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Strains under transient hygro-thermal states in concrete loaded in multiaxial compression and heated to 250 °C

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Abstract

Previous experimental research has shown that the compactive strains in concrete subjected to a load-then-heat regime exceed those measured in heat-then-load tests under compression. This excess in strain is known as transient thermal creep or load-induced thermal strain (LITS). All previous experimental research on LITS in mature concrete has been conducted in unsealed conditions, mainly under uniaxial compression (with a few biaxial compression tests, but no multiaxial tests) on specimens subjected to monotonic heating to high temperatures (>500 °C). This paper presents the findings from a novel laboratory investigation of LITS under uniaxial, biaxial and hydrostatic compression in *partially sealed* conditions, at transient temperatures of up to 250 °C. The results from 49 experiments show that LITS in the sub-250 °C range is highly dependent on the moisture flux conditions and, consequently, on the relationship between heating and drying rates.

Keywords: Strain; Transient temperature; Moisture; Multiaxial compression

1. Introduction

Predictions of, for example, the deformation response of the pre-stressed concrete in advanced gas-cooled nuclear reactor pressure vessels require knowledge of the creep, relaxation and shrinkage behaviour under thermo-mechanical load. This paper provides new experimental data in this area, and highlights the need to determine the moisture transport conditions when estimating load-induced thermal strains. The ability to perform detailed deformation analyses is most important, as it allows engineers to develop safe operational management strategies in nuclear power plants.

In the first study of cement paste and mortar under transient temperature, Hansen and Eriksson [1] tested loaded and unloaded specimens submerged in water and heated to 100 °C. They found that specimens that were first loaded and then heated (LH) deformed more than those first heated and then loaded (HL). Their results also showed that when specimens were first heated to a lower temperature of 60 °C, then cooled, loaded and heated again, the deformations were relatively small for temperatures below the level attained in the first cycle, but increased rapidly when that temperature was exceeded. The fact that the extra strain was measured on specimens submerged in water, suggested that this was a different phenomenon from the *drying creep*, previously discovered by Pickett [2]. The existence of this extra strain component, denoted transient (or transitional) thermal creep (TTC), was later confirmed in experiments on loaded concrete, micro-concrete and mortar subjected to thermal transients at temperatures up to 100 °C [3–7]. Thelandersson and Anderberg [8,9] were the first to show that TTC was present at higher temperatures (up to 800 °C) and that for higher uniaxial load (above 45% of uniaxial compressive strength f_c), it was large enough to completely suppress the free thermal expansion of concrete in the loaded direction at any temperature. Their results also showed that this strain was not affected by the heating rate (within the range 2 to 5 °C min^{-1}). Thelandersson [10] later proposed a model in which LITS was expressed as a function of only stress and temperature, but acknowledged that it was valid

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for unsealed conditions and temperatures over 300 °C and that moisture content had to be included for any other conditions.

The research of concrete under thermal transients was taken further by workers at Imperial College [11–14], who first used the term *load-induced thermal strain*. They undertook an extensive programme of tests on mature concrete with different ages (1 and 9 years), different coarse aggregates and initial moisture conditions (0%, 65% and 100%RH), loaded at different levels of uniaxial compression (0.1, 0.2 and 0.3f_c) and heated to 600 °C, at two different rates (0.2 and 1 °C min^{-1}). Their results confirmed that for a given temperature and stress level, LITS did not depend on the heating rate. Furthermore, for concretes with similar strength, this strain was not sensitive to the type of coarse aggregate (except for gravel concrete at temperatures above 450 °C), and hence it could be represented by a concrete *master-curve*, depending only on temperature and stress.

In parallel with the studies at Imperial College, researchers at the University of Braunschweig [15–17] experimented with concrete heated to temperatures of 750 °C (at 2 °C min^{-1}) under biaxial compression with different σ_1/f_c and σ_1/σ_2 ratios. Their results indicated that while LITS in the loading directions was similar to that under uniaxial compression, the expansive strains in the unloaded direction were very large, especially at lower temperatures.

Recently, the researchers in Navier Institut in Marne-la-Valee [18,19] conducted experiments on ordinary (OC), high strength (HSC) and high performance concrete (HPC), loaded in uniaxial compression and subjected to heating–cooling cycles at temperatures of up to 300 °C. They found that increased strength (or reduced water/cement ratio) led to a small increase in LITS ($\varepsilon_{OC}/\varepsilon_{HC}/\varepsilon_{HPC}=0.76/0.96/1$), but a significant reduction in free thermal strains of the unloaded specimens ($\varepsilon_{OC}/\varepsilon_{HC}/\varepsilon_{HPC}=2.86/1.55/1$). The differences in the free thermal strains were so large that the observed differences in LITS could be a result of small inaccuracies in the measurements of free strain data which were subtracted from the strains recorded in the load-then-heat tests. The two heating rates (0.1 and 1.5 °C min^{-1}) used in the experiments had little influence on the results. Another important finding was that the strains did not increase during the second heating under load, showing that, in contrast with earlier findings [4,6,7], no LITS recovery took place between the cycles, even in cases when the delay period was as long as 56 days.

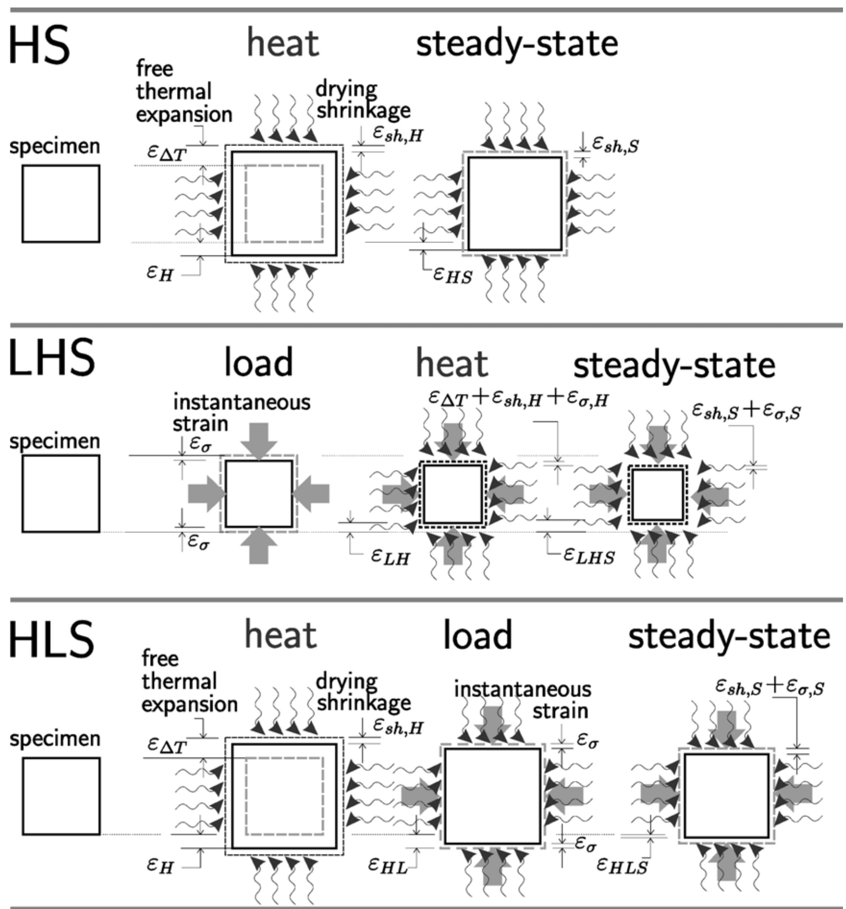
After 40 years of experimental and theoretical research of concrete under transient thermal conditions there is still no universally accepted explanation of the mechanisms that cause increased strain during the first heating of loaded cement paste and concrete. This is partly reflected in the different names given to this phenomenon. In this paper the term LITS is used because it does not imply any particular mechanism and can be simply defined as the difference between the strains measured during the heating of loaded specimens ε_{LH} (load-then-heat tests) and those recorded on specimens which were heated without load ε_H. This definition has been used by other researchers in the past [11,12,16]. As in the previous experiments, the load and the heating rate were kept constant. The only difference in this programme is a steady-state period, introduced after the heating sequence (when the specimen surface temperature reached the peak value of 250 °C) to allow the specimens to approach the state of hygro-thermal equilibrium. LITS is thus defined as $\varepsilon_{LHS}-\varepsilon_{HS}-\varepsilon_{\sigma}$, where ε_{σ} is the instantaneous (elastic) strain response to the applied load (see Fig. 1). According to this definition, LITS encompasses any strains that may occur during heating under load, such as changes in material stiffness, closing of shrinkage-induced cracks, drying creep or basic creep.

Findings from existing experimental research on LITS in concrete and hardened cement paste can be summarised as follows:

(i) LITS occurs in both concrete and hardened cement paste [5,12] only during the first heating under load. It does not occur during cooling or re-heating to the same temperature, but it starts again once the previously attained temperature is exceeded [1,18,19].
(ii) LITS occurs in specimens submerged in water and heated under load [1]. This shows that while similar and perhaps related to drying creep, LITS is not simply a result of accelerated drying [2].
(iii) LITS in hardened cement paste is 2–3 times higher than that in concrete [12]. This suggests that LITS is not a result of cracks caused by thermal incompatibility of the constituents, but a result of processes occurring in the cement paste.
(iv) LITS–temperature relationship is similar for concretes with different types of coarse aggregates but same strength and aggregate/cement ratios [12,13]. LITS is larger for concretes with lower water/cement ratios (that is, higher strength mixes) [18,19].
(v) At temperatures below 250 °C, LITS increases with the increase in moisture content, whereas at higher temperatures the initial moisture content has no effect [11].
(vi) LITS is not sensitive to heating rates [8,9,12,18].
(vii) For mature concrete (over 1 year) the age has little or no influence on LITS [12,13].

The existing knowledge of LITS is limited by the fact that all tests on mature concrete were conducted in unsealed conditions and mainly under uniaxial compression, with only few biaxial compression experiments. Considering that concrete in general is subjected to multiaxial stress states and complex moisture boundary conditions, these data cover only a limited set of special cases. Also, with few exceptions [18], most LITS tests were carried out by monotonic heating to high temperatures (>500 °C), with very little attention on the sub-250 °C range where the behaviour of concrete is strongly influenced by complex, coupled thermo–hygro-mechanical processes.

Before beginning the description of the tests, it is perhaps worth making a general observation. When performing an experiment designed to inform a constitutive model, the intention is to capture the material point response, rather than data influenced by structural effects through the presence of spatial gradients. This aim is unattainable for porous multi-phase media such as concrete. Although the concept of a representative volume is used, the scale of the mesolevel heterogeneities



$$\varepsilon_H = \varepsilon_{\Delta T} + \varepsilon_{sh,H}$$

$$\varepsilon_{HS} = \varepsilon_{\Delta T} + \varepsilon_{sh,H} + \varepsilon_{sh,S}$$

$$\varepsilon_{LH} = \varepsilon_\sigma + \varepsilon_{\Delta T} + \varepsilon_{sh,H} + \varepsilon_{\sigma,H}$$

$$\varepsilon_{LHS} = \varepsilon_\sigma + \varepsilon_{\Delta T} + \varepsilon_{sh,H} + \varepsilon_{\sigma,H} + \varepsilon_{sh,S} + \varepsilon_{\sigma,S}$$

$$\varepsilon_{HL} = \varepsilon_{\Delta T} + \varepsilon_{sh,H} + \varepsilon_\sigma$$

$$\varepsilon_{HLS} = \varepsilon_{\Delta T} + \varepsilon_{sh,H} + \varepsilon_\sigma + \varepsilon_{sh,S} + \varepsilon_{\sigma,S}$$

LITS (heating): $\varepsilon_{\sigma,H} = \varepsilon_{LH} - \varepsilon_\sigma - \varepsilon_H$

LITS (heating + steady-state): $\varepsilon_{\sigma,HS} = \varepsilon_{\sigma,H} + \varepsilon_{\sigma,S} = \varepsilon_{LHS} - \varepsilon_\sigma - \varepsilon_{HS}$

Fig. 1. Experimental sequence for different types of tests (HS: heating without load; LHS: load-then-heat; and LHS: heat-then-load) and definitions of strain components. Load-induced thermal strain (LITS) is determined as the strain difference between the LHS and HS tests.

controlling the macroscopic response, demands a very careful consideration of the through-specimen uniformity of the state variables (for example, strain, stress, temperature, moisture content, pore pressure and capillary suction). This complication cannot be ignored. It plays an important role in the interpretation of the tests described below.

2. Experimental set-up and methodology

2.1. Test apparatus

The lack of data on LITS under generalised stress conditions led to the development of mac^{2T} [20]; the University of Sheffield's apparatus for testing concrete under multiaxial compression at elevated temperature (Fig. 2). This facility comprises three independent loading frames capable of delivering true multiaxial compression ($\sigma_1 \neq \sigma_2 \neq \sigma_3$) of up to 400 MPa to 100 mm cubic specimens, at temperatures up to 300 °C. Specimen deformations are determined from displacements measured to an accuracy of 10^{-6} m using an orthogonal system of six laser interferometers.

Heat in the rig is generated by a set of six ceramic band heaters, wrapped around the steel platens and transferred to the specimen by conduction through those platens. 0.25 mm thick PTFE pads are used to suppress friction and thereby reduce shear stresses at the platen–specimen interface. During the tests the bulk of the specimen surface (>90%) is covered by the loading platens (Fig. 3), thus restricting rapid moisture evacuation, and for the heating rates typically employed in LITS tests (0.2–5 °C min^{-1}),

Fig. 2. mac^{2T} apparatus.

creating *partially sealed* conditions. This is in contrast with the previous uniaxial and biaxial compression tests in which a much larger proportion of the specimen surface area presented no constraints to the boundary moisture fluxes.

The temperature in the rig is controlled by a system of 24 thermocouples installed in the loading platens (4 on each of the six platens), at a distance of 5 mm from the surface of the specimen. The relationship between the measured platen temperature and the temperature inside the specimen was determined in calibration tests on specimens with thermocouples embedded in the centre and at locations 5 mm from the surface. These tests showed that, for concrete heated to platen temperature of 250 °C at a rate of 2 °C min^{-1}, the temperature in the centroid was 180 °C, at the time when the platens first reached 250 °C, 236 °C after 2 h and 248 °C after 12 h at constant platen temperature. This finding is consistent with thermal conduction calculations. After the first heating cycle, those specimens were cooled down to ambient temperature (20 °C) then re-heated at the same rate to 250 °C, 24 h later. The histories of free expansion recorded in the second cycle were later used to separate shrinkage from the total strains recorded in tests performed at a heating rate of 2 °C min^{-1}.

2.2. Material and specimen preparation

All elevated temperature tests in the presented experimental programme were carried out on one concrete type, selected to represent a mix typical of those used in a number of pre-stressed concrete reactor vessels in UK nuclear power plants. The constituents and their mass proportions are given in Table 1.

The concrete was cast in slabs with dimensions 740 × 620 × 150 mm. After the casting, the moulds were immersed in water and subjected to a 10 day temperature-matched curing cycle, in which the temperature reached a maximum of 65 °C after 36 h. On completion of the 7-day cycle, the slabs were removed from the moulds and returned to the tanks where they remained for a further 60 days at a temperature of 20 °C. After that, the slabs were cut into prisms with dimensions 101 × 101 × 150 mm, then cut into 101 mm cubes (by removing top and bottom 24.5 mm), and finally machined to right-regular 100 mm cubes by following a grinding sequence, using a clamping jig designed for that purpose. After the machining, the specimens were stored at room conditions and tested at different ages (between 580 and 2723 days). The mean uniaxial compressive strength of the mix was 59 MPa at 70 days (no significant strength gain was recorded beyond this age).

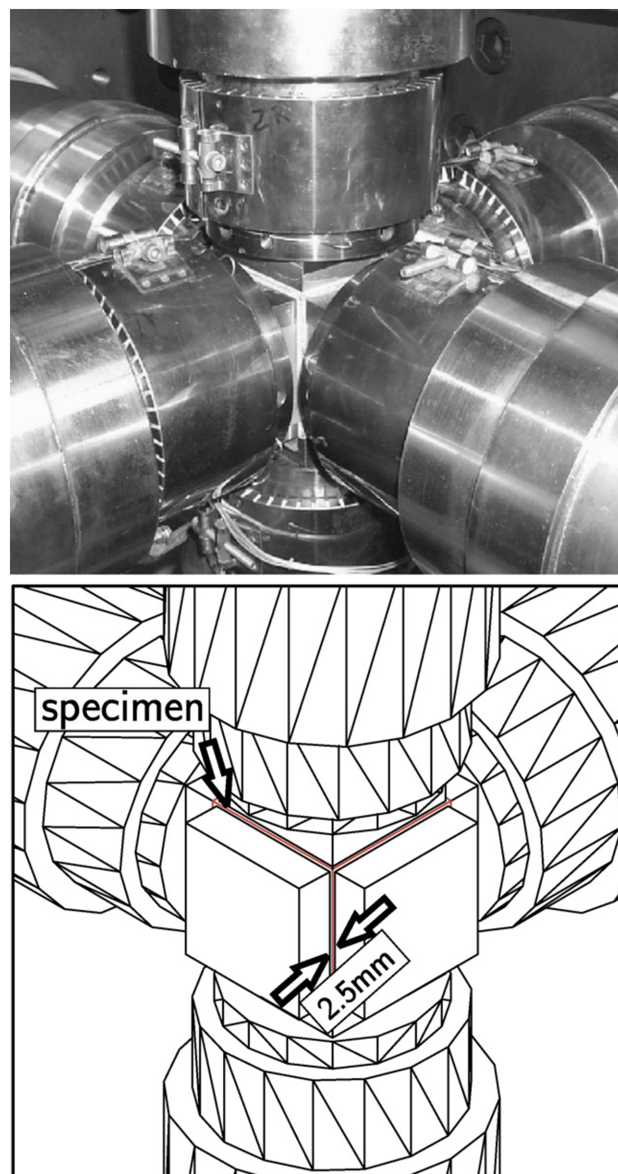


Fig. 3. mac^{2T}: loading platens.

Table 1
Mix proportions

Constituent	Mass ratio	kg m^{-3}	Constituent/binder mass ratio
OPC	1	300	0.75
PFA	0.33	99	0.25
Sand	2.45	735	1.84
Quartz-diorite 10 mm	1.39	417	1.05
Quartz-diorite 20 mm	2.78	861	2.16
Plasticiser SP4	0.006	1.8	0.0045
Water	0.56	168	0.42

2.3. Test methodology

The elevated temperature tests in mac^{2T} were performed as continuous experiments comprising two phases: (i) conditioning and (ii) deviatoric loading. In the conditioning phase, the specimens were subjected to different heat–load regimes: (HS) heated without load and held under constant temperature (hereafter referred to as *steady-state* conditions, although this does not imply that complete hygro-thermal equilibrium has been attained), (LHS) loaded first, then heated and held under steady-state conditions, (HLS) heated without load then loaded and held under constant temperature and load (steady-state) or (LHCHS) loaded first, then subjected to a thermal cycle (heat–cool–heat) followed by a steady-state period. The results of the conditioning phases were used to determine LITS defined as a difference between the strains recorded in LHS and HS tests (as shown in Fig. 1). The HLS tests were used to measure the material response under steady-state conditions, when the load was applied after the completion of the heating phase ($\varepsilon_{\mathrm{LHS}} - \varepsilon_{\mathrm{HLS}}$). The aim of the LHCHS tests was to investigate the strains during temperature cycling under constant load.

The effects of the different conditioning regimes on the properties of the material under multiaxial compression were investigated in the second, deviatoric loading phase, performed at a constant temperature of 250 °C. In each test the deviatoric load was applied in one meridional plane (at Lode angles between $-\pi/6$ and $+\pi/6$), in three cycles with gradually increasing stress levels, followed by monotonic loading to the peak. The deviatoric loading stage (to be reported elsewhere) provided data on the hot multiaxial strength, tangent stiffness, elastic stiffness, volume dilation, plastic flow and softening of the material.

This paper presents only the results of the conditioning phase: that is, LITS in concrete heated at two different rates, under uniaxial, equal-biaxial and hydrostatic load.

The two test phases are illustrated in Fig. 4, showing the time histories of platen temperature, stresses and strains recorded during an LHS test. In the conditioning phase of this particular test the specimen was (i) loaded under equal-biaxial compression ($\sigma_1 = \sigma_2 = 26$ MPa), (ii) heated to platen temperature of 250 °C at 0.2 °C min^{-1}, and (iii) kept at steady-state conditions for 24 h. The conditioning phase was followed by the deviatoric loading phase in which the specimen was loaded to the peak in triaxial compression.

2.4. Test programme

The experimental programme comprised a total of 49 tests. The specimens were heated at one of the two different rates

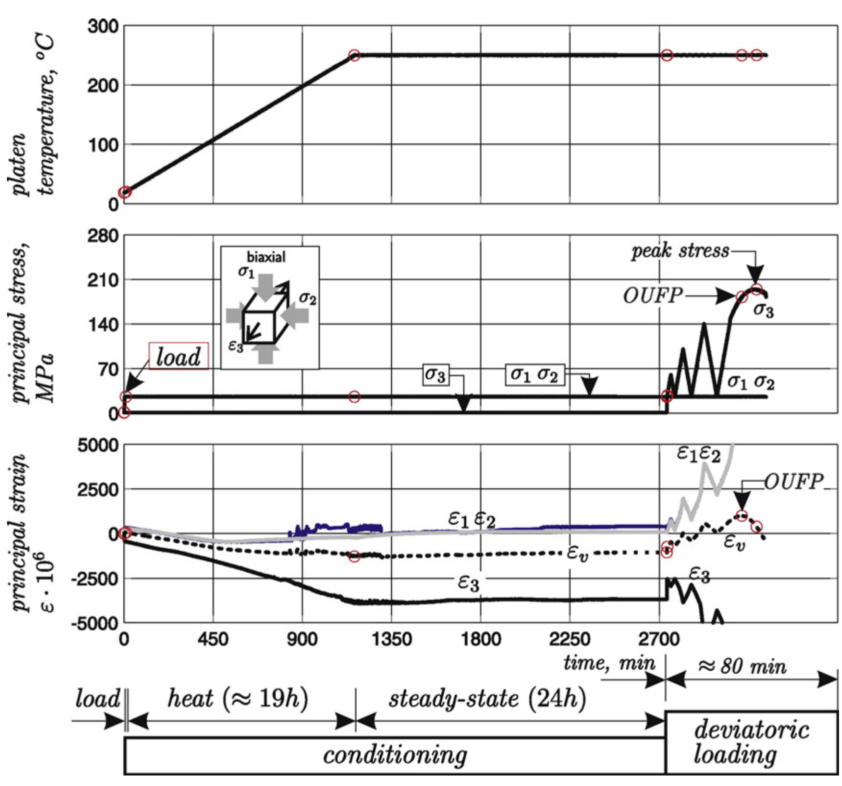


Fig. 4. Temperature, stress and strain histories in a typical biaxial load-then-heat (LHS) test.

(0.2 °C min^{-1} or 2 °C min^{-1}), under uniaxial, equal-biaxial or hydrostatic compression of either 13 MPa (0.22f_c) or 26 MPa (0.44f_c). The scope of the experiments is summarised in Table 2 showing the test series (A–E), number of repeats in each test series (N_r), test regime (loading, heating, cooling and steady-state; *LHCS*), stresses, heating rates ($\dot{T}$), and maximum temperatures ($\hat{T}$) in the heating/cooling sequences, and duration and stresses in the steady-state sequences.

3. Test results

Results from the tests performed at the faster heating rate (2 °C min^{-1}, series A and B) are given in Fig. 5. The graphs showing strains during the heating of unloaded specimens (HS tests, A1 and B1) represent drying shrinkage (ε_{sh}), obtained by subtracting the previously recorded free thermal expansion histories from the total strains measured in the tests. The strains of the specimens heated under load (LHS tests, A2 and B2), were obtained by removing the instantaneous strains that occurred as a result of the applied load at the beginning and then subtracting the (same) free thermal expansion histories from the total strains recorded in the tests. LITS is defined as the difference between the total strains measured in the LHS and HS tests, as described in Fig. 1.

The strain histories in Fig. 5 show that the shrinkage recorded in the HS tests (A1, B1) stabilised at $t \approx 180$ min, about 60 min after the platen temperature reached 250 °C, at a time when the temperature at the centre of the specimen was about 220 °C and still rising. This indicates that at this point most of the free water in the capillary pores had been removed by evaporation. The strains in the uniaxial compression tests (B2) continued to increase after $t = 180$ min, but at a decreasing rate. However, in the tests where the specimens were heated under a hydrostatic compression of 26 MPa (B2), the rate of strain increase remained unchanged even after $t = 240$ min, the point when the specimen may be considered to have approached a state of *thermal* (but not necessarily hygral) equilibrium. This indicates that the delayed drying, possibly caused by the reduced permeability under low-to-moderate hydrostatic compression, resulted in a delay in the development of LITS. The assumption of LITS being a strain that is only seen during heating needs further qualification. Depending on the specimen size and boundary conditions, LITS may continue at constant temperature as a consequence of local moisture transport driven by a non-equilibrium internal state.

The influence of the heating rate on LITS was investigated in two series of tests (C and D) in which the specimens were first heated to 250 °C at 0.2 °C min^{-1} and then subjected to extended periods of steady-state conditions (94 h in series C; 24 h in series D). The tests were performed under five different heat–load regimes: (i) heat-then-load hydrostatically (C1), (ii) heat-then-load uniaxially (C2, D1), (iii) load uniaxially then heat (C3, D2, D4), (iv) load hydrostatically then heat (C4), and (v) load biaxially then heat (D3). The stresses applied in all tests were 26 MPa (or 0.44f_c).

The results of the tests performed at the slower heating rate (C–D), presented in Fig. 6, show the strain histories obtained by removing the instantaneous strains (from the LHS and HLS results) and subtracting the free thermal expansion from the total strains recorded during the first 40 h (≈ 19 h heating plus ≈ 21 h at steady-state). The free thermal expansion in the C–D tests was assumed as a linear function of temperature ($\alpha \Delta T$), using the coefficient of thermal expansion measured in calibration tests ($\alpha = 10.5\ \mu\varepsilon$ °C^{-1}).

Fig. 7 gives a summary of the averaged strains recorded in all tests. The temperature–strain graphs show that the strains at the end of the heating sequences in the 0.2 °C min^{-1} tests (C–D) are very close to those recorded in the 2 °C min^{-1} tests (A–B) after 2–4 h at constant temperature. This suggests that LITS does reach the same value for a given temperature, regardless of the heating rate, but the temperature–strain relationship depends on the heating rate, or more generally, on the moisture conditions in the specimen. It can also be noticed that LITS sharply increases at temperatures above 100 °C, suggesting that it is accelerated with the phase-change in the free water and the resulting increase

Table 2
Test programme: conditioning phase

Test	N_r	Regime	Heating/cooling					Steady-state			
			$\overline{\sigma}_x$	$\overline{\sigma}_y$	$\overline{\sigma}_z$	$\dot{T}$	$\hat{T}$	Time	$\overline{\sigma}_x$	$\overline{\sigma}_y$	$\overline{\sigma}_z$
			MPa	M Pa	MPa	°C min^{-1}	°C	h	MPa	MPa	MPa
A1	6	*HS*	0.8	0.8	0.8	2.0	250	1.1	0.8	0.8	0.8
A2	6	*LHS*	12.9	12.9	12.9	2.0	250	1.5	12.9	12.9	12.9
B1	6	*HS*	0.9	0.9	0.9	2.0	250	2.1	0.9	0.9	0.9
B2	6	*LHS*	25.8	25.8	25.8	2.0	250	4.1	25.8	25.8	25.8
C1	2	*HLS*	0.9	0.9	0.9	0.2	250	96.0	25.9	25.9	25.9
C2	2	*HLS*	0.9	0.9	0.9	0.2	250	96.0	0.9	0.9	25.9
C3	2	*LHS*	0.9	0.9	25.9	0.2	250	96.0	0.9	0.9	26.0
C4	2	*LHS*	25.9	25.9	25.9	0.2	250	94.3	25.9	25.9	25.9
D1	3	*HS*	0.9	0.9	0.9	0.2	250	24.0	0.9	0.9	0.9
D2	4	*LHS*	0.9	0.9	25.8	0.2	250	24.3	0.9	0.9	25.8
D3	4	*LHS*	25.9	25.9	0.9	0.2	250	24.1	25.9	25.9	0.9
D4	2	*LHS*	0.9	25.9	0.9	0.2	250	25.9	0.9	25.9	0.9
E1	2	*LHCHS*	0.9	0.9	25.8	±0.2	150–20–250	94.0	0.9	0.9	25.8
E2	2	*LHCHS*	0.9	0.9	25.9	±0.2	250–20–250	73.0	0.9	0.9	25.9

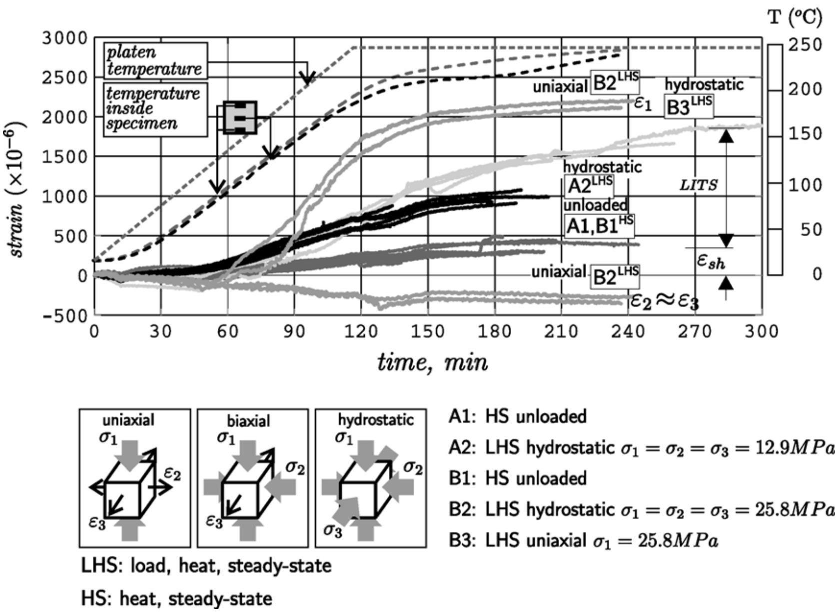


Fig. 5. Strain histories recorded in fast-heating tests (2 °C min^{-1}). Compactive strains are shown as positive.

in permeability. The absence of LITS under hydrostatic compression at $T<100$ °C can also be explained by the suppressed moisture movement due to reduced permeability through microcrack closure under volumetric compaction. The results show very little LITS differences in the direction of the applied uniaxial and equal-biaxial compression stresses. This suggests an anisotropic response. An isotropic elastic analogy would predict biaxial strains ≈30% smaller than those seen under uniaxial loading. Quite different, but not unexpected, expansions were recorded in the unloaded directions. The transverse dilation can be approximated using an apparent *LITS Poisson's ratio* (not strictly Poisson's ratio at all, but a measure accounting for the multiaxial nature of LITS [10]). At 250 °C the ν_{LITS} were noticeably larger than the conventional elastic value (≈0.2) and differed between the test paths: 0.34 for uniaxial compression ($\nu_{\mathrm{LITS}}=-\Delta\varepsilon_{\mathrm{LITS}_3}/\Delta\varepsilon_{\mathrm{LITS}_1}$) and 0.37 for equal-biaxial compression ($\nu_{\mathrm{LITS}}=\Delta\varepsilon_{\mathrm{LITS}_3}/(\Delta\varepsilon_{\mathrm{LITS}_3}-2\Delta\varepsilon_{\mathrm{LITS}_1})$).

The comparison of the averaged mac^{2T} temperature–strain curve with the results of previous uniaxial compression tests (Fig. 8) shows that the average LITS measured in mac^{2T} under 40%f_c is close to that recorded at 20–22.5%f_c in unsealed tests on similar types of concrete [9,12,16]. The previous test results show very little difference between LITS measured in tests on air-dried specimens heated at 0.2 °C min^{-1} [12] and 5 °C min^{-1} [9]. However the strains recorded in tests on saturated basalt concrete heated at 1 °C min^{-1} [12] are nearly 50% lower than those recorded on the same concrete heated at 0.2 °C min^{-1}, and thus closer to the results obtained in mac^{2T}. This indicates that even in unsealed conditions LITS is affected by delayed drying at higher heating rates.

Another indication of LITS dependency on moisture movement is the increase of strain rates at 100 °C, when the water changes phase, resulting in increased permeability of the material. This effect, noticeable in all tests, is particularly evident in

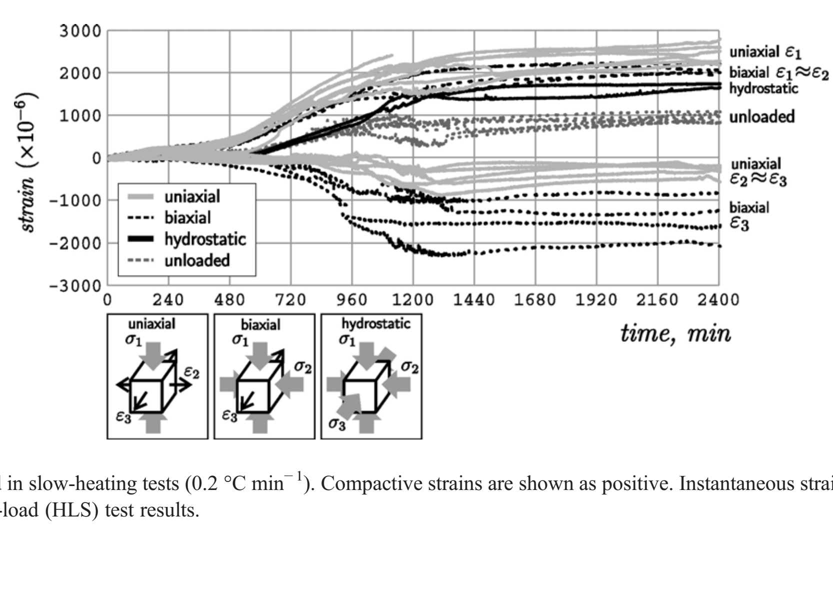


Fig. 6. Strain histories recorded in slow-heating tests (0.2 °C min^{-1}). Compactive strains are shown as positive. Instantaneous strain ε_σ has been removed from load-then-heat (LHS) and heat-then-load (HLS) test results.

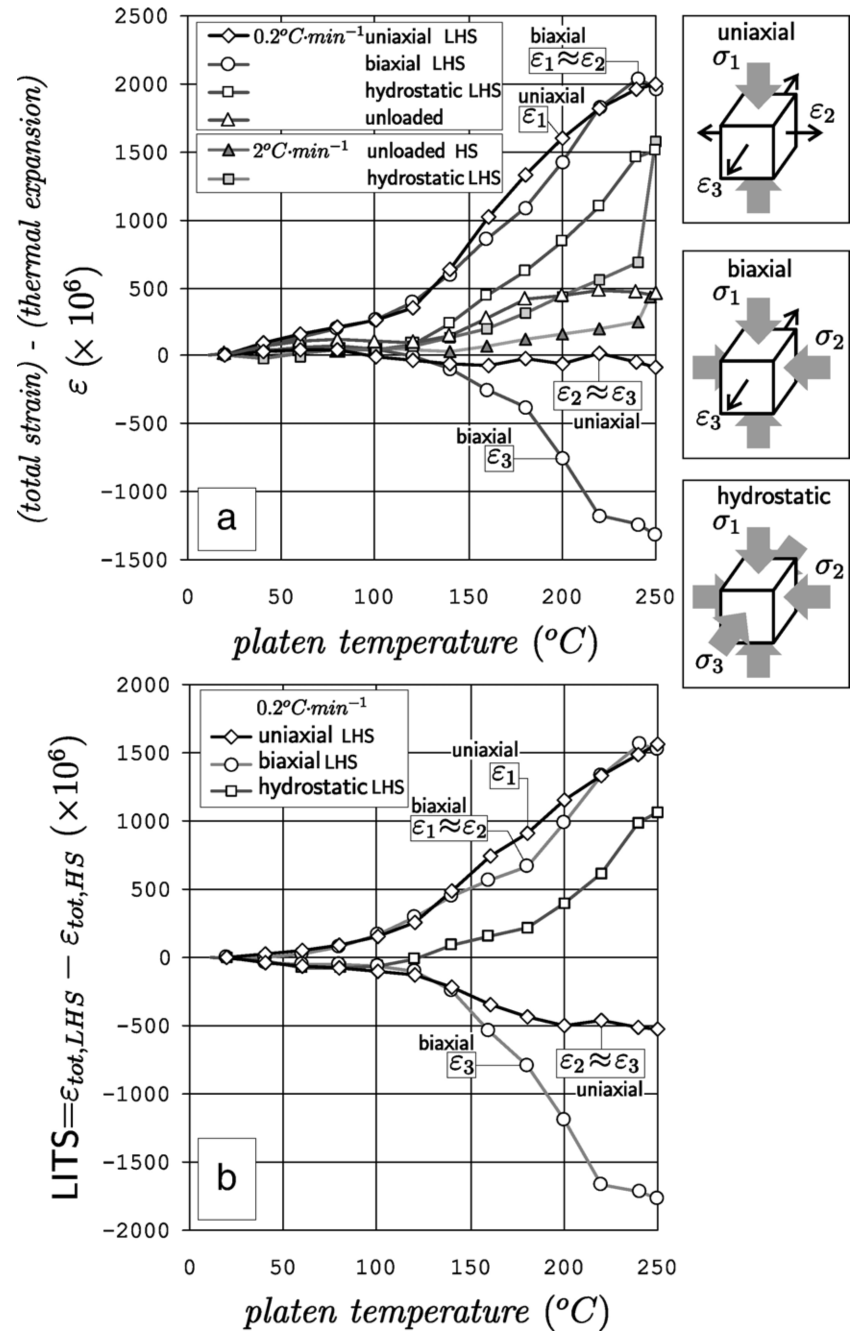


Fig. 7. Average temperature–strain relationships from all LHS and HS tests: (a) LITS and shrinkage, (b) LITS. Compactive strains are shown as positive. Instantaneous strain ε_σ has been removed from load-then-heat (LHS) test results.

the mac^{2T} results, where moisture evacuation is suppressed by the partially sealed boundaries.

LITS under equal-biaxial compression measured in the two loading directions in mac^{2T} at 250 °C is similar to that recorded by Kordina et al. [16] (Fig. 9). As mentioned above, the particular boundary conditions in mac^{2T} lead to reduced LITS at lower temperatures; a trend similar to that observed in uniaxial compression. We note that the equal-biaxial expansion recorded by Kordina in the unloaded direction was remarkably large. In those experiments, for example, an apparent LITS Poisson's ratio of 0.66 is seen at 100 °C. This effective material expansion is curious; it may have been a consequence of the brush platen arrangement in the Braunschweig rig.

The results of the temperature cycling tests (series E) are shown in Fig. 10. The strains during the heating phases (up to 150 °C in E1, and 250 °C in E2) are similar to those recorded in the other LHS tests under uniaxial compression (results of two C series tests are included in Fig. 10-b for comparison). Despite the slow heating rate, some strain increase can be noticed during the 6–12 h periods following the heating phases, and during the cooling and re-heating to the peak temperature of the first cycle. Once the temperature in the second cycle (tests E1) exceeded 150 °C, the maximum temperature of the first cycle, the strains started increasing at a rate similar to that at the end of the first cycle. The results of these tests show again that while dependent on heating and drying rates, LITS appear to have a finite magnitude for a given temperature, suggesting a finite fluid-exchange process on the microlevel. The absence of significant strain rate changes during cooling and re-heating confirms the conclusions of the previous studies [5,12,18] that LITS is a phenomenon that only occurs during the first heating of concrete to a given temperature. These results showed no evidence of *a transient increase in creep after a temperature change, both heating and cooling*, as suggested by Bažant et al. [21].

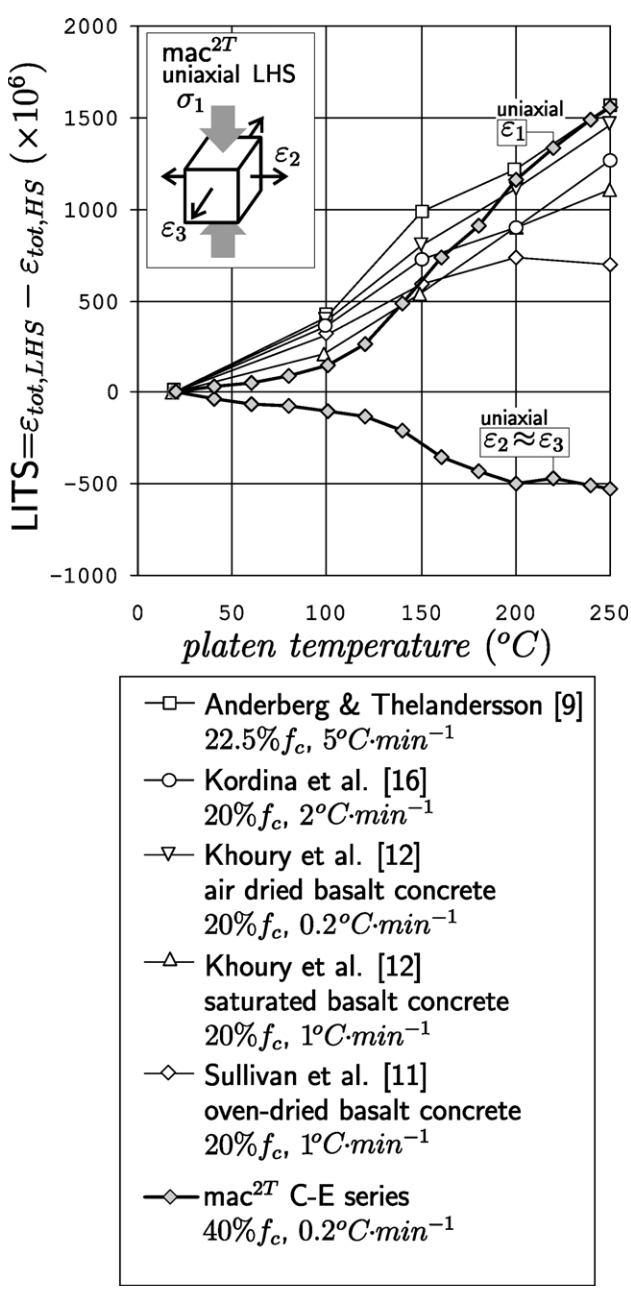


Fig. 8. LITS under uniaxial compression: comparison of average strains recorded in mac^{2T} with results of previous tests. Compactive strains are shown as positive.

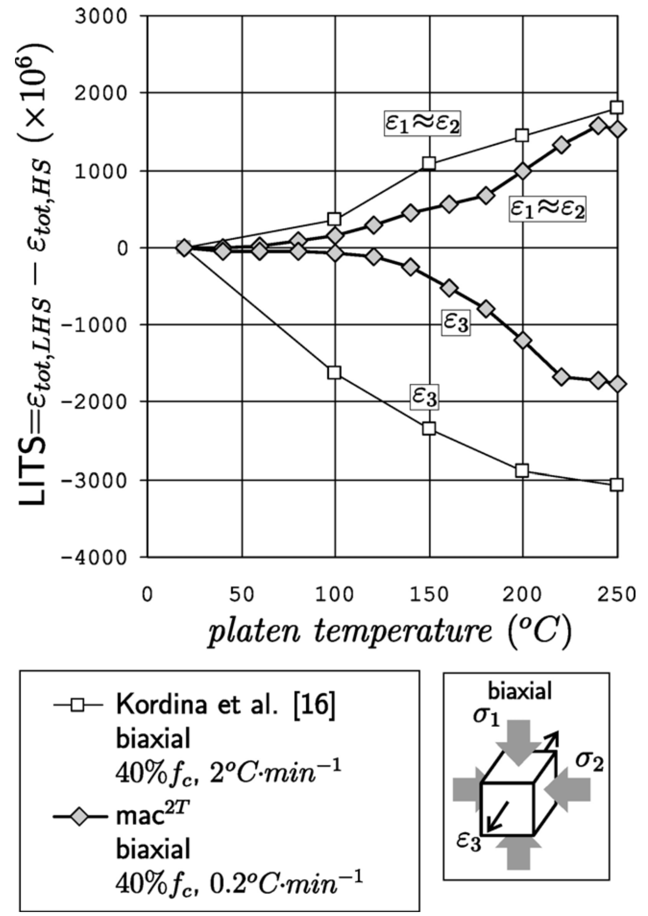


Fig. 9. LITS under equal-biaxial compression: comparison of average strains recorded in mac^{2T} with results of previous tests. Compactive strains are shown as positive.

4. Conclusions

The experimental investigation of load-induced thermal strains in structural concrete heated to 250 °C under uniaxial, equal-biaxial and hydrostatic compression, in partially sealed conditions, led to the following conclusions:

(i) LITS is a function of load, temperature and moisture movement. The uniaxial temperature–LITS curve is strongly affected by the relationship between the heating rate and the rate of moisture evacuation. If the heating rate is sufficiently high for the given moisture transport conditions (initial moisture content, permeability of the material, specimen size and boundaries), then LITS continues at constant temperature until the material reaches hygral equilibrium for that particular temperature level. This implies that there is an *equilibrium heating rate* for given moisture transport conditions, which takes account of the changes in permeability caused by the magnitude and direction of the applied load. Hence, the

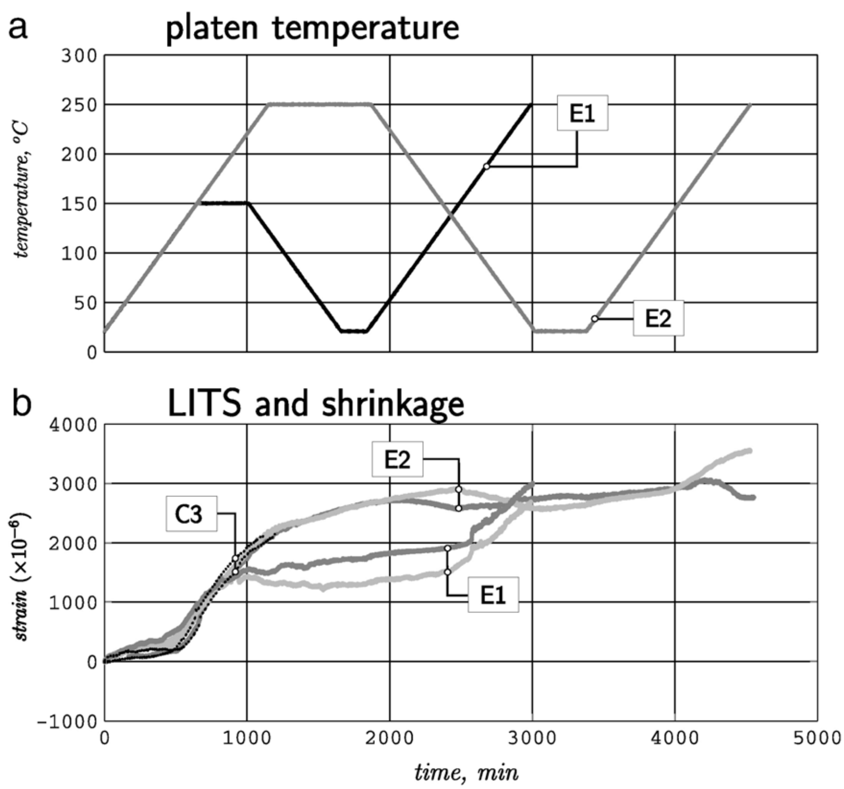


Fig. 10. LITS during thermal cycling under uniaxial compression. Compactive strains are shown as positive.

commonly accepted description of LITS as a function of load and temperature can only be applied to special cases when the heating rate is below the *equilibrium rate*. The LITS dependency on moisture transport appears to contradict the results of the early experiments in which excessive strain was observed in the load-then-heat tests on specimens submerged in water. This can be resolved by an assumption that LITS is caused by microdiffusion, or exchange of water between the adjacent gel pores (micropores) and the pores of the capillary system (macropores). This mechanism, first proposed by Hansen and Eriksson [1], was adopted by Bažant and Chern [22] as an underlying mechanism for *stress-induced shrinkage* or drying creep ("*the microdiffusion of water disrupts the solid microstructure of cement gel by promoting the debonding and rebonding process that is source of creep*"). Bažant and Chern noted that macrodiffusion, or movement of water through the macropores of the capillary system, could be eliminated as a source of increased strain, based on observations that steady-state permeation of water through concrete had no effect on creep. If microdiffusion happens in loaded concrete in drying conditions (at constant temperature), it is reasonable to expect an increased microdiffusion when the concrete is loaded and then heated. If the microdiffusion is a result of heat-induced increase in micropore pressure, rather than loss of macropore water, then it will also occur when loaded specimens are heated under water.

(ii) LITS only occurs upon first heating of loaded concrete to a given temperature and not during cooling or upon second heating to the same temperature. As soon as the temperature in the second heating cycle exceeds the previously attained level, the strains start to increase again, at a rate similar to that in the first cycle.
(iii) The biaxial compression strains in the loaded directions were close to those obtained in previous tests by others, but the expansion in the unloaded direction was significantly lower. The effective LITS Poisson's ratio at 250 °C was between 0.34 and 0.37 (from uniaxial and equal-biaxial compression data, respectively). This is considerably lower than the value of 0.46 recorded by Kordina et al. at this temperature in their biaxial tests [16]. Although the mean isotropic value $\nu_{\mathrm{LITS}} \approx 0.35$ may be useful for preliminary engineering analyses, the test data suggest that LITS are more properly viewed as anisotropic.
(iv) The LITS coefficient (β in the work of Thelandersson [10]) appears to be a function of the spherical stress component of the compression path; the value is larger for trajectories directed closer to the hydrostatic axis. This may explain the similar LITS in the major principal directions recorded under uniaxial and equal-biaxial compression.

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