Transactions, SMiRT-24
BEXCO, Busan, Korea - August 20-25, 2017
Division IX (include assigned division number from I to X)

A MOISTURE-DEPENDENT THERMAL STRAIN CONSTITUTIVE MODEL FOR CONCRETE

Giacomo Torelli[1], Parthasarathi Mandal[2], Martin Gillie[3]

[1] PhD Candidate, School of MACE, The University of Manchester, Manchester, UK
[2] Senior Lecturer, School of MACE, The University of Manchester, Manchester, UK
[3] Reader, School of MACE, The University of Manchester, Manchester, UK

ABSTRACT

This paper presents a thermal strain constitutive model for concrete, able to capture the effects of the moisture content of the material on the mechanical behaviour under compressive loads and high transient temperatures. The model is the first to account for the effect of moisture content on both load induced thermal strain (LITS) and free thermal strain (FTS) for high temperatures.

Experimental evidence shows that the deformability of loaded concrete under transient temperatures is strongly influenced by the moisture content of the material at the beginning of the thermal transient. Hence, the drying process taking place in concrete structures prior to a thermal transient significantly affects the performance of the material in case of transient thermal.

With this in mind, a new constitutive relationship is presented where the two components of the thermal strain, LITS and FTS, are formulated as a function of the water content of the material at the beginning of the thermal transient.

Specifically, LITS is modelled as the sum of a moisture-independent component, named Transient Strain (TS), and a moisture dependent component, named Transient Drying Creep (TDC). Similarly, the FTS is obtained by explicitly modelling its moisture-independent component, Pure Free Thermal Strain (PFTS), and its moisture-dependent components, named Transient Shrinkage (TS) and Transient Swelling (TSW).

The presented constitutive model is verified and validated against transient tests performed on concrete specimens having different initial moisture contents.

INTRODUCTION

Accurate understanding and modelling of the concrete material behaviour under transient thermal conditions is crucial for a reliable assessment of the effects of thermal loads on bulk concrete structures, particularly if a certain level of performance is required in the case of accidental situations. This is the case for safety-related nuclear structures, such as prestressed concrete pressure vessels [1].

When heated in absence of mechanical load, concrete presents an isotropic expansion usually referred to as Free Thermal Strain (FTS). However, experimental evidence shows that if concrete is subjected to a compressive load while heated, a different thermal strain is measured [2]. The difference in between the thermal strain measured in the case of mechanically loaded concrete and the FTS is commonly defined as Load Induced Thermal Strain (LITS) [2,3]. Such strain component has been proved to be mainly irrecoverable on cooling or unloading [2]. Besides, previous studies have reported that when concrete is loaded uniaxially, a contractive LITS develops in the direction of the load, while a dilative LITS appears along the directions perpendicular to the load [4,5], and that LITS is a markedly confinement-dependent phenomenon (Kordina, Ehm, & Schneider, 1986; Petkovski & Crouch, 2008). Such features have been included by the authors in two constitutive models meant to be used for temperatures up to 250°C and 500°C respectively (Torelli, Gillie, Mandal, & Tran, 2016; Torelli, Mandal, Gillie, & Tran, 2017).

In addition, experimental evidence showed that the two component of the thermal strain, FTS and LITS, significantly depend on the moisture conditions of the material. In the light of this, a novel moisture-dependent thermal strain model is formulated, implemented and validated against experiments.

MOISTURE-DEPENDENCY OF FTS AND LITS

Transient thermal tests performed on concrete specimens having various initial water contents showed that the evolution of FTS and LITS with the temperature depends significantly on the initial moisture condition of the material (Khoury, Grainger, & Sullivan, 1985a; Yamashita, Yoshida, & Hirashima, 2016). Such experiments showed that higher contents of water are generally linked to a more contractive behaviour. This is mainly due to the drying of concrete, which generally fully develops when the material reaches 200-250°C and leads to shrinkage and drying creep strains (Khoury, Grainger, & Sullivan, 1985b; Pickett, 1942). In addition, a moisture-dependent transient expansion of the material is observed in the same temperature range. This is due to a temperature-induced increase in the capillary pressure of the gel pores on heating which causes a temporary swelling of the cement paste matrix (Neville, 1995). For temperatures higher than 100°C, the water hosted in the gel pores evaporates and escape, leading to a recovery of the temperature-induced swelling effect. The qualitative development of FTS and LITS with the temperature, for different initial water contents, is presented in Figure 1 and Figure 2 respectively.

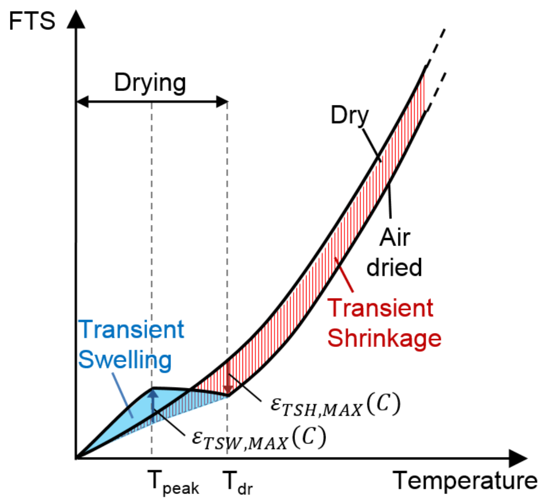

Figure 1 FTS developing in dry and air dried concrete. Schematic representation of the transient shrinkage contraction (in red) and transient swelling effect (in blue) occurring for air dried concrete.

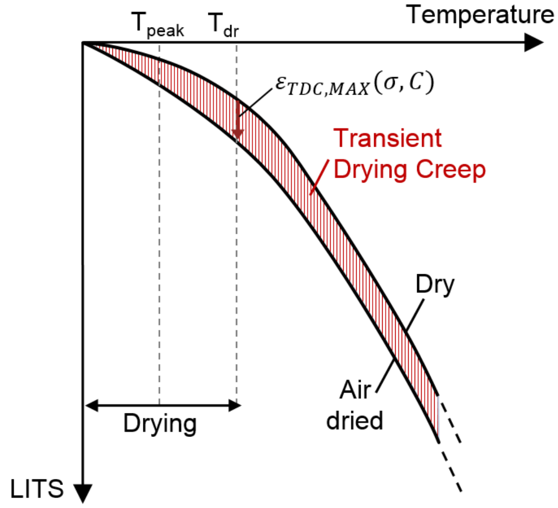

Figure 2 LITS developing in dry and air dried concrete. Schematic representation of the transient drying creep contraction (in red) occurring for air dried concrete.

CONSTITUTIVE MODEL

Moisture dependent FTS model

The FTS has been decomposed as follows in order to capture its experimentally demonstrated dependency on the initial moisture conditions:

$$\dot{\varepsilon}_{fts}(T, \bar{C}) = \dot{\varepsilon}_{pfts}(T) + \dot{\varepsilon}_{tsh}(T, \bar{C}) + \dot{\varepsilon}_{tsw}(T, \bar{C}) \quad (1)$$

Where $\dot{\varepsilon}_{pfts}(T)$, $\dot{\varepsilon}_{tsh}(T, \bar{C})$ and $\dot{\varepsilon}_{tsw}(T, \bar{C})$ are the time derivatives of the three components of FTS, namely Pure Free Thermal Strain (PFTS), Transient Shrinkage (TSH) and Transient Swelling (TSW). The PFTS is defined as a function of the temperature T only, while TSH and TSW depend on the initial water content $\bar{C}$ of the material.

$\dot{\varepsilon}_{pfts}(T)$, $\dot{\varepsilon}_{tsh}(T, \bar{C})$ and $\dot{\varepsilon}_{tsw}(T, \bar{C})$ have been defined in order to obtain the qualitative temperature development of PFTS, TSH and TSW reported in Figure 3.

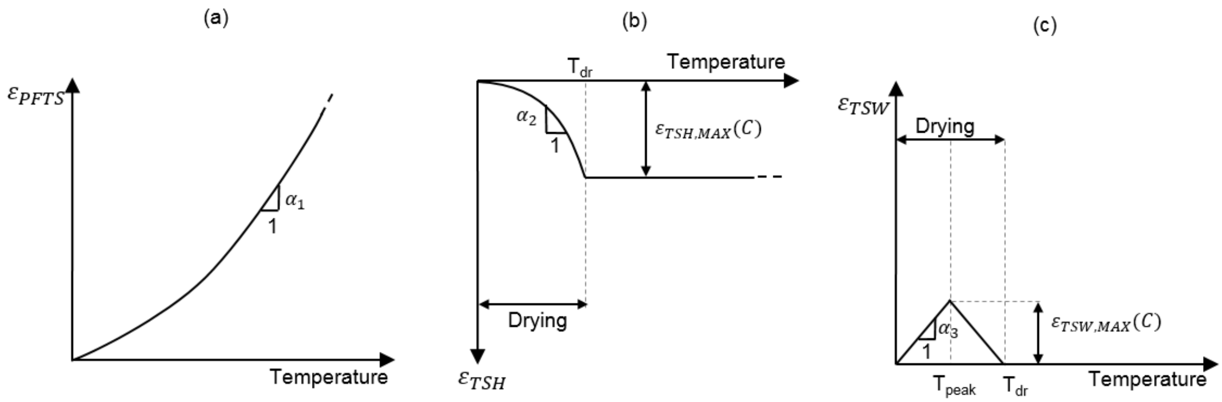

Figure 3 Temperature development of the three components of FTS: the moisture independent PFTS ε_{pfts} and the moisture dependent strain components TSH ε_{tsh} and TSW ε_{tsw}

The moisture independent PFTS has been defined as:

$$\dot{\varepsilon}_{pfts} = \alpha_1(T)\dot{T} \tag{2}$$

Where α_1 is the temperature-dependent coefficient of free thermal expansion, expressed as polynomial function of the temperature:

$$\alpha_1(T) = a_0 + a_1T + a_2T^2 + a_3T^3 + a_4T^4 + a_5T^5 \tag{3}$$

The moisture dependent TSH component was defined as:

$$\dot{\varepsilon}_{tsh} = \alpha_2(T,\bar{C})\dot{T} \tag{4}$$

Where $\alpha_2(T,\bar{C})$ is the coefficient of TSH contraction, defined so as to obtain a parabolic development of TSH with the temperature:

$$\alpha_2 = \begin{cases} 2\,\varepsilon_{tsh,max}(\bar{C})\dfrac{(T-20)}{(T_{dr}-20)^2} & for\ T < T_{dr} \\ 0 & for\ T \geq T_{dr} \end{cases} \tag{5}$$

Where T_{dr} represent the drying temperature and $\varepsilon_{tsh,max}(\bar{C})$ the maximum shrinkage strain, reached at the end of the drying phase. $\varepsilon_{sh,max}(\bar{C})$ is expressed as a function of the initial content of water $\bar{C}$ of the material.

Similarly, the moisture dependent TSW was modelled as:

$$\dot{\varepsilon}_{tsw} = \alpha_3(T,\bar{C})\dot{T} \tag{6}$$

Where $\alpha_3(T,\bar{C})$ is the coefficient of TSW expansion, analogous to the coefficients α_1 and α_2 presented above. This coefficient describes the expansion-contraction, due to the internal micro diffusion of water, per unit increase in temperature, and is defined as:

$$\alpha_3 = \begin{cases} \dfrac{\Delta\varepsilon_{TSW,MAX}(C)}{T_{peak} - 20°C} & for\ T < T_{peak} \\ -\dfrac{\Delta\varepsilon_{TSW,MAX}(C)}{T_{dr} - T_{peak}} & for\ T_{peak} \le T < T_{dr} \\ 0 & for\ T \ge T_{dr} \end{cases} \tag{7}$$

Where $\Delta\varepsilon_{TSW,MAX}(\bar{C})$ is the maximum expected TSW and T_{peak} is the temperature at which it occurs. $\Delta\varepsilon_{TSW,MAX}(\bar{C})$ is expressed as a function of the initial content of water $\bar{C}$ in the material.

Moisture dependent LITS model

Similarly, the LITS has been decomposed as follows:

$$\dot{\varepsilon}_{lits}(\sigma, T, \bar{C}) = \dot{\varepsilon}_{plits}(\sigma, T) + \dot{\varepsilon}_{tdc}(\sigma, T, \bar{C}) \tag{6}$$

Where $\dot{\varepsilon}_{plits}(\sigma, T)$ and $\dot{\varepsilon}_{tdc}(\sigma, T, \bar{C})$ are time derivatives of the two components of LITS, namely Pure Load-Induced Thermal Strain (PLITS) and Transient Drying Creep (TDC). $\dot{\varepsilon}_{plits}(\sigma, T)$ and $\dot{\varepsilon}_{tdc}(\sigma, T, \bar{C})$ have been defined in order to obtain the qualitative temperature development of PFTS, TSH and TSW reported in Figure 4.

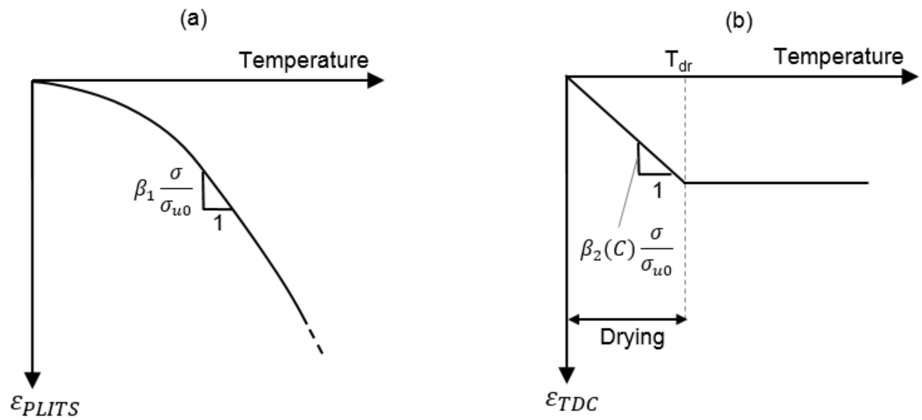

Figure 4 Temperature development of the two components of LITS: the moisture independent PLITS ε_{plits} and the moisture dependent strain TDC ε_{tdc}

The time derivative of the PLITS has been defined as:

$$\dot{\varepsilon}_{plits} = \beta_1(T) \frac{\sigma}{\sigma_{u0}} \dot{T} \tag{7}$$

Where σ is the stress in the loaded direction, σ_{u0} the compressive strength of the material and $\beta_1(T)$ the LITS function, i.e. a generic function of temperature aimed at fitting the uniaxial temperature-LITS curve, here defined as a fifth-order polynomial of the temperature:

$$\beta_1(T) = b_0 + b_1 T + b_2 T^2 + b_3 T^3 + b_4 T^4 + b_5 T^5 \tag{8}$$

Similarly, the time derivative of the TDC has been defined as:

$$\dot{\varepsilon}_{tdc} = \beta_2(T, \bar{C}) \frac{\sigma}{\sigma_{u0}} \dot{T} \tag{9}$$

Where $\beta_2(T, \bar{C})$ is the TDC derivative function which represents the increment in TDC per unit increment in temperature and stress level, defined as a function of a material parameter $B(\bar{C})$ which depends on the initial moisture condition of the material:

$$\beta_2(T, \bar{C}) = \begin{cases} B(\bar{C}) & for\ T < T_{dr} \\ 0 & for\ T \geq T_{dr} \end{cases} \tag{10}$$

Model implementation

The FTS and LITS models discussed above have been included in a 3D thermo-elastic material behaviour law. The resulting constitutive model has been implemented in the finite element code *Code _Aster* (EDF, 2013) through the code generator *MFront* (Helfer et al., 2015).

VALIDATION TEST CASES

The model has been validated by modelling the transient tests reported in (Khoury et al., 1985a), where concrete cylinders having various initial moisture conditions were heated up to 600°C at the heating rate of 0.2°C/min under constant compressive stress.

Given the symmetry of the problem, only one quarter of the specimen was modelled trough second order hexahedral finite elements (see Figure 5). The three faces lying on the planes x = 0 m, y = 0 m and z = 0 m were prevented from translating in their normal directions. A uniformly distributed pressure σ was applied to the face lying at z = 0.186 m. The evolution of the temperature field was obtained through a thermal analysis. Five different initial water contents were considered: C=0 l/m^3, C=50 l/m^3, C=106 l/m^3, C=118 l/m^3 and C=130 l/m^3.

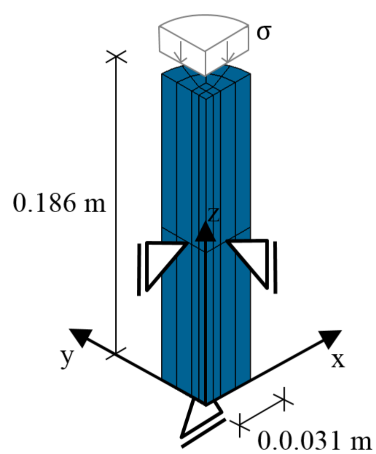

Figure 5 Mesh, boundary and loading conditions defined for modelling the uniaxial transient tests reported in (Khoury et al., 1985a)

The evolution of the moisture dependent materials parameters $\varepsilon_{tsh,max}(\bar{C})$, $\varepsilon_{tsw,max}(\bar{C})$and $B(\bar{C})$ with the water content has been defined so as to fit the experimental data and is illustrated in Figures 6, 7 and 8. The values adopted for the other parameters are reported in Table 1.

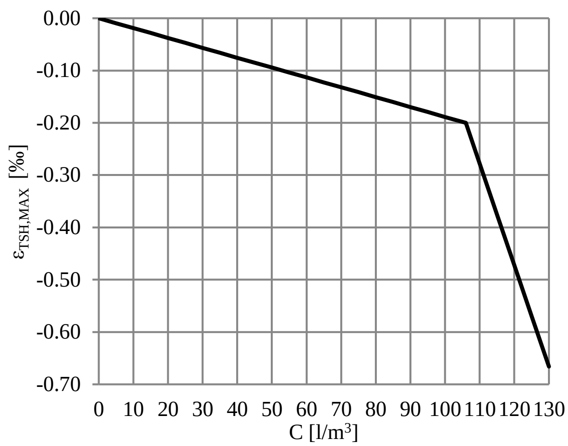

Figure 6 Maximum expected transient shrinkage $\varepsilon_{tsh,max}$ as a function of the initial water content.

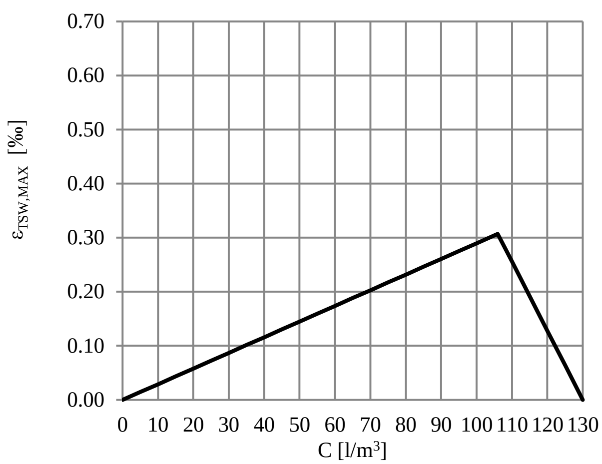

Figure 7 Maximum expected transient swelling $\varepsilon_{tsw,max}$ as a function of the initial water content.

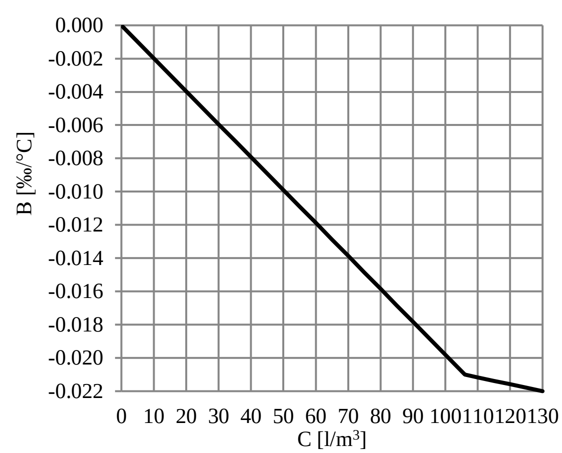

Figure 8 TDC coefficient *B* as a function of the initial water content.

Table 1: Moisture-independent material parameters

Material parameter	Value
E	47000 MPa
ν	0.25
b_0	-8.453367e-05 °C^{-1}
b_1	2.946952e-06 °C^{-1}
b_2	-3.264034e-08 °C^{-1}
b_3	1.434291e-10 °C^{-1}
b_4	-2.780193e-13 °C^{-1}
a_0	-2.29070e-06 °C^{-1}
a_1	2.84651e-07 °C^{-1}
a_2	-2.81933e-09 °C^{-1}
a_3	1.20736e-11 °C^{-1}
a_4	-2.33299e-14 °C^{-1}
a_5	1.68298e-17 °C^{-1}

The experimental FTS and LITS curves and the numerical predictions are reported in Figures 9 and 10. The match between experimental and numerical curves demonstrates the capability of the approach to take the experimentally observed moisture dependency of the thermal strains into account.

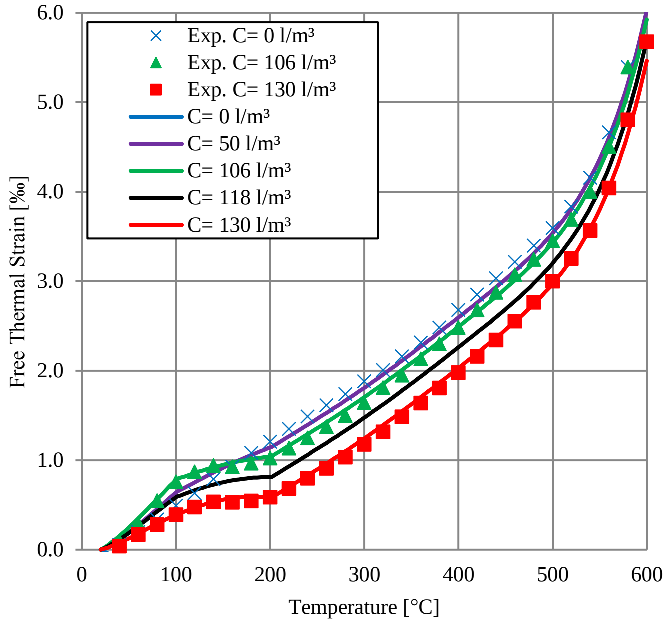

Figure 9 Experimental FTS curves and numerical results

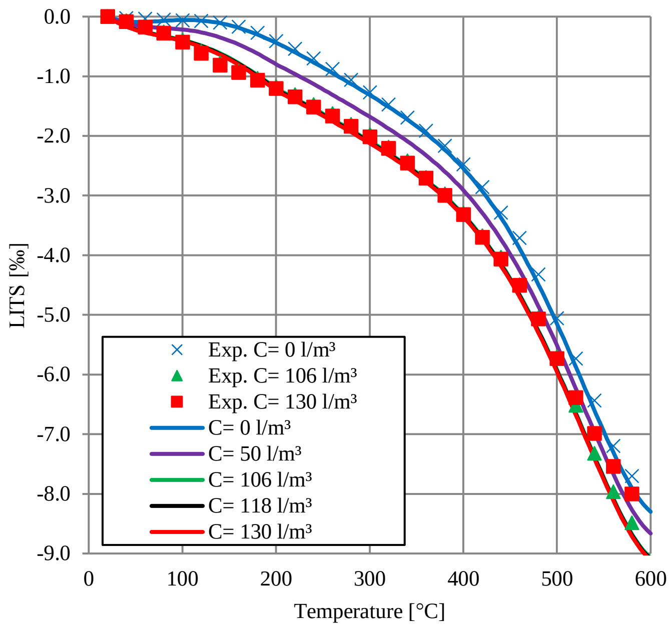

Figure 10 Experimental LITS curves and numerical results

CONCLUSIONS

The following conclusions can be drawn from this study:

- A new approach for capturing the dependency of the concrete thermal strains on the moisture conditions of the material is presented.

- The approach captures the effects of the moisture conditions of the material on the thermomechanical behaviour by explicitly modelling the thermal strain components that depend on internal moisture movement and drying.
- The proposed method allows modelling the mechanical effects the drying without attempting to model the complex drying phenomena which take place at high temperatures.
- The proposed constitutive model is calibrated against experiments performed on unsealed concrete specimens heated at the rate 0.2°C/min. Therefore, the identified material parameters should be applied with caution in the case of structural applications involving different hygral boundary conditions and heating rates.

REFERENCES

EDF. (2013). "Algorithme Non Linéaire Quasi-Statique STAT_NON_LINE." Référence du Code Aster R5.03.01 révision : 10290. . (http://www.code-aster.org). EDF-R&D/AMA.

Helfer, T., Michel, B., Proix, J.-M., Salvo, M., Sercombe, J., & Casella, M. (2015). Introducing the open-source mfront code generator: Application to mechanical behaviours and material knowledge management within the PLEIADES fuel element modelling platform. *Computers & Mathematics with Applications*, *70*(5), 994–1023. http://doi.org/10.1016/j.camwa.2015.06.027

Khoury, G. A., Grainger, B. N., & Sullivan, P. J. E. (1985a). Strain of concrete during first heating to 600 °C under load. *Magazine of Concrete Research*, *37*(133), 195–215.

Khoury, G. A., Grainger, B. N., & Sullivan, P. J. E. (1985b). Transient thermal strain of concrete; literature review, conditions within specimen and behaviour of individual constituents. *Magazine of Concrete Research*, *37*(132), 131–144.

Kordina, K., Ehm, C., & Schneider, U. (1986). Effects Of Biaxial Loading On The High Temperature Behaviour Of Concrete. *Fire Safety Science*, *1*, 281–290. http://doi.org/10.3801/IAFSS.FSS.1-281

Neville, A. M. (1995). *Properties of concrete. 4th and final edition*.

Petkovski, M., & Crouch, R. S. (2008). Strains under transient hygro-thermal states in concrete loaded in multiaxial compression and heated to 250 °C. *Cement and Concrete Research*, *38*(4), 586–596.

Pickett, G. (1942). The Effect of Chang in Moisture-Content on the Crepe of Concrete Under a Sustained Load. *ACI Journal Proceedings*.

Torelli, G., Gillie, M., Mandal, P., & Tran, V.-X. (2016). A multiaxial load-induced thermal strain constitutive model for concrete. *International Journal of Solids and Structures*. http://doi.org/10.1016/j.ijsolstr.2016.11.017

Torelli, G., Mandal, P., Gillie, M., & Tran, V.-X. (2017). A confinement-dependent load-induced thermal strain constitutive model for concrete subjected to temperatures up to 500°C. *International Journal of Mechanical Sciences. Under Review*.

Yamashita, H., Yoshida, T., & Hirashima, T. (2016). Influence of water on load induced thermal strain of concrete. In *Proceeding of the 9th International Conference Structures in Fire* (pp. 316–323).