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Effect of temperature on basic creep of High Performance Concretes heated between 20°C and 80°C

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ABSTRACT

This research concerns the uniaxial compressive basic creep of High Performance Concretes (HPC) at moderate temperatures in the field ranging from 20 to 80°C. An experimental programme was performed on four HPC envisioned for future storage structures of Intermediate Level Long-Life Nuclear Wastes. The analyze of deformations allowed to assess the impact of temperature on basic creep and Young's modulus. Thus, a damage appeared at 80°C, revealed by a decrease of Young's modulus and a strong increase of creep amplitude. From these results, the fitting of a non linear visco-elastic model, considering the temperature effects via an Arrhenius law affecting the viscosities and a thermal damage affecting the Young's modulus. The improved knowledge of the temperature effects on creep and its better integration in a constitutive finite element models are useful to assess the sensitive to delayed strains of structures subjected to moderate temperatures.

Keywords. Basic Creep, Temperature, Model, Damage, HPC.

1. INTRODUCTION

The estimation of the instantaneous and delayed behavior of concrete is necessary to propose an efficient design of concrete structures. In case of specific structures sensitive to delayed strains, such as nuclear power plants, repository structures for radioactive wastes, massive structures, the concrete boundary conditions are often characterized by moderate temperatures (between 20 and 80°C) due to exogenous (exothermic radioactive wastes) or autogenous (cement hydration of massive structures) origins. However, effects of heating under 80°C are not taken into account in civil engineering design rules (EN1992-1-2, 2005).
A very few studies, synthetized by Ladaoui et al (2011), mainly old and thus concerning Ordinary Portland Cement (OPC), have investigated the impact of moderate temperature on concrete creep. Hannant (1967) and Nasser and Neville (1965) observed a larger increase in amplitudes of basic creep under the effect of temperature on OPC characterized by high compressive strength. Thus, High Performance Concretes, generally used for massive

structures, would developed higher creep strain at moderate temperature. Their long-term mechanical behaviors could induce detrimental effects on the structure serviceability, as tension losses of prestressing, excessive deflections and cracking in case of restrained deformation conditions.
This research concerns the uniaxial compressive basic creep of High Performance Concretes (HPC) at moderate temperatures in the field ranging from 20 to 80°C. A basic creep experimental programme was performed on HPC envisioned for future storage structures of Intermediate Level Long-Life Nuclear Wastes. The objective is twofold. The study provides delayed strains evolutions allowing the estimation of the long-term behavior of HPC under in situ conditions characterized by temperatures increase which could reach 70°C due to these exothermic wastes. The analyze of deformations contributes to improve the understanding of basic creep at moderate temperature and the effect of temperature with a view to its integration in Thermo-Hydro-Mechanical models.
A campaign of uniaxial compressive basic creep tests has been led on four formulations of HPC including two fibrous concretes submitted to three different temperatures : 20°C, 50°C and 80°C. The comparative analyze of delayed deformations allowed to assess the temperature effect on basic creep kinetics and magnitudes and on Young’s modulus of HPC. From these results, the fitting of a model (Sellier and Buffo-Lacarriere, 2009), considering the effects of temperature via an Arrhenius law and a thermal damage affecting the Young’s modulus, its viscous modules parameters and an intrinsic creep potential, is proposed.

2. EXPERIMENTAL PROGRAMME

Four different types of HPC with CEM I and CEM V cement were studied: two with stainless fibres and silica fume, called CEM IF and CEM VF, and two others without fibres and without silica fume, called CEM I and CEM V. All the mixtures incorporated limestone aggregates (sand 0/4, gravel 4/12.5). The various mixture compositions are given in Table 1.

Table 1. Compositions of concretes

Components in kg/m^3	CEM I	CEM V	CEM IF	CEM VF
CEMI 52.5R CE PM-ES-CP2 (Lafarge,Val d’Azergues)	400	-	454	-
CEMV/A 42.5 N PM-ES-CP1 (Calcia, Airvault)	-	450	-	454
Limestone sand 0/4 mm, (Boulonnais)	858	800	984	984
Superplasticizer Glenium 27, MBT	10	11.25	-	-
Silica fume Condensil S95 DM	-	-	45	45
Stainless fibre IFT (L = 30 mm, Ø = 0.6 mm)	-	-	85	85
Superplasticizer SIKA Viscocrete 5400F	-	-	13.70	17.25
Water/Binder	0.45	0.41	0.32	0.33
Total water	178	183	172	178

The basic creep tests were performed in a creep system located in a heated room, following RILEM TC 129–MTH (January-February 2000; May 2000) and ASTM (2005) recommendations, for three temperatures : 20°C, 50°C and 80°C. Figure 1 presents the experimental set up.

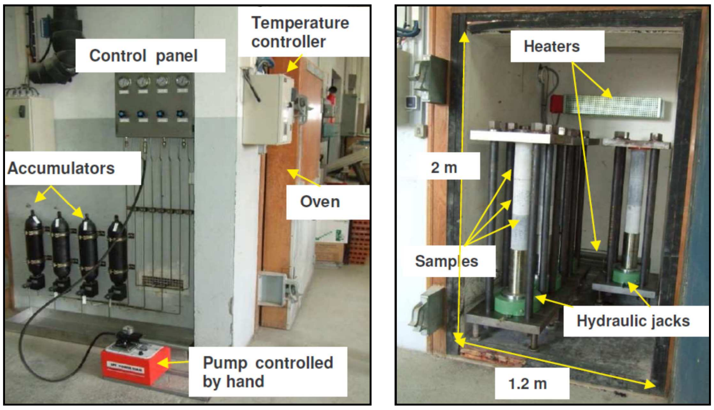

Figure 1. Experimental set up

After demoulding at one day, cylindrical specimens (Ø=110mm, h=220mm) were cured under water (20°C) until the age of creep loading for at least 300 days (427 days for 50°C tests and 300 days for 20 and 80°C tests). This treatment led to obtain stabilized hydration and prevented any influence of capillary depression, reducing coupling between creep and cement hydration and pozzolanic reactions. During creep tests, the specimens were sealed to avoid desiccation by three layers of waterproof adhesive aluminium and covered in a waterproof plastic film. They were first heated and the temperature was maintained while they were loaded at 30% of their compressive strength measured on different samples at 20°C, at the age of creep loading. Volumetric changes and axial strains were measured through LVDT sensors and gauges. The analyze presented in this paper focuses on the evolutions of uniaxial elastic and creep strains. The mechanical characteristics (compressive strengths, f_{cm}, moduli of elasticity, E_{cm}, and Poisson coefficients, ν) are presented in Table 2.

Table 2. Mechanical characteristics of all concretes.

Age	Mechanical properties	CEM I	CEM V	CEM IF	CEM VF
Test series at 50 °C					
28 days	f_{cm} [MPa]	77	65	95	83
	E_{cm} * [MPa]	42.9	40.7	44.6	41.5
	ν	0.27	0.26	0.27	0.27
Age of loading (427 days)	f_{cm} [MPa]	86	75	113	99
	E_{cm} * [GPa]	45.5	44.8	46.2	45.1
	σ_{creep} [MPa]	25.8	22.5	33.9	29.7
	ε_{inst} at 50°C [µm/m] (E_{cm} estimated [GPa])	620 (41.6)	503 (44.7)	791 (43.0	670 (44.3)
	ν	0.27	0.27	0.29	0.28
Test series at 20°C and 80°C					
28 days	f_{cm} [MPa]	74	73	115	91
Age of loading (300 days)	f_{cm} [MPa]	87	99	130	122
	E_{cm} * [GPa]	44.7	45.1	48.8	46.2
	σ_{creep} [MPa]	26.1	29.7	32.5	36.6
	ε_{inst} at 80°C [µm/m] (E_{cm} estimated [GPa])	751 (34.8)	858 (34.6)	700 (46.4)	882 (41.5)
	ν	0.28	0.29	0.27	0.29

* Young's moduli at 20°C (on specimens different from the creep ones)

The values correspond to the mean of three tests on cylindrical specimens. The tests were carried out according to RILEM recommendations at 28 days and at the age of loading. The instantaneous strains (ε_{inst}) recorded during the loading of the creep test are also given.

For all the results, the coefficient of variation (standard deviation / average value) was less than 5%. Two castings were needed to make the whole samples for the test series of creep at 50°C and those for tests at 20°C and 80°C. This explains the differences in mean values of the material characteristics that can be seen between the two series.

The fibrous mixtures developed higher mechanical properties, compressive strength and Young's modulus, than the non-fibrous ones, due to the pozzolanic reactions of silica fume and lower Water/Binder ratios. The Poisson coefficients presented low variations, whatever the type of HPC and the age of measurement.

3. EXPERIMENTAL RESULTS

Figures 2 and 3 present the evolutions of Young's moduli before creep, after heating at respectively 50°C and 80°C during creep loading, and finally after creep tests at 20°C.

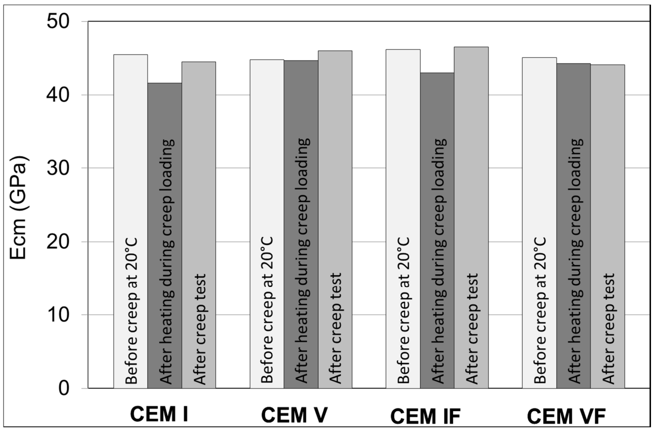

Figure 2. Evolution of Young's moduli before creep test at 20°C, after heating at 50°C and during creep loading, and after creep test at 20°C.

The variations of Young's moduli for 50°C creep test are very weak. After 50°C heating, a slight decrease can be observed for CEMI and CEM IF. It can be more correlated to the different method of estimation of the modulus of elasticity (secant modulus during loading creep, RILEM procedure for measurements before and after creep testing) than to a thermal or creep damage since the values are rather similar before and after the test at the same 20°C temperature.

The same results obtained on 80°C creep tests specimens (Figure 3) show a modification of elastic behavior with a decrease of moduli of elasticity compared to those measured before creep test at 20°C. The similar values obtained after heating during creep test and after test tend to prove that this damage can be attributed to 80°C heating and not to creep. A thermal deformation gradient between the paste and aggregates, due to their different thermal expansion coefficients could explain this damage.

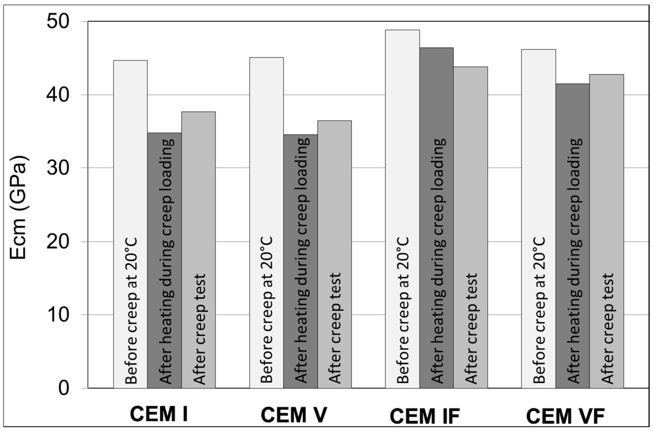

Figure 3. Evolutions of Young's moduli before creep test at 20°C, after heating at 80°C and during creep loading, and after creep test at 20°C.

Figures 4 and 5 show the evolutions of basic creep for the four HPC (dots) during 300 days of loading, t_0 corresponding to the age of loading. The continuous lines correspond to the model fitting explained further in the article. For creep at 80°C, the recordings were limited to periods between 20 and 52 days. Over these periods, the sensors became unreliable (although their use is guaranteed by the supplier for such conditions).

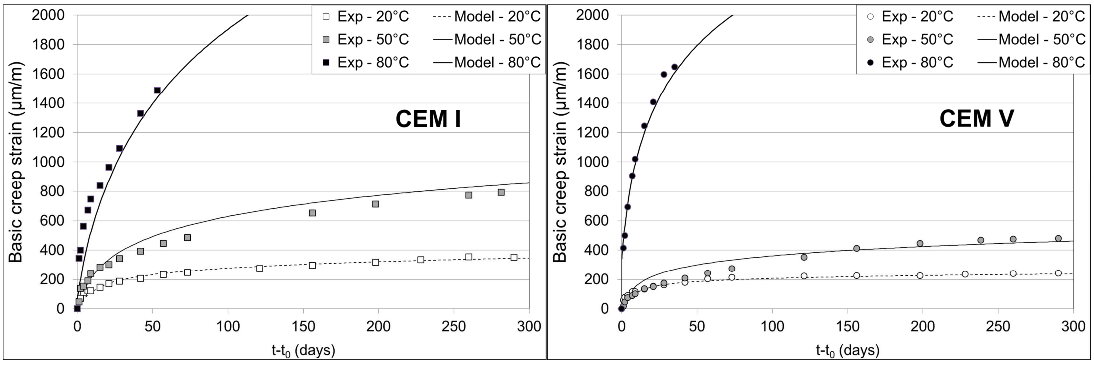

Figure 4. Basic creep for CEM I and CEM V at 20°C, 50°C and 80°C.

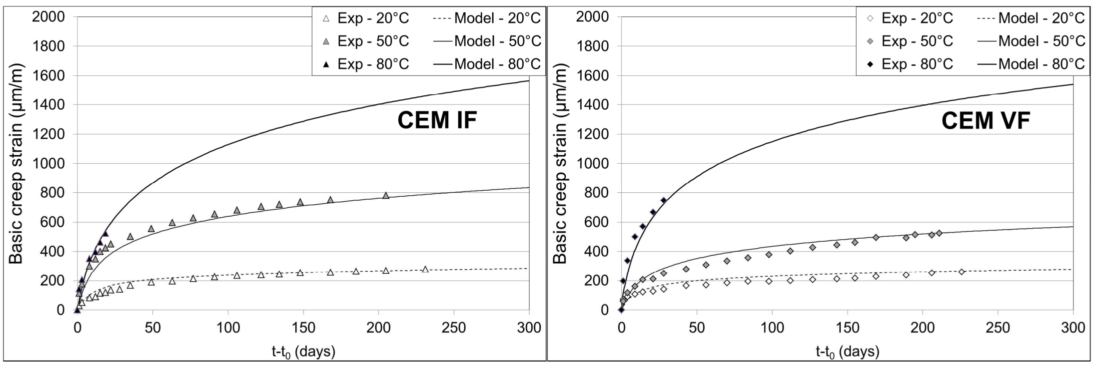

Figure 5. Basic creep for CEM IF and CEM VF at 20°C, 50°C and 80°C.

The 50°C heating led to an increase of creep rate and approximately to a doubling of amplitude of creep after 300 days of loading. Basic creep strains were between 2.0 and 3.7 times higher at 50°C than at 20°C. These values are higher than the average value of 1.80 found for 50°C creep tests at temperatures around 50°C from the literature results presented in a synthesis by Ladaoui et al (2011). The two CEM V concretes developed less creep strain compared to CEM I ones. The silica fume and fibres did not significantly modify creep amplitude. These two parameters probably had opposite effects on creep rate and counteracted each other. Between 20°C and 50°C, the temperature could change the viscosities of water, amplifying the slippage of C-S-H sheets, considered as the origin of creep phenomenon.
The creep magnitude and rate are significantly affected by the 80°C temperature. Although the short duration of testing, the creep strain are multiplied by 5.7 for CEM I, 9.2 for CEM V, 4.4 for CEM IF and 5.3 for CEM VF, after 20 days of loading. The creep rise is surely coupled with thermal damage revealed by the decrease of Young modulus.

4. PRESENTATION OF THE RHEOLOGICAL MODEL

The rheological model used to analyse these creep results was developed by Sellier and Buffo-Lacarriere (2009) (Sellier et al, 2012). In its full version, this model is written in a poro-mechanical framework to consider drying creep. This is the reason why the total stress is divided into a spherical part on the solid skeleton, a deviatoric part, and water stress due to capillary depression π^w. This is a similar technique to that used in the models proposed by Bernard et al (2003) and Ulm et al (1999) and also adopted by Benboudjema et al (2001).
Figure 6 presents the rheological model. In the case of this study, the samples were saturated in order to limit capillary stress and avoid any interaction with the drying creep. The effects of temperature and its integration in the model is presented in a second part.

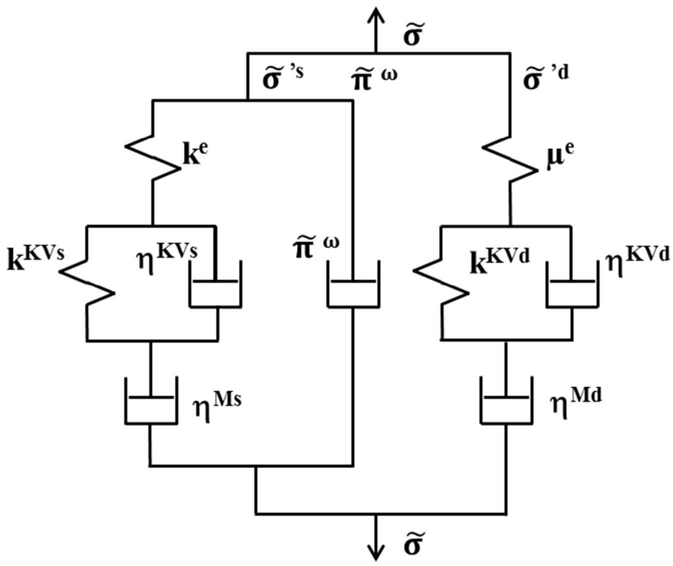

Figure 6. Rheological model.

The relationship between the stress σ and the effective stress $\tilde{\sigma}$ is classically written in accordance with damage theory using a mechanical damage D_c and a thermal damage D_{th} :

$$\sigma = \tilde{\sigma}.(1 - D_c).(1 - D_{th}) \tag{1}$$

D_c considers damage induced by the mechanical loading at ambient temperature, its detailed form is explained in (Sellier et al, 2012) (A. Sellier et al, 2013).
In Figure 6, k^e corresponds to the compressive modulus, μ^e is the shear modulus, the stage called e corresponds to elasticity:

$$k^e = \frac{E^e}{3(1-2\upsilon)} \quad \text{and} \quad \mu^e = \frac{E^e}{2(1+\upsilon)} \tag{2}$$

The creep is simulated by the KV (Kelvin-Voigt) and M (Maxwell) stages. The Kelvin-Voigt stage models the reversible part of creep and the Maxwell stage models the viscous part. The specificity of the model lies in the fact that the viscosity of the Maxwell stage evolves as a non-linear function of strain. The choice of this non-linearity is explained in detail by Sellier and Buffo-Lacarriere (2009) or (Alain Sellier et al., 2012*a*).

The basic creep deformation mentioned in this article concerns only the two bottom stages of the scheme of Figure 6 :

$$\varepsilon^C = \varepsilon^{KV} + \varepsilon^M \tag{3}$$

where ε^C is the basic creep strain; ε^{KV} is the reversible creep strain, modelled by the Kelvin-Voigt linear solid; ε^M is the permanent creep strain modelled by a Maxwell solid with non-linear viscosity.

4.1 Rheological laws

The rheological laws are first presented for a given temperature. The classical laws of viscoelasticity are used:

$$\begin{cases} k^e \varepsilon^{es} = k^{KVs} \varepsilon^{KVs} + \eta^{KVs} \dot{\varepsilon}^{KVs} \\ k^e \varepsilon^{es} = \eta^{Ms} \dot{\varepsilon}^{Ms} \end{cases} \tag{4}$$

Where k^e is the elastic modulus of compressibility; k^{KV} and η^{KV} are respectively the modulus and viscosity of the Kelvin-Voigt stage associated with reversible creep; η^{Ms} is the Maxwell fluid viscosity.

For deviatoric deformations, in the same way, we obtain :

$$\begin{cases} 2\mu^e \varepsilon_{ij}^{ed} = 2\mu^{KVd} \varepsilon_{ij}^{KVd} + \eta^{KVd} \dot{\varepsilon}_{ij}^{KVd} \\ 2\mu^e \varepsilon_{ij}^{ed} = \eta^{Md} \dot{\varepsilon}_{ij}^{Md} \end{cases} \tag{5}$$

Where μ^e is the shear elastic modulus; μ^{KVd} and η^{KVd} are respectively the shear modulus and viscosity associated with reversible deviatoric creep; η^{Md} is the non-linear viscosity associated with the permanent deviatoric creep.

To model this non-linearity, the coefficient of consolidation C_c is introduced as:

$$\begin{cases} \eta^{Ms} = C_c \; \eta^{Ms0} \\ \eta^{Md} = C_c \; \eta^{Md0} \end{cases} \tag{6}$$

where $\eta^{M(s \text{ or } d)0}$ is the initial viscosity of the material.
with:

$$C_c = \exp\left(\frac{\left|\varepsilon^{Ms}\right|}{\varepsilon^{Msk}}\right) \tag{7}$$

where ε^{Msk} is a parameter called "characteristic strain of consolidation" controlling the rate of consolidation of concrete and ε^{Ms} is the strain creep in the Maxwell element. This parameter is in accordance with the idea of an intrinsic creep potential proposed by Acker et al (2004).

4.2 Integration of temperature effects

On the basis of the analyze of elastic and creep experimental behaviors of the four HPC and according with other studies, the integration of temperature effects is proposed at the different stages of the model.

The thermal damage parameter, presented in relation (1), depends on the current temperature. It is assessed thanks to the following relationship :

$$D_{th} = 1 - \exp\left(-\left(\frac{T - T_{ref}}{\Delta T_k}\right)\right) \quad \text{with } \dot{D}_{th} \geq 0 \tag{8}$$

with T is the current temperature, T_{ref} is temperature leading to the beginning of damage, estimated at 50°C from the previous analyse of Young's moduli results, and ΔT_k is a fitting temperature parameter.

To fit the model evolution with the creep results at 50°C, a simple change of viscosity can be take into account from 20°C since only the rate of the creep seems to be activated by heat. By adopting an Arrhenius law similar to that proposed by Bažant et al (2004), the following relationship can be written :

$$\frac{\eta^{Ms}(T)}{\eta^{Ms0}(T_{ref})} = \frac{\eta^{Md}(T)}{\eta^{Md0}(T_{ref})} = \frac{\eta^{KVs}(T)}{\eta^{KVs0}(T_{ref})} = \frac{\eta^{KVd}(T)}{\eta^{KVd0}(T_{ref})} = \exp\left(\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right) \tag{9}$$

In this expression, T_{ref} is the reference temperature (in K), i.e 20°C, T the current temperature (°K), Q is the activation energy of the viscous processes (J/mol), R = 8.31 is the gas constant (J/mol.K).

In order to express the greater creep deformation capability observed at 50°C which could be the consequences of reversible differential dilatation at microscopic scale during heating, the characteristic strain of consolidation is also affected by temperature. An Arrhenius law, with the same activation energy value Q than applied to viscosities and the same reference temperature of 20°C is used :

$$\frac{\varepsilon^{Msk}(T)}{\varepsilon^{Msk0}(T_{ref})} = \exp\left(-\frac{Q}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right) \tag{10}$$

4.3 Fitting of the model parameters

The fitting of the basic creep model consists in the determinations of the value of the following parameters "characteristic strain of consolidation" ε^{Msk}, the activation energy, the thermal damage and the fitting temperature parameter ΔT_k controlling the evolution of the thermal damage. The curve fitting are presented in Figures 4 and 5. The values of the fitting parameters are detailed in Table 3.

Table 3. Rheological characteristics obtained by curve fitting.

Parameters	CEM I	CEM V	CEM IF	CEM VF
ε^{Msk}	$4.0x10^{-4}$	$1.8x10^{-4}$	$3.4x10^{-4}$	$2.8x10^{-4}$
Q (J/mol)	$1.6x10^{4}$	$1.6x10^{4}$	$1.6x10^{4}$	$1.4x10^{4}$
$D_{th80°C}$ exp	0.22	0.23	0.05	0.10
$D_{th80°C}$ model	0.28	0.45	0.05	0.15
ΔT_k (K)	91	50	585	185

The characteristic strains of consolidation are of the same range of values. It seems higher for CEM I concretes. The activation energy is found equal to $1.6x10^4$ J/mol for all concretes, except $1.4x10^4$ for CEM VF. It corresponds to a ratio of activation energy to gas constant of 1924 K, which is close to the value 2000 K obtained by Benboudjema and Torrenti (2008). It is also interesting to notice that this intensity of activation energy is close to the one of water viscosity (Briffaut, 2010). This confirms that the reduction of water viscosity with temperature is a major phenomenon which, combined with the thermal damage, leads to the creep amplitude.

The analyze of values of thermal damage fitted with the results at 80°C and experimental ones assessed from Young moduli show a rather good correlation, except for CEM V. These results confirm that fibers limit the thermal damage.

Finally, the fitting temperature parameter ΔT_k controlling the rate of thermal damage are variable, even if their values are in the same range for all the HPC, except for CEM IF. As a high ΔT_k value tends to reduce the rate of damage evolution, these fitting results also demonstrate the action of fibers for the maintain of microstructural integrity.

5. CONCLUSIONS

This study provides results of uniaxial compressive basic creep for four HPC, with two fibrous concretes incorporating silica fume, subjected to three temperatures : 20°C, 50°C., and 80°C. The analyze of evolution of Young moduli, before, after heating during loading, and after creep tests revealed a thermal damage occurring above 50°C and surely due to thermal deformation gradient between cement paste and aggregates. The creep strains at 50°C are approximately twice those obtained at 20°C during 300 days of loading. Whereas, at 80°C, the creep amplitude is multiplied by a value between 4.4 and 9.2 after only 20 days of loading.

Temperature effects have been integrated in a rheological model of basic creep. The thermal effects are considered, on one hand thanks to an Arrhenius law which affects the viscosities and the characteristic strain of consolidation and, on the other hand, taking into account a thermal damage D_{th}. The fitting of experimental basic creep has been performed and shows that the activation energy value is close to the one that controls water viscosity, traducing the role of viscosity of water on creep phenomenon through its probable effect on C-S-H sheets slippage.

A further step of this work will be to extend the experimental study to desiccation creep in temperature through data from experimental tests in progress at the LMDC.

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