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Prediction of the basic creep of concrete with high substitution of Portland cement by mineral additions at early age

Basic creep of concrete with high slag content

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ABSTRACT

The present work analyses the basic creep of concrete compositions for which 75% of Portland cement is substituted by limestone filler and/or blast furnace slag. Compressive creep tests are performed during and after the peak of hydration of the slag in order to track the effect of the slag on the development of the creep properties. An adapted version of the Model Code 2010 (MC2010) is used to model basic creep. It is observed that the high substitution rate of cement by limestone filler and/or slag leads to a significant change in the evolution of the viscoelastic properties of concrete till a significant degree of reaction of slag is reached. It corresponds to the end of the second peak of hydration due to slag. After the slag peak of hydration, the basic creep is similar to ordinary Portland cement concrete with equivalent water-to-binder ratio. For very early age, a new model is developed and is composed of two terms which consider the hydration of (i) Portland cement and (ii) slag in the aging of the specific creep function.

Keywords: Creep; modeling; early age; setting; mineral additions; hydration

1. INTRODUCTION

For usual concrete structures built in several phases, concrete deformations are restrained during the hardening process. In case of massive structures, during the first days, a significant increase in temperature takes place due to the hydration of cement and generates compressive stresses inside concrete element. A large part of the compressive stresses are reduced thanks to the viscoelastic behaviour of cement-based materials (Benboudjema et al., 2019). For example, it is shown in (Delsaute, Boulay, & Staquet, 2016) that, at very early age, the relaxation phenomenon is responsible for a decrease of 30% of the compressive stresses in only 5 minutes. More generally, for the design of a concrete dam, Slowik, *et al.* (Slowik et al., 2005) showed that at early age, the relaxation phenomenon leads to a decrease of 70% of the thermally-induced stresses in the structure. For the construction of massive structures, it is better to use binders with high slag and/or limestone filler content. The hydration process and the mechanical properties of such binder develop more slowly in comparison to conventional Portland cement. This induces lower temperature gradient within the concrete structure and thus reduces the risk of cracking of the concrete induced by the restrained of thermal deformations.

As presented in (Delsaute et al., 2017), during the hardening process and especially during the first 24 hours after setting, the Model Code 2010 overestimates the E-modulus and underestimates the creep/relaxation phenomenon of classical concrete compositions. This leads to a strong overestimation of the compressive stresses when concrete expands and to an underestimation of the tensile stresses when concrete starts to shrink. Hence, it is important to model correctly the basic creep since final setting time. However, only very scarce data are available in the literature on the viscoelastic behavior of cement-based materials at very early age. This is especially true for concrete compositions with low to medium substitution (up to 50%) of cement by mineral additions and even more true for concrete with very high substitution rate of Portland cement.

2. RESEARCH SIGNIFICANCE

In previous work, it has been shown that the logarithmic expression proposed in the Model Code 2010 is reliable to predict specific basic creep of ordinary concrete at very early age (Delsaute et al., 2017; Delsaute & Staquet, 2019) and at later ages (Le Roy et al., 2017; J.-M. Torrenti & Le Roy, 2017). An adapted version of the Model Code 2010 was used and it was observed that the effect of the age at loading is explicitly included by using the time derivative of the elastic modulus (Delsaute et al., 2017). In addition, this adapted version of MC2010 was used to model basic creep at elevated temperature and high stress level (J. M. Torrenti, 2017). The goal of this paper is to extend the testing and modelling methodology developed in (Delsaute et al., 2017; Delsaute, Boulay, & Staquet, 2016; Delsaute, Boulay, Granja, et al., 2016) to study the effect of high rate of substitution (75%) of Portland cement by mineral additions on the development of the basic creep properties since very early age till several days. More specifically, the paper aims at answer to the question: “Is the Model Code 2010 reliable to predict the basic creep behaviour of concrete with high substitution of Portland cement by mineral addition?” To answer to this question, two distinct compositions with mineral additions are compared to a reference composition with only Portland cement. The first part of the paper presents the experimental program and the preliminary results needed before having started this study. The second part of the paper focuses on the monitoring of the basic creep behaviour of the three compositions. The third part of the paper is related to the modelling of the basic creep with the adapted version of the Model Code 2010.

3. MATERIALS AND METHODS

3.1. Concrete compositions

The substitution of Portland cement by blast-furnace slag (BFS) and limestone filler is studied on three concretes for which mix proportions are given in Table 1. For each composition, the aggregate and water content is the same, only the nature of the binder changes. The first composition is a reference concrete for which the binder is only composed of Portland cement. In the second

composition and in the third composition, 75% of the Portland cement is replaced by BFS and in the third composition by BFS (50%) and limestone filler (25%). These compositions are respectively called C-REF, C-BFS and C-SCM. All materials come from the same batch of production. The chemical compositions of the Portland cement, the BFS, the limestone filler and the gypsum content are presented in (Jérôme Carette & Staquet, 2016b). Sand and gravel were oven-dried. The effective water-to-binder ratio W_{eff}/B is 0.34 for each composition. However, due of the presence of limestone filler, the effective water to equivalent binder ratio $W_{\text{eff}}/B_{\text{eq}}$ is different for the composition C-SCM and is equal to 0.45. The equivalent binder content is defined in Equation 1 according to the European standard EN 206-1.

$$B_{\text{eq}} = \text{Cement} + k \cdot \text{Limestone} \quad 1$$

The parameter k is the activity coefficient of limestone filler given by the standard ($k=0.25$). The mixing procedure is the same for each concrete mixture and is as followed: gravel and sand are mixed during (20 s), 20% of water is added (20 s mixing), binder is added (30 s mixing) and then the rest of the water is added (150 s mixing). The speed is kept constant (300 rpm). The setting was determined by monitoring the transmission of the ultrasound p- and s-waves through concrete according to the method developed in (Carette & Staquet, 2016a; Saleh, Carette, Delsaute, & Staquet, 2017). The initial and final setting times according to this method are given in Table 1.

3.2.Compressive creep rigs

Compressive creep tests were performed on frames designed at ULB (Delsaute, Boulay, & Staquet, 2016). The load is applied on the sample by increasing flat jack pressure with a pump till 40% of the compressive strength obtained experimentally on samples tested at the age of the creep loading. The flat jack is chosen according to the magnitude of the loading applied (Figure 1). A cell force is placed on the top of the sample. Displacements are measured with an extensometer composed by two stainless steel rings spaced of 200 mm and three rods in INVAR© supporting the 3 displacement sensors (Solartron© range 2 mm) placed at 120°. A dummy specimen is used to monitor the thermal and autogenous strain. Thermocouples are placed inside the dummy mould and in the room in order to

monitor the ambient temperature and the concrete core temperature. The measurements of displacement, force and temperature are sent to a computer for data recording. The sample is a cylinder with a height of 320 mm and a diameter of 100 mm. After casting, samples are sealed with a plastic sheet and a plastic cover on the top and are then placed in an air-conditioning room (20°C and RH 90%). The mould removal takes place just after setting (for the loadings at very early age) or later. Samples are then grinded on both circular end faces and surrounded by two self-adhesive aluminum sheets. The sealing has been checked by weighting the sample before and after the test with a high precision scale. No weight loss was observed. Tests are carried out in a climatic room with a temperature of $20 \pm 1^\circ\text{C}$ and a relative humidity of $50 \pm 5\%$.

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Experimental program

A certain number of fundamental properties were determined before the study of the viscoelastic behaviour of the three concrete mixes: setting time, compressive strength, the E-modulus, heat flow, activation energy and volume change (Carette & Staquet, 2016b, 2016a; Delsaute & Staquet, 2017). For consideration of the aging and the main temperature effects, concrete properties are expressed in function of the equivalent time (Equation 2). Equivalent time is based on the Arrhenius equation and is function of the age of the material t , the evolution of the temperature T ($^\circ\text{C}$), a reference temperature T_r (here 20°C), the universal gas constant R ($=8.314 \text{ J/mol/K}$) and the apparent activation energy E_a (J/mol). The apparent activation energy was defined by means of compressive strength tests at a temperature of 10 and 30°C (J Carette, 2015) and is 36, 47 and 45 kJ/mol for the composition C-REF, C-BFS and C-SCM respectively.

$$t_{eq}(t, T) = \int_0^t \exp\left(\frac{E_a}{R} \cdot \left(\frac{1}{273 + T(s)} - \frac{1}{273 + T_r}\right)\right) \cdot ds \quad 2$$

For each composition, 4 compressive creep tests with duration of few weeks were performed. The ages at loading of the creep tests were defined on basis of the results obtained from isothermal

calorimetry tests. The heat release by the paste of the three compositions was presented in (Carette & Staquet, 2016a) and is shown in Figure 2. The heat release is expressed as the measured heat release by the paste divided by the mass of Portland cement and slag. For the composition C-REF, as expected (Carette & Staquet, 2016a; Darquennes, 2009; Gruyaert, Robeyst, & De Belie, 2010), a strong increase of the heat release occurred during the setting period and the next few hours. A significant decrease of the heat release is observed during the first days when substituting cement by limestone filler and/or slag. Moreover, for the compositions C-BFS and C-SCM, a significant peak occurs between an equivalent age of 40 and 60 hours and is related to the slag hydration (G. De Schutter, 1999). The evolution of the heat release is very similar for the compositions C-BFS and C-SCM. The substitution of 25% of slag by limestone filler in the C-SCM composition slightly affects the heat release. The first peak of heat release starts sooner and has higher amplitude than the one for the C-BFS composition. The second peak is less pronounced and occurs on a longer duration. These both differences are mainly explained by the active contribution of limestone filler at very early age and by the influence of the gypsum/slag ratio on the slag reaction (Carette & Staquet, 2016a). In addition, the quantity of water available for the slag and cement hydration of the C-SCM composition is higher and can result in a higher heat flow after the peak of hydration of the slag.

From these observations, it was decided to test the C-BFS and C-SCM compositions when slag is hydrating and afterwards in order to track the effect of the slag on the evolution of the viscoelastic properties. For an adequate comparison with the reference composition C-REF, each composition is tested at a same advancement degree of reaction (ADR). The advancement degree of reaction α is defined according to Equation 3 where q is the cumulated heat release and q_{∞} is the cumulated heat release for an infinite time.

$$\alpha(t_{eq}) = \frac{q(t_{eq})}{q_{\infty}} \quad 3$$

Each composition was tested at an advancement degree of reaction of 0.38 – 0.45 – 0.6 and 0.7 as indicated in Figure 3. The corresponding equivalent ages at loading are indicated in Table 2 as well as the values of the compressive strength and E-modulus at loading ages.

In addition, as early age basic creep relates to both hydrations of the Portland cement and slag, a separation of both reactions has been carried out. For that purpose, the method proposed by Meinhard and Lackner (Meinhard & Lackner, 2008) and by Gruyaert, et al (Gruyaert et al., 2010) has been used. The cumulated heat release by the slag reaction is calculated as the difference between the total cumulated heat release of the binder and the cumulated heat release by the Portland cement with consideration of the cement-binder ratio. However, it is not possible to directly fit the evolution of the total heat release during the first hours. During this period the slag reaction is negligible and only the hydration of the Portland cement is to be considered. In addition, the reaction of the cement is enhanced by the presence of slag (Escalante-Garcia & Sharp, 2004). Therefore, a corrective factor is used to amplify the magnitude of the reaction of the Portland cement (1.25 for the C-BFS composition and 1.5 for the C-SCM composition). Then, it is possible to define the degree of reaction of both Portland cement and slag separately with consideration of the heat release for an infinite time of the Portland cement $q_{\infty,P}$ (based on the heat release by the reference composition) and the slag $q_{\infty} - q_{\infty,P}$ as expressed in Equation 4. In this equation, the index P and S correspond to the Portland cement and the slag respectively.

$$\alpha(t_{eq}) = \frac{q_P(t_{eq})}{q_{\infty,P}} + \frac{q(t_{eq}) - q_P(t_{eq})}{q_{\infty} - q_{\infty,P}} = \alpha_P(t_{eq}) + \alpha_S(t_{eq}) \quad 4$$

The result of this decoupling is shown in Figures 4 and 5. For both C-BFS and C-SCM compositions, the cumulated heat release by the slag starts to increase at an age of around 20 hours. The amplitude of the slag heat release at an age of 7 days is 105 and 98 J/g for the composition C-BFS and C-SCM respectively. For each loading age, the degree of reaction of slag α_S and Portland cement α_P is presented in Table 2. The degree of reaction of the slag at the loading ages is between 0.18 and 0.67 for the composition C-BFS, while it is between 0.15 and 0.66 for the composition C-SCM.

4.2. Experimental results

The test protocol used in (Delsaute, Boulay, & Staquet, 2016) for the compressive creep test is used for the three compositions. The compressive creep results are expressed according to the specific creep function J^* defined in Equation 5:

$$J^*(t, t') = \frac{\varepsilon_{tot}(t, t') - \varepsilon_{sh}(t)}{\sigma} \quad 5$$

where t is the age of concrete, t' is the age at loading, ε_{tot} is the total strain of the loaded specimen, ε_{sh} is the strain of the dummy specimen and σ is the stress applied on the loaded specimen.

4.2.1. Autogenous strain

First, the evolution of the autogenous strain (without external loading) of the dummy specimen for each composition is presented in Figure 6. The autogenous strain of the C-REF and C-SCM compositions obtained with the BTJADE device (Boulay, 2012) and presented in detail in a previous study (Delsaute & Staquet, 2017) are also shown in Figure 6. The evolution of the strain is set to zero at an equivalent age of 19, 41 and 39 hours for the composition C-REF, C-BFS and C-SCM respectively. This corresponds to the age of the first loading applied on each composition. The strains drawn with continuous lines correspond to the autogenous strains of the dummy specimen and those drawn with dashed lines were monitored with the BTJADE device. On Figure 6, the continuous and dashed lines are very close. Thanks to the thermal regulations used before and during testing, very limited temperature variations occurred in the samples, even during the hydration peaks. For the reference composition only, shrinkage is monitored at 19 hours of age whereas swelling is first monitored till an equivalent age of 56 and 67 hours for the C-BFS and C-SCM compositions respectively. The impact of substitution of Portland cement by limestone filler and/or slag on the evolution of the autogenous strain is highlighted by the initial swelling. For the C-BFS and C-SCM compositions, a high amount of ettringite is formed and is one of the cause explaining the swelling according to (Carette, Joseph, Cizer, & Staquet, 2018). In addition, as the limestone filler is inert, the

effective water-to-equivalent binder ratio of the C-SCM mix is higher than the one of two other mixes. This difference explains the later development of the self-desiccation and the subsequent autogenous shrinkage in the C-SCM mix which is induced by the higher quantity of water available for hydration leading to a higher relative humidity. Courard et al. (Courard & Michel, 2014) have already observed this decrease in the amplitude of the autogenous shrinkage when replacing slag by limestone filler. Moreover, during the swelling period, the E-modulus of the C-SCM mix is lower than the C-BFS mix (Jérôme Carette & Staquet, 2016b). When considering a lower E-modulus and higher water content simultaneously, it can explain the longer apparent evolution and higher magnitude of the swelling strains for the C-SCM composition. After the peak of swelling, mainly self-desiccation takes place and shrinkage starts. Autogenous shrinkage is mainly function of the evolution of the pore size distribution, the chemical shrinkage and the internal relative humidity. For mix with high substitution of Portland cement by limestone filler and/or slag content, Bouasker, et al. (Bouasker et al., 2014) found lower chemical shrinkage and a higher quantity of small pore sizes. After the peak of swelling, a higher reactivity of the slag occurs in comparison to the one of the Portland cement (see Figure 2 and Table 2). In addition, according to the Laplace law, higher tensile stresses develop in smaller pores. Because of both reasons, higher shrinkage strains are observed during this period in the C-BFS and C-SCM mixes.

4.2.2. Basic creep

Results of the specific creep function are presented in Figure 7. For each composition, the effect of the age at loading is strongly marked in the evolution of the specific creep especially for the compositions C-BFS and C-SCM. The impact of the replacement of 75% of Portland cement by slag depends on the age at loading. For very early age loading, before the peak of slag hydration, the magnitude of the specific creep is strongly affected by the presence of slag. For a total advancement degree of reaction of 0.38, the degree of reaction of the slag and the Portland cement is 0.18 and 0.58 respectively and the specific creep is 2 times larger for the composition C-BFS in comparison to the reference one. For a total advancement degree of reaction of 0.7, the degree of reaction of slag and cement is 0.67 and 0.76 and the magnitude of the specific creep is lower than the reference composition without slag. The

differences of magnitude of the specific creep are correlated to the degree of reaction of the slag which is between 0.18 and 0.67 while the degree of reaction of the cement is between 0.58 and 0.76 (see section 4.1). Therefore, it is observed that the presence of slag increases the magnitude of the basic creep at very early age and decreases its amplitude after the peak of hydration of slag. Several authors (Brooks & Neville, 1992; Chern & Chan, 1989; E. Tazawa and S. Tanaka., 1989; Li & Yao, 2001) have already shown that the presence of slag reduces the amplitude of the basic creep on hardened concrete and it is especially marked at later ages (Özbay et al., 2016). In term of kinetic, a difference is also observed for the compositions C-REF and C-BFS. The short term creep evolves faster for the C-BFS composition whereas the long term creep evolves faster for the C-REF composition. Such observation was already done by Brooks, et al. (Brooks et al., 1992) on hardened concrete for which Portland cement was replaced at 30 to 70% by slag. The substitution of 25% of slag by limestone filler increases the magnitude of the specific creep. A factor between 2 and 3 is obtained between the compositions C-BFS and C-SCM whatever the total advancement degree of reaction at loading. The degree of reaction of the Portland cement and the slag is also very similar for both compositions (Table 2). The amplitude of the specific creep of the C-SCM composition is more than 4 times higher at very early age than the one of the composition C-REF. This factor decreases when the advancement degree of reaction increases. As for the C-BFS composition, this is mainly driven by the slag reaction degree which varies more than the one of the Portland cement. In term of kinetic, a difference is also observed for the compositions C-SCM and C-BFS. The long term creep evolves faster for the C-SCM composition. These last observations related to the difference of kinetics between the three compositions are highlighted on the appendix.

4.3. Discussions

No specific consensus exists about the physical mechanisms governing the basic creep. Several theories were developed to clarify mechanisms related to basic creep according to the many studies reported in the past (Atrushi, 2003; Briffaut et al., 2012; Geert De Schutter, 2004; Forth, 2014; Gutsch, 2002; Laplante, 1993; Le Roy, 1995; Tamtsia et al., 2004). As explained in (Delsaute et al., 2017), globally each theory can be linked to two mechanisms: direct mechanisms linked to the cement

paste and responsible of the highest part of the creep amplitude and indirect mechanisms linked to the heterogeneity of the concrete. Direct mechanisms are related to the water mobility and to the solidification of the material and can be separated in short and long terms phenomena (Acker & Ulm, 2001; Bernard et al., 2003; Ulm et al., 1999). The short term phenomenon is linked to a stress-induced water movement towards the largest diameter pores and to the solidification (Bažant et al., 1997; Bažant & Prasannan, 1989) of the material. The long term phenomenon is related to viscous flow in the hydrates.

In case of replacement of cement by slag, several changes occur in the binder matrix. When submitting to drying, the incorporation of slag leads to higher water mass loss at early age. Ishida, *et al.* (Ishida et al., 2011) have observed that it is more marked at very early age and for high replacement of Portland cement by slag. This is an indicator of the higher water mobility inside the binder matrix composed with slag at early age. In addition, the evolution of the E-modulus is lower for concrete composition with slag. Therefore, the solidification of the material under load is lower for slag composition. The higher water mobility and lower rate of the E-modulus at early age are related to the lower slag reaction degree in comparison to the one of the Portland cement and it can explain the higher short term creep of concrete composition with slag.

When substituting slag by limestone filler, at early age, the water mobility is increased by the higher water content and the rate of the evolution of the E-modulus is decreased (Carette & Staquet, 2016b). The higher water mobility and lower rate of the evolution of the E-modulus at early age can explain the higher short term creep of concrete composition when substituting slag by limestone filler. The long term creep is related to the slippage between cement gels. Slippage can occur between the adjacent C-S-H layers. The presence of slag can strengthen the Van der Waals force between particles of cement gels in the concrete (Xinjie et al., 2015). In addition, the presence of slag decreases the porosity, increases the formation of C-S-H and densifies the binder matrix at later ages (Mindess et al., 2003). Thus, slag reduces the slippage between cement gels and the subsequent long term basic creep deformation. Moreover, the presence of slag can improve the mechanical performances of the interfacial transition zone (ITZ) between the aggregate and the cement paste (Carles-Gibergues, 1981;

Gao et al., 2005). A reduction of the number and length of the micro-cracks in the ITZ and the subsequent basic creep deformation is therefore expected (Xinjie et al., 2015). When replacing slag by limestone filler, long term creep increases. This can be attributed to the decrease of the reactive material (slag, clinker) content and the rising of the effective water-to-equivalent binder ratio.

It should be also noticed that some unexpected results are obtained with the composition C-SCM. For results obtained at a total advancement degree of reaction of 0.38 and 0.45, an increase in the amplitude and the kinetic of the specific creep is observed when the total advancement degree of reaction increases.

To understand the differences of amplitude between each composition occurring during the first hours after loading, mainly two parameters can be considered: the slag reaction degree at the microscopic scale and the stiffness of the concrete at the macroscopic scale. As shown in Table 2, the degree of reaction of the slag and the E-modulus vary significantly for the compositions C-BFS and C-SCM at the different ages at loading. In Figure 8, the amplitude of the specific creep function, obtained after duration of loading of 160 hours, is plotted according to the value of the E-modulus at the loading age for each composition and each age at loading. It is generally observed that the magnitude of the creep is strongly correlated to the value of the E-modulus at the age of loading. In addition, the relation between the amplitude of the specific creep and the E-modulus follows an exponential law which appears to be not directly linked to the nature of the binder.

5. MODELLING

5.1. Modelling at very early age and early age

In the present Model Code 2010 (MC2010), basic creep is expressed with a logarithmic expression and corresponds to the multiplication of an amplitude term $\varphi_{0,bc}$ linked to the mean compressive strength at an age of 28 days f_{cm} (thus independent of the age at loading) and a kinetic term β_{bc} which is function of the age at loading t' , the age after loading $(t - t')$ and the type of cement α_c .

$$\varphi(t, t') = \varphi_{0,bc}(f_{cm}) \cdot \beta_{bc}(t, t') = \frac{1.8}{(f_{cm})^{0.7}} \cdot \ln \left(\left(\frac{30}{t_{0,adj}} + 0.035 \right)^2 (t - t') + 1 \right) \quad 6$$

$$t_{0,adj} = t' \cdot \left(1 + \frac{9}{2 + t'^{1.2}} \right)^{\alpha_{cem}} \quad 7$$

where α_{cem} depends on the type of cement and is equal to 1 for CEM 52.5 N. In Figure 9, results from MC2010 are compared to the experimental results obtained on the reference composition C-REF. For each age at loading, the predicted values of MC2010 are relatively close to the experimental results. Similar observations have already been done for an ordinary concrete with similar E-modulus values at the age of loading (Delsaute et al., 2017).

It is possible to improve the modelling of the specific creep function for very early age loading by adapting the effect of the age at loading in the model. The MC2010 model is then simplified (Le Roy et al., 2017; J.-M. Torrenti & Le Roy, 2017) as shown in Equation 8, where the parameter C is related to the global amplitude of the creep, independent of the age at loading, and is expressed in MPa. The parameter τ is function of the age at loading and the composition, and is expressed in [d].

$$J^*(t, t') = \frac{1}{C} \cdot \ln \left(1 + \frac{t-t'}{\tau} \right) \quad 8$$

Results of the modelling with the adapted MC2010 are presented in Figure 10 for the composition C-REF. A very good agreement is obtained between the experimental results and the predicted values whatever the age at loading. To quantify the efficiency of the Model Code 2010 and the adapted version, the error term ξ has been computed and is defined by considering the experimental and modeling values of the specific creep for each loading at the same time after loading according to Equation 9. N_c and N_p are respectively the number of loadings and the number of measuring points for each loading. The error ξ is 2.4E-6 MPa-1 for the MC2010 and 6.0E-7 MPa-1 for the adapted MC2010. The error is then divided by a factor 4 with the adapted version.

$$\xi = \sqrt{\frac{1}{N_L \cdot N_P} \sum_{i=1}^{N_L} \sum_{j=1}^{N_P} \left(J_{\text{exp}}^*(t_i + t_j, t_i) - J_{\text{mod}}^*(t_i + t_j, t_i) \right)^2} \quad 9$$

For the C-BFS and C-SCM compositions, the best fitted values with the adapted MC2010 are presented in Figure 11 (dashed lines). Such logarithmic expression is not able to fit, at the same time, the basic creep during the first days after loading and the one corresponding to long duration of loading for very early age loadings. Therefore, only creep results obtained after one or two days of loading were considered for concrete loaded at very early age (age at loading less than or equal to a total advancement degree of reaction of 0.45) for the determination of the parameters τ and C . When considering only this part of the data for early age loadings, it can be seen that a good agreement is obtained between experimental results and the modelling particularly for loadings applied at later ages and after 1 or 2 days of loading for very early age loadings as shown in Figure 11 (dashed lines). Such way to model the basic creep leads, at very early age, to an overestimation of the basic creep during the first days after loading. The values of the parameter τ and the inverse of the derivative of the E-modulus for the different age of loading are given in Table 3. The value of the parameter τ is plotted according to the inverse of the derivative of the E-modulus in Figure 12 for each composition. Predictive values obtained with MC2010 are also presented. For the composition C-REF, a very good agreement is obtained between the optimized values fit on the experimental results and the predicted values given by MC2010. For the composition C-BFS and C-SCM, the results obtained for an advancement degree of reaction of 0.6 and 0.7 are relatively close to the results obtained for the reference composition especially for the composition C-SCM. The values of τ obtained for the C-BFS are slightly lower. On the other hand, the values of τ obtained for an advancement degree of reaction of 0.38 and 0.45 are strongly lower than the values obtained for the C-REF composition. In comparison, results of an ordinary concrete (Delsaute et al., 2017) are given also in Figure 12. The period, during which there is a divergence between the values of τ predicted by MC2010 and the optimized values fit with the experimental results, is the same for the compositions C-BFS and C-SCM and the ordinary concrete. This period stops when the inverse of the derivative of the E-modulus

is higher than $0.14 \text{ GPa}^{-1} \cdot \text{d}$ or also when the E-modulus is higher than 35 GPa . As for the ordinary concrete, the relation between the parameter τ and the inverse of the derivative of the E-modulus follows a power law. The expression is given in Equation 10 where $q=2.95\text{E}+14$, $p=-19.4$, $t_E=1\text{d} \cdot \text{GPa}^{-1}$ and $n=0.0546$.

$$\begin{cases} \tau = q \cdot \left(\frac{dE}{dt} \cdot t_E \right)^p & \text{if } \frac{dE}{dt} > 7.1 \text{ GPa} \cdot \text{d}^{-1} \\ \tau = n \cdot \left(\frac{dE}{dt} \cdot t_E \right)^{-1} & \text{if } \frac{dE}{dt} \leq 7.1 \text{ GPa} \cdot \text{d}^{-1} \end{cases} \quad 10$$

The amplitude parameter C of the adapted MC2010 is given in Table 4 for each composition. For the reference composition, the value of C obtained from experimental results is also compared in Table 3 to the value predicted by the Model Code 2010. Higher value of C is obtained with MC2010. The values obtained from C-BFS and C-SCM are strongly different from the reference concrete. The substitution of 75% of cement by slag increases the parameter C by a factor around 1.8, whereas the replacement of cement by slag (50%) and by limestone filler (25%) decreases the parameter C by a factor around 1.8.

Results of the modelling with the adapted MC2010 and the values of τ and C coming from Equation 9 and Table 4 respectively are presented in Figure 13 and Figure 14 (dashed lines) for the compositions C-BFS and C-SCM respectively. A general agreement is obtained between the experimental results and the simulated ones. However, the development of the short term creep for early age loading is strongly overestimated during the first day after loading. This highlights that the current equations used to represent the basic creep cannot reproduce the behavior of early age concrete with high substitution of cement by slag and/or limestone filler.

As state in the Model Code 2010 (“Model Code 2010 - Final Draft, Volume 1,” 2012) “Creep of concrete depends on the degree of hydration reached at a given age rather than on the age of concrete”. For the modelling of early age creep, it is therefore recommended to integrate the degree of reaction in the model. Previous studies (G. De Schutter et al., 2015; Jiang et al., 2014) have shown that the degree of hydration can be used as an aging parameter to model the basic creep of concrete composed of blended binders for which slag and fly ash correspond each to 20% of the cement mass.

However, as early age basic creep relates to both hydrations of the Portland cement and slag, the impact of both materials on the specific creep function is divided into two distinct terms as expressed in Equation 11. The term related to the Portland cement corresponds to the multiplication of the Equation 8 (reference concrete) and the ratio between the final heat release by the Portland cement and the final heat release by the paste. The term related to the slag paste corresponds to the multiplication of the ratio between the final heat release by the slag and the final heat release by the paste and a logarithmic expression for which an amplitude factor A and a kinetic factor K depend on the slag degree of reaction at the age of loading as expressed in Equation 11:

$$J^*(t, t') = \frac{q_{P,\infty}}{q_\infty} \cdot \frac{1}{C} \cdot \ln \left(1 + \frac{t - t'}{\tau(t')} \right) + \frac{q_\infty - q_{\infty,P}}{q_\infty} \cdot A(\alpha_S(t')) \cdot \ln \left(1 + (e - 1) \cdot \left(\frac{\alpha_S(t) - \alpha_S(t')}{1 - \alpha_S(t')} \right)^{K(\alpha_S(t'))} \right) \quad 11$$

For the BFS composition, the following mathematical relations are obtained for the parameter A and K:

$$A(\alpha_S) = 0.000248 \cdot \exp(-4.556 \cdot \alpha_S) \quad 12$$

$$K(\alpha_S) = \frac{1}{2.550 + 0.0102 \cdot \exp(7.556 \cdot \alpha_S)} \quad 13$$

For the composition SCM, the following mathematical relations are obtained:

$$A(\alpha_S) = 0.000389 \cdot \exp(-3.836 \cdot \alpha_S) \quad 14$$

$$K(\alpha_S) = 2.727 \cdot \alpha_S^2 - 1.817 \cdot \alpha_S + 0.538 \quad 15$$

Results of the modelling with Equation 11 and the values of A and K coming from Equations 11 to 14 are presented in Figure 13 and Figure 14 (dotted lines) for the compositions C-BFS and C-SCM

respectively. A general very good agreement is observed between the experimental results and the mathematical expressions developed for each age at loading.

These correlations between the slag degree of reaction and the amplitude and kinetic parameters are function of the type of slag, the slag content, the water-to-binder ratio and the stress level. In addition, the validity of the model proposed must be verified for longer duration of loading.

5.2. Modelling on hardened concretes

As mentioned in section 4.2., Brooks, *et al.* (Brooks et al., 1992) have performed several creep tests in sealed conditions on hardened concretes (14 days at loading) for which Portland cement has been replaced at 30 to 70% by slag coming from 4 countries. In total 10 slag-cement concretes were tested including a reference composition containing only Portland cement. Each composition had a water-binder ratio of 0.43 and a total aggregate-binder ratio of 4.11. The chemical composition of each type of slag was similar. Complete details about the chemical composition of the cement and the slag are given in (Brooks et al., 1992). Concrete are referred by CXSYZ where X is the cement content in the binder expressed in percent, Y is the slag content in the binder expressed in percent and Z is the country origin of the slag (B for Belgium, UK for United Kingdom, SA for South Africa and J for Japan). For each composition, the adapted MC2010 is used to model the specific creep. In Figure 15, the experimental results and the modeling by the adapted MC2010 of the specific creep are presented. It is observed that the adapted MC2010 is able to reproduce the specific creep function with a very good accuracy on hardened concrete with each kind of slag and slag content (up to 70%). Such good reproduction of the experimental results is related to the logarithmic evolution of the basic creep strain for long duration of loading. Therefore, it is highlighted that the long term creep of concrete composed of low, medium and high slag content follows a logarithmic trend.

From compressive strength data, the evolution of the E-modulus was defined according to Equation 16 developed by Brooks, et al. (Brooks et al., 1992) for slag concrete presented in this section. In order to define accurately the time derivative of the E-modulus, data of the E-modulus obtained with Equation 16 was fitted with the Equation 17.

$$E(t) = 1.22 \cdot f_c^{0.81} \quad 16$$

$$E(t) = E_{\infty} \cdot \exp\left(-\left(\frac{p}{t}\right)^r\right) \quad 17$$

Where E_{∞} is the predicted value of the E-modulus for an infinite time, p and r are material constant parameters. The values of the parameters p and r are presented in the Table 5. The value of the parameter τ is plotted according to the inverse of the time derivative of the E-modulus in Figure 16 for each composition. For each type of slag, it is observed that an increase of the slag content leads to a decrease of the value of the temporal parameter τ . The same effect of the slag was also observed with the C-BFS composition in comparison to the C-REF composition for composition with an advancement degree of reaction higher or equal to 0.6.

The amplitude parameter C of the adapted MC2010 is presented in Figure 17 for each type of slag in function of the slag content. For the reference composition without slag, the value of C obtained from experimental results is 179 GPa. The substitution of 30% of Portland cement by slag increases the factor C by a factor equal to around 1.5 for Belgium (300 GPa) and United Kingdom slag (334 GPa). When substituting 50% of Portland cement by slag, an increase of the parameter C is observed for each type of slag. However, high difference is observed between the values of the parameter C according to the type of slag. For higher rate of substitution of Portland cement by slag, the trend is not the same for each type of slag. For the slag coming from United Kingdom, a rate of substitution of Portland cement by slag higher than 50% decreases the amplitude parameter C. While for other compositions, higher substitution rate of Portland cement by slag leads always to an increase of the parameter C till a substitution level of 70%.

6. LIMITATIONS OF THE STUDY

The present work has been carried out at a constant curing temperature of 20°C and the load applied corresponds to a stress level of 40% for each age at loading. In the frame of early age cracking or

early age prestress, several phenomena were not considered in the model and are expected to affect the early age stress development. The following physical mechanisms are not taken into account:

- The variation in temperature during the hardening process impacts the development of the microstructure and the internal relative humidity (Jensen & Hansen, 1999). Such thermal change influences the development of the autogenous strain (Jérôme Carette & Staquet, 2018) and impacts also the basic creep properties (Bažant et al., 2004; Hauggaard et al., 1999), it is even more true for concrete composed of blended cement (Ladaoui et al., 2011). Tests at different curing temperatures and with realistic temperature histories are needed to define how the constitutive parameters are influenced by the temperature when using limestone filler and/or slag in high substitution rate of cement.
- In case of restrained deformation, the stress level is not constant and the non-linear behavior of concrete should be considered for low stress level (Delsaute, 2016; Delsaute, Boulay, Granja, et al., 2016; Forth, 2014) and high stress level (Rossi et al., 2012; Switek et al., 2016; J. M. Torrenti, 2017). Moreover, the concrete behavior is different in tension and in compression (Atrushi, 2003; Bissonnette et al., 2007; Rossi et al., 2013) and the creep recovery should be considered. Tests at different stress levels and with different stress histories are needed to define how the constitutive parameters are influenced by the stress level and by the change in stress (tension or compression) when using limestone filler and/or slag. A Temperature Stress Testing Machine (Delsaute & Staquet, 2020) could be used for such study.
- The properties (fineness, nature) of the slag and the limestone filler impact the early age development of the microstructure (Adu-Amankwah et al., 2019; Bourchy et al., 2020; Kadri et al., 2010; Nakamura et al., 1992) and thus the aging of the basic creep properties. Also this study was performed for a specific substitution rate of CEM I by limestone and or slag. This study should be extended to other substitution ratio.

Therefore further studies are still needed to correctly model the early age basic creep properties of concrete composed of a significant amount of limestone filler and/or slag. The difference of behavior

under tension and compression and the temperature history are both major influencing parameters that require more in-depth knowledge to predict the basic creep in case of restrained shrinkage at early age.

7. CONCLUSIONS

The present work analyses the basic creep of concrete compositions for which 75% of Portland cement is substituted by limestone filler and/or blast furnace slag at very early age. Three compositions have been tested. The first composition is a reference composition for which the binder is only composed of Portland cement CEM I 52.5. For the two other compositions, the aggregate and water content is the same, only the nature of the binder changes. For the second and third composition, 75% of the Portland cement is replaced by blast furnace slag or by blast furnace slag (50%) and limestone filler (25%). Compressive creep tests were performed during and after the peak of hydration of the slag in order to track the effect of the slag on the development of the creep properties. Four loadings were applied for each composition. The ages at loading correspond to an advancement degree of reaction of 0.38, 0.45, 0.6 and 0.7 for each composition. For concrete compositions with slag, it is observed that the basic creep is mainly driven by the the slag reaction degree. For low slag reaction degree ($<29\%$), the magnitude of the basic creep is twice the one of the reference composition for a similar total advancement degree of reaction. On the other hand, when the slag reaction degree is higher ($> 49\%$), the magnitude of the basic creep becomes lower. Thus the magnitude of the basic creep is strongly influenced by the degree of reaction of the slag. The partial substitution of slag by 25% of limestone filler increases the magnitude of the basic creep whatever the slag reaction degree or the total advancement degree of reaction.

An adapted version of the Model Code 2010 (MC2010) is used to model basic creep. It is possible to model accurately the specific creep especially for hardened concrete due to the logarithmic trend of the specific creep function for concrete composed of slag and Portland cement. It is observed that the replacement of Portland cement by slag leads generally to an increase of the amplitude parameter C and a decrease of the temporal parameter τ of the adapted MC2010. For very early age, creep is

overestimated during few days after loading for compositions with slag and limestone filler when using the adapted version of MC2010. This drawback can be corrected by adding a logarithmic law to the adapted version of MC2010 which considers the slag degree of reaction at the age of loading and during the loading. Therefore, the specific creep function is divided in two terms which are related to the (i) Portland cement and (ii) slag hydration.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

APPENDIX

The influence of aging on the specific creep function is observed in the change of amplitude and kinetics for the different age at loading (Figure 7). The decrease of the amplitude is inversely proportional to the age at loading and the elastic modulus (Figure 8). When each specific creep curve is normalized by the specific creep value obtained at an age after loading of 1 hour (Figure A.1), it is observed that:

- For short duration of loading ($<1\text{h}$), the kinetic is similar for each age at loading for a same composition and thus no aging effect is observed for a short duration loading on the kinetic of the specific creep. This was already observed on an ordinary concrete (Delsaute, Boulay, & Staquet, 2016) and is confirmed here for concrete composed of limestone filler and/or slag.
- For long duration loading ($>100\text{h}$), a faster development of the normalized specific creep curves is obtained for loading applied at later ages for each compositions. In figure A.2, the normalized specific creep curves of the three compositions are compared for a loading applied at a total advancement degree of reaction of 0.7. The rate of the normalized specific creep is lower for the C-BFS composition in comparison to the C-REF. This shows that the replacement of Portland cement by slag reduces the long term creep. When slag is partially replaced by limestone filler (25%), an increase of the long term creep is obtained.

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TABLES

Table 1 - Mixture proportions in kg/m³ and materials properties of the concrete composition (Jérôme Carette & Staquet, 2016b).

	C-REF	C-BFS	C-SCM
Sand 0/4	853		
Gravel 6/10	210		
Gravel 10/14	873		
CEMI 52.5 N CE CP2 NF	432	103	103
Blast furnace slag	-	291	164
Limestone filler	-	-	124
Gypsum	-	22	22
Added water	173	167	165
W_{abs}/B [/]	0.40		
W_{eff}/B [/]	0.34		
W_{eff}/B_{eq} [/]	0.34	0.34	0.45
Initial setting time t_i [h]	3.5	6.1	4.6
Final setting time t_f [h]	4.1	8.5	6.7

Table 2 – Experimental program for long duration creep tests. The age at loading is defined according to the advancement degree of reaction (α).

C-REF				C-BFS					C-SCM				
α	t_{eq}	f_c	E	t_{eq}	α_c	α_s	f_c	E	t_{eq}	α_c	α_s	f_c	E
[/]	[h]	[MPa]	[GPa]	[h]	[/]	[/]	[MPa]	[GPa]	[h]	[/]	[/]	[MPa]	[GPa]
0.38	19	19.0	38.1	41	0.58	0.18	5.8	29.5	39	0.57	0.15	4.3	18.4
0.45	24	23.6	40.2	49	0.62	0.29	7.8	36.9	48	0.62	0.22	6.1	22.5
0.6	40	27.5	43.1	66	0.68	0.49	11.4	39.9	70	0.69	0.42	9.7	33.8
0.7	71	32.0	44.6	120	0.76	0.67	20.8	42.2	118	0.75	0.66	16.8	38.9

Table 3 – Value of parameter τ from Equation 7.

C-REF				
t' [h]	19	24	40	71
Inverse of dE/dt [d.GPa-1]	7.69E-02	1.31E-01	4.41E-01	1.73E+00
τ [d]	4.04E-03	6.84E-03	5.22E-02	8.76E-02
C-BFS				
t' [h]	41	49	66	120
Inverse of dE/dt [d.GPa-1]	4.23E-02	5.33E-02	1.05E+00	8.27E-01
τ [d]	2.71E-14	1.85E-09	7.19E-04	2.03E-02
C-SCM				
t' [h]	39	48	70	118
Inverse of dE/dt [d.GPa-1]	8.81E-02	6.49E-02	1.71E-01	7.25E-01
τ [d]	9.80E-08	2.47E-08	3.20E-03	2.13E-01

Table 4 – Values of the parameter C predicted by MC2010 and obtained by optimization of each composition (in GPa).

	C-REF	C-BFS	C-SCM
Optimized value	255	455	140
Value predicted by MC2010 according to f_{cm}	315	-	-

Table 5 - Values of the parameter of Equation 17

	OPC	slag UK slag content [%]			slag Belgium slag content [%]			slag South Afrika slag content [%]		slag Japan slag content [%]	
		30	50	70	30	50	70	50	70	50	70
E_{∞}	34.3	42.7	43.1	53.8	42.1	46.8	38.9	51.1	44.6	51.1	60.4
p	1.65	2.03	4.11	4.67	1.42	3.01	2.97	4.91	7.24	3.75	7.85
r	1.14	0.64	0.91	0.44	0.55	0.55	0.65	0.55	0.72	0.52	0.33

FIGURES

- Figure 1 – Left to right: shrinkage test setup, creep test setup and dimension of the flat jack according to the loading applied [2].
- Figure 2 - Heat flow evolution from isothermal calorimetry tests. The circular markers are related to the time when compressive creep tests have started.
- Figure 3 – Advancement degree of reaction ADR in function of the equivalent age. The circular markers are related to the time when compressive creep tests have started.
- Figure 4 – Separation of the Portland cement and the slag reaction based on the heat release for the C-BFS composition.
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- Figure 6 – Evolution of the autogenous strain of the dummy specimen (the continuous lines correspond to the strain of the dummy specimen and the dashed lines are related to the autogenous strain obtained in [13])
- Figure 7 – Specific creep functions for several ages at loading.
- Figure 8 – Amplitude of the creep compliance after 160 hours of loading according to the E-modulus at the age of loading.
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- Figure 13 – Comparison between predicted value of the creep compliance obtained with the adapted MC2010 where the values of τ and C come from Equation 9 and Table 4 respectively (dashed lines), the two terms model (dotted lines) and experimental results (continuous lines) for the composition C-BFS.
- Figure 14 – Comparison between predicted value of the creep compliance obtained with the adapted MC2010 where the values of τ and C come from Equation 9 and Table 4 respectively (dashed lines), the two terms model (dotted lines) and experimental results (continuous lines) for the composition C-SCM.
- Figure 15 – Specific creep function and adapted MC2010 (dashed lines) of concrete compositions with different slag content and origin [26].
- Figure 16 – Relation between the parameter τ of the adapted MC2010 and the inverse of the time derivative of the E-modulus for concretes with different slag type and slag content. Results are compared to very early age and early age results presented in section 5.1. Results coming from Brooks, et al. [26] used the same legend marks as in Figure 15.
- Figure 17 - Relation between the parameter C of the adapted MC2010 and the slag content for concrete with different type of slag.
- Figure A.1 – Specific creep curves normalized at an age after loading of 1 hour
- Figure A.2 – Specific creep curves normalized at an age after loading of 1 hour for an advancement degree of reaction at loading of 0.7

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