of the ambient atmosphere are factors influencing the magnitudes of creep and shrinkage. These factors are the prime concern of this thesis.

The experiment reported herein concerns the study of creep and shrinkage of limestone aggregate concrete which is subjected to normal atmospheric conditions. The cylindrical concrete test specimens were made from local materials, the limestone aggregate and type III portland cement being common materials for the southwestern part of Virginia and for neighboring areas.

Most studies of creep and shrinkage are conducted under conditions of controlled temperature and controlled relative humidity. The experiment of this thesis differs in this respect since the test specimens were kept outdoors exposed to the ambient atmosphere but sheltered under a roof. The specimens were subjected to normal changes in temperature and relative humidity as in the case of actual structures in the field.
The intention of this thesis is twofold; (1) to point out the
effects which variations of temperature and relative humidity have
upon the rate and amount of creep and shrinkage of concrete, particularly
that quality of concrete that is presently being used for prestressed
cement structures and (2) to present empirical equations from which
somewhat more realistic ultimate creep values may be predicted for
exposed concrete made from limestone aggregates.
VI. SIGNIFICANCE OF CREEP AND SHRINKAGE STUDIES

According to Troxell and Davis (6), creep and shrinkage of concrete are important considerations in the design of structures because of the restraining effect of steel reinforcement, foundation supports, or adjacent concrete which is subjected to different conditions. Volume changes occurring due to creep or shrinkage may cause stresses to be induced within the structure which may cause failure of the concrete.

Contraction of concrete, either due to loss of water or temperature reductions, causes particular concern as tensile strains may be induced in the concrete. Since concrete can not withstand high tensile stresses, these stresses should be avoided wherever possible. In massive concrete structures where the outer surface has lost more moisture than the interior portion, cracking may result because of the tensile strains induced in the outer surface. Temperature and moisture differences between the exposed and unexposed surfaces of concrete slabs, such as highway pavement, may cause warping and eventually cracking of the concrete.

Creep in general, has a tendency to relieve the stress in concrete, particularly when reinforced. For a reinforced concrete member, creep causes a gradual reduction of stress in the concrete and an increase of stress in the reinforcement. In certain instances, continuous beams or slabs, creep may relieve the stresses at the more highly stressed areas and increase the stresses at lower stressed areas, resulting in a more uniform distribution of stress throughout the member.

Creep and shrinkage are noteworthy considerations in design because of their effects in the stability of a structure. In long thin concrete
members, creep may cause deflections in excess of those allowed in the
design. Also, according to Troxell and Davis\(^{(6)}\), the stresses in the
reinforcement may be increased as much as five times the ordinary cal-
culated stresses.

Creep and shrinkage are of particular interest for structures
comprised of prestressed concrete members\(^{(4)}\). Observed prestress losses
in excess of those allowed in design have caused warranted apprehension
since the stability of prestressed members depends upon certain desir-
able residual stresses. With the increasing utilization of prestressed
concrete, emphasis has been given to predicting more realistic creep
and shrinkage values to be employed in design.

Jones and Hirsch\(^{(7)}\) point out that the principal concrete proper-
ties important in design are the compressive strength, the modulus of
elasticity, the modulus of rupture, the tensile strength, shrinkage,
and creep under a sustained load. Values for all of these properties
except creep and shrinkage may be obtained in a relatively short time
for a given mixture and a given aggregate. Creep and shrinkage tests,
however, require long periods of time, ranging from a few months to
years. Thus, since the creep tests of Woolson in 1905, many such long
time tests as previously mentioned have provided the engineer with
experimental values which presently serve as a basis for design allow-
ances.
VII. DEFINITION OF SHRINKAGE

In accordance with the Joint ACI-ASCE Committee 323(8), shrinkage is defined as the "contraction of concrete due to drying and chemical changes, dependent on time but not on stresses induced by external loading."
VIII. THEORY OF SHRINKAGE

Carlson states that shrinkage is governed by the gelatinous constituents in the cement. He says that upon hydration of cement, a minutely porous calcium silicate gel is formed which is capable of holding water within its pores. The amount of this gel increases with age of hydration, and is greater for a higher water-cement ratio and for finer cements. The amount of this gel also depends upon the chemical composition; fully hydrated dicalcium silicate is nearly all gel while hydrated tricalcium silicate is a little more than half gel.

Carlson states that the crystalline materials within the gel are mostly unhydrated grains of cement particles and calcium hydroxide, a byproduct of gelatin. These crystalline materials, he states, do not contribute to shrinkage since, within the normal range of relative humidities, their volumes do not change except as hydration continues. Neville points out that hydration continues very slowly. He states that tests by Lynam revealed that 30 year old cement particles when ground were found to have remarkable cementitious properties, thus proving the existence of incomplete hydration.

According to Davis, Davis, and Hamilton, water exists within a concrete mass in three forms: 1) chemically combined water, or water of crystallization, 2) water which is held or adsorbed by the gel, and 3) free water which is contained within the capillary channels and micropores of the concrete mass.

The adsorbed water is believed to be responsible for the phenomenon of shrinkage. This water is held in the pores by certain attrac-
tive forces which are large since the surface area within the pores is large in comparison with the volume of water held. As this water is reduced by evaporation or by recrystallization of the gel, the forces which were previously acting now become effective in attracting molecules of the gel closer together, consequently there is a reduction in volume.

According to Carlson, for a given gel, an equilibrium water content and a corresponding volume exists for each atmospheric humidity to which the concrete is exposed. Should the air become drier, the water content as well as the volume becomes smaller. Similarly, if the relative humidity of the air increases, the water content as well as the volume increases. However, Carlson states that the equilibrium water content in actual structures may never be reached, for he says that the average drying season is short in comparison with the time required to reach this equilibrium condition.
IX. DEFINITION OF CREEP

Conforming with the Joint ACI-ASCE Committee 323(8), creep is defined as the "inelastic deformation, dependent on time, and resulting solely from the presence of stress and a function thereof."
X. THEORIES OF CREEP

A. Plastic Theory

The plastic theory assumes that creep of concrete is the result of crystalline flow, hence, a result of slippage along planes within the crystal lattice, similar to the plastic flow of metals. Neville\(^5\) points out that previous experiments by Voght\(^10\) revealed the modes of deformation of concrete were similar in certain respects to those of cast iron.

The plastic flow of metals, however, is an inelastic deformation occurring only when a particular stress is exceeded. But tests conducted by Glanville\(^14\) indicated that if concrete possessed a particular stress below which no inelastic deformation occurred, this stress was negligible.

Although no direct evidence of intracrystalline slip is given, Neville\(^5\) says that tests\(^10\) by Bernal, Jeffery, and Taylor indicate from their crystallographic work that both intracrystalline and intercrystalline slip may be possible.

B. Viscous Theory

According to this theory, creep is the result of flow of the cementitious materials with the particles moving over one another. Neville\(^5\) states that the majority of creep in concrete is a result of viscous flow and that the magnitude of creep will be influenced by the type of aggregate because of varying moduli of elasticity of .
different type aggregates.

Neville explains that the modulus of elasticity of concrete is the resultant modulus of a heterogeneous body subjected to external loading. The strains caused by the induced internal stresses in the various components of the heterogeneous body will depend on the moduli of elasticity of the component parts.

As Neville points out, the aggregate has a higher modulus of elasticity than does the cementitious material; thus the aggregate will have a higher stress and the cement particles will have a lower stress than the average applied stress. The aggregate undergoes an elastic deformation upon first application of the load and, soon after, undergoes plastic deformation due to these higher than average stresses. As a result of these deformations, the cementitious material will then be more highly stressed and will tend to flow, thus gradually transferring the load back to the aggregate.

As hydration continues, the gel becomes less porous and becomes more stable. The concrete properties also alter with age of hydration, both the strength and modulus of elasticity increasing with time. Therefore, the rate of creep in the aggregate, as well as the nature and extent of the crystalline products, will largely determine the rate at which the load is transferred from the cement paste back to the aggregate.

C. Elastic After Effect Theory

This theory, proposed by G. A. Maney, attempts to attribute
the phenomenon of creep under working loads to "elastic redistributions of stress and strain due to non-uniform shrinkage or 'warping'."

Tests by Gauss and Tucker\(^{(16)}\) on shrinkage of concrete cylinders have revealed that the surface concrete approaches equilibrium with the surrounding atmosphere much more readily than the central portion, thus concluding that surface concrete shrinks more rapidly than the interior concrete.

Maney states that shrinkage of concrete cylinders follows a parabolic distribution, having the greatest shrinkage at the surface and nearly zero at the center. This non-uniform shrinkage causes tension in the outer surface and compression in the central core. Maney thus concludes that these shrinkage stresses added to the stresses produced by external loading cause the time yielding to occur. That some plastic flow occurs, Maney does not deny, but he feels that the greater portion of the time yielding is elastic change caused by non-uniform shrinkage.

Pickett\(^{(17)}\) also attempts to explain the effect of non-uniform shrinkage upon creep. In his opinion, the drying of concrete causes non-uniform volume changes that result in transient stresses. These stresses combine with those induced by loading and consequently cause distributions and magnitudes of stress which are very much different from the unloaded companion specimens.

Pickett bases his analysis of creep on a non-linear stress-strain relationship of concrete. He implies that if the stress-strain relationship were non-linear, then creep would be present and not proportional to stress. The stress strain curve for concrete is non-linear, at least
for the upper part of the curve; thus, Pickett concludes that the observed effect of changes in moisture content on the creep of concrete under sustained load is due largely to a non-linear relation between the actual stresses and strains."

D. Seepage Theory

The seepage, or gel, theory assumes that creep of concrete results from loss of colloidal water within the cement gel.

Lorman\(^{(1)}\) considers creep as an inelastic deformation due entirely to the action of sustained stresses and is not to include such volume changes as shrinkage or swelling. The stresses resulting from sustained loads cause seepage of the adsorbed water of the cement gel. Upon loss of this adsorbed water, like shrinkage, the pore spaces are reduced accordingly, resulting in a reduction of volume.

According to Neville\(^{(5)}\), Ross and Seed\(^{(10)}\) explain that the vapor pressure of the moisture within the gel is increased immediately upon application of a load. In order to restore equilibrium conditions with the surrounding atmosphere, moisture is expelled or "squeezed" from the gel. As moisture is excluded from the gel, less pressure is exerted on the fluid and more stress is progressively transferred to the solid material. The rate of expulsion of water decreases with lessening pressure on the fluid. Also, the rate of expulsion of the water depends upon the rate at which the expelled water can seep away. The moisture gradient between the gel and the surrounding atmosphere and the quantity of moisture within the gel will largely determine the rate at
which moisture might be lost to the atmosphere. Any factors affecting these conditions will thus have some effect on the magnitude of creep. Factors affecting these conditions may be the water-cement ratio, fineness of cement, relative humidity, temperature, type and gradation of aggregate, mix proportions, age of concrete, compaction, and curing conditions (See references 1, 5, 6, 9, 11, 17, 18, 19).

The seepage theory states that creep, like shrinkage, results from the loss of adsorbed or held water. White\(^{(20)}\) and Lea and Desch\(^{(13)}\) experimented with concrete specimens that were emersed in benzene and noticed that no volume changes occurred. Because benzene will not hydrate lime nor be held as water of crystallization nor be adsorbed by the gel, these researchers concluded that benzene could have entered only the capillary channels and micropores. From this he concludes that free water has no effect on the volume change of concrete.

Lynam\(^{(10)}\), according to Neville\(^{(5)}\), describes both creep and shrinkage as a result of the loss of adsorbed water, expelled by pressure in the former case and drawn out by evaporation in the latter.
XI. THE EXPERIMENT

A. Object of Tests

The experiment reported herein was conducted on unreinforced concrete specimens exposed to atmospheric conditions in order to study the effects that variations in relative humidity and temperature have on creep and shrinkage. Limestone aggregates were used in the concrete mixture for the purpose of obtaining creep and shrinkage values which may be expected from this type of material.

The purpose of the experiment was twofold: to obtain results that may typify values of creep and shrinkage occurring in structures subjected to field conditions and to obtain results that may give some indication of the magnitudes of creep and shrinkage expected in concrete made with limestone aggregates.

B. Outline of Tests

The creep tests for the experiment were divided into two classifications: (1) constant load and (2) variable load. Two stress levels were used within each classification. For both classifications, there were two sets of three specimens each. One set was stressed at 1000 psi, the other at 500 psi, (see Table I). All specimens were made from a single batch of local ready mixed concrete.

A total of sixty-five specimens were made. Twelve of these specimens were subjected to loads as outlined above. Three specimens, used for control, were stored adjacent to the test specimens. Three
Table I. Disposition of Specimens

<table>
<thead>
<tr>
<th>Number of Specimens Used</th>
<th>Disposition of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Creep under 1000 psi constant stress</td>
</tr>
<tr>
<td>3</td>
<td>Creep under 500 psi constant stress</td>
</tr>
<tr>
<td>3</td>
<td>Creep under 1000 psi variable stress</td>
</tr>
<tr>
<td>3</td>
<td>Creep under 500 psi variable stress</td>
</tr>
<tr>
<td>3</td>
<td>Control (outdoors)</td>
</tr>
<tr>
<td>**3</td>
<td>Stored in moist room</td>
</tr>
<tr>
<td>*3</td>
<td>Tested for ultimate strength at 4 days</td>
</tr>
<tr>
<td>3</td>
<td>Tested for ultimate strength at 7 days</td>
</tr>
<tr>
<td>3</td>
<td>Tested for ultimate strength at 28 days</td>
</tr>
<tr>
<td>3</td>
<td>Tested for ultimate strength at 90 days</td>
</tr>
<tr>
<td>*2</td>
<td>Tested for stress-strain relation at 4 days</td>
</tr>
<tr>
<td>2</td>
<td>Tested for stress-strain relation at 7 days</td>
</tr>
<tr>
<td>2</td>
<td>Tested for stress-strain relation at 28 days</td>
</tr>
<tr>
<td>2</td>
<td>Tested for stress-strain relation at 90 days</td>
</tr>
<tr>
<td>27</td>
<td>Future strength and stress-strain tests</td>
</tr>
<tr>
<td><strong>Total = 65</strong></td>
<td><strong>Total = 65</strong></td>
</tr>
</tbody>
</table>

All specimens except (*) were stored in a moist room for 7 days curing. All remaining specimens except (**) were then moved outdoors for storage under normal atmospheric conditions.
specimens were stored in the curing room at a temperature of 70° F and a relative humidity of 100%, but they were not used in this experiment. Twelve specimens were used for ultimate strength tests, three each at 4, 7, 28, and 90 days. Eight specimens were used for determination of the stress-strain relation, two each at 4, 7, 28, and 90 days. The remainder of the specimens were not used for the tests reported in this thesis but are to be used in an extension of the study.

Changes in length of the specimens were measured with a 10 inch Whittemore strain gage; brass plugs were imbedded in the cylinders 10 inches apart along axial gage lines for reference points. Measurements on the unloaded specimens gave variations in length due to shrinkage or expansion as a result of moisture variations. Measurements of the loaded specimens include the above plus changes due to load.

C. Materials

Ready mixed concrete, obtained from the Blacksburg Block and Supply Company, Blacksburg, Virginia, was used to make the specimens for the experiment. Limestone aggregates, coarse and fine, quarried by the Montgomery Limestone Corporation, Elliott, Virginia, were used in the mixture. The grading of both the crushed stone sand and the crushed stone aggregate are shown in Tables II and III respectively.

The cement used in the mixture was type III (Incor), high early strength, made by the Lone Star Portland Cement Corporation, Lone Star, Virginia. Type III portland cement hydrates in about one-third
### Table II. Sieve Analysis for Crushed Stone Sand

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Retained Weight (Gr.)</th>
<th>Percent</th>
<th>Passed Weight (Gr.)</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. 4</td>
<td>0</td>
<td>0</td>
<td>500</td>
<td>100</td>
</tr>
<tr>
<td>No. 8</td>
<td>3</td>
<td>1</td>
<td>497</td>
<td>99</td>
</tr>
<tr>
<td>No. 16</td>
<td>200</td>
<td>40</td>
<td>297</td>
<td>59</td>
</tr>
<tr>
<td>No. 30</td>
<td>148</td>
<td>29</td>
<td>149</td>
<td>30</td>
</tr>
<tr>
<td>No. 50</td>
<td>77</td>
<td>15</td>
<td>72</td>
<td>15</td>
</tr>
<tr>
<td>No. 100</td>
<td>39</td>
<td>8</td>
<td>33</td>
<td>7</td>
</tr>
<tr>
<td>Passing No. 100</td>
<td>33</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>500 Gr.</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table III. Sieve Analysis for Crushed Stone Aggregate

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Retained Weight (Gr.)</th>
<th>Percent</th>
<th>Passed Weight (Gr.)</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1   &quot;</td>
<td>30</td>
<td>1</td>
<td>4970</td>
<td>99</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>917</td>
<td>18</td>
<td>4053</td>
<td>81</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>2413</td>
<td>48</td>
<td>1640</td>
<td>33</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>1012</td>
<td>20</td>
<td>628</td>
<td>13</td>
</tr>
<tr>
<td>No. 4</td>
<td>531</td>
<td>11</td>
<td>91</td>
<td>2</td>
</tr>
<tr>
<td>No. 16</td>
<td>66</td>
<td>1</td>
<td>31</td>
<td>1</td>
</tr>
<tr>
<td>Passing No. 16</td>
<td>31</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>5000 Gr.</td>
<td>100 %</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the time required by ordinary type I portland cement. Extra processing is given to practically every phase of making type III cement. As a result of its shorter curing period, stronger, denser, and more watertight concrete can be obtained\(^{(21)}\).

The mixture proportions for one cubic yard of concrete consisted of the following:

- 680 lb. (7.2 sacks) of type III cement \(\text{Sp. Gr.} = 3.14\)
- 340 lb. \(\text{Gal.}\) of water
- 1510 lb. of Montgomery crushed stone sand \(\text{Sp. Gr.} = 2.72\)
- 1560 lb. of Montgomery crushed stone aggregate \(\text{Sp. Gr.} = 2.71\)

These proportions were corrected for 4.3% moisture content in the fine aggregates. The ratio of fine aggregates to total aggregates was 0.49 by weight. The above mixture, according to Lin\(^{(23)}\), is typical for prestressed concrete.

D. Preparation of Specimens

Sixty-five cylindrical cardboard molds \(6'' \times 12''\) were filled with three layers of concrete, each layer being rodded 10 times. The AASHO Specification\(^{(24)}\) calls for rodding each layer 25 times, but this modification was made to prevent initial setting of the concrete prior to completion of the placing operation. Rodding each layer 10 times seemed to compact the concrete satisfactorily. All specimens were examined when the molds were removed and there was no evidence of separation or honeycombing.
After the molds were filled, four \(1/4\)" x \(1\ 1/2\)" brass plugs, to be used for deformation measurements, were inserted into each concrete specimen through holes previously drilled in the molds. These plugs were inserted in pairs at gage distances of 10 inches along axial gage lines 180° apart.

Having placed concrete in the molds, wax paper was applied on top of each and held in position by wooden covers in order to prevent excessive loss of mixing water by evaporation. After remaining in the laboratory for 24 hours, the specimens were removed from their molds, capped with a manufactured sulphur capping compound, and moved to a curing room having a temperature of 70° F and a relative humidity of 100%. Each of the sixty-five specimens was capped to provide the same area for exposure to the atmosphere.

The specimens remained in the curing room until the seventh day, at which time all but three were moved outside on the laboratory porch where they were stored for the remainder of the experiment. At this time, measurements were made on each of the creep and shrinkage specimens to establish the initial gage distances. In order to acquire the same properties as the creep and shrinkage specimens, the strength and stress-strain specimens were stored along with them throughout the experiment.

E. Properties of the Concrete

A slump test, revealing a slump of about 2 1/2 inches, was made at the time of placing the specimens. The water-cement ratio after correct-
ing for 4% moisture content in the fine aggregates was 5.62 gallons of water per sack of cement (0.5 by weight).

Strength tests at seven days resulted in an average ultimate compressive strength of 5350 psi. Strength tests at ages of 4 days, 23 days, and 90 days resulted in average ultimate compressive strengths of 4910 psi, 6150 psi, and 7060 psi respectively. All of the compressive strengths reported above are averages of three specimens tested at that time. Stress-strain tests were conducted following the strength tests. The testing apparatus did not permit stress-strain data and ultimate strength to be obtained conveniently with the same specimen. The results of all tests are shown in Figures 11 through 14 for ages 4 days, 7 days, 28 days, and 90 days respectively.

The modulus of elasticity was determined at each age by three different methods; (1) initial tangent modulus, (2) secant modulus, and (3) ACI modulus (1000 $f'_c$) (22). These moduli are shown on each of the Figures 11 through 14.

F. Testing Apparatuses and Methods

Deformations in both the loaded and unloaded specimens were measured with a 10 inch Whittemore strain gage (see Figure 1). The gage distances of the brass plugs, measured by this instrument, were indicated on a dial gage to the nearest ten-thousandths (0.0001) of an inch. Each measurement throughout the experiment was made at least three times along each gage line and was recorded if the observed variations were not greater than ± 0.0002 inches. The average of the three
FIGURE 1 WHITTEMORE STRAIN GAGE
RIGHT TO LEFT, THE GAGE, THE
STANDARD CORRECTING BAR AND THE
GAGE PUNCH

FIGURE 2 CREEP APPARATUS
recorded values was used to determine the amount of deformation occurring between periods of measurement for each gage line.

Accessories with the Whittemore strain gage, see Figure 1, include the mild steel temperature correcting bar (gage bar) and the double pointed gage punch. The gage bar was used to zero the gage dial prior to making all measurements. Since the Whittemore gage and accessories were stored in the laboratory, the gage and the gage bar were both moved outside near the test specimens for approximately one hour before measurements were made. This procedure was necessary to allow the mild steel gage bar to reach its equilibrium length for any difference in temperature of the laboratory and the outside. The Whittemore gage, however, would be little affected by temperature variations since its essential mechanisms are made of invar steel. Since mild steel and concrete have similar coefficients of expansion, about $6 \times 10^{-6}$ in./in. per °F, contractions or expansions due to temperature variations in the concrete would not be measured when the gage dial is set to zero each time prior to measuring.

The gage punch was used to make slight indentations in the brass plugs; this procedure provided precise gage points for the tips of the measuring instrument. The two conical points of the gage punch were centered on the brass plugs, and the two ends of the punch were alternately tapped until the indentations were sufficient to yield consistent results when the gage distances were measured with the Whittemore gage.

After measuring the initial gage lengths, three specimens were
placed in each of four creep apparatuses and stressed to their specified levels. Immediately after applying the load to the specimens in each apparatus, a second set of measurements was made on each specimen to determine the amount of elastic (instantaneous) deformation that had occurred. Part of this elastic deformation may have included some creep because of the time involved to load and measure the specimens for each apparatus (25). The time lag amounted to about 15-20 minutes, but measurements were repeated until readings were consistent. Except where it is specifically pointed out later, the elastic strain referred to in this thesis is considered to be the difference between the initial and the second set of measurements for the loaded specimens. All deformations occurring in these specimens after the second set of measurements were made are considered to be creep plus shrinkage.

The desired loads were applied to the specimens by a small portable jack which was inserted between the two upper plates of the creep apparatus, see Figure 2. Upon application of the loads, nuts on four tension rods were drawn down against the lower top plate. The load on the jack was then released, allowing the four large coil springs, between the lower two plates, to maintain the load on the specimens.

For the variable 1000 psi and variable 500 psi specimens, the loads were applied at the beginning of the experiment, the spring plates were bolted in place without further change or adjustment, and the loads were allowed to decrease as deformations occurred in the specimens.

For the constant 1000 psi and the constant 500 psi specimens, the loads were reset to their initial loads immediately after each period of
measurements. Readings were taken once a day initially and were extended to once a week as the creep variation decreased. Measurements were always made in the afternoon when it could be assumed that the total concrete mass would have reached temperature equilibrium with the steel testing apparatus.

Control specimens subjected to the same curing and storage conditions as the loaded specimens, but under no stress, were under observation to determine the changes in length due to shrinkage. The magnitude of creep is reported for this thesis as being the difference between the deformations of the loaded specimens and those of the unloaded specimens. These results are based on the definition of creep as given by Keeton(4), Davis, Davis, and Hamilton(11), and Jones(7).
XII. TEST RESULTS

Figure 3 shows the plots of the deformations occurring in the loaded and unloaded specimens for the five month period of investigation. The curves are plots of the averages of three specimens under each condition of loading and of three control specimens. The four upper curves include elastic (instantaneous) deformations, creep and shrinkage, whereas the lower curve represents shrinkage only.

Subtracting the elastic deformations and the deformations shown on the shrinkage curve from the deformations of the creep plus shrinkage curves gives values for creep only. These values are shown plotted in Figures 4 through 7 for the constant 1000 psi, variable 1000 psi, constant 500 psi, and variable 500 psi conditions respectively. These creep curves are similar to those presented by Keeton(4), Davis, Davis, and Hamilton(11), and Jones(7) for creep experiments conducted under controlled conditions.

Exponential expressions for the creep curves for this five month study were derived empirically by the method of averages(26). The equations for these curves are:

$$\Sigma_{(c-1000)} = 8.718 t^{0.265} \times 10^{-5} \text{ (in./in.)}$$

$$\Sigma_{(v-1000)} = 7.339 t^{0.294} \times 10^{-5} \text{ (in./in.)}$$

$$\Sigma_{(c-500)} = 7.892 t^{0.209} \times 10^{-5} \text{ (in./in.)}$$

$$\Sigma_{(v-500)} = 5.185 t^{0.275} \times 10^{-5} \text{ (in./in.)}$$
where $\Sigma$ is in inches/inch and $t$ is in days.

Experiments by Lorman (1) and Troxell, Raphael, and Davis (27) have indicated that creep reaches a limiting value at some future time, ranging from 20 to 30 years. According to Troxell, Raphael, and Davis (27) and Fluck and Washa (19), about 75% of this creep occurs within the first year. Thus, using one year extrapolated creep values obtained from Eqs. 1 through 4, the ultimate creep may be approximated as being four-thirds of the one year creep values. Troxell, Raphael, and Davis (27) state that the ultimate creep, based on one year, may be predicted with a probable maximum error of $\pm$ 15 percent; periods less than a year will yield larger errors in ultimate creep values. The ultimate creep, as predicted by Eqs. 1 through 4, are shown in Figures 4 through 7 respectively.

Lin (23) defines the creep coefficient as being the total strain, elastic plus ultimate creep strain, divided by the elastic strain; i.e.

$$C_c = \frac{\Sigma_e + \Sigma_u}{\Sigma_e}$$

Using the ultimate creep values obtained from Eqs. 1 through 4 and the elastic strain measured upon first loading the specimens (see Figure 3), the creep coefficients were found to be 2.76, 2.75, 3.13, and 3.00 for Eqs. 1 through 4 respectively. The average creep coefficient for the two conditions of constant stress is 2.94. This is in fair agreement with the value given by Lin (23).

Figures 9 and 10 show plots of average daily temperatures and
average daily relative humidities for the five month period of investigation. These values were recorded and made available by the Virginia Agricultural Experiment Station at Virginia Polytechnic Institute, Blacksburg, Virginia. These curves are plotted to point out the relationship between the variations of shrinkage (Figure 3) and the variations in atmospheric conditions.

Using the derivative of Eq. 1 (derived from the experimental data), the rate of creep for the constant 1000 psi specimens is shown plotted in Figure 8. Creep rate curves for the other load conditions give almost identical results and are not shown.

Stress strain curves for ages 4, 7, 28, and 90 days are shown in Figures 11 through 14 respectively. Also shown on each curve are three values of the moduli of elasticity computed from that curve. The modulus of elasticity was computed by the initial tangent, secant, and the ACI recommended methods.

At various intervals throughout the five month investigation, the loads on the variable stress specimens were checked for losses of stress. For the 500 psi variable stress specimens, about 110 psi (22 %) reduction of stress occurred during the first seven days of loading. For the remainder of the five month period, the stress loss was negligible, or at least too small to register any difference on the gage dial of the hydraulic jack (the smallest increment on the dial was 15 psi). The 1000 psi stress specimens incurred a stress loss of about 140 psi (14 %) during the first seven days of loading and a stress loss of about 35 psi during the remainder of the investigation. The curves of Figure 3
reveal that the variable stress curves departed from the constant stress curves during the first seven days. After this period, the deviations of the variable stress curves from the constant stress curves are nearly constant, corresponding to little or no further reduction of stress.
FIGURE 3  CREEP PLUS SHRINKAGE AND SHRINKAGE CURVES
Figure 4: Creep curve for 1000 psi constant stress

Creep in microns per in. vs. Age in days.

- Initial creep strain: $\varepsilon = 8.71 \times 10^{-5}$
- 1 year creep: $4.7 \times 10^{-5}$ in/in
- Ultimate creep: $55.5 \times 10^{-5}$ in/in
- Creep constant: $C_c = 2.75$

Figure 5: Creep curve for 1000 psi variable stress

Creep in microns per in. vs. Age in days.

- Initial creep strain: $\varepsilon = 7.35 \times 10^{-5}$
- 1 year creep: $4.15 \times 10^{-5}$ in/in
- Ultimate creep: $55.8 \times 10^{-5}$ in/in
- Creep constant: $C_c = 2.75$
Figure 6 Creep Curve for 500 PSI Constant Stress

\[ \varepsilon = 7.892 \pm 0.209 \times 10^{-5} \]

1 Yr. Creep = \(27.1 \times 10^{-5}\) in/in

Ult. Creep = \(36.1 \times 10^{-5}\) in/in

\(C_C = 5.13\)

Figure 7 Creep Curve for 500 PSI Variable Stress

\[ \varepsilon = 5.185 \pm 0.275 \times 10^{-5} \]

1 Yr. Creep = \(25.6 \times 10^{-5}\) in/in

Ult. Creep = \(34.0 \times 10^{-5}\) in/in

\(C_C = 3.00\)
\[ \frac{dF}{dt} = 2.81 \cdot 10^{-3} \times 10^{-5} \]
**Figure 11** Stress Strain Curve at 4 Days

- $f'_c = 4910$ PSI
- Moduli of Elasticity:
  - Initial Tangent Modulus = $4.25 \times 10^6$ PSI
  - Secant Modulus = $4.00 \times 10^6$ PSI
  - A.C.I. Modulus = $4.91 \times 10^6$ PSI
Figure 13: Stress-strain curve at 28 days.

- Initial tangent modulus = \(4.33 \times 10^6\) psi
- Secant modulus = \(4.25 \times 10^6\) psi
- A.C.I. modulus = \(6.15 \times 10^6\) psi

\(f'_c = 6150\) psi
Figure 14  Stress-Strain Curve at 28 Days

Moduli of Elasticity

- Δ - Initial Tangent Modulus = 4.50 x 10^6 PSI
- □ - Secant Modulus = 4.25 x 10^6 PSI
- ○ - A.C.I. Modulus = 7.00 x 10^6 PSI

f'c = 7,000 PSI
Variations in relative humidity have a pronounced effect on shrinkage as shown by the shape of the lower curve of Figure 3 when this curve is compared with the average daily relative humidity curve of Figure 10. The shrinkage increases for lower values of relative humidity and decreases for higher values of relative humidity. It should be noted in general, atmospheric conditions at the test site were such that high values of relative humidity occurred at low temperatures and low values of relative humidity occurred at high temperatures. The above relationship between shrinkage and atmospheric conditions agrees with Carlson, Troxell, Raphael, and Davis, and Lorman, that high temperatures and low relative humidities are favorable factors influencing the rate of shrinkage.

With regard to creep, the effects of variable relative humidity conditions are not nearly so pronounced as for shrinkage. The creep data of Figures 4 through 7 show some fluctuation of the plotted points from the average curve. These fluctuations seem too large to be explained by errors of measurement. When the plots of the creep values are compared with the relative humidity curve of Figure 10, about 50% of the total plotted points vary inversely with the relative humidity values. Not all the creep curve values vary in this manner, for about 28% of the total plotted points show little correlation to the relative humidity values while the remaining 22% of the total plotted points vary directly with the relative humidity values. However, it should be noted
that the relative humidity curve of Figure 10 is plotted from average values for a 24 hour period and does not indicate the actual relative humidity at the time of measurement. Also, concrete requires considerable time to reach equilibrium with the relative humidity condition to which it is subjected. Therefore, for short periods where the relative humidity fluctuates greatly, such as those shown in Figure 10, the concrete may not have been effected sufficiently to show appreciable variations in creep due to these changes.

Besides the possibility of errors in measuring the specimens (see Appendix for Errors Encountered), the fluctuations of the creep values from the average curve (Figures 4 through 7) may be affected by volume change independent of the relative humidity as well as by the change of the relative humidity. The fluctuations may be due to the heterogeneous properties of the concrete; thus the smooth curves usually representing creep may be obtained theoretically but may not be obtained experimentally.

Although the relative humidity may have some effect on creep of concrete, the evidence from this experiment is not sufficient to reach any definite conclusions.

The results of the three specimens kept in the moist room are not reported in this thesis. Erratic measurements were recorded early in the test, so the data were not collected.

The creep equations presented for the curves of Figures 4 through 7 should be used with caution in attempting to predict future creep values since they were derived for the data of the five month period of investi-
gation. Use of these equations may result in extrapolated values which are not representative of the actual long term creep in the concrete. These equations reveal that for any increase in time the value of creep will also increase. According to Troxell, Raphael, and Davis (27), the ultimate creep or limiting value of creep occurs in about 20 years. These researchers state that about 85% of the ultimate creep occurs within the first two years, with 64 to 83% of the ultimate creep occurring the first year. Since about 75% of the ultimate creep occurs within the first year (6, 19, 27), the ultimate creep values for this experiment have been predicted as 4/3 of the one year creep values which were extrapolated from the five month test values. If, however, the ultimate creep were assumed to occur at 20 years and this value were used in Eq. 1, the resulting ultimate creep value would be about 165% of the ultimate creep value as found previously.

The one year creep values extrapolated from Eqs. 1 through 4 may not be truly representative of the actual creep for that period, but because of limited test data, these values were thus used to give some indication of the expected ultimate creep.

The equations presented for the 1000 psi variable and 500 psi variable stress specimens would especially seem to be inadequate for future determinations of creep. The values of creep obtained from these equations at some later time would still be increasing, whereas the loads on the specimens would be decreasing. If creep were approximately proportional to stress (1, 11, 17), or at least a function of stress, the creep would decrease also. The curves of Figure 3 reveal
that the variable stress curves depart from the constant stress curves during the first seven days of loading. After this time, the variable stress curves remain nearly parallel to the constant stress curves for the remainder of the five month period. If creep were a function of stress, the difference in creep between the constant stress and variable stress creep curves would become larger at some later time.

Recalling that nearly all the stress loss occurred during the first seven days, any stress loss after this period probably was not sufficient to show an appreciably greater deviation between the constant and variable stress curves at the same stress level during the five month study. Figure 8 reveals that the rate of creep decreases very rapidly the first seven days and is much slower afterwards. Therefore, since the loss of stress is small, because creep and shrinkage are small, an appreciable time may have to elapse before the creep for the constant stress specimens is noticeably greater than the creep for the variable stress specimens.

The variable creep equations would probably be as representative as the constant creep equations for extrapolating one year values of creep. The ultimate creep for the variable stress specimens, however, should be higher than the actual creep since the \( \frac{4}{3} \) factor applied to the extrapolated one year creep value has been reported for creep under a constant stress. Thus, the actual creep for the variable stress specimens should have values which lie between the extrapolated one year values and the ultimate values.

As pointed out previously, the instantaneous or elastic defor-
mations, that were measured upon first loading of the specimens, may have included some creep because of the time required to complete the loading and measuring operations. The creep coefficients determined by Eqs. 1 through 4 were based on these measured elastic deformations. If, however, the elastic strains were taken from the stress-strain curve, the resulting creep coefficients would be somewhat higher than those previously calculated. Figure 3 reveals the measured elastic strains to be $31.6 \times 10^{-5} \text{ in./in.}$ and $17.0 \times 10^{-5} \text{ in./in.}$ for the 1000 psi and 500 psi respectively. From the seven day stress-strain curve of Figure 12, the elastic strains for the same stresses are $23.5 \times 10^{-5} \text{ in./in.}$ and $11.0 \times 10^{-5} \text{ in./in.}$ respectively. Thus, if the difference between the measured elastic strain and the elastic strain from the stress-strain curve were considered as creep, the numerator of the creep coefficient is increased by this amount. With the numerator having a higher value of creep and the denominator having a lower value of elastic strain, the resulting creep coefficient would be higher than the one calculated using the measured elastic strain.

The creep coefficients, using elastic strain values from the stress-strain curves, are 3.76 and 4.97 for the 1000 psi constant and 500 psi constant stress specimens respectively. The average creep coefficient is 4.36 for the constant stress specimens. The new creep equations for the 1000 psi and 500 psi constant stresses are respectively:

\[ \text{Eq. (5)} \quad \Sigma'_{(c-1000)} = 15.885 t^{0.189} x 10^{-5} \text{ (in./in.)} \]

\[ \text{Eq. (6)} \quad \Sigma'_{(c-500)} = 13.339 t^{0.153} x 10^{-5} \text{ (in./in.)} \]
Using the appropriate creep coefficient with the elastic deformation from the stress-strain curve may be more convenient to predict the ultimate creep than loading and measuring the specimens to determine the elastic deformation. Although the creep values are greater for this second set of equations, the elastic deformations are reduced by the same amount. As a result the net deformation is the same.

As shown in the results for the creep coefficients, the values for the 500 psi loads were greater than those for the 1000 psi loads. However, Lorman¹, Davis, Davis, and Hamilton¹¹, and Pickett¹⁷ assume creep to be approximately proportional to stress during the lower range of loading. The elastic strains are also approximately proportional to stress during the lower range of stress. Thus, the 1000 psi stress specimens should have about twice the values of creep and elastic strain as the 500 psi stress specimens. The creep coefficient for the 1000 psi stress specimens should be about the same as the 500 psi stress specimens since both the numerator and denominator are increased by a factor of two for the 1000 psi specimens.

However, the creep for the 1000 psi stress is not twice that of the 500 psi stress. Nor is the measured elastic strain for the 1000 psi stress twice the elastic strain for the 500 psi stress. Due to the possibility of errors (see Appendix for Errors Encountered) in the observations and the above reasoning, an average value for the creep coefficient is given to represent the potential ultimate creep for the concrete of the experiment.

The results reported in this thesis are far from being conclusive.
The limited time available for the reported experiment and the limited number of specimens tested do not warrant the use of these results in design applications. More investigations of creep and shrinkage are encouraged to indicate more conclusively the results to be expected by limestone aggregate concrete subjected to atmospheric conditions.
XIV. SUMMARY OF TEST RESULTS

Figure 3 shows the plots of the length changes occurring in the loaded and unloaded specimens for the five month period of investigation. These curves acquire their irregular shapes from the atmospheric conditions to which the specimens were exposed. The variation in relative humidity has a pronounced effect on shrinkage, as shown by the fluctuations in the lower curve of Figure 3 when compared with the relative humidity curve of Figure 10. The effect of relative humidity on creep is not nearly so pronounced as for shrinkage. Although the fluctuations of the creep values from the average curves (Figures 4 through 7) show some relation to the relative humidity curve of Figure 10, evidence is not sufficient to reach a definite conclusion as to the effect of relative humidity on creep.

The creep equations, using the measured elastic deformations, presented for the curves of Figures 4 through 7 are:

\[
\begin{align*}
\text{Eq. (1)} & \quad \varepsilon (c-1000) = 8.718 \times 10^{-5} \ t^{0.265} \ \text{(in./in.)} \\
\text{Eq. (2)} & \quad \varepsilon (v-1000) = 7.339 \times 10^{-5} \ t^{0.294} \ \text{(in./in.)} \\
\text{Eq. (3)} & \quad \varepsilon (c-500) = 7.392 \times 10^{-5} \ t^{0.209} \ \text{(in./in.)} \\
\text{Eq. (4)} & \quad \varepsilon (v-500) = 5.185 \times 10^{-5} \ t^{0.275} \ \text{(in./in.)}
\end{align*}
\]

where \( \varepsilon \) is in inches per inch and \( t \) is in days.

The ultimate creep values, predicted from the one year extrapolated values are:
The ultimate creep values predicted for the variable stress specimens are believed to be higher than the ultimate creep which would actually occur in these specimens. The ultimate creep values for these specimens are believed to be between the one year extrapolated values and the ultimate predicted values.

The creep coefficients, determined from the above predicted creep values and the measured elastic strains, are 2.76, 2.75, 3.13, and 3.00 respectively. The creep and elastic strains are approximately proportional to stress; therefore from the definition of the creep coefficient, the 1000 psi specimens and the 500 psi specimens should have nearly equal creep coefficients. To present a creep coefficient to represent the potential ultimate creep for the concrete of the experiment, an average creep coefficient of 2.94 is reported for the constant stress specimens.

The creep equations, using the strain from the stress-strain curves, for the constant stress specimens are:

\[
\text{Eq. (5)} \quad \Sigma'_u(c-1000) = 15.385 t^{0.189} \times 10^{-5} \text{ (in./in.)}
\]

\[
\text{Eq. (6)} \quad \Sigma'_u(c-500) = 13.339 t^{0.153} \times 10^{-5} \text{ (in./in.)}
\]
The ultimate creep values, predicted from the one year creep extrapolations are:

\[
\begin{align*}
(5) \quad \frac{\Sigma^t}{u(c-1000)} &= 64.7 \times 10^{-5} \text{ (in./in.)} \\
(6) \quad \frac{\Sigma^t}{u(c-500)} &= 43.7 \times 10^{-5} \text{ (in./in.)}
\end{align*}
\]

These ultimate creep values are greater than the values predicted by the previous equations, however, the net deformations remain the same. The creep coefficients for the above ultimate creep values are 3.76 and 4.97 respectively, with an average of 4.36. Hence, whichever designation of the elastic strain is used, the corresponding creep coefficient should be used accordingly.

The results reported in this thesis are too limited to be conclusive. Further investigations of creep and shrinkage, under similar conditions as this experiment, should be conducted.
A. Problems Encountered

1. Material for Plug Inserts

During the planning phase of the experiment, the type of material to be used for the plug inserts received considerable discussion. Brass, reinforcing steel, and stainless steel were considered as possible materials for the plugs.

Since the specimens under investigation were to be exposed to moist and atmospheric conditions, reinforcing steel was eliminated because of its nature to corrode easily when exposed to these conditions. The corrosive or rust particles formed in the plug indentations would be sufficient to yield faulty measurements when using the sensitive Whittemore strain gage.

Stainless steel was eliminated because of its hardness. The possibility of breaking the bond between the stainless steel plug and the concrete when marking the plugs excluded the use of this material.

Brass plugs were considered undesirable at first due to the difference in expansion characteristics between brass and concrete. Brass has a coefficient of expansion of about $18.5 \times 10^{-6} \text{ in./in. per}^{\circ} \text{F}$ while concrete has a coefficient of about $6.0 \times 10^{-6} \text{ in./in. per}^{\circ} \text{F}$. Therefore, under decreasing temperatures, the brass would tend to contract more than the concrete and would cause the plugs to become loose. However, after experimenting with various specimens
containing brass plugs, no loosening of the plugs was observed. Hence, plugs, 1 1/2 inches in length, were cut from 1/4 inch round stock and were used with satisfactory results during the five month investigation.

2. Marking the Brass Plugs

The type of gage point marks or indentations to yield consistent results with the Whittemore gage was another problem encountered in the planning phase.

An attempt was first made to use a reamer to form depressions in the brass plugs for the conical tapered points of the Whittemore gage, see Figure 1-A. Consistent measurements were not obtained by this procedure unless, possibly, a reamer having the same degree of taper as the points of the strain gage was used, see Figure 2-A. This type of reamer was not available at the beginning of the experiment and therefore was not used.

Another procedure tried was to drill a very fine hole (1/16") in the brass plugs and then slightly ream the hole to fit the points of the strain gage, see Figure 3-A. This procedure yielded more consistent results than by using only the reamer, but it was not considered sufficient for use in the experiment.

The temperature correcting bar yielded consistent readings when the gage points were applied to two pin-pointed holes in the bar. The gage punch was therefore used to slightly indent the brass plugs, see Figure 4-A. This method resulted in more consistent readings than any of the previously tried methods and was used in marking the brass
plugs in the specimens of the experiment.

B. **Errors Encountered**

A knowledge of the most likely errors to occur may aid the experimenter in obtaining more accurate measurements with the Whittemore gage. When experimental conditions are such that the temperature varies throughout the experiment, it is necessary to allow the temperature correcting bar to reach the equilibrium position for the temperature at which it is to be used. Measurements made prior to allowing the gage bar to adjust to the new temperature may yield values that are too low or too high, depending upon whether the new temperature is respectively greater or less than the previous temperature at which the gage bar was exposed. If the temperature of the gage bar were known at the time of measurement, a correction for any temperature differential may be applied to the measured values. This procedure would require a special thermometer attached to the gage bar and would be somewhat more inconvenient than allowing the gage bar to adjust to the new temperature.

Due to the sensitivity of the Whittemore gage, errors may be introduced into the measurements by inconsistent usage of the gage. The gage should be held perpendicular to the specimen or at the same angle each time when measuring the specimens. Measurements made at different angles may be in error as much or more than the actual creep and shrinkage deformations occurring for the interval between observations.
Applying the same pressure to the gage each time is also important in minimizing errors in the measurements. Acquiring a "feeling" for the gage is necessary to properly seat the gage points in the indentations in the brass plugs. The errors introduced from this cause may also be in excess of the incurred deformations of creep and/or shrinkage between observations.

Since the deformations of creep and shrinkage are in the order of thousandths of an inch for the 10 inch gage length, extreme accuracy is essential for valid results.
XVI. ACKNOWLEDGMENTS

The author is indebted to Professor W. W. Payne for his guidance and assistance throughout the investigation.

Sincere appreciation is expressed to Dr. H. M. Morris, Head, Department of Civil Engineering, for his encouragement and assistance, enabling the author to undertake graduate studies.

Sincere appreciation is also expressed to Dr. G. A. Gray, Department of Civil Engineering, for his assistance throughout the author's graduate studies.

The author expresses his thanks to Professor J. H. Lillard, Professor of Research, Agricultural Engineering, for providing temperature and relative humidity records for the period of investigation.

The author is indebted to Charles , a senior Civil Engineering student, for his assistance in the laboratory during the investigation. The author also expresses his appreciation to Tom , a junior Building Construction student, for lettering the tables and figures in this thesis.
XVII. BIBLIOGRAPHY


2. These references are tabulated in the bibliography of reference (1).


8. Joint ACI-ASCE Committee 323 Report; Proceedings of the American Concrete Institute; Vol. 49, 1953, p. 86.


10. These references are tabulated in the bibliography of reference (5).


17. Pickett, G.; "The Effect of Change in Moisture Content of the Creep of Concrete Under a Sustained Load." Proceedings of the American Concrete Institute; Vol. 38, 1942, pp. 333-356.

18. Lyse, I.; "The Shrinkage and Creep of Concrete." Magazine of Concrete Research; Vol. 11, Number 33, November 1959, pp. 143-150.


The vita has been removed from the scanned document.
AN EXPERIMENTAL STUDY OF CREEP AND SHRINKAGE
OF EXPOSED LIMESTONE AGGREGATE CONCRETE

Abstract

This thesis presents an experimental study of creep and shrinkage of concrete made from local limestone aggregate and type III cement. The cylindrical test specimens were exposed to the atmosphere in order to observe the effects that variations of temperature and relative humidity had upon creep and shrinkage. These effects are shown by graphical presentations in the thesis.

Creep strains for the five month period of investigation are shown graphically for each of four conditions of stress, 1000 psi constant stress, 1000 psi variable stress, 500 psi constant stress, and 500 psi variable stress. Exponential equations for these curves were derived from the creep data of the five month study. Ultimate creep values were predicted from these equations and are presented together with their respective creep coefficients. These values are given to represent the anticipated creep for limestone aggregate concrete subjected to field conditions.