THE CREEP OF CONCRETE
UNDER CYCLIC UNIAXIAL COMPRESSION

A Thesis presented for the

Degree of Doctor of Philosophy

by

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ABSTRACT

The thesis describes an investigation into the creep deformation of plain concrete subjected to a cyclic compressive loading. Under such loading considerably increased creep occurs, especially in the early stages, over that observed for a static stress equal to the mean of the cyclic stress. The increase is greater the greater the amplitude for a given mean stress, and greater the greater the mean stress for a given amplitude.

The creep-stress-time relationship can be expressed in terms of a power function expression for early time intervals and a logarithmic expression for later stages, if a linear creep-stress relationship is assumed. The latter assumption is reasonable for amplitudes of less than 0.4 of ultimate as long as the maximum stress is less than 0.55.

The increased creep in this linear range is explained in terms of the repeated stress reversals in the adsorbed water layers between gel particles causing a breakdown in the structure of the layers and hence increased mobility of the gel particles. Activation energy calculations indicate that movement of gel particles rather than water movement is responsible for the creep process. At stresses outside the linear range there is a large increase in creep which is shown to be due to load oriented microcracking.

Though causing increased creep, a cyclic stress below the fatigue limit has a beneficial effect on strength and modulus, the tendency being for concrete to achieve internal structural stability more rapidly than under a static stress.

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ABBREVIATIONS

A.C.I. - American Concrete Institute

A.S.T.M. - American Society for the Testing of Materials

A.S.C.E. - American Society of Civil Engineers

B.S. - British Standard

C. and C.A. - Cement and Concrete Association

D.A.S. - Deutscher Ausscheiss für Stahlbeton

M.C.R. - Magazine of concrete research

RILEM - Reunion Internationale des Laboratoires d'Essais et de Recherches sur les Materiaux et les Constructions

NOTATION

ϵ - creep

ϵ_{sp} - specific creep

t - time

σ - stress

σ_c - stress at a particular time of a cyclic stress

σ_m - mean stress of a cyclic stress

Δ - amplitude of stress of a cyclic stress

σ_s - static stress

f - frequency of a cyclic stress

p - probability of a spontaneous change of thermal energy

R - Gas constant

T - absolute temperature

Q - activation energy

Z - rate of activation

u - reduction in activation energy due to external stress

v - constant relating stress and energy for a static stress

u_a - increased reduction in activation energy due to a cyclic stress

v_c - constant relating stress and energy for a cyclic stress

a, b, c, d, f, g, h, k, - constants for empirical relationships, their specific use is explained as they occur

x - displacement

F - force

w - viscosity

m - spring rate

All stresses in the text, in figures and in tables are expressed as a fraction of ultimate prism strength unless stated otherwise.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Creep of Concrete

Creep is a phenomenon observable in most materials under certain conditions of stress and environment. Concrete is peculiar as an engineering material in that creep is significant at normal levels of stress and in normal environmental conditions. This will often have a beneficial effect in relieving high stress concentrations. However, if creep is excessive under load excessive deflections may result, causing cracking of slabs or beams, or columns may settle sufficiently to induce high stresses elsewhere in a structure.

Creep of concrete under static loading conditions has been thoroughly investigated at the phenomenological level at least. However, its deformational behaviour under repeated load has received scant attention. Failure of concrete at stresses of up to about 35% below the short term static strength, when the stress is continuously applied and removed, i.e. fatigue failure is well known. Repeated loading thus has a considerable effect on the structural behaviour of concrete, at least for high loads, and it might therefore be reasonable to expect some form of effect at lower loads, manifesting itself perhaps in a changed creep behaviour, creep being one of the most significant aspects of concrete's behaviour under sustained stress conditions below those which would produce failure.

The practical implications become immediately apparent in the case of bridges carrying high volumes of traffic or concrete road pavements.

1.2 Levels of Approach to the Study of Concrete

There are two main levels of approach to the study of concrete- the fundamental and phenomenological.

The fundamental level is concerned with the behaviour and interaction of the constituent parts that is aggregate, water and cement gel with a view to explaining the observed characteristics such as strength and creep in terms of these phase interactions.

The phenomenological approach is concerned with the behaviour of concrete as a whole such as its creep deformation under load. This leads to a large amount of essentially empirical information, which can be directly applied in practice, and most creep data to date, since it has been obtained by engineers for practical use is of this nature. This type of information though, taken by itself cannot lead to any real understanding of the actual structure and mechanism of behaviour of concrete, and much work is now being done at the fundamental level. It is when the two approaches are brought together as they have been in the study of metals, that a real understanding of the structure begins.

1.3 Proposals for Present Investigation

Since the information concerning the behaviour of concrete under cyclic loading is scarce the approach to this investigation will be essentially phenomenological. It may be hoped that besides producing some empirical data of practical application, a study of this nature made in consideration of the fundamental knowledge at present, may help throw more light onto the true nature of the creep process.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Previous Investigations

A great amount of work has been done on the creep of concrete for a large variety of mixes, curing conditions, environmental conditions of testing and sequences of sustained loading. Neville (1) gives a complete upto date account of the present state of the work. However though the data on the fatigue of concrete in compression is extensive, very little has been reported on the effects of rapidly repeated compressive loading on creep.

Van Ornum (8) in the first properly documented fatigue tests showed that the stress strain curve changed its shape from being convex towards the strain axis to concave towards this axis.

Williams (2) reported that successive application of loads tended to linearise the stress strain curve, and high levels of loading increased Youngs modulus. He also noticed increased creep after each cycle, though confusion as to its magnitude existed due to very large laboratory temperature fluctuations.

Probst (3, 4) performed the first series of tests to measure the strains in concrete subjected to a continuous cyclic compressive loading in this case at a frequency of 60 c.p.m. He observed that as with static loading creep diminishes rapidly with increased age of loading, whereas the elastic deformations are comparatively little affected. The elastic and creep deformations grew with the number of cycles, both of them stabilising for $7\frac{1}{2}$ month old concrete, the elastic long before the plastic. With 8 week old concrete no finite limit was established for the creep deformations, a phenomenon attributed by Probst to shrinkage of the young concrete.

The above referred to loadings at less than a so called critical stress of from 47 to 60% of ultimate. Above this failure eventually resulted. The stress strain curve showed reversal of curvature and Poisson's ratio decreased.

Referring to Probst's tests on reinforced concrete in compression, a static load of 7,200 kg. for 12 days produced a greater strain in the compressive section of the beam than 1.1×10^6 repetitions of cyclic loading between 7,200 kg. and 600 kg. applied previously at 90 c.p.m. to the same beam. However 0.242×10^6 repetitions of cyclic loading between 7,200 kg. and 600 kg. applied after 23 days of static loading produced no further increase in strain. However reducing the frequency of the cyclic loading to 22 c.p.m., did produce a further increase. Le Camus (5) also stated that a compression specimen loaded for 1,000 days, unloaded for 200 days then loaded cyclically at 500 c.p.m. for 100 hours with the same maximum load produced no further increase in creep.

Considering Le Camus' (5) investigations further, he found that for three sets of specimens loaded at 0.15, 0.22 & 0.30 of ultimate, 1 million repetitions of loading at 500 c.p.m. gave creep deformations equivalent to 2, 27 and 60 days of static loading of the same magnitude as the upper limit of the cyclic load. Since from this it appears cyclic loading greatly accelerates creep, the previous mentioned results on loading sequence are rather extraordinary.

It is clear that the effects of sequence of static and cyclic loading, of speed of loading and the relative magnitude of creep deformation under equivalent static and cyclic loading conditions need much further investigation for quantative results to be established. No account was taken above of the relative ages of loading or their respective durations.

These are however the only results published which attempt to compare creep under static and cyclic loading.

The first attempt at a quantative analysis of creep under cyclic loading conditions was made by Gaede (6). The tests were carried out at a frequency of 665 c.p.m., the ratio of lower to upper load being either 0.15 or 0.75. Strain was measured using dial guages on all four sides of the 10 x 10 x 50 cm. specimens, again the tests usually being stopped to take measurements. From his results he produced an equation.

$$\varepsilon = b(N.10^{-5})^{r}$$

ε = creep strain N = number of cycles

b is a function of the material and loading condition

$$b = c \times \frac{\sigma o}{K} \times \frac{10^5}{tg\beta}$$

Where σo = upper load, k = ultimate strength, $tg\beta$ = secant modulus and C is a constant which is dependent on the amplitude of loading. R was a constant (within the experimental accuracy) for each ratio of lower to upper stress. The mean value of r was 0.333 and the mean value of C was 1.82 for upper to lower load ratio of 0.14 and for 0.75 the respective values were 0.202 and 1.82.

A rheological model was then used to represent the elastic and creep behaviour.

Mehmel and Kern (7) made an investigation shortly after this which was concerned principally with the elastic deformations under repeated loading at a frequency of 380 c.p.m. The loading branch of the stress strain curve showed the reversal of curvature shown by Van Ornum and Probst, (the more so the higher the load and the smaller the cement content of the concrete) showing increasing stiffness with increasing load. The secant modulus remained constant except for heavily loaded specimens. The area of the hysteresis loop decreased during loading. The reversal of curvature was attributed to cracking at the aggregate matrix interface, the effect not being apparent in tests on hardened cement paste. This effect of microcracking on the shape of the stress strain curve has been further documented (9, 10), though not in relation to long term low load cyclic tests of high frequency.

Contrary to Le Camus' results Mehmel found that a cyclic load of upper load σ_u and lower load σ_l gave the same creep deformation at a time t as a static load of magnitude σ_u, emphasising the need for more investigation into this aspect. The strength of specimens subjected to stresses at which failure did not occur showed an increase of up to 10%.

Raju (11) in investigations into fatigue reported strength increases of up to 15% in specimens subjected to stress cycles at 180 c.p.m., below the fatigue limit. The area of the hysteresis loop showed a rapid initial decrease followed by a slow continuing decrease, changing to a rapid increase if fatigue failure occured, but continuing to decrease if failure did not occur. As before the load line in all cases became quickly concave to the stress axis and remained so.

2.2 Limitations of Previous Investigations

The above work seems to have been carried out with no clear objective in mind, that is to say general investigations without specific control of the many variables to enable quantative assessment of results possible. Clear anomalies are evident in the comparisons of creep curves for static and supposedly similar cyclic loading tests, and in the results for sequence of static and cyclic loading. Comparisons were made of load against number of cycles curves and load against time curves, rather than load against time curves for both types of loading. The load was removed for creep measurements in cyclic loading tests, yet remained on for static loading tests. Cyclic loading tests were conducted for a few days, yet static tests were continued for years. No real attempt has been made to compare static loading and cyclic loading under identical test conditions and thus no explanation has been offered for the deformatory behaviour of concrete under cyclic loading.

2.3 Requirements for Further Investigation

Since the behaviour of concrete subjected to cyclic loading appears so uncertain it would seem the initial requirements are for a thorough investigation of the effects of various loading conditions. This should probably involve a systematic variation of the load limits and frequency in cyclic tests, run in parallel with static tests on identical specimens.

To reduce shrinkage to a minimum testing would be performed at high humidity.

When the precise effects of cyclic loading have been established for one particular concrete loaded at one particular age and under one set of environmental conditions testing could then be extended to find out if the established relationships for creep under static loading (such as the accelerative effects of increased temperature) applied also to cyclic loading. The nature of results in the first part would probably give some good indications of such behaviour in the light of present knowledge on the structure and creep under static loading of concrete.

CHAPTER 3

PREPARATION OF SPECIMENS

3.1 Materials

The cement used for all tests consisted of one batch of blended rapid hardening cement ("Ferrocrete"), conforming to B.S.12: 1958. An analysis is shown in Table A.1. The aggregates were well graded Nottinghamshire quartzitic gravels. The coarse aggregate had a maximum nominal size of $\frac{3}{8}$th and the fine aggregate was $^{3}/_{16}$ths graded sand. Both aggregates conformed to the limits set out in B.S.88: 1954, the fine aggregate corresponding to zone 2 type. The fineness moduli were 5.86 and 2.94 respectively. The grading curves are shown in fig. A.1.

3.2 Mix Design

A constant mix proportion of 1:2:4 with a water cement ratio of 0.5 was used throughout the tests. This gave a prism strength of between 5,000 and 6,000 lb.f./in.^{2} at 14 days. A histogram of all batches is shown in fig. A.2.

3.3 Specimen Size

The strength of concrete prisms decreases with increased height to width ratio. Below a ratio of 1.5 there is a marked increase in strength and above 2.5 a less marked decrease. The former is due to increased lateral restraining effect of the loading plates of the machine on the ends of the specimens and the latter to the tendency towards instability in slender specimens (12, 13). It was therefore decided to use 3 x 3 x 8 inch concrete prisms which were a convenient size for the testing rigs and for instrumentation, and which had been used previously for other investigations here (14, 11) for fatigue tests, with which it was felt some useful comparisons might be made.

3.4 Casting and Curing

The specimens were cast vertically into steel moulds conforming to B.S.1881: 1952. Eight specimens were cast in each batch, enough concrete being used to ensure thorough mixing in the 2 cu. ft. capacity pan mixer. The pan of the mixer was thoroughly hosed down and excess water tipped away before use, to ensure even wetting of the pan for each batch.

The specimens were covered with wet hessian after casting until they were removed from their moulds after 24 hours and put in the curing room at a temperature of $20^{o}C \pm 1^{o}C$ and a relative humidity of $95\% \pm 2\%$.

3.5 Preparation of Ends of Specimens

The ends of the specimens were required to be perfectly flat and at right angles to the sides. The top face could not be adequately smoothed off before the concrete had set, and attempts to produce a reasonable finish by later grinding were unsuccessful. It was therefore decided to attach $\frac{1}{2}$" x 3" x 3" mild steel loading plates to the specimens using high alumina cement as the bonding medium, which gives high strength after 24 hours.

Eight capping jigs were made up as in plate 1, consisting of a machined right angle bolted to a ground plate. The loading plate was positioned as shown, two pieces of $\frac{5}{8}$" x 1" steel being laid along the exposed sides forming a $\frac{1}{8}$" deep cavity into which the paste was put. The paste had a water cement ratio of 0.3 and was allowed to set partially before use. The specimens were held firmly into the right angle, lowered onto the cement paste, and clamped in position. The pieces of $\frac{5}{8}$" steel were removed and the specimen gently tapped down; the cement paste being squeezed out until the layer was less than $^1/_{16}$" thick (plate 2). This ensured removal of most of the air bubbles. The operation was repeated on the other end of the specimen 24 hours later. During this process the specimens were covered with wet hessian and polythene sheeting to maintain the curing conditions. Specimens were generally capped when 10 days old.

It was found that this method gave accurate alignment of the plates and excellent perpendicularity. The use of a high strength hardening agent prevents premature splitting of the ends under high repeated loads found by Muir (14) and also gives the smallest scatter of strength results (14, 15).

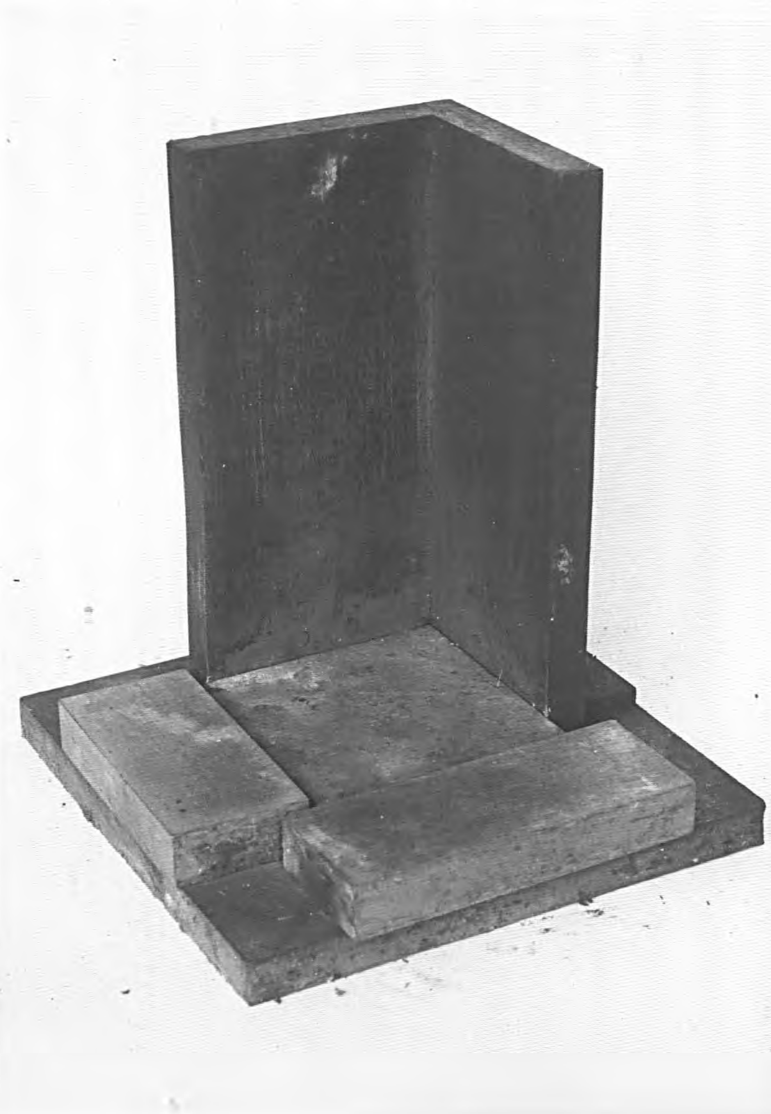

Plate 1

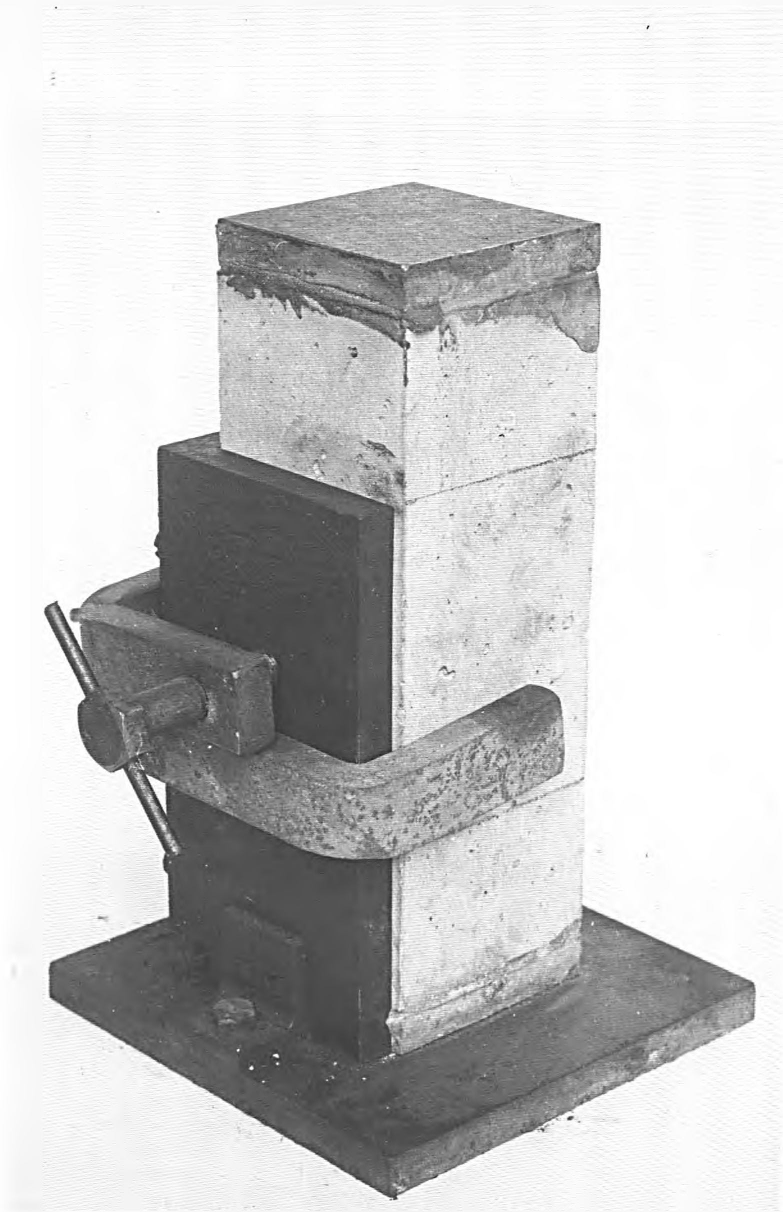

Plate 2

LOADING AND STRAIN MEASURING EQUIPMENT

4.1 Static Tests

4.1.1 Test Rig

A Losenhausen EPZ20, 20 ton jack was mounted in a frame as shown in plate 3. The jack was positioned by four rollers mounted on the jack locating against four columns rigidly mounted to the frame. The jack was driven from a Losenhausen U.H.S. dynamic control panel via a distributor. Load measurement was by a 12" pendulum dynamometer with a full scale deflection of 20 tons and accurate to ± 1%. Calibration against a Johanson 25 ton dynamometer showed exact correspondence. The automatic load maintaining device caused a fluctuation in the load of ± 0.05 tons or approximately 0.2% specimen load. The dynamometer could be read to 0.02 tons.

4.1.2 Humidity and Temperature

The Laboratory temperature showed very little fluctuation and further stabilisation was unnecessary considering the short term nature of the tests. To maintain the humidity at as high a level as possible the specimens were completely enclosed in box shaped polythene bags which were made up from polythene sheeting. $\frac{3}{8}$" of water was put in the bottom of the bag ensuring no part of the specimen was actually immersed. This method gave a wet bulb depression of 0.2°C at 20°C corresponding to a relative humidity of over 98%. The air gap between the polythene and the specimen was about $\frac{1}{2}$". The load was applied to the specimen through the polythene covering the ends.

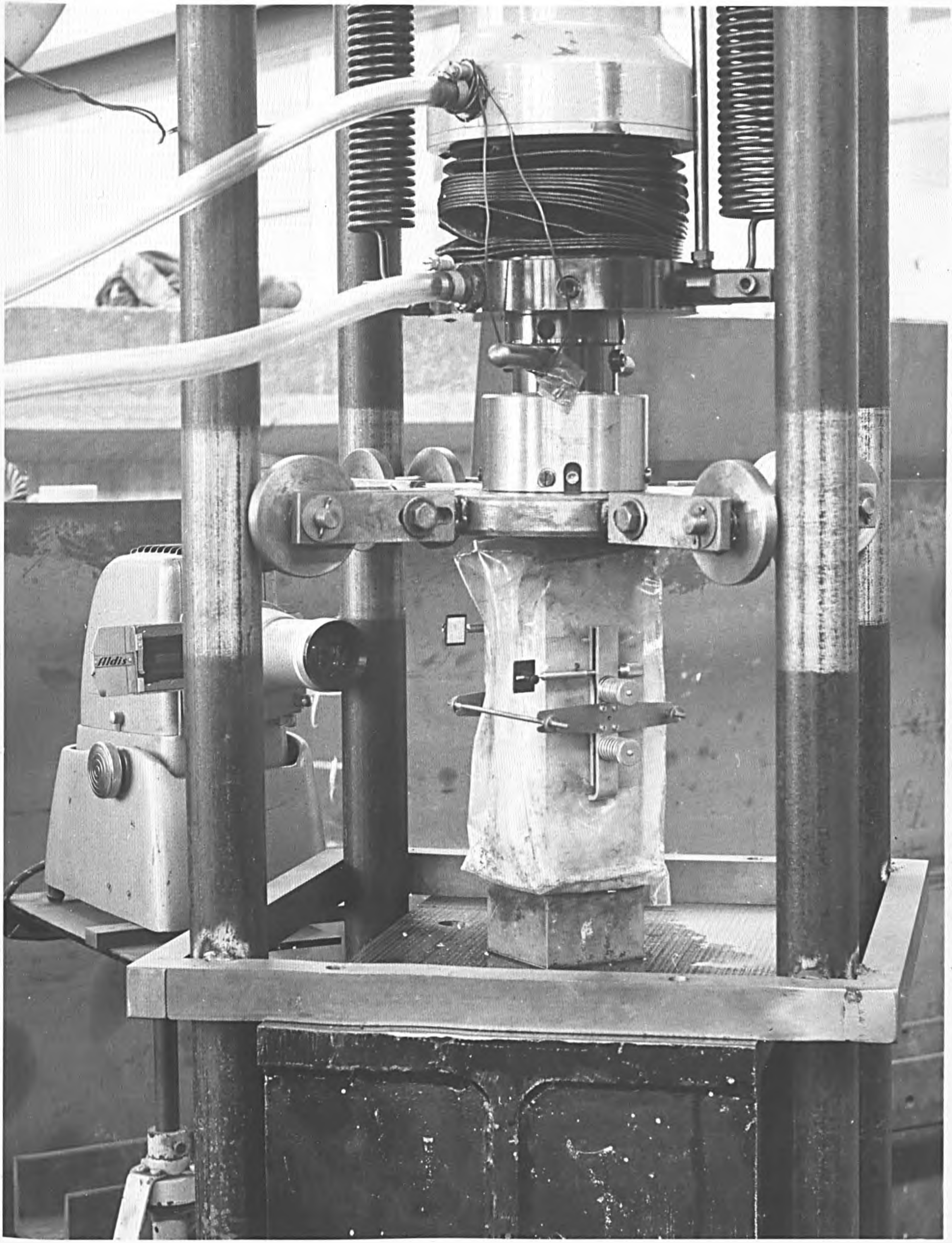

Plate 3

4.1.3 Strain Measurement

The method was the same as adopted for the cyclic loading tests described in 4.2.8.

4.2 Cyclic Loading Tests

4.2.1 Loading Machine

The cyclic loading tests were carried out on a Losenhausen U.H.S.60 universal fatigue testing machine (Plate 4) which could apply a maximum static load of 60 tons and a maximum cyclic load of 40 tons. The frequencies of loading available were nominally 190, 240, 300, 380, 460, 580, 720, 860 c.p.m.

The principle of this machine is two opposed pistons acting on a single cross head, one providing tension, the other compression, supplied by separate pumps. The compression and tension are initially balanced to produce the required minimum specimen load. The pulsator is switched on and its amplitude of stroke increased gradually. This causes the tension pressure to fluctuate cyclically from its initial maximum value to a lower value then back again and hence the specimen load to increase then decrease to the original minimum correspondingly. The compression pressure remains relatively constant due to a large damping reservoir of oil in the circuit. A complete description of the machine may be found in (16), a schematic drawing of the layout is shown in fig. 4.1.

4.2.2 Load Time Curve

The load time curve produced by the machine was nominally a sine wave. However it was found that at speeds greater than 580 c.p.m.

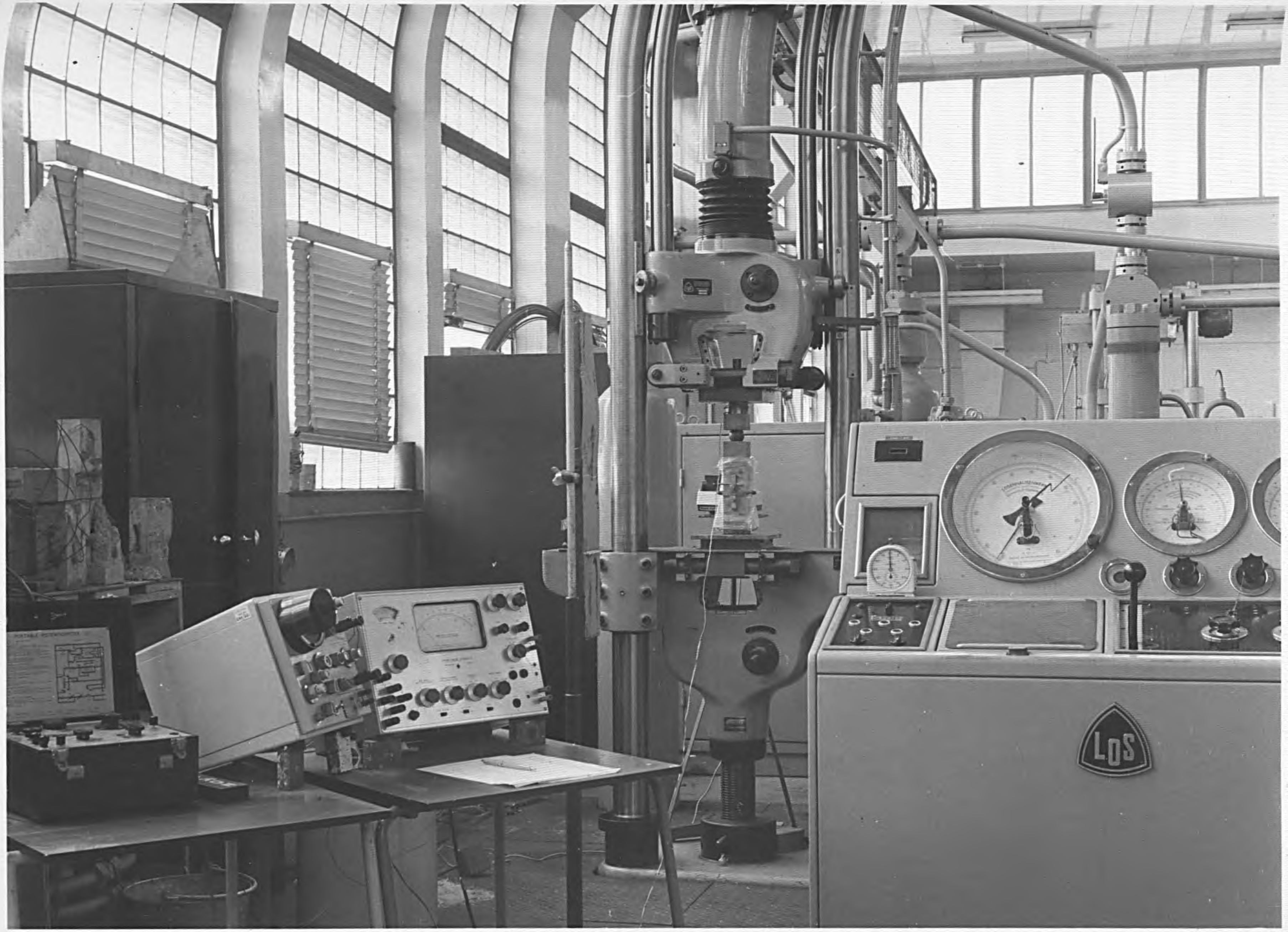

Plate 4

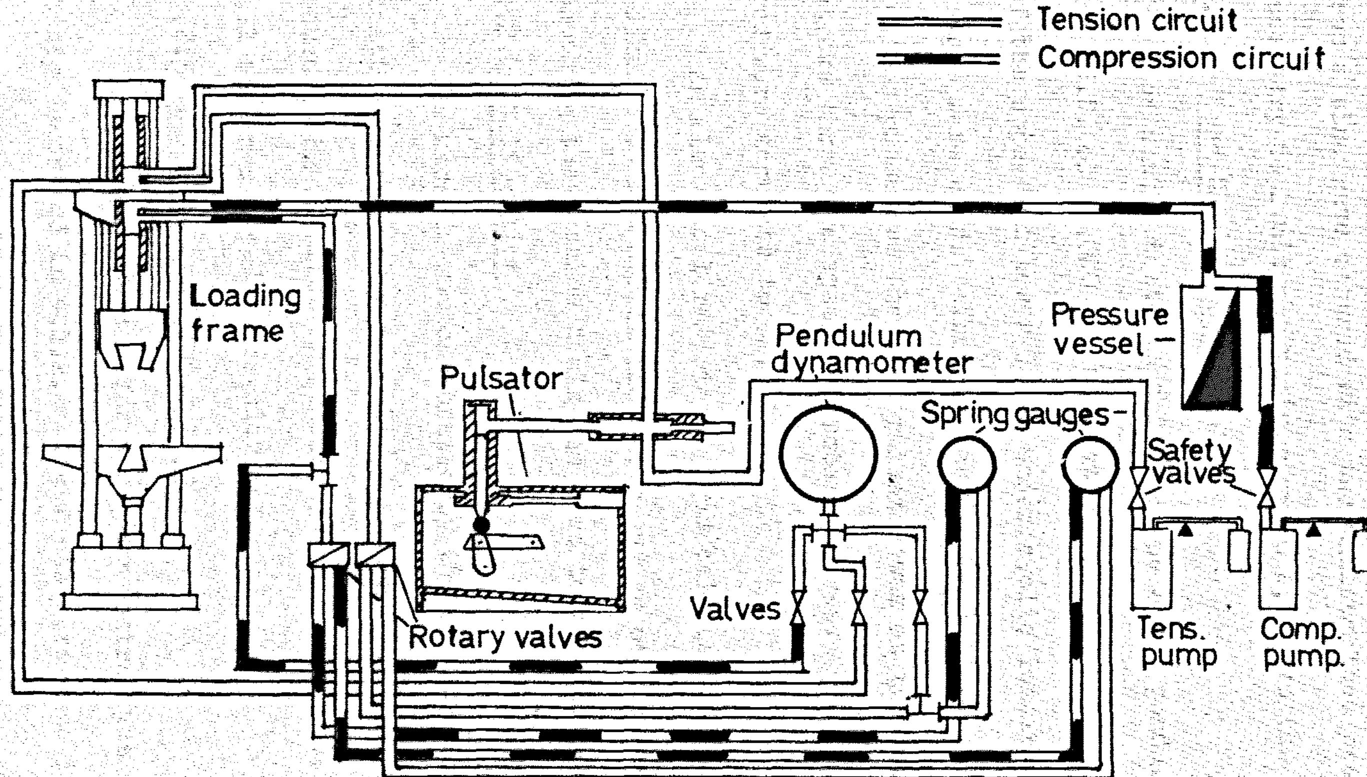

Fig. 4.1 Schematic layout of Lösenhausen UHS 60 fatigue testing machine

especially with close upper and lower load limits considerable departure from a sine wave occured with two maximum load peaks and hence it was necessary to limit the maximum cycle speed to the above value.

4.2.3 Load Measurement

For static tests in this machine a 12" pendulum dynamometer with an F.S.D. of 60,000 lb. accurate to 1% was used. For measurement of the upper and lower loads under cyclic loading two 8" spring type gauges were used. These measured the difference between compression and tension pressures when the pulsator was at the top and bottom of its stroke through a system of rotary valves. They could be read to 200 lbs. and were accurate to 3%.

An electrical resistance load cell used in conjunction with a Peekel 540 DNH strain indicator and an oscilloscope was used as a check on the machine dials and also to provide the load time curve.

4.2.4 Calibration

The machine was calibrated by the factory immediately prior to testing. From this the 25T. Johanson dynamometer was calibrated and found to be in exact agreement and this was hence forward used to calibrate all equipment used at regular intervals.

4.2.5 Humidity and Temperature

The method adopted for humidity control was the same as for the static tests described in 4.1.2. The tests were done in the same laboratory.

4.3.6 Strain Measurement Device, Number of Gauges and Gauge Length

The factors influencing the choice of strain measurement device were:

1. Sensitivity and accuracy
2. Ability to measure cyclic strain of fairly high frequency
3. Method of attachment to specimen
4. Zero stability under high humidity conditions
5. Number of gauges required on one specimen
6. Gauge length and over-all size

The choice of gauges available are:

1. Mechanical
2. Electrical Resistance
3. Semi-conductor
4. Acoustic

Mechanical gauges have too low frequency response for cyclic load applications, except for lambs mirror roller extensometers. However it is not possible to measure axial strain and lateral strain together with these and it was thought vibration would affect them so they were not chosen initially.

Acoustic gauges cannot be used for cyclic strains and semi-conductors are very temperature and humidity sensitive.

It was therefore decided to use electrical resistance strain gauges, and a method of protecting them and mounting them was developed as in 4.3.7.

The minimum gauge length considered satisfactory for the $\frac{3}{8}$" aggregate used was 2 in. (17). From investigations it was found that two gauges on opposite faces of the specimen gave satisfactory results for the mean compressive strain. The lateral strain was measured using two gauges placed at mid-height on opposite sides of the specimen.

4.3.7 Development of Electrical Resistance Strain Gauges

Internal mounting was considered, but it was not possible to develop an easily applicable method of location which would stand up to normal casting. There is also no easy means of checking the final alignment of the gauge before testing. Surface mounting was unsuitable due to the necessity with this of drying the surface of the specimen and the need to water proof the gauges.

A form of in-surface gauge was therefore developed from that described in (18). A Tinsley 2" epoxy backed foil gauge was stuck foil side up with double sided tape to thin card, which had been previously glued to hardboard with rubber solution. This held the gauge flat and enabled easy removal after preparation was complete. A layer of Araldite MY753 casting resin was brushed over the surface, which had been cleaned with trychloroethylene, and allowed to harden for 24 hours. A second layer of resin was brushed over the first and a layer of fine sand sprinkled in excess on top. The gauge was then put in an oven for 2 hours at 95°C to give complete curing of the Araldite. On removal from the oven excess sand was brushed off, and the gauge was removed from the hardboard with a sharp knife, and the cardboard and tape peeled away. A completely water proof unit was thus formed with an excellent bonding surface (plate 5). The gauge was then glued to the mould with rubber solution and casting and stripping carried out in the normal way (the gauge coming easily away from the mould). Immediately prior to testing the backing was scraped away from the soldering tags, wires were soldered on in the normal way and the joint was covered in dijel waterproof wax. Gauge alignment was excellent and the ground resistance was more than 500 MΩ

Static tests showed excellent agreement with both ordinarily mounted electrical resistance gauges and Demec gauges.

For cyclic strain measurement the gauges were connected in a full bridge circuit to a 540 DNH Peekel strain gauge bridge. In conjunction with an oscillograph using a zero method for bridge balance a sensitivity of 1×10^{-6} strain was obtained. However after several cyclic loading tests quite severe zero drift became apparent. It was thought this could be due to rapid temperature changes within the specimen due to cyclic loading or possibly fatigue at the soldered joints. However no solution could be found and their use was abandoned for cyclic loading tests of any length. Their use was continued for very high load tests in which failure occured. The short time of these tests and the large strains involved making the drift acceptable. Also with the Peekel connected to a U.V. recorder automatic recording was obtained to failure.

It would seem that electrical resistance gauges are unsuitable for

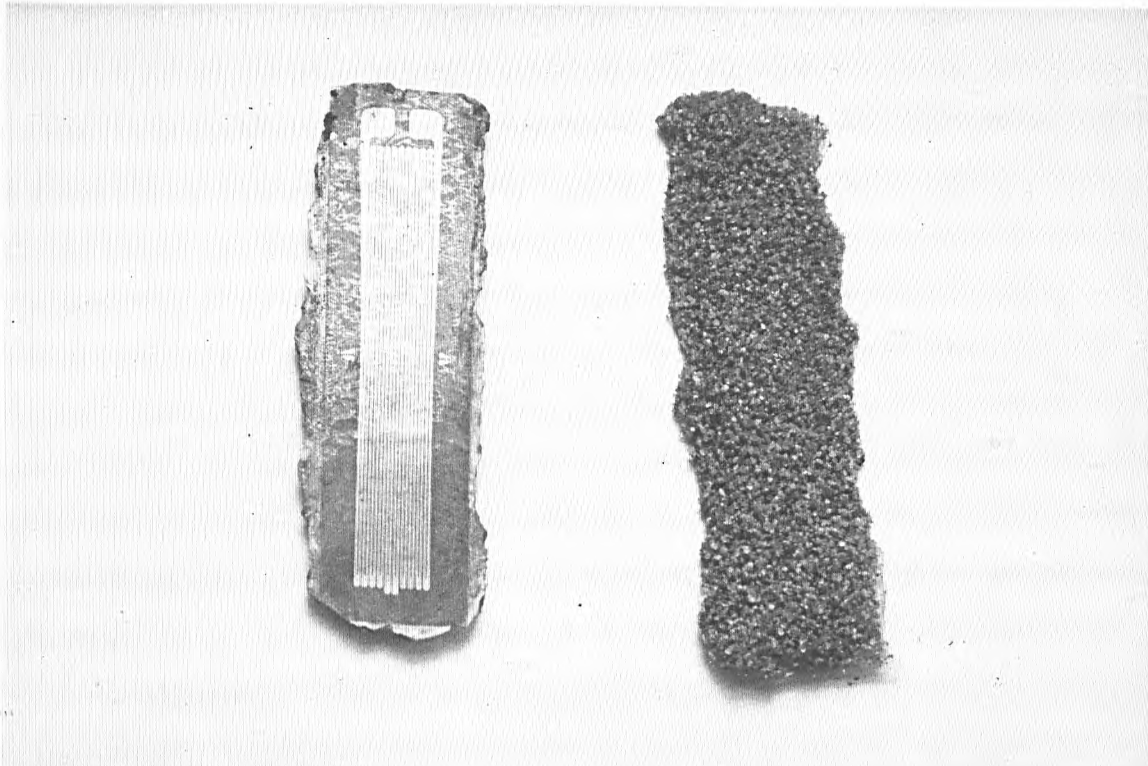

Plate 5

long term cyclic strain measurement in concrete. However under long term static test conditions the results proved excellent and it is felt that their use could be much wider.

4.3.8 Lambs 4" Mirror Roller Extensometer

Tests were made on steel using these gauges and they were found to be completely unaffected by the vibration of the specimen, and they had a sufficiently high frequency response. Their zero stability is excellent and the accuracy determined by the accuracy of machining is better than 0.01%.

A telescopic system of measurement was unsuitable for cyclic loading and a cross wire projection system, shown schematically in fig. 4.2 was used. The cross wire consisted of a slide made by photographing a thin black line drawn on white card. This gave a projected image (using an Aldis 1,000 watt bulbed projector and later a Rank Hylite 150 watt quartz-iodine bulbed projector) a quarter of a millimetre wide and of sufficient intensity to make the maximum and minimum strain values clearly discernible (Plate 6).

Using a millimetre scale at a distance of about 185 cms. from the specimen, strain values could be measured with an accuracy of $\pm$ 2.5 x 10^{-6} strain. An error in positioning the scale of 1 cm. produced an error of measurement of only 0.5% and it was easily possible to position the scale within 0.5 cms. using a tape.

Two gauges were clamped on opposite sides of the specimen outside the polythene enclosure. Small slits were cut in the polythene opposite the knife edges. These had no significant effect on the humidity conditions (plate 7).

Plate 6

Plate 7

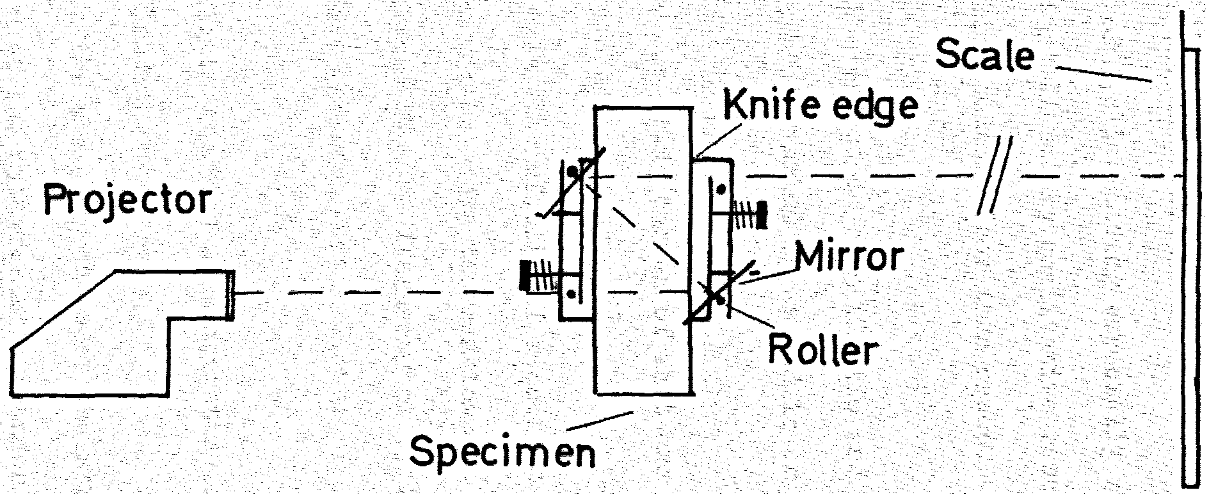

Fig. 4.2 Schematic arrangement of Lamb's extensometer equipment

TESTING PROGRAMME TESTING PROCEDURES AND METHODS OF ANALYSIS

5.1 Testing Programme

In the light of the previous discussions the following testing programme was decided upon. It can be basically split up into two parts. Part 1 provides the essential results for an attempted quantative assessment of the effects of cyclic loading especially as compared with static loading on creep, and Part II mainly qualitative results comparing some aspects of static and cyclic loading other than creep.

Part I

1. To study the effect on both elastic and creep deformation of systematically varied upper and lower load limits for cyclic loading.
2. To compare the creep curves of what are to be considered similar static and cyclic loadings.
3. To investigate the effects of sequences of static and cyclic loadings on the creep deformations.
4. To investigate how the frequency of cyclic loading affects the creep deformations.

Part II

1. To investigate the rise in temperature associated with rapid cyclic loading.
2. To compare the changing shape of the stress strain curve and the area of the hysteresis loop under cyclic loading with that under static loading.

3. To determine if significant strength gains occur under cyclic loading.
4. To determine the effect of cyclic loading on the elastic strain.

One mix, one set of environmental conditions and one age of loading will be used throughout the testing programme, as it is considered that it is of most importance to try to establish the nature of the creep process under cyclic loading as compared with static loading. Variations in mix, age of loading etc., it seems likely, will have similar effects as in static loading, but investigations as to whether this is true or not must be left until more is known about the effects of the type of loading.

5.2 Testing Procedures

5.2.1 Strength Determination

The ultimate strength of each batch of eight prisms was determined from a mean of at first five, then three specimens when sufficient quality control had been obtained to obtain a satisfactory standard deviation. All tests were carried out in a Denison 50 ton loading machine and the specimens were loaded at the standard rate of 2,000 $lb.f/in.^2$ per minute.

5.2.2 Static Tests

One prism was sealed in its polythene container and the specimen was set up and the extensometer attached and lined up, as for the cyclic loading tests. A ball seating at the base of the jack compensated for any non-perpendicularity of the end of the specimen. Having taken the zero reading the load was increased at a steady rate to maximum, the zero strain reading for creep being taken after 30 seconds.

5.2.3 Cyclic Loading Tests

One prism was sealed in its polythene container and located on the machine loading plates by alignment with a 3 x 3" ground plate which was pegged in position centrally. The extensometer was attached and aligned to give the most definite cross wire image. The load was applied through a 2" ball seating above which was a 3" diameter 30 ton capacity load cell.

One preliminary static load cycle was performed to determine the modulus and hysteresis loop area. The lower load was then set up and the pulsator switched up to the required speed. Because of the nature of the machine the amplitude of the load cycle could only be gradually increased to the maximum load value the process taking about 500 cycles or $\frac{3}{4}$ of a minute. The time zero was taken as halfway between the start of increasing amplitude and maximum amplitude. It was also because of this that an initial load cycle had to be performed to obtain the zero for creep deformation. The number of cycles was recorded with an impulse counter counting in tens. The frequency depended slightly on load varying from about 585 to 587 c.p.m., but it was constant throughout a particular test.

At the end of a test the specimen was usually tested statically to failure to compare the gain in strength with that expected for an unloaded specimen.

5.3 Definition of Strains Measured

Creep strain is defined for a static test as the increase in strain from a point 30 seconds after application of the static load.

For a cyclic loading test, the creep strain is taken as the increase in the strain measured at the maximum load point of the cycle, above the value recorded at this point on the first cycle.

5.4 Method of Analysis of Results

For both the static and cyclic loading tests the creep curves for each test were fitted to the four basic equations:

$$\varepsilon = a.t^{b} \qquad (1)$$

$$\log(\varepsilon) = a + b.\ \log(t) \qquad (2)$$

$$\varepsilon = b.\ \log\ (t + 1) \qquad (3)$$

$$1/_{\varepsilon} = a + b/t \qquad (4)$$

(ε = creep, t = time, a, b = constants)

Equation 2 represents the linearised form of equation 1 and equation 4 is the linearised form of the hyperbolic equation, ultimate creep being $1/_{a}$. The fitting was done using the method of least squares and a computer programme was developed to do this. Each creep time curve was split up into several intervals to establish if any of the equations showed a signficantly better fit to a particular part of the creep curve. The regression statistics calculated were mean error (mean differences between measured and theoretical creep), maximum error, standard error of the errors standard deviation of the errors and, the correlation coefficient. The creep rates were also calculated, based on the increase in creep between two successive times of measurement, and fitted to equations 1 and 2.

Other computer programmes were developed to enable fitting of curves such as the hyperbolic sine relationship between creep and stress, and calculation of the area of the hysteresis loop.

CHAPTER 6

ANALYSIS OF RESULTS: CREEP

6.1 Introduction

A cyclic stress pattern is most conveniently represented by a mean stress component (σ_m) and an amplitude component (Δ). Thus for a sinusoidally varying stress of frequency f, the stress at any time t is given by:

$$\sigma_c = \sigma_m + \frac{\Delta}{2} \times \sin (120\pi ft)$$

(f in c.p.m.; t in hrs.)

The σ_m component is therefore analagous to a static stress, and thus it might be expected that there would be creep due to this similar to static creep, plus an additional creep due to the Δ component. The first part of the testing programme was therefore concerned with trying to establish the separate effects of varying mean stress and amplitude on creep.

Previous work has tended to be concerned with comparing creep under a cyclic stress to that under a static stress of magnitude equal to the upper limit of the cyclic stress. For purposes of comparison and also because from a practical view point maximum stresses are of interest the second part of the programme was concerned with the effect of maximum stress in the cycle on creep. The maximum stress is also of interest as far as the onset of microcracking is concerned.

The third part was concerned with sequences of static and cyclic loading to further investigate the nature of influence of cyclic loading such as whether it is additive or accelerative.

6.2 Testing Programme

6.2.1 Part 1

Two mean stress values of 0.25 and 0.35 of ultimate were used. In the first case the amplitude was increased in steps of 0.1 from 0 to 0.4 of ultimate for different tests, and in the second from 0 to 0.6.

For the investigation into the effect of changing mean stess an amplituted of 0.2 was used, the mean stress being increased in steps of 0.1 from 0.15 to 0.55 of ultimate. A series of static tests with similar stress values to these was also done.

These values were chosen so that a range of amplitudes and mean stresses could be obtained for which the effects of possible microcracking it is hoped would be minimised. They are also well spread from within to beyond normal working stresses.

6.2.2 Part 2

The lower stress was kept constant at 0.05 of ultimate being as near zero as practicable. The upper stress was increased in steps of 0.1 from 0.15 to 0.65 for different tests. For the tests in both parts three tests were usually done for each value.

6.2.3 Part 3

Two series were done. In the first a static stress of say 0.25 of ultimate was applied for a certain length of time. Immediately afterwards a cyclic stress was applied with mean stress equal to the previous static stress (0.25) and an amplitude of say 0.2. To another specimen from the same batch the cyclic load was applied first and the static load was applied second.

In the second series a static stress was applied for a given time followed by a cyclic stress of lower stress equal to 0.05 and upper stress equal to the previous static stress. A parallel test was again done with the sequences reversed.

6.3 The Effects of Variation of Amplitude and Mean Stress on Creep

6.3.1 Variation of Amplitude

How the amplitude component of stress modifies the static 0.35 mean stress creep curve is shown in fig. 6.1. The effect is more or less uniform until an amplitude of 0.5 is reached when a ~~sudden~~ rapid increase in creep is apparent. This is probably due to microcracking affecting the creep process, at least in the initial stages. Two factors bear this **out.** Firstly an amplitude of 0.6 caused fatigue failure, which is a result of crack propagation and the 0.5 curve lies close to the 0.6 curve initially. Secondly the elastic strain showed an initial increasing period for the 0.5 amplitude test before starting to decrease. An increasing elastic strain is a characteristic of when microcracking is occuring. Referring to the log creep-log time graphs (fig. 6.2) there is quite good lineanty for the lower amplitudes indicating some form of power expression for the creep curves (see chapter 9). The change of gradient of the 0.5 amplitude curve at about three hours coincides approximately with where the elastic strain changed from increasing to decreasing, again indicating some form of change in the creep mechanism.

The tests conducted at a mean stress of 0.25 showed very similar behaviour (fig.6.3) to the above. Some microcracking is evident for

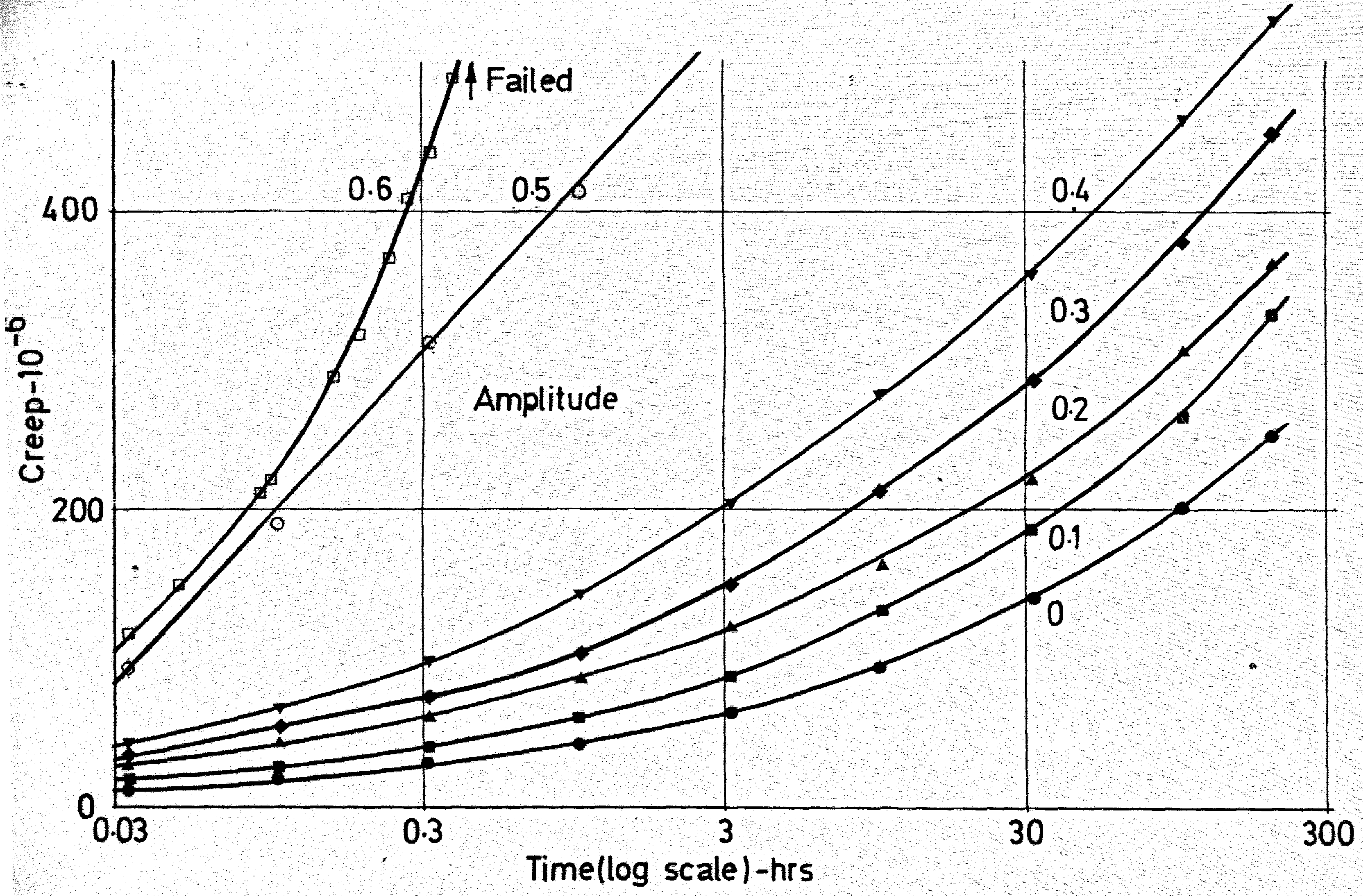

Fig. 6.1 The influence of amplitude on creep-mean stress = 0.35

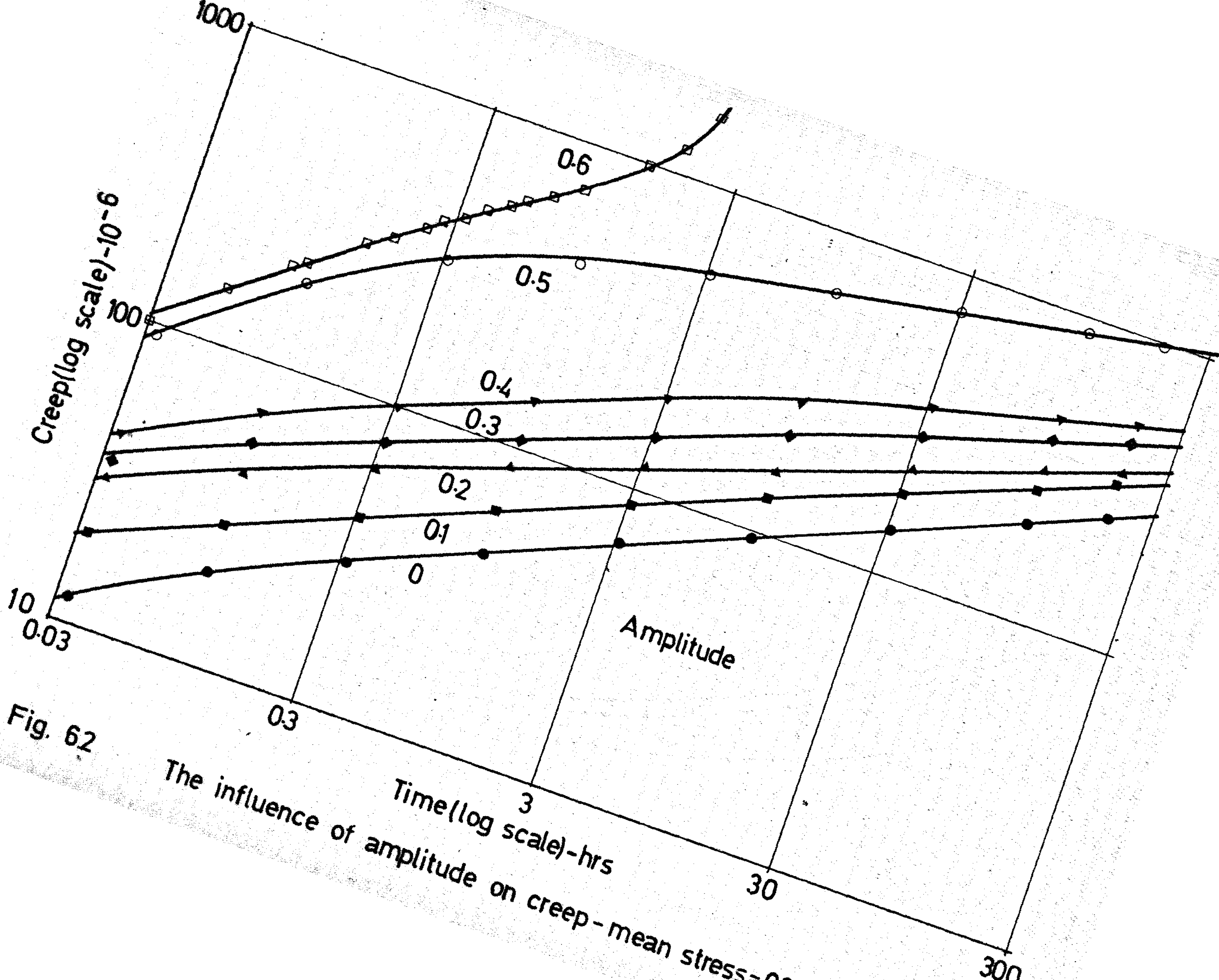

Fig. 6.2 The influence of amplitude on creep-mean stress=0.35

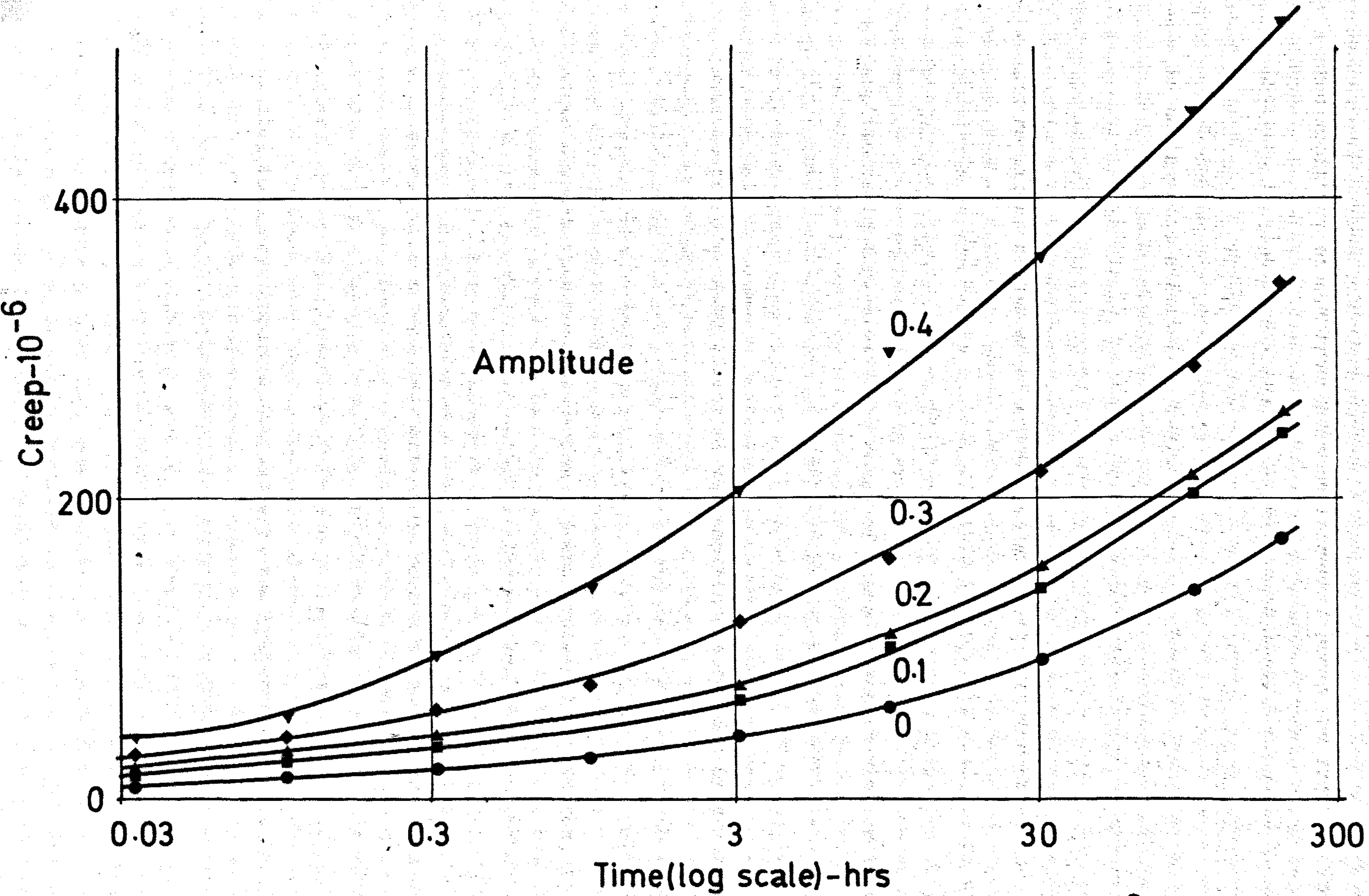

Fig. 6.3 The influence of amplitude on creep-mean stress = 0·75

the amplitude of 0.4 from the much increased creep and from the intial increase in elastic strain. This stress is lower than would be expected for microcracking to occur and it seems that the near zero lower stress is having some effect (see 6.4).

If the creep at a given time due to the 0.35 static stress is substracted from the creep at the same time due to a mean stress of 0.35 and amplitude of stress of say 0.2 we are left with the creep due to an amplitude of 0.2 alone. This amplitude creep as it will now be called, is shown plotted against time for the mean stress of 0.35 and all the amplitudes in fig. 6.4. The shape of these curves is similar to static creep curves (the 0.35 static curve is shown for comparison). If the amplitude components are divided by the static component of creep we can see the proportionate effect of the amplitude component of stress (or cyclic component) and static (or mean stress) component on creep at any time (fig. 6.5). The ratio amplitude to mean stress component of creep shows a continuous decrease - for 0.3 amplitude 2 at 2 minutes, $1\frac{1}{2}$ at 18 minutes, $\frac{3}{4}$ at 200 hours. Thus the effect of the cyclic component of stress is initially very high decreasing at first rapidly then slowly with time. The ratio just mentioned shows a tendency towards a constant value or at least to a very slow decreasing value - the higher the amplitude the higher the ratio. If the effect of a cyclic stress is related to energy input associated with the hysteresis effect in concrete it would be expected from the above results that the area of the hysteresis loop would show a continuous decrease. This has been shown to be so by

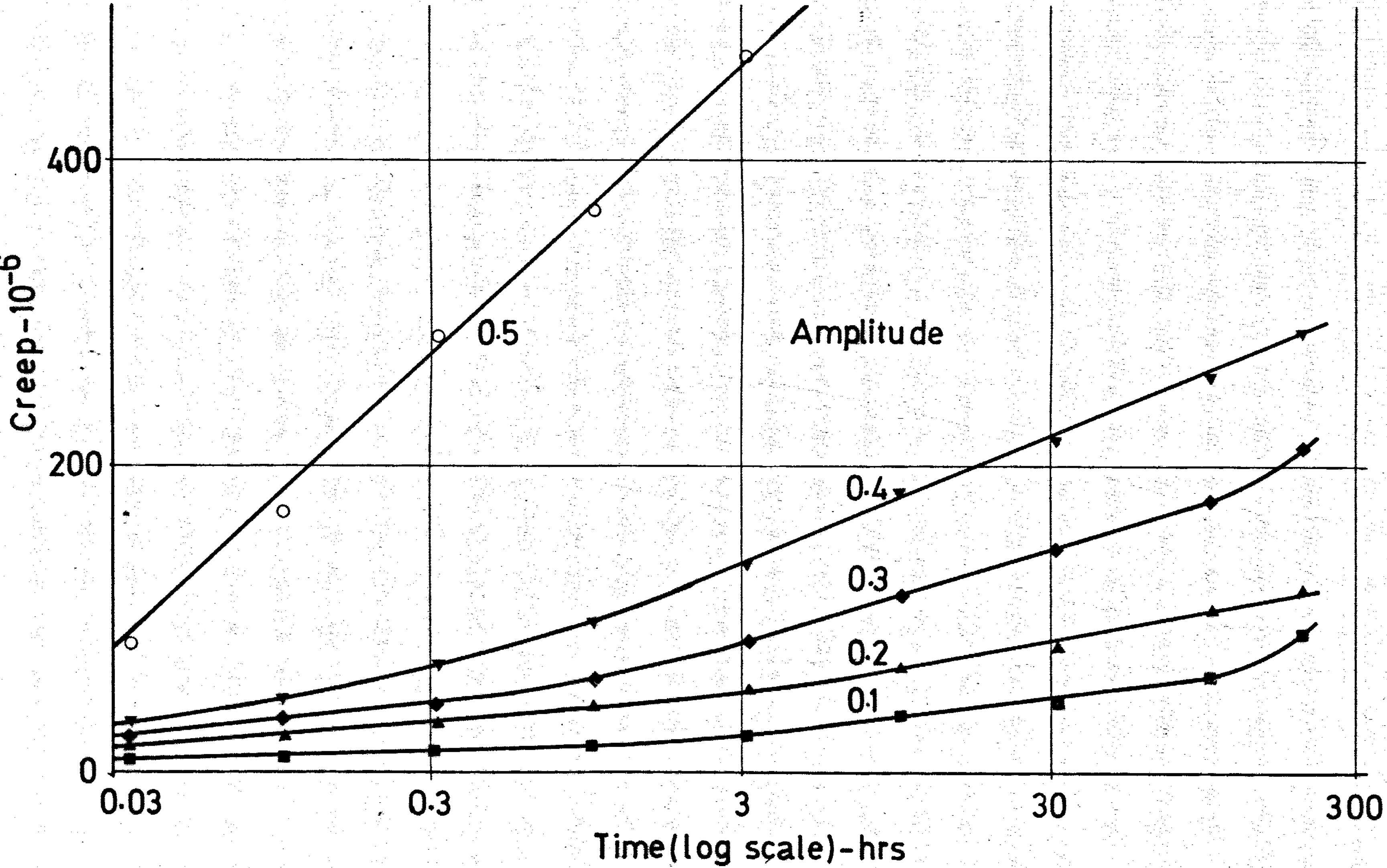

Fig. 6.4 The influence of amplitude on amplitude creep-mean stress=0.35

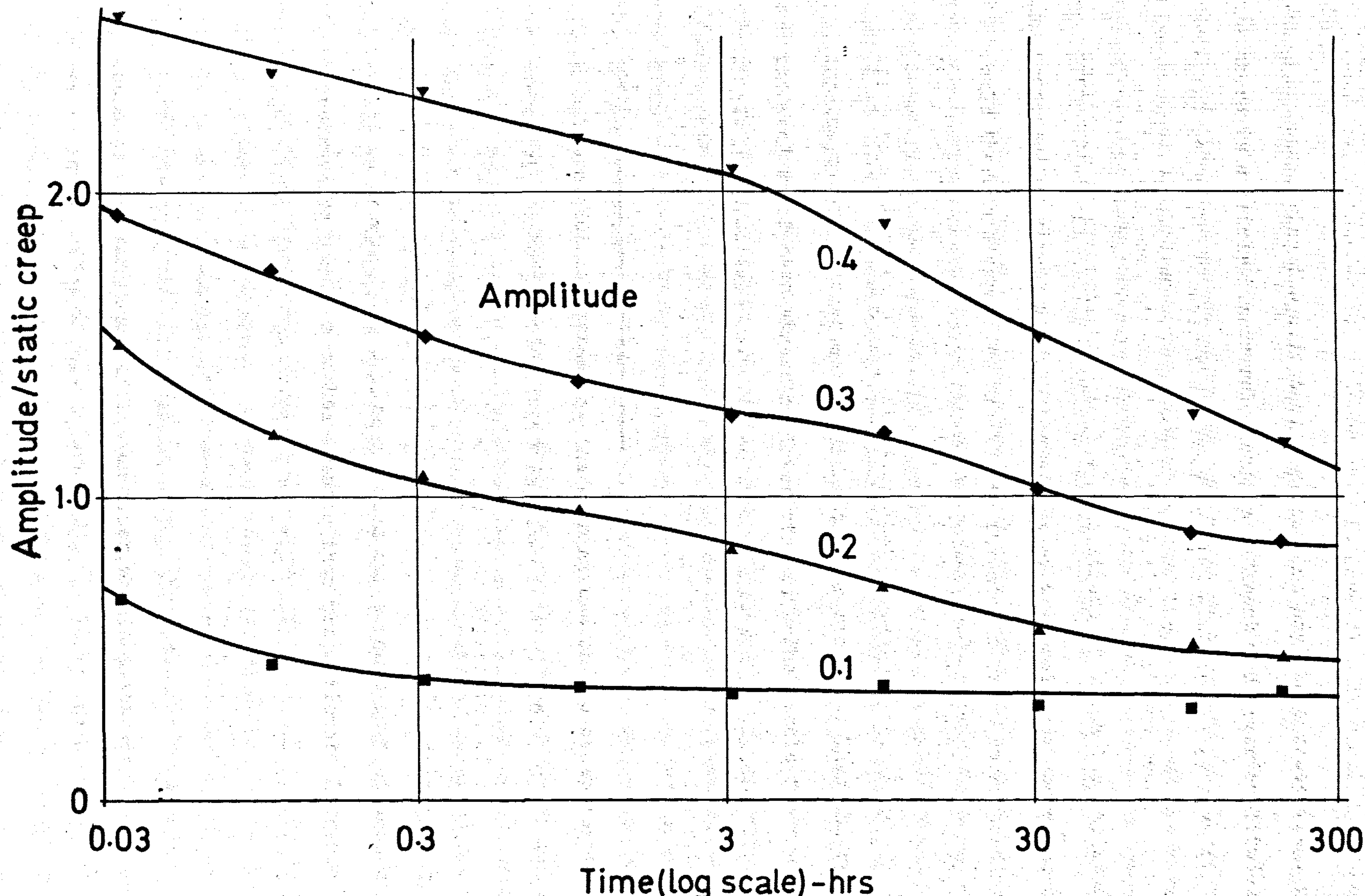

Fig. 6.5 The Influence of amplitude on the ratio amplitude/static creep -mean stress=0.35

other investigators (7, 11) and this is more closely studied in Chapter 7.

Considering the effect of amplitude on amplitude creep (fig. 6.6) there is a fairly linear relationship at least for lower amplitudes and later stages. However the curves for the mean stress of 0.35 lie above those for the mean stress of 0.25 indicating amplitude creep for a given amplitude is proportional to the mean stress at which the amplitude component of stress acts. The effect of the amplitude component of stress would therefore appear to accelerate the static creep corresponding to the mean stress at which it acts. However, if the ratio of amplitude creep to static creep is plotted against amplitude (fig. 6.7) the lines for the two mean stresses coincide at later stages. Thus the ratio is independent of mean stress at later stages. The result for the 0.4 amplitude associated with a 0.25 mean stress shows excessive amplitude creep probably due to premature microcracking as indicated earlier (see 6.4).

6.3.2 Variation of Mean Stress

The effect of increasing the mean stress on the creep-log time curves with an amplitude of 0.2 is shown in fig. 6.8. Compared with static stress curves there is a much wider separation of the cyclic stress curves at 0.03 hrs. indicating the early effect of a cyclic stress on creep. The 0.55 mean stress curve shows some effects of microcracking having a rather greater than proportionate increase in creep. Some change of gradient is also noticeable for this test on the log creep-log time curve (fig. 6.9) as was noted earlier when microcracking occurs significantly and then becomes arrested. However, microcracking seems to have much more effect on creep when amplitude of stress is high rather than when the mean stress is high and the

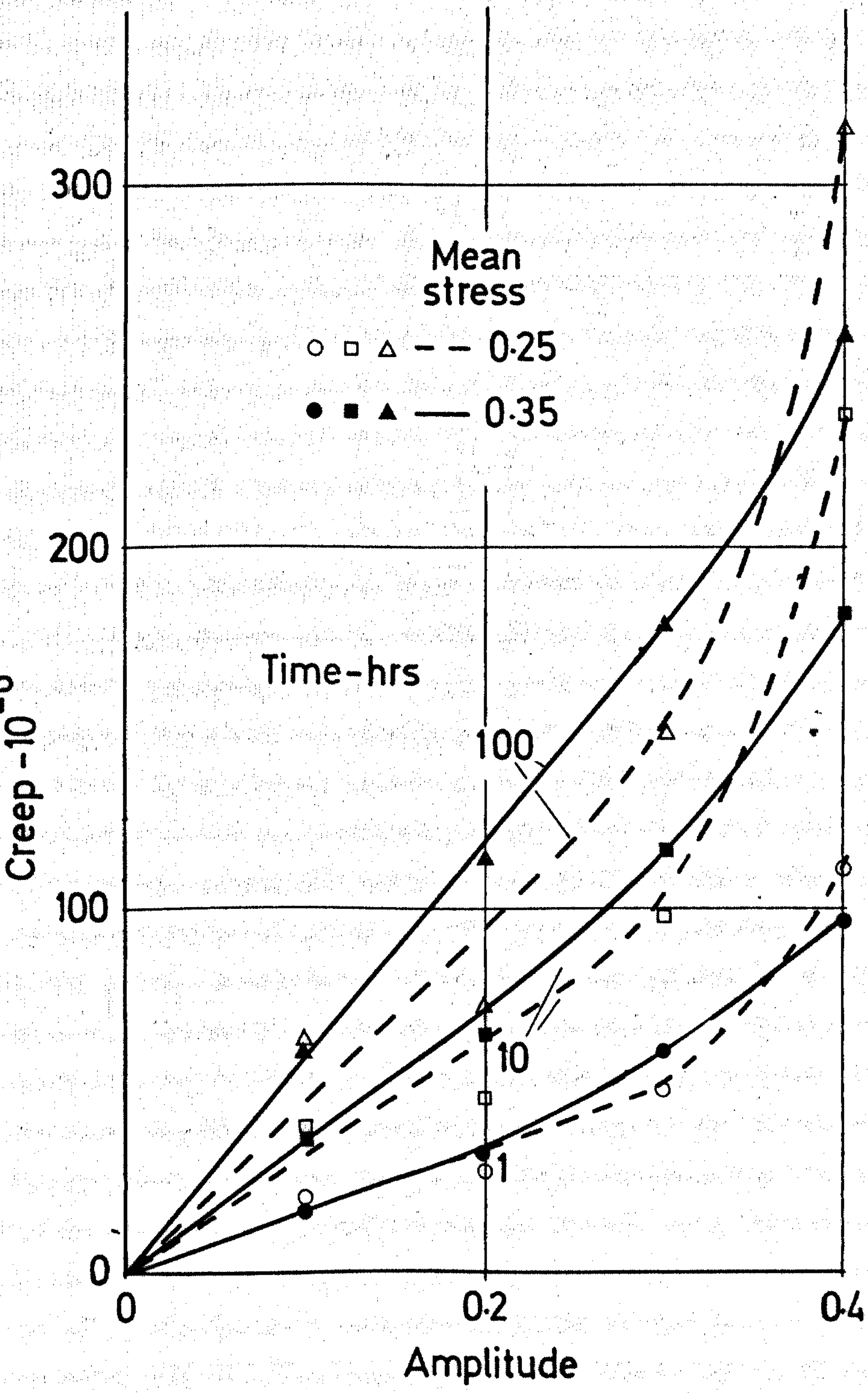

Fig. 6.6 The effect of amplitude on amplitude creep

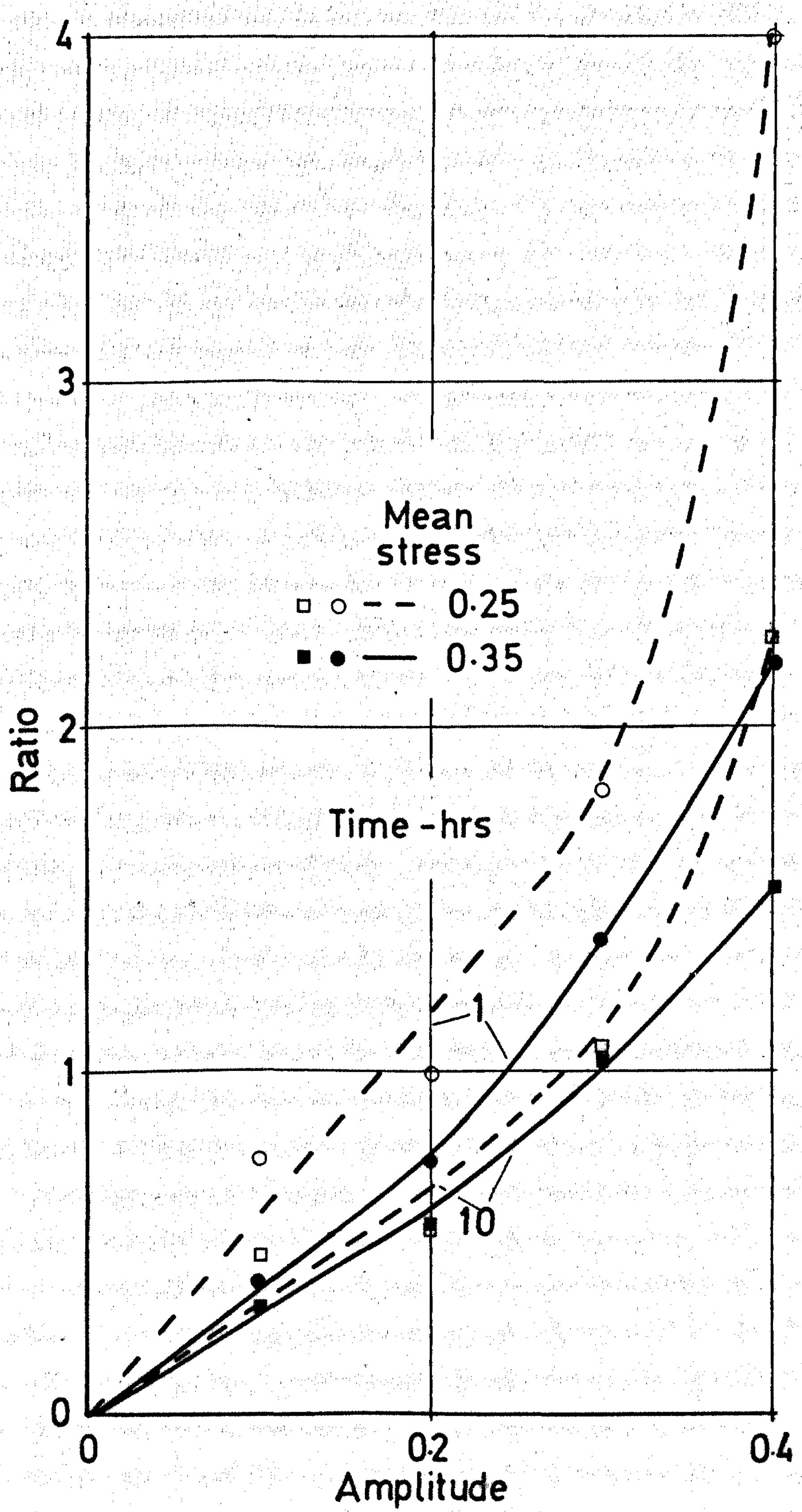

Fig. 6.7 The effect of amplitude on the ratio amplitude/static creep

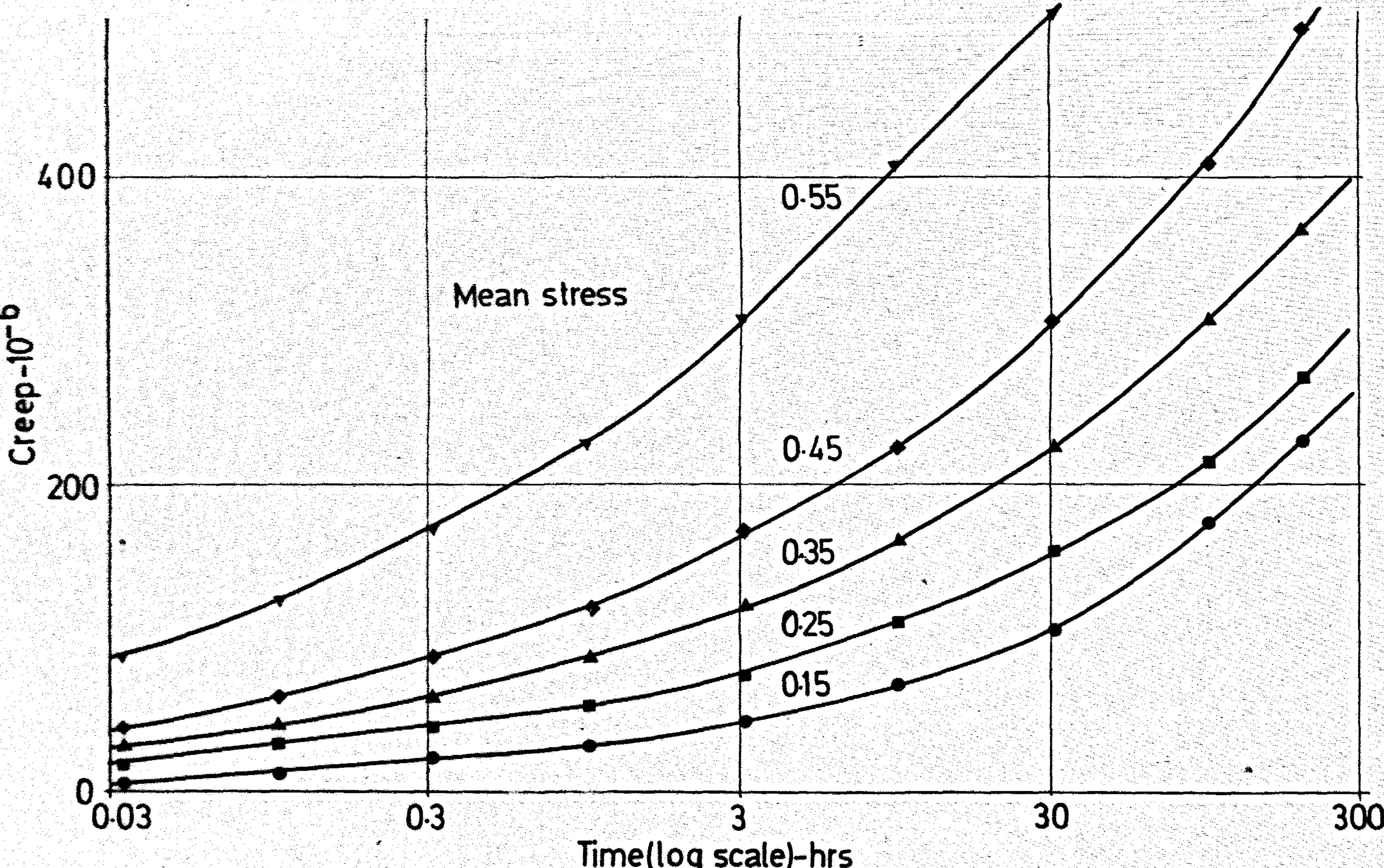

Fig. 6.8 The influence of mean stress on creep-amplitude=0·2

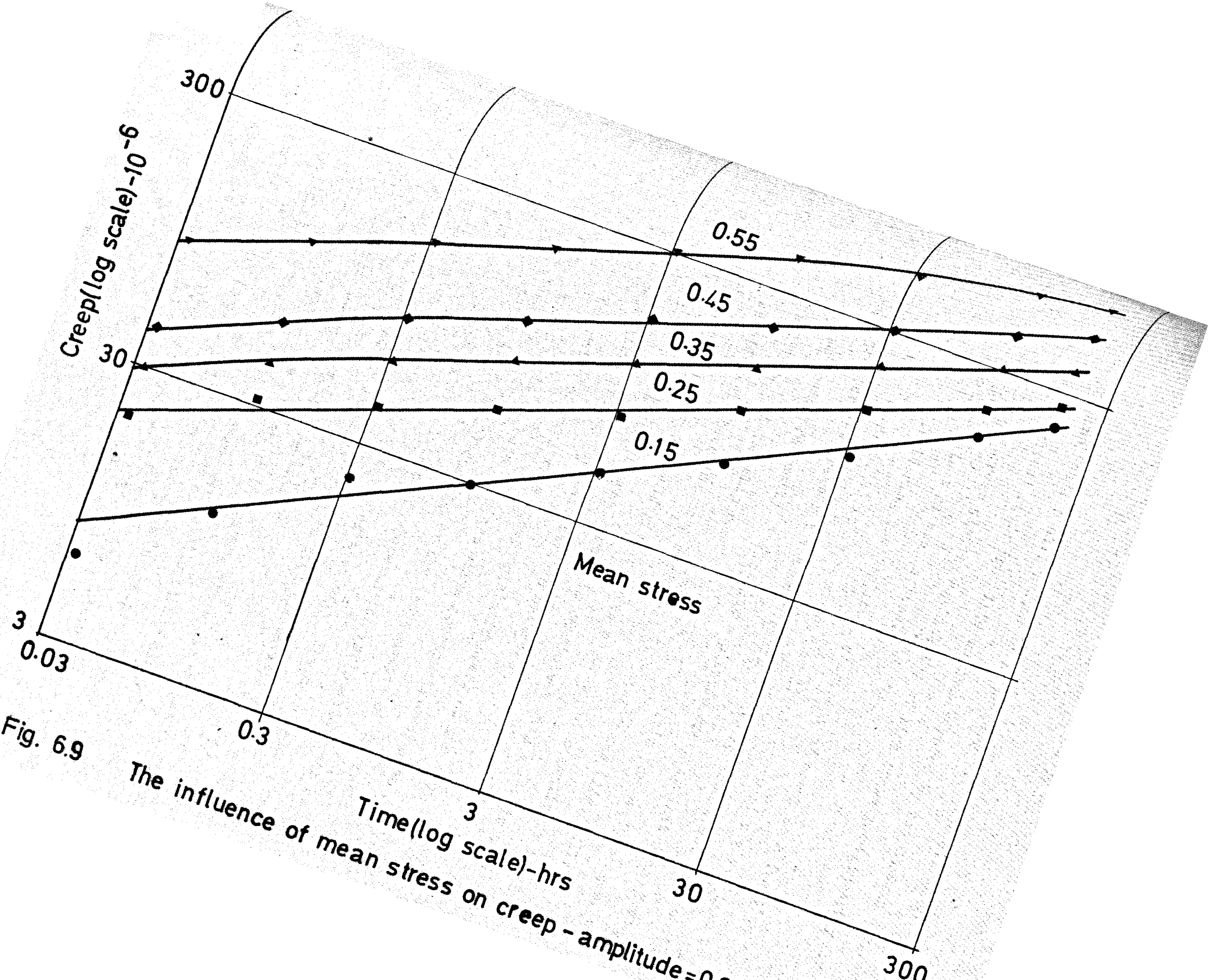

Fig. 6.9 The influence of mean stress on creep - amplitude=0.2

amplitude small. This is in keeping with the effect of amplitude of stress on fatigue life as demonstrated by the Goodman diagram (18). Log of creep plotted against log of time shows good linearity for the other values of mean stress.

Considering the amplitude component of creep as a function of time (fig. 6.10) it is seen that amplitude creep at a given time is greater the greater the mean stress. This is consistent with what was found previously. Plotting amplitude creep against mean stress shows a linear relationship passing through the origin for early stages, the relationship becoming more scattered at later times (fig. 6.11). That a zero mean stress would give rise to no creep with amplitude creep being proportional to mean stress is consistent with a cyclic stress being accelerative rather than additive in nature.

The ratio of amplitude creep to static creep at the appropriate mean stress tends to be a constant value irrespective of mean stress at later stages (fig. 6.12) confirming the independence of the ratio on mean stress. There is no relationship between the ratio and stress at earlier stages just a wider degree of scatter. The mean value shows a decreasing trend as would be expected from the earlier results.

6.4 Variation of Upper Stress Limit

A comparison of the effect of increasing the upper stress limit for cyclic stress creep-log time curves with static stress creep-log time curves is shown in fig. 6.13. The increase in creep over static creep above a stress of 0.35 is very large (fig. 6.14). Above this stress the

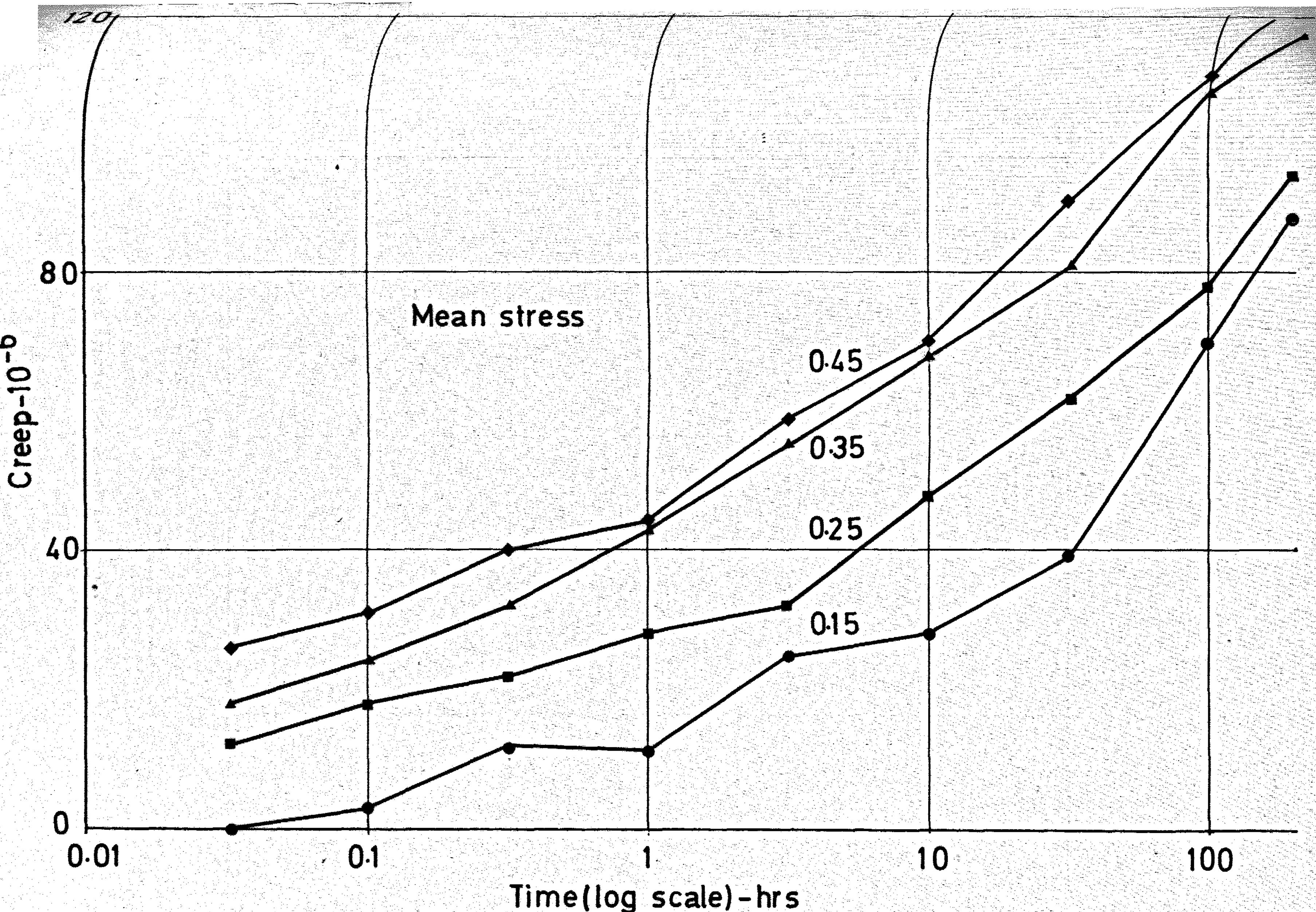

Fig. 6.10 The influence of mean stress on amplitude creep-amplitude = 0.2

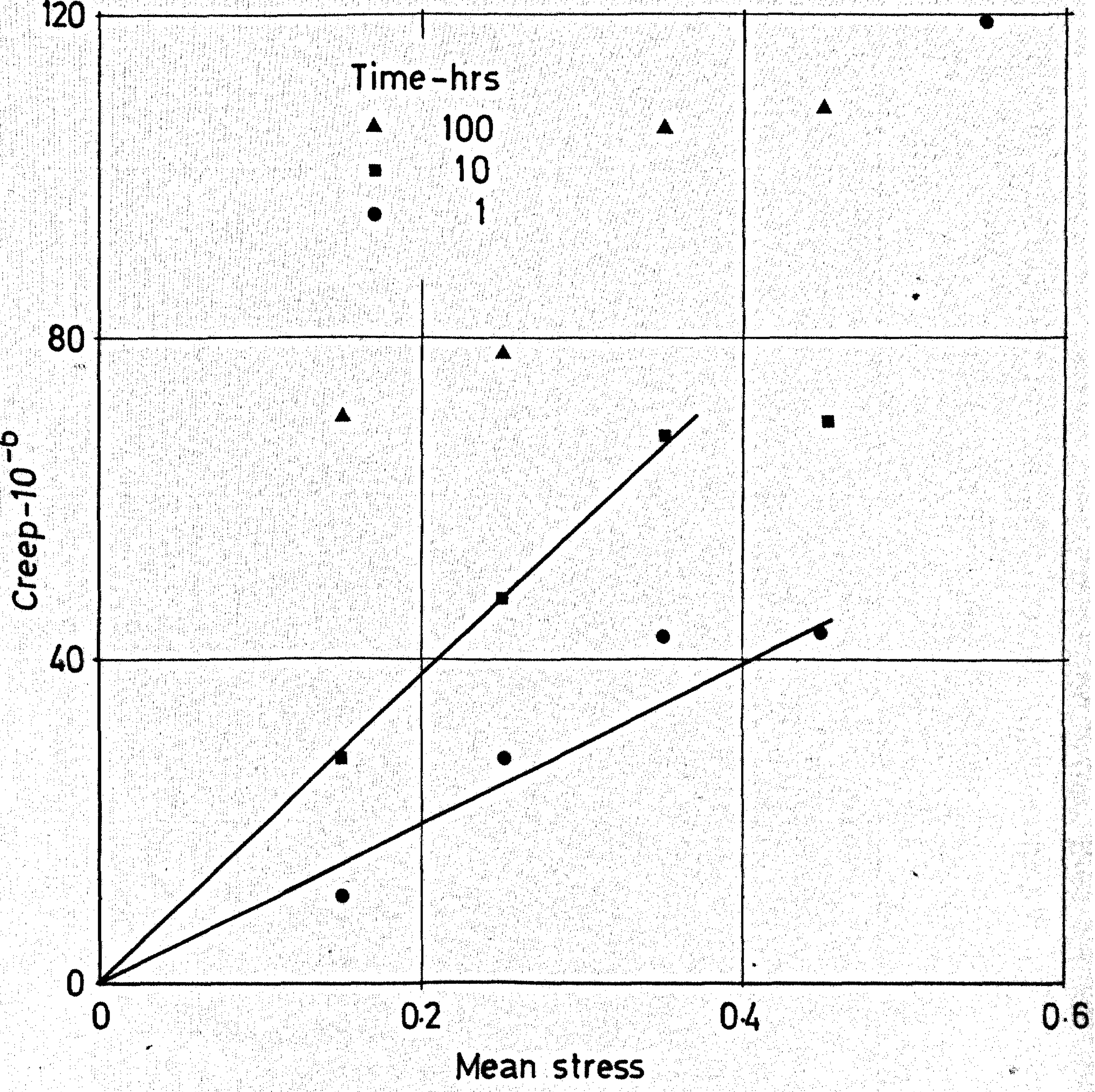

Fig. 6.11 The effect of mean stress on amplitude creep

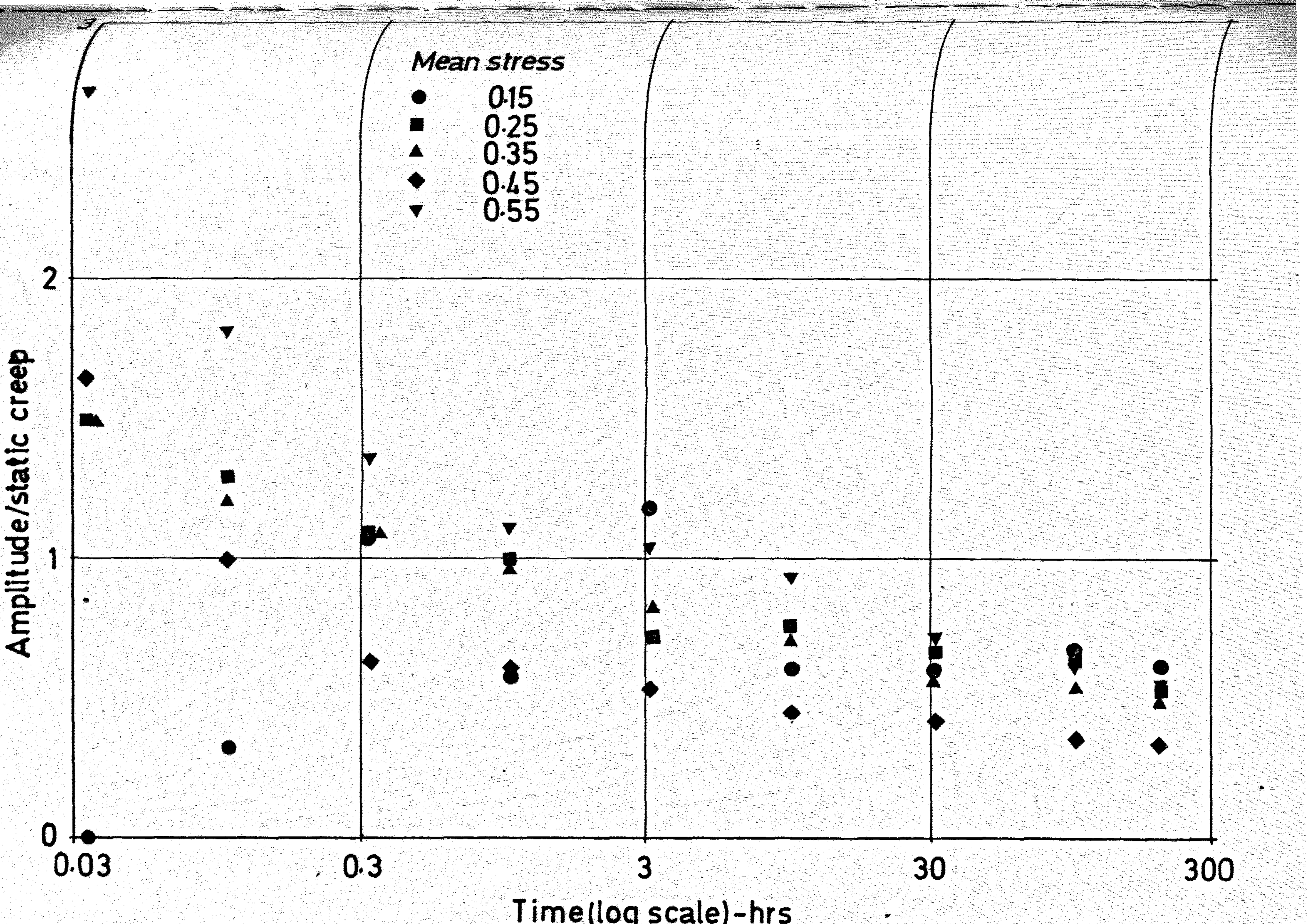

Fig. 6.12 The ratio amplitude/static creep for different mean stresses-amplitude=0·2

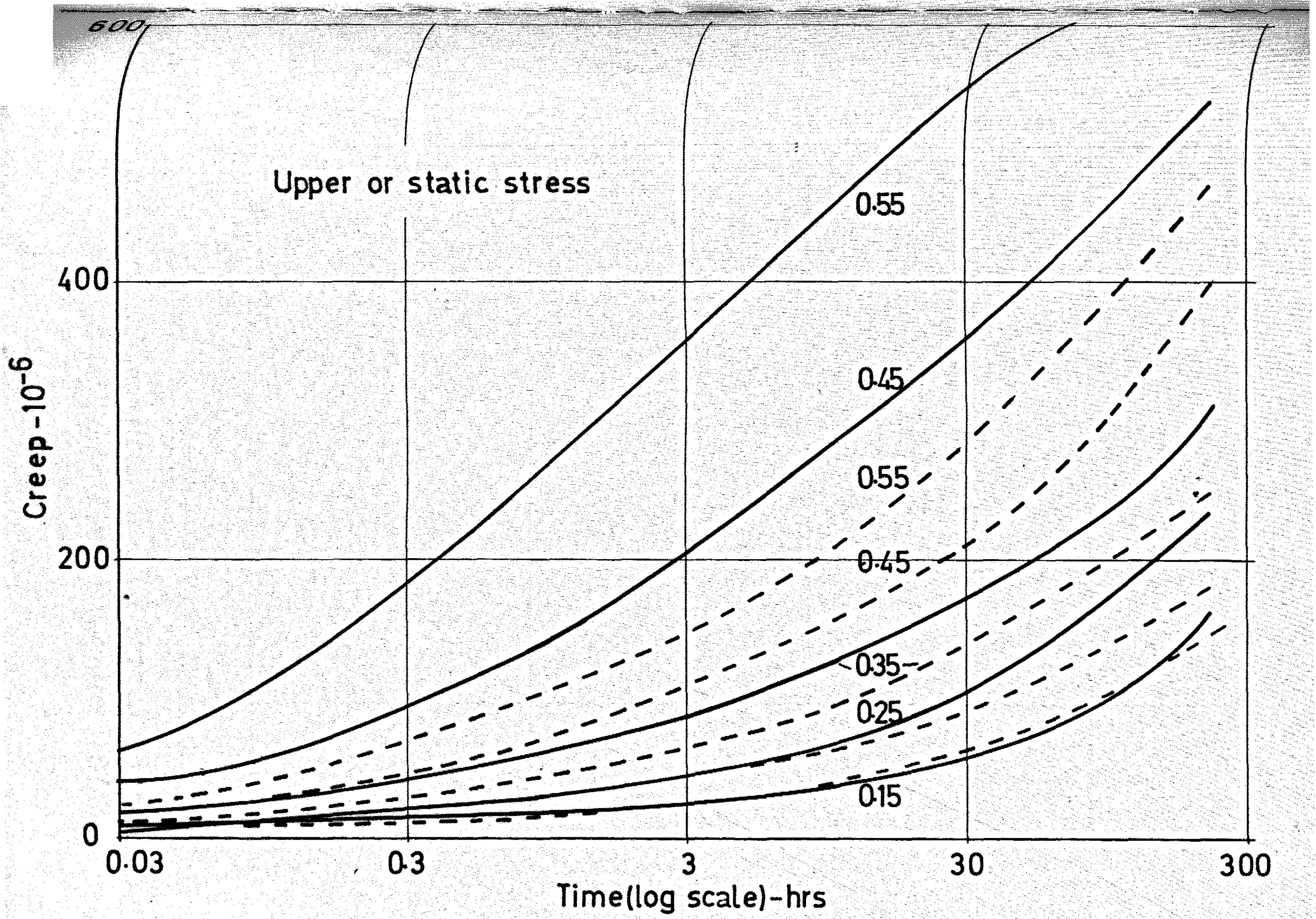

Fig. 6.13 The influence of upper stress on creep compared with static stress - lower stress = 0.05

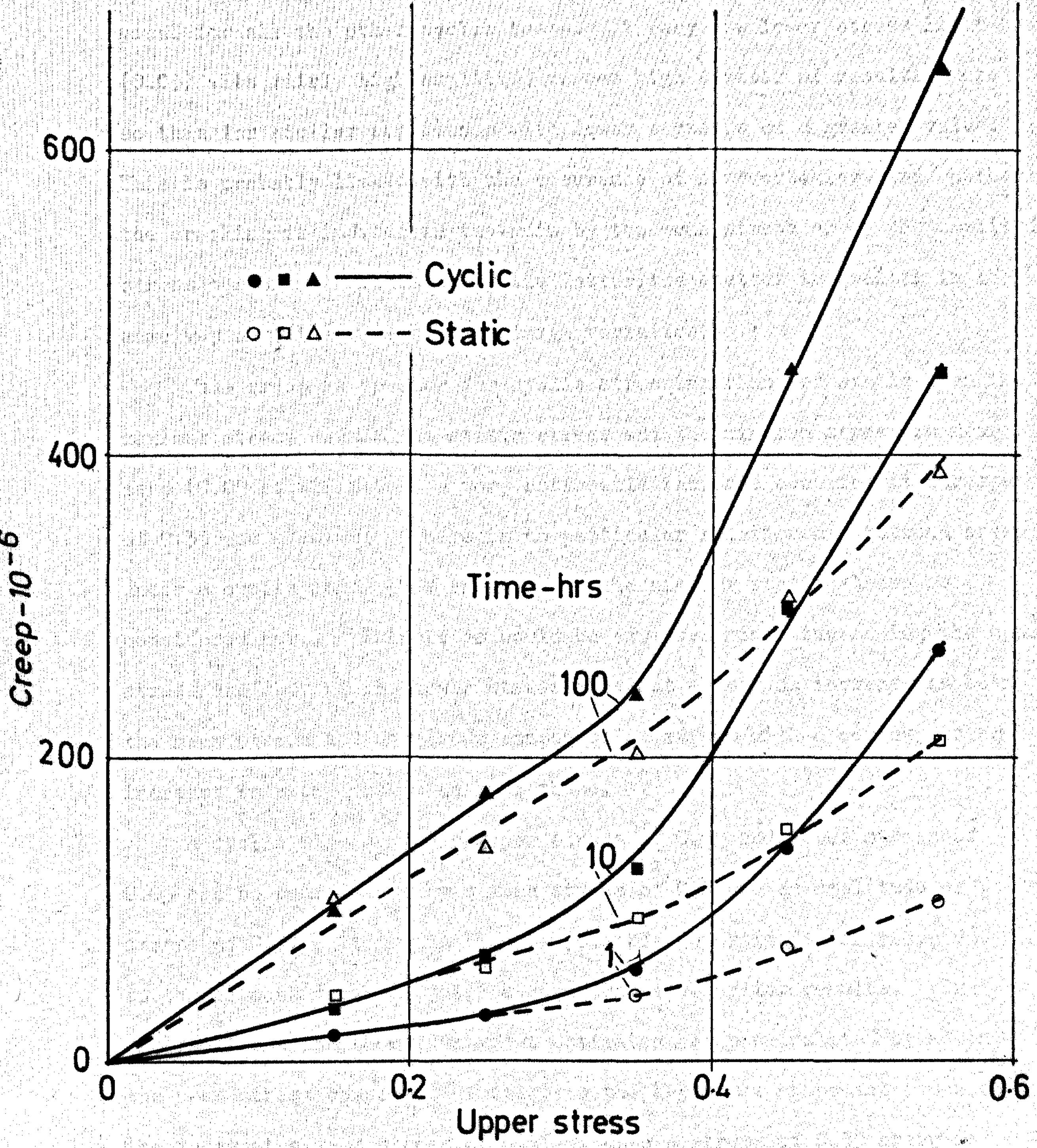

Fig. 6.14 Comparison of the effects of static & upper stress on creep (lower stress=0·05)

variation between similar cyclic stress tests was much wider than was usual for all the other cyclic tests. A very low lower stress limit (0.05) with fairly high amplitude causes high scatter of results, more so than for similar amplitudes with lower stresses of a greater value. This is probably linked with the occurence of microcracking, and whether the cracking is induced in the main by the mean stress or by the amplitude stress component - if it is by the latter the scatter is greater in the same way as fatigue tests show large variation.

Thus creep is greater for cyclic stressing than for static when the maximum stress equals the static stress and the minimum stress is near zero (0.05 of ultimate), a very noticeable increase occuring at stresses of 0.35 and greater. There is no particular relationship between creep under a cyclic stress and creep under the similar static stress as considered here. This is as would be expected since increasing the upper stress and leaving the lower stress constant causes an increase in both the mean stress and amplitude component of stress with a corresponding increase in creep due to both of these.

A cyclic stress of say upper stress of 0.35 and lower stress of 0.05 can be represented by a mean stress of 0.2 and an amplitude of stress of 0.3. It should thus be possible to estimate the creep due to the present type of cyclic stress from the earlier results. In table 1 the fourth column shows estimated creep calculated by adding the mean stress component of creep to the amplitude component based on the tests at a mean stress of 0.35. Upto a stress of 0.35 creep is

TABLE 1

Stress	Time hrs.	Measured creep ($x10^{-6}$)	Mean and amplitude creep ($x10^{-6}$)	Mean and ratio x mean creep ($x10^{-6}$)
upper = 0.15	10	36	65	35
mean = 0.1	100	100	132	91
amp. = 0.1	200	150	184	129
upper = 0.25	10	70	98	66
mean = 0.15	100	125	220	164
amp. = 0.2	200	228	295	230
upper = 0.35	10	129	169	116
mean = 0.2	100	240	302	232
amp. = 0.3	200	294	368	294
upper = 0.45	10	298	244	180
mean = 0.25	100	457	399	319
amp. = 0.4	200	519	462	381
upper = 0.55	10	453	633	534
mean = 0.3	100	654	869	762
amp. = 0.5	200	710	946	843

overestimated for each result. This agrees with the dependence of amplitude creep on mean stress as stated earlier. The fifth column shows creep calculated by adding the mean stress component to the amplitude component which was calculated by multiplying the mean stress component by the appropriate ratio taken from the 0.35 mean stress tests. Upto a stress of 0.35 the agreement with the observed values is good at all three times. For a stress of 0.45 the observed results are much higher than the estimated results, but for 0.55 the estimated results are higher than the observed ones. The former result indicates the early microcracking induced by the low lower stress, the latter may be due to the high degree of microcracking dependent creep with an amplitude of 0.5 and hence over estimate of the ratio.

It is therefore possible to estimate creep under a cyclic stress for any mean stress and amplitude from one set of amplitude variation tests and one set of static tests, provided the lower stress is 0.1 or greater and that severe microcracking is not likely to occur, using the ratio amplitude creep to static creep. However, a fair amount of experimental work is necessary to obtain these curves and further simplification on a specific creep basis is considered in chapter 8. Being able to express creep under a cyclic stress in terms of a static stress implies that factors influencing creep under a static stress will influence a creep under a cyclic stress in a similar manner, which would also be in agreement with the idea that cyclic stressing has an accelerative effect on the creep process.

6.5 Sequences of Static and Cyclic Stresses

Table 2 gives a list of the tests done in this series. The fourth column shows the creep due to the first part of the sequence, the fifth creep due to the second part and the sixth the final over-all creep. For each test the first line refers to the cyclic stress applied first, the second to the static.

Considering first the tests in which the mean stress of the cyclic stress is equal to the static stress, for an amplitude of 0.2 and mean stress of 0.25 and 0.35 the over-all creep for the cyclic stress applied first is slightly less than when the static stress is applied first. For an amplitude of 0.2 and mean stress of 0.45 and for both mean stresses at an amplitude of 0.4 the over-all creep is significantly greater for the cyclic stress applied first. The occurrence of creep due to microcracking is likely for these latter tests. If the tendency for microcracking under a cyclic stress is reduced by pre-application of a static stress then the creep when a cyclic stress is applied first would be greater. Thus at low stresses and amplitudes a previously applied static stress does not affect the accelerative effect of a cyclic stress, but at high stresses it does.

Looking again at the first two tests mentioned, if the amplitude component of creep is added to the extrapolated static curve to give a predicted curve for cyclic stress following a static stress, the agreement is quite good with the experimental curve (fig. 6.15 and 6.16). For the other tests the predicted curves obtained in this manner lie well above

TABLE 2

Upper stress	Lower stress	Static stress	First part creep ($x10^{-6}$)	Second part creep ($x10^{-6}$)	Over all creep ($x10^{-6}$)	
0.35	0.15	0.25	192	12	204	cyclic first
			110	105	215	static first
0.45	0.25	0.35	230	18	248	cyclic first
			174	110	284	static first
0.55	0.35	0.45	352	16	368	cyclic first
			220	106	326	static first
0.45	0.05	0.25	452	26	478	cyclic first
			150	134	384	static first
0.55	0.15	0.35	444	42	486	cyclic first
			160	202	362	static first
0.35	0.05	0.35	230	54	284	cyclic first
			166	52	218	static first
0.45	0.05	0.45	515	80	595	cyclic first
			280	130	410	static first
0.55	0.05	0.55	835	150	985	cyclic first
			350	195	545	static first

the experimental curves (figs. 6.17-19) which is in agreement with the effects of microcracking as mentioned previously. However for all the tests the over-all creep predicted by this superposition method is in close agreement with the observed over-all creep for the tests with the cyclic stress applied first. This means in effect that the increase in creep when a static stress is applied after a cyclic stress is similar to the increase in creep that would have occurred in the same time interval in a specimen subjected to a constant static stress. Thus removal of the amplitude component of stress causes no recovery and in consequence the effect of a cyclic stress must be accelerative of the static process. This does not in itself mean that amplitude creep is irrecoverable, however the evidence suggests that a cyclic stress does mainly affect the irrecoverable creep (see chapter 7)

Considering the tests in this series in which the upper stress of the cyclic stress is equal to the static stress, the lower stress being 0.05 throughout, from the table it can be seen that when the cyclic stress is applied first the final over-all creep is significantly greater than when the static stress is applied first, much more so the higher the stress. Referring to the cyclic stress of upper stress of 0.35, this is equivalent to a mean stress of 0.2 and an amplitude of 0.3. Thus when applying the cyclic stress after the static stress of 0.35 the mean stress is being reduced by 0.15 with a consequent reduction in creep. Also some recovery will take place (though an actual increase in length of the specimen may not occur) which will reduce the accelerative effect of the amplitude

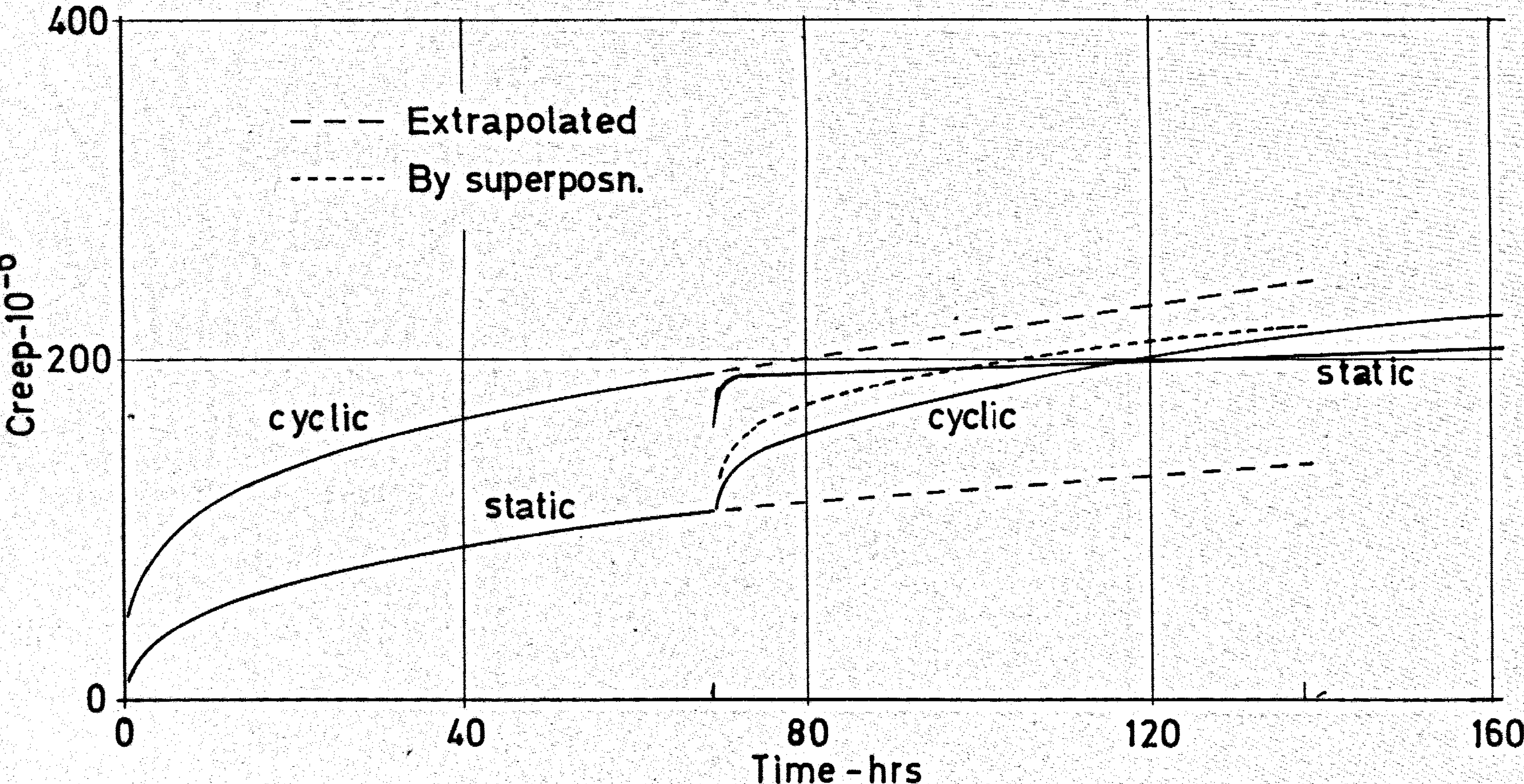

Fig. 6.15 Static & cyclic stresses in sequence - mean & static stress = 0·25, amplitude = 0·2

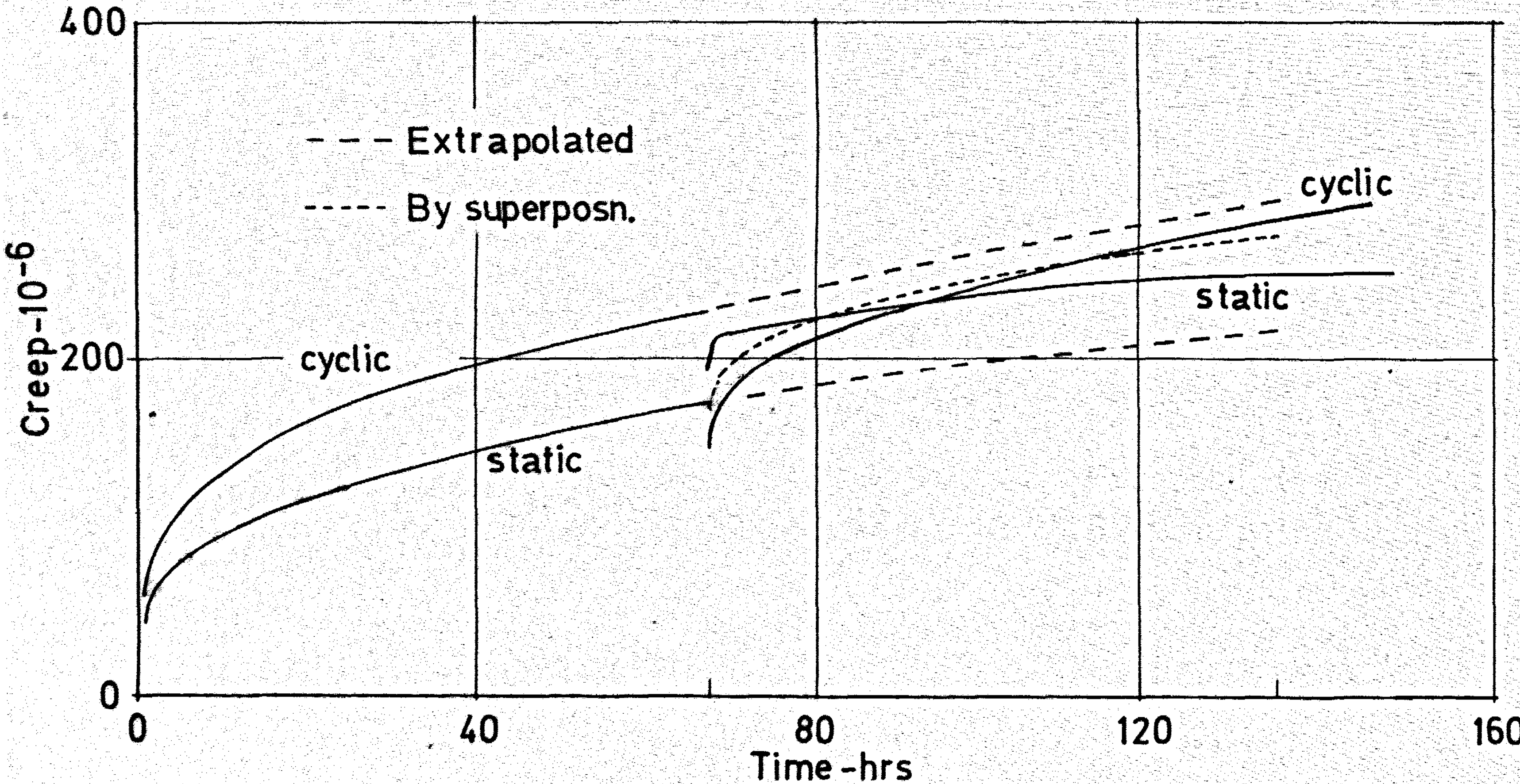

Fig. 6.16 Static & cyclic stresses in sequence-static & mean stress = 0.35, amplitude = 0.2

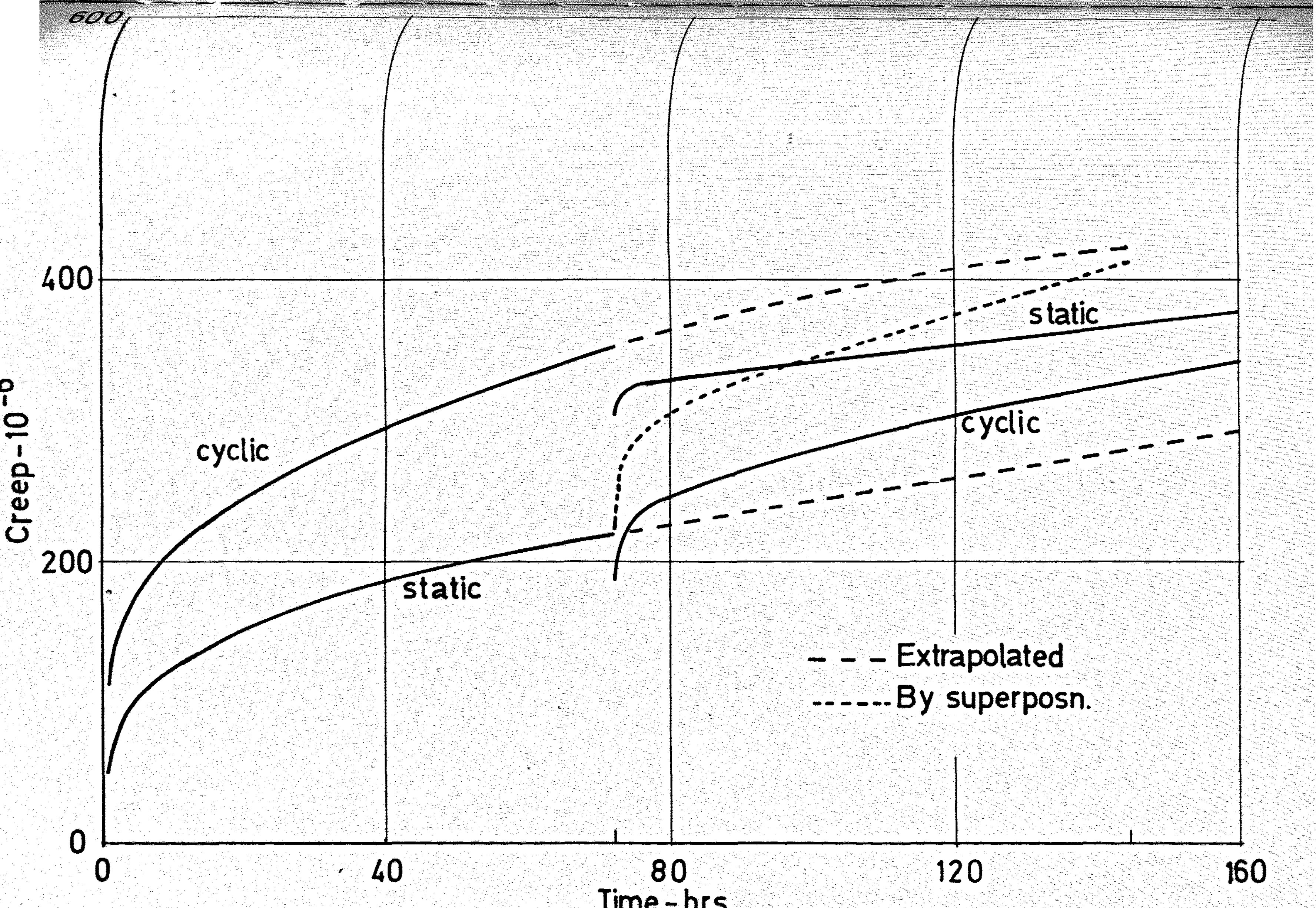

Fig. 6.17 Static & cyclic stresses in seqence - static & mean stress = 0·45, amplitude = 0·2

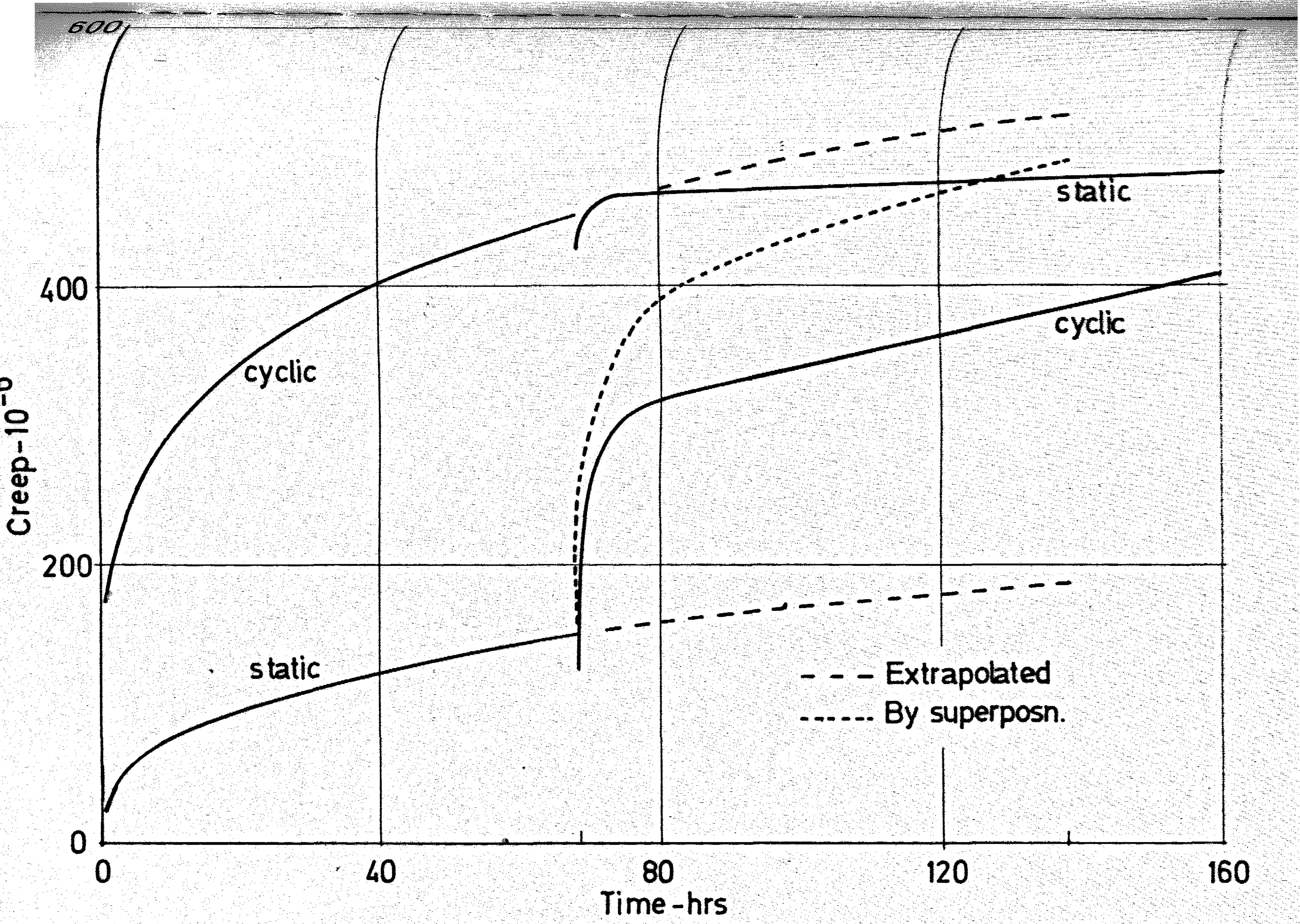

Fig. 6.18 Static & cyclic stresses in sequence - static & mean stress = 0.25 amplitude = 0.4

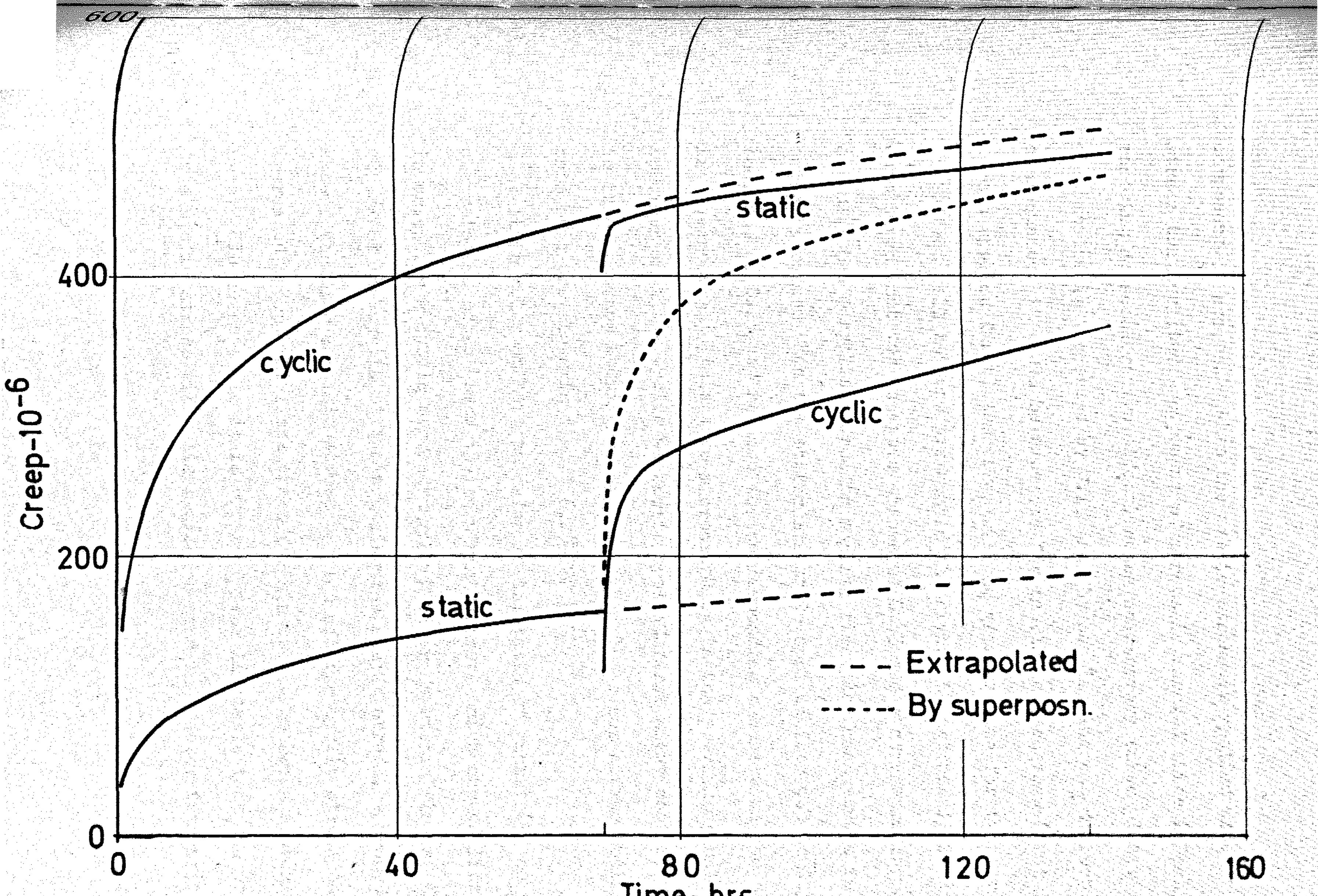

Fig. 6.19 Static & cyclic stresses in sequence - static & mean stress = 0·35 amplitude = 0·4

component of stress. When the static stress is applied after the cyclic stress the amplitude component of stress is removed which is only removing an accelerative effect, hence no recovery takes place, and the mean stress is increased by 0.15 thereby causing increased creep. In consequence, it would be expected for the latter sequence (that is cyclic stress applied first) the creep will be greater than for the former one. The effect will be more pronounced the higher the stress if it is considered that for an upper stress of 0.55 and a corresponding static stress, when a cyclic stress is applied first, the mean stress is being increased when the static stress is applied from 0.3 to 0.55, an increase of 0.25, and reduced the corresponding amount when the sequence is reversed. In this case microcracking in the previously unloaded specimen when the cyclic stress is applied first might contribute also to this sequence showing greater creep. The creep curves obtained for this part are shown in figs. 6.20-22.

It is relevant here to refer to the tests of Probst (3) on reinforced concrete and of Le Camus (5) on plain concrete which showed little increase in creep for a cyclic stress applied after a static stress, the upper stress of the cyclic stress equaling the static stress. Probst also showed that for a static stress applied after a cyclic stress there was increased creep, the final creep for his two beams being approximately the same. In these tests it is apparent from the table that the creep due to a cyclic stress with this applied second is greater than creep due to

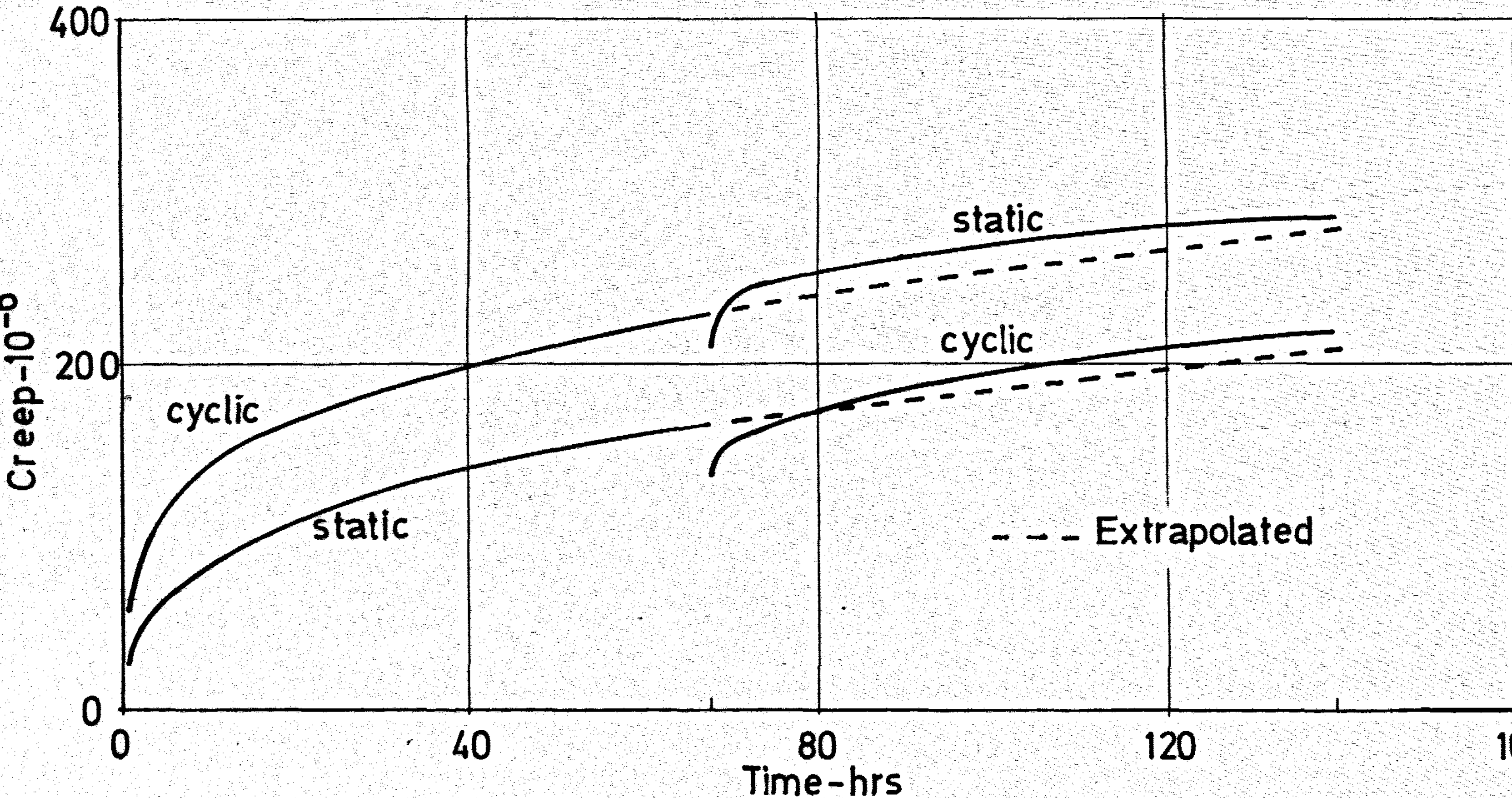

Fig. 6.20 Static & cyclic stresses in sequence - static & upper stress=0·35 lower stress=0·05

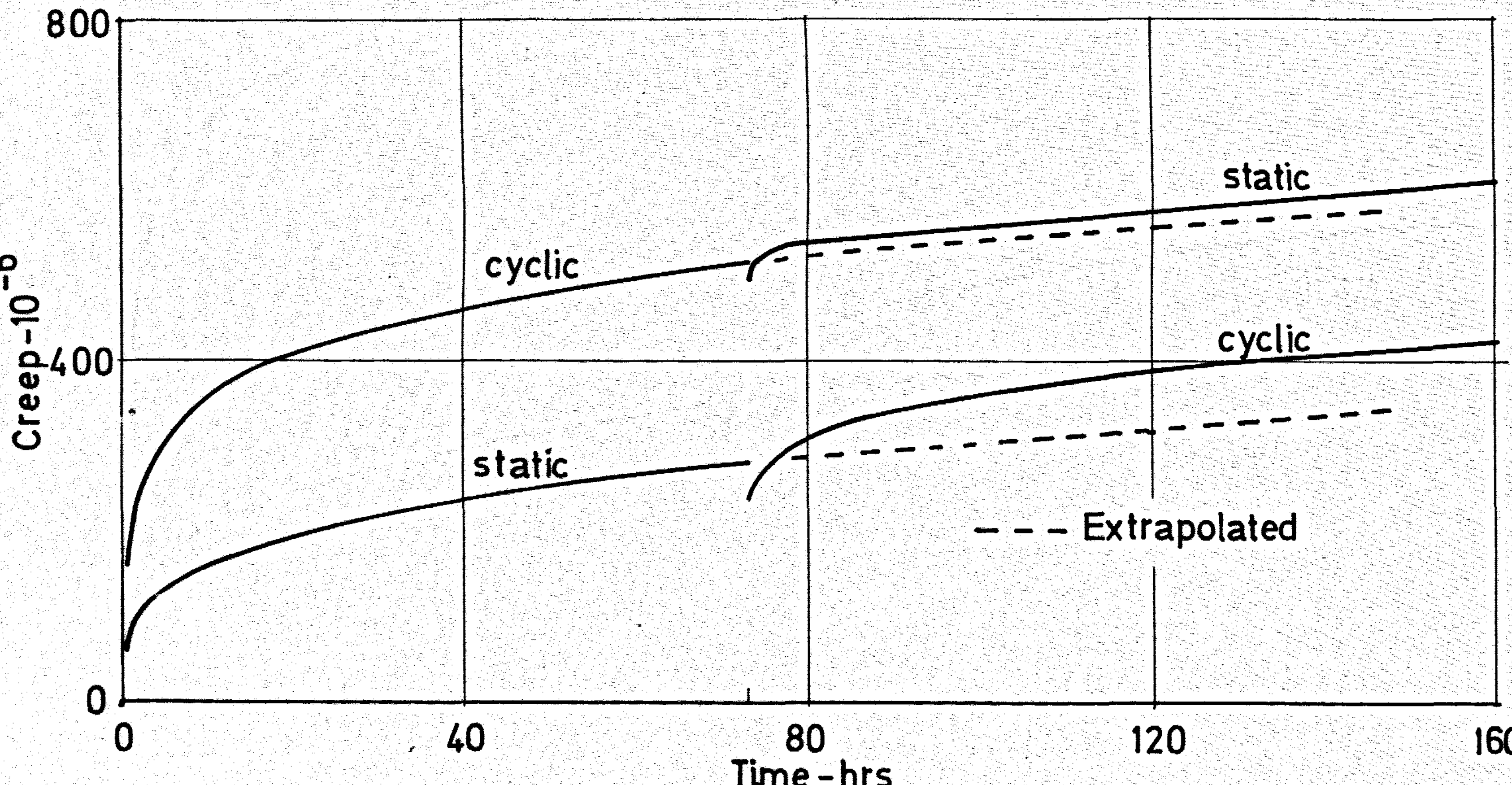

Fig. 6.21 Static & cyclic stresses in sequence - static & upper stress = 0·45 lower stess = 0·05

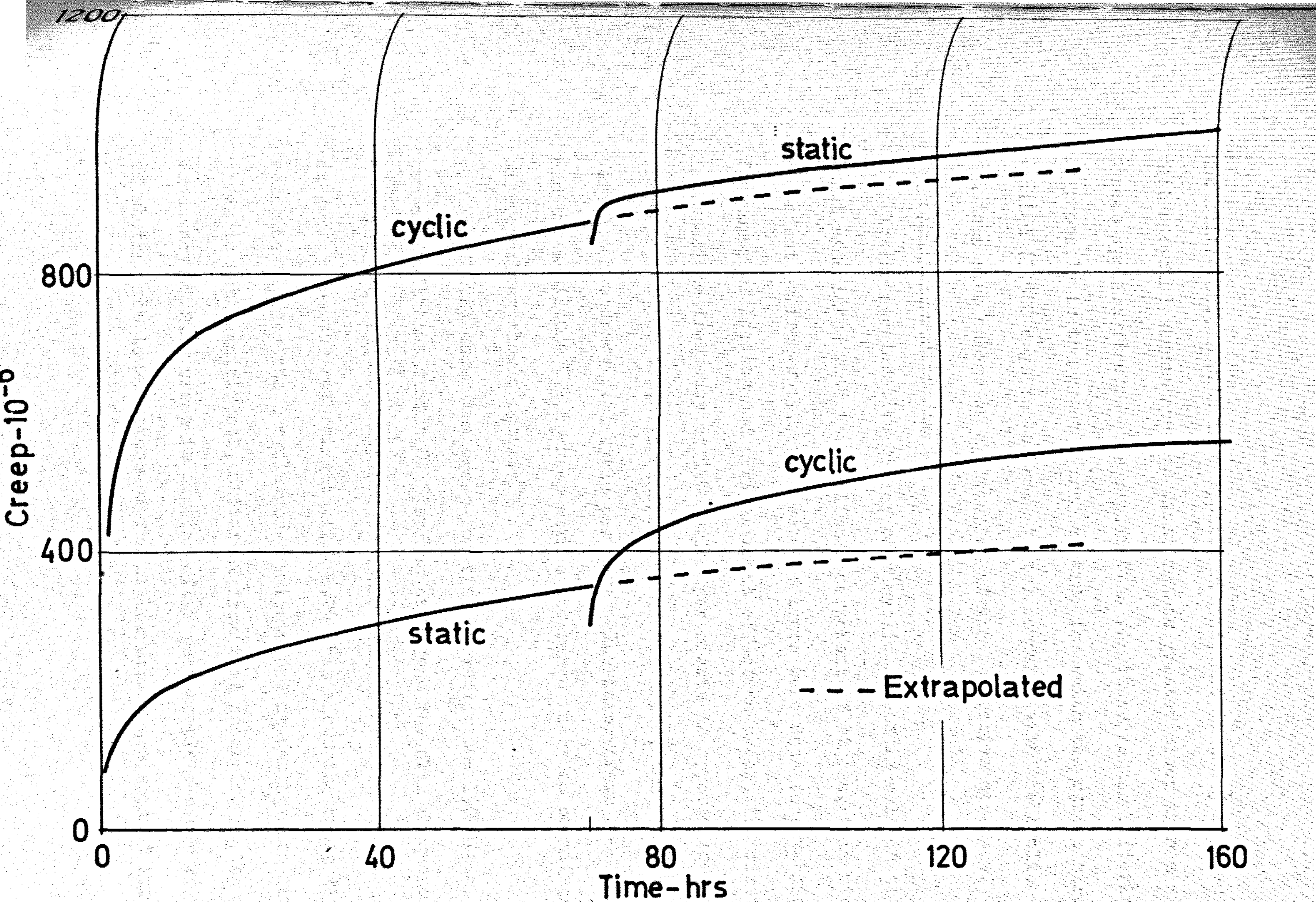

Fig. 6.22 Static & cyclic stresses in sequence - static & upper stress=0·55 lower stress=0·05

the static stress with this applied second, and it has just been shown that a cyclic stress applied first causes greater creep than a static stress applied first. The explanation for these rather differing results is probably in the great length of time for which the static stress was applied (1,000 days in Le Camus tests) compared with the cyclic stress and thus also on age on application of the respective stresses.

6.6 Variation of Frequency

If the accelerative effect of a cyclic stress is related to the energy input associated with the amplitude component of stress, this might be dependent on frequency. Two sets of tests were done to establish if frequency of loading had a significant effect on creep, the first at an intermediate frequency of 190 cycles per minute as opposed to the frequency of 586 c.p.m. used for most of the tests, and the second at a very low frequency of 1 cycle per day. The mean stress used was 0.35 and the amplitude 0.2 to keep within the range where no significant microcracking should occur.

Fig. 6.23 shows the creep-log time curve for the 190 c.p.m. test compared with the static 0.35 stress curve and the high frequency one. Reducing the frequency appears to cause reduced creep at least at later stages. However referring to fig. 6.24 this shows the creep time relationship for the 1 cycle per day tests and it can be seen that the creep is not significantly different from that occurring at the high frequency. Also creep is similar after each complete cycle regardless of whether the lower stress or the higher stress was applied first in the

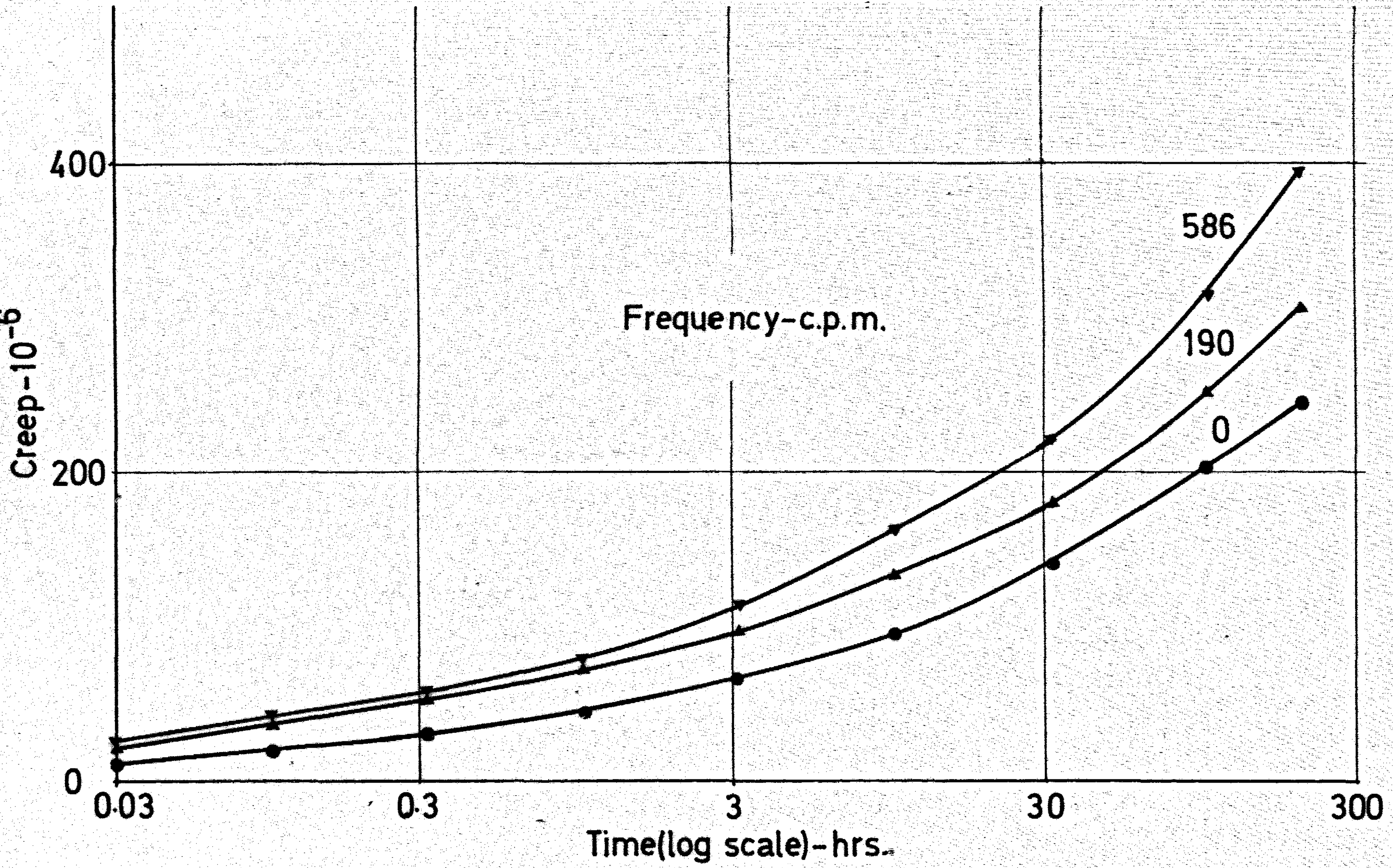

Fig. 6.23 The effect of frequency on creep-mean stress=0.35, amplitude=0.2

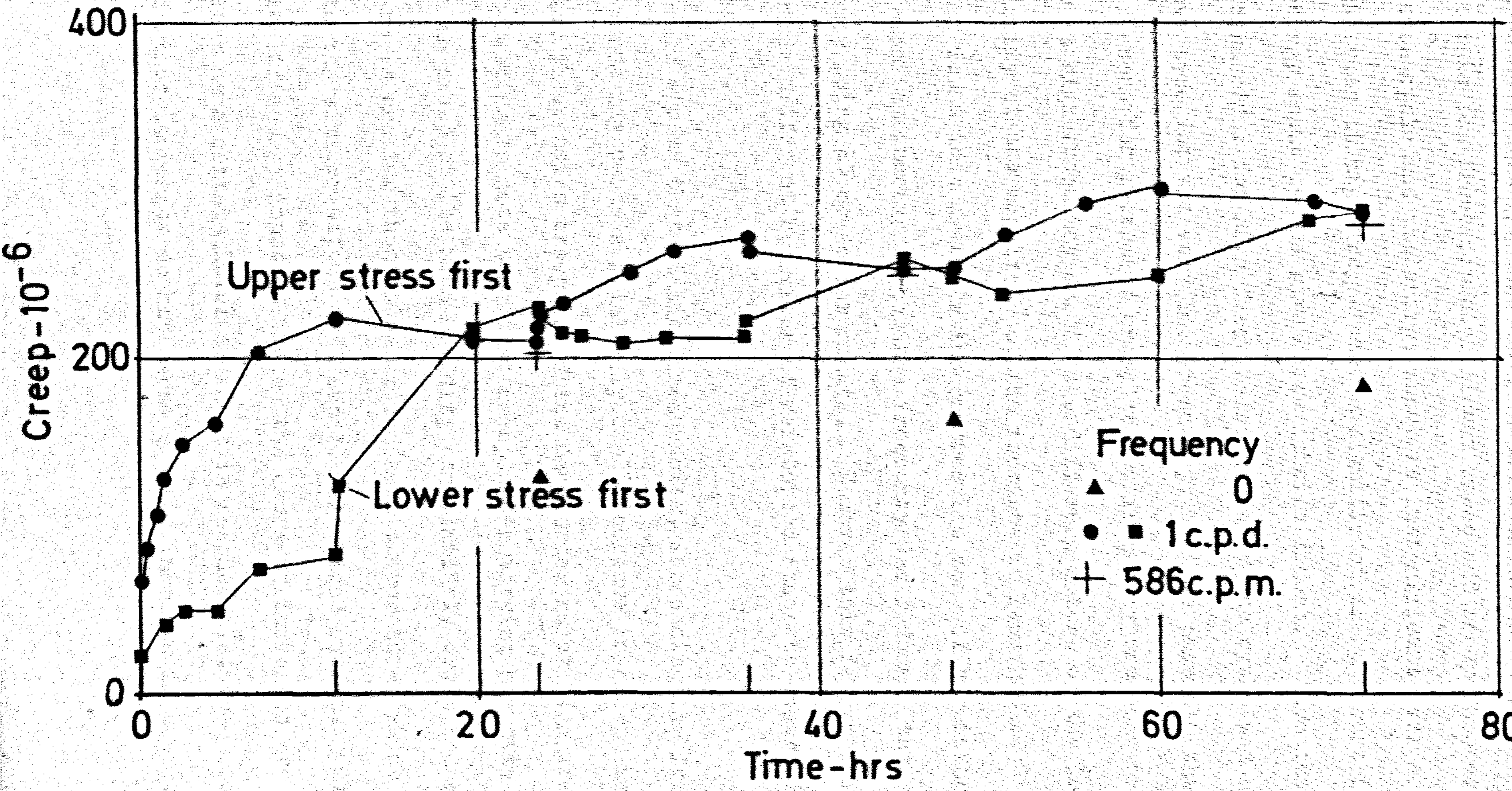

Fig. 6.24 Creep at a frequency of 1 cycle per day

test. At this low frequency significant creep and creep recovery can occur in each cycle and the energy input is insignificant over a period of time, whereas at high frequencies no significant creep occurs in a cycle but the energy input over a given time is significant. Also the stress cycle is sinusoidal for high frequencies where as the cycle was of square wave type for the very low frequency. It is possible therefore that the reasons for increased creep at low frequency are somewhat different for those at high frequency due to the different nature of the load, though the similarity of the magnitude of the increase is remarkable.

Probst found that creep in the compression zone of a reinforced concrete beam was increased when the frequency was reduced, the order of frequency being 20 or so per minute. However this is probably due to the rather different behaviour of reinforced concrete under flexural cyclic loading.

It would appear that at high frequencies, increasing the frequency a large amount may cause a relatively small increase in creep, however at very low frequencies creep is of the same order as at high frequencies. It is interesting to note here that creep under varying humidity is greater than creep at the mean humidity and similarly creep under varying temperature is greater than creep at the mean temperature, which may be related to the similar effect on creep for slow load cycles. At high frequencies if energy input is indeed the cause of increased creep it appears that as a certain level of input is reached i.e. frequency of loading further increases do not cause a great increase in creep.

6.7 Conclusions

A cyclic stress should be considered as being made up of a mean stress component and an amplitude component of stress. Creep under a cyclic stress can then be expressed in terms of a mean stress component similar to creep under a static stress of the same magnitude and an amplitude component. The amplitude component is the result of an accelerative effect on the creep process of the amplitude component of stress and is thus dependent on the mean stress at which it acts. Expressed as a fraction of the mean stress creep, amplitude creep becomes independent of the mean stress at which it acts. Thus being able to express amplitude creep in terms of mean stress or static creep implies that factors such as environment governing the static creep behaviour of concrete will have a similar effect on the creep under cyclic stress conditions, and that the mechanism for creep under a cyclic stress is basically the same. It is also possible to predict creep under any cyclic stress pattern from one set of static creep curves and one set of amplitude variation curves at one mean stress. Further it should be possible to predict creep under a cyclic stress for various types of environmental conditions, from static tests done under these conditions. The effect of frequency is small at high frequencies, higher frequencies causing slightly higher creep. However at very low frequencies creep appears to increase again and it is probable that there is a change in the nature of the process by which creep is accelerated between low and high frequencies linked with when significant creep occurs per cycle and energy input is insignificant over a given time, to when no significant creep occurs per cycle and energy input due to the hysteresis effect becomes significant.

CHAPTER 7

ANALYSIS OF RESULTS: OTHER EFFECTS

7.1 Introduction

The creep behaviour of concrete is related to some other characteristics of concrete which undergo change when a stress is applied. The differences between these characteristics (for example the elastic strain) or the similarity of them with regards to their changing with time under the effect of a static or cyclic stress may therefore give some further indication of the relationship between the creep processes occuring under the respective stress patterns.

7.2 Shape of the Stress Strain Curve

The first stress strain line on loading in compression is convex to the stress axis. This is due to the development of bond cracks between matrix and aggregate oriented parallel to the direction of application of load and is absent in neat cement paste (19). After a few applications of a cyclic stress the loading line becomes straight and eventually becomes concave towards the stress axis. This has been reported by several previous investigators (7,11) and similar behaviour was observed in the present investigation where two sets of tests were done with static and cyclic tests in parallel, one with upper and static stresses equal to 0.55 of ultimate with the lower stress of the cyclic stress equal to 0.05 and another with upper and static stresses of 0.35 of ultimate and a similar lower stress to before. Static stress strain curves were obtained at intervals throughout for both series (fig. 7, 1 - 4).

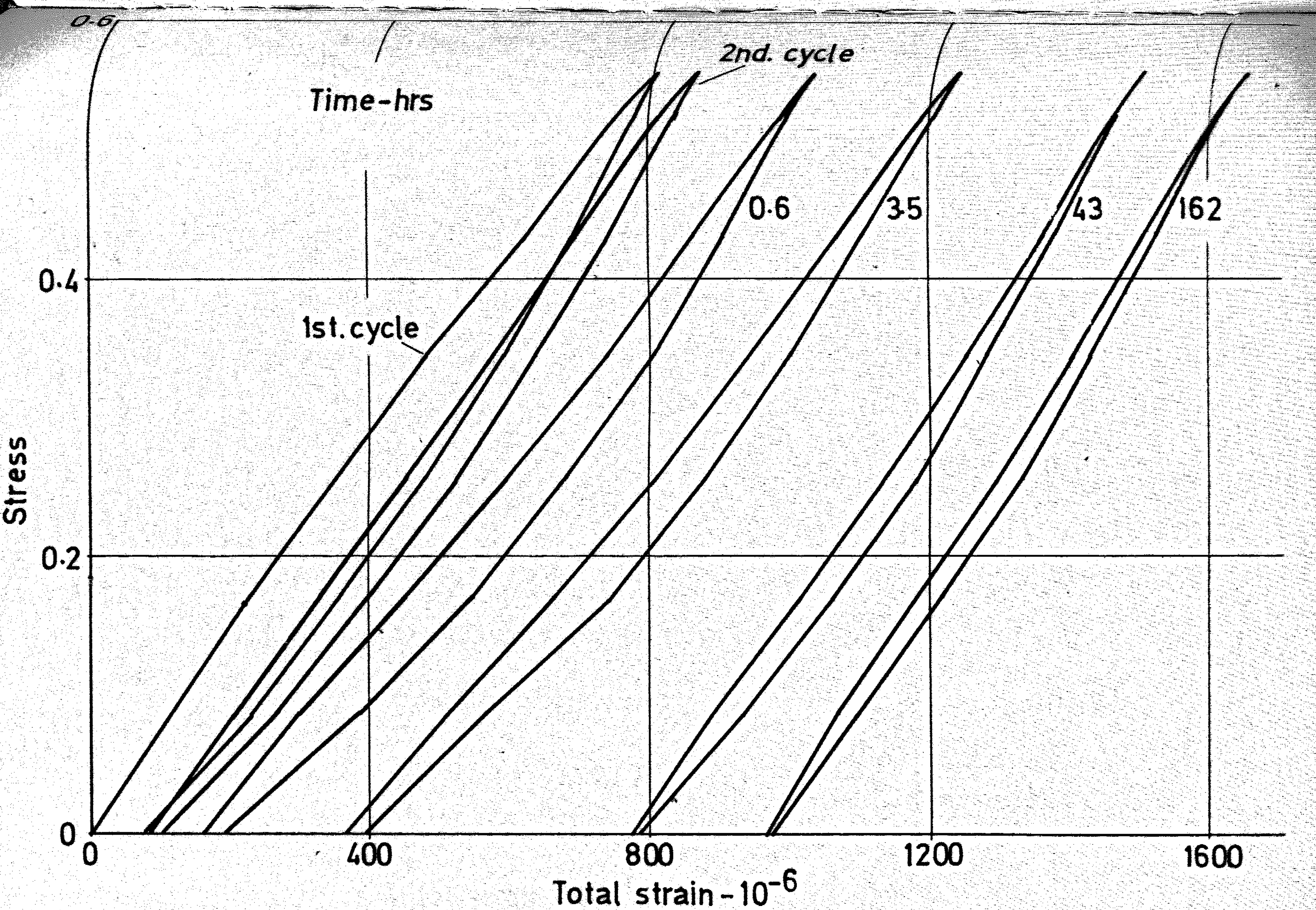

Fig. 7.1 Stress-strain curves for cyclic stress - upper stress=0·55 lower stress=0·05

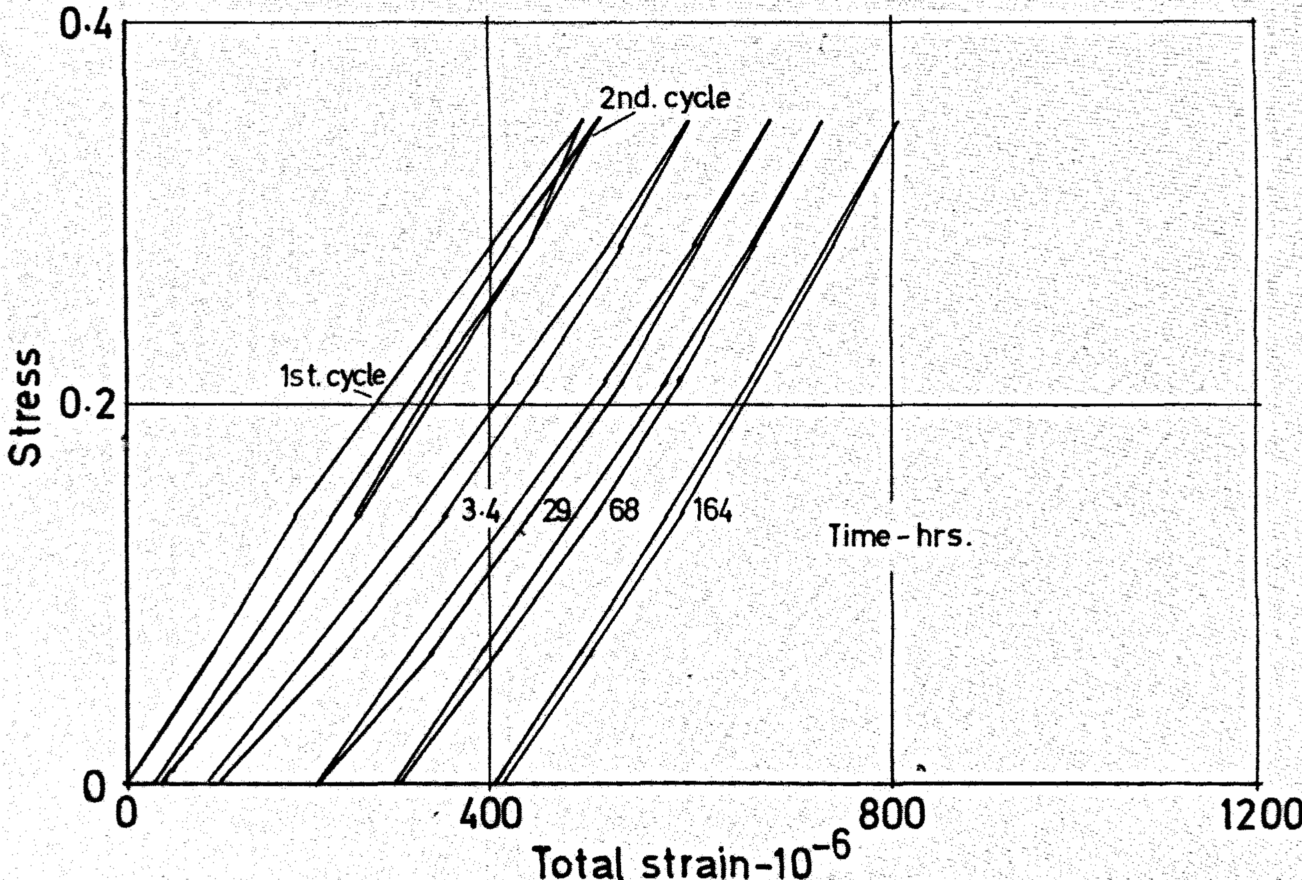

Fig. 7.2 Stress-strain curves for cyclic stress-upper stress=0·35, lower stress=0·05

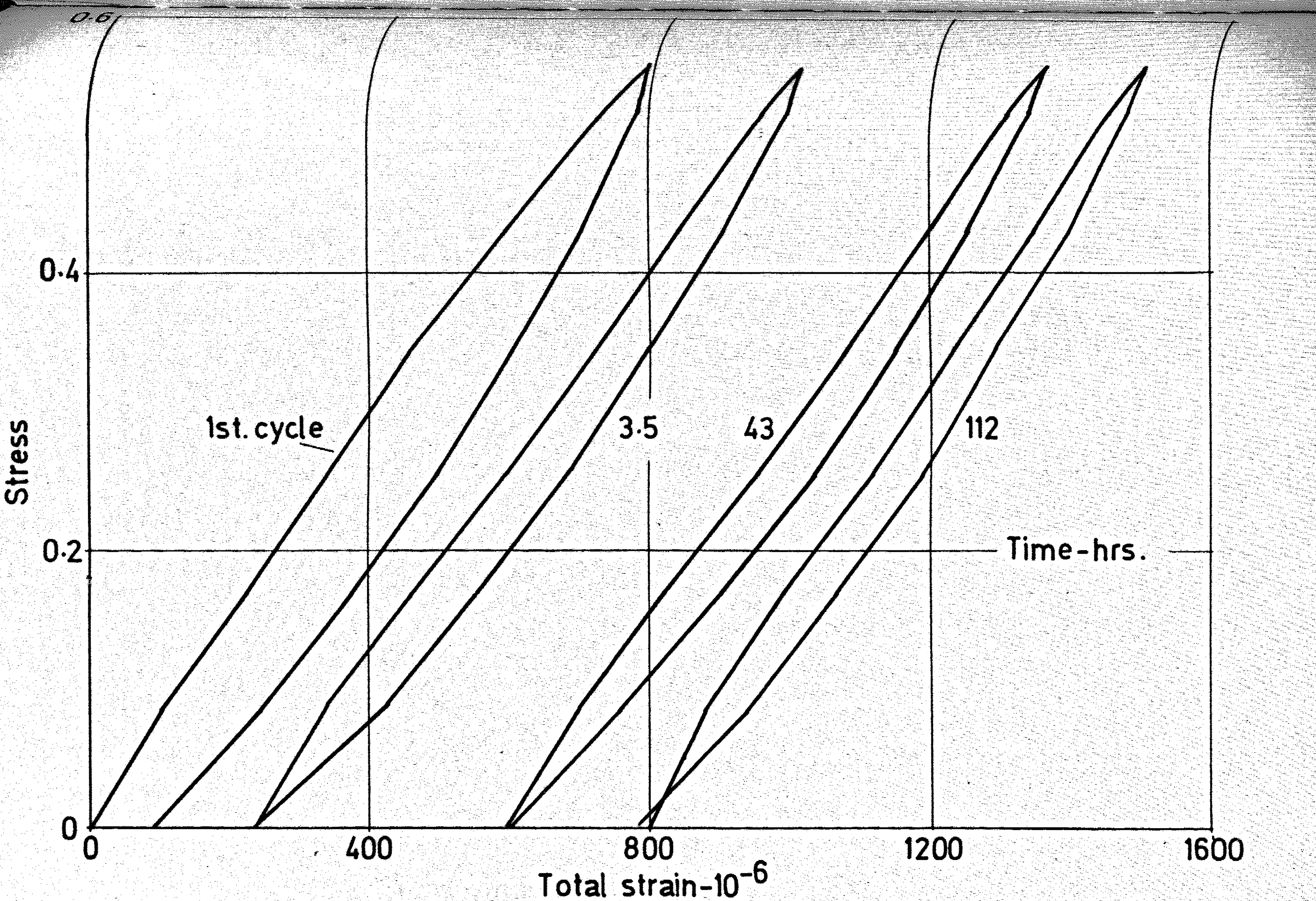

Fig. 7.3 Stress-strain curves for static stress= 0.55

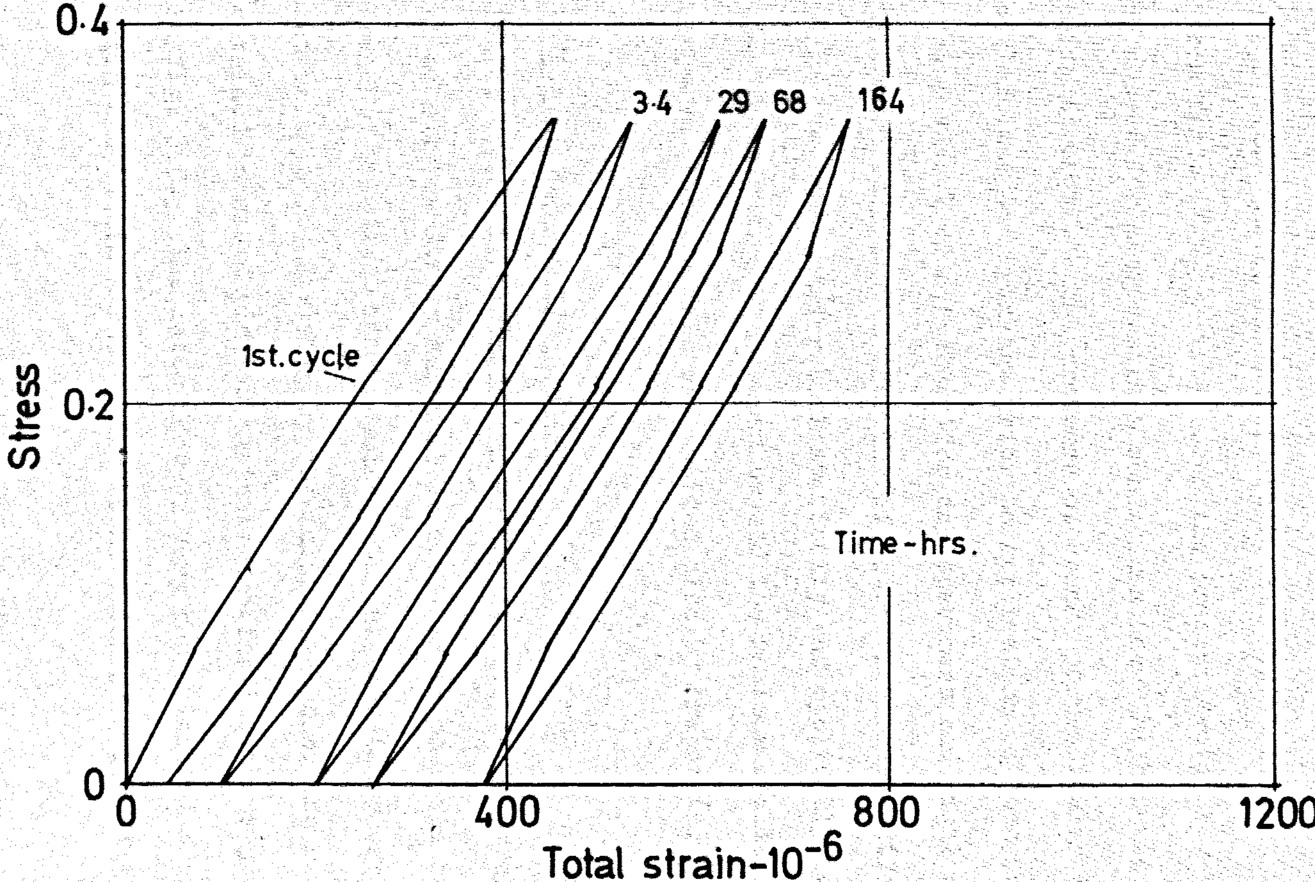

Fig. 7.4 Stress-strain curves for static stress=0·35

From the figures this reversal of curvature of the loading branch of the stress strain curve can be seen for the cyclic stresses though the concavity is not great. The degree of concavity is much greater when the fatigue stress is exceeded. This reversal of curvature is attributed by Mehmel (7) to development of bond cracks perpendicular to the direction of loading, their closing causing a progressive increase in stiffness as the load is applied. He found the effect to be absent in neat cement paste, and from figs. 7.3, 4 it is seen the present tests show the effect to be absent for static stress conditions under high humidity - the load line being straight. The presence of cracks perpendicular to the direction of load due to shrinkage prior to application of load would exaggerate the reversal of curvature for dry specimens and might cause a statically loaded specimen to show the effect. Increased stiffness in the upper ranges is apparent for both statically and cyclically loaded specimens when the stress is increased beyond the maximum applied in the previous creep tests. This was noticed also by Probst (4) and Mehmel (7).

7.3 Elastic Strain and Elastic Modulus

The elastic strain is defined here as the difference in strain between that at maximum stress and that at zero stress observed on the unloading branch of the stress strain cycle. Calculating the secant modulus based on this and dividing by the initial value of the modulus the ratio obtained is shown plotted against time, for the tests just mentioned, in fig. 7.5. The ratio shows a very rapid initial decrease for both static and cyclic stresses and both values of stress, followed

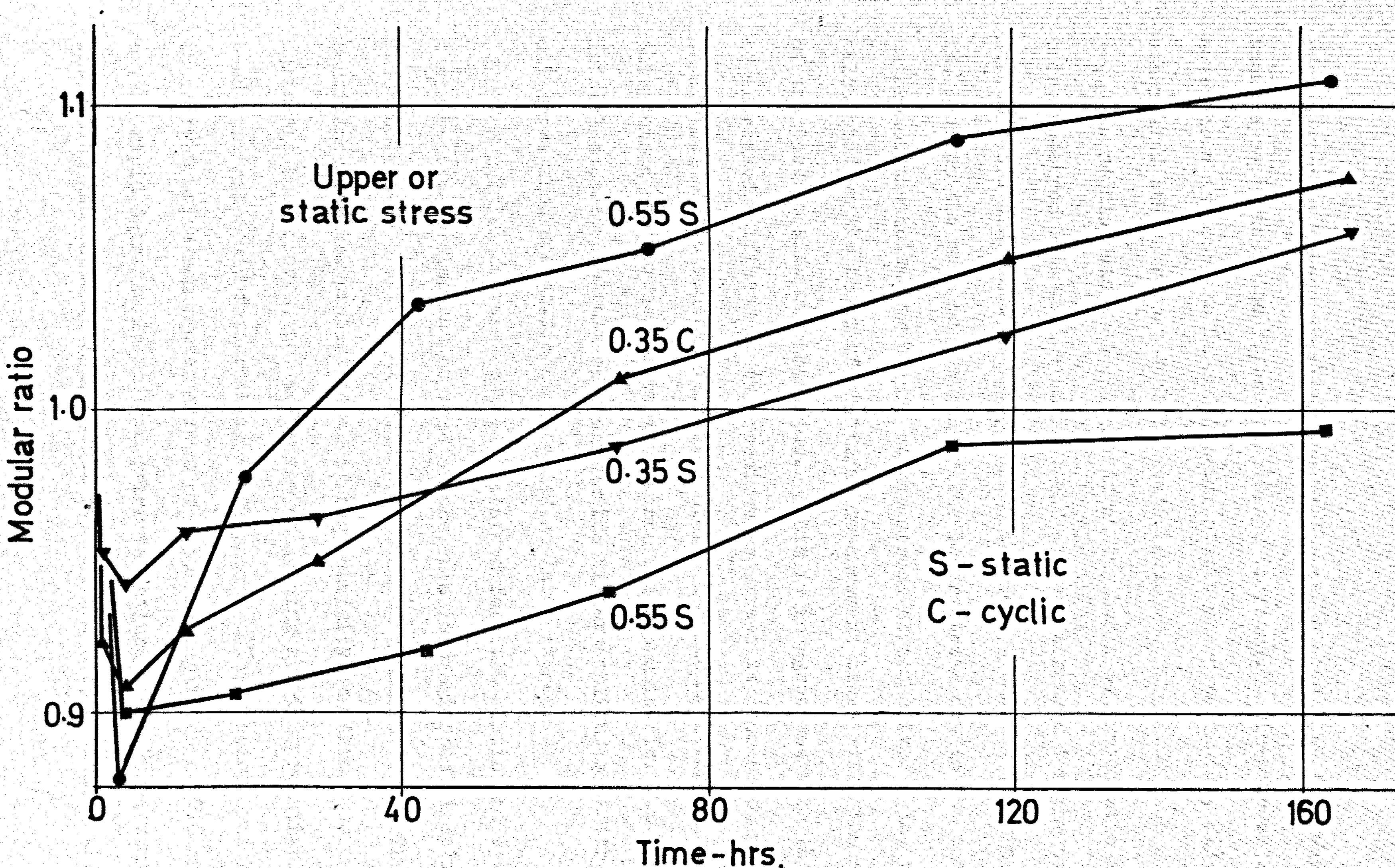

Fig. 7.5 The variation of the secant modulus with time

by a period of steady increase except for the cyclic 0.55 test which shows a rapid increase before the steady increase. Other investigators have shown an increase in modulus for static creep tests (20, 21) on the other hand others reported no increase (22).

The modulus was also calculated on the basis of the elastic strain being measured between the maximum and minimum stresses for the cyclic stress tests discussed in the previous chapter. This tends to overestimate the modulus the more so the higher the lower stress due to the concave nature of the unloading branch of the stress strain curve. The ratio calculated on the basis of the first measurement taken after the start of the test is also overestimated. This is in agreement with the effect of increased stiffness of the specimen as stress is increased. A good indication of the general variation of the modulus is obtained however using this method and curves for various tests are shown in fig. 7.6. The initial decrease is only apparent for the higher amplitudes of stress, but all tests show a significant increase at later stages.

The initial decrease may be explained for both static and cyclic tests by the development of bond cracks in a load oriented direction. These have been observed at stresses of 0.3 of ultimate (9). The conditions for the present tests of high humidity and thus absence of shrinkage bond cracks, and early age of loading and thus relatively low bond strength would favour their development. The specimen which failed in fatigue which had a mean stress of 0.35 and amplitude of 0.6 shows a very rapid decrease in modulus prior to failure (fig. 7.6), probably indicating the initiation of matrix cracks, the propagation of which

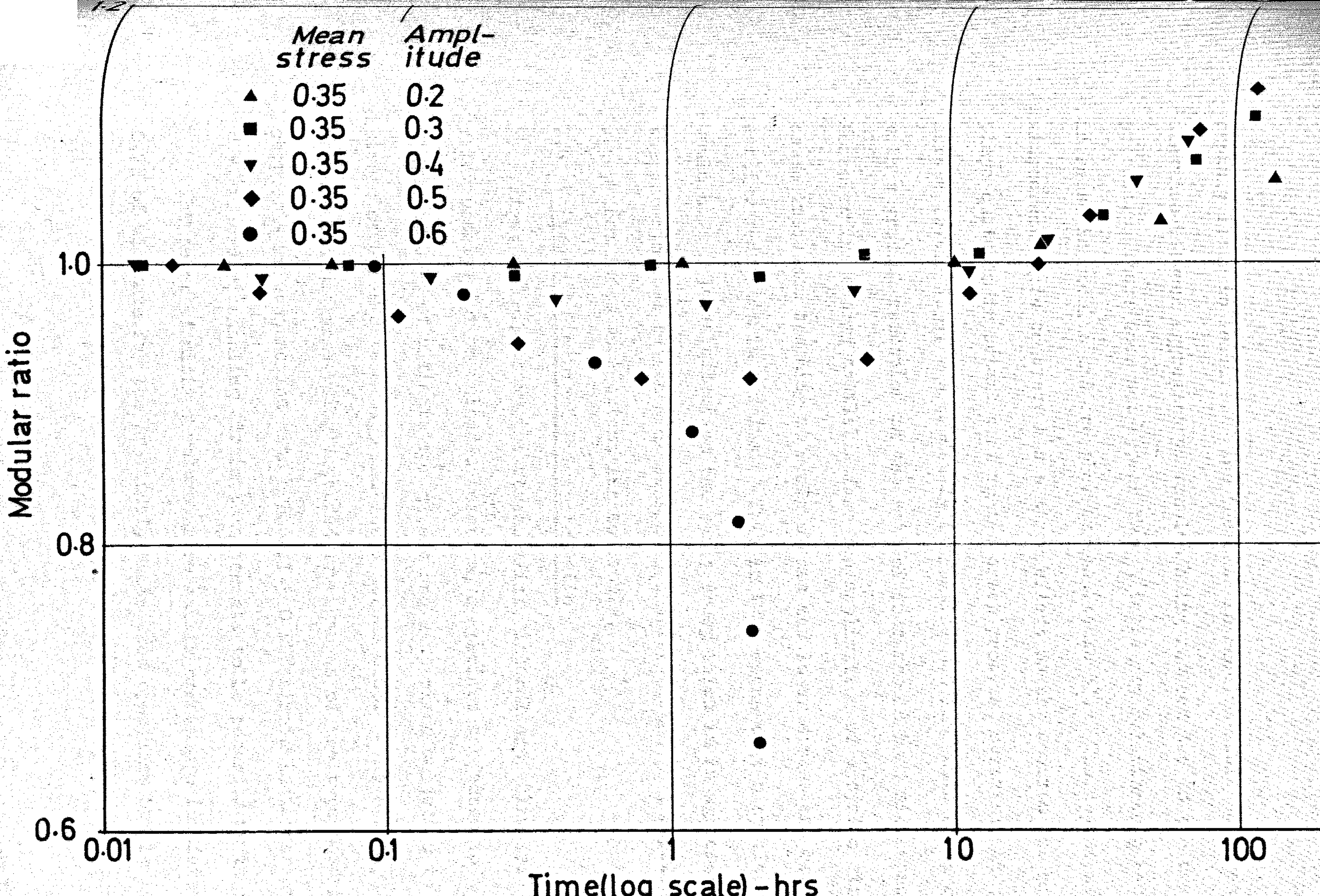

Fig. 7.6 The variation of secant modulus with time

rapidly leads to failure. The increase in modulus could be a result of the distance between aggregate particules being reduced due to the creep process. There does not appear though to be any relationship between increase in modulus and creep or stress (table 3). The degree of microcracking in concrete has a large effect on the modulus and microcracking plays quite an important part in the creep process, certainly at higher stress levels (23). A gradually increasing modulus would be in agreement with a gradual reduction in the rate of increase in bond microcracking. Moreover the energy available from the application of a cyclic stress would cause increased cracking at early stages and lower stress and consequent earlier reduction in modulus. This in turn means that a cyclic stress would have a large effect on the early creep which is in agreement, with the experimental evidence discussed in chapter 6, and that amplitude creep must be to some extent irrecoverable.

7.4 Volumetric Strain and Poisson's Ratio

Figs. 7.7 - 9 show the stress-axial, lateral and volumetric strain relationships for an unloaded specimen, a specimen subjected to a static stress of 0.55 of ultimate for a week and a specimen subjected to a cyclic stress of upper stress 0.55 and lower stress 0.05. The strain measurement was done using embedded ers gauges of the type described in chapter 4 in conjunction with a Peekel 540 DNH strain indicator and a U.V. recorder, enabling strain measurements to be recorded up to failure.

The point of minimum volume where matrix cracks are initiated is at 0.72 of ultimate for the previously unstressed specimens but is increased

TABLE 3

Amplitude	Mean stress	Test length (days)	Final creep ($x10^{-6}$)	$\frac{Ef}{Ei}$	$\frac{Hf}{Hi}$	Strength increase %
0.1	0.25	4	268	1.046	0.359	25.2
0.1	0.35	7	380	1.049	0.318	8.1
0.2	0.5	7	243	1.064	0.189	4.0
0.2	0.25	9	310	1.061	0.28	11.5
0.2	0.25	2	155	0.968	0.319	5.1
0.2	0.35	12	555	1.109	0.287	38.0
0.2	0.45	7	660	1.111	0.214	24.0
0.2	0.55	7	830	1.103	0.196	9.8
0.3	0.2	7	298	1.048	0.207	18.3
0.3	0.25	14	555	1.118	0.168	17.5
0.3	0.25	7	305	1.02	0.229	15.3
0.3	0.35	9	633	1.085	0.228	5.9
0.4	0.25	8	455	1.083	0.215	19.2
0.5	0.35	6	1,130	1.056	0.291	18.4
0.5	0.3	4	518	1.00	0.419	33.0

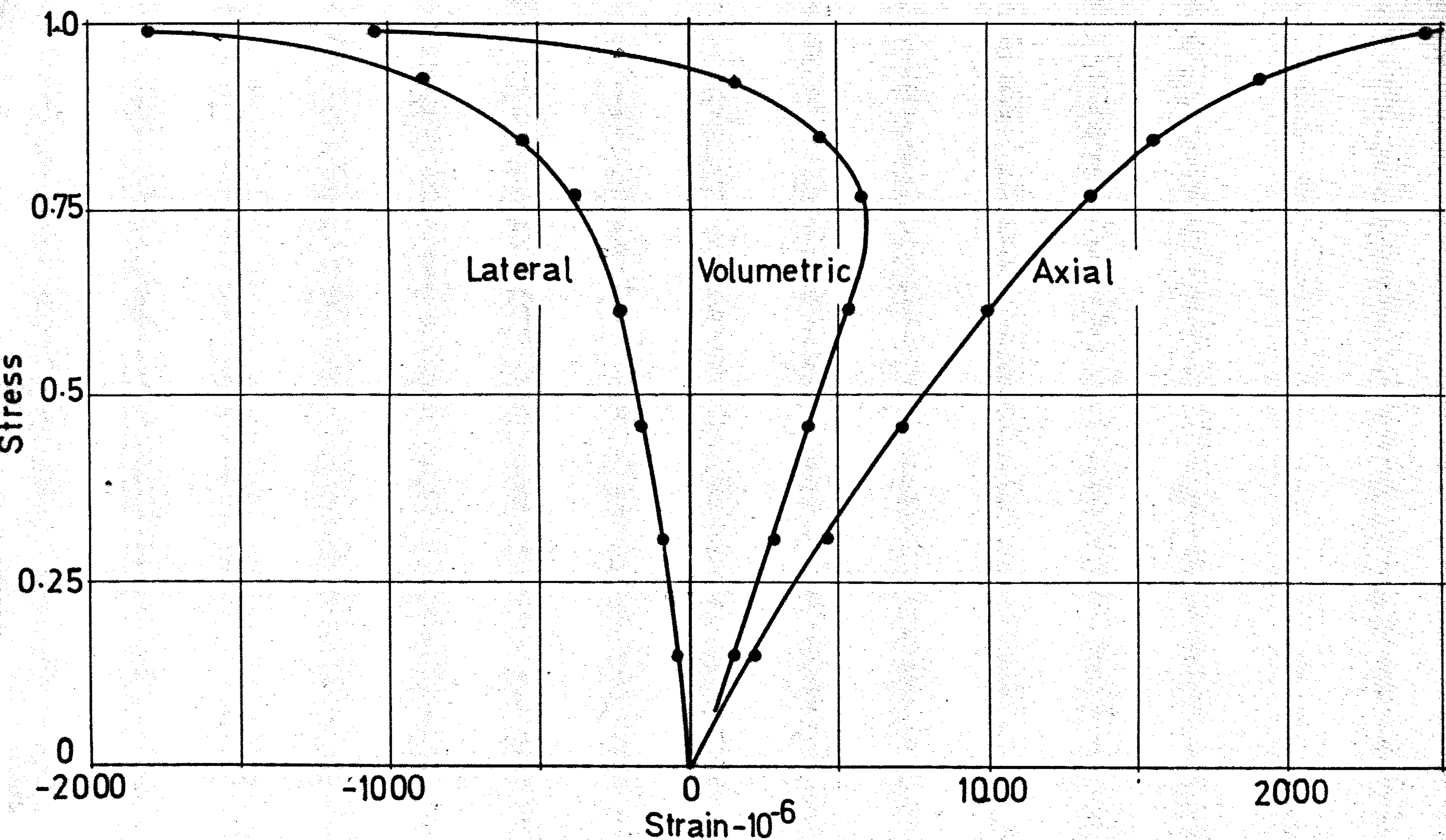

Fig. 7.7 Stress-axial, lateral & volumetric strain curves for a virgin specimen

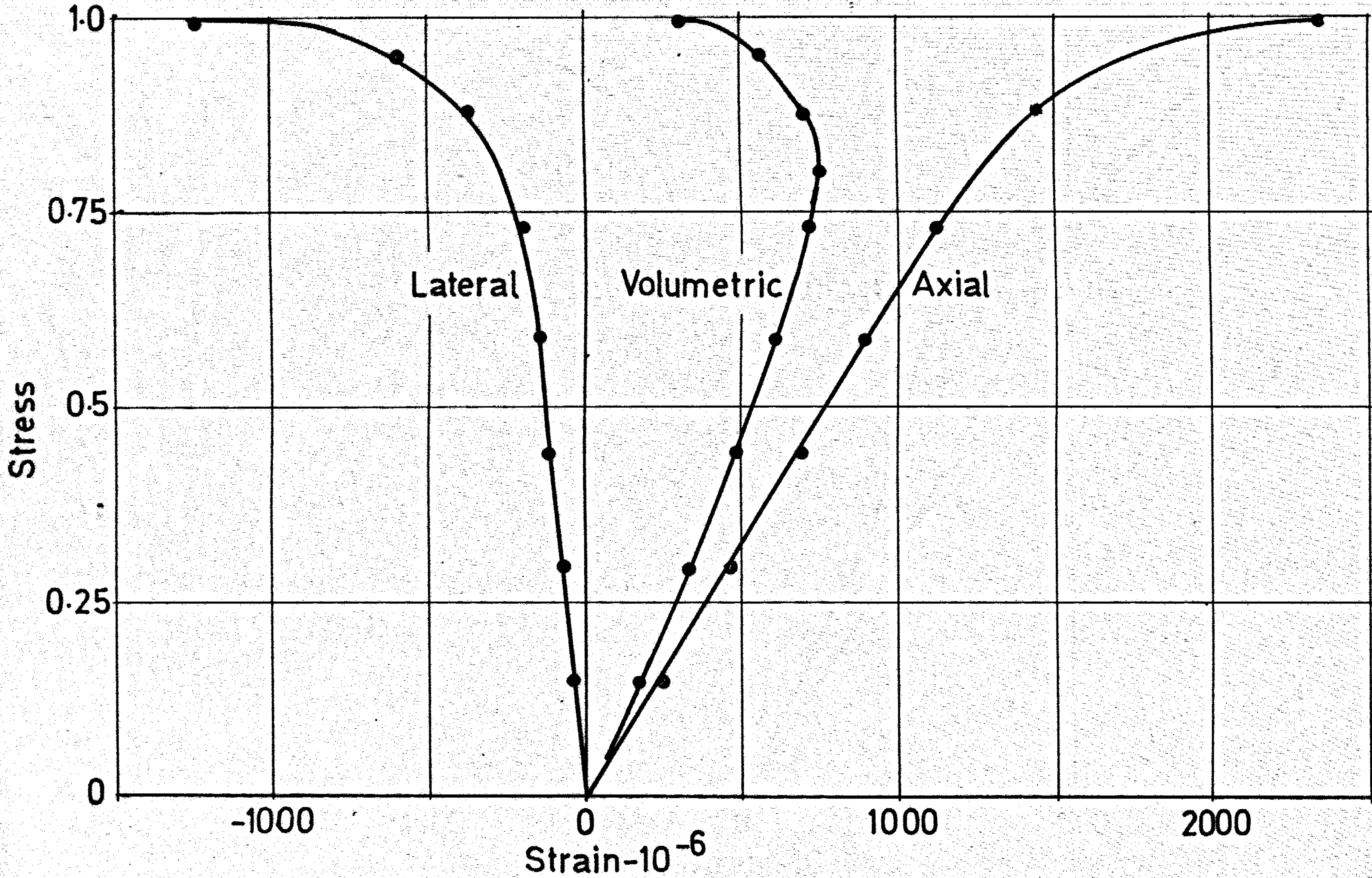

Fig. 7.8 Stress - axial, lateral & volumetric strain curves for a specimen after previous static stress=0·55

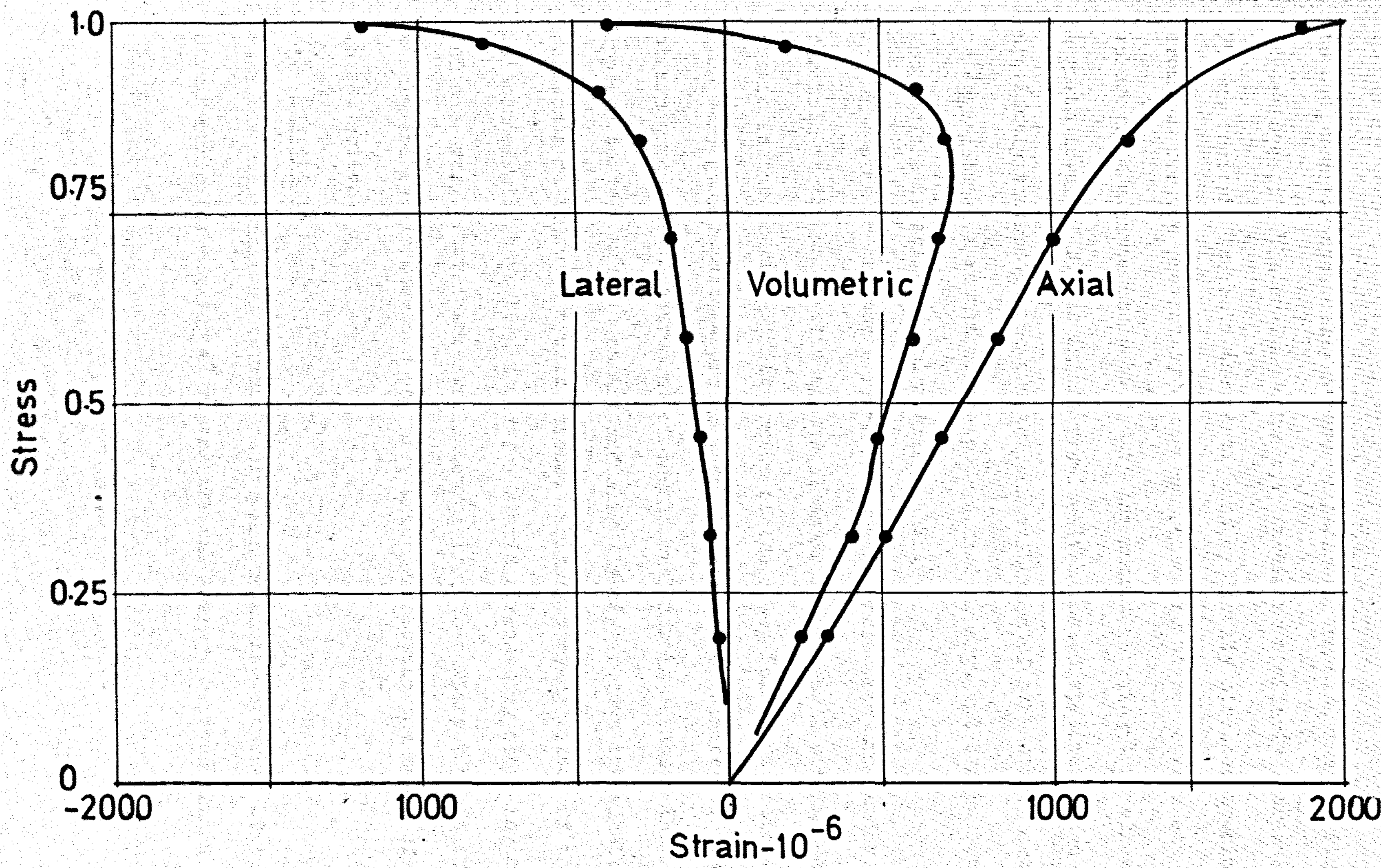

Fig. 7.9 Stress-axial, lateral & volumetric strain curves for a specimen after a previous cyclic stress-upper stress = 0·55, lower stress = 0·05

to 0.81 for the cyclically stressed specimens and 0.82 for the statically stressed one. The maximum volumetric strain is similarly increased to 750 microstrain for both the static and cyclically stressed specimens from 600 for the previously unstressed one. The higher stress at which volume is a minimum could be due to the matrix carrying less stress at a given level of stress in the previously stressed specimens than in the previously unstressed one due to redistribution of stress from matrix to aggregate as a result of creep. A similar argument can be applied too for the increase in volumetric strain.

The elastic Poisson's ratio shows a decrease with time under load for both static and cyclic stresses, again in agreement with a reduced stress in the matrix. Measurement of the creep Poisson's ratio did not give very good results - probably due to the use of electrical resistance strain gauges for measurement of the lateral strain - though the ratio appears to be roughly constant and slightly bigger than the elastic Poisson's ratio for a cyclic stress. Widely varying values of the creep Poisson's ratio have been found for static stresses by other investigators and some very precise work would be required to compare the effects of static and cyclic stresses on this, which was beyond the scope of this investigation.

7.5 Hysteresis

The area enclosed by the loading and unloading branches of the stress strain curve for a material represents the energy absorbed within the material per cycle of load. For concrete this energy absorption will depend on crack growth, some other forms of mechanism of non-elastic deformation and any rise in temperature of the specimen.

Concrete shows a large hysteresis area on the first loading cycle due to the high degree of bond microcracking occuring on this cycle. The second cycle for the tests discussed in the previous two sections showed a decrease in area to 0.53 of the 1st cycle for both stresses. Subsequent cyclic stressing causes a gradual reduction in area of the hysteresis loop of the same order of magnitude for both cyclic stresses (fig. 7.10). The statically stressed specimens show no appreciable reduction in area below that for the second cycle for about 20 hrs. after which a decrease becomes apparent for these also. The shape of the hysteresis loop for static and cyclic tests at intervals is shown in figs. 7.1 - 4. When fatigue failure occurs the hysteresis loop shows a renewed increase after the period of decrease (11) due to the extension of microcracking into the matrix, and hence increased energy absorption.

From table 3 it can be seen that the final value of the hysteresis ratio shows no relationship with creep or mean or amplitude of stress, varying between about 0.23 to 0.34. The significant factor, though, is the greater reduction for the cyclic stress than for the static stress. From this it must be that the energy absorbing phenomena associated with hysteresis decrease more rapidly for cyclic than for static stressing at first. The suggestion put forward in 7.8 that cyclic stressing causes increased early bond microcracking would be in agreement with this.

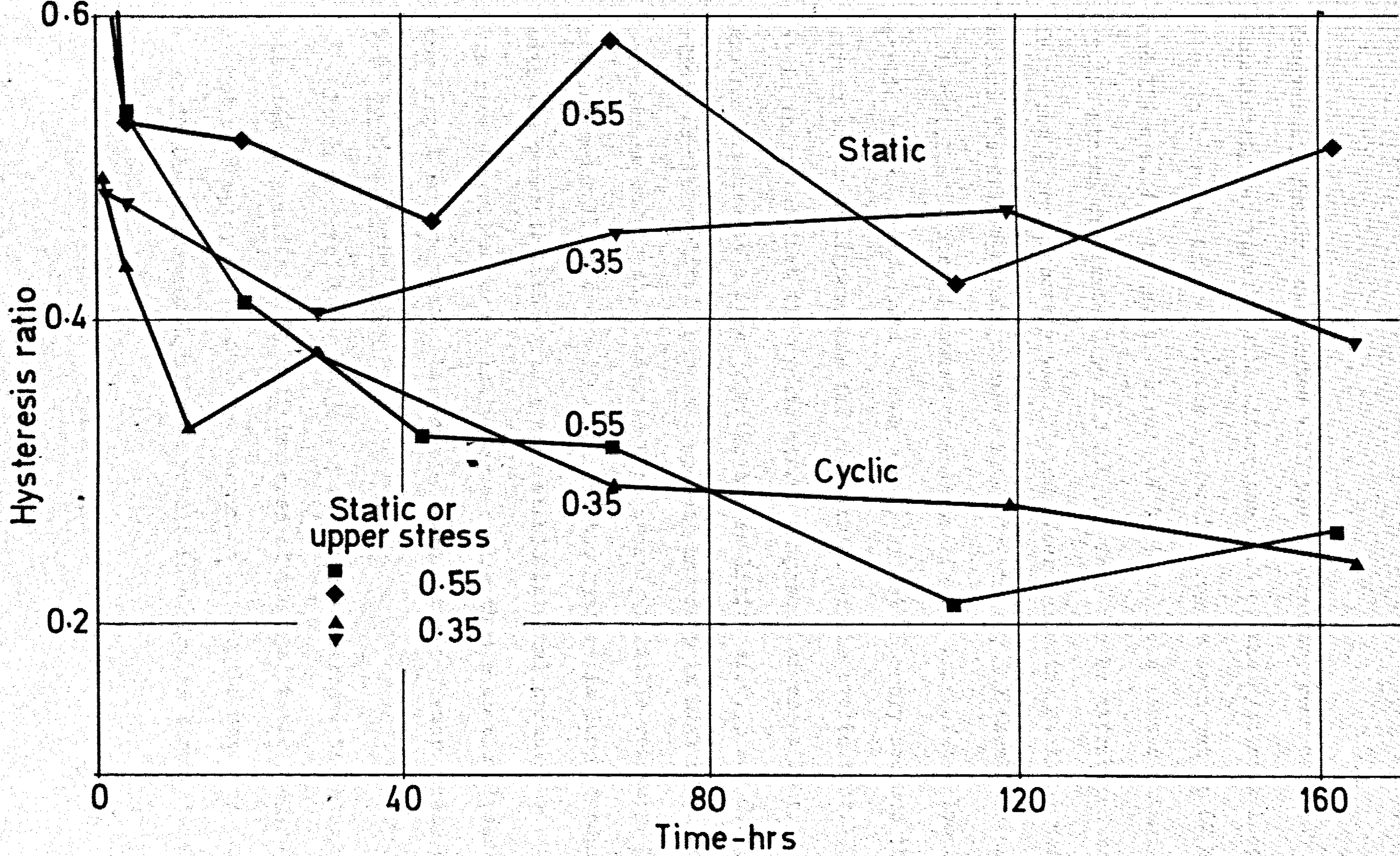

Fig. 7.10 The variation of hysteresis loop area with time

However any factors associated with the deformatory process which are not immediately recoverable will affect the area of the hystersis loop.

An increase in area of the hystersis loop is apparent at 67 hrs. and 162 hrs. for the static stress of 0.55 and to a lesser extent for the cyclic stress of limits 0.55 and 0.05. This can be attributed to the fact that 3 hrs. recovery was allowed after unloading at these points before the stress strain measurements were taken, and thus increased delayed elastic strain caused an increase in the area of the loop. The static stress test showed a much bigger effect probably because the stress was much higher than the mean stress of the cyclic test. Also this again indicates that the cyclic stress component of creep is to a large extent irrecoverable since for the stress limits of 0.55 and 0.05, the effect of the amplitude stress component on creep is high compared with the mean stress component, producing high creep yet little recovery. To comment generally a decreasing area of the hysteresis loop is consistent with the concrete tending to a more stable internal structure. That the area decreases more quickly for a cyclic than a static stress indicates more rapid achievement of the stable state for the former stress conditions.

7.6 Specimen Temperature

For a material being subjected to a cyclic stress, the energy being absorbed as manifested by a finite area of the hysteresis loop, which is not used up by structural rearrangement within the material must, to maintain thermodynamic equilbrium result in a rise in temperature of the material. Temperature measurements were made therefore on several specimens from the main testing programme at certain time intervals to establish at least qualitatively the variation, if any, of specimen temperature with time and amplitude of stress. The mean stress of the cycle has only a slight affect on the area of the hysteresis loop and consequently would not affect the temperature significantly.

The measurements were made using an iron constantan thermocouple embedded slightly below the surface of the specimen, the voltage being measured with a potentiometer which was easily readable to 5 microvolts, giving a sensitivity of 0.1°C. Fig. 7.11 shows the temperature behaviour of several specimens with time for the first 6 hrs. under load and fig. 7.12 for 80 hrs. under load.

All specimens apart from the 0.1 amplitude one show a rapid rise in the first two hours and for the 0.5 amplitude the rise continues for 4 hours, when a peak occurs followed by a gradual decrease. It is also evident that the higher the amplitude the higher the rise in temperature. For the 0.5 amplitude specimens at least, it is possible that the rise in temperature could have a significant effect on creep in the early stages, though this effect would be extremely small compared with the other effects of a cyclic stress on creep.

The temperature rise in the specimen must be associated in some way with the damping capacity of the concrete. Several parameters influence

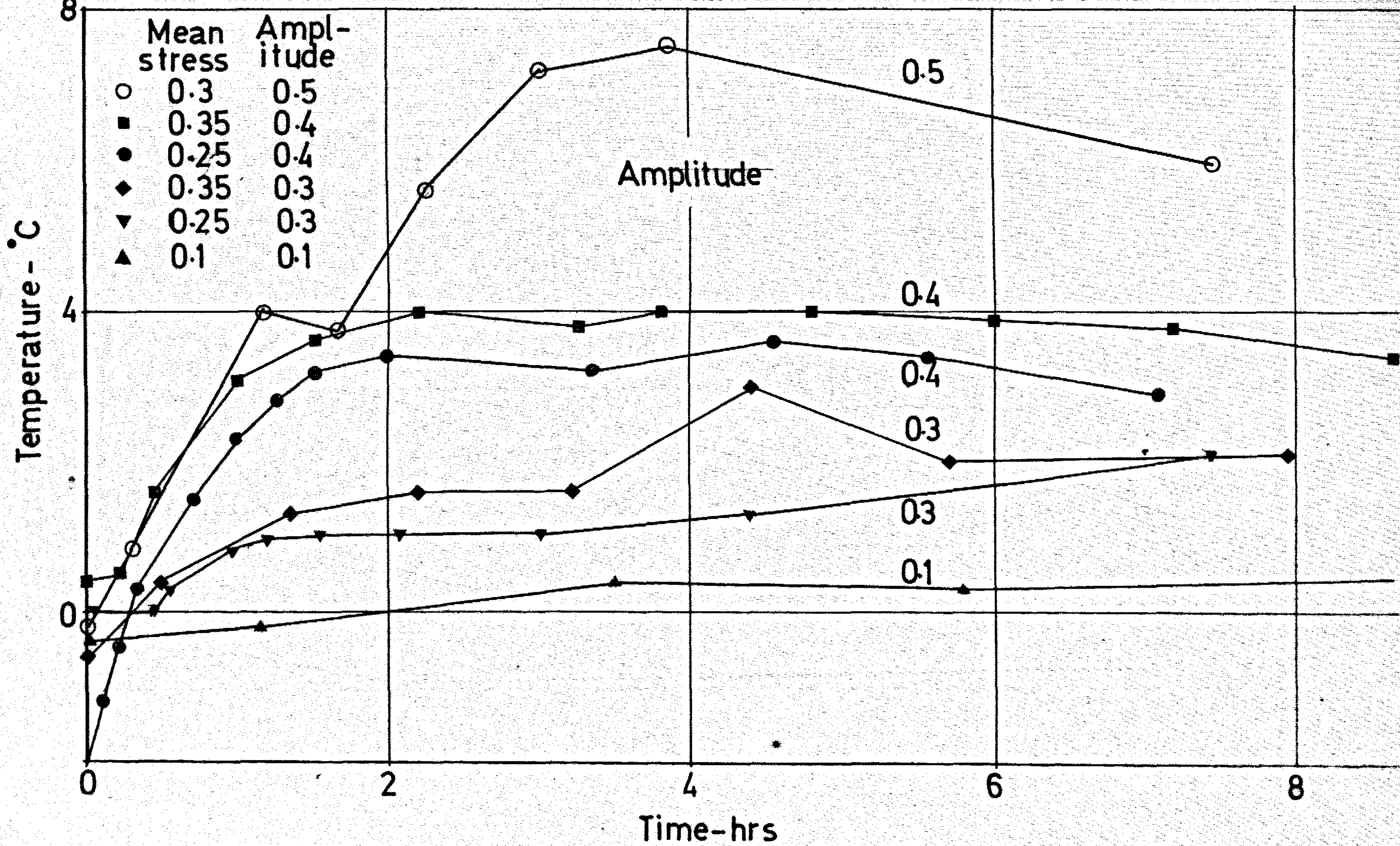

Fig. 7.11 Specimen temperature above ambient for various mean stresses & amplitudes at early stages

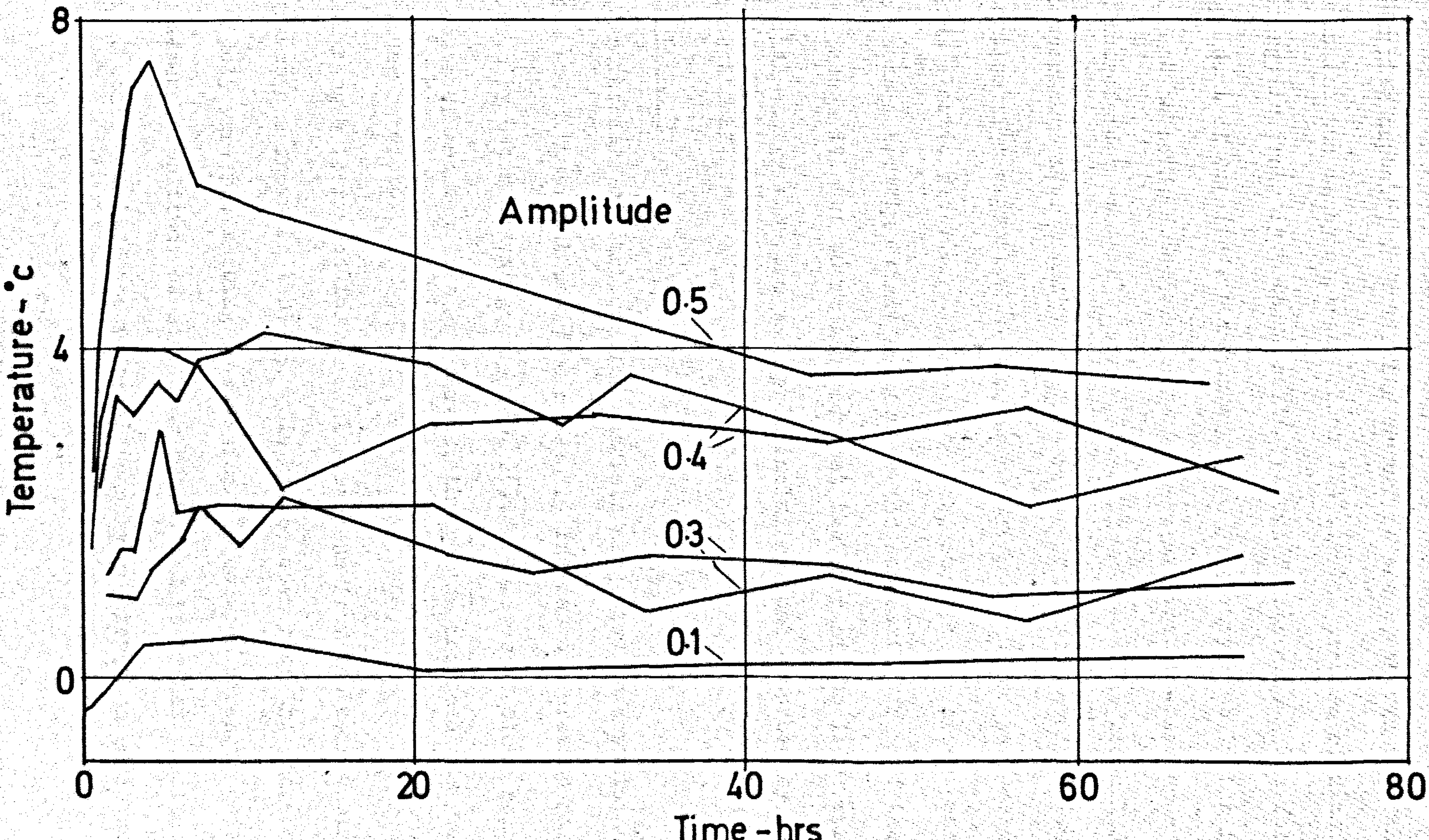

Fig. 7.12 Specimen temperature above ambient for various amplitudes for 70hrs

the damping capacity in a similar manner to creep, though the relationship between the two is by no means clear (24). The process of dissipation of energy is probably both viscoelastic and frictional. The former is independent of amplitude but dependent on frequency, the latter is dependent on both. The increased temperature with increasing amplitude must therefore be a result of a frictional process. The gradual decrease in temperature over a period of time gives at least a qualitative indication of a reduction in damping capacity and hence increased tendency towards elastic behaviour of concrete subjected to the creep process. This is to a certain extent related to the decreasing area of the hysteresis loop, though it must be remembered that the area of the loop represents the total energy absorbed per cycle including that absorbed by the creep process itself.

7.7 Strength

An increase of strength for concrete subjected to a sustained stress above that that would be caused by increased hydration has been observed by other investigators (25, 26). However no clear relationship was apparent between this and stress, though the increase was greatest for young concrete.

Strength increases for several specimens from the main testing programme are shown in table 3. It can be seen that the increases are widely varying, showing no relationship between strength gain and mean stress, amplitude of stress or creep, and it is not possible to state whether the increase is significantly greater than would be obtained for a static stress, though it could be expected to be so from the earlier results in this capter. It can be stated that the effect of a cyclic stress below the fatigue limit is in no way detrimental to strength and is often very beneficial.

Strength gains occuring during creep are attributable to the compacting action of a sustained stress and the increased formation of bonds under stress. The mechanism by which strength is affected is obviously highly random in nature, and cannot at the present time give much indication of the nature of the creep process.

7.8 Recovery

Creep recovery is defined here as the increase in strain (in opposite sense to the creep strain) over a period of time after removal of the applied stress i.e. the instantaneous strain on unloading is subtracted. The relative amounts of recovery occuring after removal of the applied stress will give some indication of whether the effect of a cyclic stress acts mainly on the recoverable or irrecoverable creep.

Table 4 shows the recovery after 1 hr. for several static and cyclic loading tests done in parallel. For the amplitude of 0.2 and static or mean stresses of 0.25 and 0.35 of ultimate the recovery is greater for the cyclically loaded specimens. For the amplitude of 0.4 the recovery is similar for both static and cyclic loading. When the static stress equals the upper stress for the cyclic stress, the lower stress being 0.05 the recovery is always greater for the static stress. Fig. 7.13 shows the recovery time curve for a cyclic stress of 0.55 upper

TABLE 4

Static stress	Upper stress	Lower stress	Static recovery $(\times 10^{-6})$	Cyclic recovery $(\times 10^{-6})$
0.25	0.35	0.15	16	30
0.35	0.45	0.25	26	35
0.25	0.45	0.05	25	24
0.35	0.55	0.15	42	41
0.35	0.35	0.05	30	23
0.45	0.45	0.05	40	20
0.55	0.55	0.05	54	29

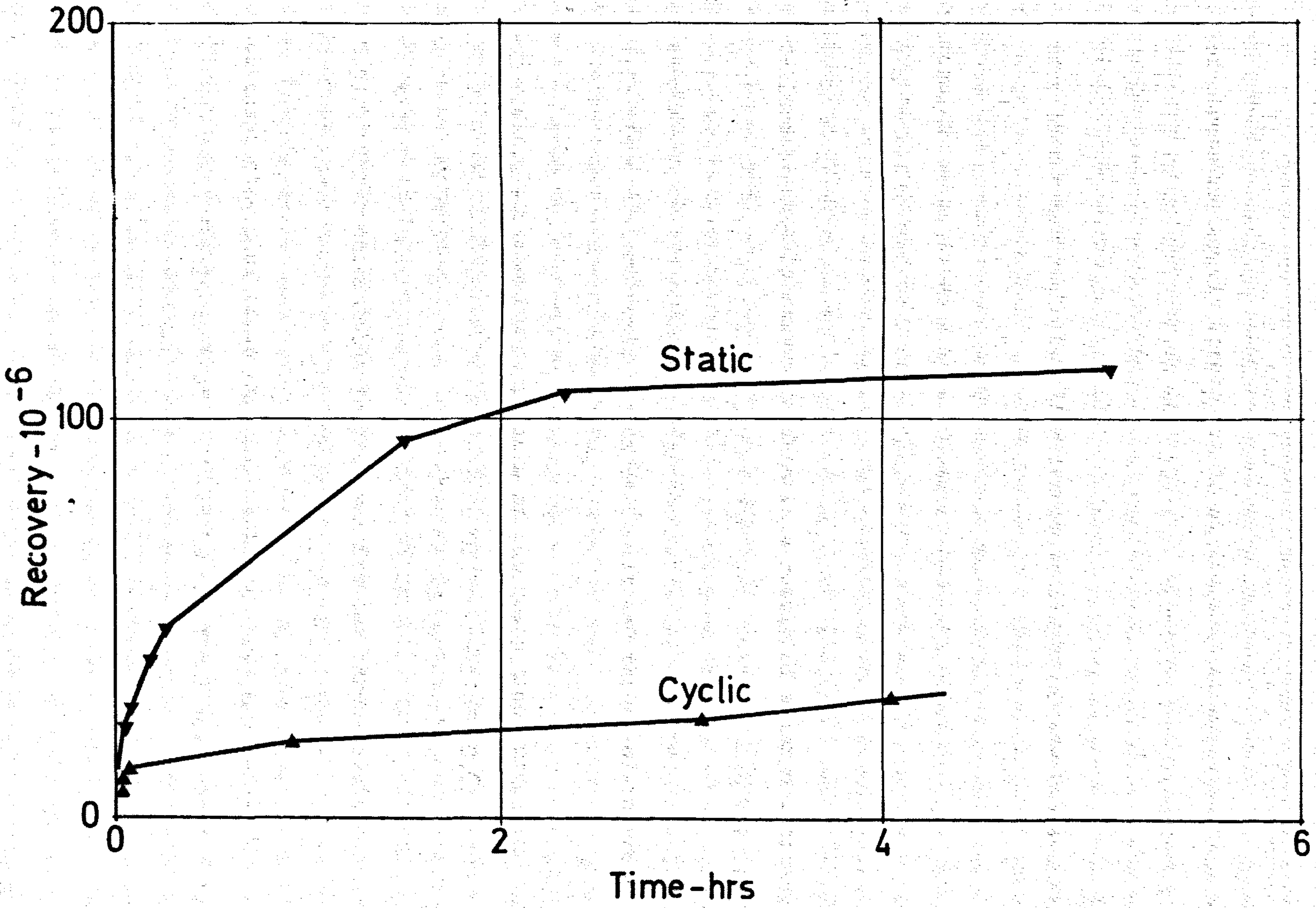

Fig. 7.13 Creep recovery for static & cyclic stress - static = upper stress = 0·55, lower stress = 0·05

stress limit 0.05 lower stress, compared with the one for a static stress of 0.55.

It seems therefore that the creep due to the amplitude component of stress is largely irrecoverable at least at moderate to high amplitudes. This is in agreement with what has been considered previously as far as microcracking might affect the creep process. However this does not mean that other mechanisms for irrecoverable creep are not important and the limited experimental work that was carried out on recovery cannot be regarded as conclusive, but merely giving some indication of the trend.

7.9 Fatigue

If the amplitude of a cyclic stress is increased sufficiently fatigue failure eventually occurs. This is a result of a large increase in the occurence of bond microcracking which eventually extends into the matrix and aggregate causing final failure as observed by Raju (11) using pulse velocity and microscopic techniques. It was though of interest to obtain some creep results when microcracking was the primary cause of creep.

Fig. 7.14 shows a comparison of the creep time curves for a specimen which failed in fatigue (mean stress 0.35, amplitude 0.6) and one subjected to a slightly lower stress level (mean stress 0.35, amplitude 0.5). The specimen that failed exhibits the three possible stages of the creep curve, i.e. primary, secondary and tertiary. These correspond to three stages of crack growth. Initial rapid growth of bond cracks, steady state development of bond cracks and final very rapid development of bond cracks causing extension of cracking into the matrix and aggregate

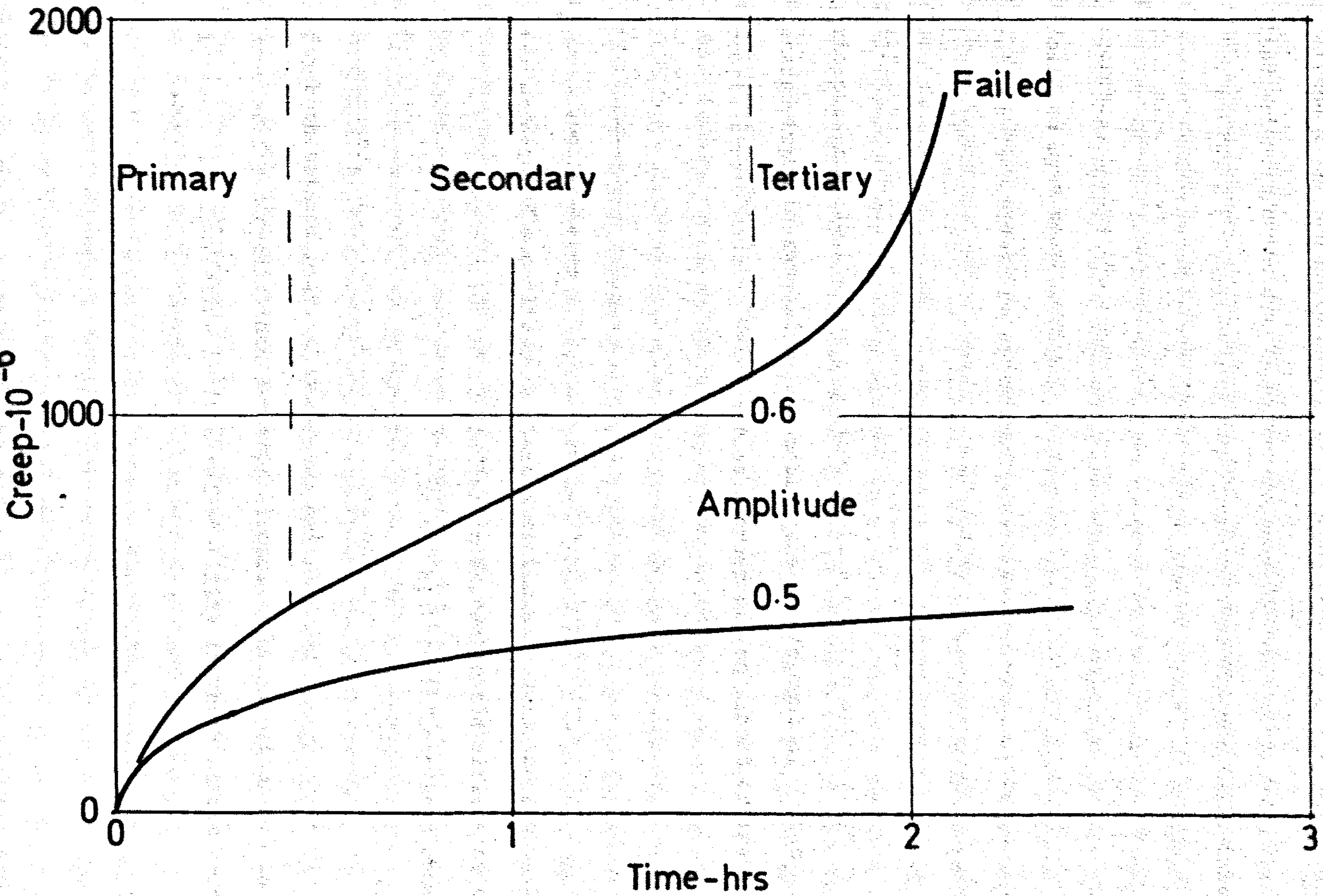

Fig. 7.14 Creep under a cyclic stress at high amplitudes-
mean stress = 0·35

and failure. The modulus showed a continuous decrease and the creep Poisson's ratio exceeded unity near failure, showing the high degree of load oriented cracking.

Making a comparison with the specimen that did not fail, initially this also shows a decrease in modulus which however soon reverts to an increase, indicating perhaps an early tendency for microcracking to increase, followed by a continuous decrease. There is however no further similarity between the curves, no secondary or tertiary creep occuring so showing the different nature of the process of deformation. Perhaps as the amplitude is increased there is a steady increase of the predominance of microcracking in the creep process until a certain critical value of energy input is reached which enables the development of cracks at a constant rate causing much increased creep and an almost entirely crack dependent deformatory process.

7.10 Conclusions

The principal feature to emerge from the results discussed is that the effects of a cyclic stress and a static stress on the properties of concrete being considered is similar in character the difference being principally one of magnitude. Thus the hysteresis loop area shows a decrease, the elastic modulus shows an increase and the strength increases, for both sets of stress conditions, but at a given time the increase is greater for a cyclic than a static stress. This implies that the concrete is gradually increasing in internal stability for both stress conditions, only the process is more rapid for a cyclic stress. Thus the effect of a cyclic stress again appears to be accelerative of the static processes.

A rapid rise in temperature, followed by a slow decrease with time, occurs under a cyclic stress. The temperature rise is higher, the higher the amplitude, but is independent of mean stress. The gradual decrease gives a qualitative indication of the reduction in damping capacity of the concrete with time and indicates a gradual tendency towards elastic behaviour, and again internal stability.

Recovery measurements indicated that a cyclic stress causes an increase in only the irrecoverable creep. This is consistent with the apparent independence of recovery with static stress (48). For an amplitude of greater than 0.4 at a mean stress of 0.35 the elastic modulus showed a decrease before starting to increase, and at an amplitude of 0.6 fatigue failure occured. This indicates the occurence of load ariented microcracking at high amplitudes causing an increase in creep due to dilatation of the specimen, which is of course irrecoverable.

CHAPTER 8

CREEP RATE AND ACTIVATION ENERGY

8.1 Introduction

When investigating the creep of concrete most attention is usually given to measurement of deformations since these are easy to measure accurately and are usually of most practical worth. However the creep deformation at a given time is necessarily dependent on the creep deformation that has occured previously and thus masks the effect in this case of to what degree the amplitude component of stress is affecting the creep process at later stages. A reasonable approximation to the rate of creep at a given time can be obtained by measuring the increase in creep over a certain time interval and then assuming the calculated rate to be the creep rate at the mid-point of the time interval.

The following represents an analysis of the creep rates for this series of tests as detailed in chapter 6, together with a consideration of the activation energy theory of creep with is essentially based on measurement of creep rate. The creep rates were actually calculated from the mean deformation of the three tests usually done for each stress, the time interval being chosen at each point to be as large as possible consistent with not introducing a large error from the curvature of the creep time curve.

8.2 Activation Energy Theory

For the activation energy theory of creep it is assumed that the energy distribution within the gel particles of cement paste is similar to the Boltzman - Maxwell - Gibbs distribution function for gases. Thus the probability p of a spontaneous change of thermal energy causing a place change is given by

$$p = a \quad e^{-Q/RT} \qquad (1)$$

R = gas constant, T = absolute temperature, Q = activation energy

The activation energy is the energy required to cause a place change per mole.

Multiplying p by the mean frequency of thermal oscillation of the particles, the rate of activation is given by

$$Z_1 = a_2 e^{-Q/RT} \qquad (2)$$

Applying an external compressive stress decreases the activation energy by an amount u in the direction of the stress and increases it by a similar amount in the reverse direction. Thus from 2

$$Z_1 = a_2 e^{-(Q-u)/RT} \qquad (3)$$

$$Z_2 = a_2 e^{-(Q+u)/RT} \qquad (4)$$

and the net rate of activation in the direction of the applied stress is therefore

$$Z = Z_1 - Z_2 = a_2 e^{-Q/RT} \; e^{u/RT} - a_2 e^{-Q/RT} e^{-u/RT}$$

$$= 2a_2 \; e^{-Q/RT} \sinh \; (u/RT) \qquad (5)$$

assuming that the relationship between u and the applied stress (σ) is of the form

$$\frac{u}{RT} = v\sigma \qquad (6)$$

Equation 5 may be expressed in terms of rate of creep and stress,

$$\dot{\varepsilon} = a \sinh (v\sigma) \qquad (7)$$

which is in the form used for creep study in metals and was derived for cement paste by Wittman (27).

8.3 Static Stress

Fig. 8.1-3 shows the creep rate for the static tests at certain time intervals plotted against stress, together with the hyperbolic sine relationship (equation 7) fitted using the least squares method, and it can be seen that the relationship fits quite well. The coefficient a decreases rapidly with time the coefficient v being also dependent on time but rather less so. Wittman (28) found a to be very dependent on time for cement paste, but v to be independent of time.

Plotting log(a) against log time shows a linear relationship (fig. 4).

thus $\log (a) = c_1 - c_2 \log (t)$

$$\therefore \quad a = e^{(c_1 - c_2 \log (t))}$$

$$= c\, e^{- c_2 \log (t)} \qquad (8)$$

from fig. 4, $c = 10.4,\ c_2 = 0.4762$

$$\therefore \quad a = 10.4\, e^{-0.4762 \log(t)}$$

from 5 $\quad a = k\, e^{-Q/RT}$

hence $\quad \frac{Q}{RT} = c_2 \log (t)$

$R = 1.985$ cal./mole. $\quad T = 295^{\circ}A$

Thus the activation energy of the creep process at any time t is given by

$$Q_t = 279 \log_e(t) \qquad (9) \quad (t >> 1)$$

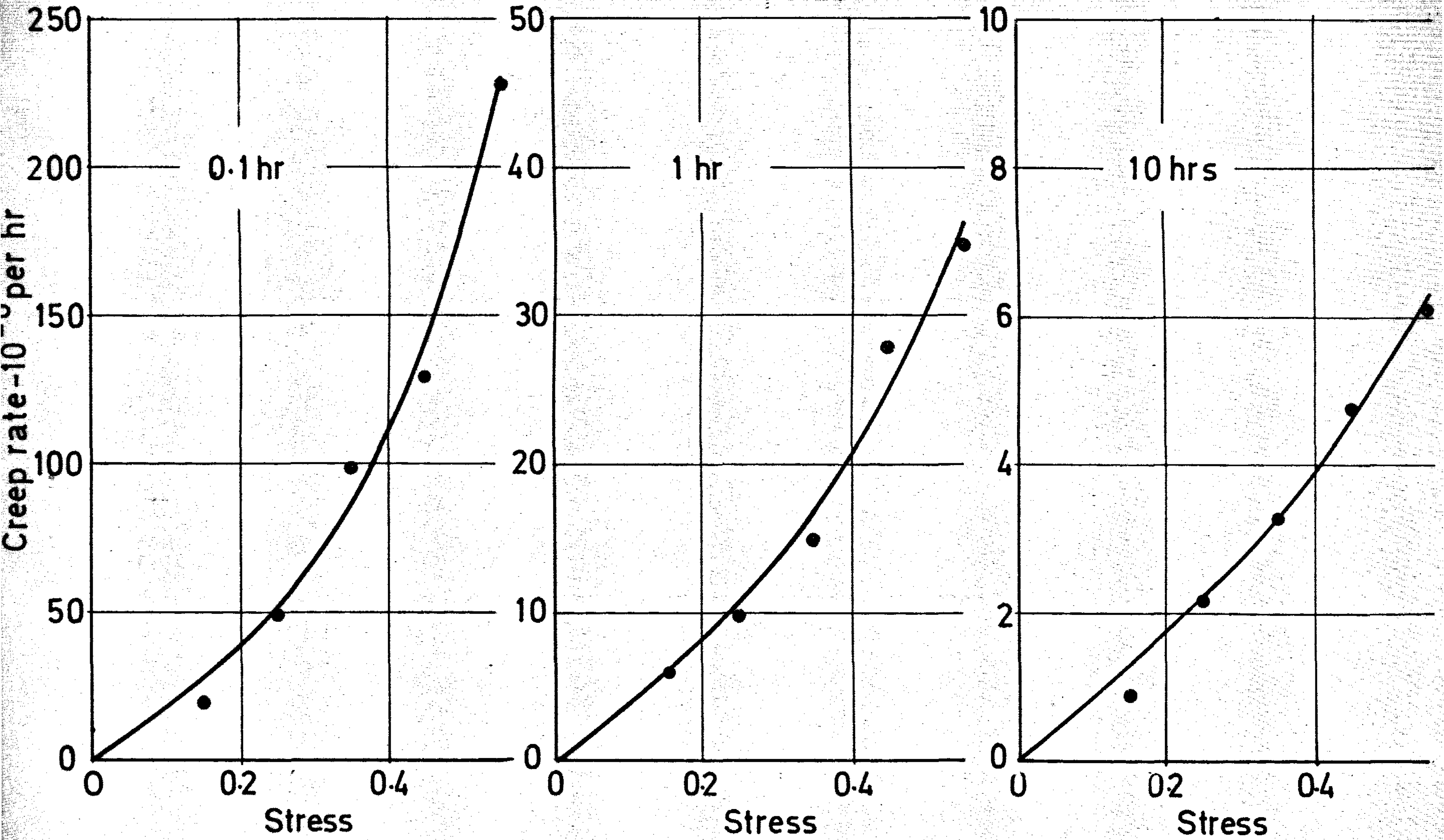

Fig. 8.1 Fig. 8.2 Fig. 8.3

Creep rate as a function of static stress at different times

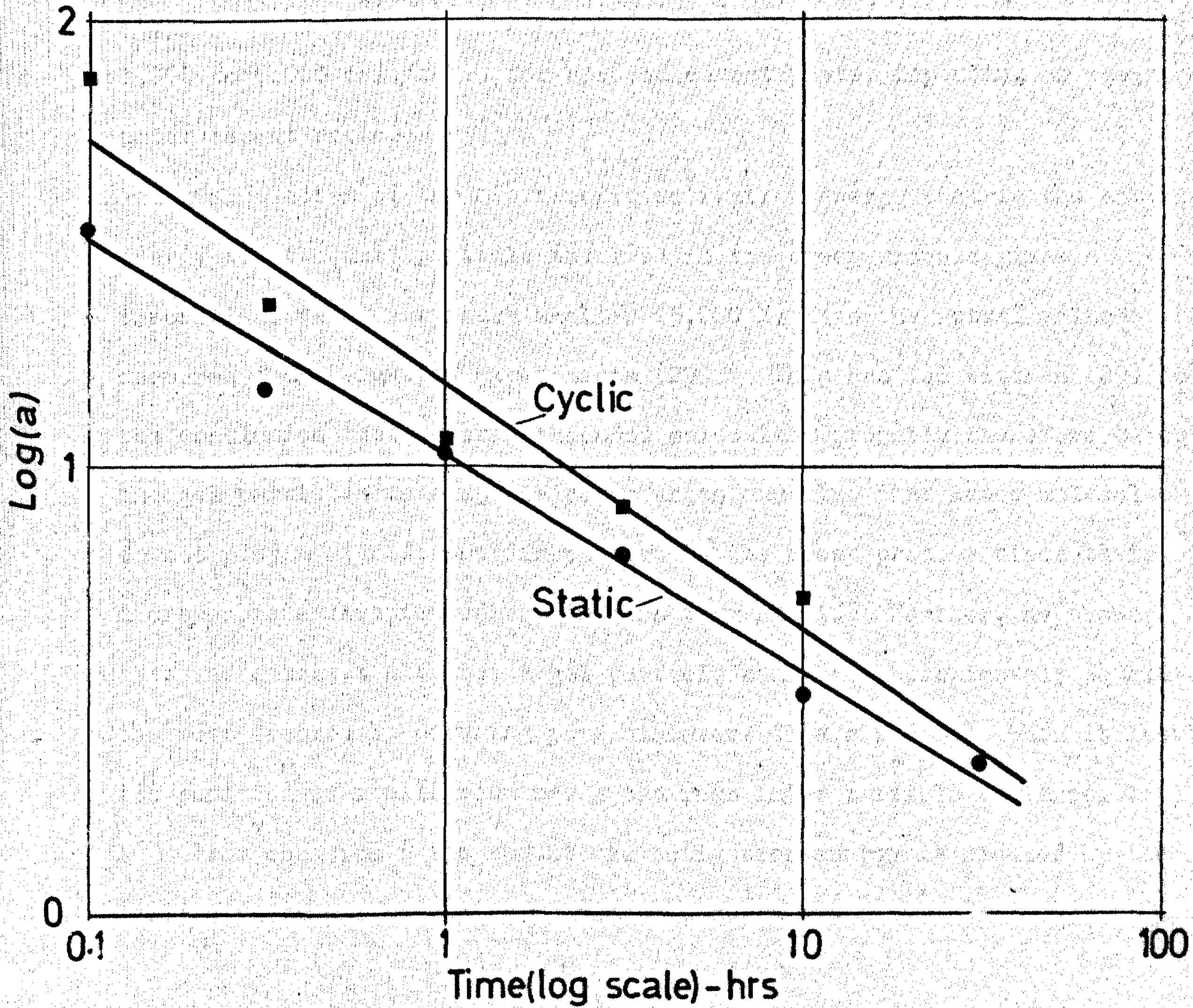

Fig. 8.4 Log(a)/time to calculate activation energy

This gives values for the activation energy after 10, 50, 100 and 1,000 hrs. under load as 643, 1090, 1,284, 1,926 cal./mole. The accuracy is ± 16% at the 5% level of significance.

These values are of the same order as those obtained by Wittman (28) for hardened cement paste, suggesting that it is the behaviour of the cement paste in concrete which is predominant in influencing the creep process. Other investigators have found values of activation energy of 1,000 to 6,000 cal./mole. for hardend cement paste, depending on age, and water cement ratio.

Calculation of the microscopic activation energy that is the activation energy for the unit particle involved in the creep process gives a theoretical value very much smaller (5,000 X) than the actual value measured from relaxtion experiments (29). This has led Wittman (29) to the conclusion that several thousand molecules, probably therefore being the gel particles make up the creep units and also that water molecules do not play a significant direct part in the creep process since their microscopic activation energy is also very small. Further, he shows that the smallest distance a gel particle can move approximately equals the most frequently occuring pore diameter, thus a particle when it leaves its position of equilibrium moves the mean inter particle distance.

From equation 6 the amount the activation energy is reduced by the applied force per percent of ultimate load is given by

$$u = 0.01 \times R \times T \times v$$

$$= 5.86\ v \text{ cal/mole./percent}$$

Some typical figures are therefore 27, 20 and 16 cal/mole./percent at 0.1, 1 and 10 hrs. respectively.

Taking the mean strength of the specimen as 5,550 lb.f./in.^{2} these values become 0.49, 0.37 & 0.28 cal./mole./lb.f./in.^{2}. The values that Wittman obtained for hardened cement paste were 0.2 for w/c ratio = 0.35, and 0.34 for w/c ratio = 0.65. They are thus within the same range, the main difference being the decreasing value of u for concrete as opposed to the constant value for cement paste. Because u is constant for cement paste a change in the value of u for concrete must be related to a change in stress within the gel rather than a change in gel properties, due to the different structure of concrete. This could be accounted for by the presence of aggregate in concrete and the consequent transfer of stress from the matrix and thus the cement gel to the aggregate during the creep process. Occurence of microcracking at the aggregate matrix interface would affect the calculated value of both u and a in the early stages. The fact that v and hence the calculated value of u is initially constant before starting to decrease implies a period of constant stress within the gel which would be compatible with some form of stress redistribution such as occurs with microcracking, or incorrect estimation of u due perhaps again to initial cracking at higher stresses.

Equation 8 may be rewritten as

$$a = ct^{-c_2}$$

the expression for creep rate then becomes

$$\dot{\varepsilon} = 10.4\ t^{-0.476} \sin h\ (v\sigma) \quad (10)$$

Thus if v were independent of time, log creep rate against log time would plot as a straight line. The plot of log rate and log time does in fact show good linearity (fig. 8.5), though the slopes are steeper than -0.48 due to the decrease in v, the mean value being -0.7. However for a given change in v, the higher the mean stress the greater the decrease of the sinh $(v\sigma)$ term in equation 10, and thus the slope should be greater the higher the stress. From fig. 8.6 this is seen to be the case, a roughly linear relationship existing between mean slope for each stress and stress.

Integrating equation 10 the creep at time t is given by:

$$\epsilon = \frac{p}{1-q} t^{-q+1} \sinh (v\sigma) - \int_0^t pt^{-q} \sigma \cosh (v\sigma) \frac{\partial v}{\partial t} dt \qquad (11)$$

where in this case p = 10.4 and q = 0.476

If v were constant the second part of 11 would be zero and a simple power function would result.

Since $\frac{\partial v}{\partial t}$ is negative the second part of equation 11 means a gradually decreasing function is being added to the first part which from the creep rate function considered earlier is probably a power function.

Plotting log creep against log time, however, does show quite good linearity for the time intervals considered in these tests, though creep after a long period would be overestimated assuming a simple power law. The gradients of the log creep log time curves are in this case not stress dependent which can be attributed to the effects of the second part of equation 11. Apart from this extra term, the effect of time dependent

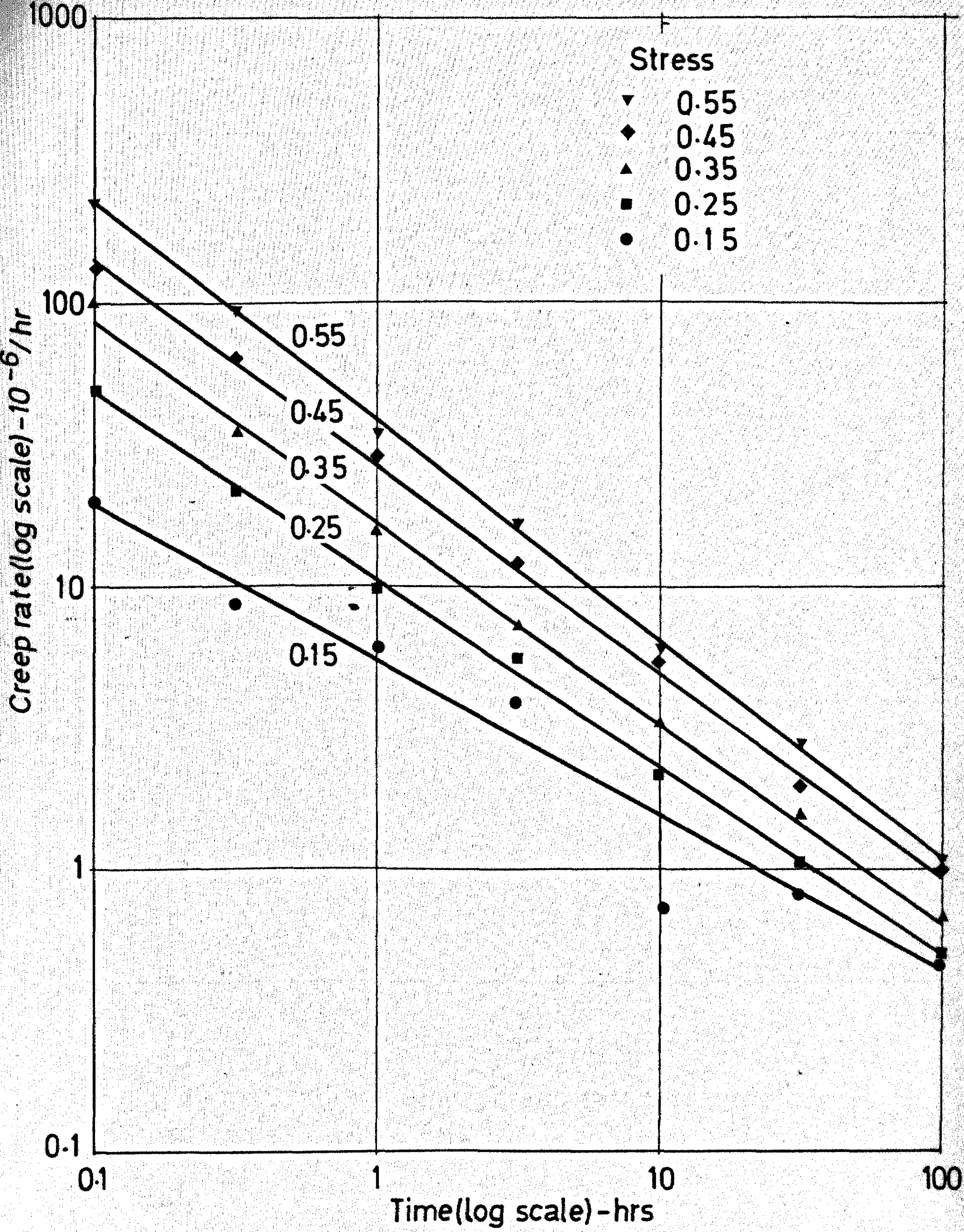

Fig. 8·5 The influence of static stress on creep rate

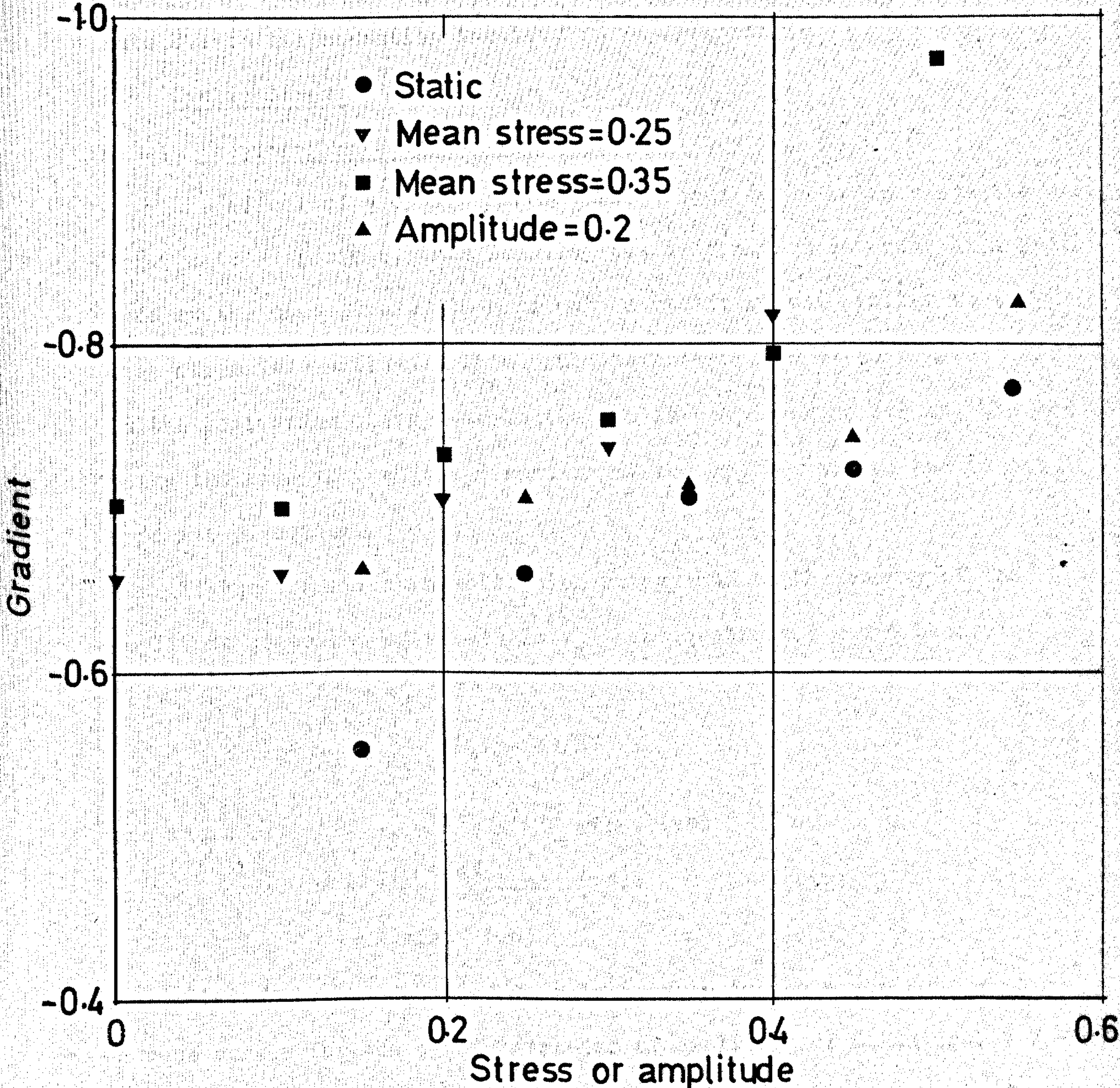

Fig. 8.6 Gradient of log creep rate/log time curves at various stresses and amplitudes

variations of v could be expected to be greater on creep than on creep rate due to the summation involved in integration.

8.4 Cyclic Stress

8.4.1 Varying Mean Stress - Constant Amplitude

The effect of a cyclic stress can be considered to increase the energy input into a specimen, thus enabling the deformation to occur at a faster rate at the mean stress, than if only a static stress similar to the mean stress was acting. This could be interpreted as an apparent reduction in the activation energy due to the cyclic component of stress, the reduction being the same in both the direction of the applied stress and in the opposite direction.

If the reduction in activation energy due to the energy of the amplitude component of stress is u_a then equations 3 and 4 become:

$$Z_1 = a_2\, e^{-(Q-u-u_a)/RT}$$

$$Z_2 = a_2\, e^{-(Q+u-u_a)/RT}$$

and therefore $Z = 2a_2\, e^{-(Q-u_a)/RT} \sinh\ (v\sigma)$

$$\text{or} \quad \varepsilon = a\, e^{u_a/RT} \sinh\ (v\sigma) \qquad (12)$$

$$= A \sinh\ (v\sigma)$$

Fitting the hyperbolic sine relationship to the creep rate - mean stress curves for the cyclic stresses of amplitude of 0.2, (figs. 8.7 - 9) shows quite good agreement, though at later times the creep rate for a mean stress of 0.15 appears to be rather high, perhaps due to the effect of a near zero lower stress as mentioned in chapter 6.

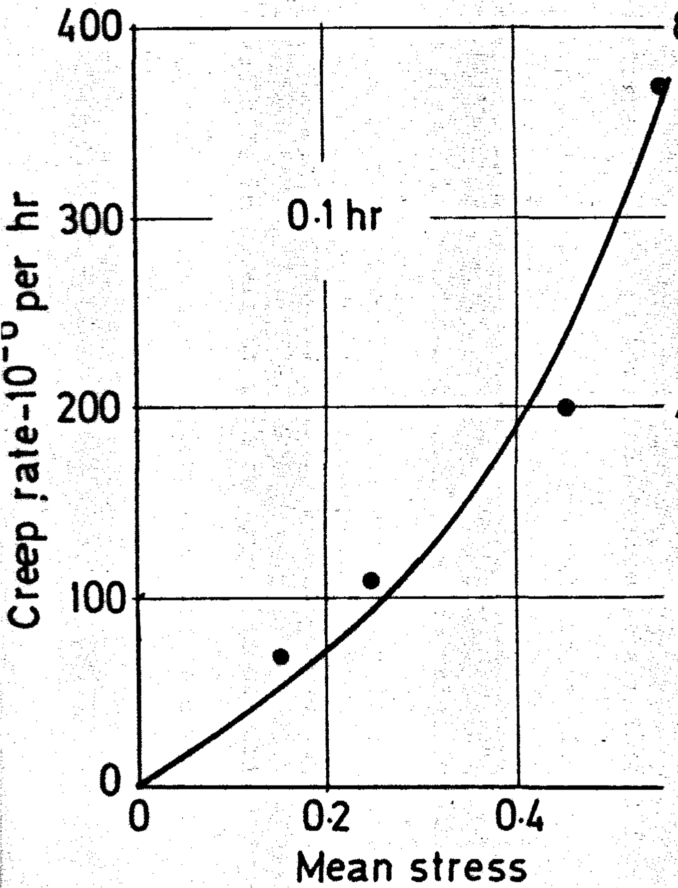

Fig. 8.7

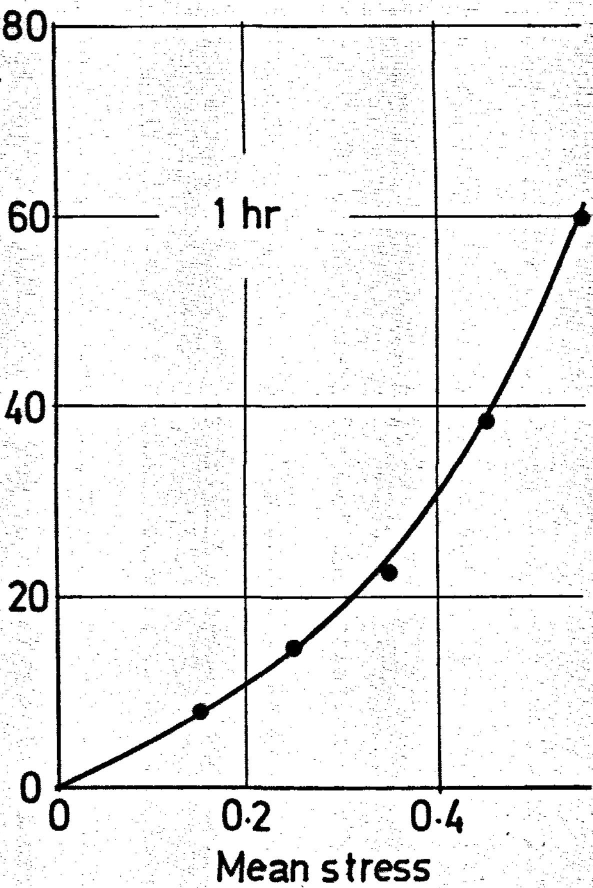

Fig. 8.8

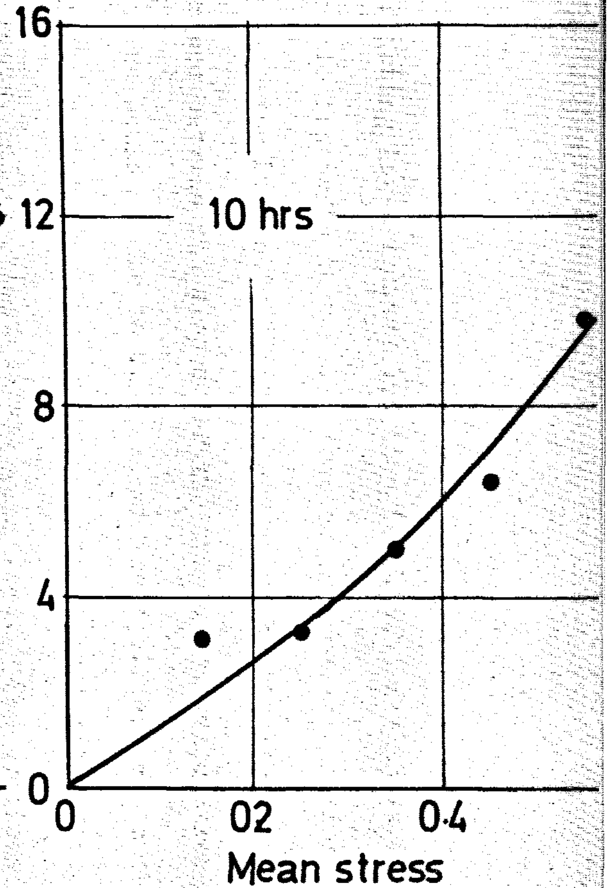

Fig. 8.9

Creep rate as a function of mean stress at different times - amplitude = 0·2

Plotting log A against log time (fig. 8.4) for these tests shows reasonable linearity though the scatter is greater than for the static tests. Using Student's t test shows no statistically significant difference between the slopes for the static or cyclic stress tests, and thus there would appear to be no significant difference in the activation energy for a static or cyclic stress within the limits of accuracy of these tests, and the time interval considered. The cyclic stress line lies above that of the static stress line, which would be in agreement with equation 12, though the difference is too small to permit calculation of u_a, with any degree of certainty.

Fig. 8.10 shows a comparison of the variation of v with time for the static and cyclic stresses. The behaviour is similar, though v for the cyclic stress shows a slight initial increase, then does not start to decrease until after v for the static stress, though the later values appear to be similar. However the value for 30 hrs. could not be calculated for the cyclic stress due to the high value of creep rate at a mean stress of 0.15, so the sinh curves were refitted for both static and cyclic stresses leaving this value out, to enable a qualitative comparison to be made at this time. The variation of this value of v is shown in fig. 8.11. It can be seen that the value for the cyclic stress falls below that for the static stress at later stages. That the value of v for the cyclic stress initially remains above that for the static stress would be in agreement with an extension of early microcracking due to the cyclic stress which was earlier suggested as a reason for the value of

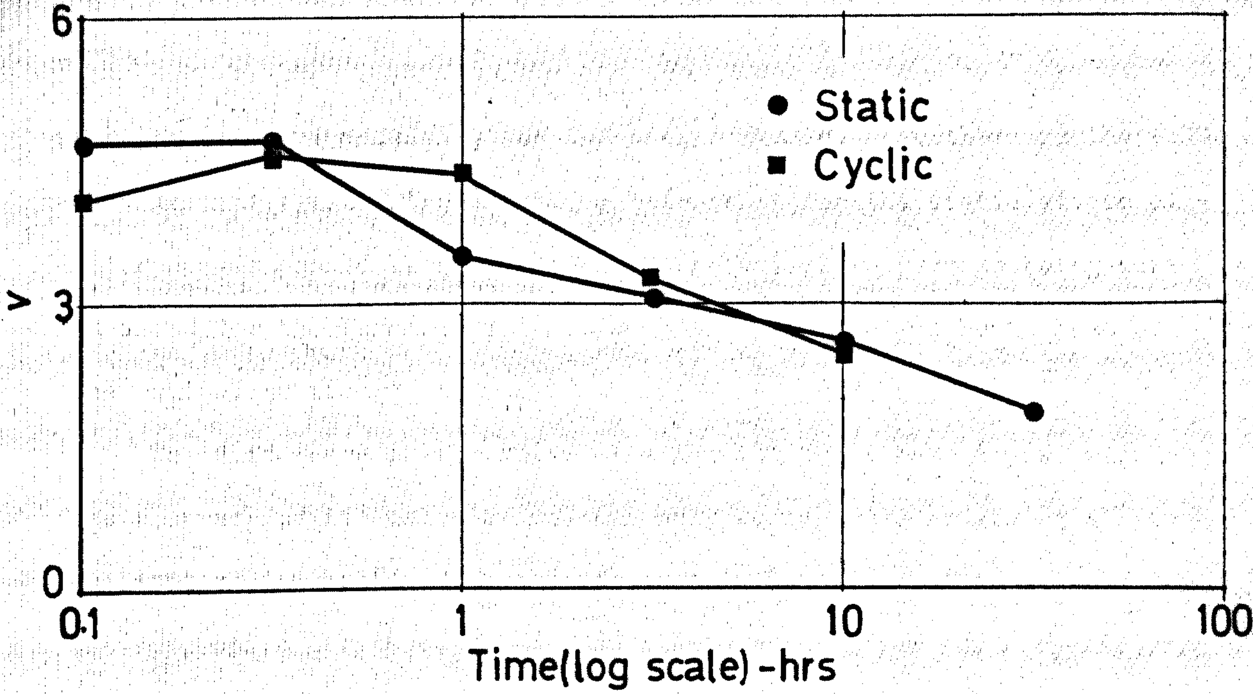

Fig. 8.10 Variation of v with time for static & cyclic (amp=0.2) stresses using results calculated from stress range 0.15 to 0.55

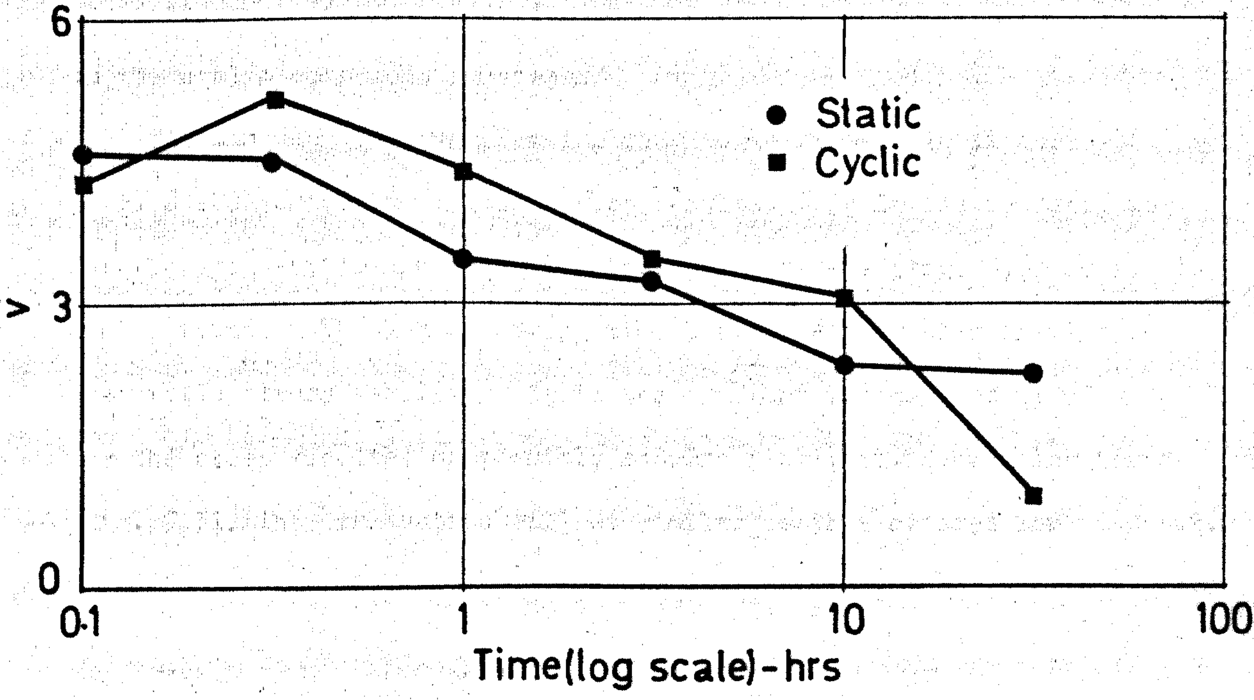

Fig. 8.11 As for fig. 8.10 but for stress range 0.25 to 0.55

v being constant initially for the static stress. Furthermore the value of v for the cyclic stress falling below that for the static stress at later stages, could be a result of the actual creep process being more advanced for the former, and thus the stress on the gel being less at the equivalent time.

The difference in the value of v for the two stress types, within the accuracy of its calculation, can only be regarded as giving a qualitative indication of the difference in behaviour of concrete under the respective stresses. The fact that v does differ for a cyclic stress means that v in equation 12 must be changed to v_c for a cyclic stress, though as was previously mentioned, this difference in v does not imply a fundamental difference in the decrease in activation energy caused by the mean stress, but rather a change of stress in the gel due to creep; the difference in a accounts for the decrease in activation energy due to the cyclic component of stress.

Plotting log rate against log time shows reasonable linearity (fig. 8.12) as for the static stress results. Again the tendency is for the gradient to increase with increasing stress (fig. 8.6) as for the static tests. The log creep-log time plot is linear also similar to the static stress results. Again the gradient is independent of stress for the creep results, or possibly showing a slightly decreasing trend (fig. 9.3). The explanation will be similar to that offered for the static tests.

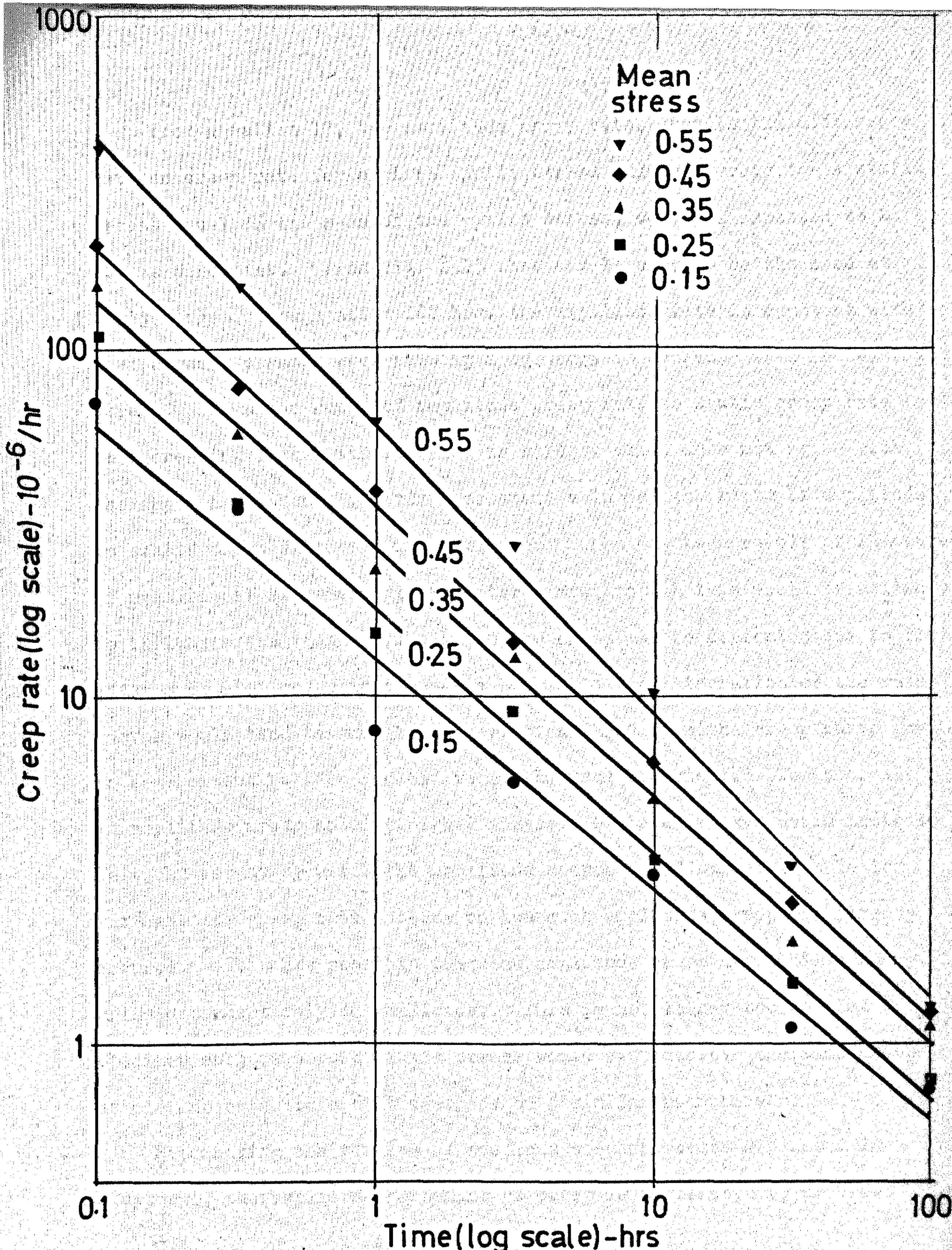

Fig. 8.12 The influence of mean stress on creep rate-amplitude = 0·2

From equation 12, the amplitude creep rate, that is the difference between creep rate for a given cyclic stress and creep rate for a static stress equal to the mean of the cyclic stress, would be expected to be stress dependent. From fig. 8.13 this can be seen to be the case at early stages, though after 100 hrs. the amplitude rate is constant with mean stress, perhaps even showing a tendency to decrease with increasing stress. Thus the ratio of amplitude creep rate to static creep rate is of decreasing order with increase in stress, which does not agree with the apparent tendency towards a constant value of the ratio of amplitude to static creep discussed in chapter 6. This may be a result of inaccuracy of measurement of creep rate at later times, though this would be unlikely to influence the trend. The ratio for creep may be distorted due to the effects of high creep in the early stages. The integration of the rate curves would tend to smooth out variations, and thus the creep curve may to some extent be less indicative of the true behaviour. The decrease in amplitude creep rate at higher stresses at later stages would indicate that the amount by which the amplitude component of stress is able to increase the creep rate depends on how much amplitude creep has already occured. It seems possible that the amplitude creep has a limiting value dependent only on amplitude. This is not to say though that a specimen subjected to a static stress would ever achieve the same creep as one subjected to a cyclic stress of a similar mean stress.

Remembering the results of the load sequence tests discussed in chapter 6, the amplitude component of creep is unaffected by previous

Time -hrs	Vertical scale x
0·1	10
1	1
10	1
100	0·1

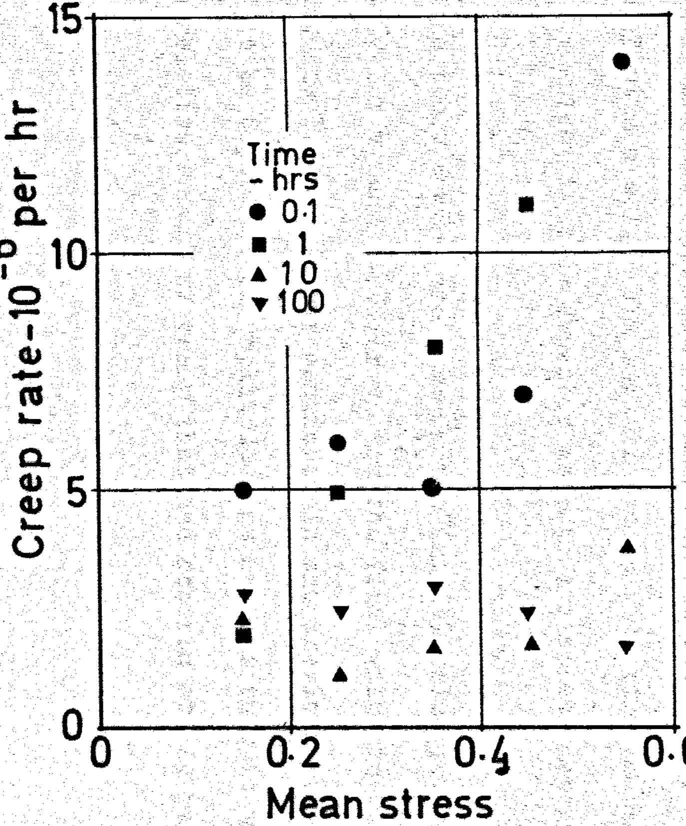

Fig. 8.13 Amp. creep rate as a function of mean stress amp.= 0·2

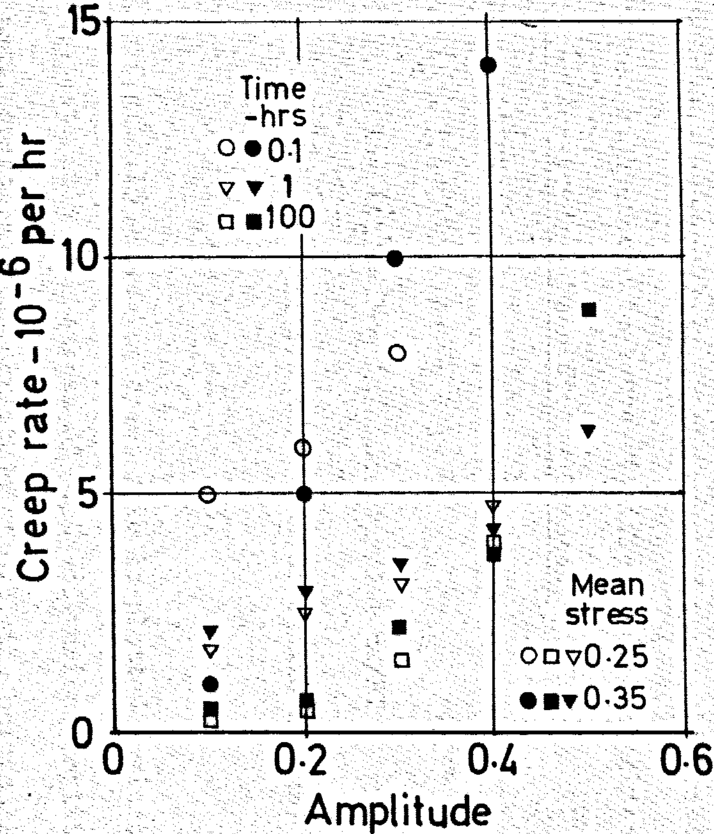

Fig. 8.14 Amp. creep rate as a function of amp.-mean stress = 0·25 & 0·35

application of a static stress equal to the mean of the cyclic stress, if the stresses are not high enough to cause significant microcracking.

8.4.2 Variation of Amplitude - Mean Stress Constant

Considering equation 12

$$\mathring{\varepsilon}_c = a.e^{u_a/RT} \sinh (v_c \sigma)$$

taking logs $\log (\dot{\varepsilon}_c) = \log (a \sinh (v_c\sigma)) + u_a/RT$

assuming $\frac{u_a}{RT} = k\Delta^n$ (Δ = amplitude of cyclic stress)

then $\log (\dot{\varepsilon}_c) = K + k\Delta^n$ - (13)

Referring to fig, 8.15 where log creep rate is plotted against amplitude for the tests at a mean stress of 0.35 and various amplitudes it can be seen that, apart from the amplitude of 0.5, the points lie on quite a good straight line. Regression lines were fitted for the first five points at the various time intervals, and the correlation was significant at the 1% level for all the lines apart from at 10 and 100 hrs., when the level of significance was 5%. This would therefore appear to verify equation 13 with n = 1. The variation of k with time as compared with v is similar, which might be expected as both are stress dependent factors.

Comparing the two $v = \frac{u}{RT\sigma}$ and $k = \frac{u_a}{RT\Delta}$ the initial value for k is 1.02 compared with 4.67 for v_s and 4.08 for v_c and the final value is 0.48 compared with 1.9 and 1.03. It was mentioned in the previous sub-section that v appeared to be dependent on amplitude in as much as that it was affected by the relative amount of creep that had occured at any particular

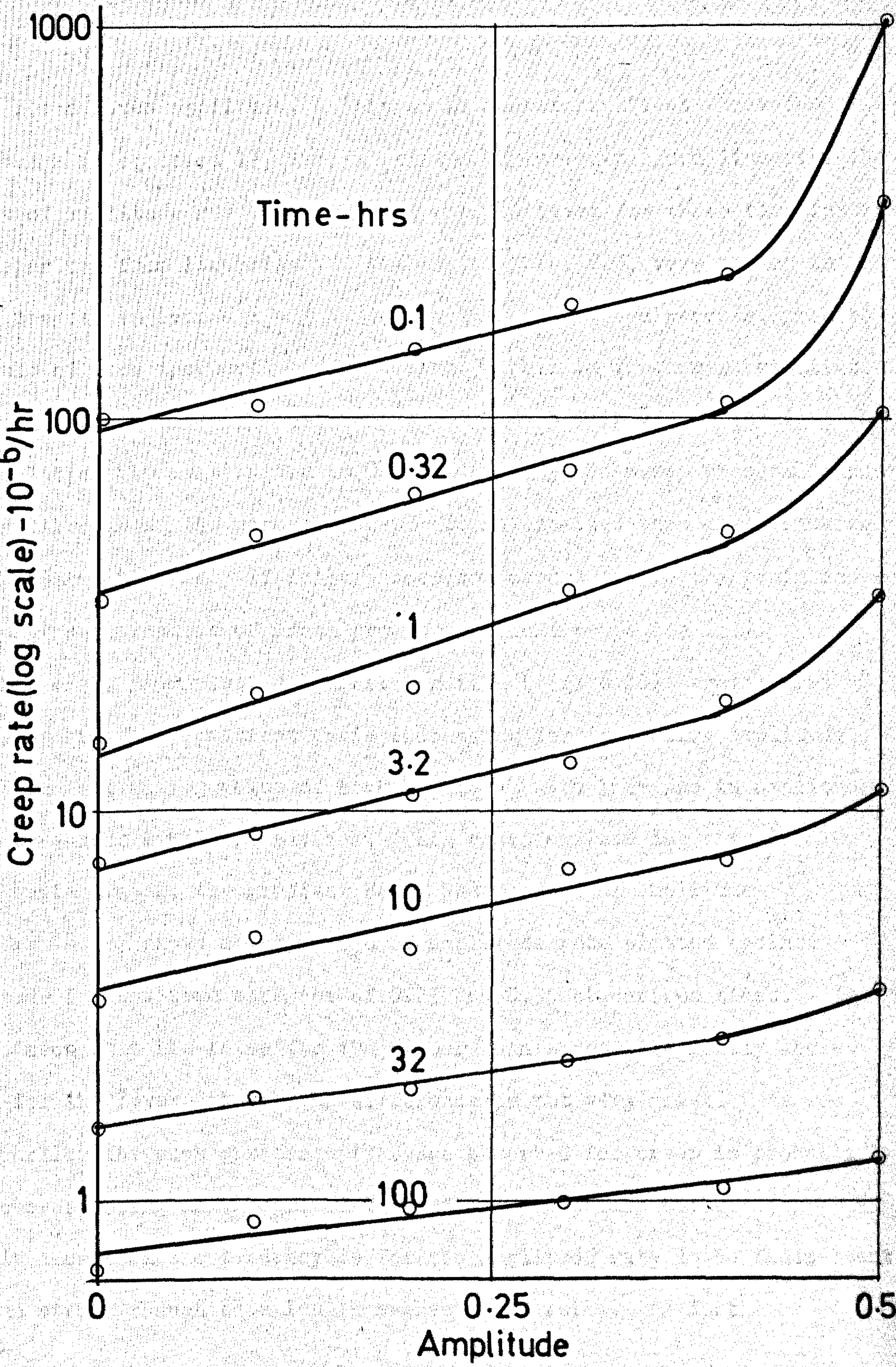

Fig. 8.15 Amplitude creep rate versus amplitude at different times

time, for a given amplitude. This would therefore affect the value of K and thus k in equation 13, though because of the quite good linearity the effect of amplitude must be fairly slight, at least for these time intervals. The departure from linearity for the amplitude of 0.5, very marked in the early stages, indicates a big change in the deformation process, probably a result of much increased microcracking. This is further substantiated by the disappearance of the effect at 100 hrs. a fairly good straight line relationship existing up to 0.5, indicating the creep process is now similar throughout the stress range. It is expected that microcracking would disappear rapidly if failure does not occur, due to the rapid increase in energy requirements of crack growth as cracks propagate (11).

Log creep rate plotted against log time (fig. 8.16) again shows good linearity, the gradient again increasing for increasing amplitude due to the decreasing value of both u_a and v_c with increase in amplitude for the reasons mentioned earlier. Log creep against log time is also again quite linear, the gradient being independent of amplitude.

Fig. 8.14 shows a comparison of amplitude rate plotted against amplitude for the mean stresses of 0.25 and 0.35 at various times. It can be seen that the rates for the higher mean stress lie mostly above those for the lower, though the difference is not very great. As was said earlier the much greater difference observed for creep is probably due to creep being an integrated form of the creep rate curve.

It does seem the tendency is for the amplitude rate to be independent of mean stress though equation 12 suggests otherwise. A further

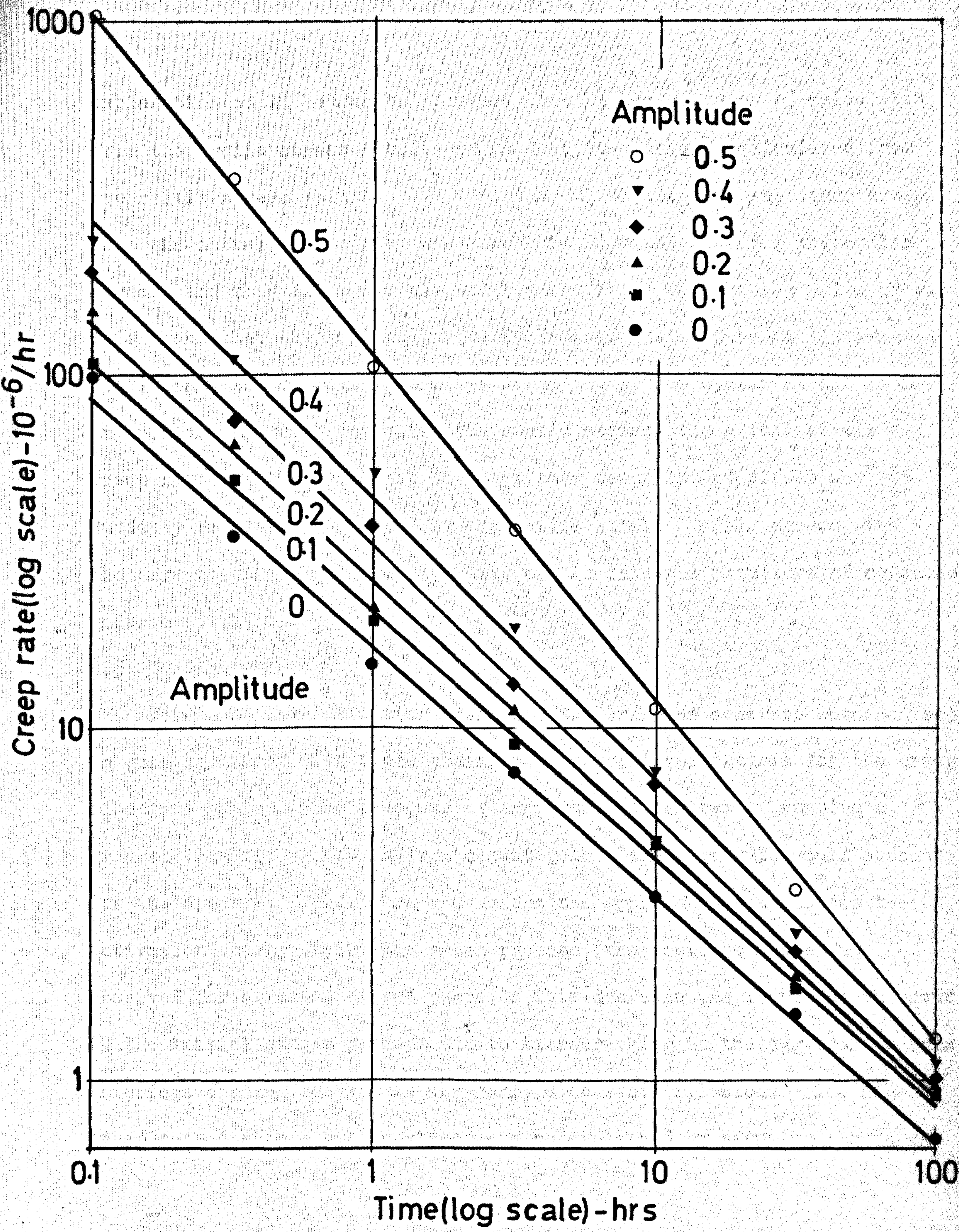

Fig. 8.16 The influence of amplitude on creep rate-mean stress=0·35.

explanation could be due to the fact that at later stages v_c calculated from the cyclic stress results is in fact less than v_s calculated from the static stress results. However in calculating the amplitude creep rate the actual static rate was subtracted from the rate for the cyclic stress, and thus allowance has not been made for the reduced value of v. This means that the amplitude rate is underestimated because the assumed static rate is too big. In other words though the cyclic stress causes an increase in creep rate over the static stress, the actual static creep rate (that observed if the amplitude component of stress was suddenly removed) is reduced by the cyclic stress. This agrees with the more rapid tendency to stability of the internal structure of concrete under a cyclic stress.

8.5 Conclusions

Values of the activation energy of the creep of concrete obtained are in good agreement with those obtained by other investigators for the creep of cement paste. The presence of aggregate in concrete, causing a gradual transfer of stress from cement gel to the aggregate would account for the apparent decrease in the amount the applied stress reduces the activation energy during the creep process, the decrease not being observed for hardened cement paste. This decrease was found not to occur in the initial stages perhaps due to microcracking at the aggregate matrix interface causing changes in the early stress distribution. The higher creep rate due to a cyclic stress can be explained by assuming the energy available from a cyclic stress causes a further reduction in activation energy equally in the direction of and in the direction opposite to the applied stress. No significant difference was found in the activation energy of creep between a static stress and a cyclic stress. The reduction in activation energy due to the mean stress component of the cyclic stress, showed an initial increase before starting to decrease, for a cyclic stress, the decrease also occuring at a later time. This was thought to be due to a greater degree of early microcracking for a cyclic stress. Microcracking was indeed responsible for a very large increase in initial creep rate for a mean stress of 0.35 and amplitude of 0.5.

The static or mean stress component of creep rate and the amplitude component are interrelated and cannot be superimposed additively in a similar manner to creep and shrinkage being unable to be superimposed.

The relationship between log creep rate and log time was shown to be linear, the gradient increasing with increasing stress or amplitude for both static and cyclic stresses, due to transfer of stress from gel to aggregate. Log creep and log time also showed a fairly linear relationship, the gradient being independent of stress or amplitude, though departure from linearity at later stages would lead to overestimation of creep after long periods.

Due to the time dependence of the coefficients in the activation energy equation it is not possible to present a general equation based on this for creep rate, or creep of concrete under a static or cyclic stress. Use of the equations however enables calculations of parameters which agree quite well with previous work and make it possible to suggest tentatively that the concept of change of position of gel particles being the fundamental cause of the creep process for both a static and cyclic stress is qualitatively if not to some extent quantatively valid. This is not to discount the presence of varying amounts of water causing considerable change in the structure of the gel and in consequence, changes in the mobility of the particles, though the role of water is considered more passive than active.

CHAPTER 9

GENERAL EXPRESSIONS AND THE APPLICATION OF RHEOLOGICAL MODELS TO CREEP UNDER A CYCLIC STRESS

9.1 Introduction

Many expressions exist which attempt to describe the shape of the creep-time curve and the influence of the many parameters which affect it. Insufficient is known about the creep behaviour of concrete to be able to deduce a theoretical relationship, and so the expressions tend to be empirical, their complexity depending on the number of parameters involved, the accuracy with which it is desired to approximate the experimental curves and the time interval being considered.

It is proposed here to consider the simplest relationships in general use to try and establish whether they are significantly different under a cyclic stress, and if so in what way. This might then enable creep under a cyclic stress to be expressed in terms of creep under some equivalent static stress, and thus give some indication as to how the more complex relationships involving parameters which were not varied in these tests might be affected, reducing the need for a great deal of experimental work to determine behaviour under a cyclic stress.

Rheological models are an aid in producing a mathematical equation to represent the creep process. They do not in themselves contribute to knowledge of the fundamental creep process. They have however been used widely to aid the formation of relationships between stress, strain and time, and it is felt it will be useful to investigate the behaviour of existing models under a cyclic stress, and how they may need to be modified to account for actual creep behaviour under a cyclic stress, thus shedding further light on how a cyclic stress modifies the static stress -strain and time relationships.

9.2 Exponential and Hyperbolic Relationships

The exponential expression for creep as put forward by McHenry (30) is based on the creep rate being of the form:

$$\frac{d\varepsilon}{dt} = a\,(\varepsilon_{\infty} - \varepsilon)$$

the solution being $\varepsilon = \varepsilon_{\infty}(1 - e^{-kt})$ (1) $(t = 0,\ \varepsilon = 0;\ t = \infty, \varepsilon = \varepsilon_{\infty})$

this again implies $\log\left(\frac{d\varepsilon}{dt}\right) = \log(a) - kt$

In these tests the relationship between the log of creep rate and time was not linear, and previous work has not shown very good agreement with the exponential equation for creep. McHenry modified it by adding a further term so that

$$\varepsilon = c(1 - e^{-dt}) + fe^{-gL}\,(1 - e^{-ht})$$

where c, d, f, g, h, are constants which are determined experimentally, and L is the age at loading. The second term is to account for higher early creep before the properties have become stabilised. It is of course possible to approximate any creep curve as exactly as required by using a sufficient number of exponential terms, but the procedure becomes very complex and is not suitable for the present purposes.

Referring back to equation 1 and taking only the first term in t of the expansion of e^{-kt}

$$\varepsilon = \varepsilon_\infty(1 - \frac{1}{1 + kt})$$

$$\varepsilon = \frac{\varepsilon_\infty kt}{1 + kt}$$

or $$\varepsilon = \frac{t}{a + bt} \quad \text{where } a = \frac{1}{\varepsilon_\infty k}, \quad b = \frac{1}{\varepsilon_\infty}$$

This is the hyperbolic expression for creep suggested by Ross (31) and similar to that of Lorman (32).

Good agreement has been found by previous investigators for this expression and experimental results, but rather poor agreement was found in the present tests unless the first 40 hrs. or so of the creep time curve was ignored, and even then the tendency was to underestimate the ultimate creep. It has in fact been found that the hyperbolic expression is more suited to creep at later times.

The hyperbolic expression is thus not very suitable for the present tests when creep is being considered over a relatively short period. Also the fact that two constants have to be determined does not lend itself to development of a simple expression applicable to both static and cyclic stresses.

9.3 Logarithmic Relationship

For specific creep ε_{sp}, age of loading L and time t, the U.S. Bureau of reclamation (33) assumes that:

$$\frac{d}{dt}(\varepsilon_{sp}) = \frac{f(L)}{t + a}$$

this means specific creep is given by:

$$\varepsilon_{sp} = f(L) \log_e (t + a) \qquad (t = 0,\ \varepsilon_{sp} = 0)$$

and in order to avoid distorting the time scale a is given the value of 1 so that:

$$\varepsilon_{sp} = f(L) \log_e (t + 1) \qquad (1)$$

(It is interesting to note here the rate of creep given by the hyperbolic expression - $\frac{d\varepsilon}{dt} = \frac{a}{(a + bt)^2}$ (a has different meaning))

In this case therefore creep should be a linear function of log(time + 1) Reference to figs. 1, 3 and 8 in chapter 6 shows that in these experiments this is not a very good fit, though it is again generally recognised that the expression is not valid for early periods under load, and furthermore the U.S. Bureau of Reclamation use it only for mass concrete and stress strength ratios of less than 0.35.

Since f(L) is dependent only on age at loading this should be a constant for a given concrete and a given age of loading. Cyclic stressing will alter the value of f(L), and it is also not possible to express a cyclic stress in terms of specific creep. Consequently the equation must be expressed in terms of actual creep, f(L) being dependent on stress and amplitude, and from now referred to as K.

The logarithmic equation was fitted to the experimental data and the coefficient K is shown plotted against stress for the static tests in fig. 9.1. The first ten hours of the creep data were not used to calculate K since this period showed greatest departure from linearity.

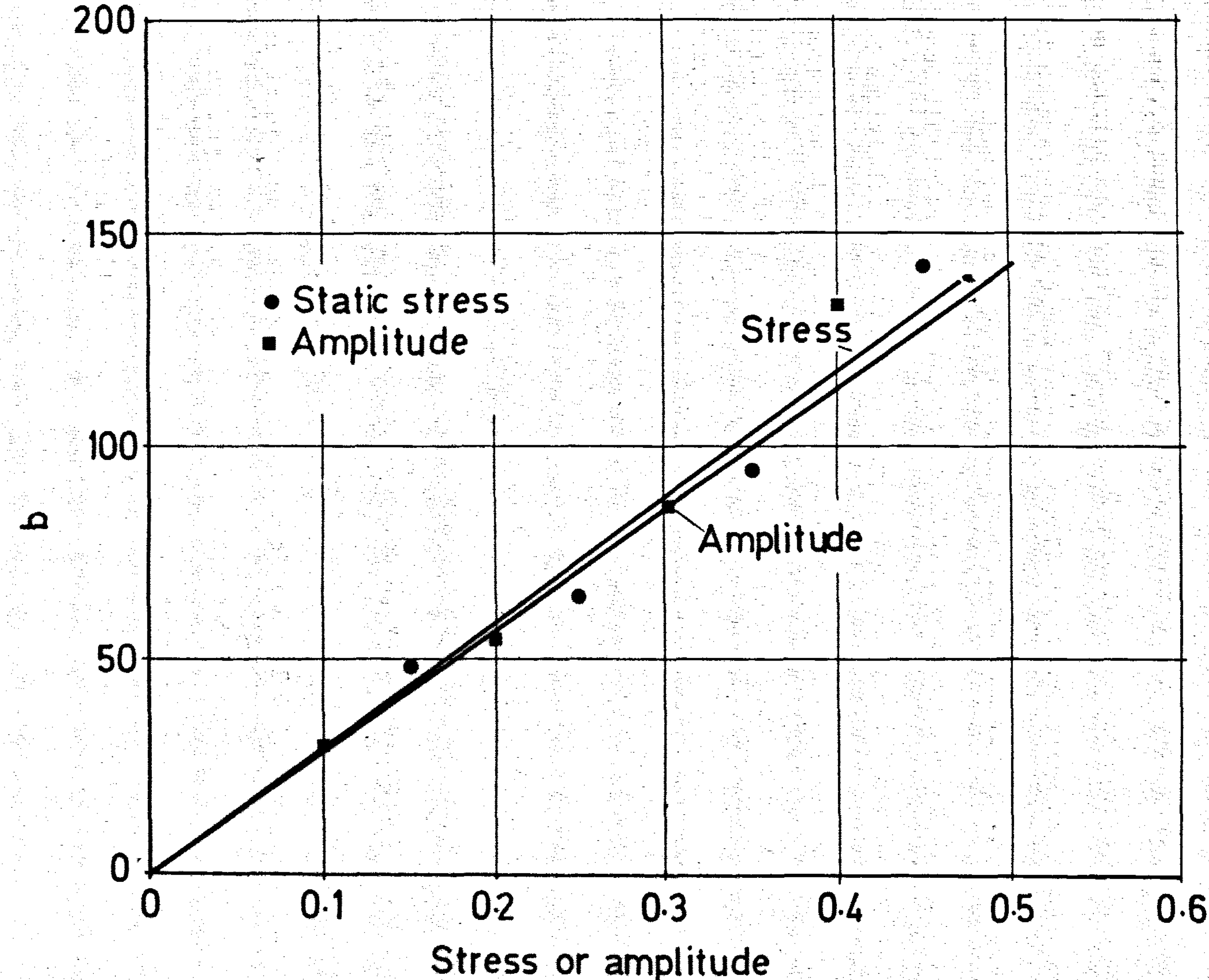

Fig. 9.1 Relationship between coefficient b of logarithmic expression and stress and amplitude

To calculate K per percent of static stress a straight line was fitted by least squares to the points up to a stress of 0.45, the relationship between stress and K being fairly linear up to this point. The result is K = 2.96 per percent. Calculating K for a stress of 0.35 this can then be subtracted from the values of K obtained for the cyclic stress tests of mean stress 0.35 and varying amplitude, to give the amplitude component K_a This is shown plotted against amplitude in fig. 9.1, and shows good linearity upto an amplitude of 0.3, the value being 2.85 per percent of amplitude. However remembering from chapter 6 that the amplitude component of creep is dependent also on the mean stress, K_a should be further divided by 35 to give K_a = 0.0813 per percent of amplitude per percent of stress.

Thus the equation for creep under a static or cyclic stress is

$$\varepsilon = \sigma_s \, (K + K_a \Delta) \, \log_{10} (t + 1)$$

$$\text{or} \quad \varepsilon = \sigma_s \, (2.96 + 0.0813 \, \Delta) \, \log_{10} (t + 1) \qquad (2)$$

Referring to table 5 ε_m represents experimental values of creep and ε_1 creep calculated using equation 2, values being shown for 30 and 100 hrs. The largest difference between values is 25% for the 100 hr. creep at a mean stress of 0.1 and amplitude of 0.1, though the error is an average rather less than 10%. There would appear to be no particular trend in the results to either under estimate or overestimate creep.

The basic difference between a logarithmic and hyperbolic expression is the former tends to infinity at infinite time and the latter tends

TABLE 5

Mean (%)	Amplitude (%)	30 hrs. ε_m $(x10^{-6})$	30 hrs. ε_1 $(x10^{-6})$	100 hrs. ε_m $(x10^{-6})$	100 hrs. ε_1 $(x10^{-6})$
15	0	65	67	105	89
25	0	94	112	140	148
35	0	142	157	202	207
45	0	214	202	300	266
25	10	140	143	204	189
25	20	156	174	214	230
25	30	218	206	289	273
35	10	188	200	264	264
35	20	222	244	308	322
35	30	288	289	386	382
15	20	104	104	175	138
25	20	156	174	214	230
35	20	223	244	308	322
45	20	304	313	408	414
10	10	58	57	100	75
15	20	104	104	175	138
20	30	175	165	240	218

to a finite limit. It is likely that a logarithmic expression would overestimate creep after a great length of time, though a hyperbolic relationship tends to have the opposite effect of predicting too early a cut off in creep.

The relationship suggested above will be more accurate for later times, and cannot be used for early times when the departure from a logarithmic curve is high. It is relatively simple, but it would be necessary to perform a series of static creep tests and a series of creep tests under a cyclic stress for one mean stress and various amplitudes to establish it for every particular type of concrete and the particular conditions required, though creep due to any load pattern is predicted fairly well with relatively few tests.

9.4 Power Functions

Power function relationships are used widely in the creep study of many materials, the form of the relationship being

$$\varepsilon = at^b \quad (3) \quad \text{(a and b constants)}$$

A is usually assumed to be some function of stress (34, 35) linear or otherwise. B is often mentioned as being approximately $\frac{1}{3}$ for many materials and has been found to have this value also for concrete. Like the logarithmic expression, creep tends to infinity at infinite time and thus long term creep is liable to be overestimated. However for these experiments it was found that this type of expression fitted the data over all better than any other. Log creep against log time should plot as a straight line, which it will be remembered from chapter 6 showed good agreement. Further the rate of creep is given by $\frac{d\varepsilon}{dt} = a.b.t^{b-1}$ which is also a power function, and again good agreement was found for log rate plotted against log time (chapter 8).

Equation 3 was fitted to the experimental results in the linearised form - $\log(\varepsilon) = \log(a) + b \times \log(t)$, since this tends to weight the points at later times, and also because it avoids forcing the curve through the origin, which biases regression estimates. For the tests where amplitude was varied at two different mean stresses, and where the mean stress was varied with a constant amplitude, the mean value of b was 0.32 in each case, and for the static tests and the tests where the upper stress was varied at constant lower stress the values of b were 0.37 and 0.34 respectively. The test to test variation was quite high, the 95% confidence limits varying between ± 0.08 to ± 0.12. Figs. 9.2-6 show b plotted against variously stress and amplitude of stress for each series. It would therefore appear that b is independent of mean stress or amplitude the over all mean being 0.333 which is in good agreement with Andrade's $\frac{1}{3}$ power expression for creep and other investigators values for concrete (34).

Plotting a against static stress, and amplitude for the tests done at a mean stress of 0.35, from fig. 9.7 it can be seen that there is a fairly linear relationship for static stress upto 0.45 and for amplitude upto 0.3. Calculating the static stress and amplitude components of a as in the previous section gives a = 1.29 per percent and a_a as 0.0499 per percent per percent. The general equation for creep then becomes

$$\varepsilon = \sigma_s (1.29 + 0.0499\,\Delta)\,t^{\frac{1}{3}} \qquad (4) \qquad (t \text{ in hrs.})$$

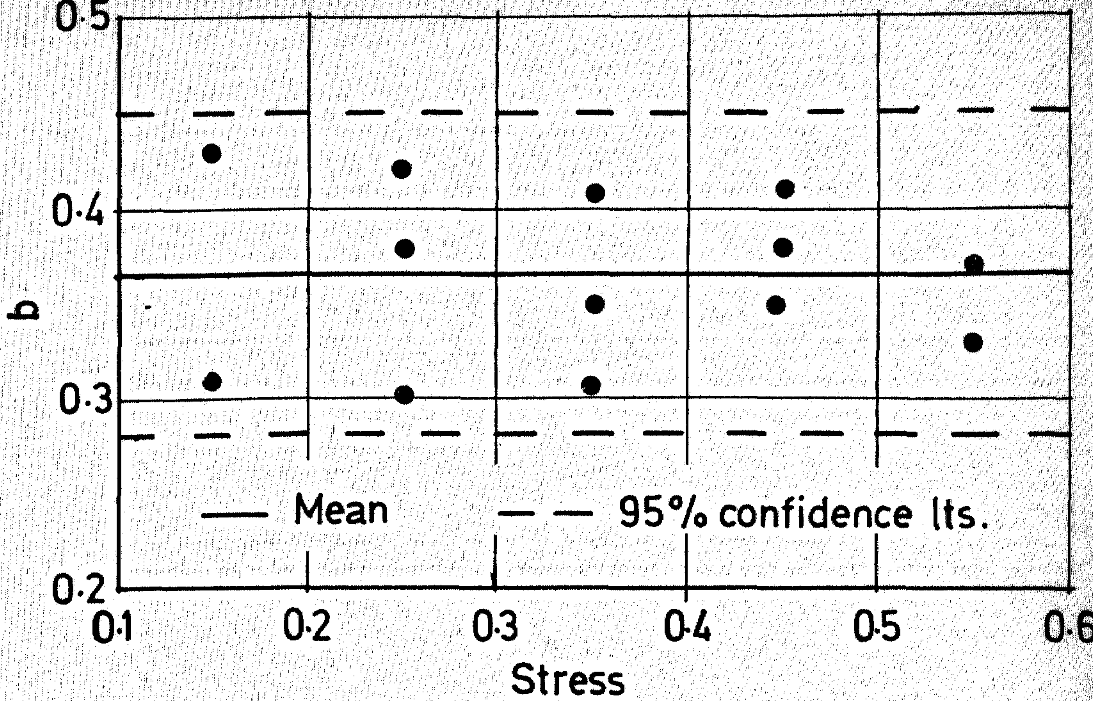

Fig. 9·2 Variation of exponent b of power function with static stress

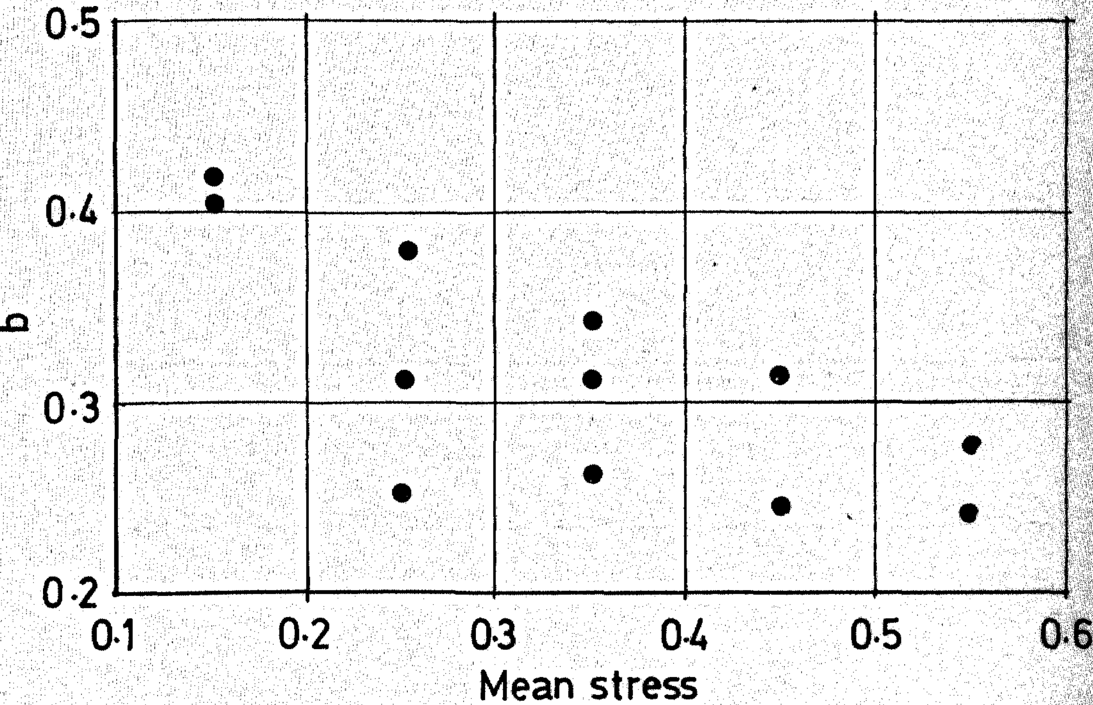

Fig. 9.3 Variation of exponent b of power function with mean stress - amplitude = 0·2

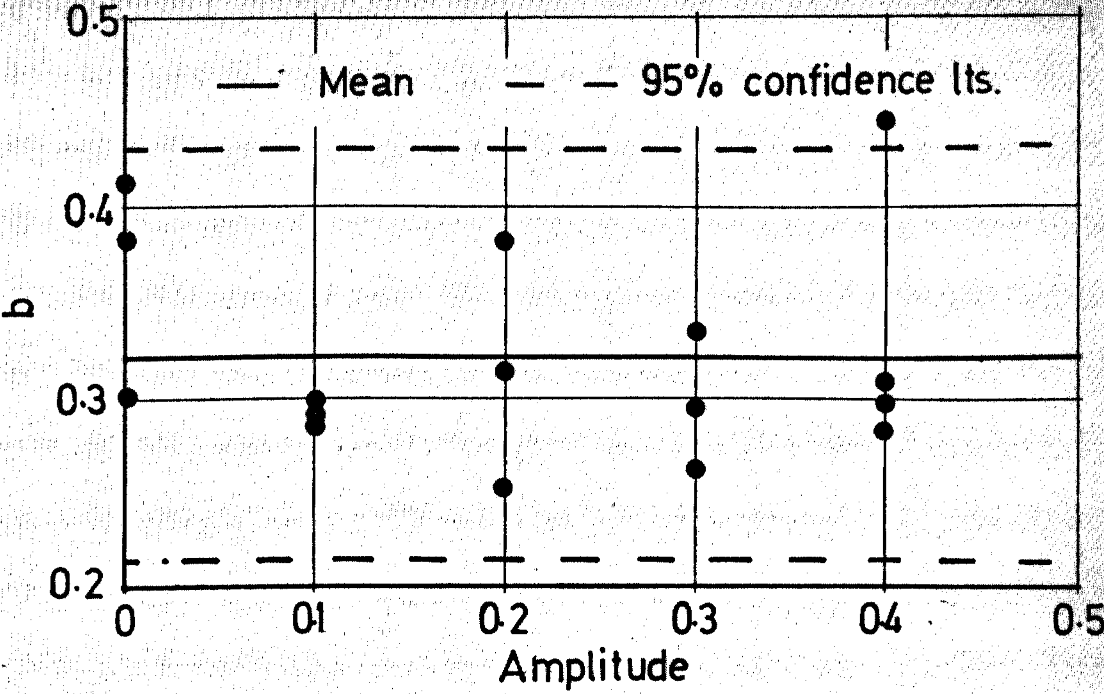

Fig. 9.4 Variation of exponent b of power function with amplitude - mean stress = 0.25

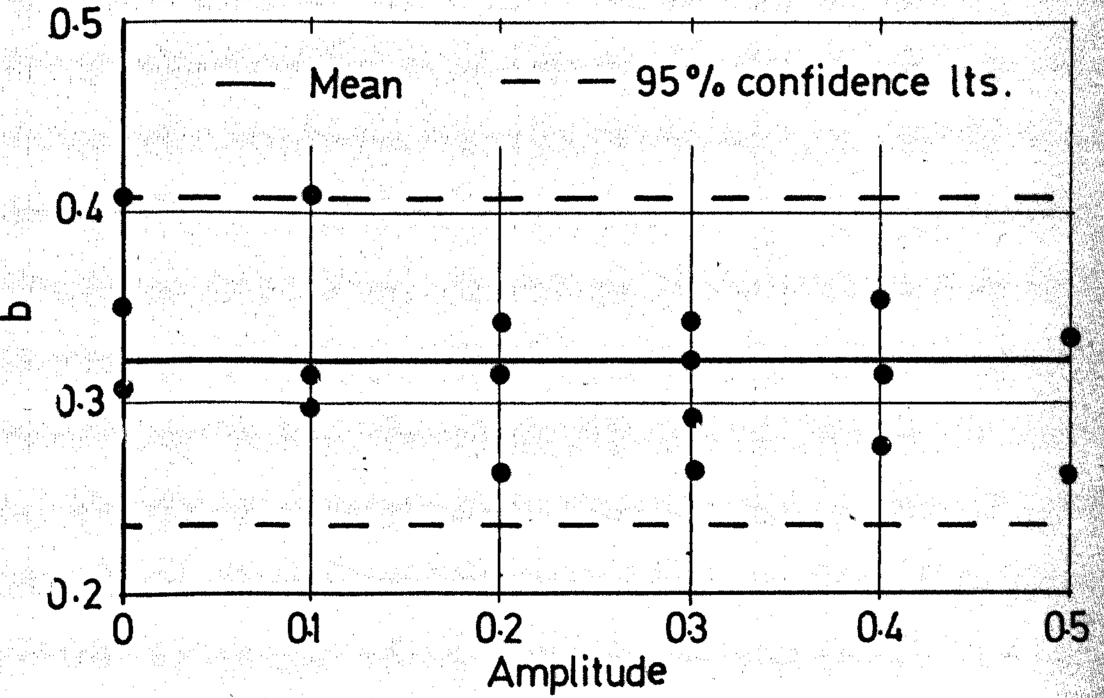

Fig. 9.5 Variation of exponent b of power function with amplitude - mean stress = 0.35

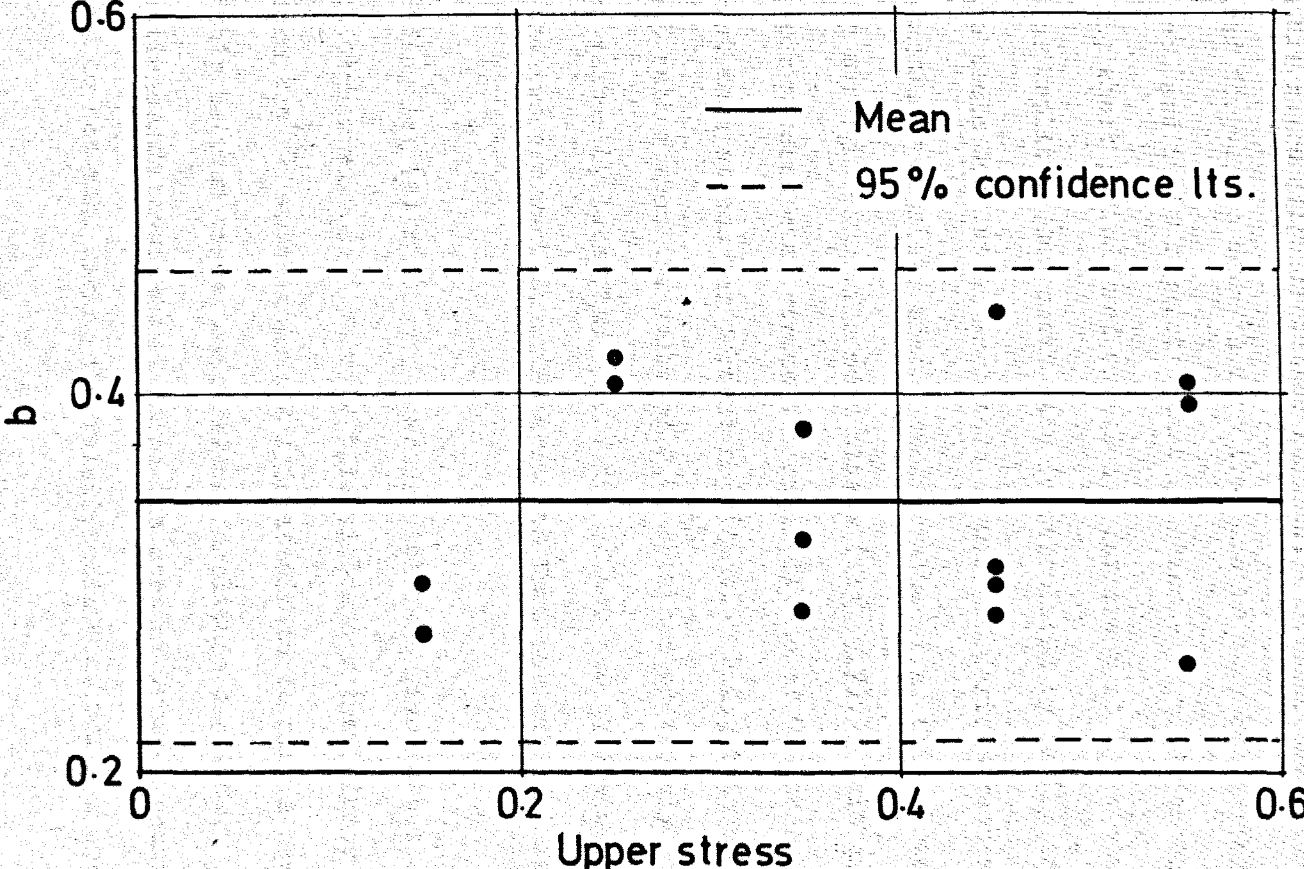

Fig. 9.6 Variation of exponent b of power function with upper stress-lower stress=0.05

Table 6 shows experimental values of creep at various stresses at 1, 10, 30 and 100 hrs., compared with creep values obtained from equation 4. The agreement is very good at 1, 10 and 30 hrs., though creep tends to be overestimated at 100 hrs. for the higher stresses, and the logarithmic relationship gives slightly better results. However the power function may be used for values down to zero time and is much better for calculating early creep, and it is suggested that equation 4 be used for early creep over fairly short periods and equation 3 for creep at later stages.

If the amplitude component of a is calculated by taking the values of a from the tests done at an amplitude of 0.2 and various mean stresses and subtracting the appropriate static stress value of a, this plots as a reasonably straight line with mean stress (fig. 9.7). This gives a value of 0.881 per percent mean stress for an amplitude of 0.2 or a value of 0.044 per percent mean stress per percent amplitude. Using this value in equation 5 rather than the value of 0.05 obtained previously would reduce the creep values by less than 5 percent. Thus the agreement is quite good between the two approaches, which suggests that basically it is a reasonable method.

Plotting log (a) against stress or amplitude gives a better straight line upto higher values. However this yields a rather clumsy relationship of the form $k_1 e^{k_2 \sigma}$ which does not lend itself to forming a general relationship between creep, mean stress, amplitude and time. The approximations made anyway when forming the sort of general equations being considered do not make making the relationship more complex worthwhile.

TABLE 6

Mean (%)	Amplitude (%)	1 hr. ε_m ($\times10^{-6}$)	1 hr. ε_p ($\times10^{-6}$)	10 hrs. ε_m ($\times10^{-6}$)	10 hrs. ε_p ($\times10^{-6}$)	30 hrs. ε_m ($\times10^{-6}$)	30 hrs. ε_p ($\times10^{-6}$)	100 hrs. ε_m ($\times10^{-6}$)	100 hrs. ε_p ($\times10^{-6}$)
15	0	19	19	42	42	65	60	105	90
25	0	28	32	62	70	94	100	140	150
35	0	45	45	96	98	142	140	202	209
45	0	76	58	154	125	214	180	300	270
25	10	49	45	101	97	140	139	204	208
25	20	56	57	110	124	156	178	214	266
25	30	79	70	160	150	218	216	289	323
35	10	62	63	133	135	188	195	264	290
35	20	77	80	162	173	222	249	308	372
35	30	107	98	213	211	288	303	381	452
15	20	30	34	70	74	104	107	175	160
25	20	56	57	110	124	156	178	214	266
35	20	78	80	162	173	223	249	308	372
45	20	120	103	224	222	304	320	408	478
10	10	19	18	36	39	58	56	100	83
15	20	30	34	70	74	104	107	175	160
20	30	62	56	129	120	175	173	240	269

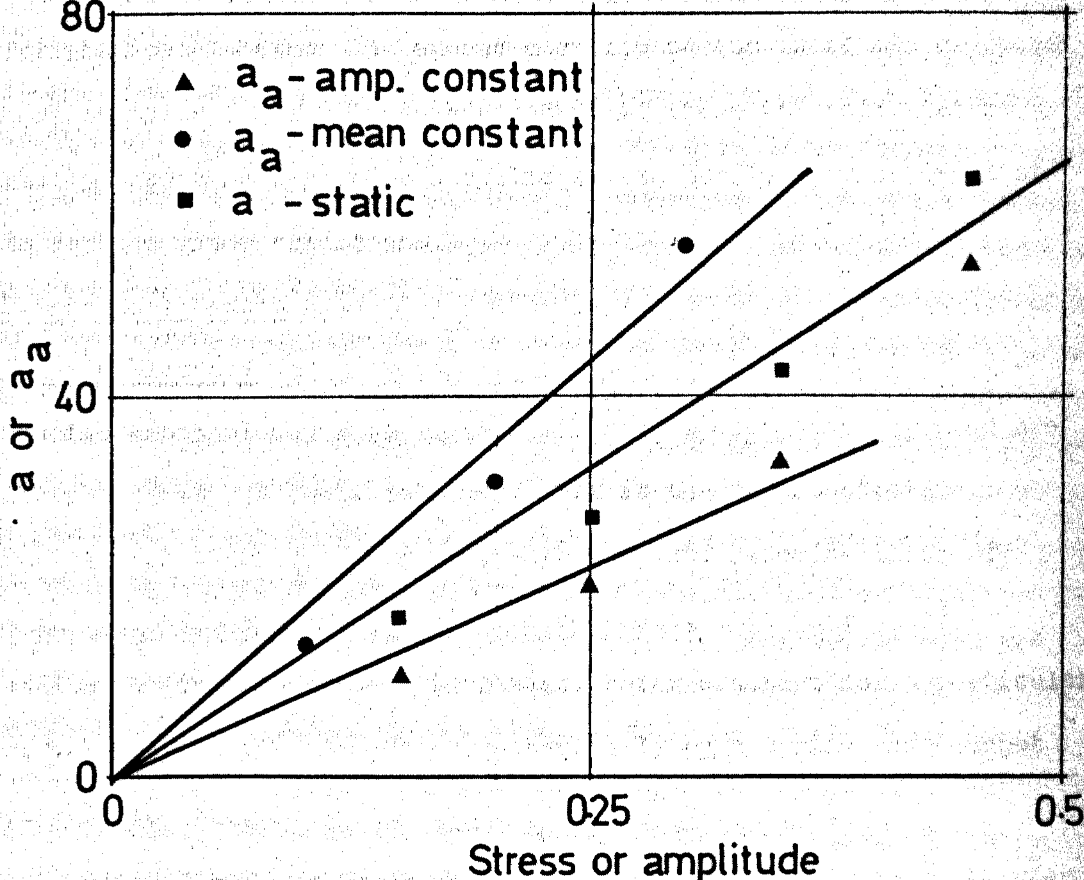

Fig. 9.7 Relationship between coefficients a & a_a of power function & stress & amplitude

Beyond mean stresses of 0.45 and amplitudes of 0.3, the departures from linearity of the relationship between mean stress or amplitude and creep become very marked, and so stresses above these values have to be considered separately.

The coefficient in the creep time curves can be expressed in the form $k_1\sigma\ (1 + k_2\ \Delta)$. The value of k_2 then solely determines the influence of the amplitude component of stress on creep, and the variation of this value for different mixes and conditions of testing environment would therefore indicate whether the amount a cyclic stress increases creep is dependent on these. If k_2 was independent of these it would then be possible to predict creep under a cyclic stress purely from static test results for the given conditions.

9.5 Rheological Models

9.5.1 Basic Elements

The two basic elements of rheological models most commonly used are one with a perfectly elastic response, that is the stress strain relationship exhibits no hysteresis, with complete recoverability of strain and one with a perfectly viscous response, that is rate of deformation is linearly related to stress, being constant for a particular stress. These can be represented mechanically by a spring and dashpot respectively the equations being

$$x = mF \quad \text{and} \quad F = w\frac{dx}{dt}$$

where x = displacement, F = applied force, w = viscosity, m = spring rate

To accommodate time dependence of properties associated with concrete both m and w may be made functions of time.

Using elements of this sort concrete is assumed to be viscoelastic in behaviour, and to account for departures from this various other elements are used such as friction elements, uni-directional dashpots, sorption elements or in fact any form of mechanical device which enables a better approximation to real behaviour to be obtained. Sometimes elements are chosen which attempt to approximate the actual microscopic behaviour of the material, but on the whole the mechanism of deformation of the model and of the actual material are in no way similar.

9.5.2 Simplest Built Up Models

The two most simple models are the Kelvin model, which is a spring and dashpot in parallel or a Maxwell model which is a spring and dashpot in series. These are represented by the two equations:

$$\frac{x}{m} + \frac{wdx}{dt} = F \qquad (6) \qquad \text{(Kelvin)}$$

and

$$\frac{dF}{dt} m + \frac{F}{w} = \frac{dx}{dt} \qquad (7) \qquad \text{(Maxwell)}$$

The deformation of a Kelvin model is given by:

$$x = Fm\,(1 - e^{-t/mw})$$

which tends to a finite limit equal to the deformation of the spring under the applied force. The Maxwell model shows an initial elastic deformation due to the spring then deforms at a constant rate depending on the viscosity of the dashpot and the applied force, thus the deformation tends to infinity. The Kelvin model exhibits complete recovery, but does not have stress relaxation properties, the Maxwell model shows only an immediate elastic recovery, but does exhibit stress relaxation. The simplest possible model able to exhibit all the phenomena mentioned is a Burgers model which is a Maxwell and Kelvin model in series. The deformation of a Burgers model is given by:

$$x = Fm_M + \frac{F.t}{w_M} + Fm_K (1 - e^{-t/(w_K - m_K)})$$

(M refers to Maxwell model, K refers to Kelvin model)

which tends ultimately to infinity at the rate of the Maxwell component and shows elastic recovery due to the Maxwell component and time dependent recovery due to the Kelvin component, the irrecoverable deformation depending on the time dependent part of the Maxwell component.

9.5.3 Models for Concrete Under a Static Stress

Qualitatively the Burgers model would appear to exhibit deformational behaviour similar to that of concrete. In fact agreement of this model with experimental results is not good (47) due to the fact that a single exponential equation does not represent concrete creep very well and also the tendency towards infinite creep at a constant rate of the Maxwell component of the model. However if the properties of the dashpots are made time dependent which was done by Vaishnav and Kesler (36) good agreement of the model with actual behaviour can be obtained, though the equation is complex to solve analytically. Many investigators have proposed models made up from springs and dashpots with dashpots having non return valves and various forms of time dependent viscosity. The equations for such models are usually very complex, the constants obtained being applicable only to the particular concretes used. The agreement of these models with actual behaviour such as for recovery and stress relaxation is generally better the more complex the model. It is interesting to note that a number of Kelvin models taken in series represents a summation of exponential expressions which can be made to agree, as accurately as required with actual creep behaviour, depending on the number taken.

An element which attempts to represent the actual creep mechanism is the sorption element suggested by Powers (37). This is two surfaces separated by a water layer up to 10 molecules thick and thus represents load bearing water. Powers model for reversible deformation of cement paste uses this in parallel with a spring to represent deformation of the elastic component. A more complex model based on the sorption model was proposed by Gopalakrishnan et al (38).

Toroja and Paez (39) introduced the idea of a spring inside a dashpot, there being frictional resistance between the walls of the dashpot and the spring coils. A dashpot empty of fluid shows time independent irrecoverable deformation where as one containing fluid shows time dependent recoverable and irrecoverable deformation. Their model does not exhibit stress relaxation.

Glucklich (40) makes use of a friction element to give irrecoverable deformation on loading and a one way dashpot in a Kelvin model to account for irrecoverable deformation. He also uses springs and friction elements in series, in parallel with a dashpot. Thus the friction elements in this Kelvin type body make it show irrecoverable deformation dependent on the previous deformation. However neither model exhibits stress relaxation.

9.5.4 Application of Models to Concrete Under a Cyclic Stress

The basic requirements of a model to represent deformation under a cyclic stress are that it should show greater deformation for a stress varying equal amounts each side of a given mean stress than at the mean stress, and that the increased deformation should be mainly irrecoverable. These requirements cannot be fulfilled by either the Kelvin or the Maxwell model which would show no increase in deformation under a cyclic stress. Two Kelvin models in series, one with a dashpot with a non return valve would qualitatively satisfy the requirements though this would imply the amplitude component was completely irreversible. Further since deformation is proportional to stress for a Kelvin model, for say a mean stress of 0.35 and amplitude of 0.2 the amplitude component of deformation for this model could be at most 0.1/0.35 times the irrecoverable component of deformation for a static stress of 0.35, and for a sinusoidal load rather less than this, which is in poor agreement with actual behaviour in which the amplitude component is more or less equal to the total time dependent deformation for this static stress.

A model consisting of a friction element in parallel with a dashpot with a non return valve the friction element being chosen to slide at just above the mean stress, could simulate the increase in irrecoverable deformation due to the cyclic stress component. The dashpot would have to be age thickening to account for the decreasing rate of deformation with time. However the disadvantage is that the force at which the friction element slides has to be proportional to the mean force but not the amplitude of the force, which makes the model valid for only particular values of the mean.

It would appear therefore that for models based on conventional viscoelastic units there is a general incompatability between behaviour under a static, and behaviour under a cyclic stress - a model with the required characteristics to describe one type of behaviour cannot describe the other. A model is required that exhibits deformation under a static stress with a fairly linear rate of deformation - stress relationship, and whose deformation is increased when the stress varies about the mean.

Use can be made of the energy available from a cyclic stress to generate heat and thus heat up a dashpot. The viscosity of the fluid would therefore decrease and it would show less resistance to deformation. The heating device could be a friction unit in series with a spring, though the disadvantage of this is a finite force is required to move the friction unit. A soft iron core moving in a coil would generate an a.c. current which could be fed to a heating element in a dashpot. A proposed model is therefore a soft iron core moving in a coil in parallel with a spring to represent the elastic deformation and provide the heat. This is in series with a Kelvin unit which has a one way age thickening dashpot with the heating element in it to represent the irreversible deformation, which it is presumed is what is affected by a cyclic stress. A further Kelvin unit is placed in series to represent the recoverable deformation.

This model is not very satisfactory however because of the implication of a heating effect causing increased deformation. Further the increased rate of deformation would be very dependent on frequency whereas the observed effect of frequency is not very great.

A more satisfactory model can be developed from a microrheological approach. In the next chapter it is postulated that a varying stress can disturb the structure of adsorbed water and thus reduce its viscosity. Considered in this light Powers sorption element would show increased deformation under a cyclic stress, though Powers does not consider the structured nature of adsorbed water. To account for irreversible deformation the sorption element must be put in parallel with a non return dashpot. A Kelvin unit or a further sorption element in parallel with a spring can represent the recoverable part of the deformation, though the latter would show a considerable increase in recoverable deformation due to the cyclic stress whereas it is thought this is in reality little affected. The properties of the adsorbed water have to be assumed to show the observed relative independence of frequency of loading. This model assumes the deformation to be dependent on removal of water from between particles but in the next chapter it is suggested that deformation is due probably to particles sliding over one another, the ease with which they can slide depending on the structure of the adsorbed layers.

A model to describe creep based on this type of behaviour is shown in fig. 9.8.SE represents what will be called a shear element. The four parts making up the element are each separated by a layer of adsorbed water.

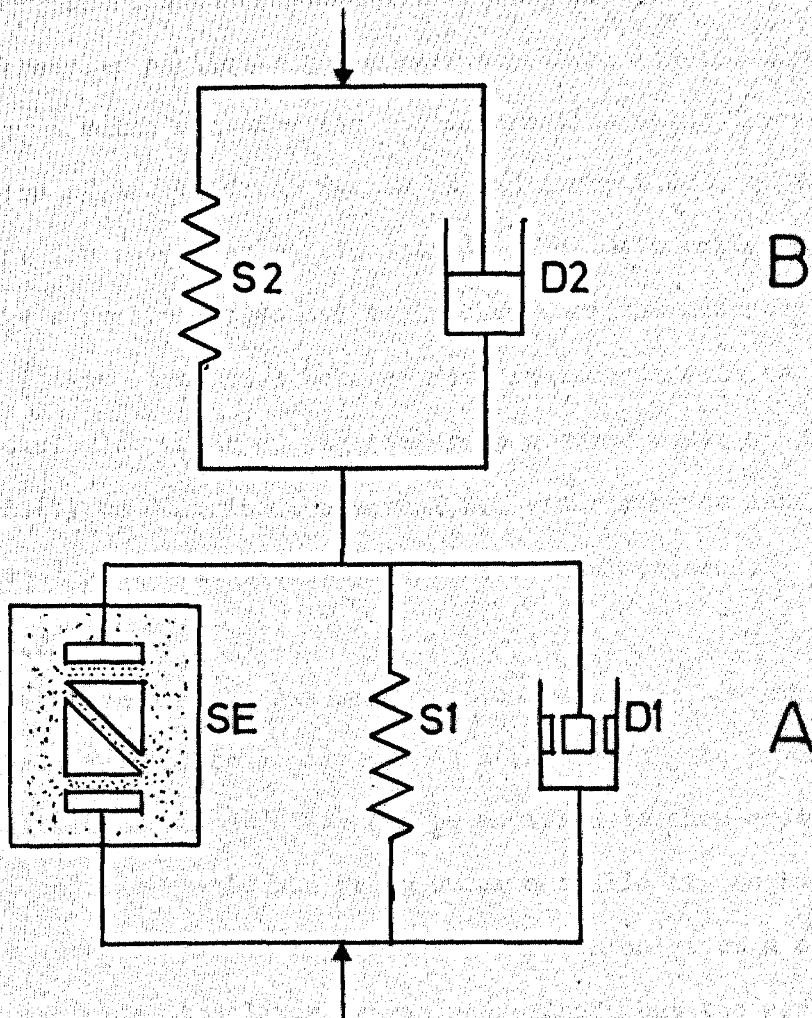

Fig. 9·8 Proposed rheological model

They are able to move relative to one another, their ability to do so depending on the structure and hence viscosity of the adsorbed layers. The spring S1 represents the gradual stabilising of the system and hence reduction in creep as particles get nearer together, and the dashpot D1 with a non return value accounts for the deformation being irreversible due to formation of new bonds. Spring S2 and dashpot D2 form a Kelvin unit to account for recoverable deformation. The deformation of part A is increased by a cyclic stress due to breakdown of the adsorbed layers.

It is felt this last model behaves most in accordance with the phenomenon actually occuring during the creep process under a cyclic stress, though its ability to describe the actual behaviour depends entirely on how it is assumed adsorbed water layers behave when stressed.

9.6 Conclusions

Assuming static creep is linearly related to stress and amplitude creep is linearly related to amplitude and mean stress, the power function relationship between creep and time can be modified to show good agreement for both creep under a static and creep under a cyclic stress in the earlier stages under load. A logarithmic expression gives a slightly better relationship for the later stages under load, but the early results must be ignored when fitting it. The power function tends to overestimate creep if extrapolated a long time beyond the measured period. The present tests suggest that the power function should not be used for extrapolation beyond about three times the measured period if this is relatively short. For extrapolation over a greater period, especially if results are available for a longer time, say a few weeks, the logarithmic expression would probably give a better approximation to later creep. If it is required to establish a stress-creep-time relationship within a measured period, the power function provides the closest fit to experimental results. Both these expressions, however, show infinite creep after infinite time under load, and since it is generally accepted that there is a limiting value to creep some form of hyperbolic expression would probably give the best indication of creep at very late stages, provided experimental results are available for a long period. Use of this expression over a short period gives a value of ultimate creep which is too small.

The application of conventional rheological models made up solely from springs and dashpots, to creep under a cyclic stress produces rather inadequate results, their behaviour under the respective stresses being incompatible. A model was suggested using these, with the addition of an electric heating mechanism to heat up the dashpot of a Kelvin model and thus reduce the fluid viscosity and increase the deformation rate. However its over all behaviour is not very satisfactory.

Using the microrheological approach, Powers sorption model was shown to have increased creep for a cyclic stress. Powers approach is an attempt to represent the actual deformatory mechanism occurring, unlike the macrorheological approach where the mechanism by which the deformation occurs is irrelevant, the model merely being a mechanical representation of a mathematical equation. In the next chapter it is suggested that particle movement, rather water movement as Powers suggests, could be the cause of the creep process and a model was suggested based on a shear slip element to represent particles sliding over one another in the adsorbed layers between them.

CHAPTER 10

CONCLUSIONS: CREEP DEFORMATIONS AND PROBABLE CREEP MECHANISMS

10.1 Introduction

Many hypotheses have been proposed by different investigators involving various combinations of behaviour of water, in its various phases, and the gel structure, to explain the creep process in hardened cement paste. It is accepted that cement paste is the principal cause of creep in concrete, the aggregate only exerting a restraining effect, though account must be taken of the aggregate-matrix interface and the possible occurence of microcracking there at high stresses contributing to creep.

An adequate explanation of the creep process has to be able to take into account all the observed experimental results. In this chapter therefore, having considered the main results and conclusions from this investigation, it is attempted to describe the effects of a cyclic stress on creep in terms of the various mechanisms and combinations thereof, which have been put forward by various investigators to explain the static creep process in cement paste and concrete. The degree of compatability between possible static mechanisms and observed behaviour under a cyclic stress will give further indication of the most likely fundamental cause of the creep process.

10.2 Environment and Shrinkage

As was mentioned earlier the specimens in these tests were in an environment of 98 to 100% R.H. No shrinkage or swelling was observed on unloaded specimens for the duration of these tests and thus creep occured under conditions of hygral equilibrium. The difference should be noted between these conditions in which moisture exchange is possible with the surrounding medium, and the sealed conditions in which no moisture exchange is possible. The internal humidity in this case is 100% whereas for the sealed condition it is rather less, depending on the age of sealing and the time after sealing. Any moisture movement that occurs for the present conditions must be stress induced.

10.3 Creep Deformations

If the mean of a cyclic stress is kept constant and the amplitude is increased in different tests, there will be an increase in creep above that occuring under a static stress equal to the mean which is proportional to amplitude for amplitudes of up to 0.3 of ultimate if also the maximum stress is less than 0.55. The ratio of this increase in creep, or amplitude creep, to the mean or static stress component of creep decreases with time. For instance for a mean stress of 0.35 and amplitude of 0.3 this ratio is 2 at 2 minutes, $1\frac{1}{2}$ at 18 minutes, $1\frac{1}{4}$ at 3 hrs., 1 at 30 hrs. and 0.8 at 200 hrs. Thus although there is an initial rapid decrease in amplitude creep from the initial high value, it still represents a significant part of the total creep at 200 hrs.

Keeping the amplitude constant and varying the mean stress for different tests, the amplitude creep is dependent on the mean stress, being greater, the greater the stress. However the ratio amplitude creep to static creep tends to become independent of mean stress at later stages, being about 0.5 at 100 hrs. for an amplitude of 0.2.

If creep rate rather than creep is considered, for a given mean stress the ratio of amplitude creep rate to static rate again increases with increasing amplitude, and also decreases with time. However for a constant amplitude and varying mean stress the amplitude creep rate tends to become independent of mean stress at later stages, and thus the ratio decreases with increase in mean stress. This difference from the creep results could be attributed to creep rate at a given time being independent of earlier high creep rate, whereas for creep this is not so. If the tests were continued over a very long period the creep results would be expected to show the same tendency.

It is questionable whether the amplitude and static components of creep rate for a cyclic stress can be considered as being additive. The evidence is that the effect of a cyclic stress is to accelerate the static creep process and it would be very unlikely that the increased creep was due to an entirely different mechanism which is simply superimposed onto the static mechanism. This being so the creep process at a given time is more advanced under a cyclic stress than under a static stress equal to the mean of the cyclic stress, and thus the true static creep rate, if the amplitude component of stress was suddenly removed would be less than that for the continuously applied static stress.

For three different cyclic stresses of mean stresses of 0.25, 0.35 and 0.45 of ultimate and amplitudes of 0.2, having applied them to specimens for 3 days and then applied static stresses equal to the corresponding mean stresses, the increase in creep over the next 3 days under the static stresses was less than the increase in creep for a continuously applied static stress over the same period. For similar stresses for the reverse order of a cyclic stress applied after a static stress the total creep tended to the same value as for the cyclic stress applied continuously over the whole period. For an amplitude of 0.4 and the two lower mean stresses, when the cyclic stress was applied second the over all creep was much less than for a continuously applied cyclic stress.

Thus pre-application of a static stress does not affect the increased creep due to a cyclic stress at an amplitude of 0.2 but it does at 0.4. The implication is therefore that an additional mechanism occurs for creep at the latter amplitude which is reduced by a previous static stress. The effect is compatible with the occurence of bond microcracks. The results for the lower amplitude, where the normal creep processes are occuring indicate that the ultimate creep for the cyclic stress is greater than that for a static stress equal to the mean stress, since the effect of applying the cyclic stress is similar to increasing the static stress, though the cyclic stress causes a much more rapid initial increase in creep. Further, if the ultimate creep was the same for a static stress as for a cyclic stress of similar mean stress, the creep time curves for different amplitudes and a given mean stress would be expected to converge, whereas such a tendency is not observed. At high amplitudes when significant microcracking does occur, the ultimate creep will obviously be greater for the cyclic stress, since for the static stress the cracking just does not occur.

If significant microcracking occurs then the increased creep due to a cyclic stress corresponding to this will be irrecoverable. However, the measurements of recovery indicate that the increased creep due to a cyclic stress is irrecoverable at all values of stress.

The difference in creep for a frequency of 586 c.p.m. and 190 c.p.m. at a mean stress of 0.35 and an amplitude of 0.2 is small, slightly less creep occuring at the lower frequency. For a frequency of 1 cycle per day the creep is similar to the creep at the higher frequency. If energy input is the governing criterion for increased creep at high frequencies, it would be expected that the increase would be frequency dependent. As this appears not to be so there must either be a maximum possible energy which is able to be absorbed by the creep process to give increased creep, the rest being dissipated as heat, or energy input is not the reason for increased creep. This latter statement is substantiated by the high creep observed for the frequency of 1 cycle per day, where energy input is very small over a given time. If the mechanism of increased creep is the same throughout the frequency range it would appear to be independent of rate of change of stress over a wide range, but very dependent on the range of variation of stress.

10.4 Other Results and Conclusions

The strength and elastic modulus increase significantly under a cyclic stress. No definitive results are available for increases in strength or modulus under a static stress and the increases for both measured in these tests varied widely. It could be expected that a cyclic stress would have caused a bigger increase in both at a given time due to the more rapid achievement of internal stability under this type of stress. The area of the hysteresis loop at a given time is less under a cyclic stress than under a static stress which gives a qualitative indication that a more rapid achievement of stability does occur for the former. It can be said quite definitely that below the fatigue limit a cyclic stress is not detrimental to either modulus or strength, and in fact often has a beneficial effect on these.

There is a rise in temperature in a specimen subjected to a cyclic stress, which is roughly proportional to amplitude. This indicates the existence of frictional damping in concrete. Maximum temperatures were 2, $3\frac{1}{2}$ and $7\frac{1}{2}$°C above ambient for amplitudes of 0.3, 0.4 and 0.5, reducing to 1, $2\frac{1}{2}$ and $3\frac{1}{2}$°C after 60 hrs. under load. The gradually decreasing temperature shows that the damping capacity is being reduced and that the concrete is tending towards elastic behaviour. The rise in temperature is insufficient to casue a significant increase in creep, compared with the other effects of a cyclic stress. Any increased creep caused by the quite high initial rise at an amplitude of 0.5 would be totally masked by the large increase in creep due to the microcracking at this amplitude.

10.5 Probable Creep Mechanisms

The principal question regarding the nature of the creep process would appear to be whether movement of water as a direct result of application of an external stress is the principal cause of creep or whether water has a passive role, only modifying the mobility of the gel particles, whose movement is the result of the applied stress, giving rise to creep. Creep in the former case can be regarded as stress induced shrinkage. In the latter case creep and shrinkage are somewhat different though again inter-related due to the relationship between shrinkage and water present.

Powers considers creep to be due to the former mechanism (41). For a given humidity water is adsorbed on the cement gel surface in a particular number of layers. Using thermodynamics he shows that if water is adsorbed in a space in the gel too narrow to accommodate the required number of layers this water will be under compression, being restrained by the surrounding gel, and thus is effectively load bearing. This so called disjoining pressure decreases with decreasing humidity explaining shrinkage. An externally applied stress causes an immediate increase in the pressure in the adsorbed water, which, if the stress is maintained, causes water molecules to move away from the stressed area by molecular diffusion, the layer becoming thinner to maintain thermodynamic equilibrium. The process does not involve transfer of stress to the solid phase. It is a reversible process and irreversible creep is accounted for by the formation of new bonds between gel particles when they become sufficiently close together.

For a cyclic stress to cause increased creep, the extra energy available or the repeated reversal of stress must somehow increase the mobility of the water molecules. In terms of Powers considerations of the nature of adsorbed water it is difficult to explain how this can occur; molecular diffusion is a slow process and could not respond to rapid reversal of stress. The increased creep due to a cyclic stress is also believed to be irreversible, and Powers theory can only account for an increase in irreversible creep via an increase in reversible creep.

The main objection to Powers' approach is in the application of thermodynamics to adsorbed water as if it was in fact bulk water. Strong evidence exists that adsorbed water is definitely structured (42) possibly upto 300Å from the surface of the adsorbate, and if this is so allowance must be made for the surface energy and number of molecules adsorbed (43). The concept of a disjoining pressure to maintain thermodynamic equilbrium then becomes unnecessary. Feldman and Sereda (43) point this out and also that surface area calculations of cement gel based on water sorption measurements will be in error due to the existence of inter-layer hydrate water. Englert and Wittman (44) confirm this and demonstrate the existence of this hydrate water using DTA measurements. The adsorption of water into this phase causes a change in the structure of the cement gel and hence a change in its volume and surface area. Water sorption measurements give values of about 200 m^2/gm for the surface area whereas nitrogen sorption measurements give about 30 m^2/gm. According to Feldman and Sereda (43) this interlayer water is responsible for a large part of the hysteresis of the length change sorption isotherm. As was pointed out by Englert and Wittman (44) there is need for a careful analysis of the distribution of water into the various phases before particular properties are assigned to it and before its fundamental contribution to the creep process can be fully understood.

According to Feldman and Sereda shrinkage is due at high humidities to increasing surface tension forces with decreasing humidity, at intermediate humidities due to increasing solid surface energy as the adsorbed layers are reduced in thickness (hence increasing Van der Waals attraction) and at low humidities due to removal of the hydrate water. Reversible creep is due to slow decomposition of the hydrate layers and liberation of water. Irreversible creep is due to the breaking and remaking in new positions of interparticle bonds. The latter is considered possible since the strength of a paste compacted after bottle hydration is the same as one made in the usual way. The bonds are therefore mechanical and fairly weak rather than chemical. There is no adsorbed water at the inter-particle boundaries.

Application of a cyclic stress could cause increased destruction of bonds due to the energy available. This would cause an initial rapid increase in irreversible creep which would soon be reduced as particles stabilised in new positions. As more particles are now in a stable position there are more possibilities for the formation of new bonds. The reversible creep which is a slow diffusion type process would not apparently be affected by a cyclic stress. Possibly the hydrate structure breaks down more quickly due to the repeated reversal of stress though this does not seem likely since the stress on the hydrate layers is small. Irreversible creep and irreversible shrinkage are, according to this theory the result of different mechanisms. There appears to be a contradiction in that loss of water from the hydrate layer is supposed to cause irreversible shrinkage whereas this mechanism is responsible for reversible creep.

Ishai (45) also considers the structure of hydrated cement to be dominated by the layered tobermorite crystals, but that there is also a solid matrix made up of partially hydrated cement grains joined by crystalline bonds. Adsorbed water is considered to be of three types depending on the width of the space in which it is adsorbed, plus zeolitic water one molecular layer thick which is part chemically combined. At high humidities shrinkage is due to surface tension forces which cause an isotropic compressive stress and thus an elastic volumetric contraction, and also a time dependent one due to a reduction in energy level of the gel by squeezing out of water from the narrow adsorbed layers. At lower humidities molecules depart from the adsorbed layers and at very low humidities from the zeolitic layers. Reduction in energy level of the system is irreversible and so is removal of zeolitic water due, according to Ishai, to spontaneous closing of vacated spaces.

Application of an external stress causes an immediate elastic response of the matrix and liquid phase. The stress in the liquid phase is then dissipated first from the capillary water to the surrounding gel. The stress in the gel pore water then eventually dissappears. The stress on the inter and intra-crystalline water continues to act indefinitely. Thus, according to Ishai, creep results in a gradual transfer of stress from the liquid to the solid phases, which Powers (41) says is not the case. Reversible creep is due purely to viscous flow of the gel-pore and capillary water. Irreversible creep is due to reduction of interparticle distances due to the diffusion of water molecules out of the inter and intra-crystalline adsorbed layers.

Since reversible creep is attributed to a purely viscous process a cyclic stress could have no effect on this. Since irreversible creep is attributed to a slow diffusion process it is hard to see how a cyclic stress can have an effect on this. The increased energy input may in some way contribute to a more rapid reduction of the energy level of the system, though the mechanism by which this could occur is not clear. The ultimate creep, according to Ishai, corresponds to the elastic deformation of the solid matrix. This would therefore be no greater for a cyclic stress than for a static stress equal to the mean of a cyclic stress, whereas it has been shown previously that this is not true. The initial high rate of creep due to a cyclic stress cannot be accounted for, since the irreversible creep process is very slow, and the reversible process is unaffected by a cyclic stress.

There are several objections to hypotheses which attribute creep to being a direct results of the viscous flow of water. Creep with simultaneous drying is very much increased over creep in hygral equilbrium, whereas the previous theories would suggest shrinkage and creep are additive. Creep in tension with simultaneous shrinkage should be reduced, since the directions of flow oppose one another, whereas in fact creep in tension is increased. Wittman (29) showed that the macroscopic activation energy for the creep process is 5,000 times bigger than that of water which makes it unlikely that creep is due to movement of single molecules of either water or gel. The relationship between the micro and macroscopic activation energy indicates that several thousand molecules, which could therefore be gel particles move together in the creep process. The use of activation energy equations to explain the creep process was discussed in detail in Chapter 8. A significant point in favour of this approach is that it is possible to produce equations for the creep process based on theoretical analysis.

Ruetz (46) states that there is always a layer of water between the points of contact of gel particles. This layer will be oriented or exhibit structure, depending on the thickness, and this is quite capable of taking static stress. Shrinkage is due to the reduction in thickness of these layers by evaporation. Also as the thickness of the adsorbed layer is reduced the surface energy of the gel particles is increased which causes the particles to contract and Van der Waals forces to increase. Though the layer is structured there is high surface mobility of the water molecules, the degree of mobility depending on the surface energy of the gel particles. Under the influence of an externally applied stress the gel particles slide relative to one another in this layer thus giving rise to creep. Obviously the higher the humidity the more freely are the gel particles are able to move and the greater the creep.

Creep is thus a pure shear process, the fact that the volume shows an overall decrease being explained by a reduction of space within the gel. To explain the high creep under conditions of drying Ruetz says that the continuous change of the structured adsorbed water prevents it achieving the stability it could have under static conditions and consequently the layer has increased mobility, allowing the particles to slide more freely over one another. If a cyclic stress is now considered this will cause a continous change in stress in the adsorbed layers irrespective of humidity. The effect on the adsorbed layers is thus similar to that of drying, a continuous change of state being imposed on them destroying their order. (It should be pointed out here that though the adsorbed layers are structured they are not a true solid and a continous process of exchange of molecules occurs with the surroundings.) Creep is thus increased in a manner similar to the increase in creep under conditions of drying. Even a slowly varying stress would disturb the structure of the adsorbed layers which may explain the small effect of frequency. The high initial creep for a static stress could also be due to the initial disturbance of these layers. Also the increase in creep for a cyclic stress could be expected to be greatest in the early stages when the gel particles are in relatively unstable positions.

The above mechanism can only account for irreversible creep, (which is the component that is believed to be significantly affected by a cyclic stress), since the process involves a reduction in energy level of the system. Reversible creep could be due to partial transfer of stress to a solid framework, which is relieved on unloading.

The solid framework would consist of gel particles which are sufficiently rigidly inter-connected as to be unable to move relative to one another. The bonds may or may not have water present in them. In concrete the aggregate will increase the rigidity of this framework.

The much increased creep at high amplitudes (0.4 and above) has been attributed to an increase in the occurence of microcracking. The effect of amplitude on cracking also depends on the ability of the mean stress itself to initiate cracks. Raju (11) showed that axial fatigue failure was a result of the propagtion of microcracks initiated probably at the matrix aggregate interface. Pulse velocity and lateral strain measurements suggested the direction of propagation was parallel to the load, and there was an accompanying decrease in elastic modulus. Fatigue failure occured for an amplitude of 0.6 and mean stress of 0.35 in the present tests. A large decrease in modulus occured and the creep poisson's ratio exceeded unity showing the existence of load oriented microcracking. At the same mean stress and an amplitude of 0.5 there was an initial decrease in modulus of 10% before it started to increase suggesting the occurrence of load oriented cracking. At an amplitude of 0.4 there was also a small decrease. The creep rate at 6 minutes for the amplitude of 0.5 was over 10 times the static rate compared with 2.4 times for the 0.4 amplitude. At 100 hrs. it was twice the static rate for the former and $1\frac{1}{2}$ times for the latter. This further indicates that an additional process is occuring at the former amplitude, which is predominant in the early stages. The energy requirements for a crack to propagate increase rapidly as the length increases, and thus if the energy available is insufficient to cause failure, propagation will rapidly decrease, which is in accordance with the observed results for rapid decrease of creep rate. At 1 hour for the 0.5 amplitude microcracking is responsible for approximately half of the observed creep and at 100 hrs. for one third.

Microcracking causes a significant increase in creep for a static stress only at stresses greater than 0.5 of ultimate. The increased energy available from a cyclic stress enables load oriented crack propagation to occur at a mean stress of 0.35 and amplitude of 0.5 and there is much increased creep due to lateral dilatation of the specimen. The ability of microcracks to propagate is very sensitive to amplitude. At an amplitude of 0.4 and mean stress of 0.35 there was little evidence of crack propagation, whereas at an amplitude of 0.5 microcracking was responsible for a great increase in creep, and at an amplitude of 0.6, fatigue failure occurred. At a higher mean stress microcracking and hence creep due to this would occur at a lower amplitude because of the reduced energy requirements for propagation from the amplitude component of stress.

10.6 Conclusions

The increased creep of concrete subjected to a cyclic stress is the result of an acceleration of the creep processes occurring under a static stress. That this is so rather than creep due to a cyclic stress being attributable to a different mechanism is borne out by the interdependence of the static and amplitude components of creep, and by the similarity in behaviour of the modulus, strength and hysteresis loop area with time between the two stress types. The cyclic stress increases the rate at which stability of the internal structure is achieved.

Though a cyclic stress was said earlier only to accelerate the creep process and thus the rate of achievement of greatest stability it cannot be said that the ultimate creep for a given mean stress is the same as the ultimate creep of a similar static stress. This is because the accelerating process of a cyclic stress opens up more possibilities for the occurence of an event such as the movement of a gel particle to a more stable position which would increase creep in the same way as an increase in static stress would. There are, therefore, two types of effect of a cyclic stress. One is to accelerate the processes that are occuring for the given static stress and the other is to enable processes to occur that could not have occured under the particular static stress alone.

Referring to the various mechanisms for creep that have been discussed, it is possible to account for the accelerative effect of a cyclic stress with varying degrees of success. The main argument about the mechanism of creep would seem to centre on whether movement of water directly results in creep or whether the existence of water merely modifies the mobility of the gel particles.

Considering creep to be due entirely to water movement, if this was by viscous flow this would be unaffected by a cyclic stress. If the movement is due to some form of diffusion process of water molecules out of inter particle spaces, it seems possible that this may be accelerated by a cyclic stress, though the mechanism by which this could occur is not clear. A diffusion process is very slow though and could not account for the initial high rate of creep under a cyclic stress.

Creep being due to movement of gel particles is explained by them sliding over one another at their points of contact, which are covered with a film of adsorbed water. The adsorbed layers are highly structured, but application of a cyclic stress could cause a breakdown in these layers due to the varying stress on them, and in consequence the particles would be able to move more freely relative to one another. The increased creep thus occuring would be highest immediately after loading due to the initial instability of the particles. The value of the activation energy of the creep process supports the hypothesis that creep is due to movement of gel particles rather than molecules of either water or gel.

To explain creep under a cyclic stress therefore, it seems probable that the process must involve the movement of gel particles relative to one another. However, in discussing the mechanism by which this movement occurs, or is increased properties have been attributed to the behaviour and structure of the cement gel-water system which are by no means firmly established. There is a general tendency, for all the mechanisms and hypotheses that have been considered, to attribute the appropriate properties to the system which will enable the deformational mechanism to be explained. Probably the situation can only be resolved by a detailed fundamental analysis of the structure of cement and the associated phases of adsorbed water, and their behaviour under stress. Only then will it be possible to offer a quantative explanation of creep behaviour under the various conditions of stress and environment in terms of the fundamental structure of cement paste or concrete.

CHAPTER 11

SUMMARY OF CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

11.1 Summary of Conclusions

A cyclic stress causes increased creep over a static stress equal to the mean stress due to an acceleration of the static creep processes. The influence of a cyclic stress decreases with time, creep at a mean stress of 0.35 and an amplitude of 0.3 being three times the creep for a static stress of 0.35 at 2 minutes and twice it at 200 hrs. The ultimate creep is however greater for a cyclic stress than the corresponding static stress.

The ratio between the increase in creep for a cyclic stress and the creep at the corresponding static stress is independent of mean stress and proportional to amplitude for amplitudes of less than 0.4 and a maximum stress of less than 0.55. Using this, creep over short finite time intervals can be expressed in terms of mean stress, amplitude and time as a power function of time, the exponent being $\frac{1}{3}$. For time intervals excluding the early part, and when extrapolation for a large time interval beyond the measured time interval is required, a logarithmic relationship between creep and time shows less tendency to overestimate creep.

The increase in creep in the relatively linear stress ranges can be explained in terms of the stress reversals disturbing the structure of the adsorbed water layers causing increased mobility of the gel particles. It is thought this effect may be little affected by frequency which would explain the small difference in creep for frequencies of 2 cycles per day 190 c.p.m. and 586 c.p.m.

The activation energy of the creep process was found to agree closely with values obtained by other investigators, which further indicates that movement of gel particles is the cause of the creep process. The activation energy equation can be modified to account for the effects of a cyclic stress, and the results from static and cyclic stress considerations were found to be compatible. There was also evidence from the activation energy theory, that stress transfer occurs from the mobile to a solid phase; perhaps cement paste to aggregate.

For high amplitudes there is a large increase in creep due to load oriented microcracking. One third of the 100 hr. creep for an amplitude of 0.5 and mean stress of 0.35 was due to microcracking. The amplitude at which microcracking occurs significantly depends on the mean stress, but it is not significant at working stresses.

A rise in temperature of the order of 3°C for an amplitude of 0.4 and which is roughly proportional to amplitude but independent of mean stress, occurs for a cyclic stress. The temperature gradually decreases with time indicating a tendency towards elastic behaviour of the concrete. The strength increased by upto 30% and the elastic modulus by upto 12% showing a tendency towards internal stability of the concrete structure. The area of the hysteresis loop decreased more rapidly for a cyclic stress than for a static stress, showing the more rapid tendency to this stability under a cyclic stress.

For stresses below which failure does not occur, a cyclic stress will not have a detrimental effect on either strength or modulus, and usually the effect will be to cause these to increase significantly.

Considerably increased creep occurs under a cyclic stress. This is principally in the first few hours under load, especially if microcracking occurs to a significant extent, but the ultimate creep will be greater for a cyclic stress than the corresponding static stress.

11.2 Suggestions for Further Research

1. This investigation was restricted to one mix and one set of environmental conditions. It would be advantageous to establish whether the same relative increase in creep occurs independent of these parameters.
2. The increased creep has been attributed to a disturbance of the adsorbed water layers. Under conditions of drying these are already disturbed and further light may be thrown on whether this is in fact the mechanism of action of a cyclic stress by whether drying creep is increased by a cyclic stress.
3. The increase in creep appears to be independent of frequency. A more intensive investigation into the effects of frequency for different stresses and over a very wide frequency range is required to establish to what extent this is in fact true, and to try and find out if there is a critical frequency where creep tends towards the value that would occur under a static stress equal to the mean.

4. At high amplitudes microcracking causes a significant increase in creep. It would be useful to establish all the combinations of amplitude and mean stress at which cracking starts to occur, and also more precisely the contribution of microcracking to creep, and the relationship between creep and fatigue. This may also give some more information on the ultimate strain concept of concrete failure.

5. Accurate measurement of the rise in temperature may give results relating creep to damping capacity and area of the hysteresis loop.

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APPENDIX

TABLE A1

COMPOSITION OF CEMENT

Oxide	Content (%)
C_aO	63.80
S_iO_2	19.47
Al_2O_3	7.65
Fe_2O_3	2.65
SO_3	2.34
MgO	1.11
K_2O	0.47
Na_2O	0.16
Loss on ignition	1.21
Insoluble residue	1.10

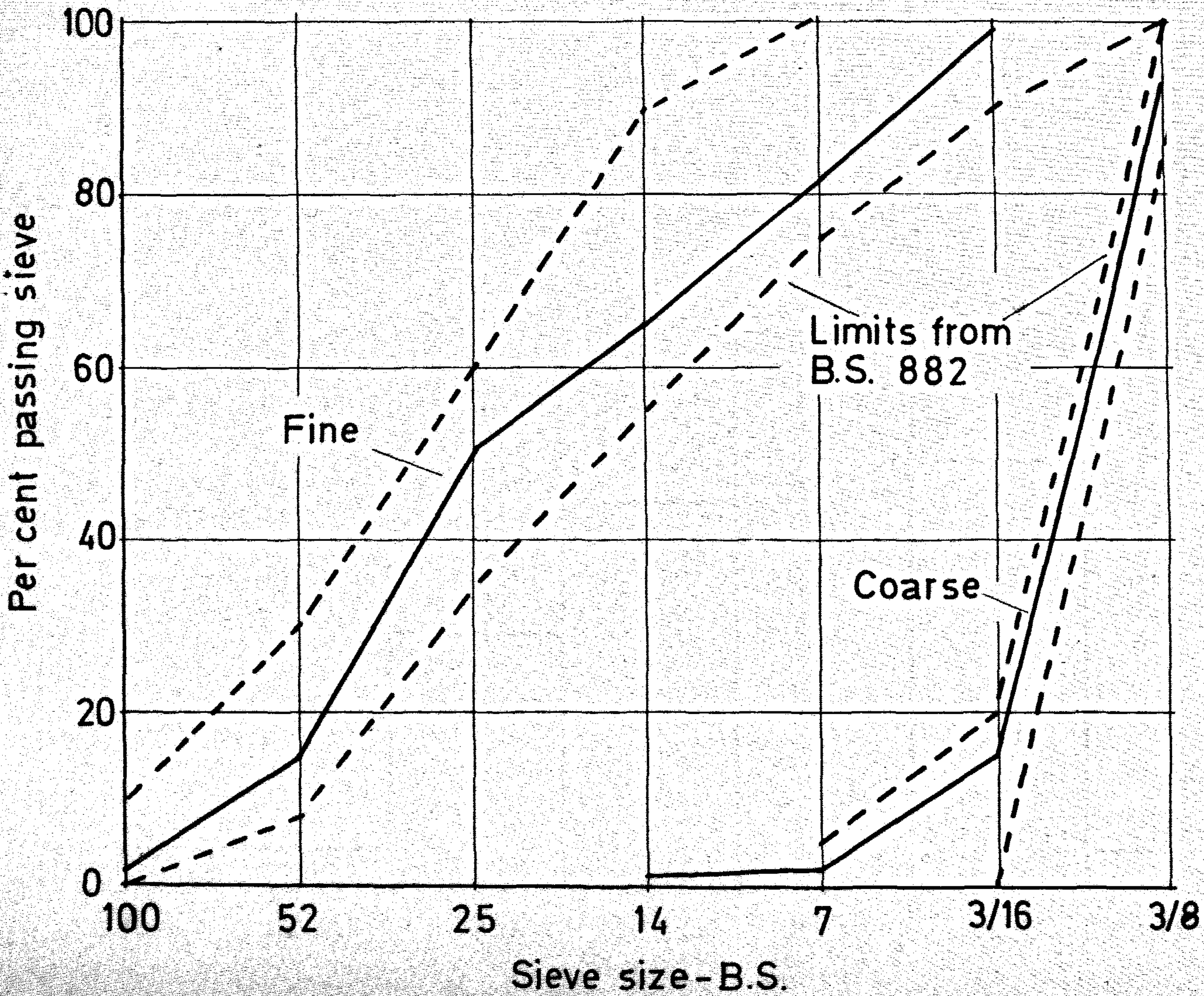

Fig. A1 Aggregate grading curves

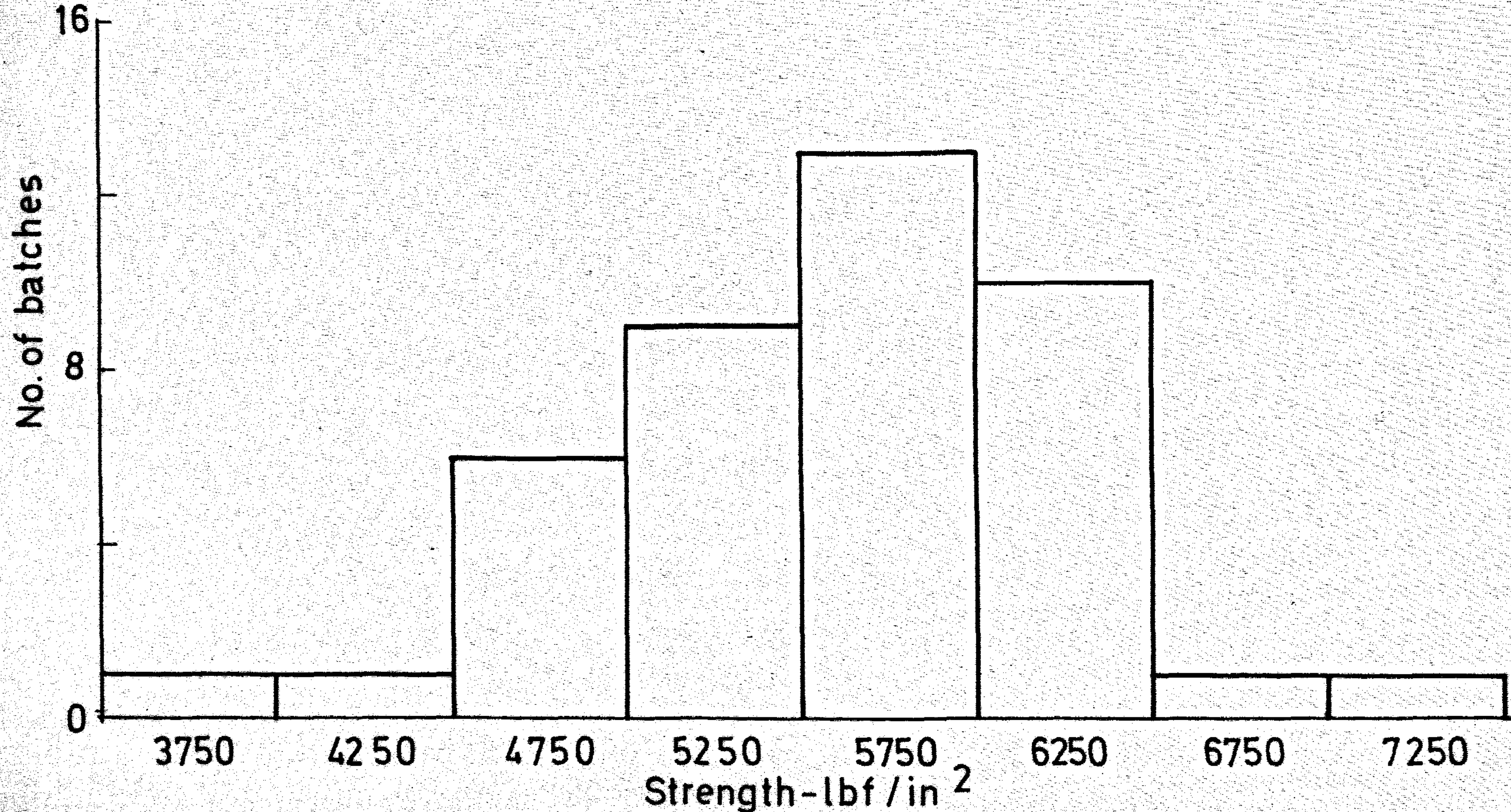

Fig. A2 Histogram of prism batch strength