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Review article

Concrete strains under transient thermal conditions: A state-of-the-art review

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ABSTRACT

Extensive research has been carried out over the past four decades on the behaviour of mechanically loaded concrete under transient thermal conditions. The purpose of this paper is to provide a concise review of the existing experimental and analytical works with a strong focus on the load-induced thermal strain (LITS) component. In order to eliminate ambiguities in definitions, the existing terms used to describe the strain components that develop in concrete under a transient thermal regime are compared and a clear definition of LITS and its components is given. The analysis of the existing experimental work shows that LITS is: a strain occurring only during first heating of loaded concrete to a given temperature; significantly influenced by the moisture flux in the temperature range 100–250 °C; and independent of aggregate type for temperatures up to about 400 °C. Examination of the existing multiaxial test data demonstrates that LITS is the result of markedly confinement-dependent phenomenon and that experiments on concrete subjected to triaxial compression and transient temperatures above 250 °C are needed. In the light of the experimental evidence, for temperatures up to about 400 °C LITS seems to be mainly due to chemical reactions and microstructural changes taking place in the cement paste, such as dehydration, drying and rearrangement of the water molecules within the cement paste. By contrast, for higher temperatures, thermomechanical damage due to thermal incompatibility between cement paste and aggregates is believed to contribute significantly to the development of LITS. Moreover, the necessity for modelling explicitly the LITS component in the case of Heating-Cooling (HC) cycles is discussed. Finally, a review of the main existing uniaxial and multiaxial explicit LITS models is given, and the advantages and drawbacks of each model are outlined.

Contents

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Nomenclature

a, b, c	polynomial coefficients
E	Young's modulus of elasticity of material
k_{tr}	transient strain coefficient
T	temperature
$\bar{T}$	normalized temperature
V_a	volume fraction of aggregates
α	thermal expansion coefficient expressing the ratio between the increment in free thermal strain and the increment in temperature
α_T	thermal expansion coefficient expressing the slope of the free thermal strain curve
β	load-induced thermal strain function for multiaxial models
C_m	triaxiality coefficient for multiaxial models
$\Delta\varepsilon_{ela}$	increment in the elastic strain
δ_{ij}	Kronecker symbol
ε	strain
$\varepsilon_{0,3}$	load induced thermal strain for load $\sigma_i/\sigma_{u0} = 3$
ε_{cr}	creep strain
ε_{cra}	smeared crack strain
ε_{cr^*}	creep strain plus transient strain
ε_{dcr}	drying creep strain
ε_{ela}	elastic strain
$\varepsilon_{ela,0}$	elastic strain at ambient temperature
ε_{heat}	strain developed during the heating phase of a load-then-heat test
ε_{ij}	components of the total strain tensor
ε_{lits}	load-induced thermal strain
ε_{lits^*}	load-induced thermal strain without increment in the elastic strain
ε_m	mechanical strain
ε_{sh}	shrinkage strain
ε_{th}	thermal expansion strain
ε_{tot}	total strain
ε_u	ultimate strain
ε_{ts}	transient strain
ε_{ttc}	transient thermal creep strain
ε_σ	instantaneous stress-related strain
ν	Poisson's ratio
ν_{lits}	load-induced thermal strain Poisson's ratio
σ	stress
σ_i	initial compressive stress before heating
σ_{u0}	compressive strength

1. Introduction

Experimental evidence shows that mechanically loaded concrete specimens exhibit a significant quasi-instantaneous load-induced thermal strain, usually referred to as LITS, upon virgin heating. Accurate understanding and modelling of this phenomenon is crucial for a reliable assessment of the effects of thermal loads on concrete structures, particularly if a certain level of performance is required in the case of accidental loads such as fire. This is the case for nuclear structures, such as prestressed concrete pressure vessels (PCPVs). For example, the recent Fukushima accident, where reactors overheated due to a failure of the power station cooling system, clearly highlights the importance of considering a wide range of possible accidental conditions in designing and assessing nuclear structures. Moreover, other applications in civil engineering occur whenever concrete is loaded in compression under transient thermal conditions, for example concrete columns subjected to travelling fires [1].

LITS plays a key role in the behaviour of concrete structures subject to heating-cooling (HC) cycles combined with sustained compressive loads, both at a material and structural level. In the case of structural elements whose thermal deformation is partially or totally constrained, its effects are mainly beneficial during the first heating. This is because LITS develops in the loaded direction, thereby mitigating the additional compressive stresses appearing in such structures due to restraint to thermal expansion [2,3]. At a material level, the development of LITS in the cement paste produces a stress-redistribution preventing the appearance of high local compressive stresses. In addition, the presence of compressive stresses on heating generally produces an overall reduction of tensile damage in the cement matrix, in the direction of the load [4]. This is because the tensile cracks that would develop in absence of compressive load, due to cement paste shrinkage and thermal incompatibility between matrix and aggregates, are prevented from developing by the compressive stress.

By contrast, significant tensile stresses and associated cracking effects may also be related to this phenomenon for specific loading and boundary conditions. This is the case for loaded concrete subjected heating-cooling cycles. Since LITS is mainly irrecoverable in terms of temperature, thermal incompatibilities between the constituents of concrete may cause severe damage at a material level during the cooling phase. Similarly, constrained structures tend to contract on cooling and an unsafe level of tensile stresses may develop as a result of a heating-cooling cycle [5]. In addition, experimental evidence shows that significant concrete damage may appear on heating concrete under compressive stresses approaching the strength of the material [6], and in the presence of high thermal and moisture gradients that lead to tensile stresses [7].

Despite these concerns, and considerable research efforts over the last forty years, a comprehensive up to date survey of LITS describing the state of knowledge and how it is best handled in analysis and design is lacking. Earlier attempts at such a survey are now either dated [3,8] or focussed on only few aspects of the phenomenon [5]. This paper aims to fill the gap by providing researchers and practitioners a comprehensive review of the topic, and by highlighting areas where further research is needed.

With these aims in mind, the first part of the paper outlines and discusses the experimentally demonstrated characteristics of LITS, as well as identifying gaps in knowledge. This leads to the second part of the paper that provides a discussion of the need to explicitly model LITS in numerical simulations, together with a critical review of the existing analytical models of LITS.

2. Transient thermal conditions and LITS

2.1. Experimental background

In order to evaluate the behaviour of concrete at high temperatures, various uniaxial test methods have been designed, among which two main types can be identified (Fig. 2-1):

- Steady-state tests, where the material is subjected to a heat-then-load (HTL) regime: first the specimen is heated uniformly to a pre-defined temperature, then a mechanical load is applied, while the temperature of the material is kept constant. (T = constant, σ varying).
- Transient tests, where the material is subjected to a load-then-heat (LTH) regime: first the specimen is mechanically loaded, then it is uniformly heated, while the mechanical load is kept constant. (σ = constant, T varying).

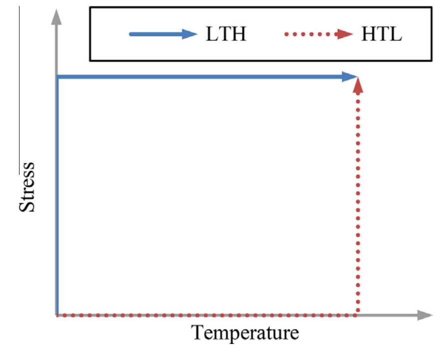

Fig. 2-1. Schematic diagram of the temperature and stress history of specimens subjected to LTH and HTL tests.

In the case of steady-state tests, the specimen is heated to a pre-defined temperature and then a specific load programme is applied [9]. If a monotonically increasing load (or, equivalently, displacement) is applied until the strength of the material is reached, the stress-strain curve corresponding to a given temperature can be obtained. Usually, HTL tests are performed with a relatively high loading rate, so that development of delayed strain components, (e.g. basic creep, drying creep and shrinkage), during the loading phase can be neglected. These tests are useful for determining the "hot" mechanical parameters of the material, i.e. Young's modulus $E(T)$, compressive strength $f_c(T)$ and ultimate strain $\varepsilon_u(T)$. Often, once thermal equilibrium is reached within the material, a pre-defined mechanical load is applied and kept constant over time. This approach allows evaluation of the "hot" Young's modulus of the material – if a moderate compressive load is applied - and the time dependent strains occurring for a HTL regime (see Fig. 3-2). Similarly, HTL relaxation tests may be performed, where an initial strain is imposed and kept constant over time, while the stress level is recorded. It is worth noting that the curves obtained from HTL tests cannot be directly used to reproduce the most common structural problems, where concrete is first loaded mechanically and then subjected to an accidental thermal transient, i.e. subjected to LTH regime. In fact, it has been demonstrated that the behaviour of concrete subjected to thermomechanical loads depends on the order in which thermal and mechanical load are applied [10].

Transient tests consist of loading a specimen (by a given stress or strain) and applying a particular temperature programme over time [11]. In order to ensure a uniform temperature field throughout the specimen and to simulate different service and accidental thermal loads, the heating rate should be in the range of 0.1–10 °C/min [3]. If a monotonically increasing thermal load is applied under constant stress, the results are often expressed by plotting the strain $\varepsilon_{heat}(T)$ developed during the heating phase as a function of the temperature of the material, for different load levels (Fig. 2-4). The applied stress is usually expressed as a percentage of the ambient compressive strength, σ_{u0}, of the material. These types of test are particularly meaningful since they effectively reproduce the design conditions of concrete structures subjected to permanent loads together with expected temperature cycles or unpredictable accidental thermal loads. On the other hand, transient tests where the total deformation is kept constant after the application of the mechanical stress can be designed. Such tests are particularly interesting in assessing the behaviour of structural elements such as columns which may be restrained during heating and therefore subjected to constant strain and varying stresses (due to restrained thermal expansion) during the rise in temperature.

2.2. Definition of Free Thermal Strain (FTS) and LITS

Existing research shows that the thermal strain of concrete is significantly reduced when a constant compressive load is applied while heating. Such a reduction has been commonly seen as an additional thermal strain component due to the presence of a constant stress occurring in the loaded direction.

Over the past 40 years, a number of terms have been used to describe this thermo-mechanical strain and its components, including LITS, transient creep (TC), transient strain (TS) and transient thermal creep (TTC). Since the physical meaning of these terms has been interpreted differently by various authors, this section aims at clearly defining LITS and its components.

When heated, concrete is generally subjected to an overall volumetric expansion. The strain in an unloaded specimen during the heating process is mainly due to two coupled phenomena: thermal expansion ε_{th}, related to the thermal expansion of the aggregates, and a contraction, related to the shrinkage strain ε_{sh}, mainly due to the evaporation of the free water contained in the pores. In general, these two mechanisms result in a global volumetric expansion, usually called stress-independent strain or Free Thermal Strain (FTS) ε_0 (Fig. 2-2). Several studies investigating the behaviour of concrete in the case of stress-free thermal load have demonstrated that concrete's expansion behaviour is highly non-linear with temperature [2,12,13]. Fig. 4-1 shows experimentally measured FTS vs temperature for various concretes [55] and the curve obtained by the FTS model exposed in [56]. Fig. 4-1 shows that such FTS is very sensitive to the content and nature of aggregates used. For simplicity, the strains in the longitudinal direction only are shown in Figs. 2-2, 2-3, and 2-5.

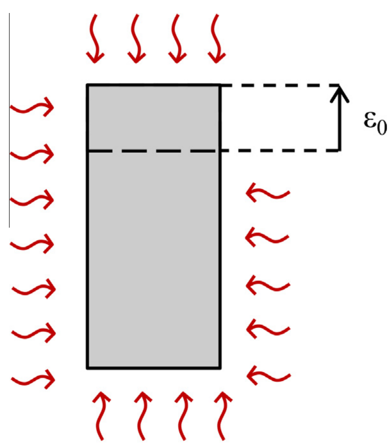

Fig. 2-2. Schematisation of FTS (ε_0) developing in a mechanically unloaded specimen subjected to a thermal load. Only the longitudinal component is shown.

If the test is repeated with the only difference being a constant compressive mechanical load applied before heating the specimen – LTH – the strain which develops during the heating phase is different from the FTS measured in the unloaded specimen – usually referred to as control specimen. This difference in strain can be seen as an additional temperature dependent strain component, occurring in the presence of a compressive stress state, hereby referred to as LITS (ε_{lits}). Although different names have been used to refer to LITS, the same physical definition has been adopted by many authors [2,5,13,14].

The strain components that develop in concrete specimens subjected to constant compressive load are schematically represented in Fig. 2-3, where ε_{tot} is the total strain of the specimen and $\varepsilon_{ela,0}$ is the elastic strain measured at ambient temperature immediately after loading the specimen.

According to this definition, LITS may be experimentally estimated as follows:

$$\varepsilon_{lits} = \varepsilon_{tot} - \varepsilon_0 - \varepsilon_{ela,0} = \varepsilon_{tot} - \varepsilon_{th} - \varepsilon_{sh} - \varepsilon_{ela,0} \quad (2\text{-}1)$$

where ε_{tot} is the total strain, ε_0 the FTS, $\varepsilon_{ela,0}$ the elastic strain for ambient temperature, ε_{th} is the thermal expansion and ε_{sh}, the shrinkage component. ε_{tot} and $\varepsilon_{ela,0}$ are measured in the loaded specimen, while the FTS ε_0 is measured in an unloaded control specimen, subjected to the same thermal load of the loaded one. According to Eq. (2−1), LITS is defined with reference to the instantaneous elastic strain measured for ambient temperature ε_0, it therefore includes an elastic strain component due to the temperature-related decrease in the elastic modulus of the material. The dependence of the elastic strain on the temperature and heating regimes (LTH and HTL) is discussed in Section 3.1.1.

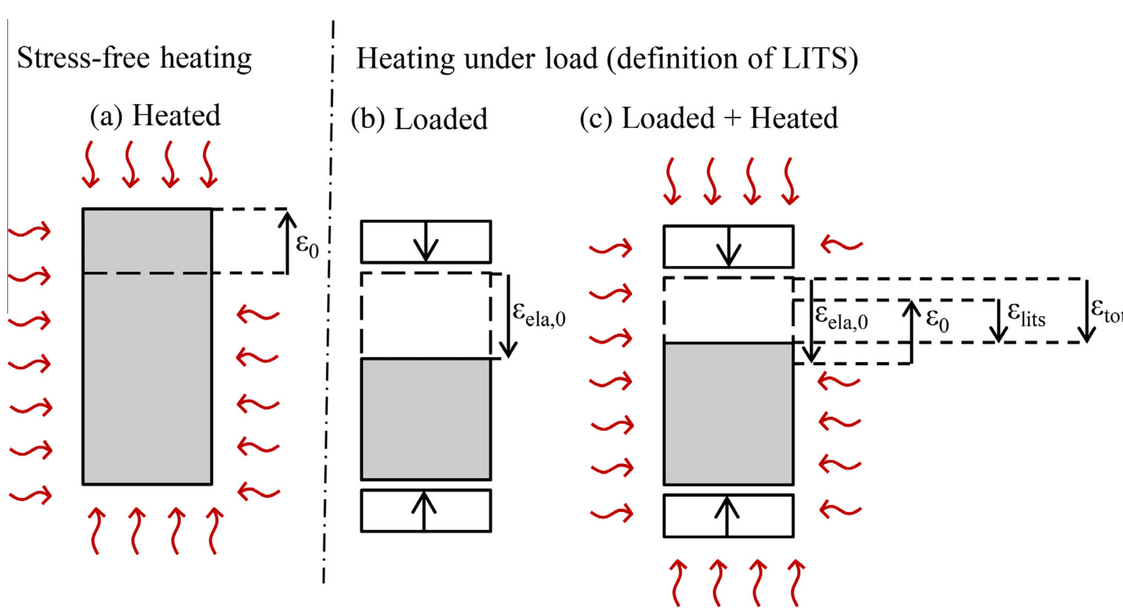

Fig. 2-3. Definition of ε_{lits}: schematisation of the strain components developing in a concrete specimen subjected to (a) stress-free heating (b) mechanical loading (c) heating under constant mechanical load.

The results of LTH tests performed for different stress levels are often expressed by plotting the strain that develops during the heating phase ε_{heat}, usually referred to as thermal strain, against the average temperature of the specimen T, where ε_{heat} is evaluated as:

$$\varepsilon_{heat} = \varepsilon_{tot} - \varepsilon_{ela,0} \tag{2-2}$$

According to the definition above, ε_{lits} may be seen as the difference between the strain developed during the heating phase ε_{heat} and the FTS ε_0:

$$\varepsilon_{lits} = \varepsilon_{heat} - \varepsilon_0 \tag{2-3}$$

Thus, if on the same chart the values of ε_{heat} for different stress levels are plotted together with the unloaded control specimen behaviour (for which $\varepsilon_{heat} = \varepsilon_0$), a curve expressing LITS as a function of temperature is produced. For each stress level it is the difference between the curve expressing ε_{heat} for that particular stress level and the curve obtained for the unloaded control specimen (Fig. 2-4).

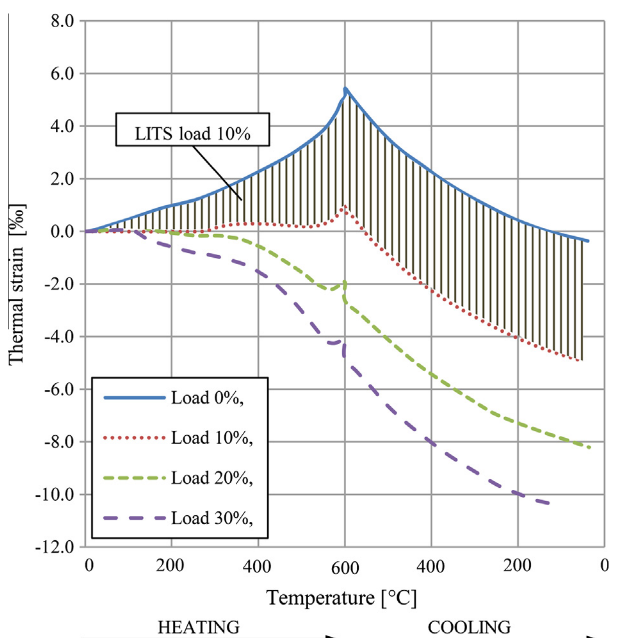

Fig. 2-4. Total thermal strain measured during a LTH test, expressed as a function of temperature, for different load levels. Aggregate: basalt. Heating rate: 1 °C/min. Adapted from [15].

It is important to underline that in several studies LITS has been defined as the difference between the total mechanical strain – stress dependent strain – and the instantaneous elastic deformation at high temperatures $\varepsilon_{ela}(T)$, thus not including any increment in the elastic strain due to a temperature rise, as shown from Fig. 2-5 [16–18].

The notation ε_{lits^*} is used here to refer to LITS according to this second definition:

$$\varepsilon_{lits^*} = \varepsilon_{tot} - \varepsilon_0 - \varepsilon_{ela}(T) \tag{2-4}$$

3. Experimentally demonstrated characteristics of LITS

The first experimental evidence of LITS emerged during the 1960s as a result of experiments by Johansen & Best [19] and Hansen & Eriksson [10]. Over the last five decades, a range of further experimental studies have documented the existence and the main features of the LITS phenomenon. A thorough review of the investigations carried out until the mid-1980s was produced by Khoury et al. [8], while several interesting partial reviews have been produced since. This section brings the survey of experimental work up to date by organizing, comparing and discussing the main outputs of the experimental research in order to identify the key features of LITS, without strictly adhering to the chronological sequence of different works.

Firstly, the experimentally demonstrated effects of temperature on elasticity and creep are discussed in order to define the different strain components of LITS. Then, the main parameters influencing LITS are analysed in the light of the experimental evidence. In particular, the dependence of LITS on the hygral, thermal and mechanical loading conditions is considered, as well as the influence of concrete material properties. Finally, a critical discussion of the experimentally demonstrated characteristics of LITS is presented, with a view to identifying its physical origins.

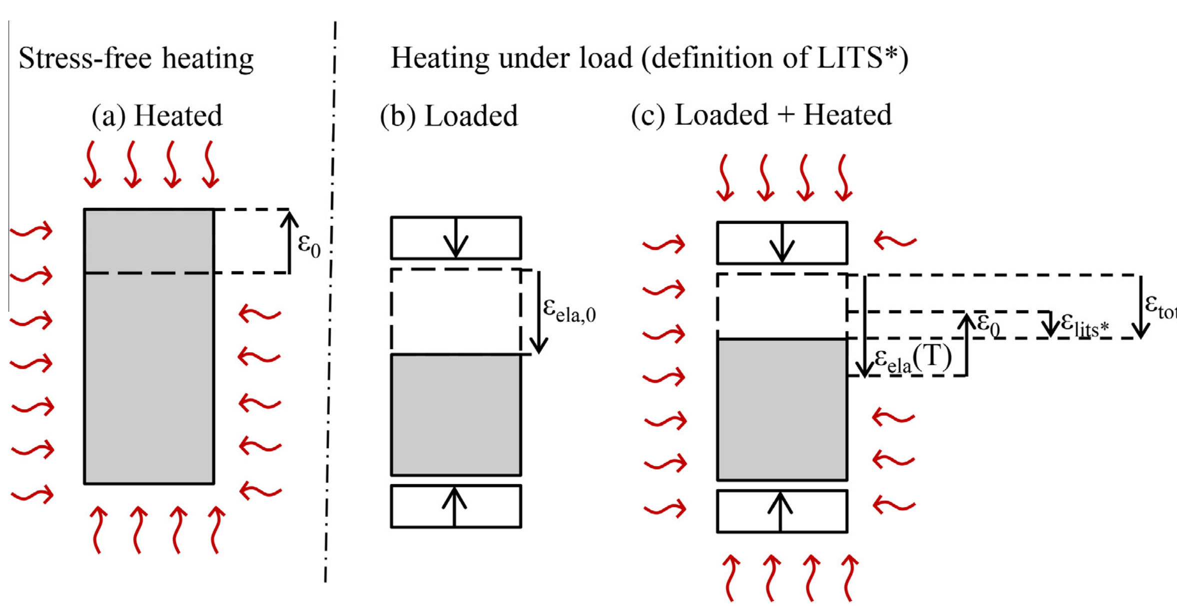

Fig. 2-5. Definition of ε_{lits^*}: schematisation of the strain components developed in a concrete specimen subjected to (a) stress-free heating (b) mechanical loading (c) heating under constant mechanical load.

3.1. Components of LITS

According to the definition of LITS reported in eq. (2 −1), it includes a contribution due to the variation of the elastic strain with temperature, and another due to the development of basic and drying creep, which are accelerated by a rise in temperature. Therefore, in order to understand the mechanisms underlying LITS and to define its components, the main effects of temperature changes on the elastic and creep strains for steady state conditions need to be outlined first.

3.1.1. Temperature and modulus of elasticity

It is well known that the elastic stiffness of concrete decreases with increasing temperatures [6,7,20–27]. Such degradation of the elasticity can be attributed to physical and chemical changes in the concrete microstructure.

The relationship between modulus of elasticity and temperature has been proved to be highly sensitive to the type of aggregates used. For example, if normal weight aggregates are used, E decrease more rapidly with increasing temperatures than in case of lightweight concrete [3,22].

The elastic modulus is also connected to the load-temperature history path. In particular, if concrete is loaded during the heating process, i.e. is subjected to a LTH regime, it develops a higher stiffness than if it is subjected to HTL regime [21,23]. Moreover, the original strength of concrete, the water to cement ratio, the type of cement and the stress level – as long as it remains in the range of 0.1 to $0.3f_c$ – have been shown to have little or no influence on the relationship [3].

In case of HTL regimes, the curve expressing the modulus of elasticity as a function of temperature may be obtained by evaluating the initial tangents of the isothermal constitutive curves.

For LTH regimes, such a curve can be obtained by measuring the elastic expansion-contraction developed during a quasi-instantaneous unloading-loading cycle performed at different temperature levels (Fig. 3-1). In this way, [16] showed that the elastic strain increment developed during transient heating, $\Delta\varepsilon_{ela}(T)$ is mainly irrecoverable, in terms of temperature, for various types of concrete including ordinary concrete and high-performance concrete. In Fig. 3-1, the instantaneous elastic strain $\varepsilon_{ela}(T)$ is represented by the heights of the peaks of the total strain evolution. It should be noted that most of the temperature-related increment in elastic strain obtained in [16] in the case of LTH regime for temperatures up to 220 °C occurs between 140 °C and 190 °C. In the authors' opinion, this aspect should be further investigated experimentally to provide the basis for a better understanding of its physical and chemical origins.

3.1.2. Temperature and creep strain

Several reports have shown that the short-term creep behaviour of unsealed specimens (those allowed to exchange moisture with the ambient atmosphere), for steady state conditions, is a function of temperature. In particular, the magnitude of creep strains increases rapidly as temperature increases [7,20,21,25,28]. Creep tests at constant, high temperatures are usually performed on unsealed specimens, since practical issues arise in imposing sealed condition for temperatures higher than 100 °C [29], especially for uniaxial stress states [30]. Fig. 3-2 shows that the effect of temperature on creep strains grows rapidly for temperatures higher than 300–400 °C.

If LTH regimes reproducing the actual accidental fire situations are taken into account, the isothermal creep contribution to the total strain developed during the heating phase is negligible with regard to the LITS. This is because the time needed for appreciable creep strains to develop is usually much greater than the duration of the transient phase, even for heating rates slower than expected in case of real heating situations [3,25]. However, in the case of a LTH regime with long-term high temperature conditions, i.e. structures subjected to severe and prolonged accidental conditions, creep strains that develop after the initial transient phase cannot be disregarded.

3.1.3. Definition of the LITS components

The experimentally measured magnitude of LITS exceeds the expected creep and elastic strain increments due to the increase in temperature during HTL tests [3,7,25,31–33]. This leads to the definition of an additional strain component, which occurs during first heating under load, known as TC [34] or TS [5,7,21,31] – see Fig. 3-3. In this work, the term TS is used:

$$\varepsilon_{lits} = \Delta\varepsilon_{ela} + \varepsilon_{cr} + \varepsilon_{ts} \tag{3-1}$$

where $\Delta\varepsilon_{ela}$ is the increment in elastic strain due to the rise in temperature, ε_{cr} is the creep strain developed during the heating phase, and ε_{ts} is the TS.

It is important to underline that it is almost impossible to design tests allowing transient strain to be measured directly [21].

For unsealed specimens, TS is itself composed of two different strain components: drying creep ε_{dcr}, due to the occurrence of an accelerated drying process on heating, and a moisture-flux-independent component TTC, ε_{ttc}:

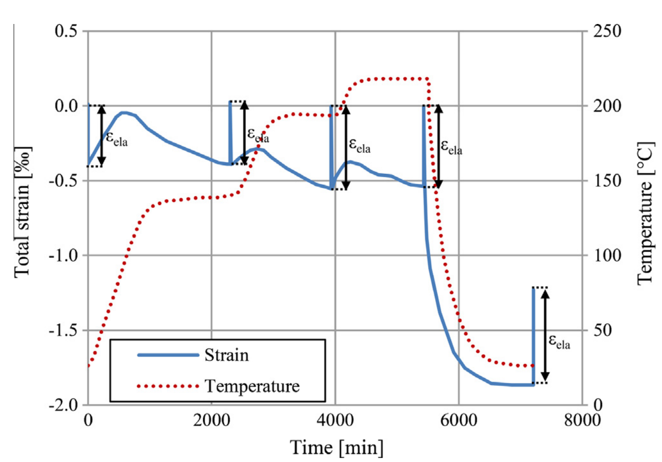

Fig. 3-1. Temperature and total strain evolution for a high performance concrete specimen subjected to a Heating-Cooling (HC) cycle in LTH regime. The peaks of strain evolution curves are due to quasi-instantaneous unloading-loading of the specimen [18].

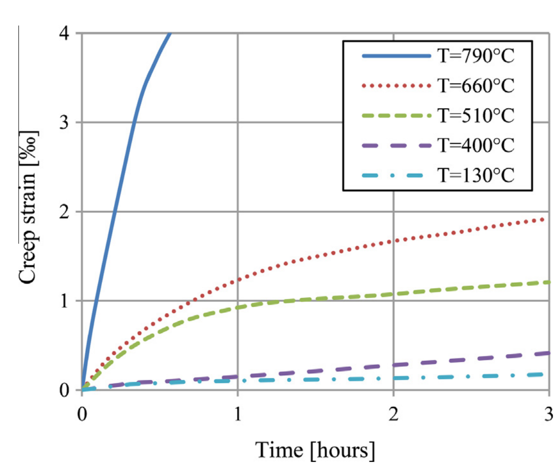

Fig. 3-2. Creep strains measured during HTL tests with constant stress level of 22.5%, at different constant temperatures [21].

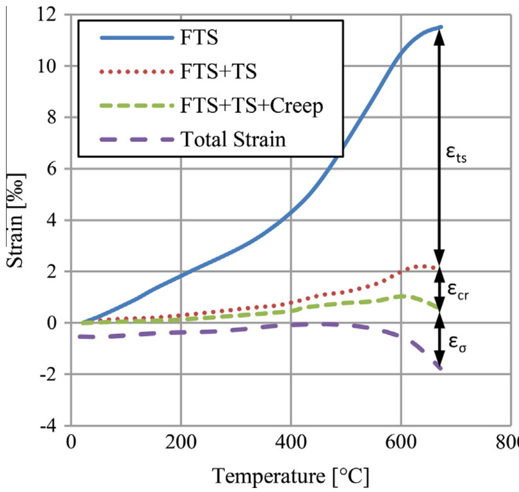

Fig. 3-3. Evolution of the LITS components with time, according to the model formulated in [21]. Load level of 35%.

Table 3-1
Strain components studied (according to the definition adopted in this work) and terms used to refer to them by different authors. Load-Induced-Thermal-Strain (LITS), Transient Thermal Creep (TTC), Transient Thermal Strain (TTS), Increment in creep, Transient Strain (TS), Transient Creep (TC).

Strain component studied	Term used	Works
LITS	LITS	[2,3,5,8,14,35–37]
	TTC	[38]
	TTS	[13]
	Increment in creep	[39]
TS	TS	[21]
	TC	[29,40]
TTC	TC	[41]
LITS*	TTC	[16,18,17]
	TTS	[37]

$$\varepsilon_{lits} = \Delta\varepsilon_{ela} + \varepsilon_{cr} + \varepsilon_{dcr} + \varepsilon_{ttc} \tag{3-2}$$

The existence of the TTC component ε_{ttc} is proven by the fact that TS develops even in case of sealed specimen, i.e. in absence of drying creep [10]. Thus, for sealed conditions, one obtains $\varepsilon_{ts} = \varepsilon_{ttc}$:

$$\varepsilon_{lits} = \Delta\varepsilon_{ela} + \varepsilon_{bcr} + \varepsilon_{ttc} \tag{3-3}$$

In Table 3-1, an overview of the definitions adopted by different authors to refer to different strain components is provided.

3.2. Hygral conditions

3.2.1. Experiments and sealing conditions

It has commonly been assumed that the hygral conditions of concrete in structures where LITS is of significance are better represented by unsealed than by sealed concrete specimens [3,42]. For example, as experimentally demonstrated by Hornby & Grainger [43], this is true of the top-cap of Prestressed Concrete Pressure Vessels (PCPVs), since the moisture vapour present in such areas can migrate relatively easily to the atmosphere through the numerous steel concrete-interfaces in case of severe thermal loads. For this reason, studies on the transient state behaviour of concrete at temperatures higher than 100 °C have focused mainly on unsealed conditions, while all tests on sealed specimens have been performed at temperatures lower than 100 °C [10,19,44–46]. One exception to this general situation is an unusual experimental study performed on specimens whose boundary conditions may be interpreted as "partially sealed", due to the presence of steel plates preventing moisture from evacuating through most of the external surfaces [14]. However, in the authors' opinion, further experimental work needs to be done to investigate the effects of sealing conditions for temperatures above 100 °C.

3.2.2. Time independency and irrecoverability

LITS is commonly regarded as a quasi-instantaneous strain component, i.e. as a time-independent phenomenon [7]. This assumption is based on the fact that it mostly occurs during the transient state phase, and the time needed for it to fully develop after the temperature has been stabilized is generally relatively little compared to the usual duration of isothermal creep. This is particularly true for unsealed specimens subjected to temperatures higher than 250 °C, where the drying process is completed (see Section 3.2.3).

Several studies have demonstrated that LITS developed on first heating is mostly irrecoverable on cooling and that if the material is reheated under sustained load, no appreciable additional LITS occurs for temperature levels lower than the maximum temperature reached during first heating [13,14,18,39,17,44,45,47]. Fig. 3-4 shows the temperature and strain histories of an unsealed concrete specimen, subjected to a relative humidity of 50% and several HC cycles, demonstrating this point clearly.

Despite normal assumptions, it is worth noting that, in reality LITS is a time-dependent phenomenon. In fact, the time needed for LITS to fully develop has been found to be strictly related to the hygral boundary conditions for low temperatures. For example, Fahmi et al. [39] demonstrated that when concrete is exposed to saturated air, i.e. is prevented from exchanging moisture with the ambient atmosphere, LITS needs much more time to develop than in case of 50% relative humidity. Moreover, in the case of 100% relative humidity, even though most of LITS develops upon first heating, several HC cycles up to 60 °C under load are needed in order for LITS to reach a limit value (see Fig. 3-4). These results suggest that moisture flux plays a key role on the time for LITS to develop and, consequently, on its occurrence upon secondary heating phases.

3.2.3. Moisture content and LITS

In case of unsealed conditions, the initial moisture content has been found to have little or no influence on the development of LITS for temperatures higher than 250 °C [2], while it has been found to influence concrete behaviour at lower temperatures [14].

Specifically, LITS developed for temperatures up to 250 °C in initially moist and air-dried specimens has been found to be comparable, while a significant reduction has been measured in the case

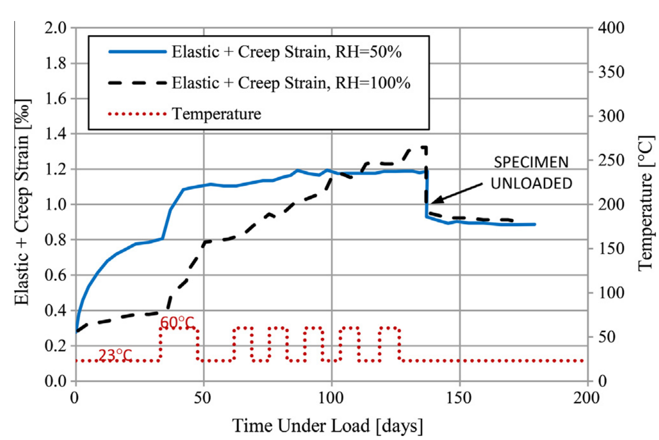

Fig. 3-4. Temperature and strain histories for a specimen subjected LTH tests with several HC cycles, for relative humidities (RH) of 50% and 100%. Adapted from [39].

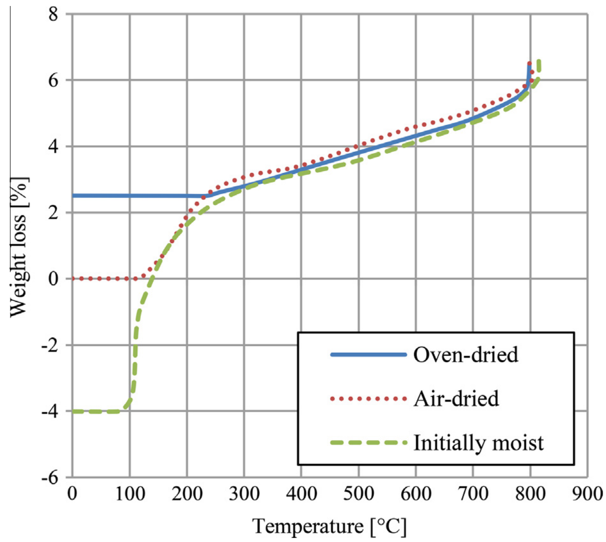

Fig. 3-5. Weight loss as a function of temperature for different initial moisture contents. Rate of heating 5 °C/min [21].

of oven-dried specimens [2]. Moreover, it was observed that above 250 °C the evolution of the LITS curve does not significantly depend on the initial water content [2], as shown in Fig. 3-6. These results are consistent with the main output of tests performed to evaluate the effect of preheating on LITS, outlined in previous sections, and with the results of stress-free-heating tests aimed at evaluating moisture loss as a function of the temperature. In fact, different authors found that the water content of stress-free specimens does not depend on the initial moisture for temperatures higher than 250 °C, meaning that the drying process is completed at that temperature level, i.e. the evaporable (free) water has disappeared (Fig. 3-5).

3.3. Thermal load

3.3.1. Effect of temperature

Of all the parameters influencing the development of LITS, temperature is the most significant. One of the main purposes of transient thermal tests is to obtain temperature-LITS curves representing the behaviour of a material point, suitable for numerical implementation to assess the behaviour of concrete structures under thermal gradients. Theoretically, this could be achieved by obtaining homogeneous temperature fields through the concrete specimen during the thermal transient phase. This would allow LITS curves representative of the actual material behaviour to be aquired, i.e. not affected by the development of thermal gradients inside the specimen. In practice, it is difficult to obtain homogeneous temperatures though the concrete sample on heating. In fact, as the thermal load is generally applied to the specimen surfaces, the heating of the core is delayed due to the thermal resistance of both matrix and aggregates as well as the evaporation (or drying) of the free water. A comparison between the maximum temperature differentials obtained by different authors [13,14,21] suggests that the size of the specimens and heating ratio are among the most important factors for controlling the temperature distribution inside the specimens. These works show that variation of these two parameters produce temperature differentials varying from 20 °C to 110 °C when the specimen surfaces reach 600 °C. Moreover, these studies suggest that the delay in the heating of the core can be minimized by designing small samples and applying low heating rates. For this reason, the discussion on the relationship between temperature and LITS reported below is based on the analysis of experimental curves obtained for low heating rates - less than 1 °C/min - and cubic or cylindrical samples having widths less than 11 cm [2,13,14]. Nevertheless, even for these experimental conditions, thermal gradients may develop, leading to temperature differentials up to 40–50 °C when the temperature of the surfaces reaches the range 500–600 °C [13]. Thus, it should be kept in mind that the experimental temperature-LITS curves discussed below may shift slightly from the ideal curve representing the response of a material point.

The development of LITS with the temperature is highly nonlinear: in general the LITS coefficient, i.e. the slope of the LITS curve, gradually increases with the temperature. However, this is only a general trend and there are various details to consider. By analysing the global trend of the LITS curve for LTH tests up to elevated temperatures (Fig. 3-7), various authors have found that LITS starts developing significantly only after 100 °C [13,14]. Such a sharp start to LITS development is probably linked to the significant drying of the cement matrix that occurs at temperatures between 100 °C and 200 °C (Fig. 3-5). Khoury et al. [2] found that, even though the LITS coefficient generally increases with temperature, for both air dried and initially moist concrete there is a minimum at about 150 °C – maybe due to the conclusion of the drying process. They also noted a slight reduction between 500 °C and 600 °C, possibly related to the $Ca(OH)_2$ content (Fig. 3-6).

3.3.2. Heating rate and LITS

For heating rates lower than 5 °C/min, the heating rate has been found to have little influence on the LITS behaviour of small specimens subjected to LTH tests [2,7,21,34], while for higher heating rates, a significant influence on FTS and LITS has been demonstrated. Such dependency is due to the appearance of substantial thermal gradients through the specimens, owing to structural effects [7]. Specifically, unloaded specimens exploded as a result of the relatively fast thermal contraction and of the strength degradation of the external layer of the material. Similarly, premature failure has been observed for loaded specimens with stress levels greater than 60% of the compressive strength [7].

3.3.3. Preheating cycles

Hansen & Eriksson [10] showed that if concrete is first subjected to a HC cycle up to 60 °C and 100 °C without being loaded, and then subjected to a LTH test, LITS develops to a lesser extent upon the second heating to the previously attained temperature. Since their specimens were submerged in water, the recorded LITS did not include drying shrinkage effects, meaning that a preheating cycle

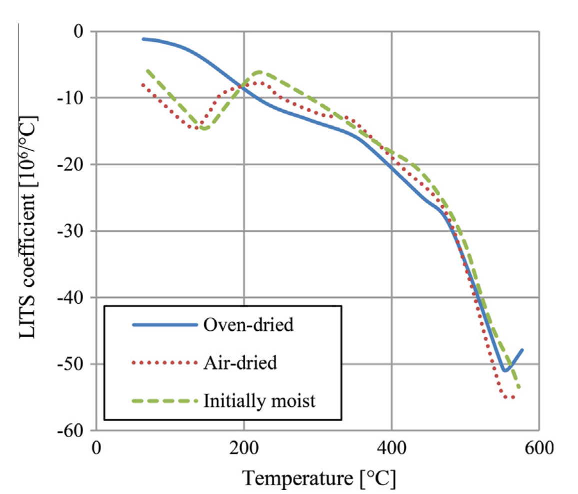

Fig. 3-6. Slope of the LITS 'master' curves obtained for initially moist and air dried concrete. Load level 30%. Rate of heating 1 °C/min [2].

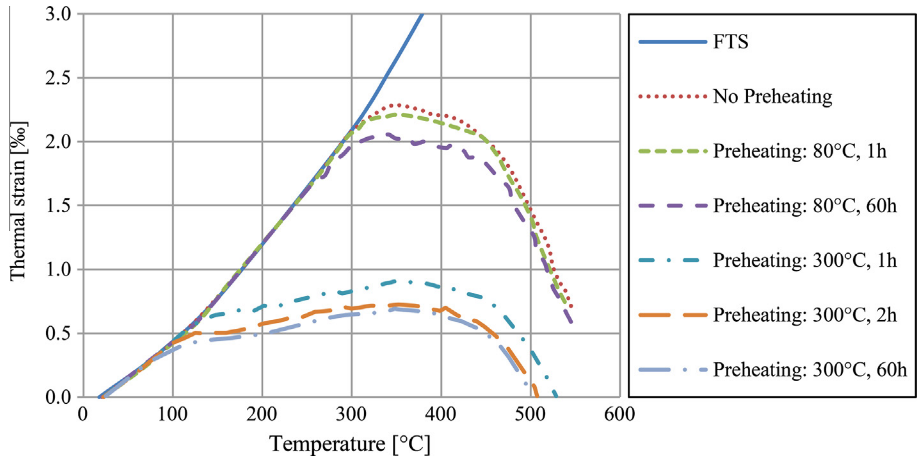

Fig. 3-7. Total thermal strain measured during a LTH test, expressed as a function of temperature, for an unloaded specimen (FTS) and a loaded specimens (load level 20%) previously subjected to different stress-free preheating cycles. Adapted from [13].

inhibits the development of the TS component. Similarly, LITS of unsealed specimens has been found to be strongly reduced in the case of stress-free preheating cycles [13,17,18,44,47], as shown from Fig. 3-7. In addition, Mindeguia et al. [13] demonstrated that the development of LITS is slightly influenced by the duration of the preheating period. In particular, when the constant temperature phase of the preheating cycle is prolonged, LITS needs higher temperatures to start developing, and its magnitude decreases (see Fig. 3-7).

Together, these studies suggest that, for practical purposes, it can be assumed that LITS is activated only when the temperature is higher than the pre-heating temperature. These results provide interesting insights into the assessment of PCPVs of Advanced Gas-cooled Reactors (AGRs), where the hydration process taking place during the early age of concrete curing may lead to the development of significant endogenous heat and, consequently, to relevant rises in temperature in absence of load.

3.4. Mechanical load

3.4.1. Influence of loading levels

As shown in Figs. 2-4 and 3-11, LITS has been shown to be reasonably proportional to the compressive load level when this is limited to 30–40% of the compressive strength [2,13,21]. This proportionality led to the concept of normalized or specific LITS [13], defined as the LITS due to a unit of stress, similar to the concept of specific basic creep, based on the well-known proportionality between the latter and applied stress for moderate stress levels.

3.4.2. LITS in the unloaded direction and multiaxiality

Most LITS test have been performed in uniaxially loaded concrete specimen, while a small number of experiments involved biaxial and triaxial compression, reproducing conditions more representative of the actual stress states of many heated concrete members.

3.4.2.1. LITS in the unloaded direction for uniaxial tests. A few works have shown that an expansive LITS strain appears in the unloaded direction in the case of uniaxial compression [6,13,14]. This leads to the definition of LITS Poisson's ratio υ_{LITS}, a coefficient analogous to the Elastic Poisson's ratio υ and defined as the ratio of transverse to axial LITS strain. Yet, the evolution of LITS in the unloaded direction with the temperature is not proportional to LITS in the loaded direction. From the analysis of the results obtained by Kordina et al. [6], shown in Fig. 3-8, it can be inferred that the temperature at which LITS in the unloaded direction starts becoming significant,

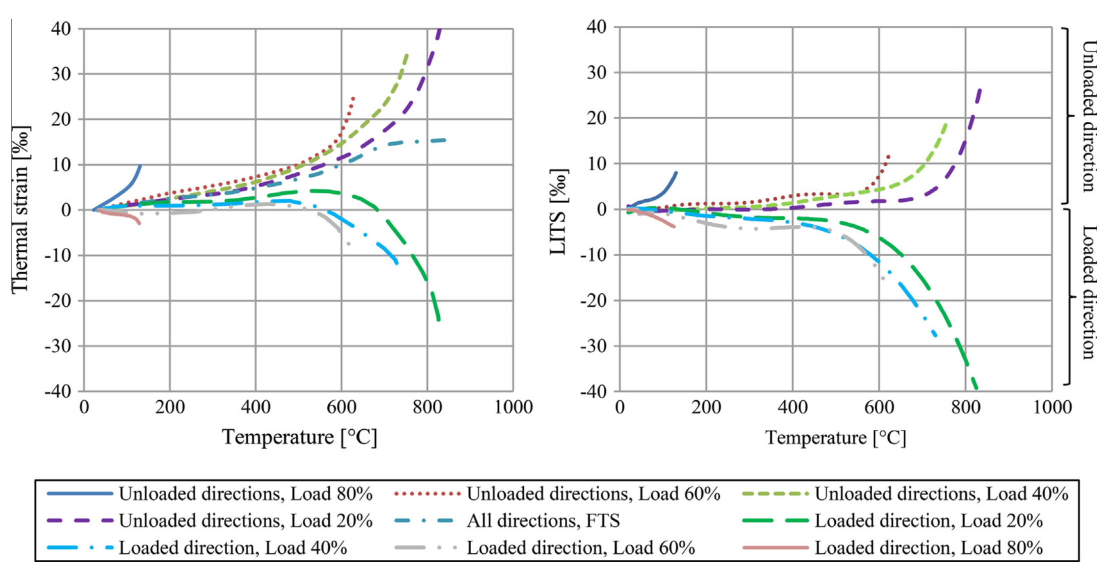

Fig. 3-8. Total thermal deformation in the loaded and unloaded direction during **uniaxial** LTH test. Load levels 0%, 20%, 40%, 60% and 80% [6].

i.e. the temperature at which the thermal strain in the unloaded direction deviates from the FTS curve, decreases with the stress level. In particular for stress levels equal to 20%, 40% and 60%, substantial lateral LITS develops starting from about 400 °C, 250 °C and ambient temperature respectively. Such results are in quite good agreement with the ones obtained by Petkovski & Crouch [14], where for a load level equal to 44% LITS in the unloaded direction was found to develop significantly above 100 °C. Moreover, this trend is also confirmed by the results obtained by Mindeguia et al. [13] for a load level of 20%, proving the existence of significant LITS in the unloaded direction after 400 °C. The authors argued that this expansion is related to the anisotropic crack pattern induced in the specimen: for temperatures higher than 400 °C, cracks parallel to the loading direction were observed, in accordance to results obtained by Ehm & Schneider [24].

3.4.2.2. LITS in the loaded and unloaded directions for biaxial tests. LTH test involving biaxial stress states have been performed at the University of Braunschweig [6,24,48] and the University of Shefield [14].

Figs. 3-8 and 3-9 and Table 3-2, produced from the thermal strain curves obtained by Kordina et al. [6], show that, in the loaded direction, the magnitude of LITS obtained for biaxial compression is comparable with the one obtained for uniaxial tests, for load levels in the range 20–60% and temperatures up to 600 °C. Similar results have been obtained Petkovski & Crouch [14] for a load level of 44% and temperatures up to 250 °C (see Fig. 3-10).

According to the results obtained by Kordina et al. [6], summarized in Table 3-2, the LITS in biaxial tests in the unloaded direction is always significantly higher than twice the lateral expansion measured in uniaxial tests. This phenomenon has been confirmed by the tests performed by Petkovski & Crouch [14]. According to these findings, a Poisson's ratio higher than the one evaluated for uniaxial compression has to be defined to express the relationship between LITS in the loaded and unloaded direction in case of biaxial tests. In other words, υ_{lits} depends on the triaxiality of the stress state. It is worth noting that, in the biaxial tests performed by Petkovski & Crouch [14], smaller LITS were recorded, particularly in the unloaded direction, probably due to the presence of partially sealed conditions obstructing the moisture evacuation and, therefore, limiting the drying creep component of LITS. Consequently, in [14] υ_{lits} at 250 °C was found to be 0.34 for uniaxial compression and 0.37 for biaxial compression, while Kordina et al. [6] previously measured a υ_{lits} of 0.46 in biaxial tests at the same temperature.

These findings suggest that, in the case of biaxial stress states, the LITS in the loaded and unloaded direction cannot be predicted by a mere superposition of the lateral expansions measured for uniaxial compression, that is concrete subjected to LTH regime exhibits a markedly confinement-dependent behaviour.

3.4.2.3. LITS in triaxial tests. To the authors' knowledge, the development of LITS in case of multiaxial stress states has been experimentally analysed only by Petkovski & Crouch [14]. They found

Table 3-2
LITS for different load levels and temperatures, in the loaded and unloaded directions, for uniaxial and biaxial tests. Adapted from [6].

Temperature [°C]	LITS loaded direction [‰]		LITS unloaded direction [‰]	
	Uniaxial	Biaxial	Uniaxial	Biaxial
Load 20%				
200	−0.80	−0.73	0.01	1.54
400	−2.01	−1.61	0.31	3.54
600	−6.23	−6.95	1.75	4.63
Load 40%				
200	−1.46	−1.66	0.16	2.55
400	−2.90	−2.73	1.40	5.11
600	−11.58	−9.28	4.33	8.52
Load 60%				
200	−3.07	−4.42	1.23	3.47
400	−3.92	−5.76	2.92	6.20
600	−13.73	−15.48	7.28	16.77

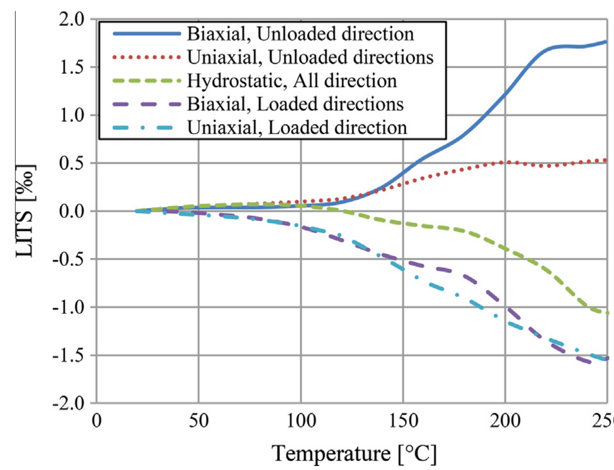

Fig. 3-10. LITS in the loaded and unloaded direction during **uniaxial**, **biaxial** and **hydrostatic** LTH test. Load level 44% [14].

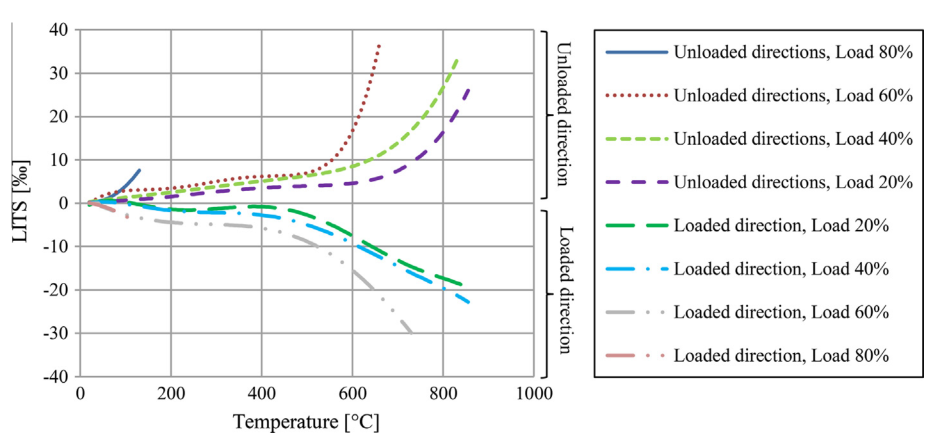

Fig. 3-9. LITS in the loaded and unloaded direction during **biaxial** LTH test. Load levels 0%, 20%, 40%, 60% and 80%. Deduced from the thermal strain curves obtained by Kordina et al. [6].

that, in the case of hydrostatic stress states, LITS starts developing significantly for temperatures above 100–120 °C and around 250 °C it reaches values close to two thirds of the LITS measured in case of uniaxial tests and biaxial tests in the loaded direction – see Fig. 3-10. However, to date there have been no LTH tests involving triaxial stress states and transient temperatures above 250 °C.

3.5. Concrete properties

3.5.1. Cement paste and LITS

It has been demonstrated that LITS occurs in hardened cement paste [2,13,44] and it is 2–3 times higher than when LITS is measured in concrete with aggregates [2]. Accordingly, different studies have shown that LITS is larger for high performance concretes, characterized by low water/cement ratios [17,18]. This could be due to the development of higher effective stresses in the cement matrix in the case of high performance concretes, where the low permeability of the cement limits the rate of mass loss with the temperature, therefore leading to higher pore pressures [49]. These results suggest that LITS is a phenomenon taking place in the cement paste, and is somehow restrained by the aggregates, i.e. that it is proportional to the cement content.

3.5.2. Aggregates and LITS

Several studies shown that unlike what happens for the FTS, the nature of aggregates has little or no influence on LITS for moderately high temperatures, while it becomes an influencing parameter for extremely high temperatures. The temperature at which the LITS curves for different aggregates start to slightly deviate from each other has been found to be in the range 300–450 °C [2,12,13].

As a consequence, Khoury et al. [2] stated that a 'master' LITS curve exists, expressing LITS as a function of temperature for a given stress/strength ratio, preheating condition, heating rate and curing regime, regardless of the type of concrete.

3.5.3. Influence of age of concrete at loading and heating

Parrot [47] found that the magnitude of LITS occurring in unsealed specimens in the case of LTH regimes is quite sensitive to the instants at which concrete is loaded and heated. In particular, LITS was found to decrease with both the age of concrete at loading, and the time between loading and heating. However, it is worth noting that the tests only explored such sensitivity for ages of less than 1 year. In fact, Fig. 3-11 shows that for ages at between 1 and 9 years, LITS does not vary significantly [2,15].

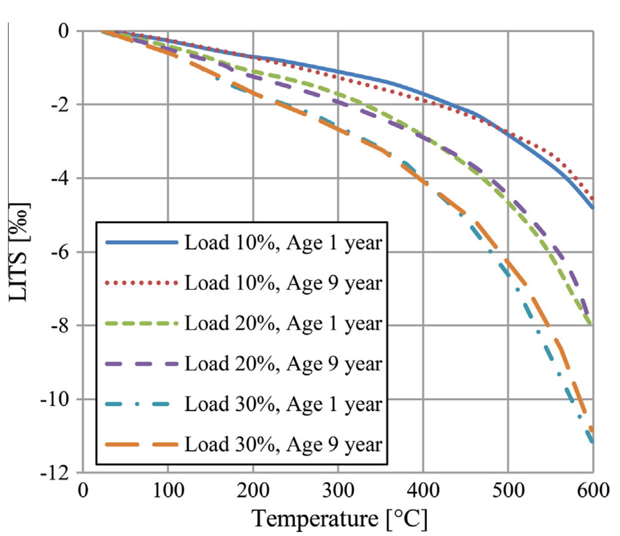

Fig. 3-11. LITS 'master' curves obtained for different stress level and age of concrete. Rate of heating 1 °C/min [2].

Therefore, LITS can be seen as an age-independent phenomenon for scenarios involving mature concrete.

3.6. Discussion on the physical origins of LITS

Despite the number of experimental and theoretical works that have been published over the last four decades on the subject, the complexity of the mechanisms underlying LITS has prevented the elucidation of a unique and universally accepted explanation of the phenomenon. For this reason, this section outlines and discusses the various theories of the physical mechanisms causing LITS, in the light of the existing experimental evidences. As discussed in Section 3.1, LITS is a complex phenomenon involving the interaction of different strain components. Accordingly, different physical and chemical phenomena may be identified as possible sources of LITS. Representing TS the biggest contribution to LITS, its components, namely drying creep and TTC, are discussed below.

3.6.1. Drying creep

In the case of transient tests performed on unsealed specimen the cement paste dries when heated, leading to the development of an accelerated drying creep effect. This strain component corresponds to the drying creep, also called the Picket effect [50], which is defined for ambient temperatures as the difference in between the creep measured at drying and the sum of shrinkage and basic creep.

Part of the drying creep phenomenon is due to the so called micro cracking effect [51,52]. When unloaded concrete is dried, the general non uniformity of moisture distribution and evacuation leads to the temporary development of local tensile stresses. This results in the appearance of irreversible expansion strains due to the development of tensile plastic strains and micro cracks. However, if a compressive load is applied while drying, tensile stresses are prevented from occurring on planes normal to the direction of compression. This results in a load-related strain component on drying, due the absence of micro cracking and plastic tensile strains. Such deformation occurs in the direction of the load and is usually referred to as micro cracking effect component of the drying creep.

In addition, the existence of another mechanism, termed micro diffusion effect has been postulated in [53]. This mechanism is represented by a stress-related local transport of water from the CSH gel pores (micro pores) to the adjacent capillary pores (macro pores). The water which diffuses into the gel pores might determine the breakage of bonds in the cement gel, producing an overall contraction of the material in the direction of the compressive stress.

3.6.2. TTC

The fact that the strains that develop during transient conditions are much higher than the expected strain due to isothermal creep, accelerated drying creep and increment in elastic strain, suggests that other mechanisms, causing TTC, exist during heating under sustained load.

At low temperatures, concrete degradation due to thermal incompatibility between aggregates (which tend to expand) and cement paste (which tends to shrink) is unlikely to be one of the causes of TTC, since it has been experimentally proved that TTC takes place to a higher degree in pure hardened cement paste [44,45], and does not depend on the nature of aggregates, when those are included in the mixture.

Similarly, the development of cracks due to thermal gradients is unlikely to be the main mechanism leading to TTC, considering that TTC develops even for very slow heating rates, i.e. in case of negligible thermal gradients [10].

Instead, many scholars hold the view that, for low temperatures, TTC is mainly due to physical disintegration and chemical reactions taking place in the cement paste in conjunction with a rapid internal mass transfer in the porous media, while the thermal incompatibility between cement and aggregates significantly influences the development of TTC for high temperatures [7,13,26].

For temperatures up to 300–400 °C, a temperature rise might cause an increase of the rate of chemical decomposition of the cement paste (mostly due to the dehydration of CSH and CH), together with a migration of water molecules from the gel pores to the capillary pores, which may occur even in case of sealed conditions, i.e. in absence of drying [10]. A possible explanation of TTC in this temperature range is that, when a simultaneous sustained compressive load is applied, such temperature-dependent material transformations lead to a strain in the loaded direction [7].

By contrast, for temperatures higher than 300–400 °C, the development of crack patterns has been documented even for slow heating rates, whereas TTC has been proved to increase sharply and to depend on the aggregate type. An implication of these observations may be that the thermal incompatibility between aggregates and cement causes cracking, i.e. a thermomechanical damage, therefore contributing to the development of TTC for this temperature range [2,13].

4. LITS models

This section reviews the literature on uniaxial and multiaxial LITS models. Since FTS is the other component of strain that develops during heating ε_{heat} (see Section 2.2), and is therefore a crucial contribution to be implemented in a material model, a concise review of the most common FTS models is firstly given. Afterwards, a discussion of the necessity of explicitly including LITS in concrete behaviour laws is presented. Finally, the main existing uniaxial and multiaxial models are outlined and critically discussed.

4.1. FTS models

FTS, $\varepsilon_0(T)$, is commonly modelled simply as a function of temperature, T, and obtained from stress-free heating tests directly. Usually it is expressed by functions involving a limited number of parameters such as low-order polynomials of temperature.

A common way to express ε_0 as a polynomial of temperature is to express it as a function of a thermal expansion coefficient α:

$$\varepsilon_0 = \alpha(T - T_0) \quad (4\text{-}1)$$

where T_0 is a reference temperature and α is a polynomial expressed as a function of temperature. For normal weight concrete with siliceous aggregates, Lie [54] proposed expressing α as a linear function of the temperature, thus obtaining a parabolic FTS strain curve:

$$\alpha = (a \times T + b) \quad (4\text{-}2)$$

where the calibration of parameters a and b leads to:

$$\alpha = (0.008T + 6)10^{-6} \quad (4\text{-}3)$$

Another interesting function, designed to fit the FTS curve for temperatures above 600 °C, where a stabilisation of the thermal strain has been experimentally observed [55], has been proposed by Nielsen et al. [56] and Pearce et al. [29] – see Fig. 4-1. According to this formulation, a coefficient α_T is defined as the ratio of strain rate $\dot{\varepsilon}_0$ to the temperature variation rate $\dot{T}$, i.e. the slope of the FTS curve, therefore having a different physical meaning to the α coefficient defined in (4-1):

$$\dot{\varepsilon}_0 = \alpha_T \dot{T} \quad (4\text{-}4)$$

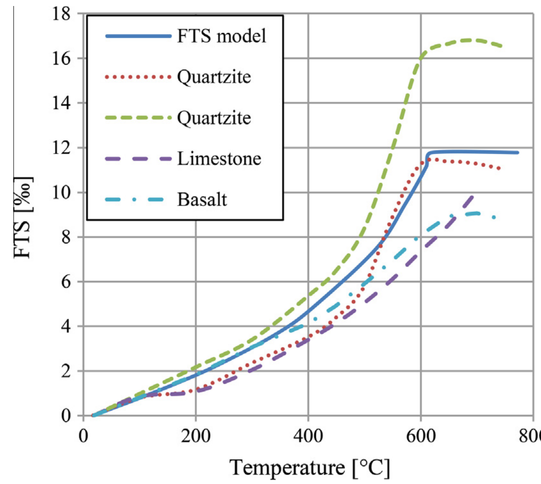

Fig. 4-1. Experimental FTS vs temperature for various concretes [55] and the curve obtained by the FTS model exposed in [56].

For quartzite normal weight concrete, α was defined as:

$$\begin{cases} \alpha_T = \frac{6\times10^{-5}}{7-\bar{T}} & \text{for } 0 \leqslant \bar{T} \leqslant 6 \\ \alpha_T = 0 & \text{for } \bar{T} > 6 \end{cases} \quad (4\text{-}5)$$

where

$$\bar{T} = \frac{T - 20\,°\mathrm{C}}{100\,°\mathrm{C}} \quad (4\text{-}6)$$

4.2. Implicit and explicit uniaxial LITS models

The inclusion of LITS in uniaxial constitutive laws for concrete is fundamental to reliably analysing the behaviour of structures subjected to transient fire conditions [57]. For this reason, several implicit and explicit models of LITS have been formulated over the past decades.

The term explicit has come to be used to refer to models where the LITS component (or the TS component, when a creep component is included) is explicitly formulated in the constitutive law, in addition to the instantaneous stress-related strain [41]. For explicit models, the following strain decomposition is generally adopted:

$$\varepsilon_{tot}(\sigma, T, t) = \varepsilon_0(T) + \varepsilon_\sigma(\sigma, T) + \varepsilon_{cr}(\sigma, T, t) + \varepsilon_{ts}(\sigma, T) \quad (4\text{-}7)$$

where σ is stress, T temperature, t time, ε_0 FTS, ε_σ the instantaneous stress-related strain, ε_{cr} is the isothermal creep strain and ε_{ts} is the TS. It is worth noting that the instantaneous stress-related strain $\varepsilon_\sigma(\sigma, T)$ may be modelled as stress history dependent, i.e. as an elastoplastic component, so that different values of ε_σ may be obtained for the same stress state but different stress histories. The explicit strain decomposition presented in Eq. (4-7) may also be modified by considering the creep strain and TS as a single creep component, denoted as ε_{cr^*}:

$$\varepsilon_{tot}(\sigma, T, t) = \varepsilon_0(T) + \varepsilon_\sigma(\sigma, T) + \varepsilon_{cr^*}(\sigma, T, t) \quad (4\text{-}8)$$

where

$$\varepsilon_{cr^*}(\sigma, T, t) = \varepsilon_{cr}(\sigma, T, t) + \varepsilon_{ts}(\sigma, T) \quad (4\text{-}9)$$

Being impossible to experimentally uncouple the creep strain and TS, this last form is sometimes preferred to the (4-7).

For explicit models aimed at studying the short-term behaviour of structures subjected to accidental fires, the creep term appearing in the (4-7) may be omitted. This leads to a time-independent formulation, where the creep developed on heating is included in a LITS∗ term - see definition given in Section 2.2 - which replaces the TS of the (4-7):

$$\varepsilon_{tot}(\sigma,T) = \varepsilon_0(T) + \varepsilon_\sigma(\sigma,T) + \varepsilon_{lits^*}(\sigma,T) \tag{4-10}$$

It should also be noted that, according to Eqs. (4-7), (4-8) and (4-10) the TS is always seen as a purely thermomechanical strain component representing both the drying creep and TTC components. Such models could be refined by distinguishing these two strain components and including the dependency of the drying creep strain on the hygral conditions of the material.

In contrast to explicit models, implicit models consider the instantaneous stress-related strain ε_σ and the LITS ε_{lits} (or TS ε_{ts}) as a single mechanical elastoplastic strain component ε_m:

$$\varepsilon_{tot}(\sigma,T,t) = \varepsilon_0(T) + \varepsilon_m(\sigma,T) + \varepsilon_{cr}(\sigma,T,t) \tag{4-11}$$

The main disadvantage of the implicit models is that they are unable to capture the difference between HTL and LTH regimes, since they always implicitly consider the TS component, i.e. they are suitable only for LTH conditions. Moreover, they present drawbacks even in case of LTH conditions involving mechanical unloading of the material. This is because they treat TS as a fully reversible strain component, since the unloading stiffness is defined as the tangent of the mechanical stress-strain curve, which implicitly includes TS [41]. Such limitations result in an overestimation of the real unloading elastic stiffness (see Fig. 4-2).

In the authors' opinion, the strain decomposition to be adopted when formulating a constitutive law including LITS should be chosen as a function of the structural application for which the model is designed:

- In the case of structures subjected to LTH regimes where the temperature increases and the stress is approximately constant, implicit models can be adopted – see Eq. (4-11). Since an implicit LITS formulation is able to capture the concrete behaviour for these particular loading conditions, the use of complex explicit models is deemed to be unnecessary.
- For applications involving all the other possible stress-temperature paths, explicit models are needed.
- If a material model has to be formulated to study the short-term behaviour of structures subjected to generic stress-temperature paths, the time dependent creep strain component can be disregarded, and the strain decomposition described in Eq. (4-10) can be adopted.
- By contrast, if the long-term behaviour of the material has to be represented, the strain decomposition described in Eqs. (4-7) and (4-8) may be preferred.

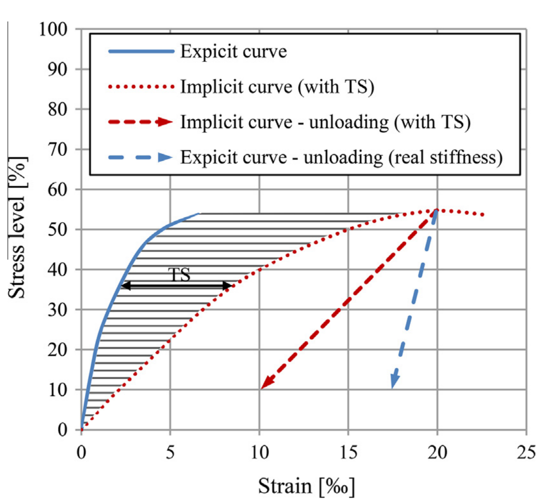

Fig. 4-2. Stress-strain curves for implicit and implicit models at 500 °C [41].

- For applications involving generic stress-temperature paths and high moisture gradients, Eqs. (4-7), (4-9) and (4-10) could be further modified to include a moisture-dependent drying creep strain component.

4.3. Uniaxial explicit LITS models

4.3.1. Anderberg and Thelandersson's TS model

Anderberg and Thelandersson [21] proposed a uniaxial constitutive model based on the decomposition of the total strain expressed in Eq. (4-7). The instantaneous stress-strain model, allowing evaluation of ε_σ at high temperatures, and the isothermal creep component ε_{cr}, were calibrated from the results of HTL tests. By contrast, the transient strain model was formulated and calibrated in order to fit the difference between the total thermal strain ε_{tot} measured in LTH tests and the instantaneous and creep strains ε_σ and ε_{cr}, evaluated for transient conditions according to the models formulated for steady state regime. Since the TS evaluated this way was found to be nearly proportional to the FTS for the analysed concrete mixture (quartzite aggregates) and temperatures up to 500 °C (see Fig. 4-3), a uniaxial model expressing the TS as linearly proportional to the applied stress level and the thermal strain was formulated:

$$\varepsilon_{ts} = k_{tr}\frac{\sigma}{\sigma_{u0}}\varepsilon_{th} \tag{4-12}$$

where σ is the applied compressive stress, σ_{u0} is the compressive strength of the material at ambient temperature, ε_{th} is the FTS and k_{tr} is a material parameter, which was found to vary between 1.8 and 2.35 to fit different experimental results.

However, the authors recognized that, even though the approximation of TS given by the model at temperatures around and above 550 °C may be acceptable for some practical purposes, such linear correlation between thermal strain and TS is not suitable for accurately describing the TS at temperatures above 550 °C. In addition, the assumption of a linear proportionality between TS and FTS seems to contrast with experimental results obtained for different types of concrete, where for decreasing water to cement ratios the FTS decreased while the TS increased [16–18].

4.3.2. Nielsen's LITS model

Nielsen et al. [56] proposed modelling LITS as linearly proportional to the applied stress level and to the temperature:

$$\varepsilon_{lits} = \frac{\sigma}{\sigma_{u0}}a(T-T_0) \tag{4-13}$$

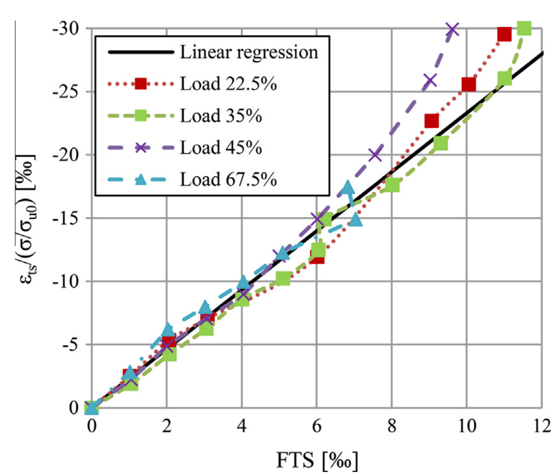

Fig. 4-3. Ratio of TS to stress level plotted against the FTS obtained in [21] for concrete with quartzite aggregates and temperatures below 500 °C. Heating rate 5 °C/min. The straight line is obtained from linear regression (k_2 = 2.35).

where the coefficient a was calibrated as $a = 3.8 \times 10^{-5}\,^{\circ}\mathrm{C}^{-1}$ in order to best-fit the LITS model proposed in [36] in the temperature range 20–500 °C. Such model was in turn conceived to fit the LITS "master curve" obtained in [2] – see Fig. 3-11 – and is described in detail in Section 4.3.4.

Such LITS formulations can be seen as a modified Anderberg and Thelandersson TS model, where the linear coefficient of thermal expansion $\alpha(T)$ remains constant with temperature and is included, with the coefficient k_2, in the coefficient a. The main advantage of this model is the possibility of calibrating the LITS coefficient a independently of the thermal expansion coefficient $\alpha(T)$. Actually, such independency is suggested by the fact that FTS is strongly influenced by the nature of aggregates, while LITS mainly takes place in the cement paste (see Sections 3.5.1,3.5.2 and 3.6).

Although this model may be useful for some practical purposes, its linearity does prevent it from capturing the sharp increase in LITS that typically occurs at high temperatures – above around 400–500 °C.

4.3.3. Diederichs' LITS model

With a view to conveniently fitting the highly nonlinear curve expressing LITS as a function of the temperature, Diederich's model expresses LITS as a third order polynomial of the temperature [58]:

$$\varepsilon_{lits} = \frac{\sigma}{\sigma_{u0}}\left[a_1(T - T_0) + a_2(T - T_0)^2 + a_3(T - T_0)^3\right] \tag{4-14}$$

where the coefficients T_0, a_1, a_2 and a_3 were calibrated to fit experimental data provided by Diederichs [59] as follows:

$$\begin{aligned} T_0 &= 20\,^{\circ}\mathrm{C} \\ a_1 &= +0.0412 \times 10^{-3}\,^{\circ}\mathrm{C}^{-1} \\ a_2 &= -1.72 \times 10^{-7}\,^{\circ}\mathrm{C}^{-1} \\ a_3 &= +3.3 \times 10^{-10}\,^{\circ}\mathrm{C}^{-1} \end{aligned} \tag{4-15}$$

Such models involve more parameters than the Nielsen's model but allows an accurate fit to experimental LITS curves, particularly for temperatures above 400–500 °C.

4.3.4. Terro's LITS model

Terro [36] formulated a LITS model in the light of the LITS "master" curve identified by Khoury et al. [2]. The proposed expression takes into account the experimentally demonstrated dependency of LITS on the volume fraction of aggregates V_a and is valid for stress levels up to 30% of the compressive strength:

$$\varepsilon_{lits} = \varepsilon_{0,3} \times \left(0.032 + 3.226\frac{\sigma_i}{\sigma_{u0}}\right)\frac{V_a}{0.65} \tag{4-16}$$

where σ_i is the initial compressive stress before heating, and $\varepsilon_{0,3}$ is the value of ε_{lits} when $\sigma_i/\sigma_{u0} = 0.3$.

For concrete with calcareous and lightweight aggregates, $\varepsilon_{0,3}$ is expressed by a fourth order polynomial of the temperature:

$$\varepsilon_{0,3} = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 \tag{4-17}$$

where

$$\begin{aligned} a_0 &= -4.39 \times 10^{-5} \\ a_1 &= 2.73 \times 10^{-6} \\ a_2 &= 6.35 \times 10^{-8} \\ a_3 &= -2.19 \times 10^{-10} \\ a_4 &= 2.77 \times 10^{-13} \end{aligned} \tag{4-18}$$

While for LITS of Thames gravel, which departs from the master curve for temperatures above 400 °C, a fifth order polynomial of the temperature is defined:

$$\varepsilon_{0,3} = b_0 + b_1T + b_2T^2 + b_3T^3 + b_4T^4 + b_5T^5 \tag{4-19}$$

where

$$\begin{aligned} b_0 &= -1.626 \times 10^{-3} \\ b_1 &= 5.803 \times 10^{-5} \\ b_2 &= 6.364 \times 10^{-7} \\ b_3 &= 3.611 \times 10^{-9} \\ b_4 &= 9.280 \times 10^{-12} \\ b_5 &= 8.806 \times 10^{-15} \end{aligned} \tag{4-20}$$

This model is suitable for modelling the highly nonlinear evolution of TS with temperature, similarly to Diederichs model, with the advantage of including the effect of the volume fraction of aggregate V_a.

4.3.5. Discussion

It is worth noting that the calibration of the coefficients defining the LITS curves is a crucial modelling phase.

This is because such parameters do not have an intuitive physical meaning and the polynomial curves are sensitive to them. In this regard, for example, it may be verified that increasing by 5% the coefficients a_0, a_1, a_2, a_3 and a_4 defined in the Terro's model produces respectively a LITS variation of 1%, 1%, 9%,11% and 18%, considering a temperature of 600 °C and load level of 20% the cold compressive strength.

This is because such parameters do not have an intuitive physical meaning and the polynomial curves are sensitive to them. For the presented models, the parameters have been calibrated so as to fit the behaviour of the typical concrete mixes used in the nuclear industry four decades ago. Therefore, the best way to accurately represent the thermomechanical properties of current and future concrete mixes, is to re-calibrate them via LTH tests. However, if no experimental data are available, it is reasonable to use the coefficients initially provided by the different authors. In particular, if temperatures beyond 400 °C are examined, the authors of this paper recommend using the curves provided by Terro [36], since they can reproduce the highly nonlinear LITS development, they have been obtained considering a number of different concrete mixes, and they take into account the influence of the volume fraction of aggregate V_a.

4.4. Multiaxial explicit models

4.4.1. Thelandersson's LITS model

Thelandersson [31] proposed a multiaxial generalisation of the uniaxial model presented in [21], conceived as an extension of isotropic, temperature dependent, linear-elastic behaviour. If E and v are treated as time dependent, the time differentiation of the isotropic thermoelastic law gives:

$$\dot{\varepsilon}_{ij} = \frac{1+\upsilon}{E}\dot{\sigma}_{ij} - \frac{\upsilon}{E}\dot{\sigma}_{kk}\delta_{ij} + \alpha\delta_{ij}\dot{T} + (\gamma_1\sigma_{kk}\delta_{ij} + \gamma_2\sigma_{ij})\dot{T} \tag{4-21}$$

where

$$\begin{cases} \gamma_1 = \frac{d}{dT}\left(-\frac{\upsilon}{E}\right) \\ \gamma_2 = \frac{d}{dT}\left(\frac{1+\upsilon}{E}\right) \end{cases} \tag{4-22}$$

The strain component defined by the last term of (4-21) can be seen as a thermomechanical strain representing the LITS strain in case of transient regime:

$$\dot{\varepsilon}_{ij}^{lits} = (\gamma_1\sigma_{kk}\delta_{ij} + \gamma_2\sigma_{ij})\dot{T} \tag{4-23}$$

The material parameters γ_1 and γ_2 describe the proportionality between stress level, temperature variation and thermomechanical strain rate, and for practical purposes they can be calibrated by fitting the experimental results of LTH tests. Accordingly, the total strain can be written as:

$$\dot{\varepsilon}_{ij} = \frac{1+\upsilon}{E}\dot{\sigma}_{ij} - \frac{\upsilon}{E}\dot{\sigma}_{kk}\delta_{ij} + \alpha\delta_{ij}\dot{T} + \dot{\varepsilon}_{ij}^{lits} \quad (4\text{-}24)$$

The author proved that this model captures the general trend of the experimentally estimated thermal strain curves. However, when the combinations of stress and temperature approach crushing failure, the model does not provide accurate results.

4.4.2. De Borst & Peeters' LITS model

A modified version of the thermomechanical strain component defined by Thelandersson has been formulated by de Borst & Peeters [60]. Here the LITS strain component is incorporated in a concrete constitutive model that includes a smeared crack model. According to this model, the general strain rate decomposition is defined in matrix notation as:

$$\dot{\underline{\underline{\varepsilon}}}_{tot} = \dot{\underline{\underline{\varepsilon}}}_{cra} + \dot{\underline{\underline{\varepsilon}}}_{ela} + \dot{\underline{\underline{\varepsilon}}}_{0} + \dot{\underline{\underline{\varepsilon}}}_{lits} \quad (4\text{-}25)$$

where $\dot{\underline{\underline{\varepsilon}}}_{tot}$ is the total strain rate tensor, $\dot{\underline{\underline{\varepsilon}}}_{cra}$ the crack strain rate tensor, $\dot{\underline{\underline{\varepsilon}}}_{ela}$ the elastic strain rate tensor, $\dot{\underline{\underline{\varepsilon}}}_{0}$ the thermal strain rate tensor, and $\dot{\underline{\underline{\varepsilon}}}_{lits}$ the LITS rate tensor.

In [60], the LITS component has been obtained by modifying the expression proposed in [31], In particular, the material coefficients γ_1 and γ_2 have been expressed as:

$$\gamma_1 = -\upsilon_{lits}\frac{k_{tr}\alpha}{\sigma_{u0}} \quad (4\text{-}26)$$

$$\gamma_2 = (1+\upsilon_{lits})\frac{k_{tr}\alpha}{\sigma_{u0}} \quad (4\text{-}27)$$

In the above equations υ_{lits} is a material parameter, analogous to the elastic Poisson modulus υ, allowing a description of the strain in the unloaded directions. Moreover, such coefficients allow the behaviour to be modelled as isotropic and LITS in the unloaded direction to be modelled as proportional to the term $k_{tr}\alpha/\sigma_{u0}$, similarly to that suggested for the loaded direction in [1]:

$$\dot{\varepsilon}_{ij}^{lits} = \frac{k_{tr}\alpha}{\sigma_{u0}}(-\upsilon_{lits}\sigma_{kk}\delta_{ij} + (1+\upsilon_{lits})\sigma_{ij})\dot{T} \quad (4\text{-}28)$$

4.4.3. Pearce's LITS model

Recently, Pearce et al. [29] also proposed an extension of Thelandersson's model, where the total strain is decomposed as (ignoring conventional creep strains and plastic strains):

$$\dot{\underline{\underline{\varepsilon}}}_{tot} = \dot{\underline{\underline{\varepsilon}}}_{ela} + \dot{\underline{\underline{\varepsilon}}}_{0} + \dot{\underline{\underline{\varepsilon}}}_{lits} \quad (4\text{-}29)$$

where the loss of strength and stiffness of the material due to the mechanical processes were modelled by a thermal and mechanical damage model.

With regard to the third component, they modified the expression (4-28) by substituting the term $k_{tr}\alpha$ with a generic function of the temperature $\beta(T)$, aimed at fitting the experimental data by eliminating the dependency of LITS on the FTS:

$$\dot{\varepsilon}_{ij}^{lits} = \frac{\beta(T)}{\sigma_{u0}}(-\upsilon_{lits}\sigma_{kk}\delta_{ij} + (1+\upsilon_{lits})\sigma_{ij})\dot{T} \quad (4\text{-}30)$$

In particular, they defined $\beta(T)$ by imposing the same LITS curve obtained by the bi-parabolic model proposed in [32] in case of uniaxial load.

4.4.4. Discussion

Of above models, the one proposed by Pearce et al. [29] allows the more accurate modelling of the uniaxial LITS curve while also containing material parameters with an intuitive physical meaning. Following the same approach suggested by the authors, it is theoretically possible to implement whichever uniaxial law (see Sections 4.3.1,4.3.2,4.3.3 and 4.3.4) in 3D by adequately modifying the formulation of the generic function of the temperature $\beta(T)$ defined in Eq. (4-30).

The major limitation of all the above triaxial models is represented by the hypothesis of confinement-independent development of LITS, e.g. by the analogy with isotropic elasticity. Indeed, such an assumption prevents capturing the markedly confinement-dependent development of LITS discussed in Section 3.4.2 which, for temperatures above 250 °C, is not even fully understood experimentally yet.

5. Summary and conclusions

In this paper, firstly, a review of the experimentally demonstrated characteristic of LITS was given. This section classified the main testing methodologies in order to identify the most appropriate experimental procedures for reproducing transient and steady-state loading conditions. Then, the two main components of thermal strain measurable under constant load, i.e. FTS and LITS, were defined. The experimentally identified characteristics of the FTS were discussed, while an analysis of the effects of temperature on elasticity and isothermal creep strain was necessary prior to formulating the definition of LITS components. Once the different contributions had been identified, the effects of different parameters on the development of LITS and its physical origins were outlined in the light of experimental evidence. In particular, it was found that LITS is:

- a quasi-instantaneous strain component in the case of unsealed conditions,
- strongly nonlinear and mostly irrecoverable with respect to temperature,
- reduced by stress-free preheating cycles,
- an age-independent phenomenon for ages at loading higher than one year and temperatures up to about 450 °C,
- almost proportional to the compressive stress level,
- independent of the initial moisture content for unsealed conditions and temperatures above 250 °C,
- independent on the heating rate for heating rates lower than 5 °C/min,
- significantly influenced by moisture flux in the range 100–250 °C,
- independent on the nature of aggregates for temperatures up to about 400 °C,
- a strongly confinement-dependent phenomenon,
- mainly due to chemical and physical reactions taking place in the cement paste for temperatures up to about 400 °C, while also due to thermal incompatibility between aggregate and cement paste for higher temperatures.

It was also found that new triaxial LTH tests, involving temperatures higher than 250 °C, are needed to understand and reliably model the behaviour of concrete in such loading conditions.

Secondly, this study reviewed the mathematical models of LITS available in the literature. The main differences between implicit and explicit LITS models were examined. In particular, the necessity of using explicit models when modelling HC cycles and when the stress is varying over time was underlined. Then, the main features of the existing uniaxial and multiaxial models were presented with a view to outlining their strengths and limitations. In this regard, it was highlighted that:

- Anderberg and Thelandersson's model cannot be applied to a wide range of concrete mixtures, since the assumption of LITS dependency on the thermal expansion coefficient α has been proved to be unacceptable in general.
- Nielsen's model is quite simple and allows LITS to be modelled regardless of free thermal expansion. However, it cannot capture the typical sharp increase in LITS for temperatures higher than 400 °C, a significant limitation for fire analyses.
- Diederich's and Terro's models both allow accurate fits to experimental curves, while involving a higher number of parameters than earlier models.
- Pearce's multiaxial LITS models combines the main advantages of Thelandersson's and De Borst & Peeters's models: it involves material parameters having an intuitive physical meaning and it allows fitting of LITS curves regardless of the coefficient α. However, due to their nature, such models cannot describe the strongly confinement-dependent development of LITS.

The following conclusions can be drawn from the present study:

- In recent years, there has been an increasing interest in the modelling of LITS. This is due to the necessity of assessing the fire resistance of concrete structures such as nuclear pressure vessels, containers for chemicals, water towers or reservoirs, silos, and building structures in fire (particularly travelling fire) conditions.
- Earlier experimental work on LITS necessarily focused on uniaxial loading conditions. This provided a basis for understanding the behaviour of framed structures but also left many questions about the multiaxial behaviour of bulk concrete structures open. In recent years, there has been an increasing interest in this area.
- Even though more recent tests on multiaxial loading conditions have begun to fill the gaps in knowledge, more experimental research is required to understand the triaxial behaviour of concrete for temperatures higher than 250 °C.
- The experimental knowledge is reflected in the available analytical models: the uniaxial models are more comprehensive and firmly linked to experimental evidence than the multiaxial ones. In this regard, most of the multiaxial models estimate the triaxial behaviour by the assumption of confinement-independent development of LITS, which is in contrast with the experimental evidence. Therefore, further research should be carried out to develop multiaxial models able to capture the confinement-dependent behaviour of heated concrete.
- Most of the available models have been formulated and calibrated for concrete mixes used in the 1970–1980s. As a consequence, it would be advisable to re-calibrate them via new tests performed on appropriate modern concrete mixes.

Competing interests statement

The authors declare no competing interests.

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