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#### 17 Abstract

14

16

18 The conditions that lead to Transient Thermal Deformation (TTD) of concrete subjected to 19 various temperatures and compressive loads in sealed conditions are analysed and a model 20 based on a two-scale porosity is proposed. In this model, water expands in the smaller pores 21 and diffuses progressively to the capillary pores at the upper scale. It is then shown that the 22 water overpressure in smaller pores and the duration of the diffusion process between the two 23 scales of porosity control the TTD. It is also shown that creep or shrinkage before the 24 temperature transition mitigates TTD. The aim is to provide a model able to predict the 25 conditions for TTD to appear and the amplitude of the TTD under various thermo-mechanical 26 conditions. The TTD model is implemented in an existing basic creep model, fitted and 27 compared with different experimental results.

#### 28 I. Introduction

In the framework of research surveys steered by the French agency for nuclear waste management (Andra) and the Laboratoire Matériaux et Durabilité des Constructions (LMDC) of Toulouse University, the effect of thermo-hydro-mechanical conditions on concrete deformations have been studied in order to predict the long-term behaviour of High

33 Performance Concrete (HPC). As nuclear wastes are exothermic, they could induce a rise in 34 temperature (up to a maximum of 50 °C) and a dilation of concrete containment structures 35 which, in return, could lead to a soil reaction and then a loading of the tunnel during the temperature rise. Concomitance of this temperature rise and mechanical loading are 36 favourable to the appearance of Transient Thermal Deformation (TTD) of concrete, so the 37 38 phenomenon has to be quantified. The few experimental studies available in the literature for 39 the 20 °C to 100 °C temperature range show that, if concretes are loaded and heated 40 simultaneously, they develop greater deformation than if they are heated first and loaded later 41 [1] [2]. This additional strain, called Transient Thermal Deformation (TTD), has been observed 42 up to 105 °C, which is the threshold temperature for C-S-H dehydration [3] [4] [5] [6]. Above 43 this temperature, these authors consider TTD as dehydration creep attributable to chemical transformation due to the temperature increase, which leads to a rearrangement of the 44 45 microstructure.

The aims of the present work are to clarify the conditions needed for TTD to exist, to understand the physical mechanism that controls it, and then to propose a model able to improve existing creep models in order to consider the influence of the chronology of the thermo-mechanical conditions. After an overview of experimental evidence concerning transient thermal deformation phenomena, the creep model proposed by Sellier et al. [7] is recalled and is improved so as to take TTD into account. The efficiency of the proposed modelling is tested by comparing numerical results with the experimental data.

53 **II.** 1

#### **II.** Experimental evidence

According to available data bases [9] [10], transient thermal deformation is irreversible and, if concrete is subjected to heating/cooling cycles under load, TTD only occurs during heating periods. Cagnon et al. [10] have measured the experimental deformations of a mature concrete

57 (made with CEM I cement) subjected to two thermo-mechanical conditions: first heated and then loaded and, conversely, first loaded and then heated. Figure 1 presents the strain 58 59 evolutions for the two thermo-mechanical conditions. Contraction is conventionally considered as a negative deformation. The concrete heated first and loaded one day later (blue 60 curves) does not develop TTD, unlike the concrete loaded first then heated one day later 61 62 (green curves) which does develop TTD. This comparison has shown that the TTD component does not modify the long-term creep kinetics but is just a temporary acceleration 63 64 of creep. These observations are in accordance with the model of transient thermal creep proposed by Bažant and Kaplan [15]. However, in their model, transient thermal creep can 65 reappear at each temperature variation while the concrete is loaded. Experiments performed 66 67 by Cagnon did not confirm this aspect, as shown in Figure 1. During the second heating cycle under loading, the two strain evolutions are similar, revealing that TTD does not reappear 68 69 after the first heating.



70 71 72 73 74 75

Figure 1: 1<sup>st</sup> thermo-mechanical conditions: elastic strain, basic creep, thermal dilation and TTD for a sample loaded first (plotted in green) and a sample heated first (plotted in blue), with modelling.  $t_0$  corresponds to the end of water curing and  $R_c$  is the compressive strength (experimental results from [10])

This non-repeatability in case of heating is one of the main points of discussion. For several authors [5] [10] [11], TTD appears only once, with the first heating, and it can reappear only if the temperature peak reached in previous heating is exceeded. Fahmi et al. [9] showed that saturated concrete developed TTD even after several cycles of heating/cooling. However, for concrete stored at 50% RH, this repeatability did not exist. Thus, he showed that the water content modified the amplitude of the TTD. This strain dependence on the degree of saturation has been confirmed by Cagnon et al. [10] and Hansen and Eriksson [12]. Moreover, the loading rate and heating kinetics can also influence TTD [1].

To explain this phenomenon, various assumptions have been proposed. According to Khoury and Parrot [11] [13], the origin of TTD could be a differential thermal dilation between the

85 various concrete phases and the associated microcracking. However, TTD is also observable 86 on cement paste, so its origin cannot be attributed only to the differential thermal dilation 87 between paste and aggregates. Torrenti [14] proposed a damage model coupled with creep to simulate the transient thermal deformation. In his model, the evolution of damage amplifies 88 89 the stress and thus the viscoelastic strain; the additional strain obtained is considered to be the 90 TTD. Experimentally, the evolution of Young's modulus measured before and after thermo-91 mechanical tests at 40 °C in [10] showed that TTD did not damage the material. Several 92 authors suggest that the transient thermal deformation phenomenon has its origin in water 93 movement at the nanoporous C-S-H scale [10] [12] [15] [16] [17]. Some models proposed are 94 usually based on self-desiccation [15] or thermal activation [6] [18] [19] and are a function of 95 the thermal variation rate  $(\dot{T})$ . Thus, according to these models, the transient thermal strains 96 will be repeated in case of heating cycles, whatever the maximum temperature reached, which 97 is not in accordance with Cagnon's experimental observations. Thus, there is a need to 98 improve the understanding and the modelling of this phenomenon. For this purpose, a double-99 scale porosity model with water transfer from one scale to the other is proposed. The 100 overpressure in the finest porosity is assumed to control the material viscosity. This 101 dependence of the viscosity on the pressure at nanoscale is implemented in an existing basic 102 creep model and successfully confronted with literature results.

103 III.

**Modelling of experiments** 

104 This section first presents the creep model in which the TTD is to be implemented. A lot of 105 creep models are proposed in the literature. Benboudjema et al. [20] split the basic creep into a 106 spherical and a deviatoric part. Thus de spherical creep corresponding to a migration of 107 adsorbed water in micro and nanoporosity and the deviatoric creep is the sliding of C-S-H 108 layers. The model is based on the assumption that the basic creep kinetics of concrete is 109 controlled by two antagonistic phenomena: the material viscosity, which allows creep, and a

110 consolidation phenomenon, which corresponds to a transfer of stresses from viscous particles (typically C-S-H bundles) to elastic particles (other hydrates and aggregates). As the stresses 111 112 in the non-viscous particles increase, the C-S-H are unloaded, which slows down their strain 113 rates. TTD is assumed to take place in the nanoporisity of C-S-H bundles: due to the 114 temperature rise, the embedded water dilates and its pressure increases, transiently modifying 115 the bond between C-S-H particles and so their viscosity. Once this overpressure has been 116 depleted by diffusion of water from the C-S-H to capillary pores, the C-S-H bundles return to 117 their initial configurations and the creep velocity returns to that of basic creep.

118

#### **III.1. Principles of the creep model**

The model chosen to implement the TTD phenomenon is described in [7]. As explained above, in this model the slowdown of creep kinetics is due to a consolidation phenomenon that increases the apparent material viscosity. The consolidation function assumes that there is a strain potential that is intrinsic to the concrete, and each deformation (shrinkage and creep) consumes this potential and consolidates the material, thus slowing down creep. The strain is modelled with a Maxwell model in which the viscosity evolves with the strain [7]; this strain corresponds to  $\varepsilon^{MC}$  in Eq. (1).

126 Meanwhile, Cagnon et al. [10] observed experimentally that TTD did not modify later creep 127 kinetics. In other words, the creep kinetics is the same at the end of the TTD whatever the 128 TTD magnitude. Everything happens as if the concrete fluidifies momentarily, without any 129 effect of TTD on the consolidation process. From a macroscopic point of view, this is similar 130 to a temporary fluidification of concrete that disappears approximately with the end of 131 heating. As basic creep and TTD are both viscous strains but only the basic creep creates a consolidation, the creep strain  $\varepsilon^{M}$  in Eq. (1) has be decomposed into two parts: a 132 consolidating strain  $\varepsilon^{MC}$  (corresponding to the initial basic creep model proposed in [7]) and 133

an un-consolidating strain  $\varepsilon^{M\bar{C}}$  for the TTD. The former corresponds to the basic creep, which 134 depends and acts on the consolidation process, and the latter, corresponding to the TTD, 135 136 depends on the consolidation but does not act on it.

137 
$$\frac{\partial \varepsilon^{M}}{\partial t} = \frac{\partial \varepsilon^{MC}}{\partial t} + \frac{\partial \varepsilon^{M\overline{C}}}{\partial t}$$
(1)

138 The two components of this creep model are explained below: first the basic creep part, then 139 the TTD.

140

### **III.2.** Basic creep equations

The strain  $\varepsilon^{MC}$  corresponding to basic creep comes from Sellier et al. [7]. It is briefly recalled 141 142 in this part.

#### 143 Permanent creep *III.2.1*.

144 In each main direction,  $I_{1}$ , of elastic strain, the basic creep velocity, presented in Eq. (2), is proportional to the elastic strain  $\varepsilon_I^E$  via a characteristic time  $\tau_I^M$ : 145

146 
$$\frac{\partial \varepsilon_I^{MC}}{\partial t} = \frac{\varepsilon_I^E}{\tau_I^M} \cdot C^w$$
(2)

In Eq. (2),  $C^w$  stands for the influence of water content on creep velocity. It is given by Eq. 147 148 (3). The temperature acts through the moisture effect because water viscosity changes with 149 temperature [21]. This effect is modelled with an Arrhenius law in Eq. (4). In this equation,  $E_W^a$  corresponds to the water viscosity activation energy ( $\approx 17000$  J/mol), R is the perfect gas 150 151 constant (8.31 J/mol/K) and  $T_{ref}$  is the reference temperature (for which  $\tau_{ref}^{M}$  (Eq. 6) is fitted). As C-S-H properties also depend directly on the water content, the term  $C_s^w$  (Eq. 5) is 152 153 used. It corresponds to the water saturation of the porosity, Sr, and allows creep velocity 154 reduction when the concrete dries.

155 
$$C^w = C^w_s \cdot C^w_T$$
 (3)

156 
$$C_T^w = exp\left(-\frac{E_W^a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$
(4)

$$157 \quad C_s^w = Sr \tag{5}$$

158 The characteristic time  $\tau_I^M$  of Eq. (2) is defined by Eq. (6) where  $\tau_{ref}^M$  is a fitting parameter 159 (reference characteristic time) characterizing the initial creep velocity of a saturated concrete 160 never loaded before.

161 
$$\tau_I^M = \tau_{ref}^M. C_I^c \tag{6}$$

162  $C_I^c$  is the consolidation function. It allows the creep velocity to be modified according to the 163 creep that has already occurred and the thermo-mechanical conditions that are integrated into 164 the creep coefficient *k* presented in Eq. (8)

165 
$$C_I^c = \frac{1}{k} exp\left(\frac{1}{k} \left(\frac{\varepsilon_I^{MC}}{\varepsilon_I^E}\right)^+\right)$$
(7)

166 The function  $C_I^c$  increases with the permanent strains  $\varepsilon_I^{MC}$  due to shrinkage and creep, 167 expressing a material consolidation. Thus, it induces a function enhancing the characteristic 168 time and leading to a creep velocity decrease.

169 
$$k = k_{ref} . C_p^T . C^M$$
 (8)

In this equation,  $C_p^T$  (Eq. 10) and  $C^M$  (Eq. 11) stand for the thermal and the mechanical effects on creep potential, respectively, according to Sellier et al. [7].  $C_p^T$  considers the effect of thermal damage and  $C^M$  the effect of mechanical damage. Thus, in case of thermo-mechanical variations, the potential is automatically adapted.  $k_{ref}$  is the creep coefficient calculated in Eq. (9). Note that these temperature effects are not the causes of TTD but only the causes of basic creep velocity dependence on the temperature.

176 
$$k_{ref} = \frac{\varepsilon_{ref}^M}{\varepsilon_{ref}^E}$$
(9)

177  $\varepsilon_{ref}^{M}$  is a fitting parameter called the reference creep potential, which represents an inherent 178 permanent delayed strain characteristic of the material;  $\varepsilon_{ref}^{E}$  is the reference elastic strain 179 defined as the material deformation under uniaxial compressive stress of 33% of its 180 compressive strength.

According to Ladaoui et al. [22], the differential dilation between paste and aggregates could cause thermal damage and increase creep potential. This damage is modelled with an Arrhenius law, as presented in Eq. (10).

184 
$$C_p^T = \begin{pmatrix} exp\left(-\frac{E_p^a}{R}\left(\frac{1}{T} - \frac{1}{T_{thr}}\right)\right) & if \ T > T_{thr} \\ 1 & if \ T \le T_{thr} \end{cases}$$
(10)

185  $T_{thr}$  is the threshold temperature ( $\approx$ 45 °C for the material studied in [22]) above which thermal 186 damage occurs, and  $E_p^a$  is a fitted activation energy ( $\approx$ 25000 J/mol).

187 The  $C^{M}$  coefficient takes the possible non-linear effect between creep potential and 188 mechanical loading level into account, through an equivalent Drucker-Prager shear stress  $\tau^{DP}$ . 189 In Eq. (11), the critical shear stress  $\tau^{DP}_{cr}$  is the critical value causing tertiary creep by micro-190 structure damage.

191 
$$C^M = \frac{\tau_{Cr}^{DP}}{\tau_{Cr}^{DP} - \tau^{DP}}$$
 (11)

192 To consider the beneficial effects of triaxial confinement in reducing the impact of deviatoric 193 stress,  $\tau^{DP}$  is calculated in Eq. (12), which corresponds to a Drucker-Prager criterion:

194 
$$\tau^{DP} = \sqrt{\frac{\sigma^{d}:\sigma^{d}}{2}} + \delta \frac{Tr(\sigma)}{3}$$
(12)

195 where  $\sigma^d$  is the deviatoric part of the stress tensor and  $\delta$  is the confinement effect coefficient. 196 The critical shear stress is linked to a corresponding uniaxial critical compressive stress 197 intensity,  $\sigma_{cr}$ , presented in Eq. (14).

198 
$$\tau_{cr}^{DP} = \frac{\sigma_{cr}}{\sqrt{3}} \left( 1 - \frac{\delta}{\sqrt{3}} \right) \tag{13}$$

199 
$$\sigma_{cr} = \frac{2}{3} R_c \left(\frac{\chi^M}{\chi^{M-1}}\right) \tag{14}$$

200  $\chi^{M}$  is a non-linear creep coefficient corresponding to non-linear creep amplification observed 201 under a compression stress of 66% of the compressive strength and is close to 2 for an 202 Ordinary Portland Cement based concrete [7].

#### 203 III.2.2. Reversible creep

In this model, a reversible creep is modelled using a Kelvin module  $\varepsilon_I^K$  (Eq. 15). The maximum amplitude of reversible creep is made proportional to the elastic strain by means of parameter  $\psi^K$ .

$$207 \qquad \frac{\partial \varepsilon_I^K}{\partial t} = \frac{1}{\tau^K} \left( \frac{\varepsilon_I^E}{\psi^K} - \varepsilon_I^K \right) \tag{15}$$

208 The characteristic time  $\tau^{K}$  is defined by Eq. (16), where  $\tau_{ref}^{K}$  is a fitting parameter associated 209 with a reference time characterizing the initial material recovery.

$$210 \quad \tau^K = \tau^K_{ref}. C^w_T \tag{16}$$

A thermal effect parameter  $C_T^w$  affects the reversible creep velocity in the same way as for the permanent creep Eq. (4).

#### 213 III.3. Modelling of Transient Thermal Deformation

214 The strain associated with the TTD is  $\varepsilon^{M\bar{C}}$  in Eq. (1). It is now presented and explained.

215

#### III.3.1. Physical phenomenon

According to Vlahinić et al. [23], transient creep under moisture content variation can be modelled by a modification of the material viscosity in relation to the fluid interflow at nanoscale. This flow is activated to balance a pressure difference between two pore regions, macropores and nanopores. In our case, if the material is heated, nanoporous water dilation

220 changes C-S-H organization and consequently modifies their apparent viscosity until the 221 overpressure induced by the water dilation is depleted by the flow from C-S-H intra porosity 222 to the capillary porosity at the upper scale. During this process, the C-S-H viscosity is reduced 223 and the phenomenon can be considered as a transient fluidification of concrete, which causes 224 creep amplification. The pressure difference between capillary and nanoporosity causes water 225 to diffuse from nanopores to capillary pores until the pressures rebalance. Consequently, if the 226 material is heated long enough before mechanical loading, the water transfer is finished 227 before the creep strain develops and TTD does not occur. Thus, the transient thermal 228 deformation can appear only if the loading is applied before the fluidification is over and thus before the system has returned to a steady state. 229

230

#### III.3.2. Water transport equation

To model the nanoporous pressure  $P^n$  in C-S-H bundles, a poro-mechanics analogy is proposed (Eq. 17).

$$233 P^n = M^n \left( \phi^n - \phi^n_{ref} \right) (17)$$

For a unit volume of concrete, the water pressure  $P^n$  is proportional to the difference between 234 the C-S-H nanoporous water volume,  $\phi^n$ , and to a reference volume,  $\phi^n_{ref}$ . At this scale, the 235 236 porosity is an adsorbed layer that stays saturated with water even if the hygrometry is low (down to 11% RH) according to Jennings [24]. Thus,  $\phi_{ref}^n$  can also be considered equivalent 237 238 to the initial nanoporous volume of C-S-H. The C-S-H gel represents approximately 70% of 239 the cement paste volume for classical cementitious material (Portland cement), and the 240 average porosity is 28% [26]. According to Jennings [27], the nanoporosity of C-S-H is of the 241 order of 18% of the global porosity. Consequently, the nanoporous volume is roughly 3.5% of the cement paste volume  $(0.7 \times 0.28 \times 0.18 = 0.035 \text{ m}^3/\text{m}^3 \text{ of cement paste})$ . The proportionality 242 coefficient  $M^n$  is also defined in the framework of the poro-mechanics analogy, through Eq. 243

(18). It is a Biot modulus at the C-S-H scale, which considers the interactions between C-S-Hand water.

246 
$$\frac{1}{M^n} = \frac{b^n - \phi_{ref}^n}{K^r} + \frac{\phi_{ref}^n}{K^w}$$
 (18)

where  $b^n$  is the Biot coefficient for nano sites ( $\approx 0.65$ ) [25];  $K^r$  is the C-S-H stiffness;  $K^w$  is the water compressibility, which can be considered as a constant in the temperature range studied ( $\approx 2$  300MPa). Under the assumption that C-S-H stiffness is about 30 GPa [28], the Biot modulus is approximately 28 GPa.

The flow necessary to rebalance the pressure difference between nanoscale and capillary scale is defined through Eq. (19) for a unit of material volume. The pressure difference is dissipated by water diffusion until the system is balanced, i.e.  $P^n = P^c$ .

$$254 \quad \frac{\partial m^{n \to c}}{\partial t} = -\frac{k^n (P^n - P^c)}{\eta(T)} \cdot \rho(T) \tag{19}$$

In this equation, the mass flow  $\frac{\partial m^{n \to c}}{\partial t}$  from the nanoporous to capillary scale depends on the 255 256 water nanoporous pressure  $P^n$ , water capillary pressure  $P^c$ , fluid apparent viscosity  $\eta$  and fluid density  $\rho$ , which depend on the temperature. A fitting parameter  $k^n$  is introduced to 257 258 control the flow velocity. This parameter can be considered as a dimensionless coefficient of 259 permeability at nanoscale. Its value can vary because the morphologies of C-S-H change 260 according to the concrete formulation (high density or low density C-S-H for instance). At the 261 capillary scale, the water capillary pressure, Eq. (20), is obtained from the Van-Genuchten 262 isotherm, without the gas pressure, according to the assumption proposed by Mensi et al. [29] 263 and presented as a function of capillary saturation state  $Sr^{c}$ .

264 
$$P^{c} = -M^{c}(T) \cdot \left(Sr^{c\left(-\frac{1}{mvg}\right)} - 1\right)^{(1-mvg)}$$
 (20)

mvg is the fitting parameter controlling the shape of the isotherm curve, and  $M^c$  is a fitting parameter proportional to the capillary tension (Eq. 21), and thus depending on the temperature in order to respect an isothermal model with temperature variation (Figure 2) as proposed by Chhun [30].



In this equation,  $M^{c, ref}$  is the capillary tension coefficient at the reference temperature,  $T_{ref}$ , and  $\Delta T_{ref}$  is a reference temperature variation presented in Table 1. The capillary tension, and consequently the water capillary pressure, decrease when heating is applied.

Constants	Value used
$\Delta T_{ref}$	20 K
T <sub>ref</sub>	293 K
M <sup>c,ref</sup>	10 MPa
mvg	0.26

275

*Table 1: Values of constants used to model the capillary tension* [30]

276 The effect of temperature, T, on water density,  $\rho$ , is modelled using the empirical equation

277 proposed by Thiensen, Eq. (22) [31].

278 
$$\rho(T) = \rho^{ref} \left[ 1 - \frac{(T - T_1)^2 \cdot (T - T_2)}{T_3^2 \cdot (T - T_4)} \right]$$
 (22)

 $\rho^{ref}$  is the reference water density at 273 K and at atmospheric pressure; the other parameters are presented in Table 2. The water density decreases with heating as represented in Figure 3 within the studied temperature range.

Constant	Value used for water
$T_1$	269.017 K
$T_2$	574.797 K
$T_3$	722.86 K
$T_4$	342.349 K
$ ho^{ref}$	999.975 kg/m <sup>3</sup>

282

Table 2: Values of constants in Thiensen equation

Ladaoui et al. [21] model the water viscosity evolution with temperature, Eq. (23), with an Arrhenius law as the  $C_T^w$  coefficient of Eq. (4):

285 
$$\eta(T) = \frac{\eta^{ref}}{e^{-\frac{E_W^a}{R}\left(\frac{1}{T} - \frac{1}{T^{v, ref}}\right)}}$$
 (23)

286 This law is a function of a reference viscosity  $\eta^{ref}$  (2.07x10<sup>-14</sup> MPa.d) at a reference 287 temperature  $T^{\nu,ref}$  (273 K). The evolution of the viscosity is presented in Figure 3. It 288 decreases with temperature rise, which facilitates the C-S-H movement by lubrication.



 $\frac{289}{290}$ 

Figure 3: Modelling of water density and apparent viscosity evolution versus temperature [31] and [21].

291 Considering the small quantity of water exchangeable between nanoscale and capillary scale, 292 the water supplied to the capillary porosity is assumed not to affect the capillary pressure, 293 which is mainly controlled by the water exchanges at capillary scale only.

The introduction of the nanoporous water pressure (Eq. 17) in the diffusion equation (Eq. 19) links the capillarity pressure and the nanoporous water pressure (Eq. 24).

$$296 \qquad \frac{\partial P^n}{\partial t} = \frac{(P^c - P^n)}{\tau^n} \tag{24}$$

297 with  $\tau^n$  the characteristic time for the evacuation of nanoporous pressure defined in Eq. (25).

298 
$$au^n = \frac{\eta(T)}{M^n \cdot k^n}.$$
 (25)

Therefore, the state variable of this physical phenomenon is simply the C-S-H nanoporouswater pressure.

301 Figure 4 illustrates the pressure evolution of nanoporous water modelled with the parameter 302 values (Table 4) used to fit Cagnon's experimental data [10] (Figure 1 and Figure 7). When 303 the temperature rises, the water thermal dilation creates an overpressure in nanoporosity until 304 the temperature stabilizes. From that moment, water diffusion allows the nanoporous water 305 pressure to decrease until it returns to equilibrium with the capillary pressure. When cooling, 306 the nanoporosity is in depression and the water diffuses from the capillary to the nanoporous 307 volume. If the material is heated quickly, the water in the nanopores does not have enough 308 time to be evacuated and the pressure is amplified.



309 310 311

## $P^c = 0 MPa.$

#### 312

#### III.3.3. Evolution of transient thermal deformation

313 As for basic creep (Eq. 2), the transient thermal deformation is assumed proportional to the 314 elastic strain  $\varepsilon_I^E$ , Eq. (26).

315 
$$\frac{\partial \varepsilon^{M\overline{C}}}{\partial t} = \frac{\varepsilon_I^E}{\tau_I^M} \cdot C_n^W$$
(26)

The Maxwell characteristic time  $\tau_1^M$  presented in Eq. (26) is the same as in Eq. (6), but it is affected by the coefficient  $C_n^w$  used to model the influence of nanoporous water pressure on the C-S-H viscous behaviour. This coefficient has to make a temporary decrease of the material viscosity possible as long as the nanopressure is not depleted, which induces an equation of the form (27):

321 
$$C_n^w = \begin{pmatrix} \frac{P^n}{P_k^n} & \text{if } P^n > 0\\ 0 & \text{if } P^n \le 0 \end{pmatrix}$$
 (27)

322 If the C-S-H intra porosity is in depression or at equilibrium with respect to the water 323 capillarity ( $P^n = P^c$ ),  $C_n^w$  is equal to zero, which means that TTD does not occur. But, in case 324 of nanoporous overpressure, a linear relation between  $C_n^w$  and  $P^n$  controls the TTD kinetics 325 through the fitting parameter  $P_k^n$  (which has the dimension of a pressure). Thus, if a saturated, 326 mechanically loaded material is subjected to heating, an overpressure appears and leads to

327 TTD. Over time, the nanoporous pressure decreases to balance the capillary pressure, slowing328 the TTD kinetics.

In Figure 5, the maximum TTD velocity is reached at the maximum temperature and decreases quickly until falling to zero just a few hours later (due to water diffusion). With these equations, if a concrete is heated a long time after its mechanical loading, the TTD is lower than if it was heated just after its mechanical loading. Before the rise in temperature, the shrinkage and creep of concrete will increase the consolidation (and so the characteristic time  $\tau_I^M$ ), and consequently decrease the TTD velocity according to Eq. (26).



As shown by Fahmi et al. [9], for saturated concrete ( $P^c = 0 MPa$ ), the TTD can be repeated if temperature cycles are close together because the consolidation cannot progress enough to significantly affect the characteristic time of these delayed strains.

#### 341 IV. Application

335 336 337

The equations introduced previously were tested on experimental results from Cagnon et al. [10]. This part presents the application to sealed samples. The sealing was used to prevent the desiccation of the specimens during the tests. Before the tests, samples were cured in water at

- 345 20 °C for more than 3 months after casting to allow their hydration to stabilize, then they were
- 346 sealed just before thermo-mechanical conditions were applied.

The concrete used was a High Performance Concrete made with CEM I cement. The values of its instantaneous mechanical properties and its coefficient of thermal expansion are presented in Table 3. The experimental and calculated strains were obtained on uniaxial compressive loading at 24.3 MPa. To model the TTD, the creep parameters were required, thus basic creep was also modelled.

	Value
Young's modulus E (GPa)	45.5
Compressive strength (MPa)	82.9
Poisson's coefficient $(v)$	0.2
Coefficient of thermal expansion (K <sup>-1)</sup>	$4.10^{-6}$
Table 3: Concrete properties	

The modelling of elastic strain and the basic creep presented in Figure 6 allowed fitting parameters to be determined, which are summed up in Table 4 ( $\tau_{ref}^{M}$ ,  $\tau_{ref}^{K}$ ,  $\psi^{K}$  and  $\varepsilon_{ref}^{M}$ ).

355 These parameters were maintained for all the following modelling.

352



Figure 6: Experimental modelled strain evolutions under loading (30%Rc) versus time from t<sub>0</sub> date of loading at 20°C with instantaneous elastic strain and creep strain (experimental results from [10])

359 Figure 7 shows the experimental evolutions of strain corresponding to a second set of thermo-

360 mechanical conditions from Cagnon's data, which will be used for modelling. In this test,

361 sealed concrete was loaded one day before heating and was then subjected to thermo-362 mechanical variations as detailed above the graph.

In this figure, the model is first used without TTD (black curve), in order to show the 363 underestimation of strain when TTD is not considered. It is obvious that, in this case, the 364 basic creep modelling with thermal activation is not sufficient, and the missing part 365 constitutes the TTD. TTD appears early and its amplitude can be estimated at approximately 366 300 µm/m. However, it is noteworthy that the velocity of strains after 10 days, computed by 367 368 the model fitted above, is of the same order as found experimentally. This result shows clearly 369 that TTD is a strain shift that occurs during heating without affecting the consolidation 370 phenomenon responsible for the basic creep curve shape.

When the TTD model is activated, the TTD parameters  $(k^n \text{ and } P_k^n)$  are fitted using a least-371 squares method. The parameter values are given in Table 4 and the completed model is 372 373 presented in Figure 7.



375

Figure 7: 2nd thermo-mechanical conditions: elastic strain, basic creep, thermal dilation and TTD, with and without TTD modelling (experimental results from [10])

379 To test the model, the first thermo-mechanical evolution presented in Figure 1 was modelled 380 with the same set of parameters (the result of model fitting is shown in Figure 1). Some 381 samples (plotted in blue, mean value) were heated then loaded and others (plotted in green, 382 mean value) were loaded then heated. From the comparison of model and experimental 383 results, the model was found to be able to predict the measured strain evolution with the same 384 set of parameters if TTD occurred. The effect of consolidation on repeatability of TTD in the 385 case of a heating cycle was also taken into account as shown by the green curve. As expected, 386 TTD appears with the first heating. However, during the second heating, the previous consolidation (due to creep and shrinkage), and consequently the characteristic time  $\tau_{\rm L}^{\rm M}$ , are 387 388 sufficient to prevent TTD from occurring again. If the thermal cycle had been closer in time, 389 the consolidation would have been less developed and the TTD could have been repeated. 390 This may be especially relevant for saturated concrete, which thus has not been previously 391 consolidated by capillarity tension.

392

376 377 378

Model parameter	Value
$\tau^{M}_{ref}$ (days)	4
$\tau_{ref}^{K}$ (days)	10
$\psi^{\vec{K}}(-)$	10
$arepsilon_{ref}^{M}$ (-)	8.8.10 <sup>-5</sup>
,	102
$\mathbf{D}^{n}$ (1.2.)	$7.16.10^{-19}$
$P_k^n$ (kPa)	
k <sup>n</sup> (-)	
Table 4. Fitting para	meters for concrete creep and transient thermal deformation





395 Based on experimental observations, the TTD known to occur only if heating occurs after or 396 simultaneously with the mechanical loading is similar, at the macroscopic scale, to a sort of a 397 transient fluidification conditioned by two other phenomena: firstly, the concrete should not 398 have undergone creep before loading and, secondly, the water saturation must be sufficient 399 during the heating. If these four conditions (loading, heating, no or slight creep before 400 heating, high saturation ratio) are fulfilled, then TTD can occur. To model the occurrence and 401 the amplitude of the TTD as simply as possible, it is assumed that the origin of the TTD 402 remains in the nanoporous water of C-S-H. When heated, nanoporous water dilates and 403 changes the C-S-H viscosity until the local overpressure at this scale is depleted by diffusion of this water towards the capillary porosity. The proposed model then allows simulations of 404 405 various experimental strain evolutions to be performed under several thermo-mechanical 406 conditions with a single set of parameters. This model is sufficiently easy to use to be 407 implemented in a basic creep structural model. This possibility will now allow the risk of 408 TTD to be automatically considered in finite element structural analysis. Despite this 409 modelling, which can determine the occurrence and the amplitude of the phenomenon, 410 determining the physical reasons why the viscosity of C-S-H bundles is so dependent on the 411 water pressure at nanoscale remains a challenge, especially for researchers working on 412 homogenization theory and on modelling at atomic scale.

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#### 416 **References**

417 [1] Schneider U. (1982), Behavior of concrete at high temperatures, Paris: RILEM-Report to Committee, 72.

[2] Illston J.M., Sanders P.D. (1973), The effect of temperature change upon the creep of mortar under torsional loading,
 Magazine of Concrete Research 25 (84), 136-44.

- 420 [3] Sabeur H., Meftah F. (2008), Dehydration Creep of Concrete at High Temperatures, Materials and Structures 41 (1), 421 17-30.
- 422 [4] Gawin D., Pesavento F., Schrefler B.A. (2004), Modelling of Deformations of High Strength Concrete at Elevated
   423 Temperatures, Materials and Structures 37 (4), 218-236.
- 424 [5] Mindeguia J-C., Hager I., Pimienta P., Carre H., La Borderie C. (2013), Parametrical study of transient thermal strain 425 of ordinary and high performance concrete, Cement and Concrete Research 48, 40-52.
- 426 [6] Nechnech W., Meftah F., Reynouard J.M. (2002), An elasto-plastic damage model for plain concrete subjected to high 427 temperatures, Engineering Structures 24 (5), 597-611.
- 428 [7] Sellier A., Multon S., Buffo-Lacarriere L., Vidal T., Bourbon X., Camps G. (2016), Concrete creep modelling for
  429 structural application: non-linearity, multi-axiality, hydration, temperature and drying effects, Cement and Concrete
  430 Research 79, 301-315.
- [8] Sellier A., Buffo-Lacarriere L. (2009), Toward a simple and unified modeling of basic creep shrinkage and drying creep
   for concrete, European Journal of Environmental and Civil Engineering 10, 1161-1182.
- 433 [9] Fahmi H.M., Polivka M., Bresler B. (1972), Effects of sustained and cyclic elevated temperature on creep of concrete,
  434 Cement and Concrete Research 2 (5), 591-606.
- 435 [10] Cagnon H., Vidal T., Sellier A., Bourbon X., Camps G. (2018), Transient thermal deformation of high performance
   436 concrete in the range 20°C-40°C, under review Cement and Concrete Research.
- 437 [11] Khoury G.A., Grainger B.N., Sullivan P.J.E. (1985): Transient thermal strain of concrete: literature review, conditions
  438 within specimen and behaviour of individual constituents, Magazine of Concrete Research 37 (132), 131-44.
- 439 [12] Hansen T.C., Eriksson L. (1966), Temperature Change Effect on Behavior of Cement Paste, Mortar, and Concrete
   440 Under Load, Journal Proceedings 63 (4), 489-504.
- [13] Parrot, L.J. (1974), Lateral strains in hardened cement paste under short and long-term loading, Magazine of Concrete
   Research 26 (89), 198-202.
- [14] Torrenti J.M. (2017), Basic creep of concrete-coupling between high stresses and elevated temperatures, European
   Journal of Environmental and Civil Engineering, 1-10.
- [15] Bažant Z.P., Kaplan M.F. (1996), Concrete at high temperatures: material properties and mathematical models,
   Longman Concrete design and construction series, 412-424.
- [16] Bažant Z.P., Hauggaard A.B., Baweja S., Ulm F-J. (1997), Microprestress-solidification theory for concrete creep. I.
  Aging and drying effect, Journal of Engineering Mechanics, 123 (11), 1188-1194.
- [17] Bažant Z.P., Cusatis G., Cedolin L. (2004), Temperature Effect on Concrete Creep Modeled by Microprestress Solidification Theory, Journal of Engineering Mechanics 130 (6), 691-99.
- 451 [18] Schneider U. (1988), Concrete at high temperature-A general review, Fire Safety Journal 13 (1), 55-68.
- 452 [19] Anderberg Y., Theandersson S. (1976), Stress and deformation characteristics of concrete at high temperatures:
   453 experimental investigation and material behavior model, Lund Institute of Technology 54, 1-84.
- 454 [20] Benboudjema F., Meftah F., Torrenti J.M. (2005), Interaction between drying, shrinkage, creep and cracking 455 phenomena in concrete, Engineering Structure 27, 239-250.
- 456 [21] Ladaoui W., Vidal T., Sellier A., Bourbon X. (2011), Effect of a temperature change from 20 to 50°C on the basic creep 457 of HPC and HPFRC, Materials and Structures 44 (44), 1629-1639.
- [22] Ladaoui W., Vidal T., Sellier A., Bourbon X. (2013), Analysis of interactions between damage and basic creep of HPC
   and HPFRC heated between 20 and 80°C, Materials and Structures 46 (1-2), 13-23.
- 460 [23] Vlahinić I., Thomas J.J., Jennings H.M., Andrade J.E. (2012), Transient creep effects and the lubricating power of
- 461 water in materials ranging from paper to concrete and Kevlar, Journal of the Mechanics and Physics of Solids 60, 1350-462 1362.

- 463 [24] Jennings H.M. (2004), Colloid model of C–S–H and implications to the problem of creep and shrinkage, Materials and 464 Structures 37 (1), 59-70.
- 465 [25] Ulm F.-J., Constantinides G., Heukamp F.H. (2004), Is concrete a poromechanics material? A multiscale 466 investigation of poroelastic properties, Materials and Structures 37, 43-58.
- 467 [26] Powers T.C. (1968), The thermodynamics of volume change and creep, Materials and Structures, 1(6), 487-507.
- 468 [27] Jennings H.M. (2008), Refinements to colloid model of C-S-H in cement: CM-II, Cement and Concrete Research 38 (3), 275-89.
- 470 [28] Vandamme M., Ulm F-J. (2009), Nanogranular Origin of Concrete Creep, Proceedings of the National Academy of
   471 Sciences 106 (26), 10552-57.
- 472 [29] Mensi R., Acker P., Attolou A. (1988), Séchage du béton: analyse et modélisation, Materials and structures 21 (1),
  473 3-12.
- 474 [30] Chhun P. (2017), Modélisation du comportement thermo-hydro-chemo-mécanique des enceintes de confinement
   475 nucléaire en béton armé-précontraint, PhD Thesis Université Paul Sabatier Toulouse, France.
- 476 [31] Tanaka M., Girard G., Davis R., Peuto A., Bignell N. (2001), Recommended Table for the Density of Water between 0
  477 °C and 40 °C Based on Recent Experimental Reports, Metrologia 38 (4), 301-309.