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Effects of stress during heating on strength and stiffness of concrete at elevated temperature

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A R T I C L E I N F O

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Concrete in structures exposed to high temperatures is practically always heated under stress. Yet, there are few experimental studies in which the concrete was heated under stress and then loaded to the peak, and most of these were performed under uniaxial compression. This paper reports on an experimental study of the effects of different heat–load regimes on the stress–strain behaviour of partially sealed concrete under multiaxial compression, at elevated temperature. The specimens were first heated (stressed/unstressed), then loaded to the peak in multiaxial compression. In contrast with previous experimental research, the results show that concrete heated under relatively low compressive stress has lower strength and stiffness than concrete heated without load. The results suggest that the presence of stress during first heating produces a specific damage, which could be the cause for a major component of the *load induced thermal strain* (LITS) in concrete.

1. Introduction

The first experiments on concrete heated under stress were reported by Malhotra in 1956 [1]. The author found that the *hot* strength of specimens that were heated under constant stress of approximately 0.2 f_c (where f_c is uniaxial compressive strength at ambient temperature) was higher than that of specimens heated without load. The difference increased with the increase of temperature, from 4% at 200 °C to 21% at 500 °C. In 1971 Abrams reported on a study [2] in which specimens of six different concretes were (i) loaded in uniaxial compression to 0.25, 0.40 and 0.55 of compressive strength f_c, (ii) heated to 204 °C, 482 °C and 704 °C, and (iii) tested to peak stress in uniaxial compression. The results confirmed Malhotra's findings, showing 5–25% higher *hot* strengths than the companion specimens heated without stress, in all tests, regardless of aggregate type, mix proportions, compressive strength at ambient temperature, temperature at which the specimens were heated or level of stress during heating.

In 1966 Hansen and Eriksson [3] discovered that cement and mortar specimens heated under load deformed more than specimens that were first heated and then loaded. Moreover, this relatively large extra strain, which became known as transient (or transitional) thermal creep (TTC), was only observed during the first heating to a certain temperature. In the last 40 years TTC was investigated in experiments on different types of concrete, subjected to different (moderate) uniaxial [4,5] and biaxial [6] stress levels and heated, at different rates, to temperatures of up to 600 °C. This experimental research focussed on the temperature–strain relationships and the material and environmental factors that had influence on them. It was generally accepted that the mechanism that caused this strain was some form of creep, although this was never supported by any direct experimental evidence.

Khoury et al. renamed this strain to *load induced thermal strain* (LITS) and defined it simply as a difference between strains during heating of stressed and unstressed concrete [5]. They assumed that it was a result of several different mechanisms, with transient thermal creep and drying creep as main contributors. In one of their test programmes Khoury et al. heated concrete specimens to 600 °C under uniaxial compression of 0.1, 0.2 and 0.3 f_c [5], then cooled them down and tested at ambient temperature [7]. They found that the residual strength was significantly higher than that of the control specimens (heated without load), reaching maximum at stresses between 20% and 30% of f_c. The authors assumed that the strength increase was due to “densification of the cement paste” and “reduction of tensile stresses during cooling”. In 1988 Schneider [8] presented results showing increase of modulus of elasticity when the specimens were heated under stress between 0 and 0.30 f_c, but very little change for stresses between 0.3 and 0.5 f_c; for concrete tested at temperatures between 150 °C and 750 °C. He concluded that it was “evident that the *stressed strength* is higher than *unstressed strength*”.

There are, however, some experimental data that do not support a general conclusion that load during heating has beneficial effects on the strength of concrete. Anderberg and Thelandersson ([4], 1976) found that heating under stresses between 0.1 f_c and 0.45 f_c increased significantly the modulus of elasticity, reduced the “ultimate strain” (strain at peak load), but had practically no effect on the *hot* compressive strength.

In 1993 Sarshar and Khoury presented a study [9] in which specimens produced from 5 different mixes were heated to temperatures up to 600 °C at 1 °C min^{-1} and 3 °C min^{-1}, under 0.1 f_c and 0.15 f_c

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stress, and tested to peak stress immediately after reaching peak temperature, after a period at constant temperature and after cooling. They found that the *hot* strength of concrete with firebrick aggregates heated under 0.15 f_c stress was slightly higher than that of the control specimens, but the concrete with Lytag aggregates showed no difference. In contrast to the concrete behaviour, the cement paste specimens heated under load, after cooling, developed cracks in the direction of the load. Their (residual) strength was much lower than that measured on specimens heated without load. The authors had no explanation for this, other than the assumption that aggregates prohibited this behaviour in concrete specimens.

Another finding of the Sarshar and Khoury study [9] was that the strength of their cement paste specimens was also affected by the heating rates, with OPC specimens heated faster (3 °C min^{-1}) showing lower strength at 300 °C, but similar strength at 500 °C. The silica fume paste specimens showed opposite behaviour: similar strength at 300 °C, but complete disintegration when heated at 3 °C min^{-1} to 520 °C. The strength of concrete specimens, however, increased with the increase of heating rate, confirming the similar findings in earlier studies [7,10]. The authors attributed this effect to weakening of the material due to increased periods of exposure to high temperature.

In large structural cross sections subjected to elevated temperature the moisture content in the concrete varies in time and space. In general, the behaviour of concrete at elevated temperature depends on a number of coupled thermo-hygro-mechanical factors, such as heating rate, temperature level, stress magnitude and direction, initial moisture content and vapour pressures; as well as their history (first heating, heating–cooling cycles, load–heat regimes, etc.).

Lankard et al. ([11], 1971) investigated the effects of moisture content by testing sealed and unsealed specimens, heated without load to temperatures of up to 260 °C. They found that heating of unsealed specimens resulted in little loss of uniaxial compressive strength and small reduction of modulus of elasticity. Heating of sealed specimens, however, led to about 50% loss of strength and nearly 70% reduction in modulus of elasticity. Callahan et al. ([12], 1978) compared unsealed-hot and sealed-residual properties of limestone concrete. They found that at 250 °C (i) unsealed-hot strength was 35% higher than sealed-residual strength, and (ii) modulus of elasticity, while dramatically reduced by high temperatures, was similar for the two test conditions. Callahan et al. [12] concluded that data from unsealed tests “cannot be used to predict the behaviour of sealed specimens”.

Despite the fact that structural concrete is generally subjected to multiaxial stress conditions, practically all experimental research has been carried out on specimens loaded in uniaxial compression. The only experimental investigation of concrete under biaxial compression at elevated temperature was carried out by researchers at the University of Braunschweig [6]. They heated unstressed specimens to different temperatures (up to 600 °C, at 2 °C min^{-1}) and then loaded to peak stress in biaxial compression, applied at a variation of σ_1/σ_2 ratios. The results show different shapes of biaxial strength envelopes recorded at different temperatures. At lower temperatures (ambient to 300 °C) the maximum stress was recorded for $\sigma_1/\sigma_2=0.5$; whereas the maximum stress at 600 °C was recorded for $\sigma_1/\sigma_2=1$. The only multiaxial compression tests at elevated temperature were performed in the triaxial torsional rig at Northwestern University [13]. This research was focussed on studying strains under multiaxial compression at elevated temperature and in controlled hygral conditions. The tests were mainly limited to low stress levels, and the subsequent strength or stress–strain behaviour at high stress levels were not investigated.

In 2003 Černý et al. presented a detailed experimental study of the effects of different heat–load regimes on thermal and hygric properties of Portland cement mortar [14]. Specimens loaded to 0.9 f_c were heated to 800 °C at a relatively high rate of 6.7 °C min^{-1} and compared to specimens heated without load. The moisture diffusivity for specimens heated without load was found to be 10 times greater than that for specimens heated under load. The authors explained this difference by assuming that explosive pore failures were caused by build-up of pore pressures during heating of unstressed specimens, whereas the load applied before heating created cracks which prevented the increase in pore pressures.

Concrete strength at elevated temperature still attracts significant attention from researchers. Experimental studies carried out in the last 10 years focussed on the effects of various material characteristics on residual strength of unstressed concrete heated to high temperatures [15–18]. A review of the research on concrete at elevated temperature that was carried out in China in the period between 1990 and 2001 [19], also shows a focus on residual, uniaxial compression strength of unsealed specimens heated without load. The exceptions were one study in which the tests were performed under biaxial compression, and one in which the specimens were heated under load.

This review shows that most of the research of concrete at elevated temperature has been carried out by heating relatively small, unsealed, unstressed specimens, at relatively low heating rates and then loading them to peak stress in uniaxial compression. The results of these experiments are not directly applicable to real-life cases of concrete structures subjected to fire or other elevated temperature situations. In reality, most of the material in structural concrete elements is partially sealed and heated under various multiaxial stress conditions.

The conclusions derived from the existing experimental data are that: (i) the strength of concrete heated under load is either higher than or equal to the strength of concrete heated without load (both for *hot* and residual *cold* strength); (ii) longer exposure to elevated temperatures reduces strength (hence higher heating rates resulting in shorter exposure also improve strength), and (iii) compressive strength is reduced more if the concrete is heated in sealed conditions.

The study presented in this paper was designed to address the lack of experimental data on the effects of heating under different stress conditions on the subsequent (*hot*) stress–strain behaviour of concrete under multiaxial compression.

2. Experimental set-up, test specimens and methodology

2.1. Experimental set-up

The experiments presented here were carried out in mac^{2T} [20], the University of Sheffield's apparatus for testing concrete under multiaxial compression at elevated temperature (Fig. 1). This facility comprises three independent 4 MN frames which can deliver 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. During the test the specimens are heated through 95 mm^2 steel loading platens (Fig. 1b), which are always in contact with the specimen, covering over 90% of its surface and creating *partially sealed* conditions.

2.2. Concrete mix and specimen preparation

All tests in the presented experimental programme were carried out on one type of structural concrete, similar to those used in concrete structures in UK nuclear power plants. The materials used for the mix were: (i) crushed quartz-dolerite for coarse aggregates (10 mm and 20 mm), (ii) marine-dredged, washed calcareous quartz sand (archive material) as fine aggregate, (iii) Ordinary Portland Cement (Hope Valley, 300 m^2/kg), (iv) Ferry Bridge PFA with 7–10% residue on 45 μm sieve, 4% loss of ignition and less than 2% moisture content, and (iv) Daracem® SP4 plasticiser; with mix proportions given in Table 1.

All tests were performed on 100 mm (nominal size) cubic specimens. The concrete was cast in slabs with dimensions 740 × 620 × 150 mm. After casting the concrete was subjected to a 10 days temperature-matched curing cycle ($T_{max}=65$ °C reached after 36 h), after which 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

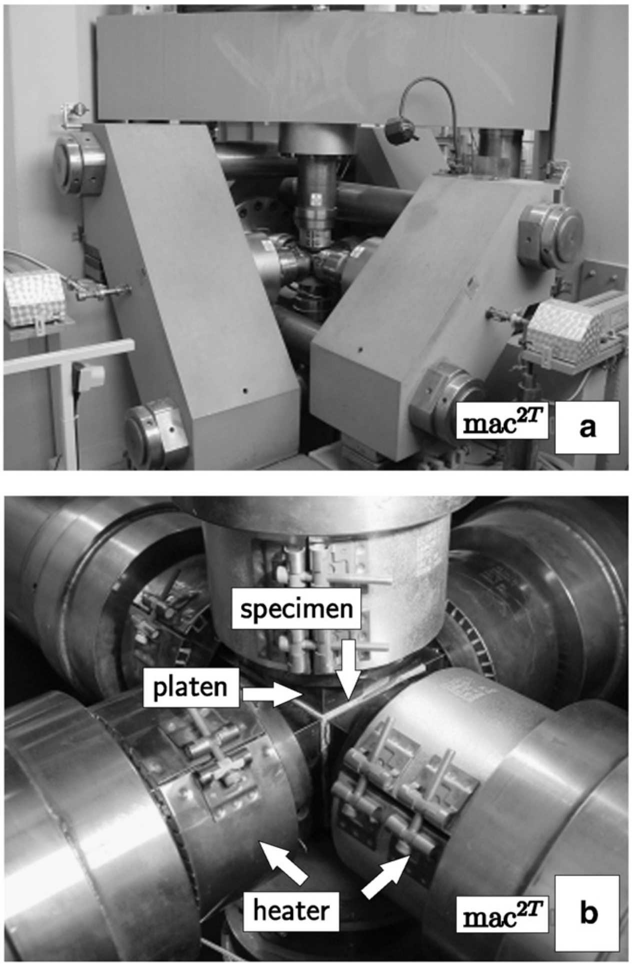

Fig. 1. mac^{2T} tests facility: (a) loading frames, and (b) loading platens and heaters.

(i) cut into prisms with dimensions 101 × 101 × 150 mm, (ii) then cut into 101 mm cubes (by removing top and bottom 24.5 mm), and finally machined to right-regular 100 mm cubes. 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).

2.3. Test methodology

The investigation of the influence of different heat–load regimes on the *hot* stress–strain behaviour of concrete was carried out as a part of an experimental programme that included a study of load induced thermal strain (LITS) in concrete subjected to multiaxial stress and heated to 250 °C [21].

All tests in the programme were performed as continuous experiments comprising two phases: (i) conditioning (LITS measurements) and (ii) deviatoric loading (loading to the peak, following different multiaxial stress paths).

2.3.1. Conditioning phase

The conditioning phases comprised transient (heating *H* and cooling *C*) and steady-state sequences (*S*), during which the specimens were either loaded (*L*) or unloaded. All tests were carried out by applying one of the following four heat–load regimes: (*HS*) heating without load and holding at steady-state (constant temperature), (*HLS*) heating without load, loading, and holding at steady-state conditions (constant load and temperature), (*LHS*) loading, heating and holding at steady-state, and (*LHCHS*) loading, temperature cycling (heat–cool–heat), and holding at steady-state.

Table 1
Concrete mix proportions.

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

Low-to-moderate stresses used in the conditioning phases were chosen to represent service conditions in a three-dimensional structure under multiaxial compression. One of the following three loads was used in the tests (see Fig. 2): (L_h) hydrostatic compression: $\sigma_1 = \sigma_2 = \sigma_3 = \sigma_c$, ($L_C$) uniaxial compression: $\sigma_1 = \sigma_c$; $\sigma_2 = \sigma_3 = \sigma_0$ (compression meridian plane, $\theta = \pi/6$), or (L_E) equal biaxial compression: $\sigma_1 = \sigma_2 = \sigma_c$; $\sigma_3 = \sigma_0$ (extension meridian plane, $\theta = -\pi/6$, shown as an example in Fig. 2); where σ_c was either 13 MPa (0.22 f_c) or 26 MPa (0.44 f_c), and σ_0 was a small contact stress (nominally 1 MPa).

The specimens were heated to the maximum platen (or surface) temperature of $\hat{T} = 250$ °C at a constant rate of either 0.2 °C min^{-1} (*slow*) or 2 °C min^{-1} (*fast*). Calibration tests on specimens with embedded thermocouples showed that when the concrete was heated to surface temperature of 250 °C at 2 °C min^{-1}, and then kept at constant temperature, the centre of the specimen reached this temperature after 12 h. The periods of constant surface temperature (*steady-state*), ranging from 24 to 96 h, were added to the transient temperature sequences primarily to monitor the strain changes (LITS/creep), but also to allow thermal and hygral equilibrium in the specimen before starting the deviatoric loading phase. The strains measured during the conditioning phases were used to determine LITS, defined as a difference between the total strains recorded in *LHS* and *HS* tests [21].

2.3.2. Deviatoric loading phase

The effects of different conditioning regimes on the stress–strain behaviour of the material under multiaxial compression were investigated in the second, deviatoric loading phase, performed at a constant temperature of 250 °C. When the conditioning phase was completed, the specimens were first loaded to hydrostatic compression ($\sigma_1 = \sigma_2 = \sigma_3 = \sigma_c$) and then loaded deviatorically. The deviatoric load was applied in three cycles between σ_c and 0.25, 0.50 and 0.75 of (predicted) peak stress, followed by monotonic loading to the peak. All tests were performed by conventional multiaxial loading, where the minor principal stresses were kept constant, while the major and intermediate principal stresses were increased proportionately, depending on the Lode angle θ. In this test series, the deviatoric loads were applied in one of the following three meridional planes (Fig. 2): (L_C) compression ($\theta = \pi/6$; $\sigma_1 = \sigma_c + \Delta\sigma$, $\sigma_2 = \sigma_3 = \sigma_c$), ($L_S$) shear ($\theta = 0$; $\sigma_1 = \sigma_c + \Delta\sigma$, $\sigma_2 = \sigma_c + \Delta\sigma/2$, $\sigma_3 = \sigma_c$), and (L_E) extension ($\theta = -\pi/6$; $\sigma_1 = \sigma_2 = \sigma_c + \Delta\sigma$; $\sigma_3 = \sigma_c$).

The test methodology is illustrated on three typical tests presented in Fig. 3: (a) time history of platen temperature in the three tests, (b) time histories of the three principal stresses recorded in each of the three tests, (c) deviatoric section graphs that show the loading directions in both conditioning and deviatoric loading phases of each test, and (d) stress paths in the three tests, plotted in $\xi - \rho$ coordinates, in their respective meridional planes. The three tests shown in Fig. 3 were carried out by the following test procedures:

- $L_{Ez}HSL_{Cz}$: The specimen was (i) loaded in triaxial extension to $\sigma_x = \sigma_y = 26$ MPa; $\sigma_z = 1$ MPa (L_{Ez}; marked as load$_1$ in Fig. 3b, d), (ii) heated to 250 °C (*H*), (iii) kept under steady-state conditions for 24 h (*S*), (iv) loaded to hydrostatic compression by increasing σ_z to 26 MPa

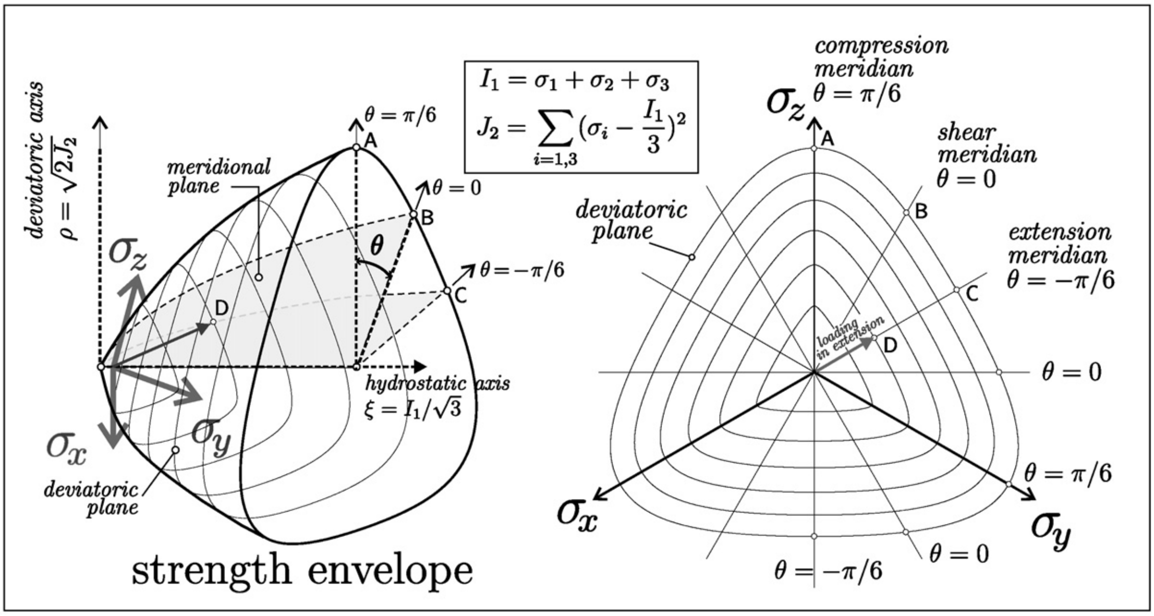

Fig. 2. Multiaxial compression testing: strength envelope, deviatoric sections and meridional planes.

(marked as load$_2$ in Fig 3b, d), and (v) loaded deviatorically in the compression meridian plane (L_{Cz}), by increasing σ_z in three cycles (c_1, c_2 and c_3, see Fig. 3b, d), and then to peak stress, while keeping $\sigma_x = \sigma_y$ constant at 26 MPa (conventional triaxial compression test). The load directions in Fig. 3c show that the specimen was first subjected to extension in the z-direction, during the conditioning stage, and then loaded to the peak in compression in the z-direction, during the deviatoric loading stage.

- $L_{Ez}HSL_{Ez}$: The specimen was (i) loaded in triaxial extension (L_{Ez}), (ii) heated to 250 °C (H), (iii) kept in steady-state conditions for 24 h (S), (iv) loaded to hydrostatic compression (load$_2$), and (v) load deviatorically in triaxial extension (L_{Ez}), by cycling $\sigma_x = \sigma_y$, while keeping σ_z constant at 26 MPa. Fig. 3c shows that the specimen was first loaded in z-extension in the conditioning stages, and then loaded to the peak in the same direction (z-extension).
- HSL_{Szx}: The specimen was (i) heated to 250 °C (H) without load (or, to be precise, under 1 MPa contact stress on all faces), (ii) held in steady-state conditions for 24 h (S), (iii) loaded to hydrostatic compression σ_c (load$_2$), and loaded in the shear meridian plane (L_{Szx}) by increasing σ_z in three cycles (c_1, c_2 and c_3, see Fig. 3b, d) and monotonically to the peak, while maintaining σ_x at $\sigma_c + \sigma_z/2$ and σ_y constant at $\sigma_c = 26$ MPa. The deviatoric section graphs in Fig. 3c show that the specimen was heated without load and then loaded to peak stress in the plane of the z–x shear meridian.

All stress histories in Fig. 3b show that in the last loading cycle, once the maximum stress of the 3rd cycle was exceeded, the loading rate was reduced. The reason for this is that when the specimen was loaded to the peak, the control of the major principal stress axis (or axes, in the extension meridian tests) was changed from stress to strain, so that the tests could run safely into the post-peak range. In all tests, the stress controlled loading–unloading was carried out at ±15.5 MPa min^{-1}, whereas the strain rate in the strain-controlled range was 600 με min^{-1}. In the strain-controlled sequences of tests performed in the shear meridian plane, the intermediate stress was controlled by updating the loading/unloading rate in order to maintain the constant ratio with the (measured) major principal stress.

2.3.3. Moisture conditions

In all tests of this programme the cyclic loading to the peak was performed at 250 °C, either after 21.5 h heating at 0.2°C min^{-1} or 2 h heating at 2 °C min^{-1} and extended periods at constant temperature (4–96 h). All tests were performed as continuous experiments in which the concrete was loaded in the post-peak region, which caused damage to the specimens and loss of material (debris). As a result of this the loss of moisture during heating could not be measured. The loss of mass during heating of hydrostatically loaded concrete was measured on control specimens heated in the rig for 24 h and then removed, without cyclic loading to the peak. The loss was 52 kg m^{-3}, about 15% lower than the 61 kg m^{-3} loss recorded for unsealed (and unloaded) specimens that were heated in an oven for 24 h at the same temperature. The loss of mass in control specimens heated in the oven for 22 days at 105 °C was between 39 and 45 kg m^{-3}. Additional heating of these specimens in the oven, for 24 h at 250 °C, resulted in a total loss of 60–61 kg m^{-3}, an almost identical loss with that of specimens that were not previously subjected to 22 days heating at 105 °C. A sudden increase in strain rate (LITS) at about 100 °C, noticed during the conditioning phases [21], but not in other LITS tests performed in unsealed conditions [5,6,24], was interpreted as an effect of the partially sealed conditions in the rig. This was particularly noticeable in tests in which the specimens were heated at a higher rate of 2 °C min^{-1} [21].

3. Test programme

The programme of experimental tests was designed to investigate:

(i) LITS under different loading/heating conditions (hydrostatic, uniaxial and equal biaxial compression), two different load levels 13 MPa (0.22 f_c) and 26 MPa (0.44 f_c), two heating rates (2 °C min^{-1} and 0.2 °C min^{-1}) and temperature cycling;
(ii) Creep (or delayed LITS) under *steady-state* conditions, with different duration (4–94 h), under different loads (hydrostatic, uniaxial and biaxial compression), following different heating–loading regimes;
(iii) Effects of heating–loading regimes on the subsequent *hot* stress–strain behaviour of the material (tangent stiffness and strength) under different multiaxial stress conditions.

The maximum temperature, heating rates and load during heating are representative for parts of prestressed concrete reactor vessels in operational conditions, rather than typical concrete structures in fire which are subjected to higher temperatures and heating rates. The data could however be useful for finite element modeling of massive

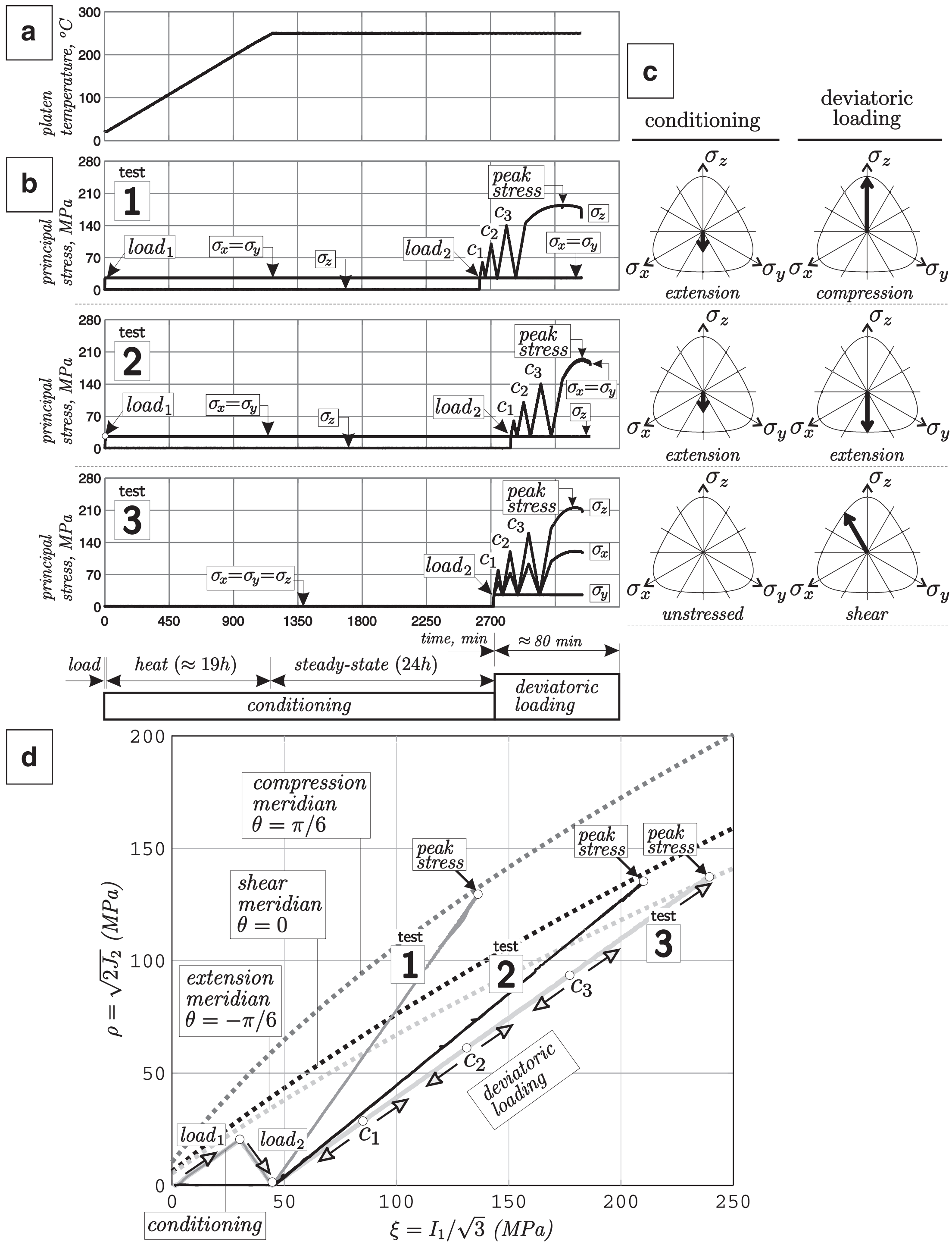

Fig. 3. Test methodology: test phases and heating–loading regimes; (a) temperature time history, (b) stress time histories in three typical tests, (c) meridional planes of load during conditioning and deviatoric loading stages, and (d) load paths in $\xi-\rho$ space.

concrete structures in fire, where the temperature and the heating rate inside thick sections could be much lower than those near the surface, and yet have significant influence on the stress–strain behaviour of the structure as a whole.

In Table 2 is presented the full programme of 24 different tests, performed in 5 series (A–E). N_r is the number of repeats of each test (the total number of tests is 49). The series denotes a change in test parameters: (A) heating under low hydrostatic confinement ($0.22\,f_c = 13$ MPa) and fast heating ($2°\mathrm{C\,min}^{-1}$); (B) same heating rate (fast), but higher hydrostatic confinement ($0.44\,f_c = 26$ MPa); (C) introducing heating under uniaxial compression, low heating rate ($0.2°\mathrm{C\,min}^{-1}$) and long steady-state periods (96 h), (D) a combination of loading directions during conditioning and deviatoric loading to the peak to investigate potential anisotropy induced by stress during heating; and (E) cyclic heating of loaded specimens (load, heat, cool, re-heat and then load to the peak).

The test code (in Table 1) denotes the series, number of the test in the series and the meridional plane in which the specimen was loaded during

Table 2
Test programme.

Test	N_r	Regime	Heating/cooling		Steady-state		Deviatoric loading		
			$\bar{\sigma}_x/\bar{\sigma}_y/\bar{\sigma}_z$	$\dot{T}$	$\bar{\sigma}_x/\bar{\sigma}_y/\bar{\sigma}_z$	Time	σ_c	$(k_x/k_y/k_z)^*$	θ
			MPa	$\frac{°C}{min}$	MPa	h	MPa		
A1C	3	HSL_{Cx}	1/1/1	2.0	1/1/1	1.1	13	1/0/0	$\pi/6$
A1E	3	HSL_{Ez}	1/1/1	2.0	1/1/1	1.1	13	1/1/0	$-\pi/6$
A2C	3	L_hHSL_{Cx}	13/13/13	2.0	13/13/13	1.5	13	1/0/0	$\pi/6$
A2E	3	L_hHSL_{Ez}	13/13/13	2.0	13/13/13	1.5	13	1/1/0	$-\pi/6$
B1C	2	HSL_{Cx}	1/1/1	2.0	1/1/1	2.1	26	1/0/0	$\pi/6$
B1E	2	HSL_{Ez}	1/1/1	2.0	1/1/1	2.1	26	1/1/0	$-\pi/6$
B1S	2	HSL_{Sxy}	1/1/1	2.0	1/1/1	2.1	26	1/0.5/0	0
B2C	2	L_hHSL_{Cx}	26/26/26	2.0	26/26/26	4.1	26	1/0/0	$\pi/6$
B2E	2	L_hHSL_{Ez}	26/26/26	2.0	26/26/26	4.1	26	1/1/0	$-\pi/6$
B2S	2	L_hHSL_{Sxy}	26/26/26	2.0	26/26/26	4.1	26	1/0.5/0	0
C1S	2	HL_hSL_{Szx}	1/1/1	0.2	26/26/26	96.0	26	0.5/0/1	0
C2S	2	$HL_{Cz}SL_{Szx}$	1/1/1	0.2	1/1/26	96.0	26	0.5/0/1	0
C3S	2	$L_{Cz}HSL_{Szx}$	1/1/26	0.2	1/1/26	96.0	26	0.5/0/1	0
C4S	2	L_hHSL_{Szx}	26/26/26	0.2	26/26/26	94.3	26	0.5/0/1	0
D1C	1	HSL_{Cz}	1/1/1	0.2	1/1/1	24.0	26	0/0/1	$\pi/6$
D1E	1	HSL_{Ez}	1/1/1	0.2	1/1/1	24.0	26	1/1/0	$-\pi/6$
D1S	1	HSL_{Szx}	1/1/1	0.2	1/1/1	24.0	26	0.5/0/1	0
D2C	2	$L_{Cz}HSL_{Cz}$	1/1/26	0.2	1/1/26	24.3	26	0/0/1	$\pi/6$
D2E	2	$L_{Cz}HSL_{Ez}$	1/1/26	0.2	1/1/26	25.8	26	1/1/0	$-\pi/6$
D2S	2	$L_{Cy}HSL_{Szx}$	1/26/1	0.2	1/26/1	25.9	26	0.5/0/1	0
D3C	2	$L_{Ez}HSL_{Cz}$	26/26/1	0.2	26/26/1	24.1	26	0/0/1	$\pi/6$
D3E	2	$L_{Ez}HSL_{Ez}$	26/26/1	0.2	26/26/1	24.1	26	1/1/0	$-\pi/6$
E1S	2	$L_{Cz}HCHSL_{Szx}$	1/1/26	± 0.2	1/1/26	94.0	26	0.5/0/1	0
E2S	2	$L_{Cz}HCHSL_{Szx}$	1/1/26	± 0.2	1/1/26	73.0	26	0.5/0/1	0

k_i is stress proportion factor: $\sigma_i = \sigma_c + k_i \Delta\sigma; i = x, y, z$.

the deviatoric loading stage (L_C for compression, L_E for extension and L_S for shear). The number denotes the conditioning regime: tests with the same number in a series (e.g. A1C/A1E, D1C/D1E/D1S) were performed by following the same conditioning regime and then by deviatoric loading to the peak in one of the three meridional planes (L_C, L_E or L_S). The code for the conditioning regime (in Table 2) denotes the test sequences: *H* for heating, *L* for loading (L_h hydrostatic, L_C compression, L_E extension, or L_S shear), *S* for steady-state, and *C* for cooling).

The three stresses during the heating/cooling and steady-state sequences, given in Table 2 as $\bar{\sigma}_x/\bar{\sigma}_y/\bar{\sigma}_z$, represent the nominal values. The values averaged from hours of recording (typically at 1 sample/second) were slightly different (within ±2% of the nominal values).

4. Test results

4.1. Test Series A and B: fast heating under hydrostatic stress

The first two series of load-then-heat (*LH*) tests were performed on specimens that were first loaded hydrostatically to two stress levels: 13 MPa ($0.2f_c$) in Series A; or 26 MPa ($0.2f_c$) in series B, and then heated to 250 °C at a rate of 2 °C min^{-1} (*fast*).

The control specimens (tests A1C/E and B1C/E/S in Table 2) were heated without load, kept at steady-state surface temperature for short periods of time (1.1 h/2.1 h), loaded hydrostatically to 13/26 MPa, and then loaded to the peak in different meridional planes: compression (A1C/B1C), extension (A1E/B1E) or shear (B1S); at constant surface temperature of 250 °C. The same deviatoric loading paths were used in the tests (A2C/E and B2C/E/S) in which the specimens were heated under load.

The comparatively higher strength of specimens heated under uniaxial stress, observed in previous studies, has been attributed to LITS which relaxed the thermal stresses and hence reduced the damage caused by the thermal incompatibility between the aggregates and the cement paste [5]. It was expected that heating under hydrostatic compression, which reduces thermal expansion in all directions, would lead to greater reduction of damage and, consequently, to greater relative increase in strength.

On the contrary, the results of Series A tests (Fig. 4) showed that specimens heated under hydrostatic compression had significantly reduced strength and loading stiffness, in both compression (Fig. 4a) and extension (Fig. 4b) meridional planes. This suggested that while the presence of load during heating reduced the thermal expansion (and the associated damage), it must have introduced some new mechanism (*load induced thermal damage*) that produced even greater damage, so that the combined effect was strength reduction. Another explanation for these unexpected results would be that the hydrostatic compression reduced vapour permeability and delayed the drying of the specimens. This could have affected the stress–strain behaviour of the stressed (*LHS*) specimens in two ways: (i) *delayed* LITS, which during the deviatoric loading stage would have been seen as increased strain, resulting in reduced loading stiffness, and (ii) reduced strength as a result of damage caused by increased pore pressures at high stress levels (near the peak).

The same behaviour was observed in the tests of Series B (Fig. 5), in which the specimens were heated under a higher level of hydrostatic compression ($0.44 f_c = 26$ MPa), and then tested deviatorically in the planes of compression (Fig. 5a), extension (Fig. 5b), and shear (Fig. 5c) meridians.

In Series B the steady-state periods were extended from 1.5 h to 4.1 h, to allow sufficient time for reaching thermal and hygral equilibrium in the specimen. This indeed resulted in stabilisation of the measured strains, which was interpreted as *completed* LITS and thermal equilibrium in the specimen. The strain stabilisation could not be considered as sufficient proof that the specimens had reached the same moisture content as that in the specimens heated without load (*HS* tests). It could, however, be assumed that some moisture was removed during the extended steady-state period (at 250 °C). This reduction in moisture content had no noticeable effect on the subsequent stress–strain behaviour under deviatoric loading. The specimens subjected to load-then-heat (*LHS*) regimes still showed lower loading stiffness and strength than the specimens heated without load (*HS*).

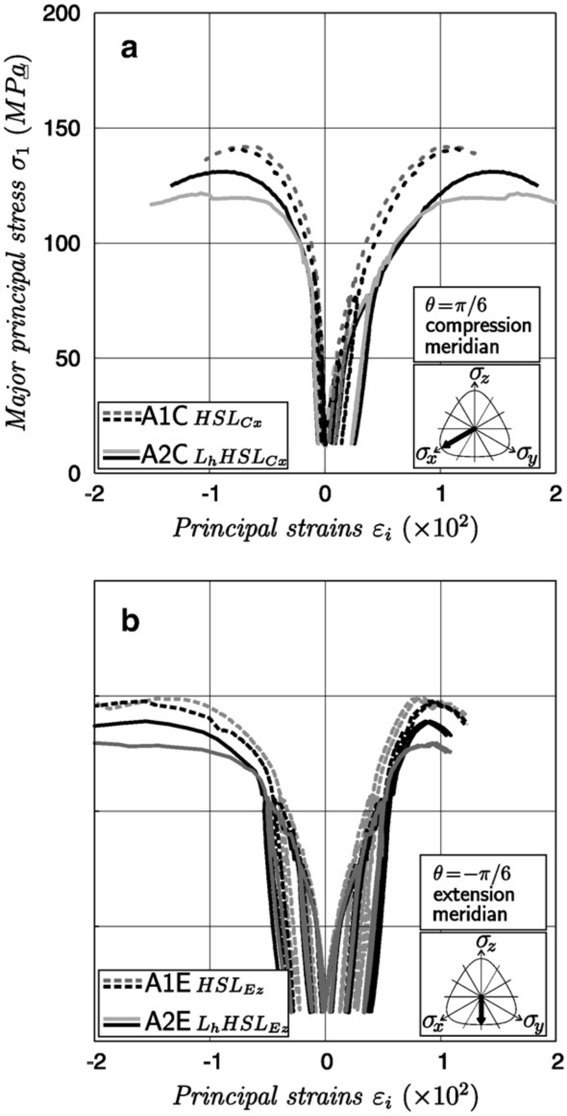

Fig. 4. Test Series A (fast heating under hydrostatic compression $\sigma_c = 0.22\,f_c$): stress–strain behaviour in the plane of (a) compression and (b) extension meridian.

4.2. Test Series C: slow heating under hydrostatic and uniaxial compression and long steady-state periods

In test Series C the heating rate was reduced to 0.2 °C min^{-1} and the steady-state period was extended to 96 h. All deviatoric tests were performed by loading in the plane of the shear meridian ($\theta = 0$). Two sets of specimens (C1 and C2) were heated without load (*H*), then loaded either hydrostatically (L_h) or uniaxially (L_{Cz}) and kept under steady-state conditions (*S*). This regime (*HLS*) was different from the *HS* regime in the first two series, as the specimens were loaded before the start of the steady-state phase. One of the reasons for this change was to isolate the effects of load during heating (transient stage) from these of load at constant elevated temperature (steady-state). The regime in the load–heat tests (C3 and C4) was the same as in the previous two test series (*LHS*): the specimens were first loaded (L_h or L_{Cz}), then heated (*H*) and kept under steady-state conditions (*S*).

The stress–strain graphs recorded in the deviatoric loading stage (Fig. 6a) show again that heating under hydrostatic compression (C4S:L_hHS) resulted in lower strength and loading stiffness than heating without load. The load applied immediately after heating and kept constant for 96 h (C1S:HL_hS) had no noticeable effect on the subsequent stress–strain behaviour during deviatoric loading. The stress–strain behaviour was the same as in the previous tests when no load was applied during steady-state.

In this series, considering the slow heating (over 19 h to reach 250 °C) and long steady-state periods, during which all specimens (both *LHS* and *HLS*) were subjected to the same load, it could be assumed that the differences in moisture content between the *HLS* and *LHS* specimens were relatively small. If this is true, then the difference in strength and stiffness between the *LHS* and *HLS* specimens could only be attributed to damage that occurred during the heating (under stress).

This conclusion was soon challenged by the results recorded in the other four Series C tests in which the specimens were conditioned under uniaxial compression. One set of specimens was heated without load (C2S:$HL_{Cz}S$), the other under uniaxial compression (C3S:$L_{Cz}HS$). In both cases, after completing the heating stage, the concrete was kept under uniaxial compression for 96 h. This time the deviatoric stress–strain behaviour (Fig. 6b) shows very little difference between specimens heated with and without load.

However, the consistency of the hydrostatic compression results, showing strength and stiffness reduction in the planes of all three meridians, suggests another possible interpretation. Heating under hydrostatic compression would have produced cracks with random orientation, resulting in strength reduction in all meridional planes. On the other hand, heating under uniaxial compression could produce cracks in planes normal to the applied load which would have little effect on strength in the same direction (in the same meridional plane).

The effect of heating rate on strength and stiffness of the material is illustrated in Fig. 6c in which the stress–strain graphs of the Series B tests (2 °C min^{-1}) are added to these recorded in the corresponding tests of Series C (0.2 °C min^{-1}). In all *LH* tests the specimens were heated under hydrostatic compression. The higher heating rates resulted in significant reduction in strength and loading stiffness. This is in contrast with previous experimental studies performed at similar heating rates of 0.2–1 °C min^{-1} [5] and 1–4 °C min^{-1} [1], in which lower heating rates, and consequently, longer exposure to high temperature led to reduction in strength. The difference could be attributed to two factors: (i) different concrete mixes and (ii) different moisture boundary conditions. The previous experiments were conducted on unsealed OPC concrete specimens, whereas the tests in this study were performed on partially sealed specimens of denser concrete produced with OPC/PFA (3:1) binder. Both factors contribute to reduced moisture removal, resulting in damage caused by increase in pore pressures during heating. Similar effects were observed in some previous studies [9] in which denser concretes suffered more damage during faster heating (3 °C min^{-1} compared to 1 °C min^{-1}).

4.3. Test Series D: cracks orientation during heating under stress

Series D was designed to test the idea of potential anisotropy generated by heating under (moderate) deviatoric stresses.

In the first 3 tests the specimens were subjected to the standard *HL* regime of heating unstressed specimens to 250 °C at 0.2 °C min^{-1}, holding under constant temperature for 24 h, loading to hydrostatic stress of 26 MPa and loading to the peak in the planes of the compression (D1C), extension (D1E) or shear (D1S) meridian.

The other 6 tests (each performed twice) were also standard load–heat tests comprising loading, heating, steady-state and deviatoric loading stages. The difference this time was the combination of loading directions during conditioning (load during heating) and deviatoric loading (Fig. 7).

4.3.1. Compression meridian tests

In test D2C the specimens were heated under uniaxial z-compression and tested to the peak in the plane of the same compression meridian (*compression–compression* test). In D3C the specimens were heated

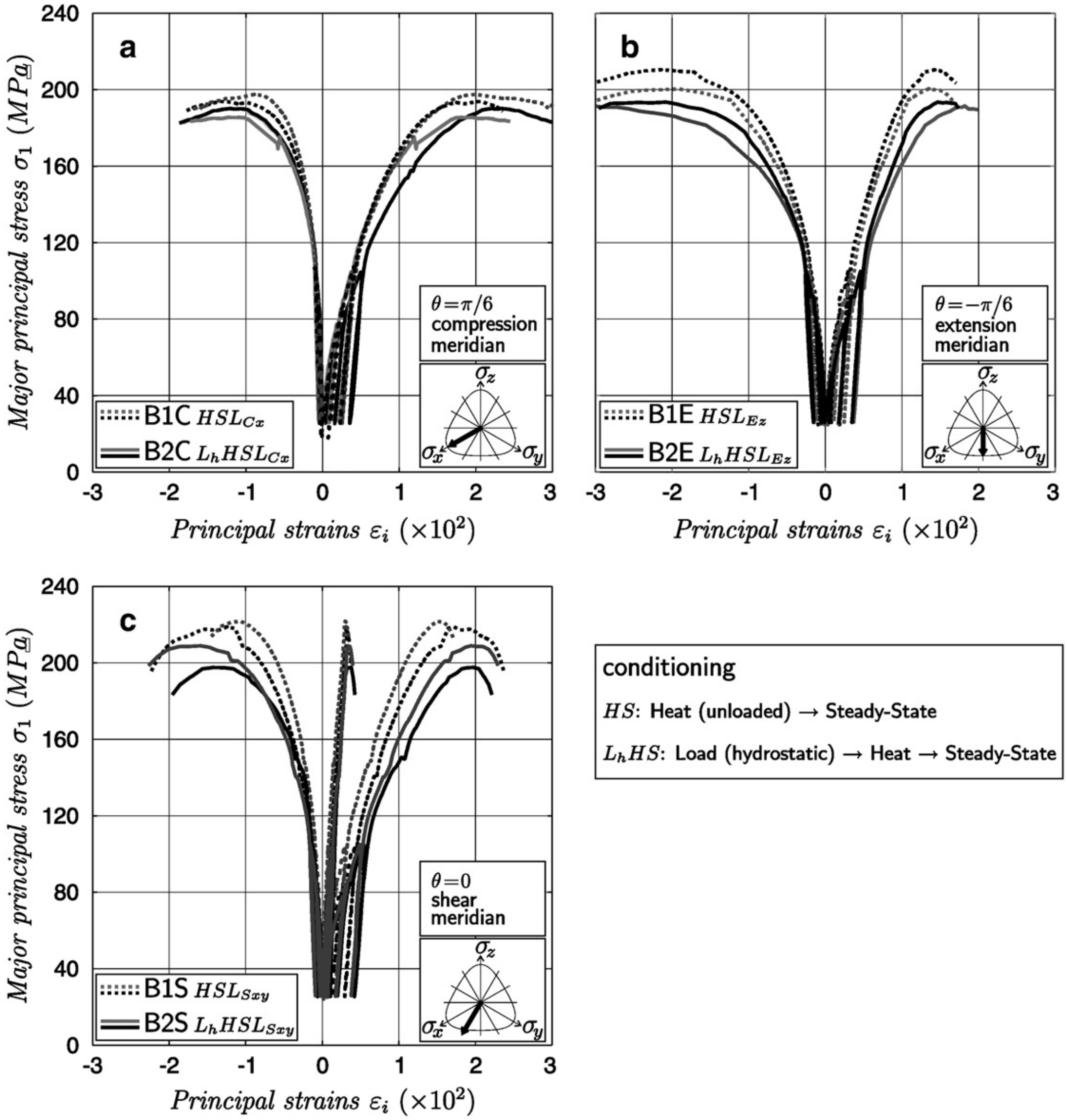

Fig. 5. Test Series B (fast heating under hydrostatic compression $\sigma_c = 0.44 f_c$): stress–strain behaviour in the plane of (a) compression, (b) extension and (c) shear meridian.

under z-extension (equal biaxial compression $\sigma_x = \sigma_y$) and then tested in z-compression (*extension–compression* test). The stress–strain graphs of these 2 tests are presented in Fig. 7a, together with the results of D1C, the corresponding *HL* test. As in the previous series, there was practically no difference in the stress–strain behaviour between concrete heated under uniaxial compression (D2C) and concrete heated without load (D1C). There was, however, a clear difference in stress–strain behaviour when concrete was heated under biaxial compression (extension meridian) and then tested in the compression meridian plane. The specimens heated under load had significantly lower strength and loading stiffness than the specimens heated without load.

4.3.2. Extension meridian tests

The results of the three different extension meridian tests (Fig. 7b) show lower strength when the specimens were heated under equal biaxial compression (D3E: *extension–extension* test) than these heated without load (D1E). One of the two D2E tests (*compression–extension*) also shows lower strength of the specimen subjected to load during heating, but the other shows similar behaviour to that of specimens heated without load.

4.3.3. Shear meridian tests

In the previous test series (Series C) heating under uniaxial compression (L_{Cz}) followed by deviatoric loading in the plane of the nearest shear meridian (L_{Szx} at $\pi/6$) produced results similar to these when both load during heating and deviatoric phase were on the same compression meridian. The deviatoric stress–strain behaviour was very close to that of specimens heated without load (C2S vs. C3S in Fig. 6b). This time however, specimens heated under compression on the C_y meridian (L_{Cy}) and then loaded to the peak in the plane of the far shear meridian (D2S:L_{Szx} at $5\pi/6$) showed lower strength and loading stiffness than the specimens heated without load (D1S).

The strength reduction in the shear meridian tests (D2S vs. D1S in Fig. 7c), together with the reduced strength recorded in the extension tests on specimens heated under uniaxial compression (D2E vs. D1E in Fig. 7b) suggest that heating under (moderate) uniaxial compression produces cracks normal to the applied load. The three compression meridian tests (Fig. 7a) also support a conclusion that cracks during heating develop in planes normal to the principal stress directions, rather than parallel to them.

The results of the extension tests (D3E, Fig. 7b), however, show similar strength and stiffness reduction in specimens heated under

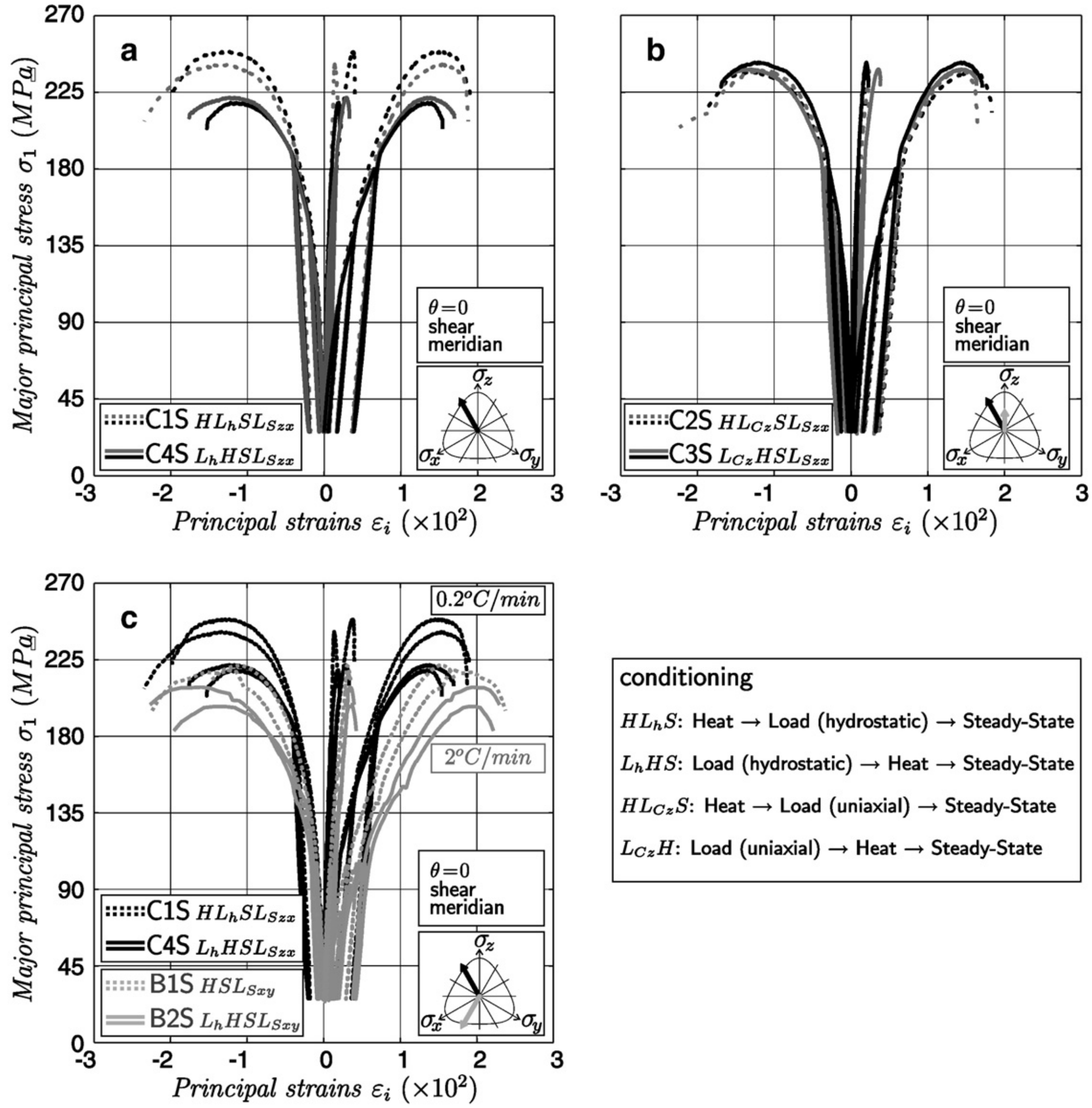

Fig. 6. Test Series C (slow heating) under: (a) hydrostatic compression $\sigma_c = 0.44\,f_c$, and (b) uniaxial compression $\sigma_z = 0.44\,f_c$, followed by extended steady-state periods, and loaded deviatorically in the plane of the shear meridian; (c) effects of heating rate on stress–strain behaviour of specimens heated under hydrostatic compression.

equal biaxial compression and then loaded in the same (extension) meridional plane. This means that heating under equal biaxial compression did not produce cracks normal to the principal stress direction. The fact that the strength reduction of about 5% is smaller than the 10% observed in specimens heated under hydrostatic compression, suggests the hydrostatic component of (deviatoric) stress during heating produces randomly orientated cracks.

4.4. Test Series E: heating–cooling–heating under load

The effects of temperature cycling of loaded specimens were investigated in two sets of tests in which the specimens were (i) loaded under uniaxial compression ($L_z = 26$ MPa $= 0.44\ f_c$), (ii) heated at 2 °C min^{-1} to either 150 °C (tests E1S) or 250 °C (tests E2S), (iii) cooled to 20 °C, (iv) heated to 250 °C, (v) kept at steady-state for 73 h, and (vi) tested to peak stress in the plane of the shear meridian (L_{Szx}). At the end of both first heating and cooling sequence, the specimens were kept at steady-state for 6 h. The results of the deviatoric loading stages of these tests are presented in Fig. 8, together with the results of two tests on specimens heated without load (Series C tests). The comparison of the stress–strain curves shows that heating–cooling–heating cycles of stressed specimens had very little effect on the subsequent stress–strain behaviour. This is in contrast with the results of a study carried out by Campbell-Allen et al. [22]. The authors found that when unstressed concrete was subjected to thermal cycling (heating–cooling), its stiffness was significantly reduced with every cycle. The limited data from the Series E tests indicates that temperature cycling under load (and in partially sealed conditions) does not introduce additional damage in the material.

It should be noted that LITS recorded at the end of the heat–cool–heat cycle were almost identical to these recorded at the end of the first heating of stressed specimens to 250 °C [21].

5. Summary of results, discussion and conclusions

This paper presents an experimental study of the effects of different heating–loading regimes on the subsequent stress–strain behaviour of concrete loaded to peak stress, under different multiaxial compression loads (compression, shear and extension meridian), at elevated temperature of 250 °C. The investigation was focused on the differences in stress–strain behaviour (strength and loading stiffness) between specimens heated without load (unstressed) and specimens

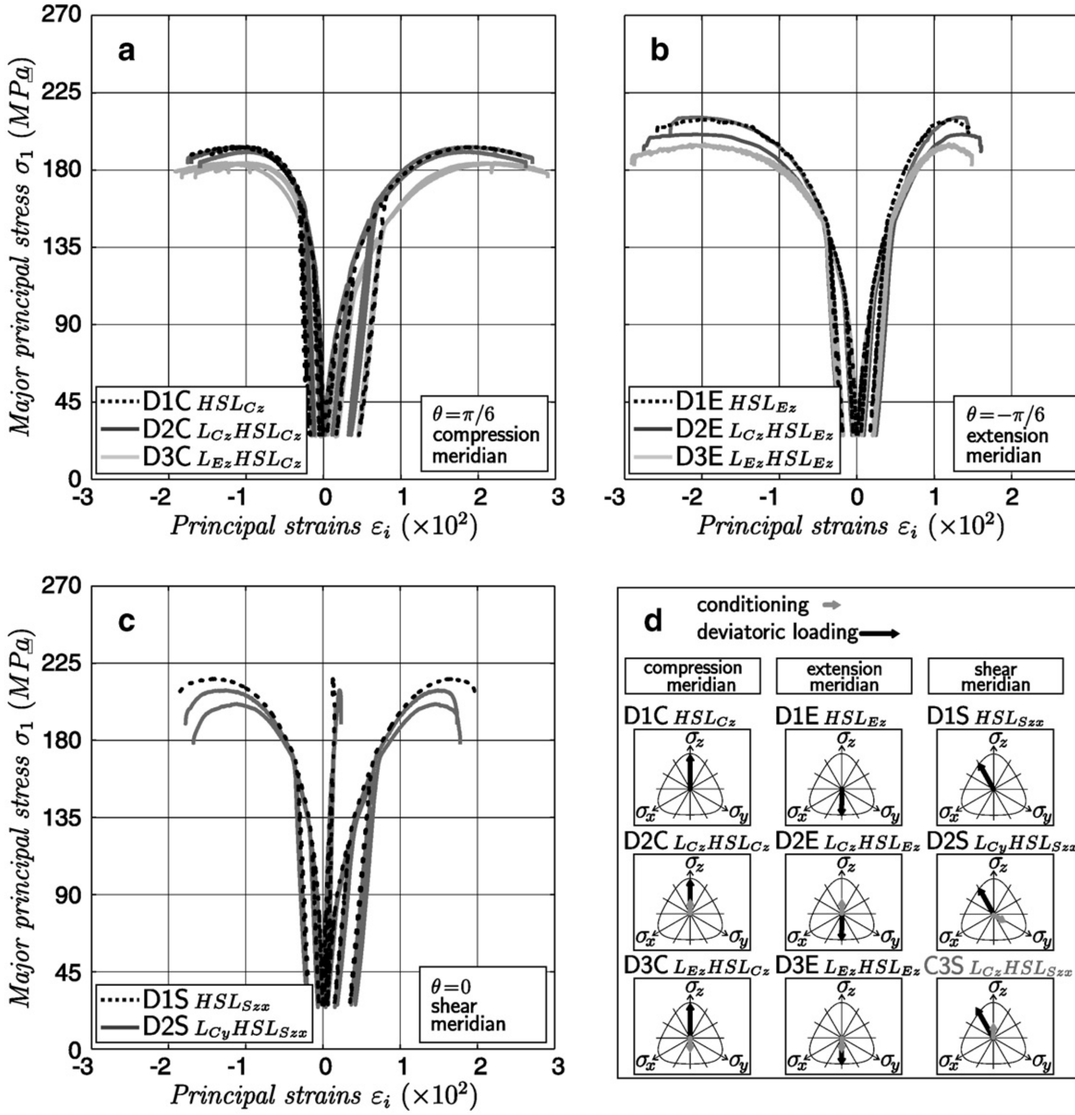

Fig. 7. Test Series D (anisotropy induced by heating under stress): stress–strain behaviour of specimens heated under different deviatoric loads and loaded in the planes of (a) compression, (b) extension and (c) shear meridian; (d) stress regimes during conditioning and deviatoric loading stages.

heated under moderate hydrostatic, uniaxial and equal biaxial compression. All tests were performed on one type of mature structural concrete in *partially sealed* conditions.

The results of the tests can be summarised as follows:

1. Concrete heated under hydrostatic compression and tested to peak stress in all three meridional planes (compression, shear end extension) showed about 10% lower strength than concrete heated without load.
2. Concrete heated under uniaxial compression and then tested to peak stress in the *same direction* (either in the plane of the same compression meridian or in the nearest shear meridian at $\theta = \pm\pi/6$) showed very little difference in strength and loading stiffness from concrete heated without load.
3. Concrete heated under uniaxial compression and then tested to peak stress in the *opposite direction* (either in the plane of the extension meridian at $\theta = \pi$, or the shear meridian at $\theta = 5\pi/6$) had lower strength and loading stiffness than concrete heated without load.
4. Concrete heated under equal biaxial compression (extension meridian) showed lower strength and loading stiffness than concrete heated without load, both in the same (extension) and the *opposite* compression meridional plane.
5. Strength and loading stiffness decreased when concrete was heated (both stressed and unstressed) at higher rate.
6. Heating–cooling–heating of loaded concrete did not produce any noticeable difference in stress–strain behaviour from concrete heated only once to the same temperature.

Černý et al. [14] showed that when specimens were heated under high load levels ($0.9 f_c$), the overall damage of the material was reduced. They suggested that the cracks produced by the initial load reduced the build-up of vapour pressure in micropores during heating, thus preventing explosive microcrack opening. Bažant and Chern [23] first proposed that transient thermal creep (or LITS) was caused by microdiffusion, a process in which the moisture moving from micropores to macropores removes some of the solid material, creating micro-damage in the material.

The damage of the micropore structure in the cement paste offers a possible explanation for a damage mechanism that is compatible with observations of previous experimental studies [3–5,21,24], in which LITS occurred only during the first heating of stressed concrete to a given temperature, but not during cooling or re-heating to the same temperature level. Assuming that moderate load does not introduce (initial) damage in the microstructure, its presence during heating

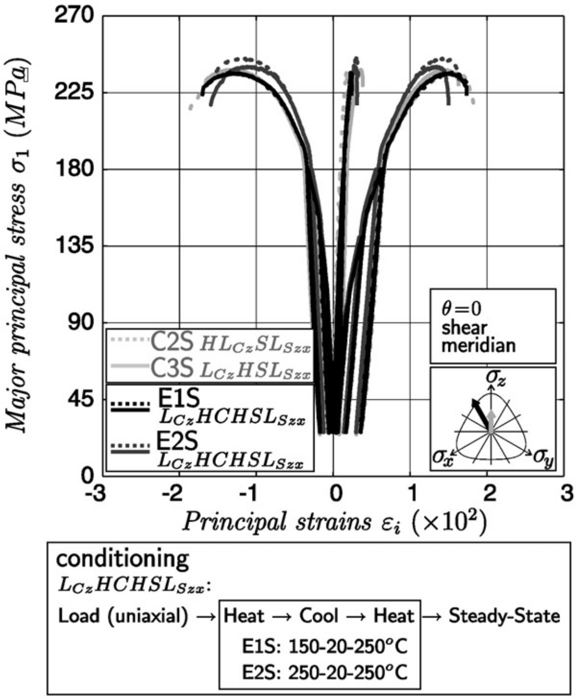

Fig. 8. Test Series E (temperature cycling): stress–strain behaviour of specimens subjected to heat–cool–heat cycle under stress.

would act as a constrain to the micropore expansion, thus increasing the potential for build-up of vapour pressure. For given stress, moisture and temperature conditions, this would lead to a finite amount of cracks in the microstructure, resulting in a finite level of load induced thermal strain (LITS). Cooling and re-heating to the same temperature (under the same stress and moisture conditions) would not introduce new cracks and LITS would remain constant. Any further increase in temperature, however, would increase the vapour pressure in the yet undamaged micropores, introducing new cracks and increasing LITS.

This investigation provides further support for the existence of the described mechanism and its direct link to LITS observations. Hydrostatic compression during heating would produce micro-cracks in all directions. Similarly, but to a lesser extent, this would happen under any load with significant hydrostatic component (e.g. equal biaxial compression). On the other hand, uniaxial compression (or any multiaxial stress with a small hydrostatic component) would act as a constraint only in the direction of the major principal stress. In this case the increased pressure in the micropores may produce cracks in planes normal to the direction of the major principal stress, rather than parallel with it (which is the case when concrete is loaded at constant temperature). The assumption that this is a damage that only occurs during first heating of stressed concrete was supported by the fact that thermal cycling (heat–cool–heat) of stressed concrete did not produce any additional reduction in strength and stiffness.

The existence of this damage mechanism does not contradict the findings of previous experimental studies in which the presence of load during heating (or the resulting LITS) was beneficial for the *hot* strength of concrete. LITS reduces the thermal expansion of the concrete, thus reducing development of cracks as a result of differences in thermal expansion of the constituents (*free thermal damage*). Hence, the overall effect of stress during heating on strength and loading stiffness would depend on the balance between the two opposing mechanisms. In concretes with relatively small *free thermal damage* (such as PFA concretes similar to the one tested in this study), the effects of damage caused by stress during heating would be greater than the beneficial effect of reduced thermal expansion. In such cases heating of stressed specimens will result in lower strength and loading stiffness than heating of unstressed specimens.

It should be noted that the results of this study are directly applicable only to cases where LITS has a significant effect on the stress–strain behaviour of the material: relatively low temperatures (250 °C) and low heating rates (2 °C min^{-1}). For higher temperatures and heating rates, typical for standard fire engineering applications, the damage processes and the stress–strain behaviour of the material are governed by other factors such as large thermal strain gradients, higher pore pressures and chemical changes in the cement paste.

The results of this experimental study provide strong indication that (i) the presence of load during first heating of concrete creates a specific damage mechanism (*load induced thermal damage*), and (2) this damage is a major contributor to *load induced thermal strain* (LITS) in concrete.

The existence of *load induced thermal damage* is just one possible explanation for the observed results and firm conclusions can only be made if different cracking patterns are directly observed in specimens subjected to different heat–load regimes. A new research programme on the effects of heat–load regimes on concrete, currently under way in Sheffield, will include additional deviatoric loading tests and, more importantly, direct damage detection by using Scanning Electron Microscope imaging, porosity and permeability measurements, as well as X-ray diffraction measurements for detecting potential chemical changes in the material.

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