SESSION 5

The influence of loading age and temperature on the long term creep behaviour of concrete in a sealed, moisture stable, state

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RÉSUMÉ

Les résultats d'essais de fluage à long terme sur différents bétons chargés après avoir été recouverts d'un anti-évaporant, entre 7 et 400 jours, et entre 20 et 95°C, montrent que la déformation est directement proportionnelle au temps si temps et déformation sont en coordonnées logarithmiques. La modification de la vitesse du fluage d'après cette représentation de la déformation a été étudiée en fonction de la température, selon une relation d'Arrhénius modifiée, et il est apparu qu'il existe une corrélation suffisante pour le béton sous anti-évaporant, dans un état d'humidité constante, et dans certaines conditions d'essai. On montre que les prédictions à long terme sur le fluage du béton, d'après les données théoriques relatives à un matériau complexe à plusieurs phases, ne peuvent être qu'erronées à ce stade de l'étude.

SUMMARY

Results of long term creep measurements on a number of concretes in a sealed state loaded at ages for 7 days to 400 days at temperatures ranging from 20° to 95° C, show that deformation increases directly with time when both deformation and time are plotted logarithmically. The change in creep rate from this deformation presentation was then related to temperature using a modified Arrhenius expression and indicated that a reasonable correlation existed for sealed, moisture stable, concrete for certain test conditions. Prediction of concrete deformation from multiphase composite material theory is shown to give erroneous long term creep predictions at this stage of its development.

To provide data for the design of prestressed concrete pressure vessels for nuclear power stations subject to sustained load and temperature for a design life of 30 years, extensive creep tests have been made on sealed concrete, to simulate mass concrete conditions in the structure.

Test Series I was on a concrete ($a/c = 4.4$; $w/c = 0.42$) made with a limestone coarse aggregate, the specimens being cast into their polypropylene sealing jackets and then stored at 20° C prior to being heated to the test temperature shortly before loading to a stress (σ) of 2116 p.s.i. Load was applied at 7, 28, 60, 180 and 400 days after casting at temperatures of 20°, 40°, 65° and 93.5° C. Generally, the results obtained were for the average behaviour of 3 specimens per test condition. Full details of the tests are given in [1].

Initial results indicated that creep could be regarded as linear with respect to logarithmic time from loading [1] but as the time under load became greater, a definite upward steady trend on this time scale was apparent. Figure 1 illustrates one set of results when load was applied at 60 days. Plotting the results on a log /log basis showed that for the sealed condition, the experimental curves were linear, even at 6 years after loading, although from the design viewpoint, semi-log presentation was necessary. Figure 2 shows that the log /log relationship applied approximately for each test age and temperature.

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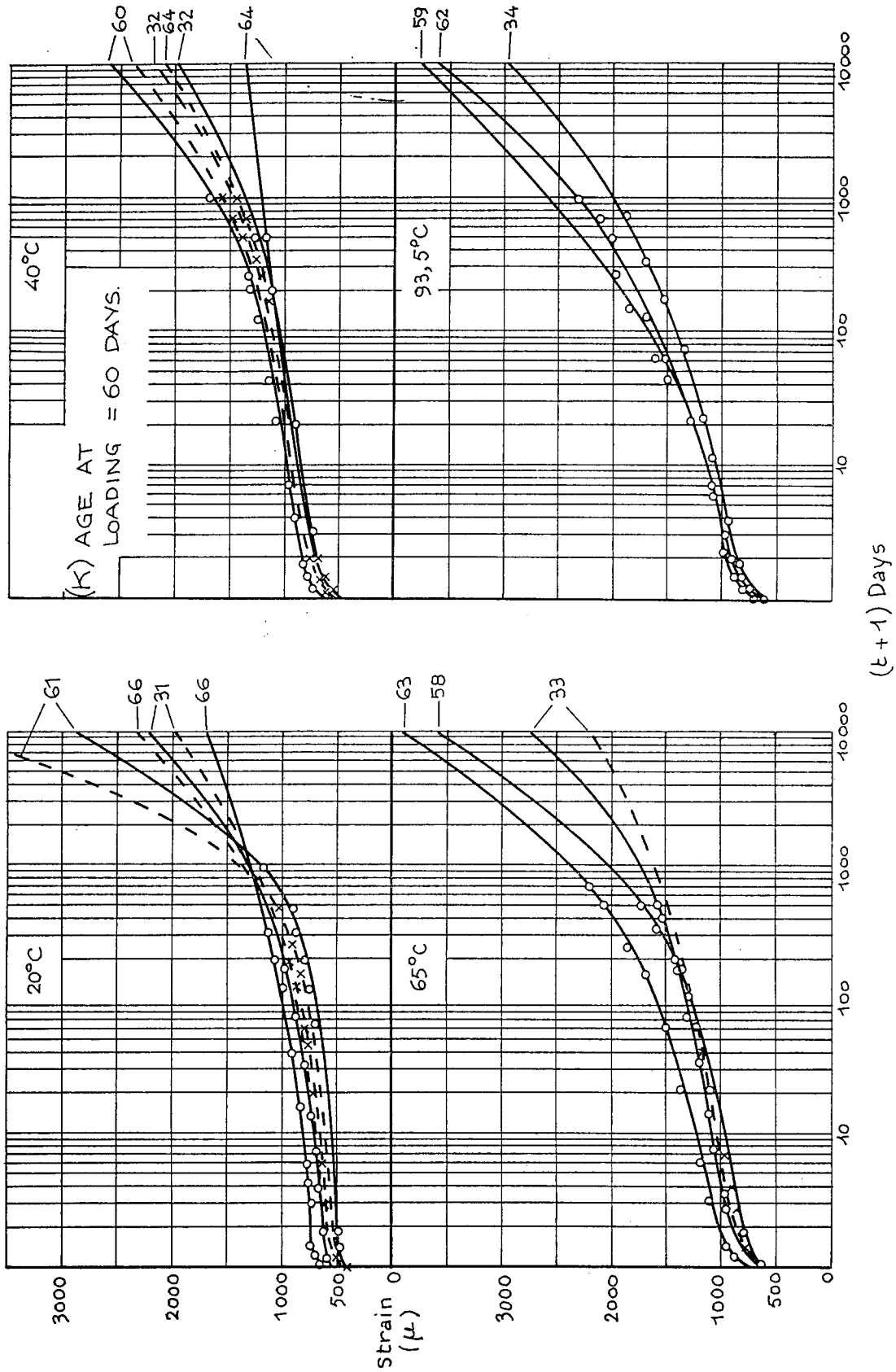


FIG. 1. — Series I. Summary of Experimental Creep Data.

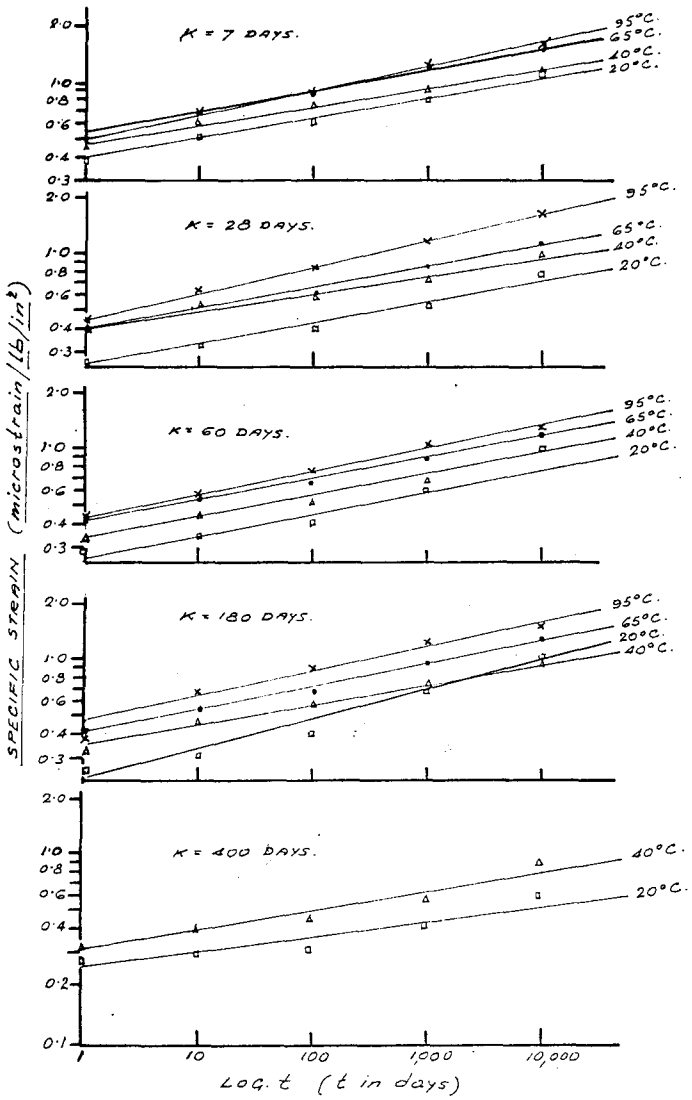


FIG. 2. — **Test Series I. Limestone Concrete. $E_A = 11.0 \times 10^6$ p.s.i.**

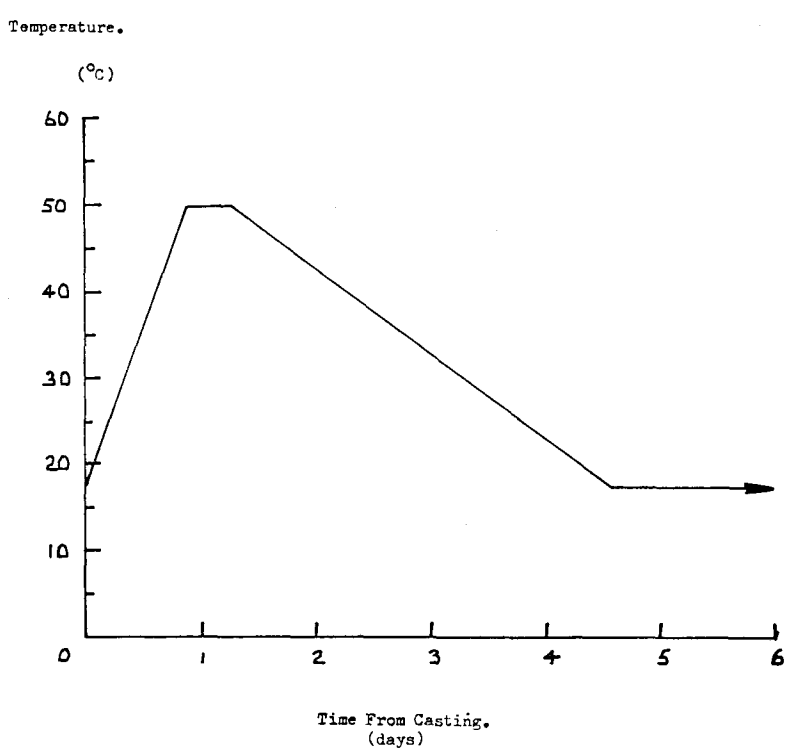


FIG. 3. — **Temperature Regime Applied to Series II & III Specimens.**

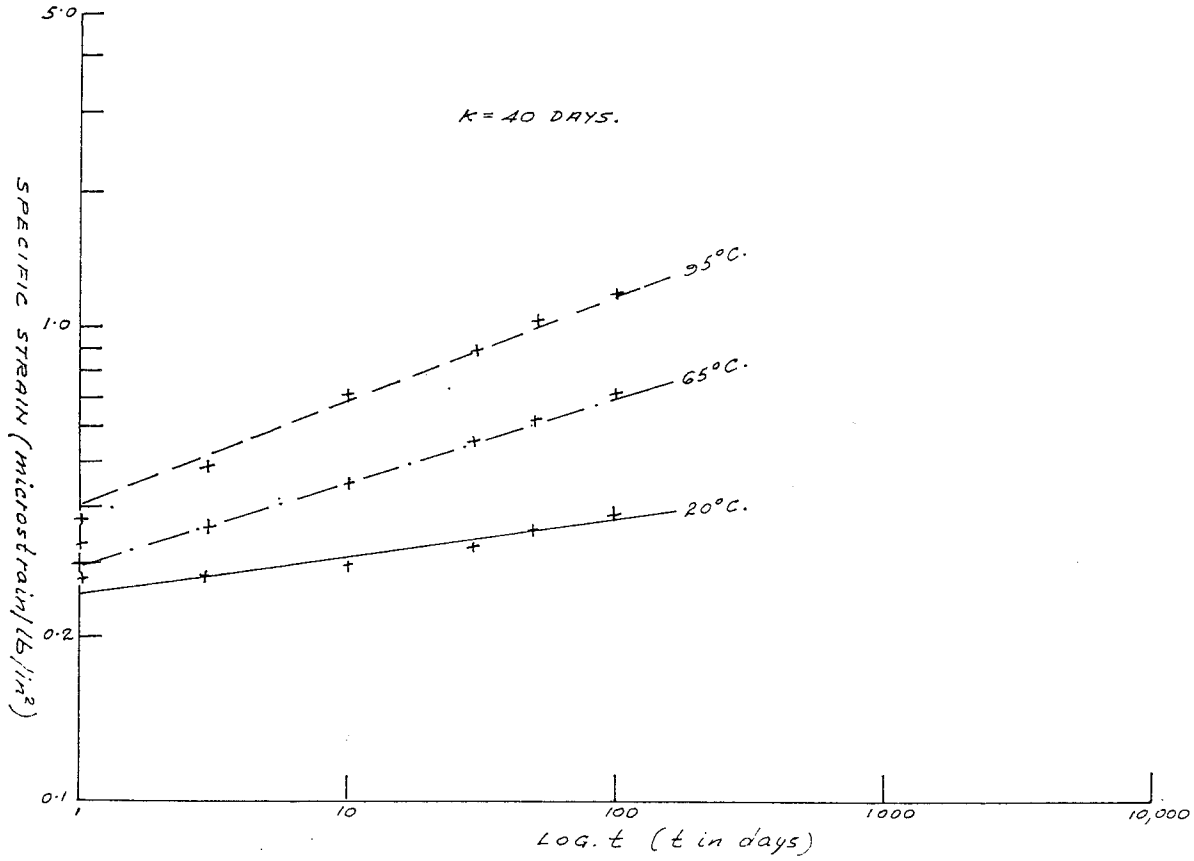


FIG. 4. — Test Series II. Dolerite Concrete. $E_A = 160 \times 10^6$ p.s.i.

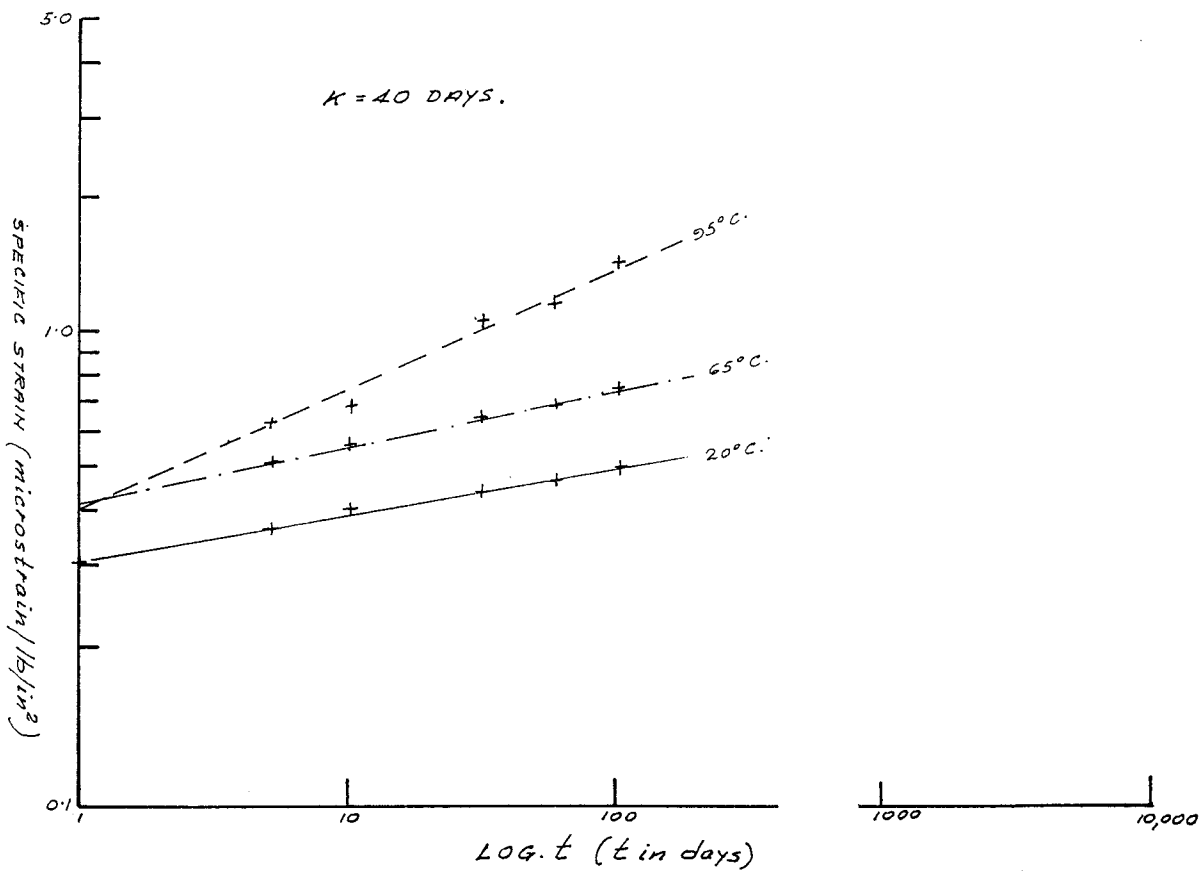


FIG. 5. — Test Series III. Dolerite Concrete. $E_A = 11.5 \times 10^6$ p.s.i.

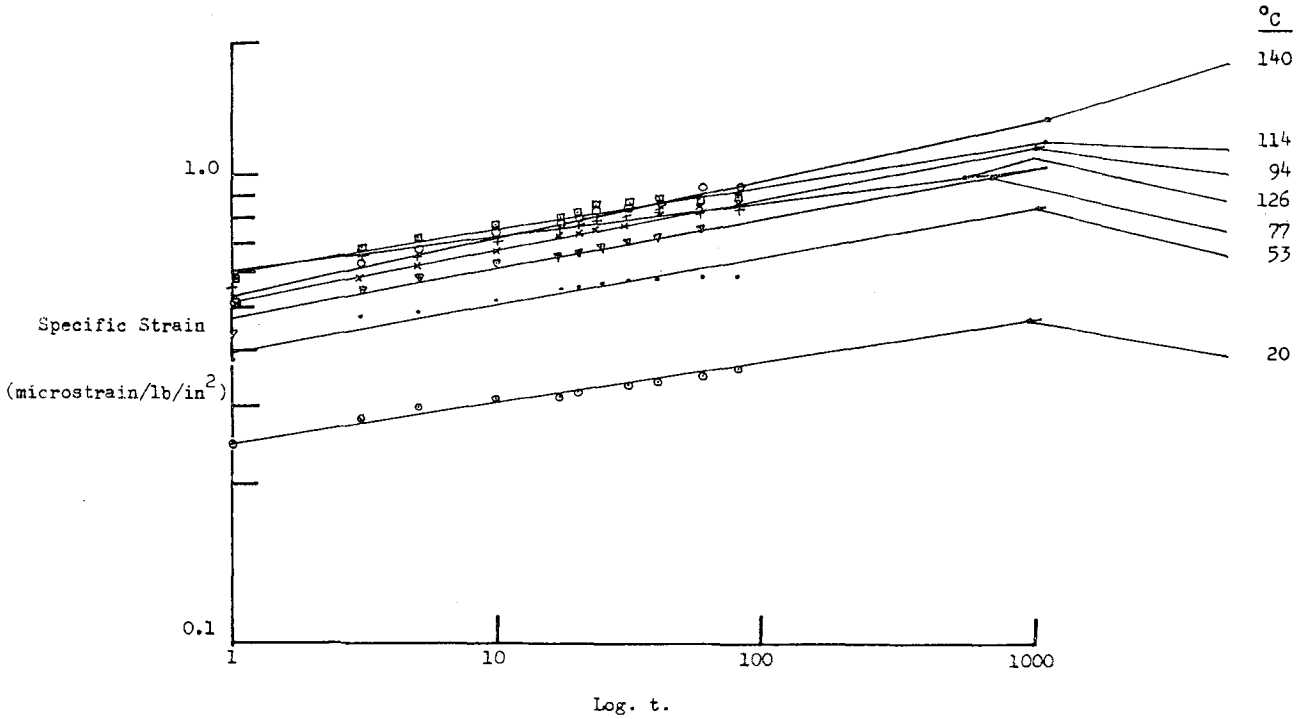


FIG. 6. — **G. L. England [3]. Gravel Concrete. Age at loading 10 days.**

Temp. °C	Slope(n)	Intersept ('Y' Axis)
140	0.142	0.560
126	0.084	0.620
114	0.100	0.610
94	0.069	0.520
77	0.110	0.480
53	0.100	0.400
20	0.086	0.250

Thus, the load/deformation characteristics could be expressed by:

$$\log \quad \varepsilon = \log a + n \log (t)$$

$$\text{i.e.} \quad \varepsilon = a(t)^n \qquad (1)$$

where ε = specific strain, microstrain/lb/in²

t = time under load, days

a = a factor decreasing with age at loading (K) and increasing with temperature (θ)

n = a factor also decreasing with age at loading (K) and varying with temperature (θ).

Control unloaded specimens indicated that a very small expansion or contraction (± 100 microstrain) could occur with time at temperature, but in view of its low magnitude—in relation to creep strain, was not subtracted from the deformation data. Sealing jackets tended to leak at elevated temperature but did not appear to affect the creep curve shape.

To simulate even more closely construction conditions, Series II and Series III concretes, made with different quartz dolerite coarse aggregates, were subject, prior to 20° C storage, to a heat of hydration temperature cycle obtained from the temperature regime of large concrete pours during the (inst) 14 days from casting. Figure 3 shows the applied temperature regime.

Figures 4 and 5 for these two concretes showed that the log/log relationship again applied as it did also for data presented by England (fig. 6), Hannant (fig. 7), Neville (fig. 8) and Maréchal (fig. 9).

At an early stage of the prediction of the long term deformation behaviour of both Series II and Series III concretes for design use, an attempt was made to predict the deformation behaviour using a multiphase theory for concrete found to approximately apply for a range of inclusion materials with E values from 0.04 to 30 × 10⁶ p.s.i.

Creep was considered by taking the " effective " E value as,

$$E = \frac{\sigma}{e + c}$$

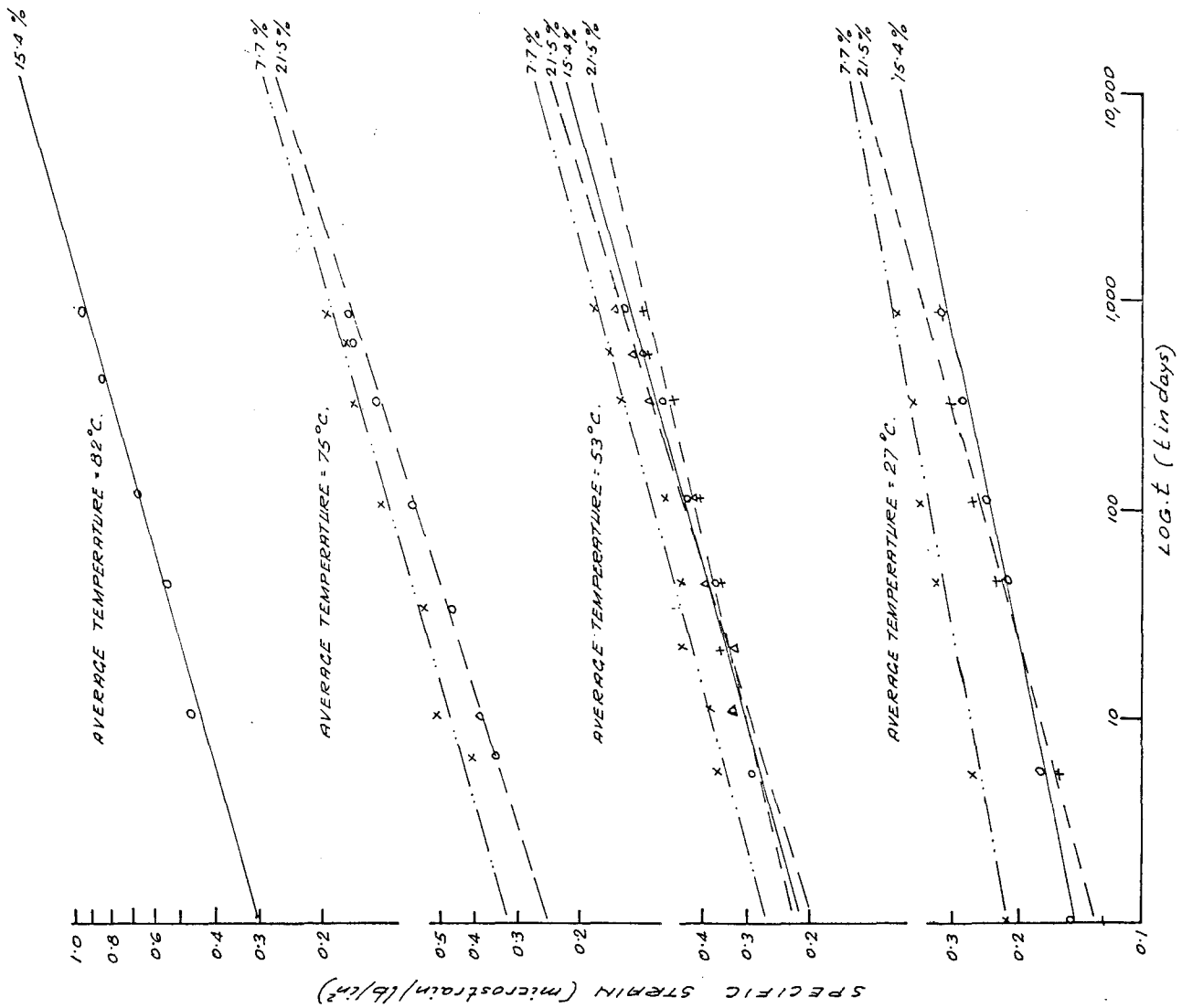
where σ = applied stress

e = elastic deformation

c = creep at the time considered.

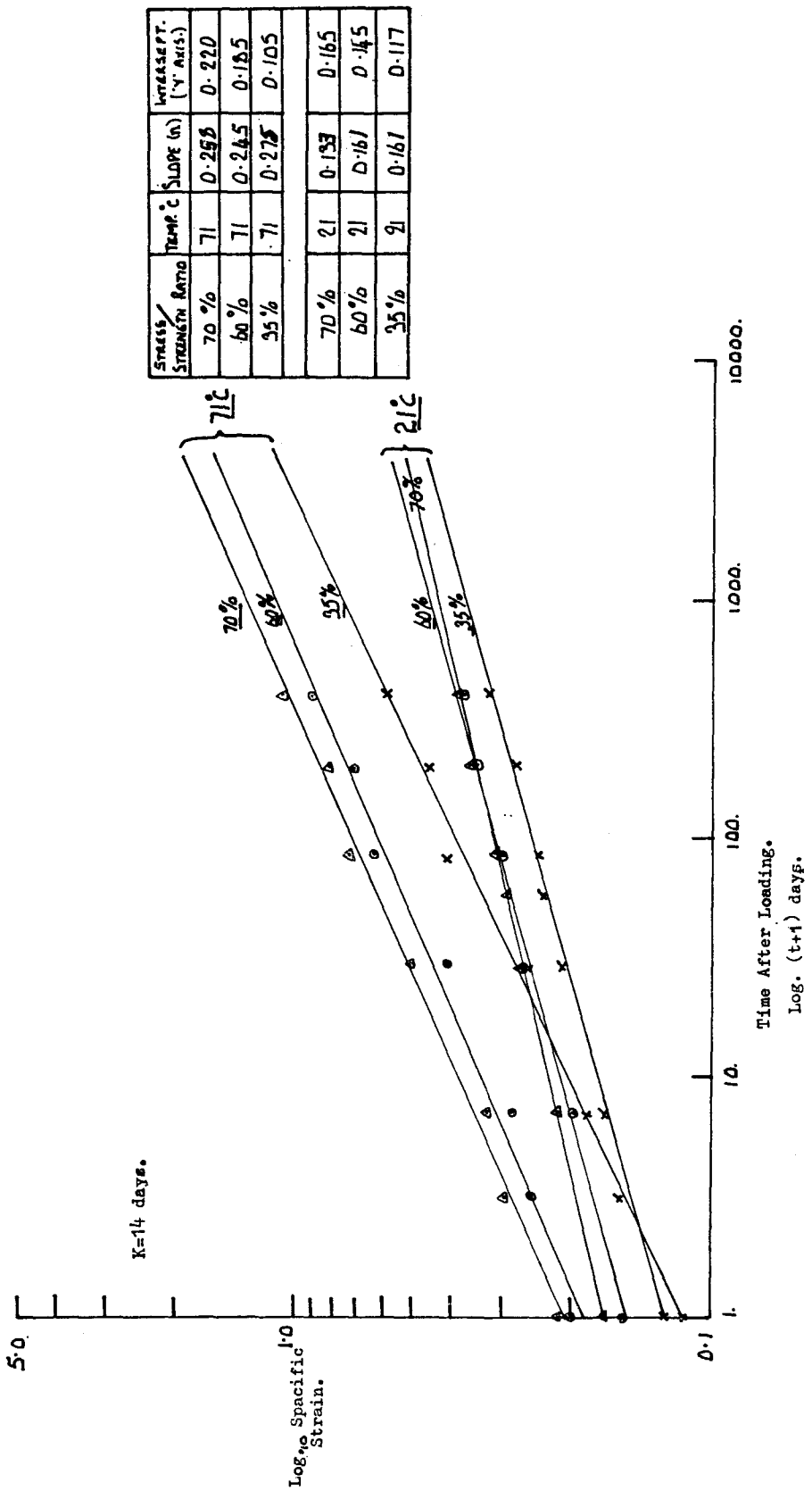
Figure 10 illustrates the predictions made from deformation data obtained for the Series II concrete and indicates that although the initial elastic deformation was reasonably predicted, correcting for the change in E_a values long term creep was significantly in error, particularly at elevated temperature. Correction was made for changes in volumetric proportion of the constituent materials.

At present, prediction is based on limited creep data from specimens loaded at 14, 40, and 100 days, the 40 days results are shown in figures 4 and 5.



STRESS/ STRENGTH RATIO.	TEMP. °C.	SLOPE (m)	INTERSEPT. 'y' AXIS
15·4 %	82	0·133	0·300
21·5 %	75	0·182	0·240
7·7 %	"	0·162	0·310
21·5 %	53	0·181	0·200
15·4 %	"	0·196	0·210
21·5 %	"	0·134	0·220
7·7 %	"	0·162	0·260
21·5 %	27	0·142	0·120
15·4 %	"	0·121	0·140
7·7 %	"	0·101	0·215

FIG. 7. — **D. J. Hannant [4]. Limestone Concrete.**



Stress/Strength Ratio	Temp. °C	Slope (n)	Intercept. ('Y' Axis)
70 %	71	0·258	0·220
60 %	71	0·245	0·185
35 %	71	0·278	0·105
70 %	21	0·133	0·165
60 %	21	0·161	0·145
35 %	21	0·161	0·117

FIG. 8. — A. M. Neville [5]. Dolomite/Hornblende Concrete.

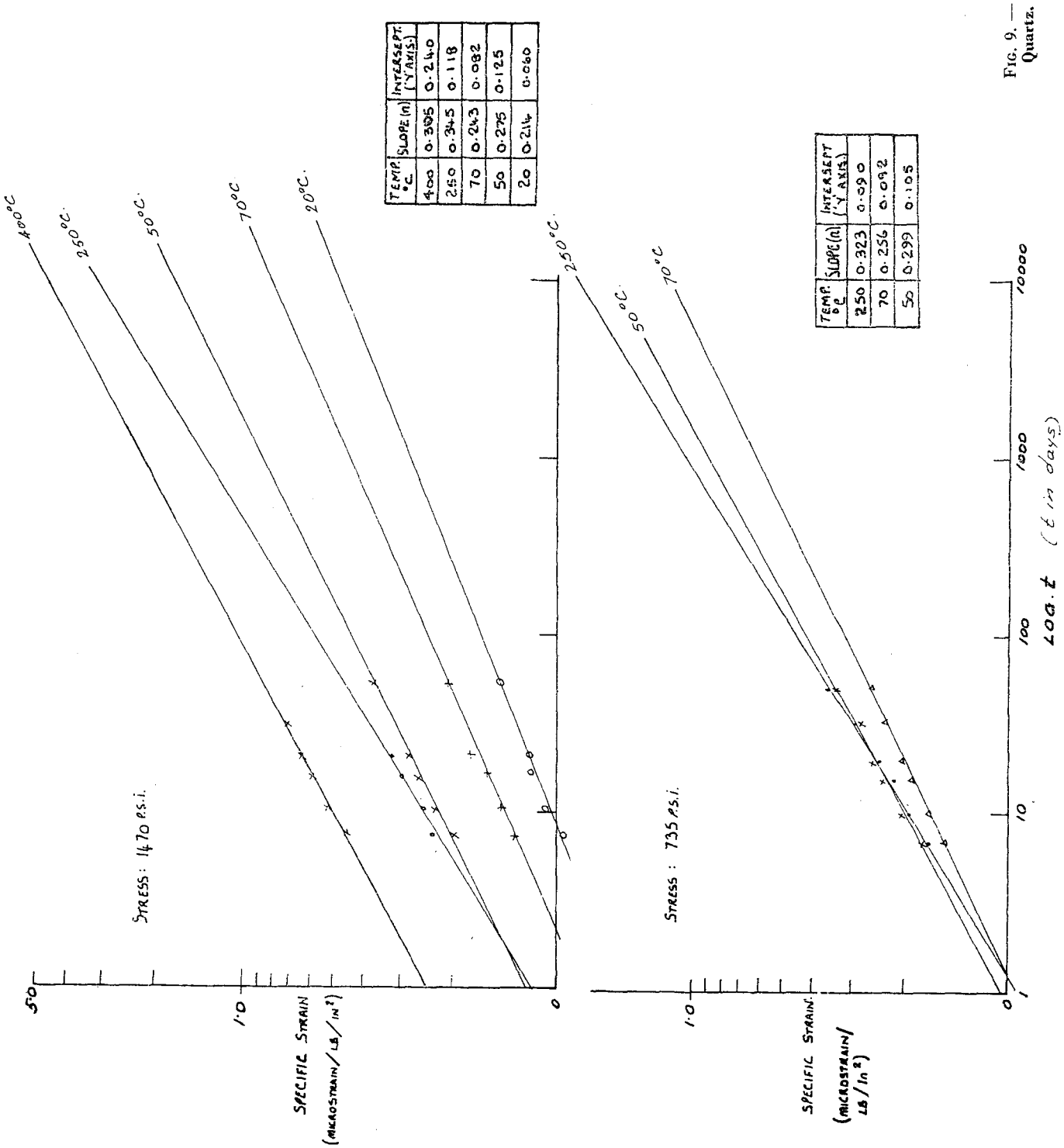


FIG. 9. — J. C. Maréchal [6]. Quartz. Gravel. Concrete.

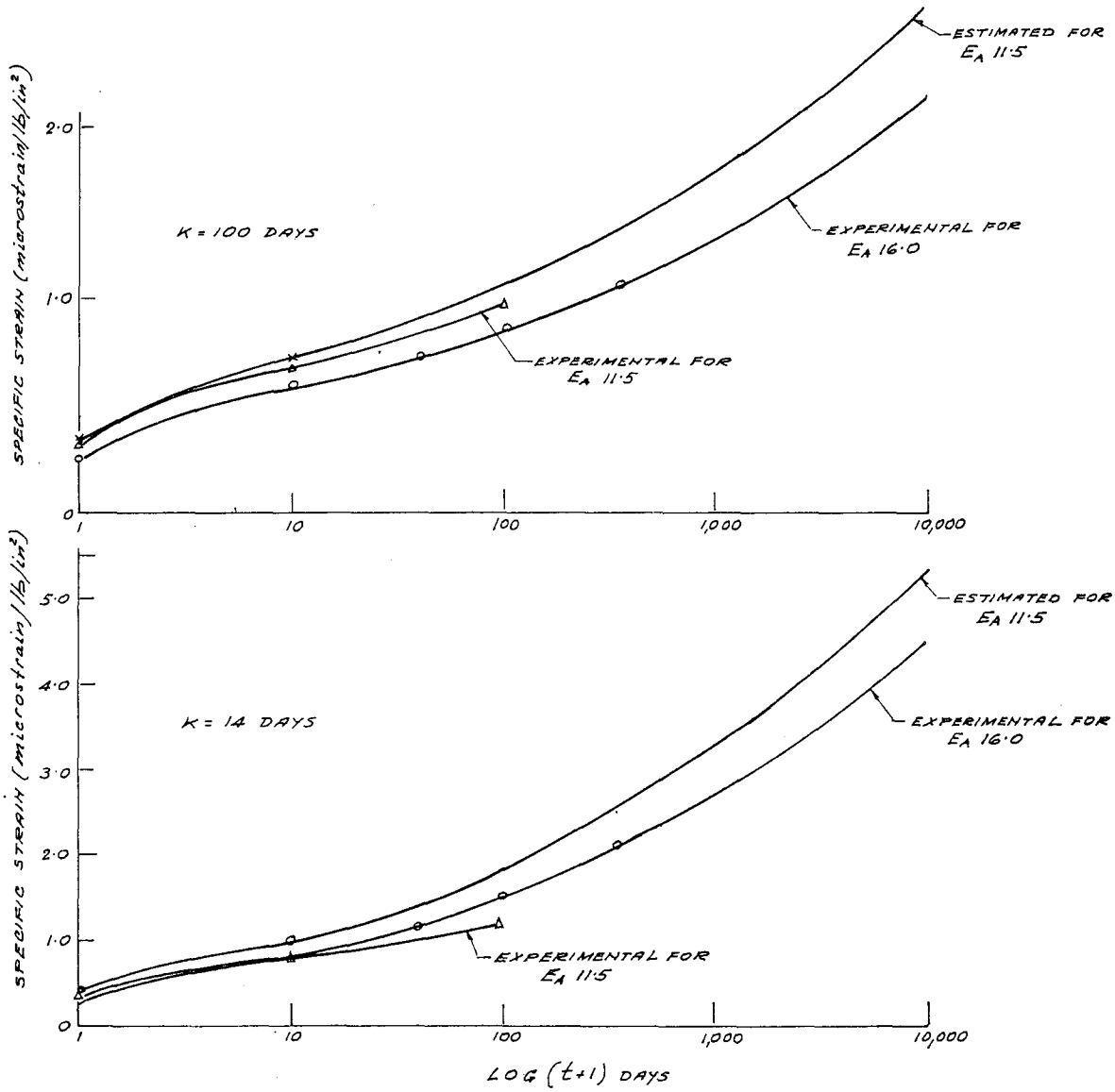


FIG. 10. — **Multiphase Equation. Comparison between Estimated and Experimental Series II Concrete. Temperature : 95 °C.**

U. COUNTO'S EQUATION (1) $\frac{1}{E'_c} = \frac{1-\sqrt{V_A}}{E'_m} + \frac{1}{\left(\frac{1-\sqrt{V_A}}{\sqrt{V_A}}\right)} E'_m + E_A$

Recently, an examination has been made of the variation of the creep flow rate, as represented by (n), the slope of the log /log plots, against temperature. It was assumed that a modified Arrhenius activation energy equation could be applied to the rate of deformation with time,

i.e. $n = a.\sigma.\exp\left(^{-E/R\theta}\right)$ (2)

where n = the creep rate per unit applied stress' obtained for the log /log plot

a = a constant

σ = stress

E = activation energy

R = gas constant

θ = absolute temperature, ⁰ Kelvin

$\therefore \log n = \log a + \log.\sigma - E/R\theta$ (3)

If this expression was valid, then log n would be directly related to $1/\theta$. Figures 11 and 12 show the n values obtained from the log /log plots, plotted on this basis. It can be seen that for the Series II and III 40 day results, which were for hydration heat cycled concrete, a decrease was discernable, whereas for the Series I concrete, kept at 20⁰ C from casting, a minimum value existed at 40⁰ C. Age generally reduced the n value as would be expected due to the effective reduction in stress level (σ) associated with strength development with time. Hannant's results for water saturated, stored concrete but kept in a sealed state from heating, showed a similar decrease with $1/\theta$ increase. Series I, II and III concretes had similar n values of about 1.0, indicating that for mass concrete, quite a simple creep temperature relation may apply except at early ages when the effective stress level would be high. Here, a minimum appeared to occur at 65⁰ C.

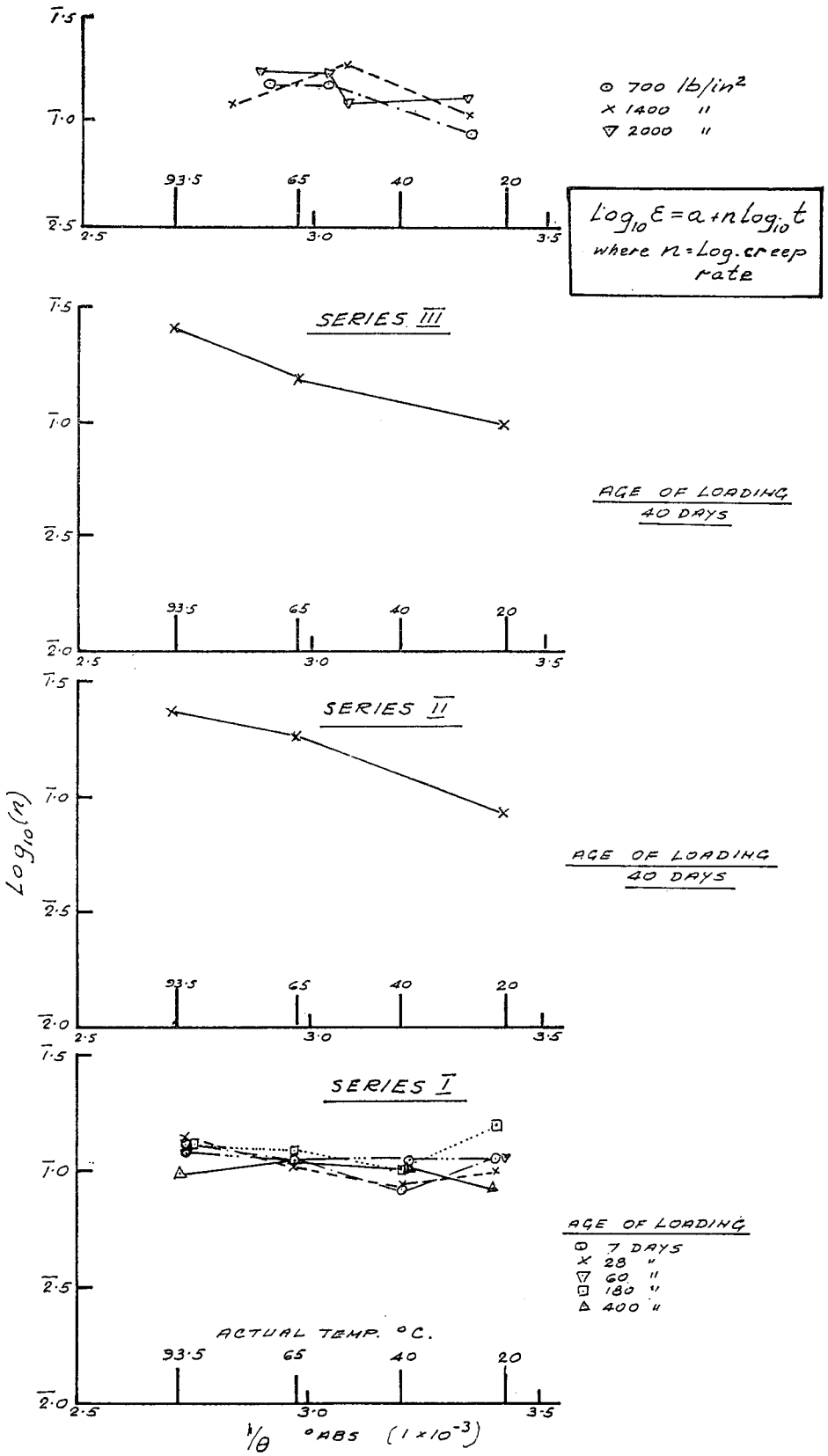


FIG. 11. — D. J. Hannant [4].

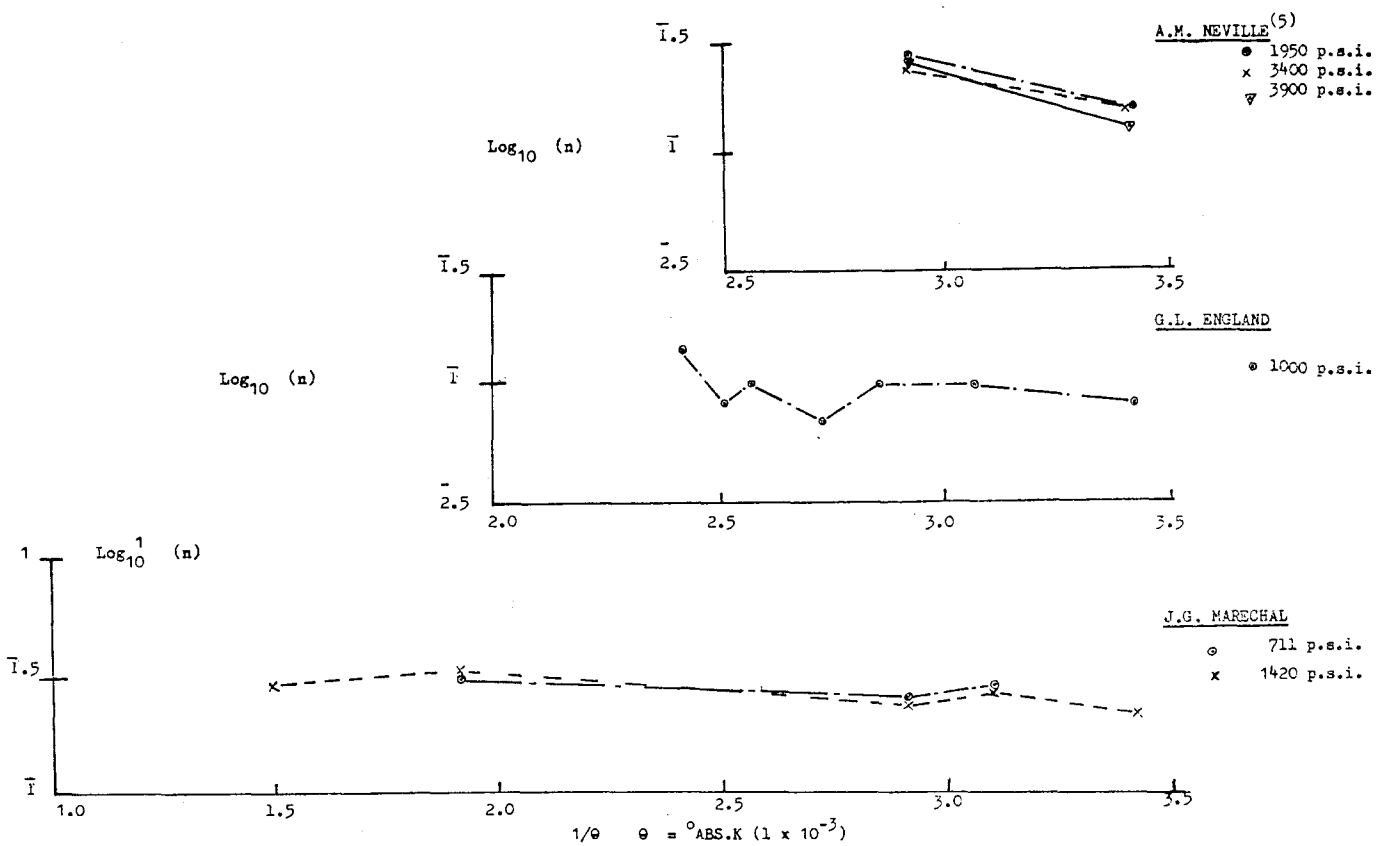


FIG. 12.

England, Neville and Maréchal's *n* values showed somewhat different modes of behaviour, which could be accounted for by a relatively low stress level, a different state prior to loading (kept at temperature shortly after casting), and to possibly drying occurring during the creep process, respectively. From Maréchal's results, it could be that the activation energy E, is not changed significantly, but an extra term should be added to Eq (3) to account for the vertical displacement associated with the drying process.

The above hypothesis, that the creep rate may be directly associated with the activation energy of the concrete system, is being further investigated to take into account the effect of the stress state, that is, the stress /strength ratio existing at the time of load application, since initial results indicate the sensitivity of the creep rate to this factor. Ultimately, it is believed that for concrete in a sealed, equilibrium state, its deformation behaviour may be derived from a knowledge of its strength variation with age, the stress level and the temperature concerned.

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