JOURNAL OF MATERIALS SCIENCE 17 (1982) 2037–2046

The weather and its influence on the creep of glass fibre-reinforced cement composites

H. G. ALLEN, C. K. JOLLY
Department of Civil Engineering, University of Southampton, Southampton, UK

This paper describes an unusual programme of long-term creep tests on glass-fibre reinforced cement (GRC) boards. The specimens were mounted out-of-doors and loaded in tension. The deformations were monitored continuously by means of special weather-proof extensometers. The recording system is shown to operate in a reliable and consistent manner. The effects of weather and of stress can be separated by comparing the responses of stressed and unstressed specimens. Humidity variations have a dominant effect on the results, but a numerical relationship between humidity and strain remains to be found. Stress causes strains which follow well-defined creep curves once the effects of weather have been allowed for. The experiments are continuing.

1. Introduction

In a recent paper [1] one of the authors described the results of a three-year programme of creep tests carried out on glass fibre-reinforced cement (GRC) specimens. Those tests were conducted in air-conditioned rooms in which the temperature and the relative humidity were controlled. It was observed that most of the creep deformation occurred in the first year and that creep strains were very large when the applied stress was close to the point where the ordinary stress–strain curve changes from steep to shallow. At such stresses there was a risk of premature failure.

In those earlier tests some of the specimens were kept in humid conditions. Although this had no consistent effect on the creep deformations, it did cause the specimens to display a marked degree of embrittlement when, at the end of the investigation, they were removed from the creep machines and tested to destruction in the laboratory. Supplementary tests showed that the extensional deformations (i.e. the strains) caused by switching from dry to humid conditions (or vice versa) were larger than most of the creep strains recorded.

It is clear that the deformation of GRC panels in service depends at least as much on the humidity of the atmosphere as it does on the stress level. Moreover there is a possibility that stress and humidity changes may interact to influence the durability and dimensional stability of the material.

These considerations led the authors, with the support of the Building Research Station, to commence a new and rather unusual long-term creep testing programme. In these tests the specimens of GRC are again loaded in tension, but the strains are monitored automatically and are processed by a computer. The unusual aspect of the investigation lies in the fact that all of the specimens, the creep-loading machines and the extensometers are located out-of-doors, exposed to all the normal fluctuations of the weather, from hour to hour and from season to season. In this way a unique record has been obtained of the effect of natural changes in temperature and humidity on the behaviour of specimens under load.

This paper describes the tests and presents some of the earlier results. Some measurements are continuing at the time of writing; these later results will be presented in a subsequent paper.

2. Materials

The test pieces were cut from boards about 10 mm thick. These boards were manufactured at the Building Research Station by the spray-suction technique. Some boards used a cement paste matrix; others used a mortar matrix (i.e. they included sand).

The boards discussed in this report were labelled MT and MV. Board MT was cast on 12 July 1977, using a neat Porland cement matrix with Cemfil 630 fibres chopped to 32 mm. The initial water–cement ratio was 0.47; the final value, after extracting surplus water by suction, was 0.28. The glass content of the de-watered board was 5.15 wt %.

Board MV was cast on 14 July 1977; it differed from the other board in that the matrix consisted of a mixture of Portland cement (70 wt %) and Leighton Buzzard sand which passed a 3.2 mm sieve. Otherwise the differences were small. The water–cement ratio was 0.47 initially, 0.29 finally. The water–solids ratio was 0.33 initially, 0.20 finally. The glass content of the de-watered board was 4.92 wt %. The glass fibres were the same as those in board MT.

The normal curing process involved keeping the material damp at ambient temperature for 28 days but, in addition to this, parts of each board were subjected to an accelerated ageing process by immersion in water at 50° C for 50 days.

Fig. 1 shows how the boards were cut for the preparation of test specimens. Each narrow strip provided two rectangular specimens (25 mm wide) for tensile testing in the laboratory. Each of the wider strips provided a single large dumbell specimen (38 mm wide at the waist) for creep testing.

3. Apparatus

The creep-testing machines are improved versions of the ones used in the test programme reported previously. Fig. 2 shows the construction of a typical machine, in which load is applied to the specimen by a lever and deadweights. A specially-built extensometer is displayed in Fig. 3. The design is based on a parallel-motion linkage which has been used in the laboratory with great success for many years. It has the advantage that there are no knife-edges or hinges requiring extremely precise workmanship. The extension of the specimen is detected by a linear variable displacement transducer (LVDT). The linkage is designed to ensure that the LVDT measures true changes of the distance between the gauge points, even though it does not lie on the axis of the specimen. Fig. 4 shows the test site, with a total of 16 machines located on the roof of a building of medium height in Southampton. The cables from the transducers are taken indoors to a Schlumberger 24-channel a.c. signal conditioning device. The output from this is monitored by a Mycalex 30-channel data logger, which records the results on punched paper tape. In general strains are recorded at hourly intervals, but much more frequent readings were taken in the period following the moment of application of load to a specimen. All of the information on the paper tape is transferred to magnetic discs, where it is available for processing by computer.

Some of the extensometers are mounted on "control" specimens, i.e. on GRC samples which were cut from the boards in the normal way, but which are free of all stress. Two of the extensometers are mounted on stress-free Invar bars, which have a negligible co-efficient of expansion. This was done in order to monitor the effects of

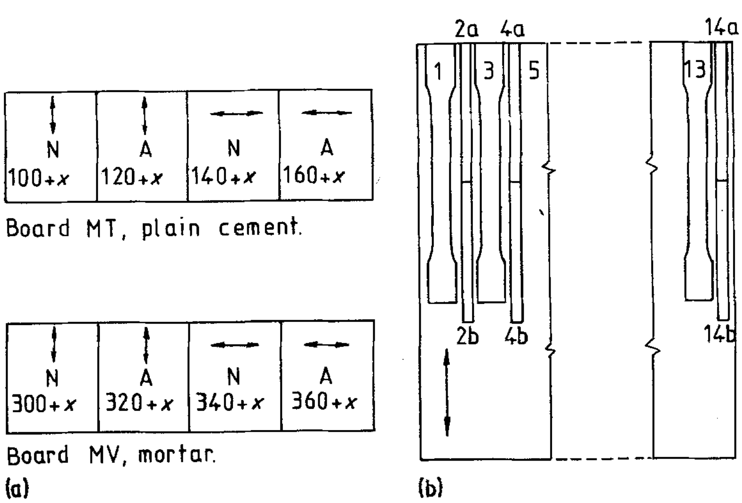

Figure 1 Showing the arrangement and numbering of specimens: arrows show direction of load, N = normal cure, A = accelerated cure, the numbers indicate the specimens from a typical panel, showing the values of *X*.

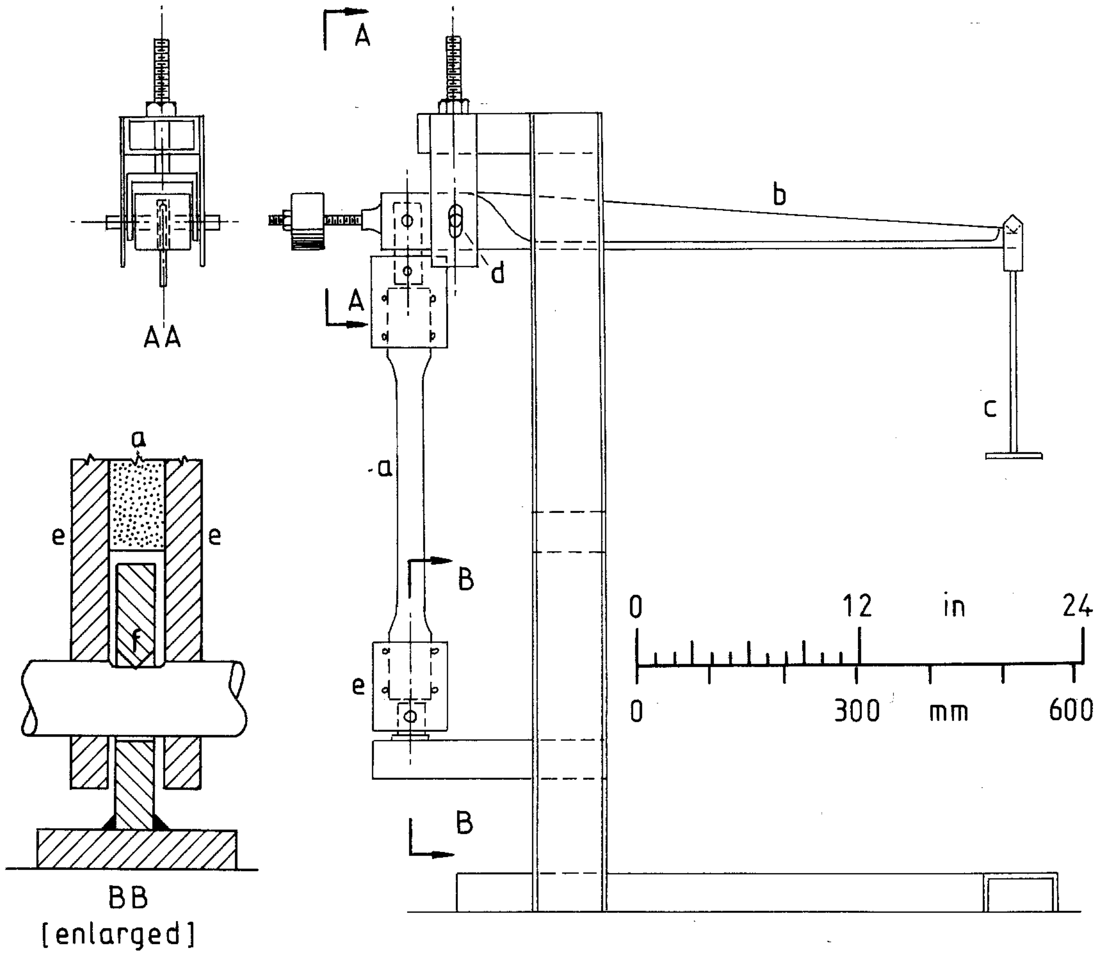

Figure 2 The creep loading machine showing (a) test specimen, (b) lever, (c) hanger for weights, (d) fulcrum adjustable for height (roller bearings), (e) clamping plates and (f) knife-edge bearing on accurately centred notch on pin.

temperature changes on the extensometer, the transducer and the cables. Finally, two recording channels are allocated to temperature-sensing devices, one of which is shrouded with a damp wick. In this way wet and dry temperature are recorded, from which the relative humidity can be calculated.

Strains can be measured to an accuracy of about $\pm 1 \times 10^{-6}$.

4. Original properties of the boards

Before the creep tests were started, five groups of narrow specimens were tested in tension in the laboratory in order to establish the characteristics of the boards. Each group was intended to include fourteen specimens. The mean results for each group are given in Table 1.

Some of the boards supplied showed signs of cracking when they were unpacked from their wooden crates; it is not possible to say whether this was caused by the curing process or by handling. These cracked panels were not tested. The panels that were tested seemed rather brittle, as the figures for the ultimate strain (ϵ_u) in Table I show. The last row in the table represents an extreme case in which eight specimens from the batch were too brittle to machine, leaving only six to be tested. Because of these results it was decided not to test the duplicate panels MU and MW. Instead, arrangements were made for the Building Research Station to prepare a fresh pair of panels (A11 and A12) in order to carry out confirmatory tests. The results of these tests will be given in a later paper.

Some typical stress–strain curves are depicted in Fig. 5.

5. Presentation of results of long-term tests

In general the results are presented with the

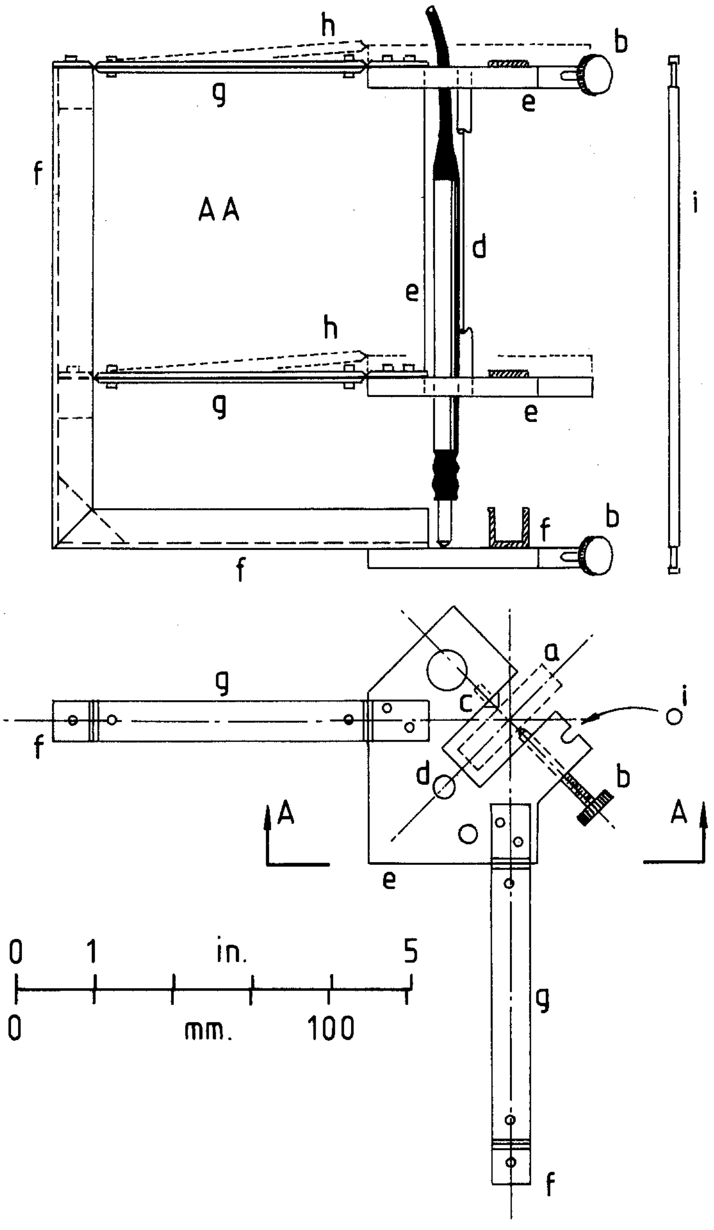

Figure 3 The extensometer showing (a) position of specimen, (b) clamping screws, (c) point adapted to suit thickness of specimen, (d) linear variable displacement transducer (LVDT), (e) rigid inner frame, (f) rigid outer frame, (g) connecting arms, (h) broken lines which show movement of inner frame in relation to outer frame and (i) removable bar to set gauge length.

time scale running horizontally. Two time scales are given. One, in hours, provides a convenient relative measure of time. The other, in days, shows the time which has passed since an arbitrary starting point, which is noon on 31 December 1977. This absolute time scale is essential if events in the records are to be related to changes in the weather patterns, and if comparisons are to be made between tests which started at different times. (It is useful to remember that 1000 hours is almost six weeks).

The vertical scales represent strain (in units of 10^{-6}) or temperature (°C) or relative humidity (per cent) as may be appropriate. Positive values of strain represent an extension. Each specimen tested is identified by a number, which allows it to be identified in Fig. 1.

6. Temperature, humidity and their effect on the recording system

Fig. 6a shows the unshaded surface temperatures recorded by the "dry" sensing device. There is a seasonal variation from about 20° C in mid August to about 2° C in January, with frequent fluctations of ± 10 degrees superimposed on the overall trend. The signal from the extensometer mounted on the

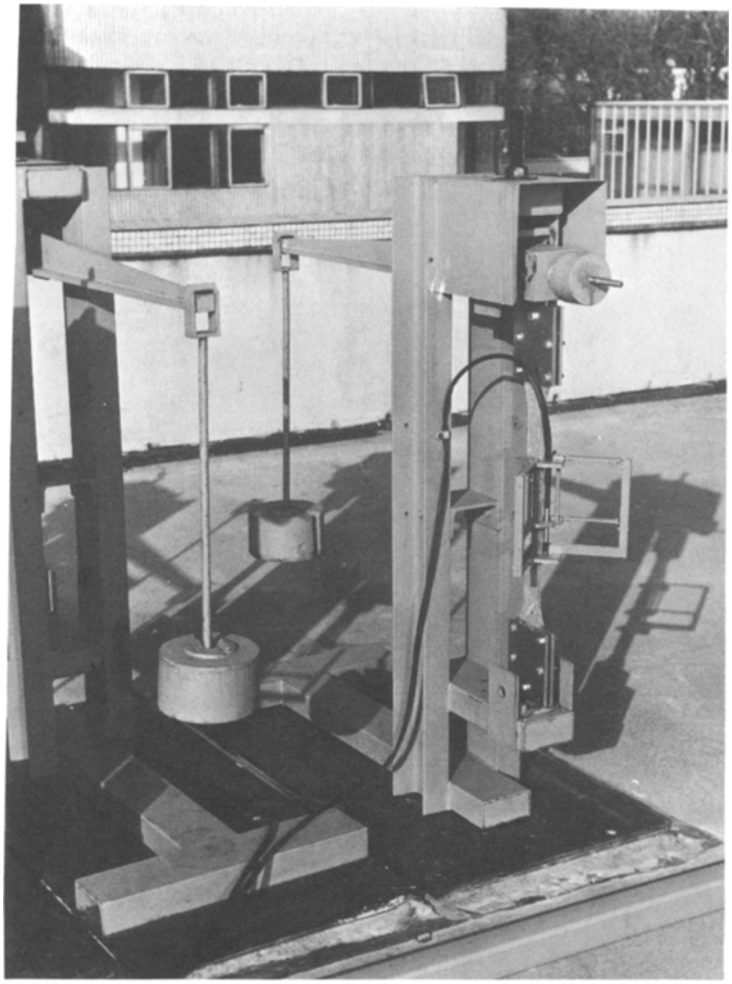

Figure 4 Creep loading machine in position at test site.

stress-free Invar bar No. 2 is shown in Fig. 6b. This signal represents the spurious strain indicated by the extensometer as it expands and contracts with changes of temperature. It includes any effect which temperature changes may have on the transducer and the cable. The seasonal effect of temperature is apparent, with a signal varying between about -200 microstrain in Mid-August and about $+100$ in January. These variations are sufficiently large to make it essential to compensate for them in the interpretation of the later creep results.

A plot of temperature against the "strain" readings from the extensometer on the Invar bar reveals a very strongly linear relationship of the form $\epsilon = (105.84 - 15.185T) \times 10^{-6}$ where the temperature, T, is in degrees Celsius. When used to calculate Invar "strains" from the recorded temperatures, this relationship has a standard error of estimate of 15.55. In effect this means that the

TABLE I Results of preliminary laboratory tests, showing mean values of tensile strength, σ_u, strain at failure, ϵ_u, and Young's modulus, E. All tests carried out in 1978.

Board	Specimens	Matrix	Alignment	Cure	Date of test	σ_u (N mm^{-2})	ϵ_u ($\times 10^{-6}$)	E (N mm^{-2})
MT	102a, b to 114a, b	Cement	Transverse	Normal	Feb.	6.86	1020	22 600
MT	122a, b to 134a, b	Cement	Transverse	Accelerated	Feb.	2.46	440	25 300
MT	142a, b to 154a, b	Cement	Longitudinal	Normal	June	8.62	870	35 900
MV	302a, b to 314a, b	Mortar	Transverse	Normal	Feb.	7.46	820	27 600
MV	322a, b to 334a, b	Mortar	Transverse	Accelerated	Feb.	2.25	110	See text

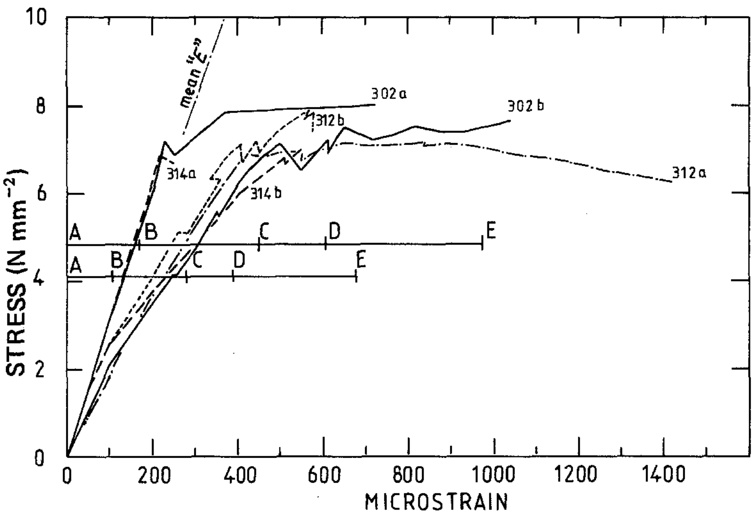

Figure 5 Stress–strain curves from laboratory tests compared with corrected strains measured on creep Specimens 301 and 313 showing AB; Strain at zero hours, AC; Strain at 500 hours (3 weeks), AD; Strain at 1000 hours (6 weeks), and AE; Strain at 8018 hours (48 weeks). Time is measured here from the instant of application of load. The specimens are unbroken at E.

equation quoted can predict the strain for 68% of readings if a tolerance of ± 1° C is allowed for the value of T.

In Fig. 7c this transformation has been applied to a typical segment of the temperature curve, and it has been plotted to an enlarged time scale. Superimposed on it is the corresponding part of Fig. 6b. The close correspondence between the two curves demonstrates the efficiency of the recording system. Incidentally the graph in Fig. 7a also illustrates the daily temperature cycle.

The relative humidity (r.h.) (Fig. 6c) is generally very high. A mean curve drawn through the plotted points varies from about 65% in June to 95% in December. Moreover the r.h. commonly rises to 100% at night or at times during the day, except during May, June and July. When it rains, the r.h. at the surface of the wet specimens is

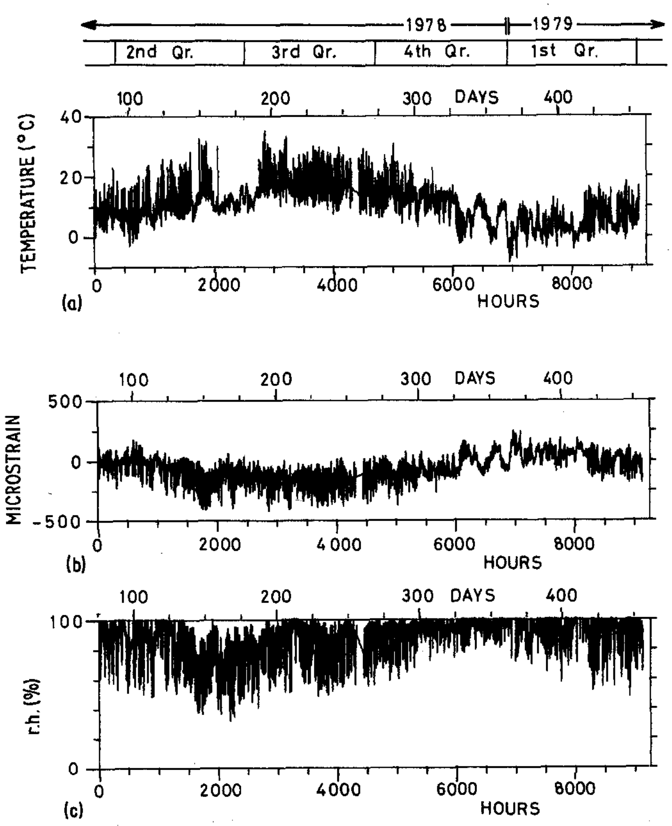

Figure 6 Basic data showing (a) "dry" surface temperatures, (b) "strains" recorded by extensometer on unstressed Invar bar and (c) relative humidity. For an explanation of the time scales, see Section 5.

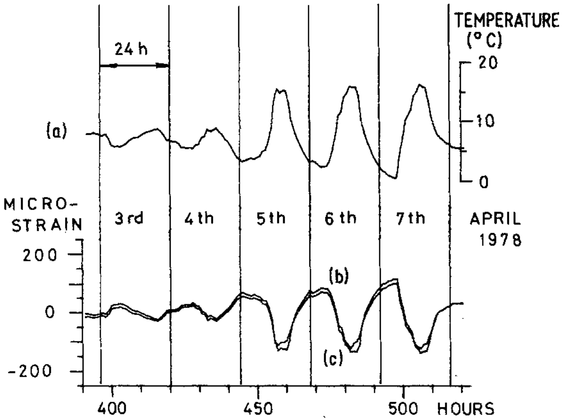

Figure 7 Response of the extensometer to variations of temperature showing (a) portion of record of "dry" surface temperature (from Fig. 6a) (b) "strains" recorded by extensometer on unstressed Invar bar (from Fig. 6b) and (c) response of extensometer, as calculated from Curve a, using the equation in the text. The vertical lines indicate midnight.

taken as 100%. The lowest r.h. levels (around 35%) are reached only rarely. The results confirm the generally-held view of the dampness of the English climate; this dampness needs to be remembered when the long-term properties of GRC are being assessed.

7. Effects of weather on stress-free GRC specimens.

Fig. 8a shows the readings from the extensometers mounted on two specimens (307 and 309) taken from board MV. These "control specimens" were free of all stress. The results are expressed in terms of "strain"; they include the true strain of the specimen (extension divided by gauge length), caused by changes in temperature and humidity and also the influence of temperature on the extensometer. Assuming that temperature changes affect all extensometers equally, it seems reasonable to subtract the readings of the Invar bar (Fig. 6b) from the mean of those of the control specimens (Fig. 8a). The result is displayed in Fig. 8b. This demonstrates the effect of the weather on the stress-free material. The steep increase in strain in the first 500 hours or so (3 weeks) is caused by the fact that the specimens had previously been stored in the laboratory in much drier conditions. It agrees quite well with the results of laboratory tests in the earlier investigations (see earlier footnote) which showed that a change from dry to damp conditions can cause positive strains of up to 1400×10^{-6}, of which the greater part occurs in the first 500 hours.

The seasonal movement of the control specimens can easily be seen in Fig. 8b, where (apart from local variations) the range of strain is about 500×10^{-6}, with lowest values in June and September and the highest ones in January, February and March.

The daily movement of the control specimens can be seen in Fig. 9c, which shows a small part of Fig. 8b to a greatly expanded time scale. Fig. 9a

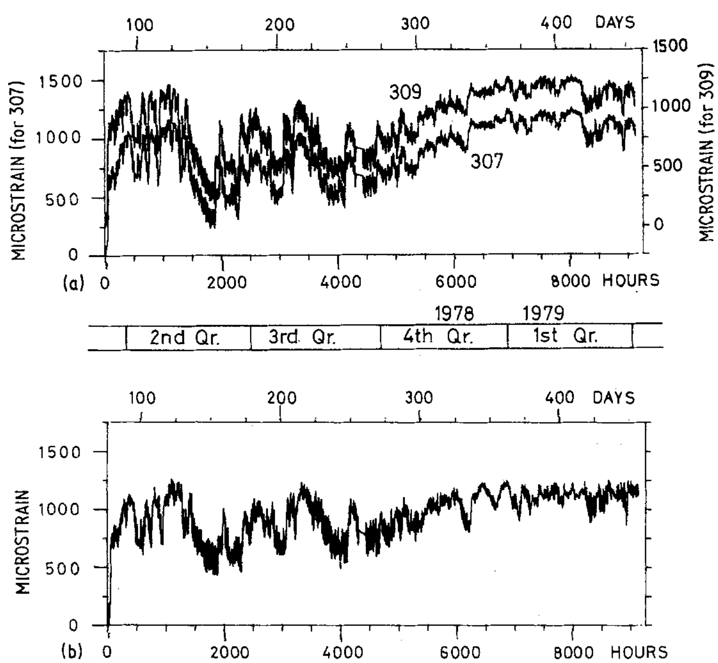

Figure 8 Strains recorded on control specimens showing (a) strains actually recorded on unstressed control specimens, and (b) the mean of the two curves in a, *minus* the "strains" recorded on the Invar bar, Fig. 6b. This curve indicates the true effect of the weather on the control specimens.

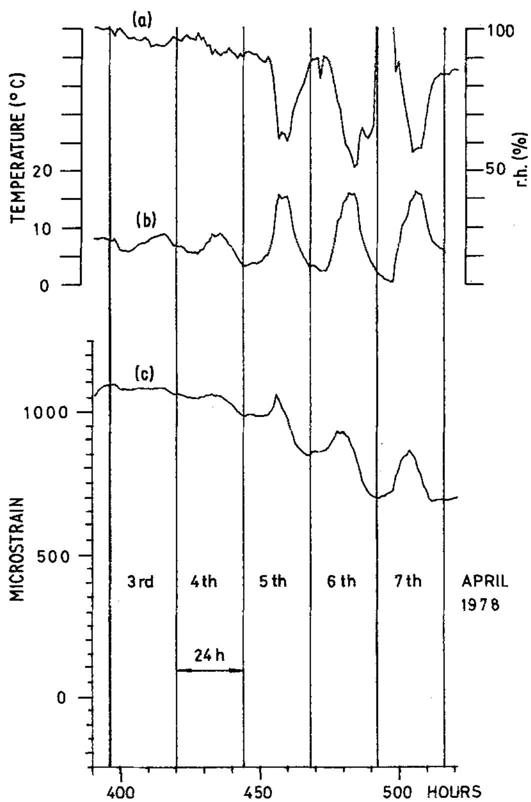

Figure 9 Daily changes in control specimens showing (a) relative humidity, (b) "dry" surface temperatures and (c) a portion of Fig. 8b to an enlarged time scale. This represents the mean of the strains from the control specimens 307 and 309, *minus* the "strains" from the Invar bar. Vertical lines are drawn at midnight.

and b also show the temperature and r.h. over the same period. The daily cycle of temperature and humidity clearly has an important effect on the specimens.

The relationship between the weather and the extension of the control specimens is still being investigated, but it is not a simple one. A change in temperature probably has an almost immediate effect on the strain. The earlier investigation showed that a change in r.h. has an effect which is rapid at first, stabilizing slowly over a period of three weeks or more.

Finally the close agreement between the curves for the two control specimens (Fig. 8a) should be noted. This is taken as further evidence of the reliability of the recording system.

8. Long-term effect of stress on GRC specimens

Fig. 10 shows strain readings obtained from specimens 301 and 313. The record in Fig. 10, like those in Figs. 6 and 8, begins at 17 March 1978 when the specimens were first exposed. No load was applied until 2 May 1978, when stresses equivalent to about 60% of the short-term tensile strength were applied and then maintened.

The curves in Fig. 10 have been obtained by substracting the Invar records (Fig. 6b) from the raw results. This automatically eliminates the error due to thermal expansion of the extensometer etc. The effect of the correction is to make small adjustments to the ordinates without making any significant change in the character of the graph as a whole.

It is important to realize that the large increase in strain in the first hundred hours is caused by the specimens being placed in a humid outdoor environment; they carry no load at this stage. The effect of the application of the load (at 2 May or about 1100 hours) is virtually invisible. This serves to emphasize the fact that changes of length caused by short- and long-term weather changes easily exceed extensions caused by the application of relatively large stresses.

The effects of weather can be separated from the effects of stress by taking the mean of the raw results of the control specimens (Fig. 8a) and subtracting it from the raw results of Specimens 301 and 313 (not shown). If it is assumed that temperature and humidity have the same effect on all specimens (whether loaded or not) and on all extensometers, then this calculation automatically elimates the influence of the weather. (Note that the results from the Invar bar are *not* used here). The results are shown in Fig. 11. The effect of applying the load (at about 1100 hours) can now be seen quite clearly as a sudden small extension. For the preceding 500 hours both specimens were quite stable. Afterwards, however, there was a gradual increase in strain, levelling off at about 7000 hours or 40 weeks after the load was applied. Graphs of the creep strain minus the instantaneous strain, plotted against log time (not illustrated) show a sigmoidal shape consistent with a transition from an initial state of equilibrium to a new final one.

9. Relationship between creep strains and the stress–strain curve

Fig. 5 shows the stress–strain curves obtained in the laboratory from Specimens 302, 312 and 314. These specimens are the ones which lie closest to the creep specimens discussed in this report, i.e. to

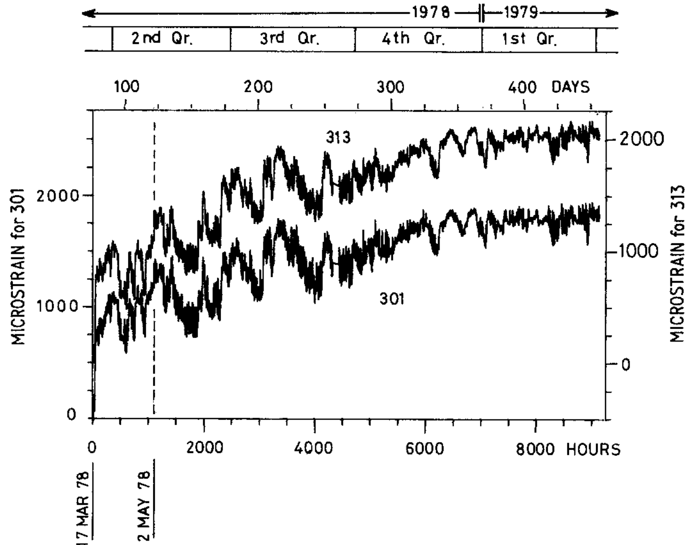

Figure 10 Strains in loaded specimens showing strains recorded on loaded Specimens 301 and 313, *minus* the "strains" recorded on the Invar bar (Fig. 6b). These curves represent the strains in the loaded specimens, corrected for the effects of temperature on the extensometers. They show the combined effects of weather and stress on the specimens.

certain creep specimens in board MV. Superimposed on the diagram are two horizontal lines.

The upper line is drawn at a stress of 4.82 N mm^{-2}, which is the stress applied to the creep specimen 301. The horizontal distance AB represents the "instantaneous" strain which was measured when load was first applied to the creep specimen*. The distance AC is the total strain at 500 h after the application of load, so BC is the creep strain at 500 h. Similarly AD represents the total strain at 1000 h. The test was discontinued 8018 h after loading, at a total strain of 970×10^{-6}, at the point E.

The lower horizontal line shows equivalent results for Specimen 313, which was discontinued at the same time at a total strain of 680×10^{-6}.

The diagram illustrates some important facts. First of all, the stresses chosen for these two creep tests (about 60% of the short-term ultimate stress) are not far short of the limit of proportionality, where one would expect to detect the first signs of cracking in a laboratory test. Secondly, the points B lie close to the ordinary stress–strain curves, showing that the creep specimens, when first loaded, behave in much the same way as laboratory specimens, despite the period of acclimatization which they spent in the open air. Thirdly, by three weeks (point C) the creep strains (BC) had already exceeded the instaneous strains (AB). The effective modulus of elasticity (i.e. the slope of the line joining the origin to the point C) would therefore be less than half of the value of

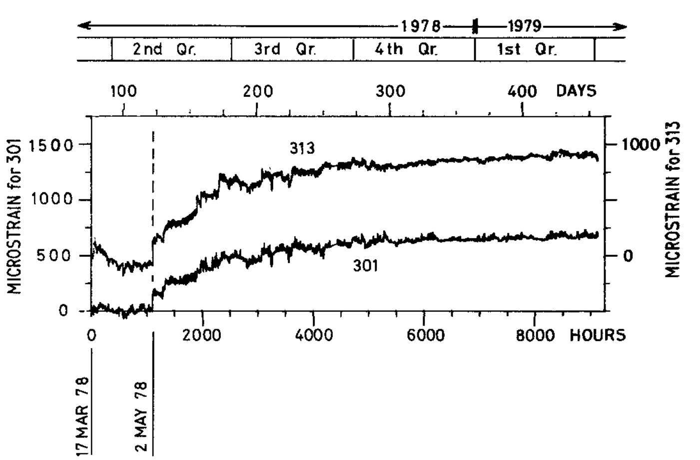

Figure 11 Strains in loaded specimens showing strains recorded on loaded Specimens 301 and 313 *minus* the mean of the uncorrected strains from the control specimens (Fig. 8a). These curves represent the effect of stress alone; the influence of weather on the specimens and on the extensometers has been eliminated.

*It took about 30 sec to apply the full load to the specimen; the "instantaneous" strain was actually measured between 30 and 60 sec after the beginning of the application of load.

Young's modulus measured in the laboratory. Fourthly these particular specimens remained unbroken after about 48 weeks under load, by which time the strains AE were comparable with the ultimate strains measured in the laboratory (Table I, 302-314).

It should be remembered that these are the strains that are associated with stress. If the effects of the weather are *not* removed, then the overall strains which occurred during the period of exposure are much larger, as shown in Fig. 10.

10. Conclusion

It has been shown that it is perfectly feasible to perform tensile creep tests on a material like GRC out-of-doors in order to monitor the combined effects of weather and stress. Instrumentation has been shown to be reliable. It has proved possible to obtain similar results from similar specimens treated in similar ways. The use of stress-free control specimens has given useful information about the effect of weather (espcially humiidity). Furthermore the principle of superposition works sufficiently well for the effects of stress and the effects of weather to be separated in the records of the stressed specimens.

The results have been given in detail for a small number of specimens whose behaviour was representative of the entire set. A summary of the results for all specimens will be published at a later date when the tests are complete. This later publication will include information about premature failures (which were not uncommon) and also about the confirmatory tests on panels A11 and A12.

Reference

1. H. G. ALLEN, *Int. J. Cement Comp.* 2 (1980) 185.

Received 30 October and accepted 10 December 1981