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CREEP BEHAVIOR OF PORTLAND CEMENT MORTAR AND CONCRETE UNDER BIAXIAL STRESS

Final Report

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ABSTRACT

Equipment developed at the Oak Ridge National Laboratory was used to make uniaxial and biaxial creep tests on mortar, normal weight concrete and lightweight concrete using both sealed and unsealed specimens. Some of the results are questionable because of the poor performance of the strain gages. Nevertheless, useful information was obtained on shrinkage, creep and Poisson's ratio. Generally speaking, the results were consistent with the work of other investigators. Both the shrinkage and creep were highest for the mortar and lowest for the normal weight concrete and intermediate for the lightweight concrete. The shrinkage and creep were highest for the unsealed specimens. A Poisson's ratio effect in creep was noted but the magnitudes were slightly less than those expected for elastic loadings.

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1. INTRODUCTION

1.1 Initiative for this Study

By early 1970, the Oak Ridge National Laboratory had completed the construction of apparatus for testing concrete under uniaxial and biaxial stresses. The equipment consisted of four uniaxial and eight biaxial creep testing frames, loading systems, pressure maintaining systems, special mechanical strain gages, molds, sealing apparatus and related accessories. Because of changes in their program, they were not able to use this special equipment and offered it to the University of Illinois provided an acceptable program of study using it was completed and reported. The University had to provide, in addition, an electric hydraulic pump and strain gage readout equipment.

No funds were provided for this study. This lack of financial support became a most serious problem since the University of Illinois' budget was reduced at the time the study was to start. This had not been anticipated at the time agreement on the contract was reached. The lack of funds resulted in the program being extended over several years with many changes in personnel, including the principal investigator.

1.2 Scientific Background

Although the behavior of concrete under multiaxial stresses has been investigated for many years, interest was increasing at this time because of the advent of nuclear pressure vessels which are subjected to a complex state of stress. The behavior of concrete under multiaxial stresses is also of importance in the design and estimation of the long time performance of other engineering structures incorporating plates and shells.

Numerous studies have been conducted to determine experimentally the short time strength behavior of concrete subjected to multiaxial stress states. Detailed literature reviews on this topic are available (1, 2)*. It is generally agreed that the strength of concrete under triaxial compression is larger than the strength of concrete under uniaxial compression, and that it approximately follows Mohr's failure theory although the intermediate stress has some effect.

Under a biaxial stress state of equal compression in two perpendicular directions, the strength of concrete may be from 10 to 20 per cent larger than the uniaxial strength. However, some data (3) indicate that this strength increase is dependent on the particular type and concentration of aggregates used. No significant strength increase of concrete under biaxial compression is likely to occur for lightweight aggregate concrete. For mortar, the strength increase is less than for normal aggregate concrete.

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* Numbers in parentheses refer to the list of references.

The modulus of elasticity and Poisson's ratio under short time loadings are essentially independent of the shear state to which concrete is subjected.

Some tests on the behavior of concrete under restrained biaxial stresses, particularly creep, have been reported (4-10). The evaluation of creep deformations under multiaxial stresses is greatly facilitated if the principle of superposition can be applied:

$$\varepsilon_1 = \varepsilon_{c1} - \nu_c \, \varepsilon_{c2} - \nu_c \, \varepsilon_{c3} \tag{1}$$

where ε_1 = total creep strain in direction 1,

$\varepsilon_{c1}, \varepsilon_{c2}, \varepsilon_{c3}$ = creep strains in directions 1, 2, 3, caused by principal stresses acting in these directions only, and

ν_c = Poisson's ratio for creep

Assuming that creep is proportional to stress and that ν_c is constant, Eq. 1 can be reduced to

$$\varepsilon_1 = \{\sigma_1 - \nu_c \, (\sigma_2 + \sigma_3) \} \cdot \bar{\varepsilon}_c \tag{2}$$

where $\sigma_1, \sigma_2, \sigma_3$ = principal stresses, and

$\bar{\varepsilon}_c$ = specific creep, uniaxial creep strain per unit stress.

If ν_c is constant and independent of the applied stress ratio, then creep under multiaxial stress states can be determined from the specific creep and Poisson's ratio as determined in uniaxial creep tests.

In several previous investigations (4-10) Poisson's ratio for creep have been determined. However, the results from these studies are contradictory. Some investigators found the Poisson's ratio for creep to be 0 (4, 5), others reported values between 0.05 and 0.15 (9) while one researcher (8) reported that Poisson's ratio for creep is approximately equal to the elastic Poisson's ratio. If the latter were true, estimation of creep under multiaxial stresses would be very much simplified, as shown above.

It is generally agreed that the discrepancies between previous investigations are at least in part due to differences in test conditions. One researcher (10) suggested that the Poisson's ratio for creep is to a large extent dependent on the moisture content and drying conditions of concrete while under load. Poisson's ratio for creep of concrete which does not dry during loading is almost equal to the elastic Poisson's ratio; however, it is considerably smaller for concrete which is allowed to dry under load. Poisson's ratio for creep also appears to be dependent on the ratio of applied stresses, and is largest in the direction of the smallest principal stress (9).

There are no data presently available clearly showing the effect of aggregate concentration on the creep of concrete under multiaxial stresses. Some data (11) show that aggregate stiffness can have a significant effect on creep of specimens under multiaxial load and that the differential for different stiffnesses depends on whether the concrete is sealed or not.

1.3 Experimental Program

The summary of previous research indicates that Poisson's ratio for creep of concrete under multiaxial stresses may be highly influenced by the moisture state of concrete during loading, and the applied stress ratio. The objective of this investigation was, therefore, to investigate the influence of these parameters upon the creep behavior of mortar and concrete under multiaxial stresses and to check the validity of previously reported and contradicting experimental data. The study was limited to studies of biaxial stress states in compression only.

Because of the limited capacity of the available testing equipment, the experimental program was subdivided into two phases, as shown in Table 1.

2. EXPERIMENTAL PROCEDURES

2.1 Materials

Type 1 portland cement was used to manufacture all the specimens.

All the aggregates, sand, gravel and lightweight aggregate, met all the appropriate American Society for Testing and Materials specifications. The gravel had a nominal 1-in. (25-mm) maximum size. The lightweight aggregate was made in a rotary kiln and had a 3/4-in. (19-mm) maximum size. No admixtures were used.

2.2 Fabrication of Specimens

All materials were proportioned in general accordance with the recommendations of the American Concrete Institute, mixed in a counter rotating pan mixer and vibrated into rigid machined molds. The specimens were 3 by 6 by 6-in. (76 by 15.2 by 15.2-mm) prisms. At an age of about 24 hr. the specimens were moved from the molds and placed in a 100 RH, 73F (23C) room for curing.

The specimens for Phase A were kept in the moist room until an age of 90 days when they were removed and placed in a 50 RH, 73F (23C) environment, either loaded or unloaded.

The specimens for Phase B specimens were kept in the moist room until sealed in copper. These specimens were coated with epoxy before being sealed with the aid of special apparatus to assure that there were no voids between the copper and the concrete. The joints in the copper were sealed with solder. These specimens were also loaded at an age of 90 days.

The strain measuring devices were specially developed for this project and had not been used previously. Portions of the gages had to be embedded at the time of casting. Extreme caution was required for the sealed specimens to assure that an adequate seal was developed around portions of the gage without interfering with its operation.

2.3 Strength

The average compressive strength of the concretes and mortar at the time of loading was approximately 6000 psi (41.4 MPa).

2.4 Loading

The specimens were loaded on the 3 by 6-in. (76 by 15.2-mm) faces through rigid aluminum platens with thin teflon sheets between the platens and the specimen. The loads shown in Table 1 were generated and maintained by a hydraulic system.

Strain gage readings were taken before loading. The strain gage had a feature which permitted gas pressure to be applied to the gage at the beginning and any time during the tests to determine if there was creep or other deformation in the gage which might affect accuracy. Any drift was applied to subsequent strain readings as a correction. Therefore, readings were also taken with the gas pressure applied before a load was applied.

The load was applied in a few seconds and the first strain gage readings under load were normally taken 5 min. after loading was initiated. The interval between strain readings increased with age.

3. EXPERIMENTAL RESULTS

3.1 Introduction

For the unsealed specimens the shrinkage is shown in Figs. 1 to 3 and the creep in Figs. 7 to 15. For the sealed specimens the shrinkage is shown in Figs. 4 to 6 and the creep in Figs. 16 to 24. Values of Poisson's ratio computed from the creep data are shown in Figs. 25 through 33. In these figures strain is represented by ε and Poisson's ratio by ν. The subscripts, V, H, and T, represent the principal planes.

Therefore, all of the data which are shown in the figures comes directly or indirectly from readings of the loads and strains during the tests. The loads were determined reasonably accurately. However, there exists considerable doubt as to both the sensitivity and accuracy of the strain readings. The difficulty apparently lies within the strain gage.

3.2 Shrinkage and Creep of Unsealed Specimens

When a creep test on an unsealed specimen is made, both the shrinkage and creep are measured and in order to determine the creep the shrinkage must be subtracted from the measurements obtained in the laboratory. Thus, accurate determination of the shrinkage is mandatory for an accurate determination of the creep. The shrinkage behavior of the unsealed mortar, Fig. 1, normal weight concrete, Fig. 2, and lightweight concrete, Fig. 3, appears to be reasonable. The appropriate values shown in these three figures were subtracted from the measured combined shrinkage and creep to obtain the creep curves shown in Figs. 7 through 15.

The creep curves shown in Figs. 7 through 15 appear reasonable and of appropriate magnitude for most specimens. However, there are a number of discrepancies. For instance, the transverse strains in Figs. 9, 10, and 12 do not appear to be correct. Also, when equal biaxial stresses were applied the vertical and horizontal creep should have been of equal magnitude but they were not for the mortar, Fig. 8, although close for the normal weight concrete, Fig. 11, and the lightweight concrete, Fig. 14.

3.3 Shrinkage and Creep of Sealed Specimens

The data for the shrinkage of the sealed specimens, Figs. 4 to 6, are so poor that it was impossible to determine the proper location of the curves. One reason for these results might be because of leaks in the seals. While there is an indication of some leakage, the large scatter in the data indicates problems with the strain gages. The problem is compounded by the difficulty of sealing around the gages without interfering with their operation and the small shrinkages which occur in sealed specimens.

Consequently, considerable judgment was required in determining the creep curves for the sealed specimens, Figs. 16 to 24. Some leakage probably occurred in BM3, Fig. 16, and BM1, Fig. 17 because the transverse strains tend to decrease rather than increase with time. However, similar unexplained trends were indicated in the several unsealed specimens.

4. ANALYSIS OF RESULTS

4.1 Shrinkage

The shrinkage of the unsealed specimens, Fig. 1 to 3, was consistent with previous results. It was greatest for the mortar, least for the normal weight concrete, with the lightweight aggregate concrete in between. However, the magnitude of the shrinkage for all three materials was slightly less than expected.

The shrinkage of the sealed specimens, Fig. 4 to 6, is difficult to assess because of poor results. Nevertheless, the relative shrinkage of the three materials appears to be appropriate although the magnitude of the shrinkage appears to be higher than expected when compared with that of the unsealed specimens.

4.2 Creep

Although the data are not sufficiently accurate for detailed analysis some general indications which are consistent with published data are evident.

In general, creep strain in the direction of the maximum stress, σ_1, is of the greatest magnitude under a uniaxial force. As the lateral stress, σ_3, is increased, the creep strain parallel to σ_1, is expected to decrease even though σ_1 has not changed. The data for neither the sealed nor unsealed specimens fully support this expectation, but the indication exists. Also, it is clear that when the lateral stress is one-third of the vertical stress, the creep strains are also in this approximate ratio, that is, the specific creep is approximately the same.

The sealed specimens exhibited less creep than the unsealed specimens as expected; however, the difference was greater than anticipated.

The magnitude of creep was greatest for the mortar and that for the lightweight concrete was somewhat greater than for the normal weight concrete.

4.3 Poisson's Ratio

Poisson's ratios computed from the creep strain data are shown in Figs. 25 to 33 for the unsealed specimens. The data from the sealed specimens were not sufficient to permit determining Poisson's ratio. Although the results vary considerably from specimen to specimen and even, in some cases, at different ages for the same specimen, it is clear that there is a Poisson's ratio effect for creep. Poisson's ratio for the unsealed mortar and concretes tested appears to average about 0.15. This magnitude and variation are similar to those found by Kennedy (12).

5. SUMMARY AND RECOMMENDATIONS

5.1 Summary

Although much of the data from the strain measuring gages was doubtful, the general behavior was consistent with the results of other investigators.

The shrinkage was greatest for the mortar, least for the normal weight concrete, and intermediate for the lightweight concrete for both the sealed and unsealed specimens.

The unit creep was greater for a uniaxial stress than for a biaxial stress. As the major stress in a biaxial loaded specimen was kept the same for all specimens and the minor stress increased, there is some indication that the unit creep decreased. Also, the specific creep in a biaxial loaded specimen appeared to be similar in the directions of the stresses. The sealed specimens exhibited less creep than the unsealed specimens. The creep was greatest for the mortar and that for the lightweight concrete was somewhat greater than for the normal weight concrete.

A Poisson's ratio effect was noted for both the sealed and unsealed specimens, although for the sealed specimens the results are too variable to make any conclusions. For the unsealed mortar and concretes the creep Poisson's ratio appeared to be about 0.15, somewhat less than the expected elastic Poisson's ratio.

5.2 Recommendations

Since the strain gages used in these tests did not perform satisfactorily, the tests could be rerun profitably provided adequate funding and accurate strain measuring devices are available. Such tests would determine more precisely the effect of moisture on creep and the relative magnitudes of creep, Poisson's ratio, for the different loadings and for different types and quantities of aggregates.

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Table 1

Experimental Program and Specimen Designations

Stress, psi*		Mortar	Concrete	
σ_1	σ_3		Normal Wt.	Light Wt.
Phase A (50% R.H., 73F*)				
2000	2000	AM1	ANW1	ALW1
2000	670	AM2	ANW2	ALW2
2000	0	AM3	ANW3	ALW3
0	0	AM4	ANW4	ALW4
Phase B (sealed, 73F)				
2000	2000	BM1	BNW1	BLW1
2000	670	BM2	BNW2	BLW2
2000	0	BM3	BNW3	BLW3
0	0	BM4	BNW4	BLW4

* 73F = 23C
2000 psi = 13.8 MPa
670 psi = 4.6 MPa

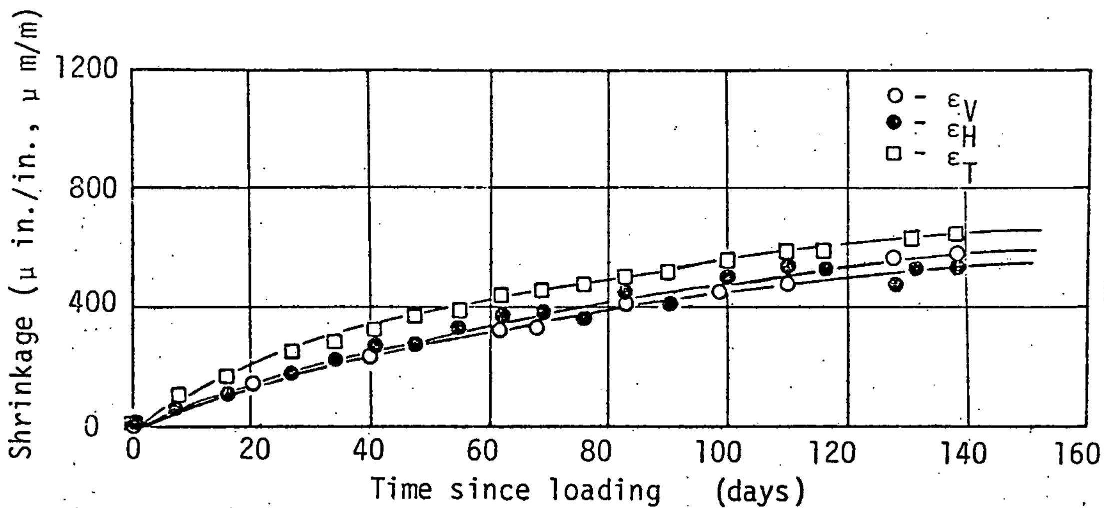

Fig. 1 -- Shrinkage of unsealed mortar: AM4

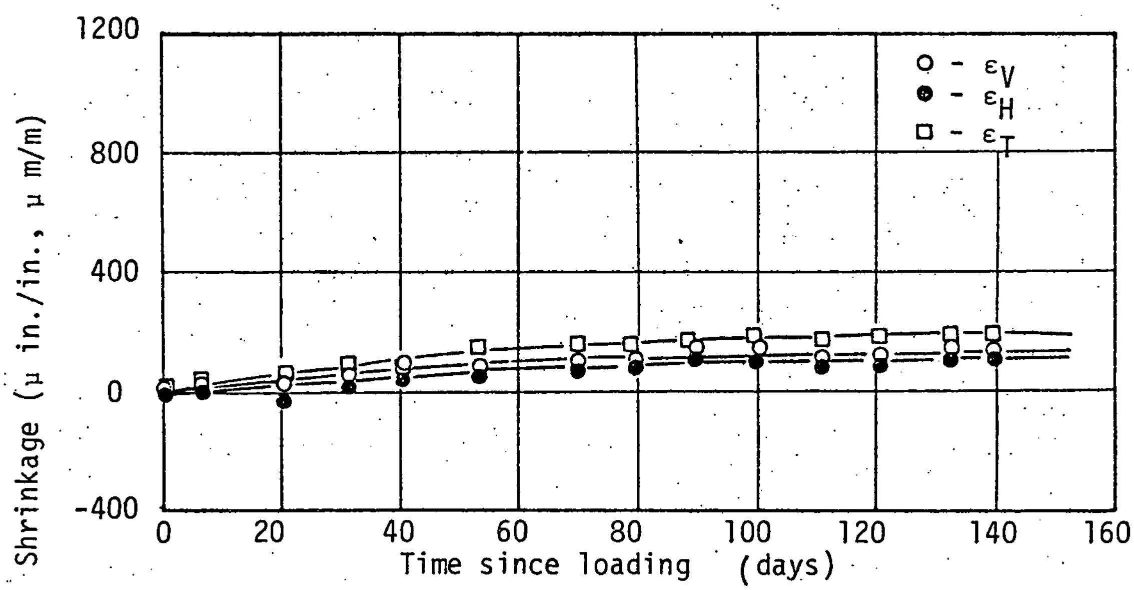

Fig. 2 -- Shrinkage of unsealed normal weight concrete: ANW4

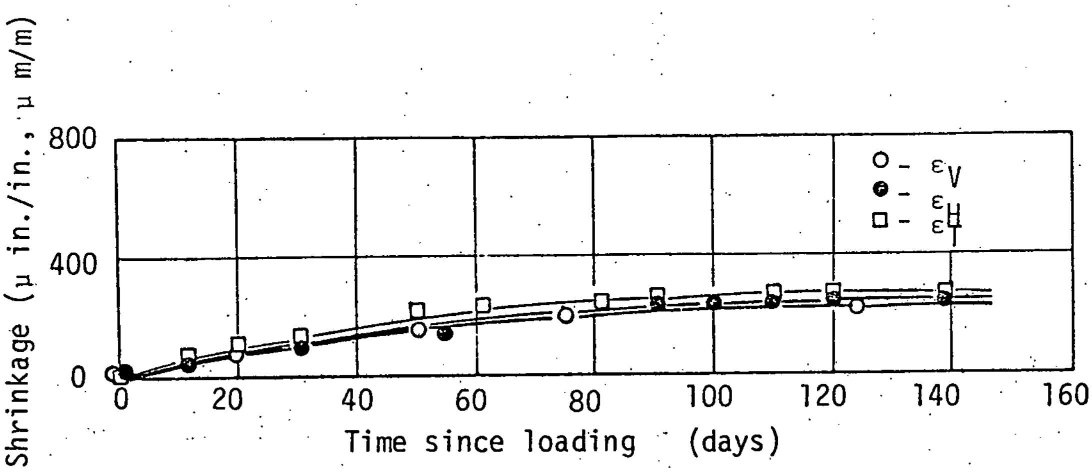

Fig. 3 -- Shrinkage of unsealed light weight concrete: ALW4

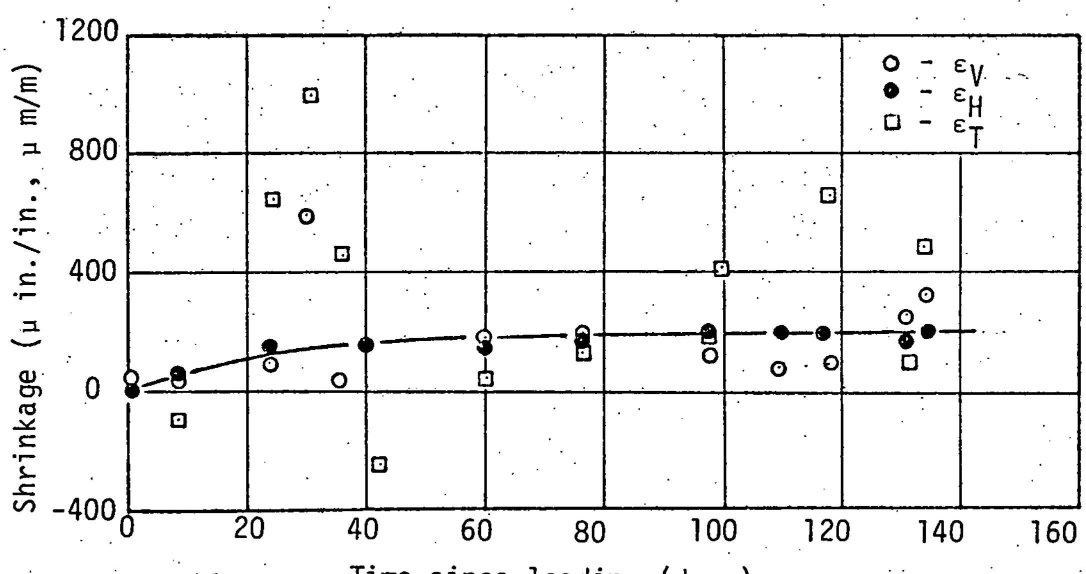

Fig. 4 -- Shrinkage of sealed mortar: BM4

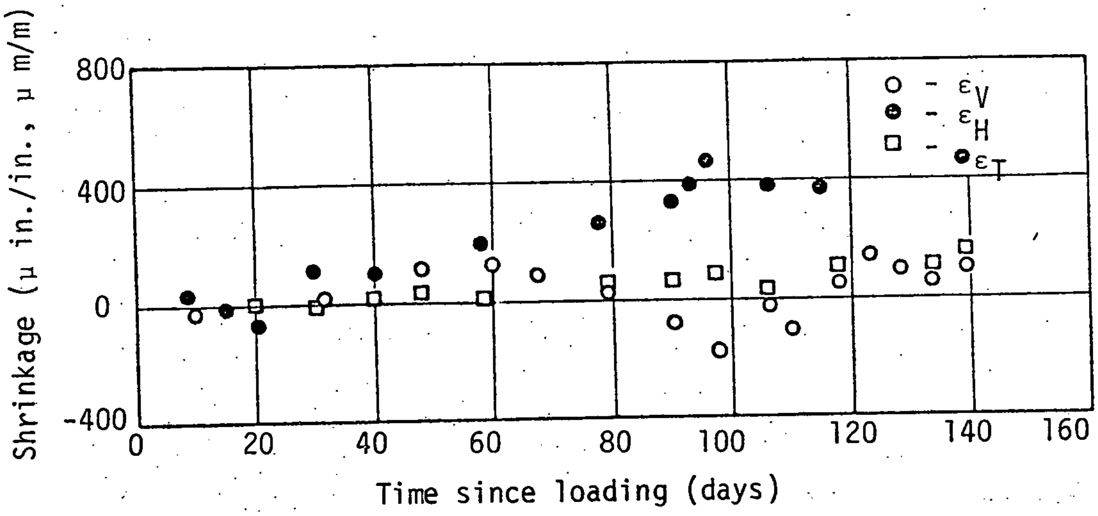

Fig. 5 -- Shrinkage of sealed normal weight concrete: BNW4

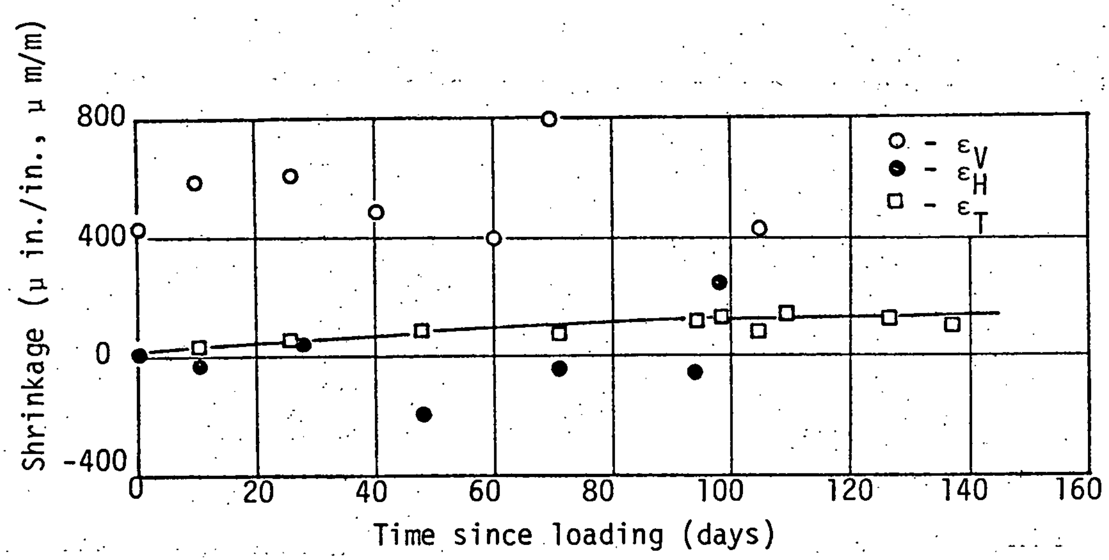

Fig. 6 -- Shrinkage of sealed light weight concrete:BLW4

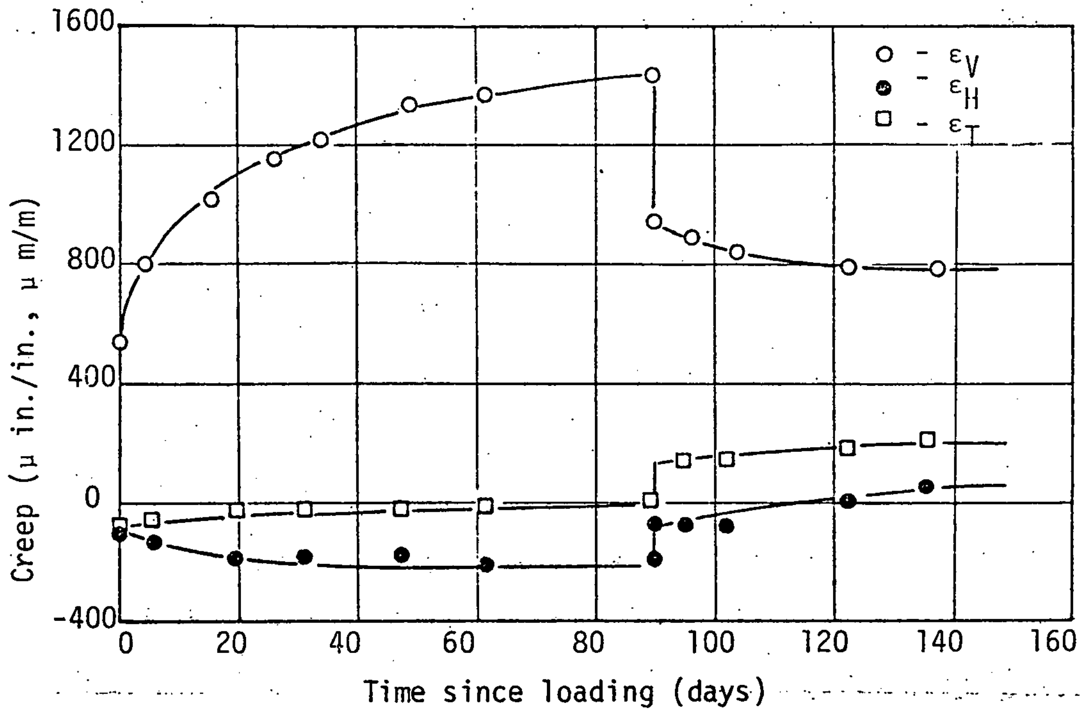

Fig. 7 -- Creep of unsealed mortar under uniaxial load: AM3

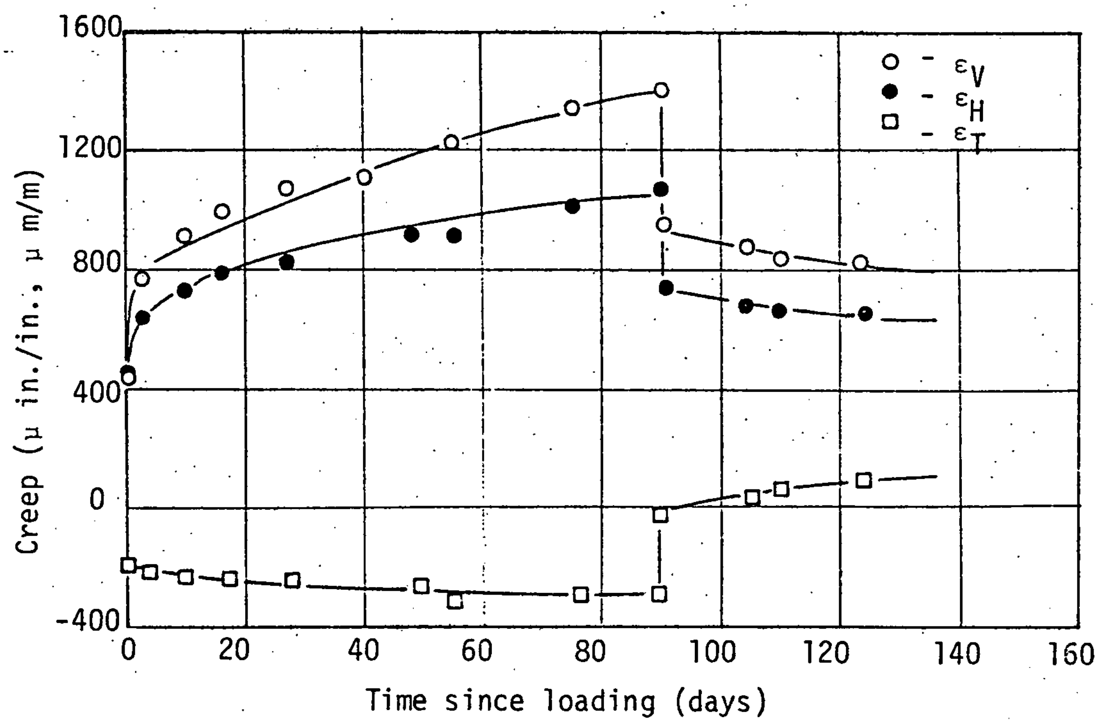

Fig. 8 -- Creep of unsealed mortar under equal biaxial loads: AM1

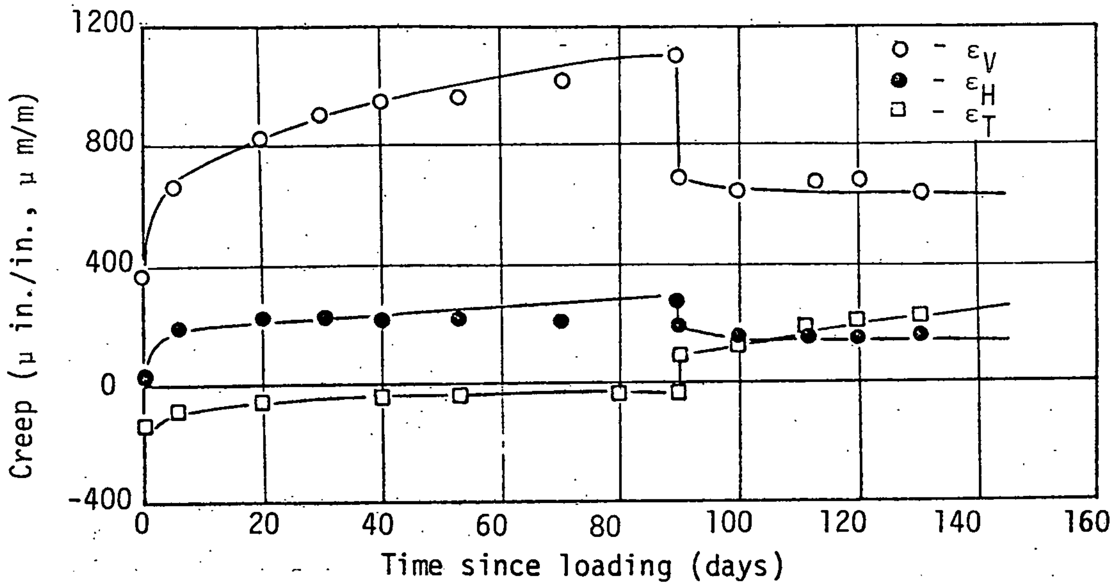

Fig. 9 -- Creep of unsealed mortar under unequal biaxial loads:AM2

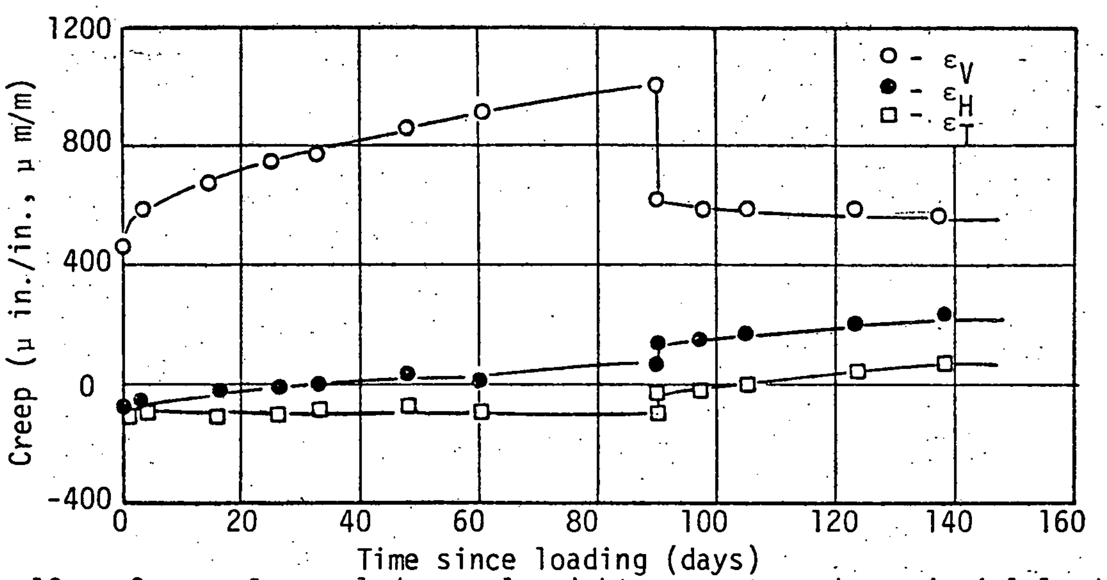

Fig. 10 -- Creep of unsealed normal weight concrete under uniaxial load: ANW3

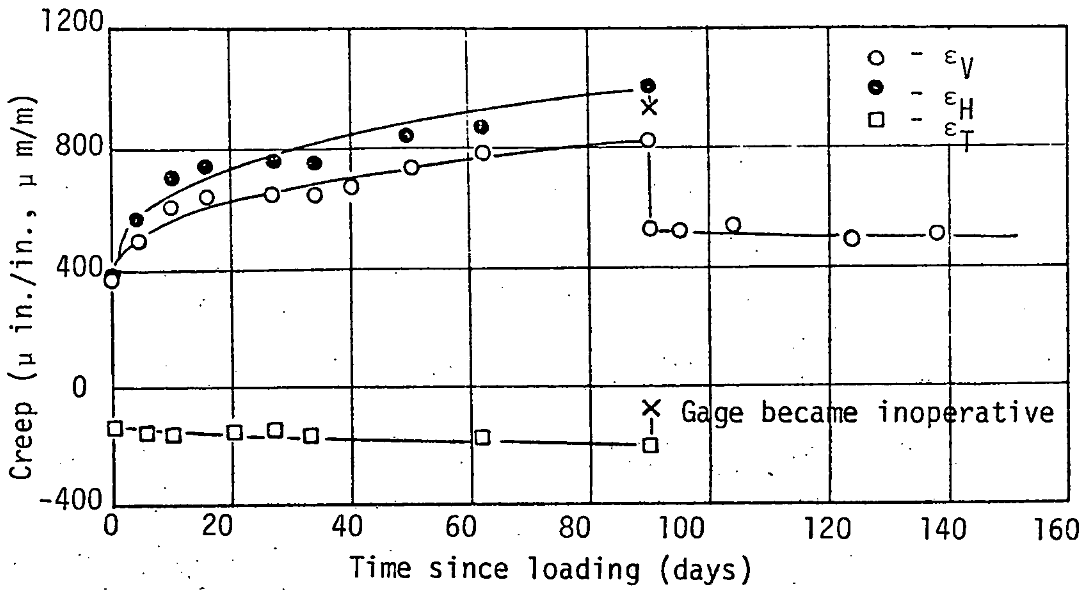

Fig. 11 -- Creep of unsealed normal weight concrete under equal biaxial loads: ANW1

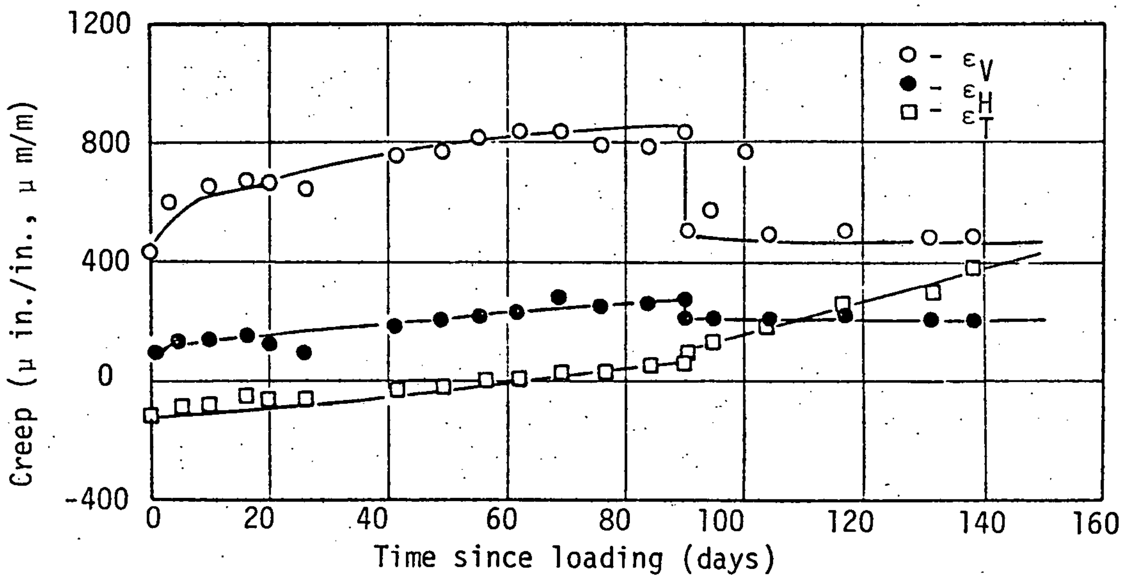

Fig. 12 -- Creep of unsealed normal weight concrete under unequal biaxial loads: ANW2

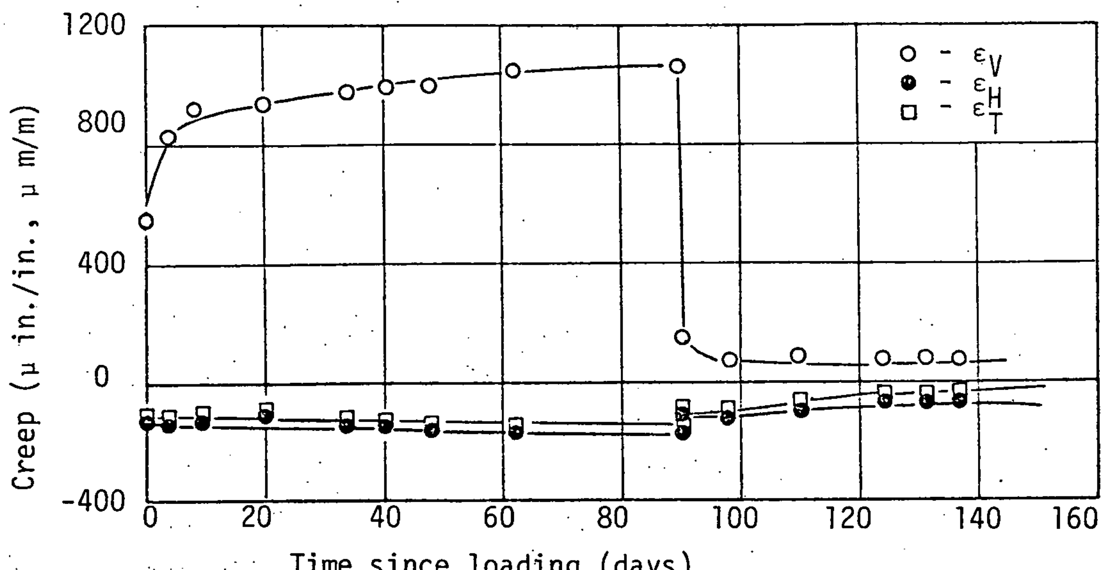

Fig. 13 -- Creep of unsealed light weight concrete under uniaxial load: ALW3

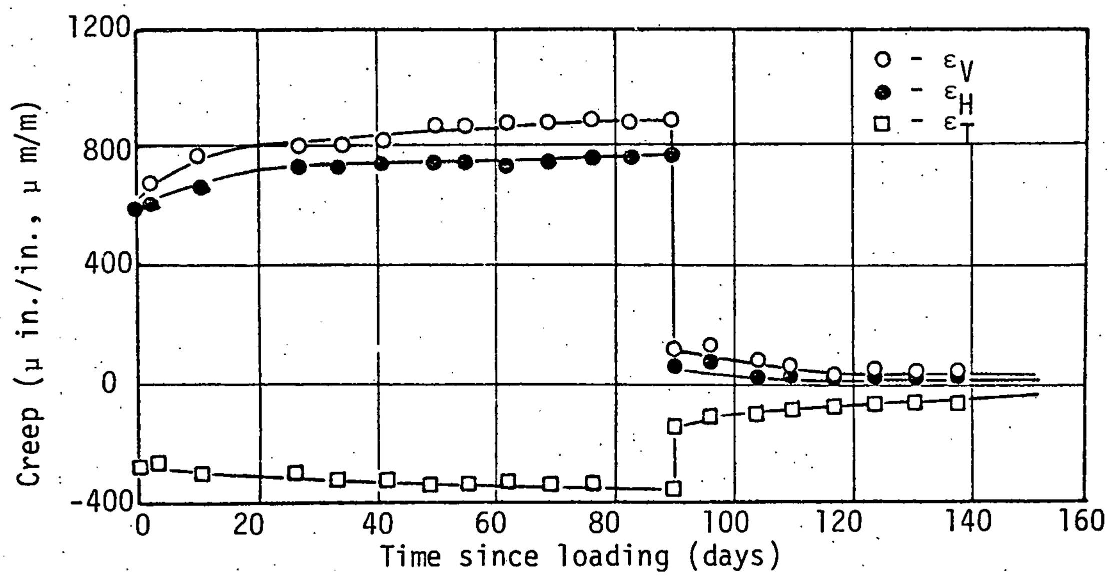

Fig. 14 -- Creep of unsealed light weight concrete under equal biaxial loads: ALW1

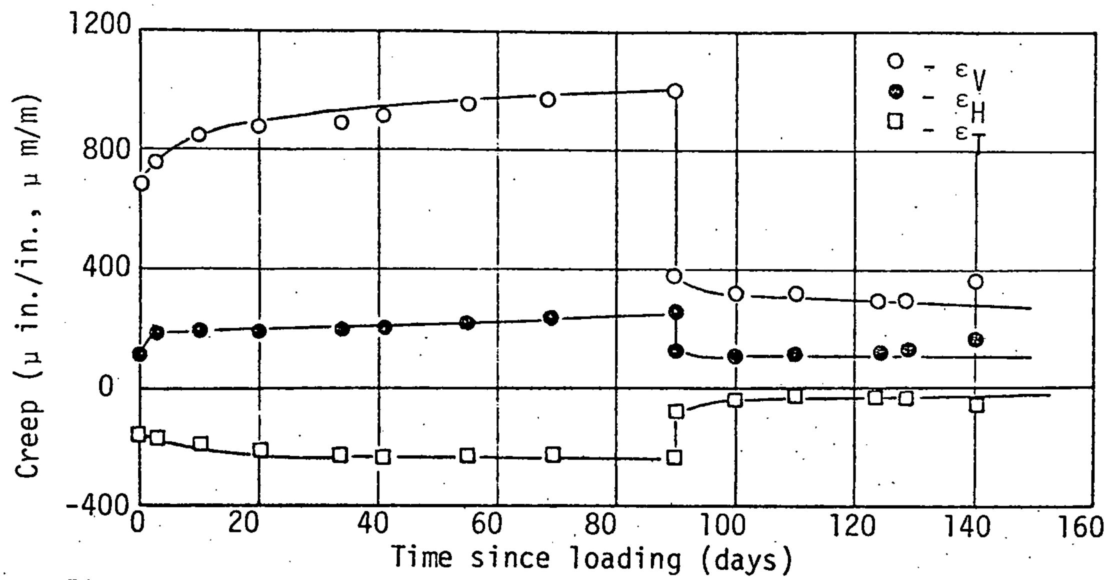

Fig. 15 -- Creep of unsealed light weight concrete under unequal biaxial loads: ALW2

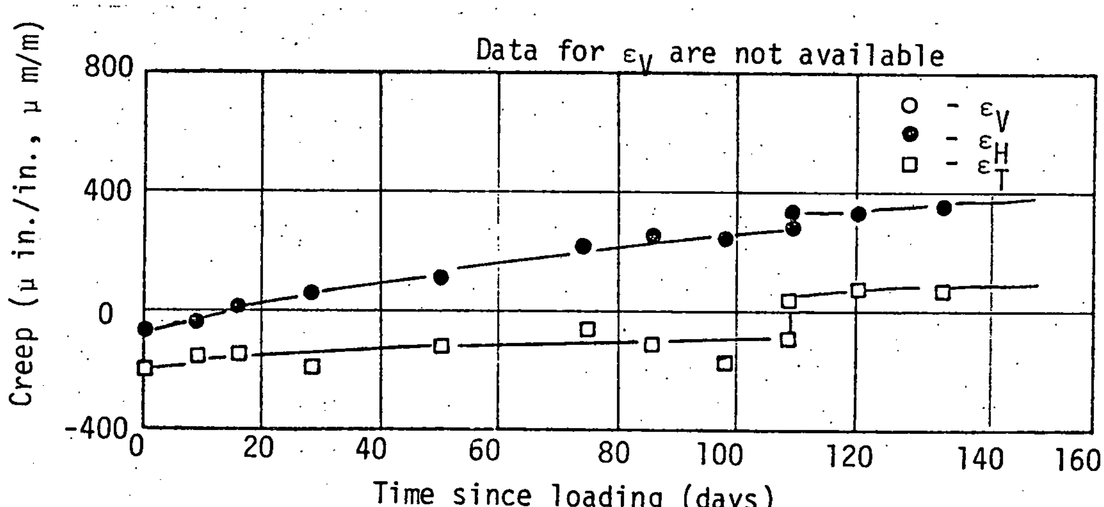

Fig. 16 -- Creep of sealed mortar under uniaxial load: BM3

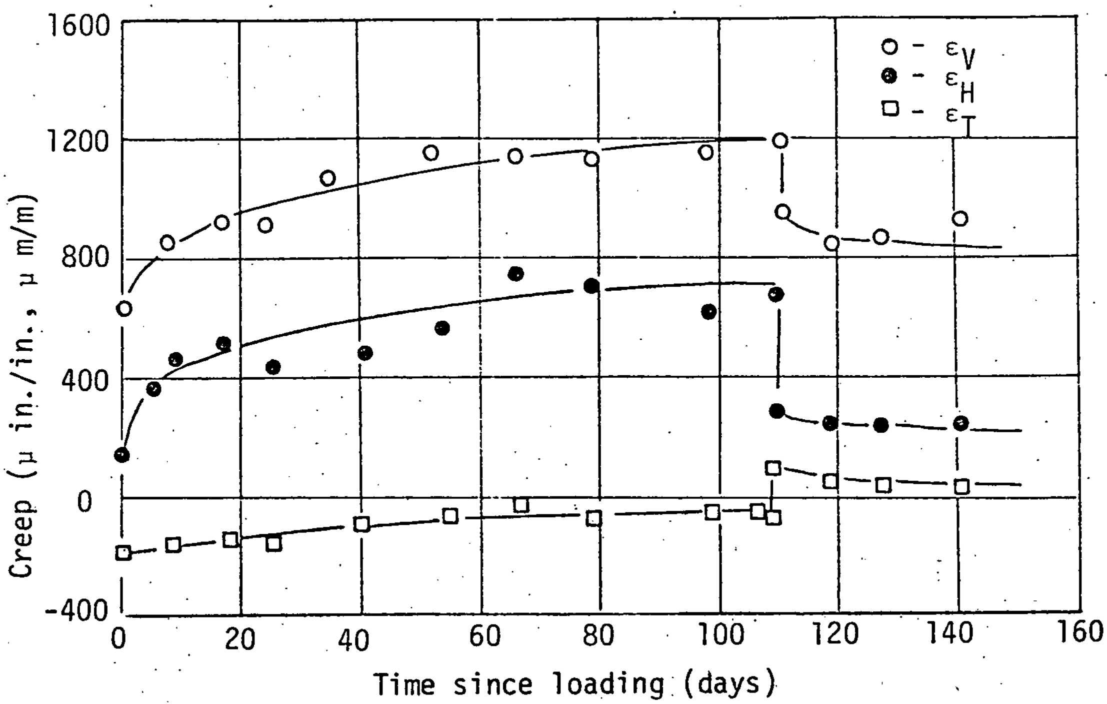

Fig. 17 -- Creep of sealed mortar under equal biaxial loads: BM1

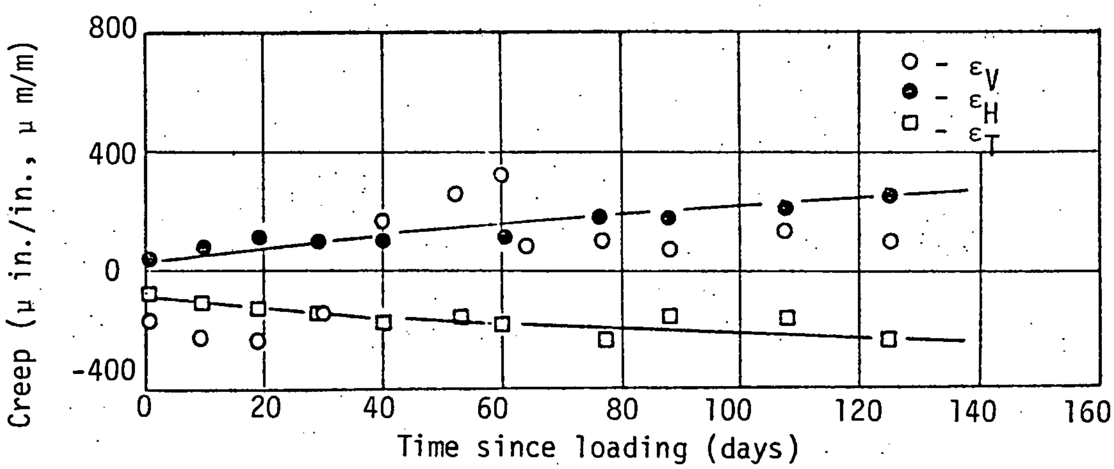

Fig. 18 -- Creep of sealed mortar under unequal biaxial loads: BM2

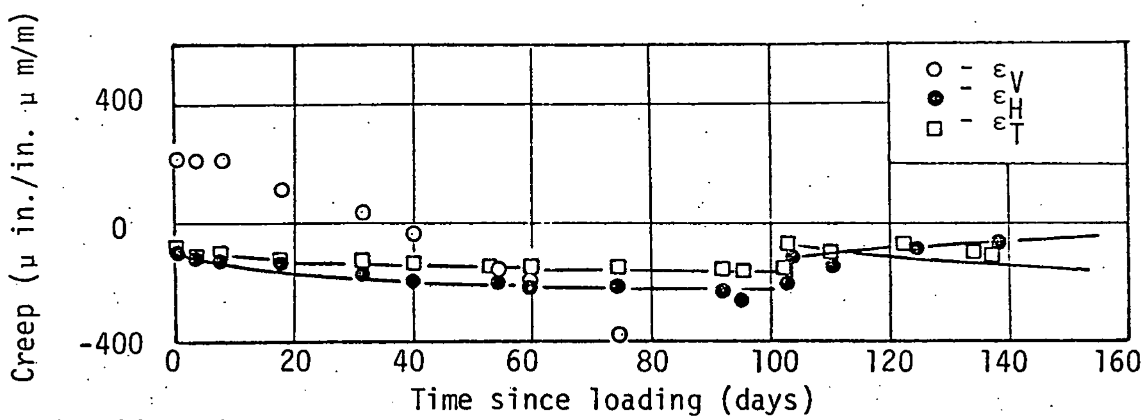

Fig. 19 -- Creep of sealed normal weight concrete under uniaxial load: BNW3

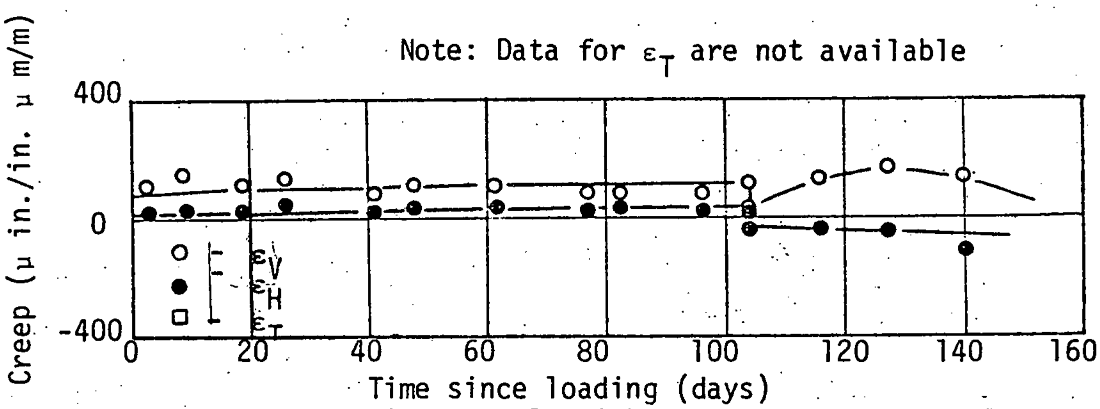

Fig. 20 -- Creep of sealed normal weight concrete under equal biaxial loads: BNW1

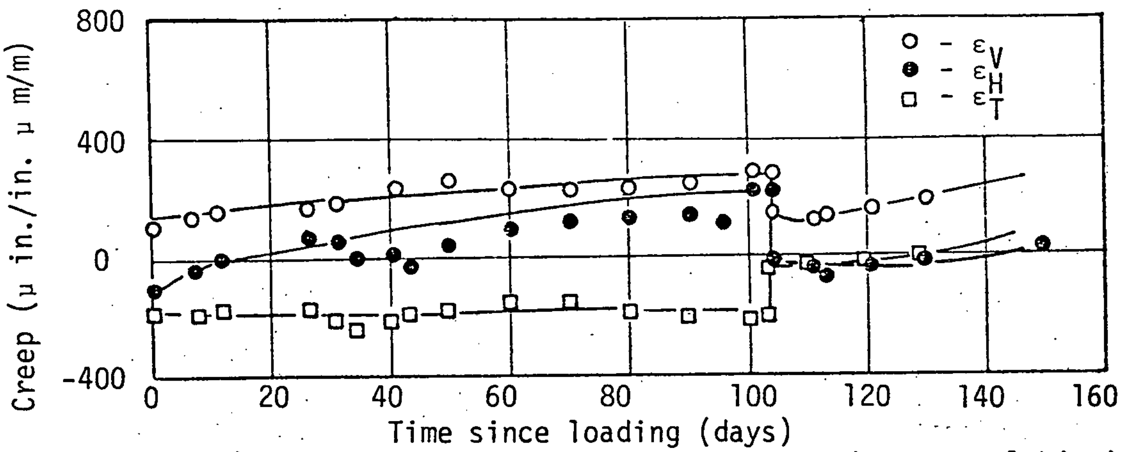

Fig. 21 -- Creep of sealed normal weight concrete under unequal biaxial loads: BNW2

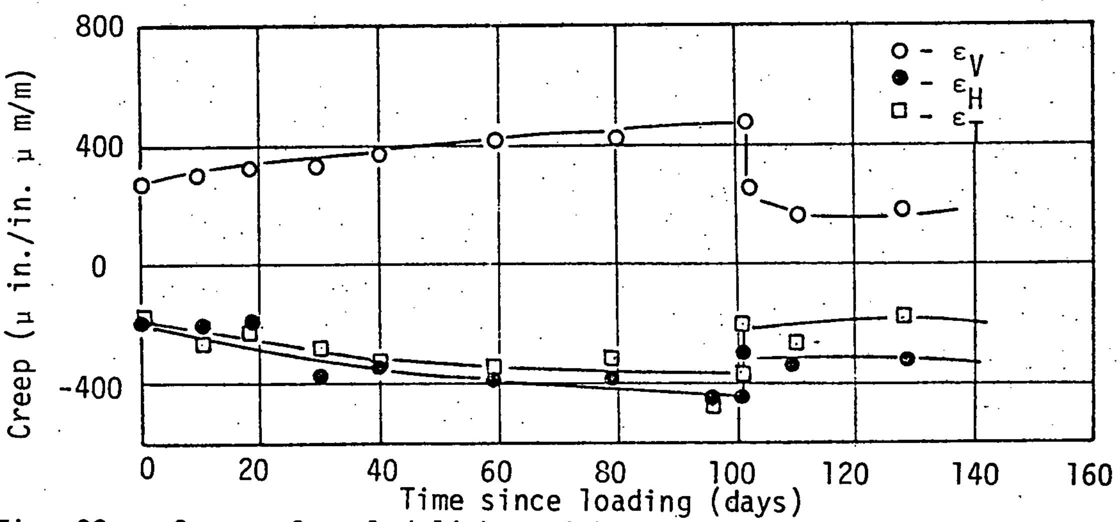

Fig. 22 -- Creep of sealed light weight concrete under uniaxial load: BLW3

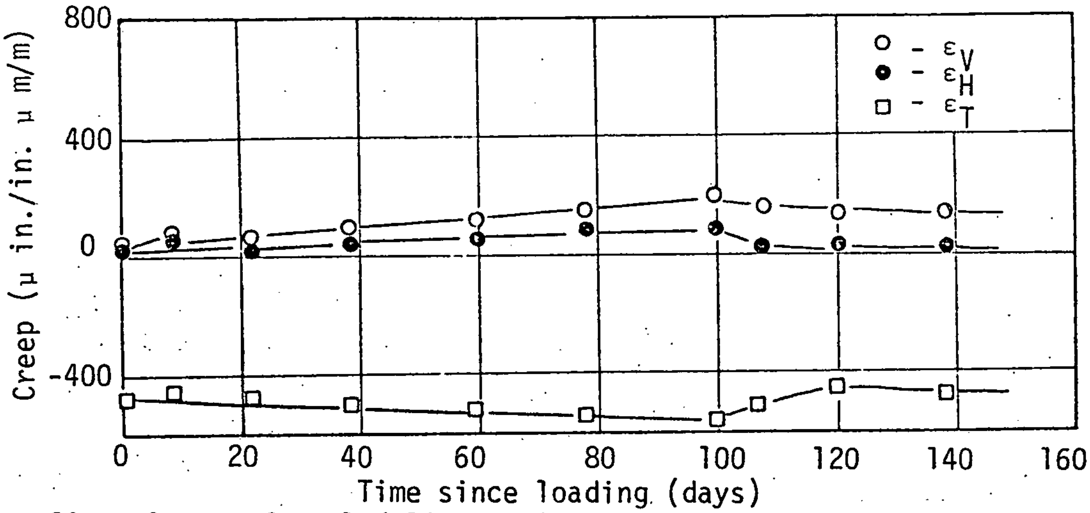

Fig. 23 -- Creep of sealed light weight concrete under equal biaxial loads BLW1

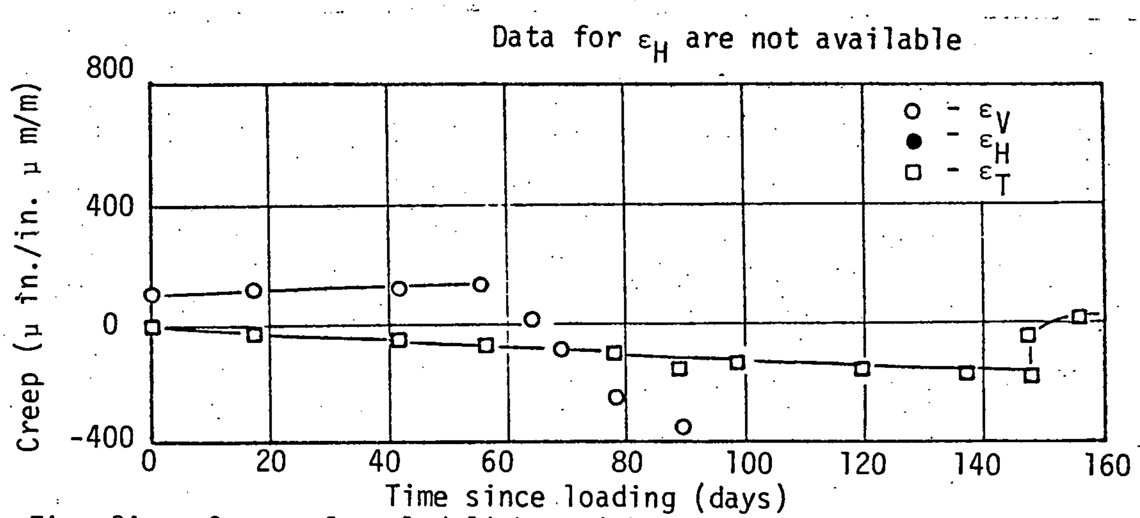

Fig. 24 -- Creep of sealed light weight concrete under unequal biaxial loads: BLW2

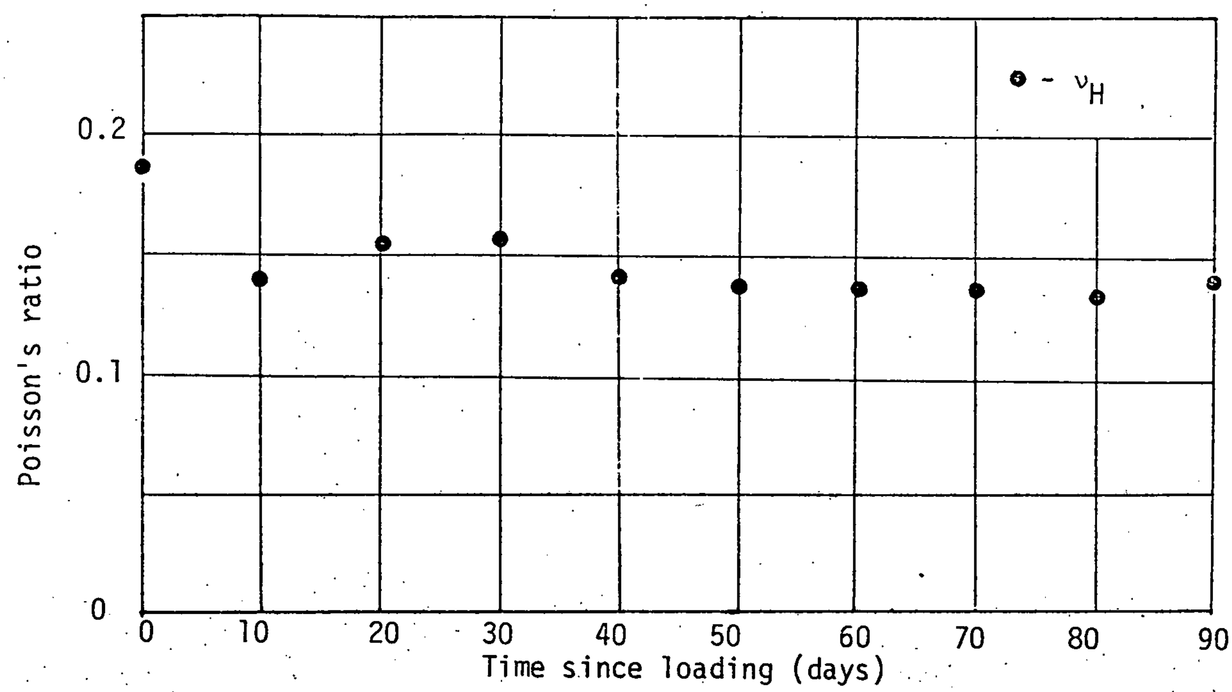

Fig. 25 -- Poisson's ratio in creep for unsealed mortar under uniaxial load: AM3

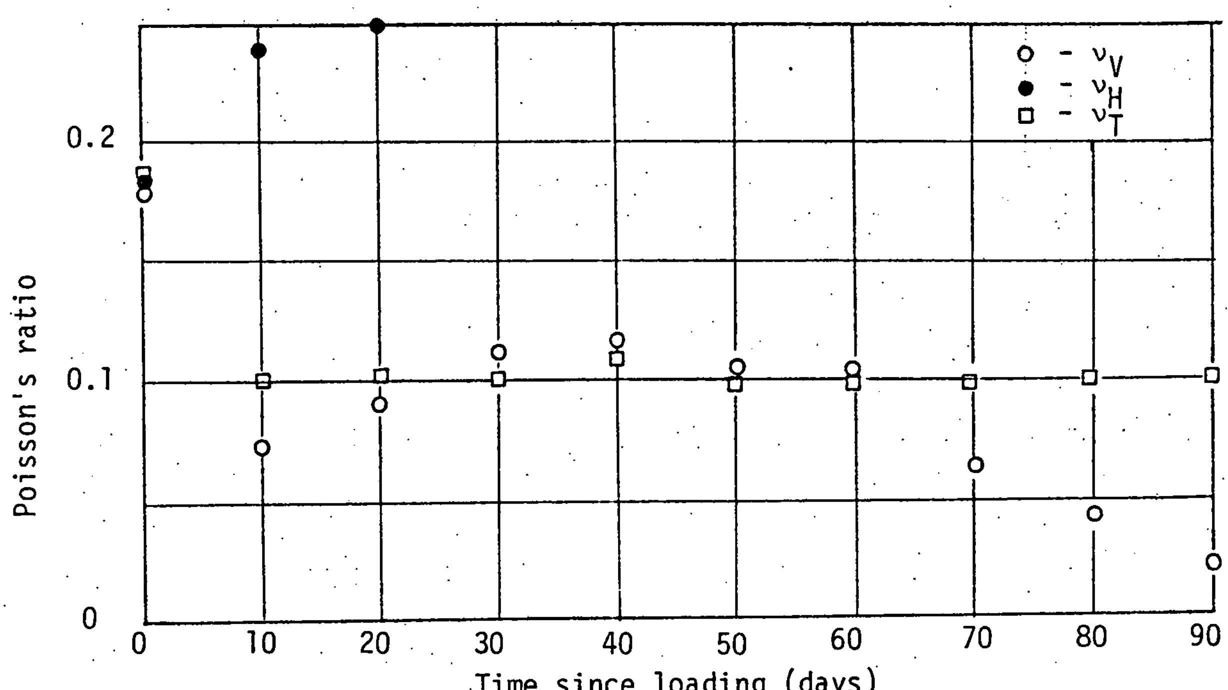

Fig. 26 -- Poisson's ratio in creep for unsealed mortar under equal biaxial loads: AM1

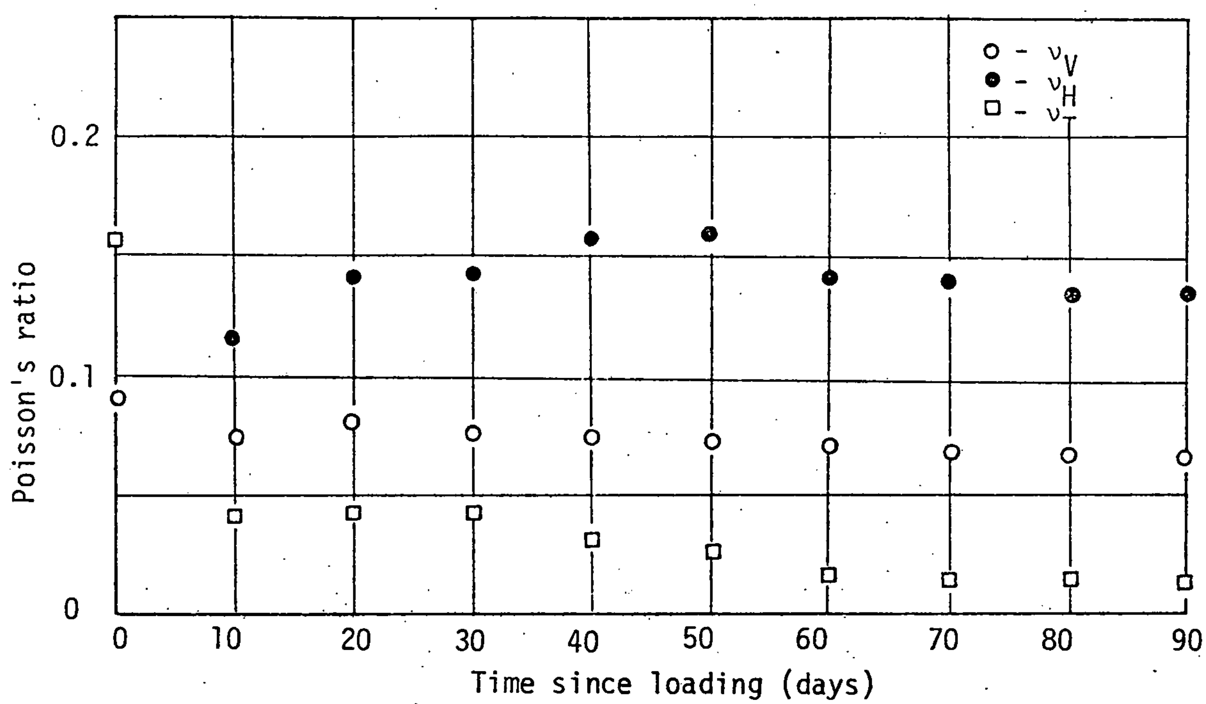

Fig. 27 -- Poisson's ratio in creep for unsealed mortar under unequal biaxial loads: AM2

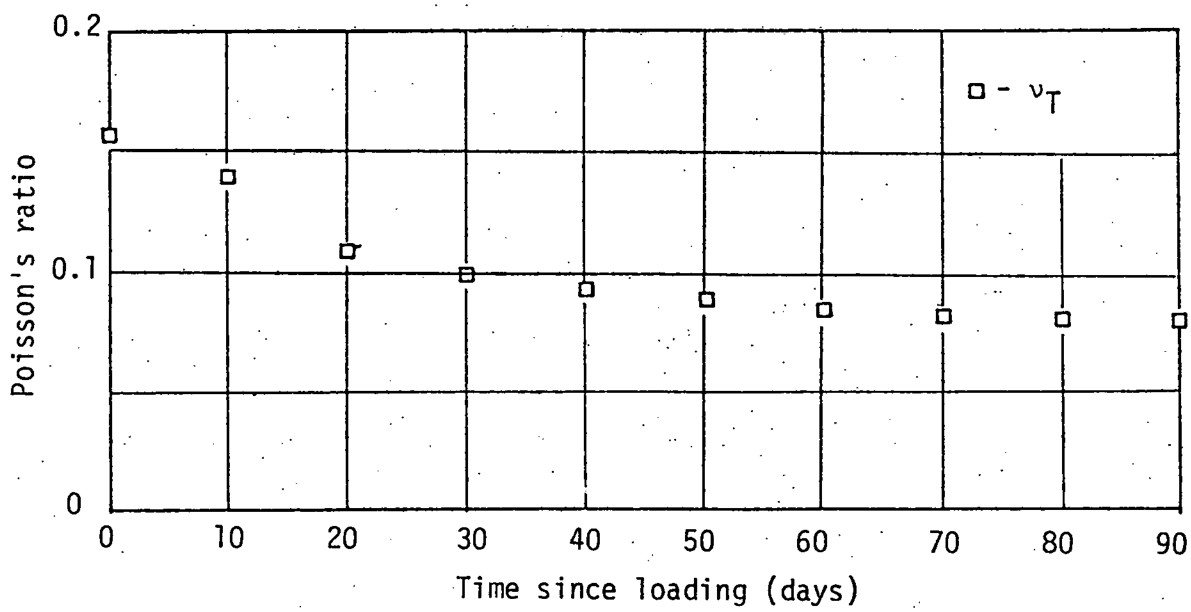

Fig. 28 -- Poisson's ratio in creep for unsealed normal weight concrete under uniaxial load: ANW3

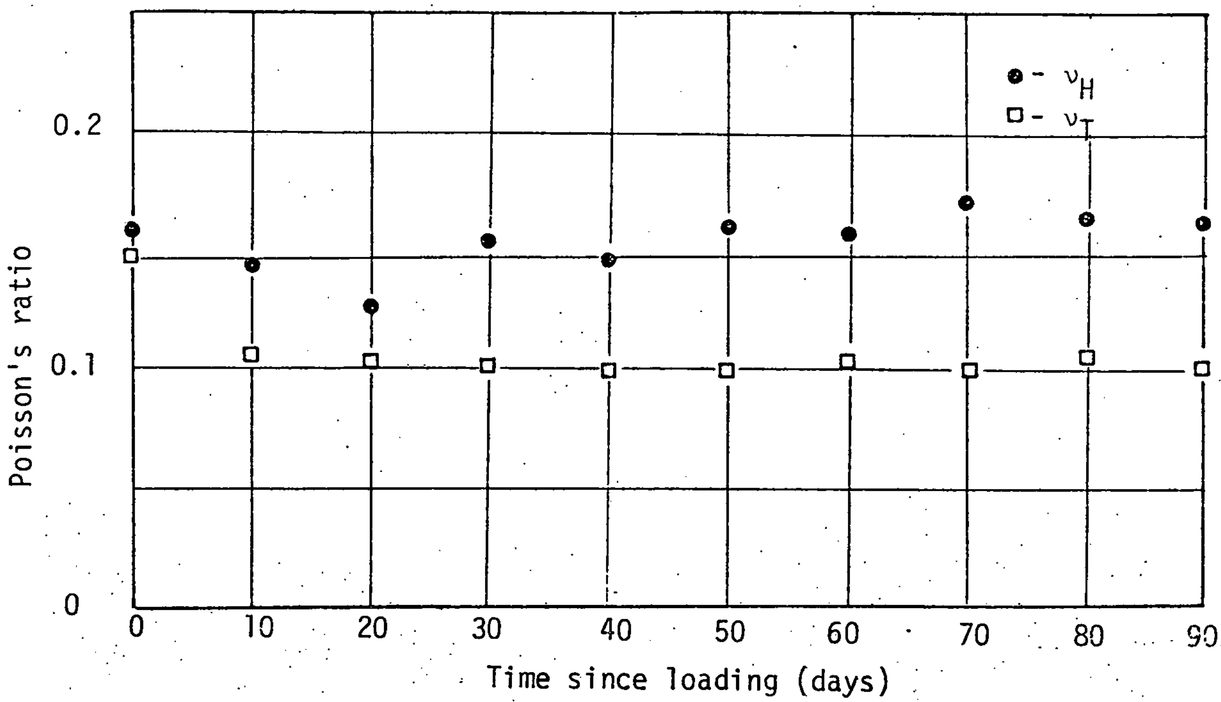

Fig. 29 -- Poisson's ratio in creep for unsealed normal weight concrete under equal biaxial loads: ANW1

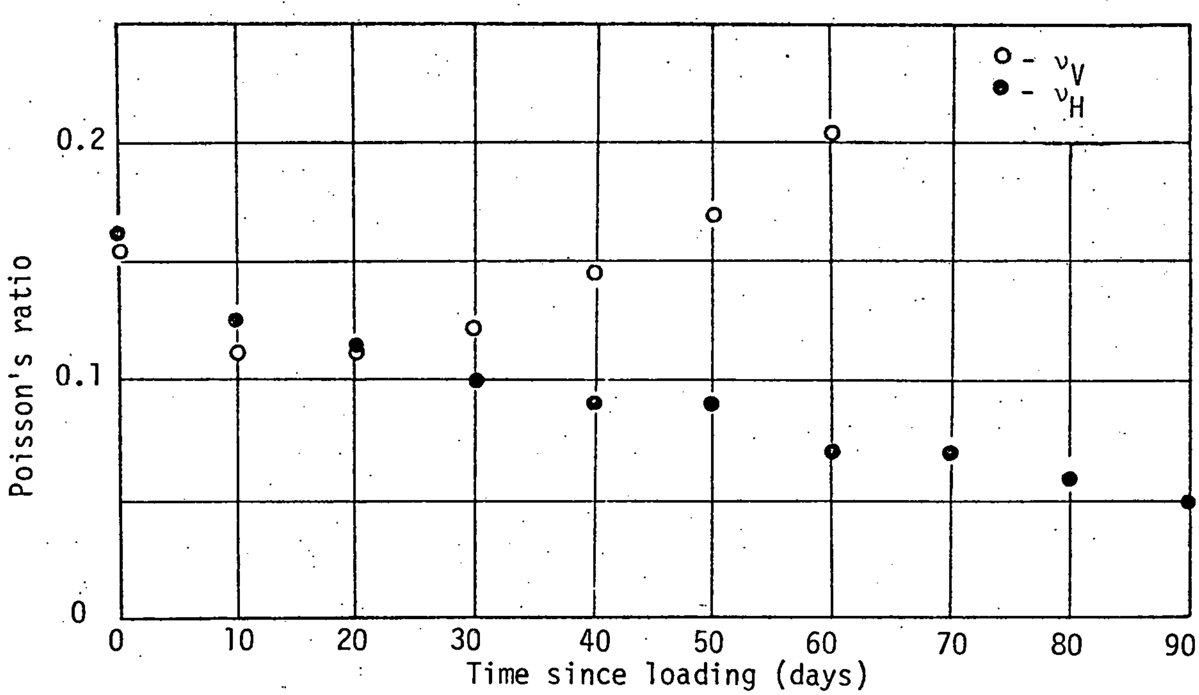

Fig. 30 -- Poisson's ratio in creep for unsealed normal weight concrete under unequal biaxial loads: ANW2

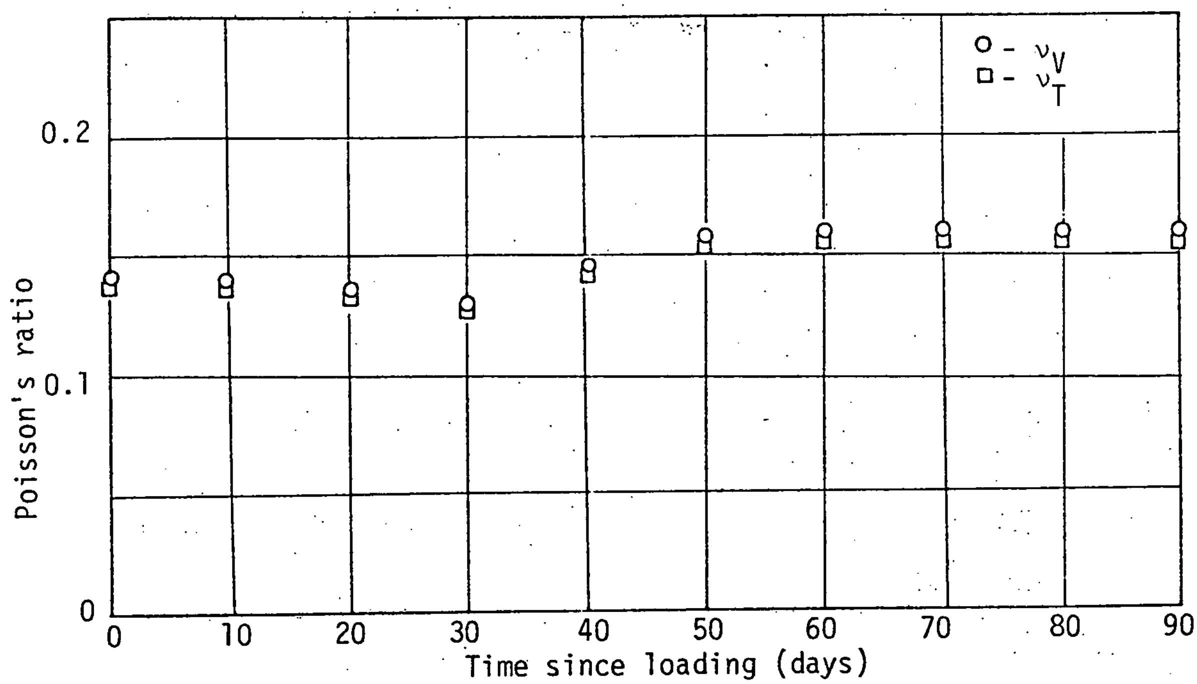

Fig. 31 -- Poisson's ratio in creep for unsealed light weight concrete under uniaxial load: ALW3

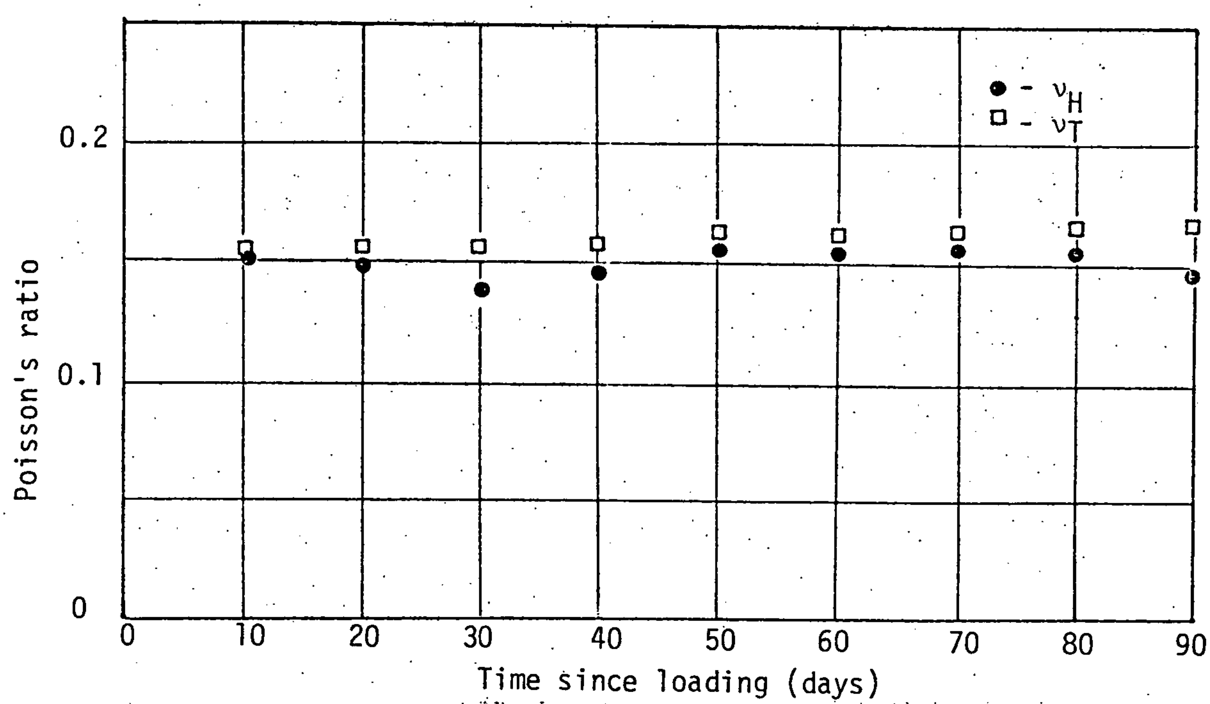

Fig. 32 -- Poisson's ratio in creep for unsealed light weight concrete under equal biaxial loads: ALW1

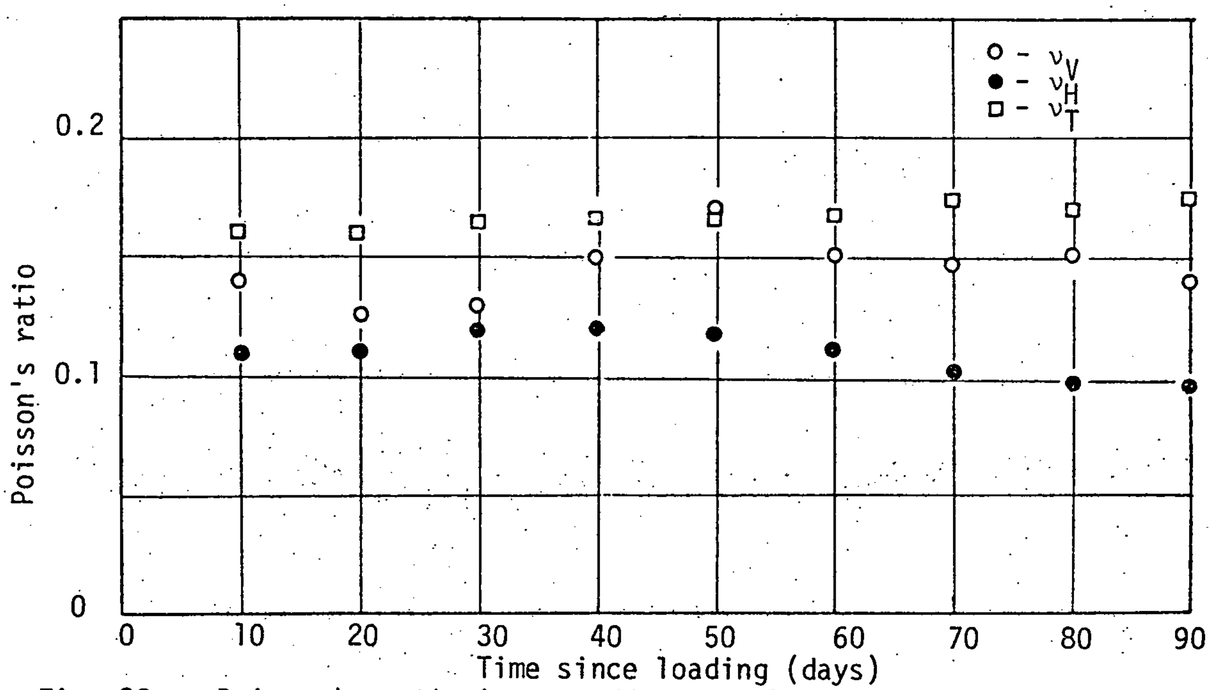

Fig. 33 -- Poisson's ratio in creep for unsealed light weight concrete under unequal biaxial loads: ALW2