Behaviour of slag cement concrete under restraint conditions

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ABSTRACT. *Some constructions built with slag cement concrete exhibit cracking at early age due to restrained shrinkage. To determine the slag effect on cracking, this study focuses on the autogenous deformation evolution of concretes characterized by different percentages of slag (0 and 42% of the binder mass) under free and restraint conditions by means of the TSTM device (Temperature Stress Testing Machine). Despite the fast kinetics of its autogenous deformation, the cracking appears later for the slag cement concrete than for the Portland cement concrete. This behaviour is related to the swelling of its cementitious matrix at early age and its large capacity for relaxing the stresses.*

RÉSUMÉ. *Certains ouvrages réalisés à l'aide de bétons formulés avec du ciment au laitier de haut-fourneau ont présenté de la fissuration au jeune âge suite à la restriction de leurs déformations différées. Pour comprendre l'effet du laitier sur le risque de fissuration de ces bétons, cette étude s'est concentrée sur l'évolution de la déformation endogène de bétons contenant différentes teneurs en laitier (0 et 42 % de la masse du liant) en conditions libre et restreinte à l'aide du dispositif TSTM (Temperature Stress Testing Machine). Malgré une cinétique plus rapide de leur déformation endogène, le béton formulé avec du ciment au laitier de haut-fourneau se caractérise par une fissuration plus tardive que le béton formulé avec du ciment Portland. Ce comportement est dû à la présence d'une expansion de leur matrice cimentaire au jeune âge et à leur plus grande capacité à relaxer les contraintes.*

KEYWORDS: *blended cement, cracking, creep, relaxation, TSTM.*

MOTS-CLÉS : *ciment composé, fissuration, fluage, relaxation, TSTM.*

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1. Introduction

Slag cement concrete is widely used in Belgium. However, some structures built with slag cement concretes have exhibited early age cracking due to restrained shrinkage resulting from autogenous, thermal and drying components (Darquennes *et al.*, 2006). This phenomenon may jeopardize the durability and the functionality of the structure. In order to limit the cracking risk of concrete structures, it is necessary to study in depth the behaviour of slag cement concretes under restraint conditions. Indeed, the study of free shrinkage is not enough to quantify this risk because it does not take into account all the factors affecting the stress development inside the material such as the restriction degree of material, the relaxation of its stresses, the evolution of its tensile strength and its rigidity… Several tests have been developed to estimate the cracking risk of the cementitious material, such as the ring tests, the plate tests and the passive longitudinal tests (Bentur *et al.*, 2003). Generally, these experimental tests allow determining the number of cracks, their width and the evolution of the stresses inside the concrete sample. However, this evolution strongly depends on the geometry and the rigidity of the material used to obtain the restraint conditions. To eliminate these drawbacks, an active longitudinal test named Temperature Stress Testing Machine (TSTM) was developed at the beginning of the 1980's (Springenschmid *et al.*, 1994). With this device, a total degree of restriction of the concrete sample can be obtained by means of applying a compressive/tensile stress on a dog-bone shaped concrete specimen to keep its length constant with a manual or an automatic system.

To determine the slag effect on the cracking risk of concrete, a TSTM device was developed in the laboratory of the Civil Engineering department at the Université Libre de Bruxelles (ULB). With this device, autogenous deformation of concrete mixtures characterized by different percentages of slag (0 and 42% of the binder mass) was measured under free and restraint conditions. Their relaxation capacity was also determined by means of tensile and compressive creep tests.

2. Materials

Two kinds of cements, namely CEM I 52.5 N and CEM III/A 42.5 LA, were used. They differ by their slag content (0% and 42% respectively), but the clinker of these cements has the same origin. The specific area of these cements and their density are quite similar (Table 1). Concretes associated with these two cements are indicated in the following as CEM I and CEM III/A respectively. In the studied concrete mixtures, the water-binder ratio (w/b) and the binder (clinker + slag) content are kept constant and equal to 0.45 and 375 kg/m³ respectively. Their superplasticizer content differs to obtain a similar slump value (80 mm). The larger admixture content for CEM I delayed its setting times which values were close to that of CEM III/A. The concrete mixture proportions are given in Table 2.

Table 1. *Cements characteristics*

Cements	CEM I 52.5 N	CEM III/A 42.5 LA
Clinker content (%)	95	58
Slag content (%)	/	42
Specific area (m^2/kg)	445	447
Density (kg/m^3)	3.09	3.01

Table 2. *Concrete mixture proportions*

Composition (kg/m^3)	CEM I	CEM III/A
Cement	375	
Water	164.6	166.95
Total water	169	
Superplasticizer	5.63	2.63
Sand 0/0.5	492	
Sand 0.5/1	126	
Sand 1/3	104	
Limestone 2/6	311	
Limestone 6/10	438	
Limestone 10/14	415	

3. Experimental methods

3.1. *The TSTM device*

For monitoring autogenous shrinkage under free and restraint conditions, a Temperature Stress Testing Machine (TSTM) was developed. Basically, it consists of a Walter+Bai LFMZ 400 kN electromechanical testing setup, where one end of the specimen is restrained by a steel head and the displacement of the other end is controlled by a motor moving the steel head (Figure 1). In this study, the dog-bone sample was characterized by a cross-section equal to 100 x 100 mm^2 in its center and 100 x 150 mm^2 at its extremities. The sample extremities were characterized by a rounded shape in the transition area, which limits the concentration of stresses and an early cracking in this area. The straight part (center of the specimen) was 1 m long. To minimize friction between the mould walls and the sample, the inner surface of the formwork was covered with a Teflon sheet and a thin plastic film was installed before casting the concrete. This feature also allowed preventing water evaporation. A thermal control system located around the formwork was designed to obtain isothermal conditions in the specimen. Thanks to this thermal regulation system, the thermal gradient related to the hydration process was limited to a value inferior to 1°C for a Portland cement concrete.

Displacements were measured by means of two transducers placed on the straight part of the sample and separated by a distance of 750 mm to limit the effects of boundary conditions. They were mounted on a rigid frame fixed to the TSTM frame. These sensors are characterized by a measuring range of 12 mm and accuracy of about 0.4 µm. They were in contact with an invar rod screwed on a threaded rod anchored in the sample directly after casting. These invar rods are characterized by a low dilation coefficient limiting the effect of ambient temperature on the displacement measurements. They were kept in their initial position thanks to a brass ring before the beginning of the test. This time was attained during the setting of concrete mixture at a moment characterized by a significant rigidity of the studied material. In parallel, the temperature evolution was also monitored using a thermocouple placed in the middle of the concrete specimen.

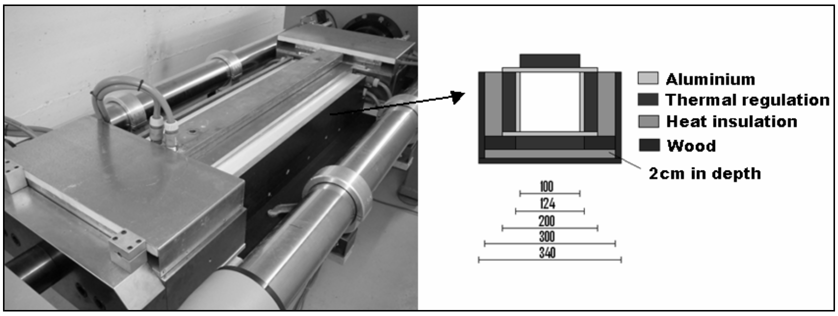

Figure 1. *The TSTM device with its thermal regulation system and a cross-section*

In the beginning of the restrained shrinkage measurement, the sample placed in the TSTM was initially restrained by the stiffness of the frame with the motor being turned off until the stress inside concrete reached a threshold value of 0.01 MPa (Figure 2). At that particular moment, the displacement transducer readings were zeroed and the concrete sample could deform freely until the recorded deformation in the central part of the specimen reached a deformation threshold equal to 6.7 µm/m marking the end of the first cycle. After that, the load was adjusted to pull the specimen back to its initial length. Then, the applied load at the end of the adjustment process was kept constant during the following cycles until the deformation in the sample reached again the deformation threshold value. This experimental procedure was applied many times until cracking of the specimen. It is similar to the one used by Charron *et al.* (2004). It allows avoiding early cracking. During this test, four parameters were continually monitored: the applied load, the deformation of the sample, its temperature and the displacement of the moving head.

The TSTM was also used to monitor the autogenous deformation under free condition, obtained by cancelling the load applied to the sample as soon as the built-up stress reached a value equal to 0.01 MPa.

These experiments realized under free and restraint conditions allowed determining the stress build-up in the specimen and the evolution of the free and restrained shrinkage in the concrete sample.

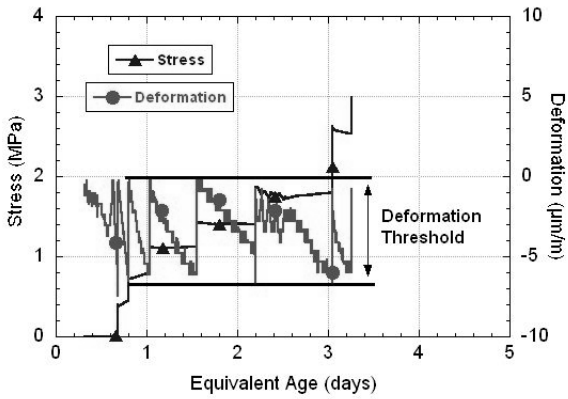

Figure 2. *Compensation deformation cycles and stress evolution for CEM I*

From these experimental results, an estimation of the material capacity to relax the stresses can be also derived using Equation [2]. This parameter allows decreasing the value of stresses developing inside concrete samples due to restrained shrinkage. So, an accurate determination of this parameter is important to obtain an actual estimation of the cracking sensitivity of the slag cement concrete. However, this first estimation of the relaxation capacity is based on several hypotheses: the restrained sample does not undergo damage, the development of its modulus is similar to that of the free sample and the theory of superposition of deformations and stresses is valid. Basic tensile creep tests were also realized on the dog-bone specimens with the TSTM to check the relaxation capacity determined from Equation [2]. A loading equal to 30% of the tensile strength at the loading age was applied at the first day after the concrete mixing and maintained during five days.

$$\sigma_{el}(t_i) = \sigma_{el}(t_{i-1}) + \frac{E(t_i) + E(t_{i-1})}{2} \left(\varepsilon(t_i) - \varepsilon(t_{i-1})\right) \qquad [1]$$

$$R = \frac{\sigma_{el}(t_i) - \sigma_{\exp}(t_i)}{\sigma_{el}(t_i)} \ 100 \qquad [2]$$

where $\sigma_{el}(t_i)$ is the theoretical stress at time t_i developing inside an elastic material, $E(t_i)$ is the tangent elastic modulus at time t_i calculated from deformations and stresses under restrained conditions, $\varepsilon(t_i)$ is the deformation under free conditions at time t_i and $\sigma_{exp}(t_i)$ is the experimental stress at time t_i .

3.2. *Compressive creep*

Basic compressive creep tests were also realized on cylindrical specimens (diameter Ø = 10 cm and height h = 35 cm). The loading was applied the first day after the concrete mixing by means of a flat jack placed under the specimen (Figure 3). The load was equal to 30% of the compressive strength at the loading age. Loading stability was checked during all the test period. In parallel, additional non-loaded companion specimens having the same dimensions were used to measure free shrinkage. Strain measurements for both the creep and shrinkage specimens were recorded by three LVDT's placed at 120° on Invar bars linked on a steel ring fixed on the concrete specimens (Figure 3). All specimens were stored in an air conditioned room at a temperature of 20°C and a relative humidity (R.H.) equal to 50%. They were isolated from ambient humidity by a layer of aluminium tape.

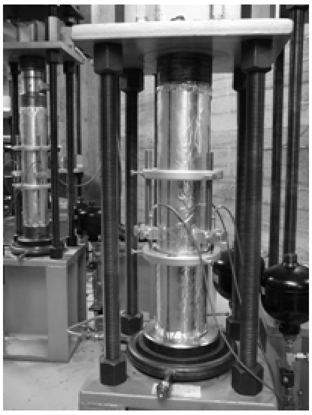

Figure 3. *Compressive creep devices with sealed cylindrical samples*

4. Results and discussion

4.1. *Free and restrained shrinkage*

The free autogenous deformation measurements on the dog-bone specimens (Figure 4) showed that the autogenous deformation of CEM III/A was characterized by a swelling of its cement matrix at early age. This phenomenon is probably related to the formation of hydration products (Darquennes *et al.*, 2009). Beyond this phase, the shrinkage rate was larger for CEM III/A than for CEM I. From 2 days, the value of shrinkage expressed from a time characterized by the development of a stress equal to 0.01 MPa inside the concrete specimen was larger for CEM III/A than for CEM I. A larger shrinkage value was also measured on the cylindrical specimens for CEM III/A. These modifications of behaviour related to the addition of slag would lead to an increase in the cracking risk of CEM III/A.

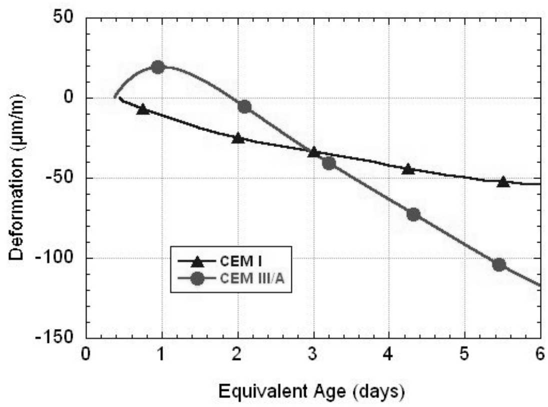

Figure 4. *Evolution of autogenous deformation at 20°C under free conditions*

Cracking depends also on other factors such as tensile strength, degree of restriction, relaxation of stresses, rigidity... These different parameters are taken into account with the restrained shrinkage test realized with the TSTM. The threshold value of 0.01 MPa was reached at 15.4 h and 25.7 h for CEM I and CEM III/A respectively. This delay of the appearance of the tensile stresses threshold for the slag cement concrete is due to its cement matrix expansion. From Figure 5, it is clear that CEM I was the first to crack at 3.3 days for a stress equal to about 3 MPa. Cracking occurred at 4.6 days for CEM III/A and for a similar value of tensile stress. The stress value at the cracking age was equal to about 70% of tensile strength measured by a splitting test. This percentage is close to the cracking threshold value suggested by Turcry *et al.* (2006), equal to 75% of the tensile strength.

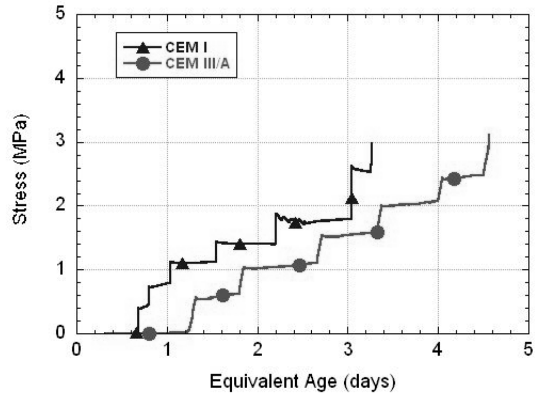

Figure 5. *Stress evolution at 20°C under restraint conditions*

From the evolution of the free and restrained shrinkage, an estimation of relaxation can be determined for the studied concrete mixtures (Equation [2]). It is found that the relaxation capacity was larger for CEM III/A than for CEM I (Figure 6). Finally, these experimental results showed that the studied slag cement concrete under isothermal (20°C) and restraint conditions was characterized by a lower cracking sensitivity at early age than the Portland cement concrete thanks to the expansion of its cement matrix and its large ability to relax stresses.

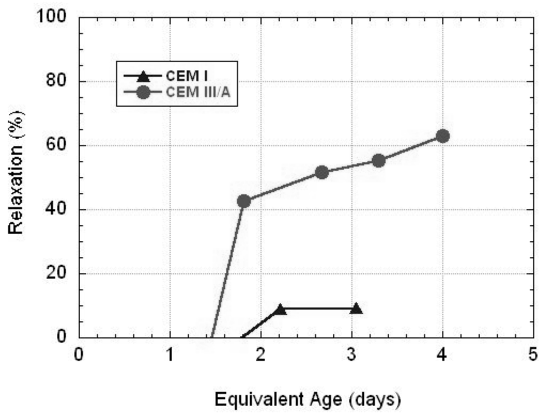

Figure 6. *Relaxation evolution at 20°C*

4.2. *Basic tensile and compressive creep*

Figure 7 presents the results of tensile and compressive creep tests for CEM I and CEM III/A. Creep is defined as the difference between the total deformation measured under loading and the autogenous and thermal deformations. In accordance with Rilem (TC107-CSP, 1998), these results are presented as specific creep (Equation [3]). It is obvious that the tensile specific creep of CEM III/A was larger than that of CEM I (Figure 7). However, specific creep did not grow continuously with age, in particularly for CEM III/A. The low difference between the shrinkage deformation and the total deformation (creep + shrinkage) can explain this behaviour (Figure 8). Notice that the sealed creep deformation showed in this figure was expressed without the elastic deformation. To validate these first observations, basic compressive creep tests were also realized. The experimental results (Figure 7) led to the same conclusion. This difference of behaviour for CEM I and CEM III/A is probably related to their microstructure. Indeed, the C-S-H content and the cement matrix porosity, two parameters affecting creep kinetics, are different for these concrete mixtures (Darquennes *et al.*, 2009).

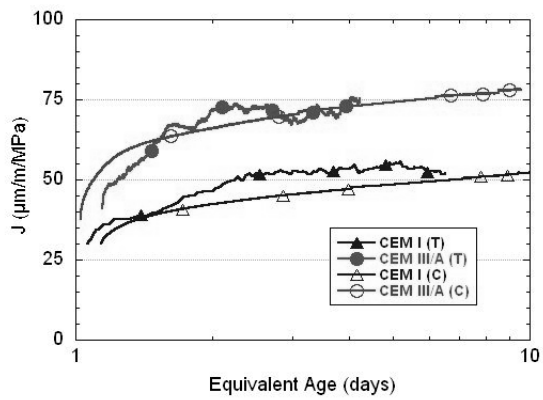

Figure 7. *Specific compressive (C) and tensile (T) creep for a loading applied the first day, equal to 30% of the tensile and compressive strength measured at the loading age*

$$J(t,t_0) = \frac{\varepsilon_{ci}(t_0) + \varepsilon_{cc}(t,t_0)}{\sigma_0(t_0)} \qquad [3]$$

Where J is the specific creep at time t for a loading at time t_0, σ_0 is the initial stress value applied at t_0, ε_{ci} is the instant deformation at t_0, ε_{cc} is the creep deformation at t for a loading at t_0.

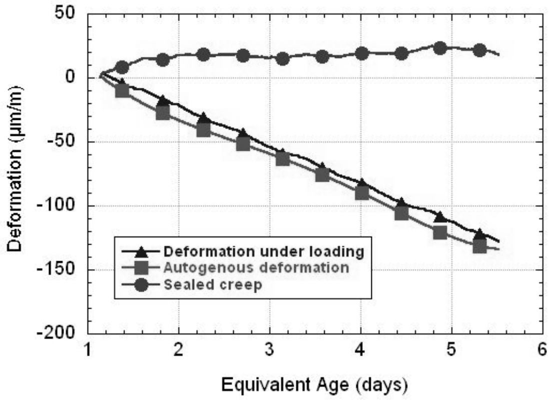

Figure 8. *Deformation components for CEM III/A – Elastic deformation equal to 23 $\mu m/m$*

Comparison of the basic tensile and compressive creep showed that their elastic moduli characterizing the instantaneous deformation were similar (Table 3). This observation is in accordance with some results found in the literature (Galloway *et al.*, 1976). Moreover, the evolution of compressive and tensile specific creep with respect to time was also similar. Differences were inferior to 10 µm/m/MPa. This difference is the one observed in tensile creep tests (Atrushi, 2003; Darquennes, 2009). Nevertheless, similarities between basic tensile and compressive creep are still an open question in the literature (Pane *et al.*, 2002; Reinhardt *et al.*, 2007). Therefore, additional tests (*e.g.* parametrical studies on the loading period, the loading age and the stress/strength ratio) are needed to confirm these preliminary observations.

Table 3. *Compressive and tensile loading - Compressive and tensile elastic modulus*

	Loading (MPa)		E (GPa)	
	Compressive	Tensile	Compressive	Tensile
CEM I	7.8	0.78	32.50	33.40
CEM III/A	4.2	0.57	26.50	25.00

5. Conclusions

Despite a faster kinetics and a larger amplitude of its free autogenous deformation, the studied slag cement concrete showed a lower cracking sensitivity under restraint conditions than the Portland cement concrete. This behavior is related to the expansion of its cement matrix at early age delaying the occurrence of autogenous shrinkage and to its larger capacity to relax internal stresses. This last observation was confirmed by basic tensile and compressive creep tests. From these experiments it appeared that the tensile specific creep at early age was more important for the slag cement concrete than for the Portland cement concrete.

The study on basic creep underlined some similarities for the cementitious material behaviour under compression and tensile loading: the same elastic modulus and a similar evolution of the specific creep as function of time. However, the previous conclusions are only valid for the specific experimental conditions and therefore further experimental campaigns will be conducted in the near future.

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