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1 On the origins of Transient Thermal Deformation of 2 Concrete

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15 *Keywords: concrete; creep; modelling; temperature; transient thermal deformation*
16

17 **Abstract**

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**

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

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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
36 temperature rise. Concomitance of this temperature rise and mechanical loading are
37 favourable to the appearance of Transient Thermal Deformation (TTD) of concrete, so the
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
44 transformation due to the temperature increase, which leads to a rearrangement of the
45 microstructure.

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

53 II. Experimental evidence

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

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

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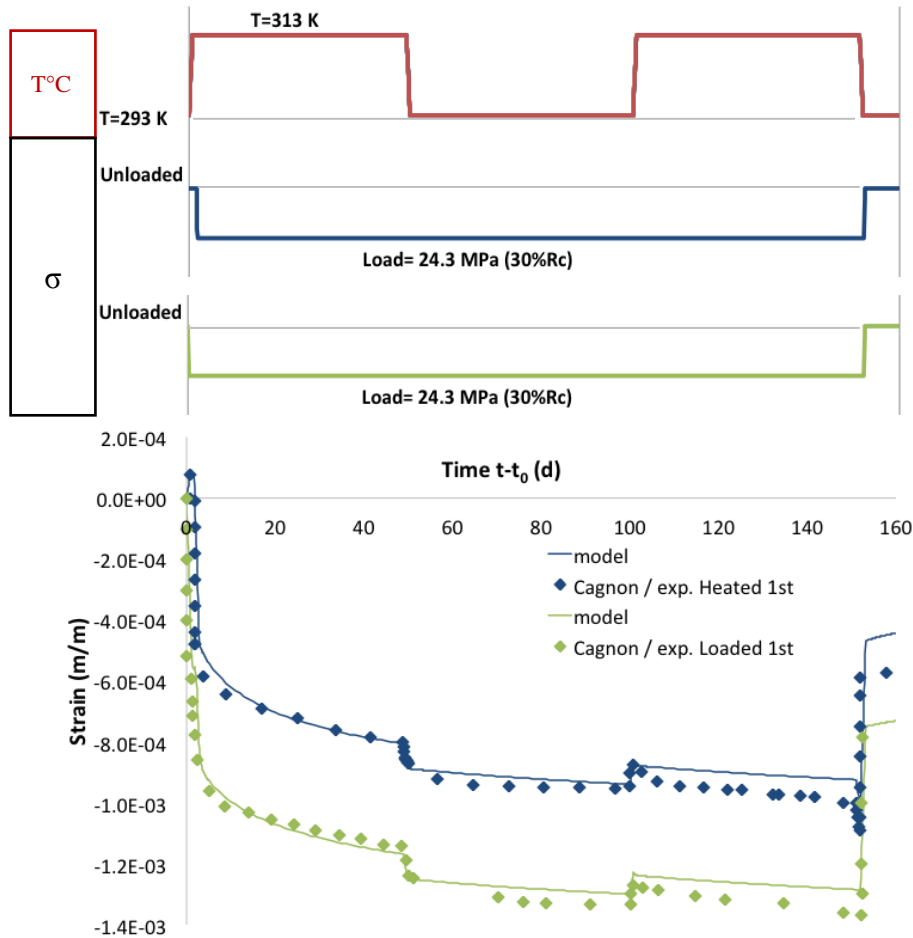


Figure 1: 1st thermo-mechanical conditions: elastic strain, basic creep, thermal dilation and TTD for a sample loaded first (plotted in green) and a sample heated first (plotted in blue), with modelling. t_0 corresponds to the end of water curing and R_c is the compressive strength (experimental results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

70
71
72
73
74

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

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

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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
88 simulate the transient thermal deformation. In his model, the evolution of damage amplifies
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

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110 consolidation phenomenon, which corresponds to a transfer of stresses from viscous particles
111 (typically C-S-H bundles) to elastic particles (other hydrates and aggregates). As the stresses
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 nanoporosity 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**

119 The model chosen to implement the TTD phenomenon is described in [7]. As explained
120 above, in this model the slowdown of creep kinetics is due to a consolidation phenomenon
121 that increases the apparent material viscosity. The consolidation function assumes that there is
122 a strain potential that is intrinsic to the concrete, and each deformation (shrinkage and creep)
123 consumes this potential and consolidates the material, thus slowing down creep. The strain is
124 modelled with a Maxwell model in which the viscosity evolves with the strain [7]; this strain
125 corresponds to ε^{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
132 consolidation, the creep strain ε^M in Eq. (1) has been decomposed into two parts: a
133 consolidating strain ε^{MC} (corresponding to the initial basic creep model proposed in [7]) and

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

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

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**

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

143 **III.2.1. Permanent creep**

144 In each main direction, i , of elastic strain, the basic creep velocity, presented in Eq. (2), is
145 proportional to the elastic strain ε_i^E via a characteristic time τ_i^M :

$$146 \quad \frac{\partial \varepsilon_i^{MC}}{\partial t} = \frac{\varepsilon_i^E}{\tau_i^M} \cdot C^w \quad (2)$$

147 In Eq. (2), C^w stands for the influence of water content on creep velocity. It is given by Eq.
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,
150 E_W^a corresponds to the water viscosity activation energy (≈ 17000 J/mol), R is the perfect gas
151 constant (8.31 J/mol/K) and T_{ref} is the reference temperature (for which τ_{ref}^M (Eq. 6) is
152 fitted). As C-S-H properties also depend directly on the water content, the term C_s^w (Eq. 5) is
153 used. It corresponds to the water saturation of the porosity, S_r , and allows creep velocity
154 reduction when the concrete dries.

$$155 \quad C^w = C_s^w \cdot C_T^w \quad (3)$$

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

157
$$C_s^w = Sr \quad (5)$$

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

161
$$\tau_I^M = \tau_{ref}^M \cdot C_I^c \quad (6)$$

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

166 The function C_I^c increases with the permanent strains ε_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
$$k = k_{ref} \cdot C_p^T \cdot C^M \quad (8)$$

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

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

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

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

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

185 T_{thr} is the threshold temperature (≈ 45 °C for the material studied in [22]) above which thermal
 186 damage occurs, and E_p^a is a fitted activation energy (≈ 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 τ^{DP} .
 189 In Eq. (11), the critical shear stress τ_{cr}^{DP} is the critical value causing tertiary creep by micro-
 190 structure damage.

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

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

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

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

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

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

200 χ^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**

204 In this model, a reversible creep is modelled using a Kelvin module ε_I^K (Eq. 15). The
205 maximum amplitude of reversible creep is made proportional to the elastic strain by means of
206 parameter ψ^K .

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

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

$$210 \quad \tau^K = \tau_{ref}^K \cdot C_T^w \quad (16)$$

211 A thermal effect parameter C_T^w affects the reversible creep velocity in the same way as for the
212 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**

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

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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
229 before the system has returned to a steady state.

230 **III.3.2. Water transport equation**

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

$$233 \quad P^n = M^n (\phi^n - \phi_{ref}^n) \quad (17)$$

234 For a unit volume of concrete, the water pressure P^n is proportional to the difference between
235 the C-S-H nanoporous water volume, ϕ^n , and to a reference volume, ϕ_{ref}^n . At this scale, the
236 porosity is an adsorbed layer that stays saturated with water even if the hygrometry is low
237 (down to 11% RH) according to Jennings [24]. Thus, ϕ_{ref}^n can also be considered equivalent
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
242 the cement paste volume ($0.7 \times 0.28 \times 0.18 = 0.035 \text{m}^3/\text{m}^3$ of cement paste). The proportionality
243 coefficient M^n is also defined in the framework of the poro-mechanics analogy, through Eq.

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

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

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

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

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

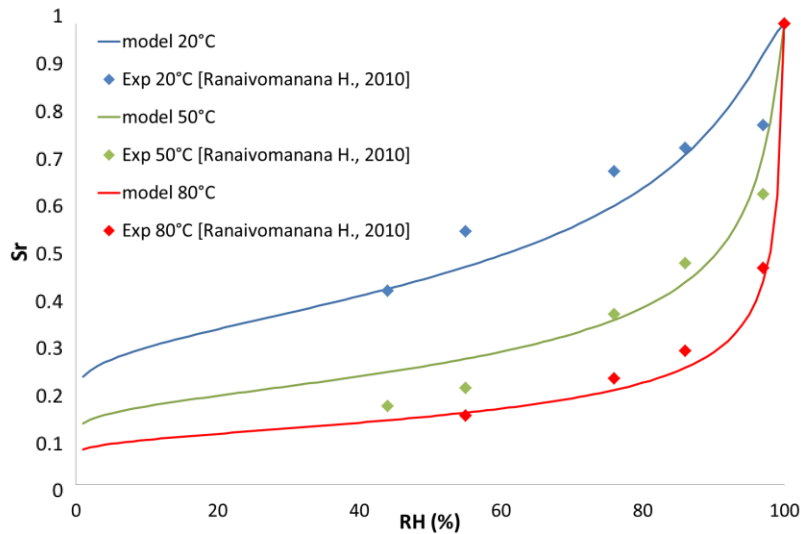
255 In this equation, the mass flow $\frac{\partial m^{n \rightarrow c}}{\partial t}$ from the nanoporous to capillary scale depends on the
256 water nanoporous pressure P^n , water capillary pressure P^c , fluid apparent viscosity η and
257 fluid density ρ , which depend on the temperature. A fitting parameter k^n is introduced to
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 .

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

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

$$269 \quad M^c(T) = M^{c,ref} \left[\exp \left(-\frac{T-T_{ref}}{\Delta T_{ref}} \right) \right] \quad (21)$$



270
 271 Figure 2: Modelling of desorption isotherms at different temperatures [30]

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

Constants	Value used
ΔT_{ref}	20 K
T_{ref}	293 K
$M^{c,ref}$	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, ρ , is modelled using the empirical equation
 277 proposed by Thiensen, Eq. (22) [31].

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

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

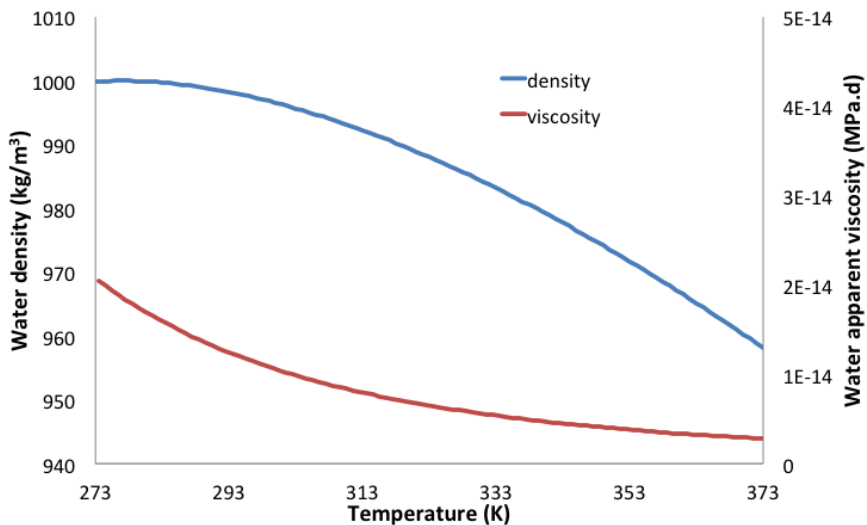
Constant	Value used for water
T_1	269.017 K
T_2	574.797 K
T_3	722.86 K
T_4	342.349 K
ρ^{ref}	999.975 kg/m ³

282 *Table 2: Values of constants in Thiensen equation*

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

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

286 This law is a function of a reference viscosity η^{ref} (2.07×10^{-14} MPa.d) at a reference
 287 temperature $T^{v,ref}$ (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.



289
290

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

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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.

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

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

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

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

299 Therefore, the state variable of this physical phenomenon is simply the C-S-H nanoporous
300 water 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.

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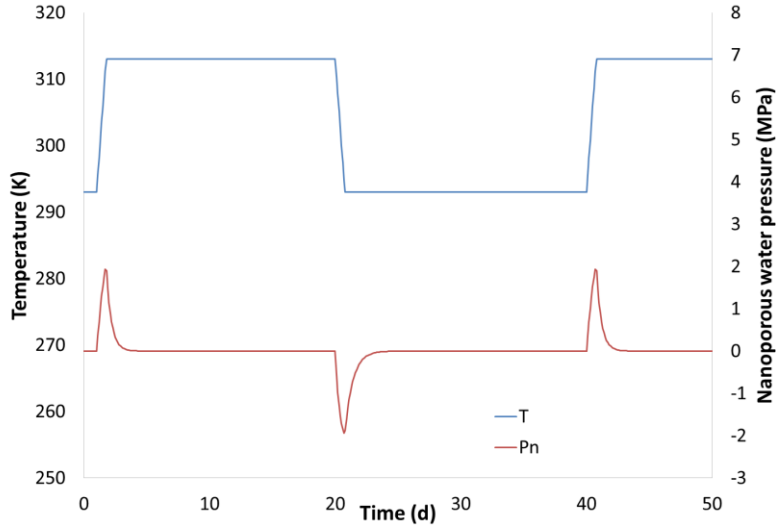


Figure 4: Example of water nanoporous pressure evolution under temperature cycle (20-40-20 °C) with $k^n = 7.16 \times 10^{-19}$ and $P^c = 0$ MPa.

III.3.3. Evolution of transient thermal deformation

As for basic creep (Eq. 2), the transient thermal deformation is assumed proportional to the elastic strain ε_I^E , Eq. (26).

$$\frac{\partial \varepsilon^{M\bar{c}}}{\partial t} = \frac{\varepsilon_I^E}{\tau_I^M} \cdot C_n^w \quad (26)$$

The Maxwell characteristic time τ_I^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):

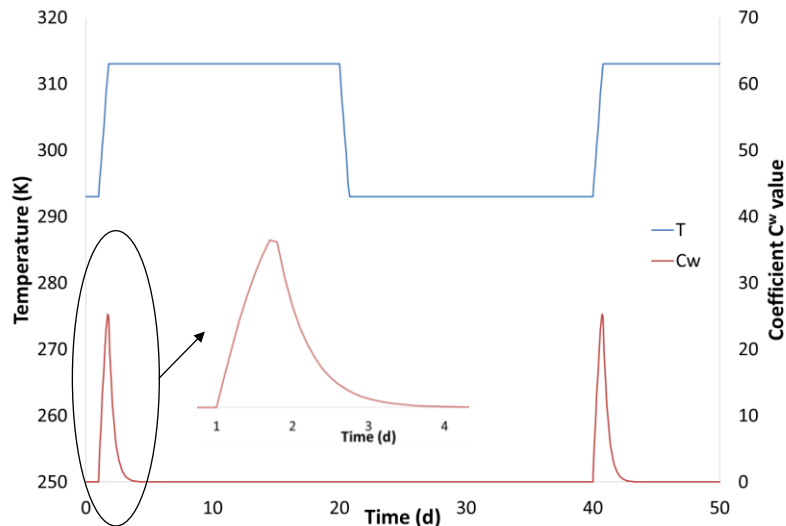
$$C_n^w = \begin{cases} \frac{P^n}{P_k^n} & \text{if } P^n > 0 \\ 0 & \text{if } P^n \leq 0 \end{cases} \quad (27)$$

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

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

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



335
336
337 *Figure 5: Example of evolution of moisture coefficient C_w^n with time under temperature cycle $T(20-40-20^\circ\text{C})$ with $k^n=7.16 \times 10^{-19}$, $P_k^n=102\text{kPa}$ and $P^c=0\text{MPa}$.*

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

341 IV. Application

342 The equations introduced previously were tested on experimental results from Cagnon et al.
343 [10]. This part presents the application to sealed samples. The sealing was used to prevent the
344 desiccation of the specimens during the tests. Before the tests, samples were cured in water at

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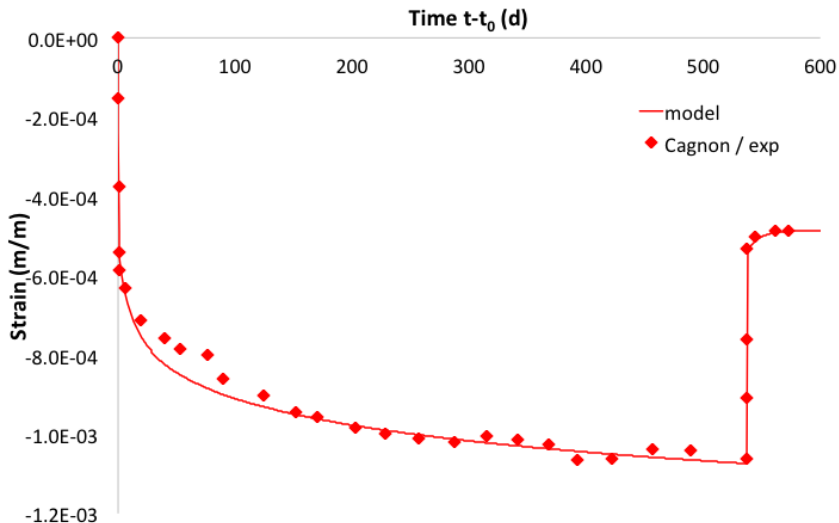
345 20 °C for more than 3 months after casting to allow their hydration to stabilize, then they were
 346 sealed just before thermo-mechanical conditions were applied.

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

	Value
Young's modulus E (GPa)	45.5
Compressive strength (MPa)	82.9
Poisson's coefficient (ν)	0.2
Coefficient of thermal expansion (K^{-1})	4.10^{-6}

352 *Table 3: Concrete properties*

353 The modelling of elastic strain and the basic creep presented in Figure 6 allowed fitting
 354 parameters to be determined, which are summed up in Table 4 (τ_{ref}^M , τ_{ref}^K , ψ^K and ε_{ref}^M).
 355 These parameters were maintained for all the following modelling.



356 *Figure 6: Experimental modelled strain evolutions under loading (30%Rc) versus time from t_0 date of loading at 20°C with*
 357 *instantaneous elastic strain and creep strain (experimental results from [10])*
 358

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,

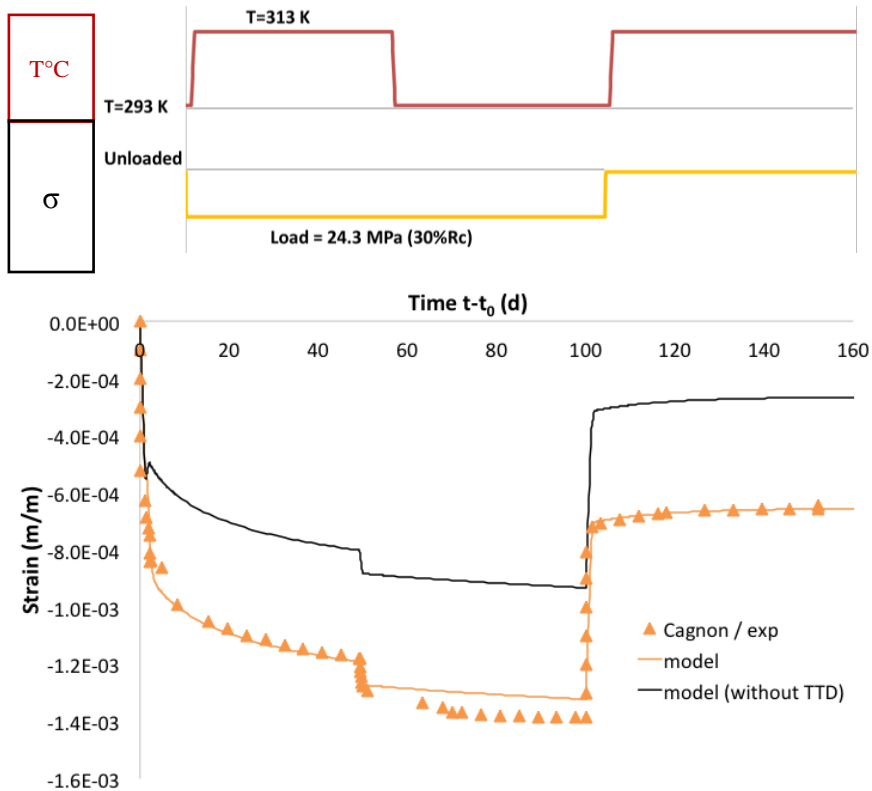
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361 sealed concrete was loaded one day before heating and was then subjected to thermo-
 362 mechanical variations as detailed above the graph.

363 In this figure, the model is first used without TTD (black curve), in order to show the
 364 underestimation of strain when TTD is not considered. It is obvious that, in this case, the
 365 basic creep modelling with thermal activation is not sufficient, and the missing part
 366 constitutes the TTD. TTD appears early and its amplitude can be estimated at approximately
 367 300 $\mu\text{m/m}$. However, it is noteworthy that the velocity of strains after 10 days, computed by
 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.

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

374



375

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376 *Figure 7: 2nd thermo-mechanical conditions: elastic strain, basic creep, thermal dilation and TTD, with and without TTD*
 377 *modelling (experimental results from [10])*
 378

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
 387 consolidation (due to creep and shrinkage), and consequently the characteristic time τ_1^M , are
 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

Model parameter	Value
τ_{ref}^M (days)	4
τ_{ref}^K (days)	10
ψ^K (-)	10
ε_{ref}^M (-)	$8.8 \cdot 10^{-5}$
	102
P_k^n (kPa)	$7.16 \cdot 10^{-19}$
k^n (-)	

393 *Table 4: Fitting parameters for concrete creep and transient thermal deformation*

394 **Conclusion**

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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
404 of this water towards the capillary porosity. The proposed model then allows simulations of
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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