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Evaluation of the restrained shrinkage cracking potential of Self Compacting Concrete for modules for radioactive waste disposal

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ABSTRACT

For the disposal of radioactive low- and intermediate-level short-lived waste, surface disposal modules will be built in Belgium. In order to withstand accidental loading conditions, the walls of these constructions are densely reinforced, making an implementation in traditional vibrated concrete not self-evident. A Self Compacting Concrete can facilitate this execution. Questions however exist with regard to the cracking tendency of these concretes against restrained shrinkage, since this might impair the safety of the radioactive waste disposal. Therefore analyses of restraint shrinkage cracking potential of two SCC mixtures, especially developed for this application, was conducted within a research project presented in this paper.

Keywords: Self Compacting Concrete, restraint shrinkage, ring test, relaxation, cracking potential

1. INTRODUCTION

In 2006 the Belgian federal government approved the disposal of radioactive low- and intermediate-level short-lived waste (LILW-SL) in a surface disposal. For this purpose 34 disposal modules will be built. Their design loads include earthquakes and other major mechanical impacts. This results in modules with massive concrete walls, floors and roof slabs. The walls of these constructions are densely reinforced. Consequently an execution in traditional vibrated concrete (VC) is not that straightforward. The University of Ghent and the Belgian Building Research Institute (BBRI) were commissioned by the Belgian National Agency for Radioactive Waste and Enriched Fissile Materials (ONDRAF/NIRAS) to develop dedicated Self Compacting Concrete (SCC) mixtures. Due to the specific mix design of SCCs, characterized by the use of a higher paste volume and lower coarse aggregate content, SCCs might be prone to higher shrinkage and as a result potentially produce a higher restrained shrinkage cracking tendency. This might impair the service life of the structure and the safety of the radioactive waste disposal, by for instance allowing the ingress of aggressive media and water flows. Within this paper this cracking potential of the developed SCC mixtures was evaluated and compared to the VC reference. Since free shrinkage experiments alone do not allow for assessing this potential for cracking, given that other parameters such as creep, stiffness and toughness play an important role, in addition restrained shrinkage experiments were conducted. This paper presents a detailed analysis of the cracking (and relaxation) tendency of the developed SCC mixtures based on an experimental campaign using ring-tests in comparison with theoretical models.

1.1 Material compositions

The overall study was composed of two parts. Two SCC compositions were developed in the first part. In the second part the cracking tendency was evaluated. The SCC compositions had to meet several boundary conditions, of which the most important are: (1) use of non-reactive limestone aggregates, sand and fillers, (2) incorporation of a minimal portlandite content for durability reasons (this resulted in the minimal use of 350 kg/m³ cement of the type CEM I LA LH SR3), (3) an absolute W/C ratio of 0.47, (4) incorporation of organic products were not authorized with the exception, if need be, of naphthalene or polycarboxylate superplasticizers, and (5) a characteristic compressive strength of at least 50 MPa had to be reached. Taking into account the nature and specificities of the wall elements which need to be erected, the research partners defined the fresh concrete parameters to which the SCC mixtures need to satisfy: (1) slumpflow of around 750 mm, (2) V-funnel between 5 and 10 s, (3) L-box > 90%, sieve stability < 10%, (4) minimal decline in fresh properties within a time-frame of 2 hours.

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On the basis of these boundary conditions two distinct SCC mixtures were developed, one powder based (SCC I) and one VMA (Viscosity Modifying Admixture) based (SCC II). The SCC mixes are presented in Table 1. In addition, a reference (traditional) vibrated concrete (VC) was also evaluated. This VC is very similar to the concrete previously developed specially for this application and also satisfies the above mentioned boundary conditions with regard to composition. The mix composition of this VC is slightly different from the original one in order to adapt for small changes observed in the aggregates distribution of the raw materials.

Table 1. Mix compositions of the different tested SCC and VC mixes.

		SCC I	**SCC II**	**VC**
CEM I LA HSR	[kg/m³]	367	363	361
Limestone filler	[kg/m³]	220	170	62
Limestone 0/4	[kg/m³]	836	827	746
Limestone 2/6	[kg/m³]	284	310	401
Limestone 6/14	[kg/m³]	474	489	173
Limestone 6/20	[kg/m³]	-	-	473
Water	[kg/m³]	174	167	169
PCE superplasticizer	[kg/m³]	9	10	2.5
Nanosilica	[kg/m³]	-	13	-
W/C ratio	[-]	0.47	0.46	0.47
Slump	[mm]	-	-	190
Slumpflow	[mm]	730	730	-
V-funnel	[s]	8	9	-

1.2 Experiments

For all tested mixtures in the scope of this research some basic mechanical characteristics were determined, namely: compressive strength and E-modulus. For the determination of the compressive strength the recommendations of the European standard EN 12390-3 were followed. Cubic specimens, with sides of 150 mm, were utilized. For the determination of the secant E-modulus of concrete the Belgian standard NBN B15-203 was adopted. The specimens were prismatic, with dimensions of 100 x 100 x 400 mm³. To assess the development of the mechanical properties with ageing, the compressive strength and stiffness were tested at 1, 3, 7 and 28 days.

The total (free) shrinkage of the different mixtures was evaluated using prismatic specimens of 150 x 150 x 600 mm³. The specimens were removed from the molds after 24 hours, after which they were stored at 60 % RH (± 5 %) and 20 °C (± 2 °C). The change in longitudinal length was monitored by means of measuring points glued to the 4 sides of the specimens. A measuring basis of 200 mm was utilized within this study.

Several test methods have been developed to assess the cracking potential of concrete mixtures[1-6]. A number of researchers prefer prismatic specimen geometries, using either ‘passive-restraint’ or ‘active-restraint’[3-4], the major advantage of these test methods being the straightforward data interpretation. These experimental set-ups are however very complex and moreover, it is very difficult to provide adequate restraint to the specimens. Ring tests are often preferred due to their simplicity and versatility[5-6]. A concrete annulus is cast around a hollow steel cylinder. As self-desiccation and water-exchange with the environment occurs during ageing, the steel ring will prevent the concrete from shrinking, inducing tensile stresses in the concrete. The strain developed in the steel ring is measured by means of strain gauges placed at mid-height, on the inner circumference of the hollow steel cylinder. The ring test is often adopted for material evaluation and quality control testing thanks to its adequate restraint level (being around 70-80%), low cost, simple geometry and simple test-setup. A large variety of ring test geometries have been used in literature. The American Association of State Highway and Transportation Officials (AASHTO) developed a provisional standard test method (AASHTO PP34- 99: Standard Practice for Cracking Tendency Using a Ring specimen) for the assessment of the cracking potential of concrete using this ring test. The ring test geometry prescribed by AASHTO PP34-99 is summarized in Table 2. Even though this provisional standard test method is often applied in literature, several researchers reported that this method only provides a limited restraint; as a result a long delay may occur before visible cracking can be observed. The American Society for Testing and Materials (ASTM) developed an alternative test geometry which provides more restraint. The specifications of the ASTM C 1581-04 (Standard Test Method for Determining Age at Cracking and Induced Tensile Stress Characteristics of Mortar and Concrete Under Retrained Shrinkage) can also be found in Table 2. To obtain a higher restraint the thickness of the concrete annulus is considerably reduced which might limit the comparison with practical applications like for concretes with large aggregates or long fibre reinforcement.

Table 2. Ring test geometries.

		AASHTO	ASTM	BBRI (this study)
Inner radius steel (R_{IS})	[mm]	140	152	140
Inner radius concrete ($R_{IC} = R_{OS}$)	[mm]	152.5	165 ± 1.5	160
Outer radius concrete (R_{OC})	[mm]	228.5	203 ± 1.5	235
Height (h)	[mm]	152	150 ± 6	75
Thickness steel (t_s)	[mm]	12.7 ± 0.4	12.5 ± 0.13	20
Thickness concrete (t_c)	[mm]	75	38 ± 1.5	75
Notional size (h_0)	[mm]	150	76	75
Relative humidity (RH)	[%]	50 ± 4	50 ± 4	60 ± 5
Temperature (T)	[°C]	21 ± 1.7	23 ± 2	20 ± 2
Drying conditions	[-]	*circumference*	*circumference*	*top and bottom*

In both standards circumferential drying is prescribed. This drying condition results in uniform shrinkage through the height of the specimen but not in the radial direction. Consequently a complex stress distribution develops in the concrete which furthermore changes in shape over time, making an estimation of the stresses generated into the concrete very difficult without a complete knowledge of the developed drying gradient. Top and bottom drying would result in a more uniform drying and shrinkage along the radial direction of the specimen (but not along the height direction), with the development of the highest stresses at the inner radius of the concrete annulus. In this case the developed actual maximum stress can be calculated using equation 1. A full derivation of this equation can be found in [7], but is beyond the scope of this paper.

$$\sigma_{Actual-Max} = -\varepsilon_{steel}(t).E_s.\left(\frac{R_{OS}^2+R_{OC}^2}{R_{OC}^2-R_{OS}^2}\right).\left(\frac{R_{OS}^2-R_{IS}^2}{2.R_{OS}^2}\right) \qquad (1)$$

With:	ε_{steel}	Strain recorded on the steel ring
	E_s	Modulus of elasticity of steel
	R_{IS}, R_{OC}, R_{OS}	Inner radius of steel and outer radius of concrete and steel, respectively

For this drying condition the theoretical maximum elastic stress which would develop in the concrete in the absence of stress relaxation can be determined by means of equation 2. Hence, an estimation of the stress relaxation can be made, by comparing the actual maximum stress based on measured strain deformations on the rings with the theoretical maximum elastic stress mainly derived from the ring geometry and free shrinkage of the samples.

$$\sigma_{Elastic-Max} = \frac{\Delta\varepsilon_{SH}.E_C.\left(\frac{R_{OS}^2+R_{OC}^2}{R_{OC}^2-R_{OS}^2}\right)}{\left(\frac{E_C}{E_S}.\frac{[(1+\nu_S).R_{IS}^2+(1-\nu_S).R_{OS}^2]}{(R_{OS}^2-R_{IS}^2)}\right)+\left(\frac{[(1-\nu_C).R_{OS}^2+(1+\nu_C).R_{OC}^2]}{(R_{OC}^2-R_{OS}^2)}\right)} \qquad (2)$$

With:	$\Delta\varepsilon_{SH}$	the incremental free shrinkage of the concrete
	E_c	the modulus of elasticity of concrete
	υ_s/υ_c	Poisson coefficient of steel and concrete, respectively

In this study a modified ring test was adopted (see Table 2). The thickness and height of the concrete annulus was set to 75 mm allowing for testing of a wider range of concrete types (in contrast with the ASTM ring geometry). The thickness of the steel hollow cylinder was chosen as such that the restraint imposed by the steel cylinder is comparable to that of the ASTM standard. A top and bottom drying condition was preferred allowing a more detailed theoretical analysis and comparison of the results. The notional size (h_0) is also comparable to that of the specimens for the determination of the total (free) shrinkage, allowing thereby for a direct usage of these results in equation (2).

2. RESULTS AND DISCUSSION

2.1 Mechanical properties

The variation of the compressive strength and the secant E-modulus with age of the different concrete mixtures are presented in figure 1. These results reveal that the compressive strength of the SCC mixtures is higher than that of the VC at an age of 28 days. At this age nonetheless the secant E-modulus is very similar for all studied mixtures. At early age mixture SCC II is especially characterized by a lower compressive strength and E-modulus. This lower compressive strength at early age might be a point of concern with regard to formwork removal times. For the specific foreseen application however this is not an obstacle, since in general longer formwork removal times are used for durability reasons. The lower early age stiffness might on the other hand potentially result in more relaxation of the material, which might be beneficial for the restrained shrinkage behavior.

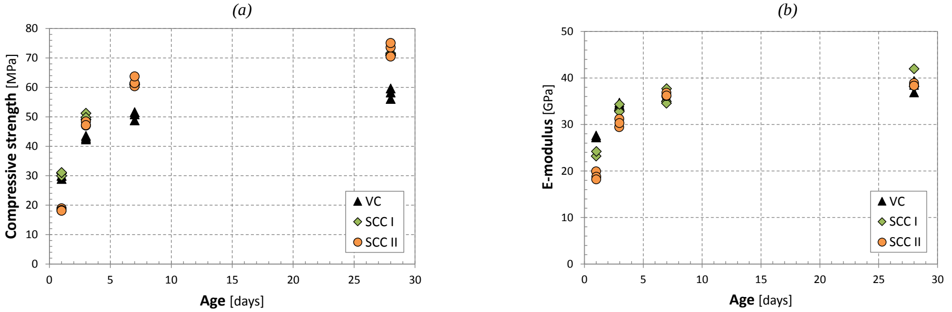

Figure 1. Evolution of compressive strength and secant E-modulus with age of the concrete.

2.2 Free total shrinkage

Free total shrinkage measurements for the three mixtures are presented in figure 2. In contrast to what was expected these results show that all of the mixtures are characterized by a quite similar shrinkage behavior, with an average shrinkage of around 450 µm/m at an age of 300 days. Also the development of shrinkage with time is very similar for all the mixtures. The higher paste content of the SCC mixtures thus does not seem to greatly influence the shrinkage behavior in this study. Apparently, this effect is counterbalanced by other factors.

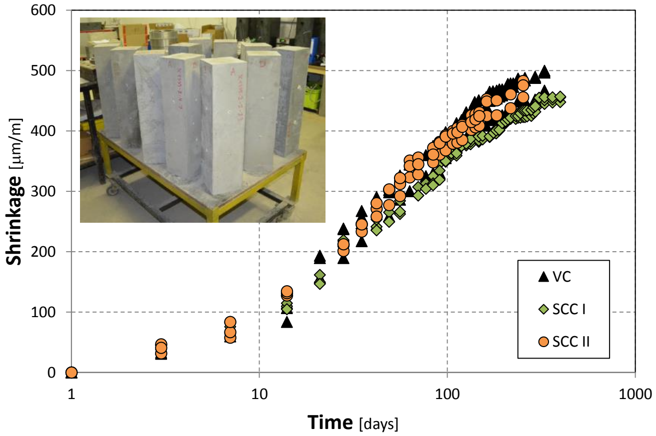

Figure 2. Total (free) shrinkage of the different studied compositions.

2.3 Restrained shrinkage

For each concrete mixture 3 ring specimens (cf. BBRI setup in § 1.2) were manufactured. The measurements obtained by the 4 strain gauges positioned at the inner circumference of the hollow steel cylinder were converted, by means of equation (1), to the (maximal) tensile stress generated in the concrete (at the edge with the hollow steel cylinder). These stresses are plotted in figure 3 for the 9 ring specimens. It can be clearly seen that tensile stresses occurring for SCC mixtures are much higher than those in the VC mixture. This difference cannot be solely explained by the E-modulus of the material. On average the SCC I and SCC II respectively reach ± 5.3 MPa and ± 5.8 MPa, whilst the VC mixture tends to reach a plateau at an average tensile stress of ± 3.8 MPa. Of the 3 samples of the SCC II mixture 2 cracked, respectively after 115 and 146 days. Also for the VC mixture 1 specimen cracked after 209 days. None of the SCC I specimens cracked within a period of 400 days.

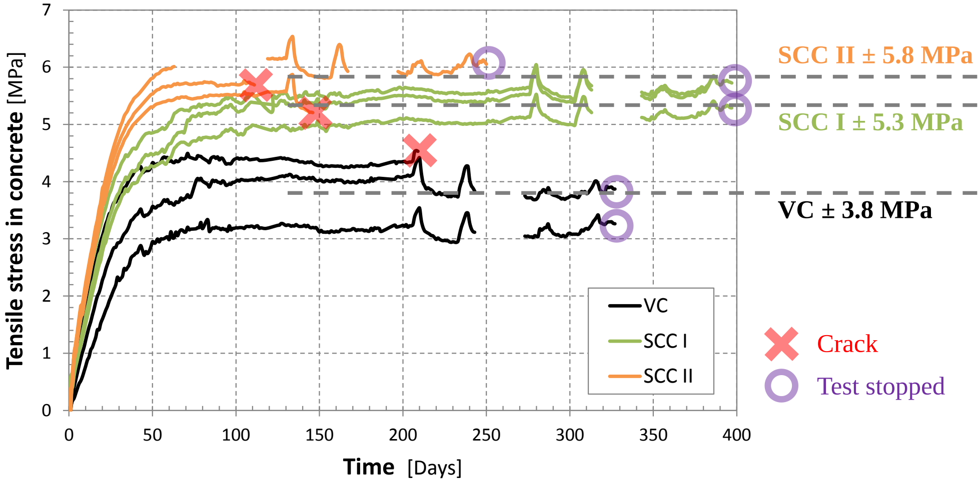

Figure 3. Maximal tensile stress developed in the concrete rings as a result of the restraint.

The relaxation of the different ring specimens was back calculated by means of the restrained shrinkage results presented in figure 3 and the theoretical predictions of the elastic stress build-up in the specimens (see equation (2)) determined on the basis of the determined material properties in § 2.1 an § 2.2. This evaluation revealed that the SCC mixtures were prone to less relaxation. After stabilization, on average a relaxation of respectively ± 48% and ± 38% were observed for SCC I and SCC II, where the VC presented a relaxation of ± 68%. Since all mixtures presented a similar stiffness and free shrinkage this observation can directly be related to the positioning of the different mixtures in figure 3 (as the theoretical predicted elastic stress development is very similar for all 3 mixtures) were the SCC II mixtures presented the highest tensile stresses and the VC the lowest.

In order to better understand the results an in depth analysis of the cracking potential is needed. In order to achieve this the tensile capacity of the material was evaluated. The splitting tensile strength was determined on different specimens, more precisely on:

(1) classical cylindrical specimens, with a diameter of 150 mm and a height of 300 mm, tested at an age of 28 days, 3 of these specimens were tested for each composition;
(2) prismatic specimens with a cross section of 150 mm by 300 mm, taken from the shrinkage specimens and tested at the end of the exposure period of the restraint shrinkage specimens (age of 250 to 400 days), 4 of these specimens were tested for each composition;
(3) prismatic specimens with a cross section of 75 mm by 75 mm, taken from the shrinkage specimens and tested at the end of the exposure period of the restraint shrinkage specimens (age of 250 to 400 days), 4 of these specimens were tested for each composition;
(4) sections of the ring specimens (see figure 4) with a cross section of 75 mm by 75 mm, cut and tested at the end of the exposure period of the restraint shrinkage specimens (age of 250 to 400 days), 5 of these specimens were tested for each composition.

When analysing these results, which are presented in figure 4, a clear size-effect can be observed. The specimens with a cross section of 75 x 75 mm² present a splitting tensile strength 40 to 70% higher than the specimens with a cross section of 150 x 300 mm². The results obtained on sections taken from the ring specimens and shrinkage specimens with similar cross section also do not seem to indicate that the sustained tensile loading on the ring specimen induces micro-cracking into the concrete resulting in lower tensile strength.

Due to the considerable size-effect which exists on the splitting tensile strength results, a comparison of the restrained shrinkage results (see figure 3) with the splitting tensile strength obtained on the sections of the ring specimens (see figure 4) was realised to evaluate the cracking potential. This analysis delivers a cracking potential (= developed tensile stress/tensile capacity) for the VC mixture of ± 65% and respectively of ± 70% and ± 85% for the SCC I and SCC II mixtures, at the end of the exposure period. It can thus be concluded that the SCC I mixture has more or less the same cracking potential as the VC mixture. On the other hand the SCC II mixture seems to be more crack sensitive under these restraint levels. This is also reflected in the high number of cracked ring specimens for the SCC II mixtures. It should be emphasized that to fully evaluate the cracking potential an in depth statistical analysis is required, taking into account the dispersion which exists on the results (individual strain measurements on each of the ring tests and characteristic tensile strength). This statistical effect also explains why one of the specimens of the VC mixture cracked and none of the SCC I mixture, even though the (average) cracking potential is very similar for both mixtures.

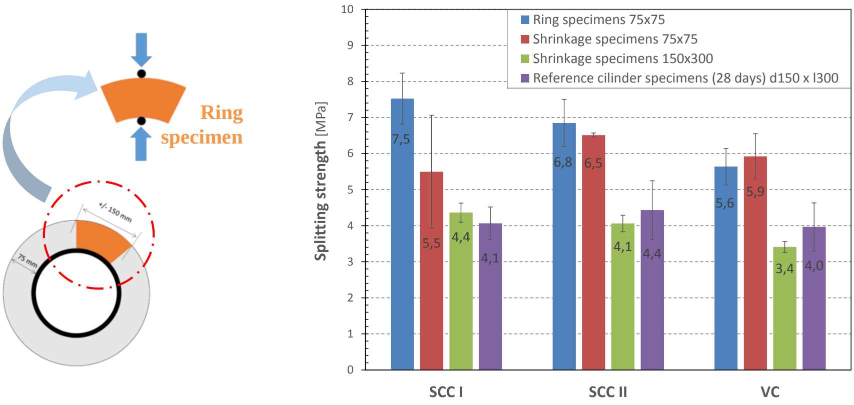

Figure 4. Splitting tensile strength and size-effect of the different studied mixtures.

3. CONCLUSIONS

Due to the specific requirements imposed on to the disposal modules, the restrained shrinkage cracking tendency of the developed SCC mixtures needed to be analyzed. The results obtained in the scope of this study have shown that even though the two studied SCC mixtures are characterized by a similar free shrinkage behaviour and stiffness as a traditional vibrated concrete (VC) mixture, the restrained shrinkage behaviour is distinctly different. The SCC mixtures develop in general higher tensile stresses due to the restraint imposed by the hollow steel cylinders. The relaxation potential of the SCC mixtures is also distinctly lower than that of the VC mixture. On the other hand the higher tensile strength of the SCC mixtures allows the material to withstand higher tensile stresses. As a result, the SCC I mixture exhibits a comparable cracking potential as the studied VC mixture. But even though the cracking potential under the studied restraining conditions is the same for SCC I and VC mixtures, a potential crack in SCC I mixture could be characterized by a greater crack opening due to the higher tensile stresses occurring in that concrete. The tensile stresses developed in the SCC II mixture due to the imposed restraint are too important with respect to the tensile capacity of the material and as a result the SCC II mixture presents a higher cracking potential then the two other mixtures.

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