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Unified modelling of the temperature effect on the autogenous deformations of cement-based materials

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ABSTRACT

Temperature effects are of primary importance for designing concrete structures. Some of the early age temperature effects on the concrete behaviour can be accurately taken into consideration by well-known maturity functions. However, the effect of temperature on the autogenous deformations development is more complex, and results in contradictory evidence. This paper studies the influence of various isothermal curing temperatures from 10 °C to 30 °C on the autogenous deformations of concrete. Binary and ternary binders containing up to 30% of limestone filler and 70% of blast-furnace slag are studied. The amplitude of both the self-desiccation deformation and the early age swelling deformation are observed to decrease with increasing temperature, whatever the binder nature. Mechanisms for this observation are suggested, and a corresponding model is developed. The effect of the binder nature, age and temperature on the autogenous deformations is assessed with this model. Based on this new model, it is shown that the effect of temperature on the autogenous deformation development can be either beneficial or detrimental, depending on the nature of the binder.

1. Introduction

Temperature effects are of primary importance for designing concrete structures. Depending on the whole curing temperature history of the structure, a single concrete composition can result in variable material properties. This is especially important for massive concrete structures, which undergo important early age temperature variations. More importantly, in such structures, there exists a temperature history gradient, resulting in localized stresses. Such structures require specific engineering knowledge and processes in order to limit the concrete cracking potential [1].

In particular, the sensitivity of concrete to temperature is dependent on the nature of the binder. Mineral additions such as fly ash, blast-furnace slag or limestone filler each have an influence on the hydration kinetics, which is in term affected by temperature in a unique way.

Some of these early age effects can be accurately taken into consideration. It is the case of most mechanical properties (setting time, elastic modulus, strength, Poisson's ratio), which are known to be mostly affected by temperature through the modification of the hydration kinetics. Well known maturity functions, such as the equivalent age expression in Eq. (1) are thoroughly used. It describes the accelerating effect of a given temperature history T in comparison with a reference temperature T_r. R is the universal gas constant (=8.314 J/mol/K). The apparent activation energy (E_a, expressed in kJ/mol) describes the sensitivity of concrete to a temperature variation.

$$t_e = \sum_{0}^{t} e^{\left[\frac{-E_a}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)\right]} \Delta t \tag{1}$$

The ultimate values of mechanical properties are also affected by the curing temperature. At higher temperature, the faster hydration results in a less homogenous matrix with coarser pores, and therefore to lower mechanical properties [2,3]. This explains the so-called crossover effect, which generally appears after several days, and is significant for high temperature variations. This effect is therefore not significant at early age for temperature between 10 °C and 30 °C, even for binders with high temperature sensitivity such as in presence of blast furnace slag [4].

For structural applications, the effect of temperature on other properties such as autogenous deformation is generally considered in numerical computations with a classical maturity-based approach, even when significant temperature rises are considered [5,6]. However, the effect of temperature on the delayed deformations (autogenous and drying deformation, creep) is more complex, and results in contradictory evidence, in particular for the autogenous deformation development [7–12]. More specifically, the effect of temperature on the autogenous deformation includes consequences on both the kinetic and the amplitude. The kinetic factor can be taken into account by an evolving apparent activation energy which significantly differs from the mechanical or chemical activation energy. The apparent activation energy with and without mineral additions is typically in the range of 30–60 kJ/mol for compressive strength or heat release measurements

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[4]. For the autogenous deformation, values of E_a between 60 and 120 kJ/mol are reported [7–9,11]. In this case, E_a changes significantly through hydration, and cannot be approached by a constant value. This is due to the faster development of shrinkage up to a lower value when increasing the curing temperature. This effect is attributed to the combination of two mechanisms when temperature is increased, i. e accelerated hydration reactions, and increase in the ultimate relative humidity [7,10]. This is due to the effect of temperature on the enthalpy of vaporization of water. At high temperature, the lower heat of vaporization induces a higher water pressure. Therefore, for the same free water content, the relative humidity is higher, and the capillary pressure and resulting self-desiccation deformation is lower. Some inconsistent temperature effects were also observed when the concrete presents early age swelling peaks [8]. In any case, all authors agree on the observation that a mechanical E_a is unsuitable for the prediction of temperature effect on autogenous deformation, and that the resulting E_a is hydration-dependent and can vary significantly depending on the concrete mix design.

A new methodology, inspired from work of Barcelo et al. [13] was previously described for decoupling the thermal, the self-desiccation and the swelling deformations (Fig. 1) [14]. It was developed based on binders containing various supplementary cementitious materials (SCM) such as limestone filler and blast-furnace slag. This methodology is based on the combined measurement of the autogenous deformation and of the degree of hydration. The aim of this paper is to assess the effect of temperature (tests at 10 °C, 20 °C and 30 °C) on the self-desiccation deformation and on the swelling deformation. Following this, a new predictive model for the effect of temperature on the autogenous deformation is proposed.

2. Materials and method

2.1. Materials

The studied binders are composed of CEM I 52.5 N, limestone microfiller (LMF), blast-furnace slag (BFS) and gypsum. Four concrete compositions are studied (Table 1). In addition to a reference composition (C1) containing only CEM I, compositions C2 and C3 contain 70% of BFS and 30% of LMF respectively. Finally, C4 contains 25% of CEM I, 30% of LMF and 40% of BFS. Gypsum is added in order to keep the sulfate content constant between all compositions. The water/binder ratio (w/b) is kept constant between all compositions. The activation energy E_a, extracted from Ref. [4] is shown for all concrete compositions. Additional information related to the chemical composition of each binder component can be found in Ref. [4].

Table 1
Composition and properties of concrete mixtures (kg/m^3).

	C1	C2	C3	C4
Aggregate 10/14	873	873	873	873
Aggregate 6/10	210	210	210	210
Sand 0/4	853	853	853	853
Cem I 52.5	432	104	285	103
GGBFS	0	291	0	164
LMF	0	0	126	124
Gypsum	0	22	10	22
Water	173	167	169	165
w/b [−]	0.4	0.4	0.4	0.4
E_a [kJ/mol]	35.9	51.1	39.1	49.7
E_s 28 d [GPa]	51.8	51.7	48.4	50.0
f_c 28 d [MPa]	53.2	38.7	46.4	33.8
f_c 90 d [MPa]	58.3	44.0	48.6	39.6
f_c 365 d [MPa]	61.4	49.6	52.3	46.3
slump class	S1	S1	S3	S2

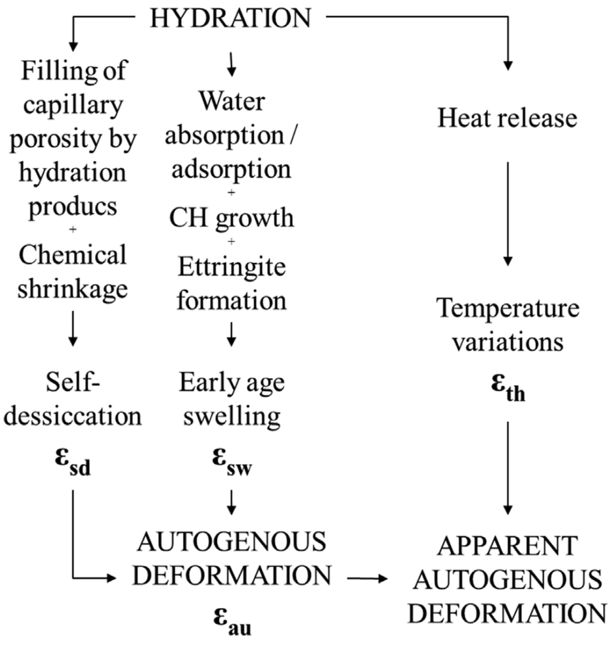

Fig. 1. Mechanisms of the autogenous deformation [14].

2.2. Test setups

2.2.1. Setting time determination from ultrasonic measurements

The final setting time t_0 is considered as the time when significant deformations might result in the development of stresses in concrete. Before the final setting, the stiffness of concrete can be neglected, and therefore the autogenous deformation has no impact on the structural behaviour of concrete. After t_0, the stiffness increases, and any deformation of the cement paste might induce a heterogeneous stress state inside the material due to internal (aggregates) or external (structural) restraint. Therefore, the autogenous deformation is only considered after the final setting time. This parameter was measured with the ultrasonic method, according to a new methodology developed in Ref. [15]. The final setting time is defined as the time when the dynamic elastic modulus curve, determined through the coupled measurement of ultrasonic P-wave and S-wave velocity, reaches its maximal rate of increase. Tests are performed on each concrete composition at 10 °C, 20 °C and 30 °C, and were already presented in a previous publication [4].

2.2.2. Degree of hydration from isothermal calorimetry

The decoupling strategy presented in this paper requires the knowledge of the degree of hydration for each composition. The degree of hydration is determined at 10 °C, 20 °C and 30 °C from heat flow measurement with an 8-channel TAM Air isothermal calorimeter. These measurements are performed on mortars corresponding to mixes C1, C2, C3 and C4, without large aggregates, and were already presented in a previous publication [4]. The degree of hydration is modelled with a new model, based on the model developed by Freisleben-Hansen and Pedersen, adapted (Eqs. (2)–(4)) to the hydration of SCM-based materials [4]. This model superimposes two s-shaped curves, with respective amplitudes a_1 and a_2 [J/g], time constants τ_1 an τ_2 [h], and exponents β_1 and β_2 [-]. The ultimate heat release Q_∞ [J/g] can be approximated by the sum of the amplitude parameters, and the degree of hydration $\alpha(t)$ is obtained by dividing the cumulated heat release by Q_∞.

$$Q(t) = a_1 .\ e^{-\left(\frac{\tau_1}{t}\right)^{\beta_1}} + a_2 .\ e^{-\left(\frac{\tau_2}{t}\right)^{\beta_2}} \tag{2}$$

$$Q_\infty = a_1 + a_2 \tag{3}$$