Restrained shrinkage and cracking tendency of Self-Compacting Concrete incorporating supplementary cementitious materials (SCMs)

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RÉSUMÉ. Les études expérimentales menées sur les constructions en béton autoplaçant (BAP) ont montré que le retrait de séchage est l'un des principaux paramètres responsables de leur fissuration. Le présent travail s'intéresse à l'étude de l'impact des additions minérales tel que le laitier de haut fourneau; les cendres volantes et le métakaolin sur le retrait empêché de béton autoplaçant (BAP). Quatre formulations de BAP avec un rapport constant eau sur liant (E/L=0,368) ont été réalisées. Trois formulations de BAP ont été fabriquées par l'usage de trois ciments industriels de norme européenne EN 197-1: CEM I 52.5N (ciment Portland), CEM III/A 52.5L (ciment au laitier) et CEM V 42.5N (ciment composé au laitier et les cendres volantes), une quatrième a été effectuée en remplaçant 15% de ciment Portland par du métakaolin. Sur la base des résultats obtenus, nous avons constaté qu'à long terme, le retrait empêché du BAP-CEM III est supérieur à celui du BAP à base de ciment portland et de CEM V. La substitution de 15% du ciment Portland par du métakaolin, a diminué le retrait, l'utilisation des additions minérales a de son coté, réduit les ouvertures de fissures d'au moins un facteur de 2.

ABSTRACT. Experience studies the constructions of self-compacting concrete (SCC) show that the drying shrinkage is one of the major parameters responsible for their cracking. This paper investigated the impact of the supplementary cementitious materials (SCMs) such as high blast-furnace slag; fly ash and metakaolin on restrained shrinkage of self-compacting concrete (SCC). Four SCCs mixtures were performed using a constant water-to-binder ratio (w/b) of 0.368. Three SCCs mixtures were manufactured using three industrial cements according to European standard EN 197-1: CEM I 52.5N (Portland cement), CEM III/A 52.5L (slag cement) and CEM V 42.5N (blended cement containing slag and fly ash), another was performed by substituting 15% of Portland cement by metakaolin. Based on the findings of this study, the result analysis showed that, a long-term restrained shrinkage of SCC-CEM III is higher than Portland cement SCC and SCC-CEM V. The replacement of 15% of the Portland cement by metakaolin, decreases the free total shrinkage and also the use of SCMs (slag, metakaolin and fly ash) reduces the crack openings by at least a factor of 2.

MOTS-CLÉS : *béton autoplaçant, additions minérales, retrait empêché, fissuration.*

KEY WORDS: *self compacting concrete, supplementary cementitious materials, restrained shrinkage, cracking.*

1. Introduction

Experience studies the constructions of self-compacting concrete (SCC) show that the drying shrinkage is one of the major parameters responsible for their cracking. Indeed, their composition with a volume of paste greater than the ordinary concrete induces greater shrinkage and increases their susceptibility to cracking. Cracking is a complex phenomenon, which is dependent on several factors including free shrinkage, age dependent material property development, creep relaxation, shrinkage rate, and degree of restraint. Even small cracks in concrete will cause problems in concrete. Using mineral admixtures as cement replacement substance in concrete has a tendency to increase by the future in order to provide greater sustainability in construction industry. The partial replacement of cement by mineral admixtures can refine the porosity of the mixture and also reduce the pore diameters consequently a decrease the total shrinkage and also opening of crack width that increase the durability of concrete [PHI 07]. To resolve the previously mentioned problems the restrained ring test will be further investigated in this research. Ring tests generally will induce cracking and allow for the comparison of various concrete mixtures. A restrained ring test is not standardized but must be designed for each case to model a specific type of restraint.

There is also a concern with stress relaxation of concrete when addressing the early age reactions. Stress relaxation is the loss of stress over time with a constant level of strain in the concrete. The strain is generated by shrinkage forces but during the early ages it is difficult to account for any mechanisms providing a means of stress relaxation. There is no correlation between the magnitudes of early age and long term shrinkage. The shrinkage occurring during these two stages should be taken together as the "total shrinkage" for a concrete. In some cases, such as poor curing conditions with rapid drying, the first day's shrinkage can easily exceed the long-term measurements. The long-term shrinkage due to drying was equivalent in all cases, though the first day had a significant change to the magnitude of "total shrinkage" and thus affected the expected cracking. The purpose of this research is to determine the shrinkage and cracking potential of self-consolidating concrete due to various changes in mixture proportions. Analytical solutions are used for the calculation of the residual stresses that are induced by non-uniform shrinkage.

2. Materials and methods

2.1. Materials

A granular class 0/4 sand (S) with a density of 2.6 t/m³ and limestone gravel (G) with 6.3/10 granular class, 2.66 t/m^3 of density were used in this study. Three cements according to European standard EN 197-1: CEM I 52.5N (Portland cement), CEM III/A 52.5L (slag cement) and CEM V 42.5N (blended cement containing slag and fly ash); limestone filler (LF) and metakaolin (MK) were tested.

Table1. *Composition and physical properties of cements and mineral additions*

Name	CEM I	CEM III	CEM V	LF	MK
Clinker content (% in mass)	98	36	54	_	_
Slag content (% in mass)	_	62	25	_	_
Fly ash content (% in mass)	_	_	20		
Specific Surface Blaine (cm²/g)	3650	4263	4250	41	17000
Specific gravity (g/cm³)	3.15	2.98	2.85	2.	2.4

Table 2. *Mix proportions and physical properties at the fresh state*

Composition (kg/m³)	SCC-CEM I	SCC-CEM I/MK	SCC-CEM III	SCC-CEM V
Aggregate 6.3/10	760	760	760	760
Sand 0/4	780	780	780	780
CEM I	330	280.5	330	330
CEM III	-	-	-	-
CEM V	-	-	-	-
Limestone filler	240	240	240	240
Metakaolin	-	49.5	-	-
Water	210	210	210	210
Superplasticizer	2.8	4.4	2	2.5
w/b	0.368	0.368	0.368	0.368

Slump (cm)	66	68	69	67
Segregation (%)	8.3	7	9.6	7.9
L-Box (H_2/H_1)	0.82	0.83	0.87	0.84

Their composition and properties are given in Table 1. A total of four SCCs mixtures with a constant water-to-binder ratio (w/b) of 0.368 and a total binder content of 570 kg/m³ were investigated. Designations, mix proportions and physical properties at the fresh state of the different SCCs are given in Table 2.

2.2. Testing methods

2.2.1. Compressive and splitting tensile strength measurements

The compressive strength was measured on 70 mm x70 mm x70 mm specimen at the curing ages of 1, 7, 28, 90 and 360 days. The split tensile strength was measured according to NFP 18-412 standard on cylindrical specimen (Φ110 mm x H220 mm). In this test, the specimen was placed horizontally between the loading surfaces of the compression testing machine and the load was applied till failure of the cylinder. The split tensile strength R_t was then calculated using the Equation (1). The compression and the split tensile tests were conducted on compression testing machine of capacity 3000 kN.

$$R_t = \frac{2F}{\pi DL} \quad [1]$$

Where F is the compressive load value at failure, D and L are respectively the diameter and the length of the tested cylindrical specimen.

2.2.2. Restrained shrinkage testing

The restrained shrinkage test was performed in accordance with AASHTO PP34-98 standard practice for estimating the trend of concrete cracking. The concrete was cast around a steel ring that had an inner diameter (r_1) of 260 mm and an outer diameter of 310 mm (r_2). The concrete ring had a diameter of 380 mm (r_3) and a height of 140 mm. The geometry of the ring is described in Figure 1. Three strain gauges are glued at mid-height outer surface of the steel ring to control the deformation in the steel ring caused by the shrinkage of concrete. Other three strain gauges are glued at mid-height on the outside surface of the concrete ring to measure the restrained shrinkage of concrete as shown in Figure 1. As the concrete shrinks, a compressive stress is produced in the steel ring, which is balanced by a tensile stress in the concrete. When cracking occurs in the concrete, the stress and thus the strain in the steel ring is released. Strain gauges were connected to a computer. The deformation values were recorded every 5 minutes for 40 days. Measurements of crack opening were also recorded every 5 minutes using a crack sensor. Specimens were then placed in a air-controlled environment of $20\pm1°C$ and $50\pm2\%$ relative humidity. In order to ensure a radial drying, the top surfaces of the concrete rings are protected from drying by a double layer of aluminum adhesive.

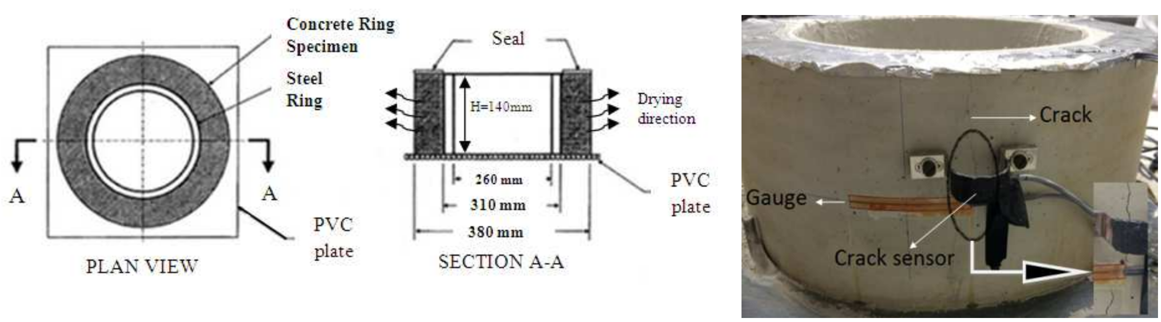

Figure 1. *Restrained ring specimen geometry and device.*

2.2.3. Calculation of residual stress in the rings

The ring test was used to measure the restrained shrinkage and predict cracking in cementitious materials (mortar, concrete). This test may also give information about the residual stresses present after cracking that develop in these materials at the interface with the ring. Indeed, must be considered the concrete ring as a cylinder exposed to uniform pressure on its internal surface, while the metal ring is exposed to the same pressure on its outer surface. The residual stress can be calculated thanks to an analytical approach proposed by [GAO 13]. According to this approach, one can calculate the maximum residual stress developed in the concrete according to the deformation measured by the strain gauges placed on the concrete rings. These stresses were calculated according to the following Equation:

$$\sigma_{eff}(t) = \sigma_{tot}(t) - \sigma_R(t) \quad [2]$$

Where $\sigma_{eff}(t)$ is the effective stress due to the shrinkage; $\sigma_{tot}(t)$ is the total stress measured by the strain gauges and $\sigma_R(t)$ the stress due to creep. $\sigma_{eff}(t)$ is calculated using the following Equation:

$$\varepsilon_{eff}(t) = \varepsilon_{sh}(t) - \varepsilon_{creep}(t, t_0) \quad [3]$$

Where ε_{sh} is effective shrinkage strain that actually be used for generation of shrinkage stress in the concrete ring, t and t_0 are loading end and the load start time respectively. ε_{creep} is the creep strain after loading period of (t-t_0). The creep strain may relate with the effective shrinkage strain by a so-called creep coefficient factor φ:

$$\varphi(t, t_0) = \frac{\varepsilon_{creep}(t,t_0)}{\varepsilon_{eff}(t,t_0)} \quad [4]$$

Different models exist for the prediction of creep coefficient of concrete, in this study the CEB-FIP 1990 model for estimating the creep coefficient is used. From calculating the creep coefficient, one can obtain effective shrinkage strain by:

$$\varepsilon_{eff}(t) = \varepsilon_{sh}(t)\left[1 - \frac{\varphi(t,t_0)}{1+\varphi(t,t_0)}\right] \quad [5]$$

After considering creep of concrete, the interfacial pressure stress generated from concrete shrinkage should be reduced. Gao et al [GAO 13] obtained the interfacial pressure stress after considering creep relaxation for varied loading history as:

$$q = \frac{-\frac{2}{r_3^2-r_2^2}\sum_{i=1}^{n}\left[1-\frac{\varphi(t,t_i)}{1+\varphi(t,t_i)}\right]\int_{r_2}^{r_3}\varepsilon_{shi}\, r\, dr}{\frac{1}{E_1}\frac{(1-\mu_1)r_2^2+(1+\mu_1)r_3^2}{r_3^2+r_2^2}+\frac{1}{E_2}\frac{(1-\mu_2)r_1^2+(1+\mu_2)r_2^2}{r_2^2+r_1^2}} \quad [6]$$

On the other hand, the interfacial stress q can be related to the inner surface strain on the steel ring, ε_θ:

$$q = -[1 - \left(\frac{r_1}{r_2}\right)^2]E_2\varepsilon_\theta \quad [7]$$

The strain ε_θ is measured from experiments by the gauges on the steel ring.

3. Results and discussion

3.1. Compressive and tensile strength

The compressive strength of the different mixtures at different ages is shown in Figure 2. As can be expected, the compressive strength of all the studied SCCs enhances by the age. This enhancement is more intense for SCCs with SCMs. Compared to the reference SCC, SCCs with SCMs exhibit lower compressive strength at very early age. In fact, at one day of aging, the compressive strength of SCC-CEM I/MK, SCC-CEM III and SCC-CEM V is respectively 18%, 54% and 56% lower than the one of SCC-CEM I. However, at 7 days, the compressive strength of SCC-CEM I/MK is only 6% lower than the one of the control SCC and at 28 days, it became slightly higher. The latter observation is in agreement with the results found in previous studies for ordinary concretes containing metakolin [KHA 05]. However for high performance concrete, MK seems to have more significant influence. The obtained result suggests that MK have an important effect on the development of hydrates even before 28 days of aging probably due to its pozzolanic reactivity and to nucleation sites that it offers [KHA 05]. Compared to SCC with MK, SCCs with CEM III and CEM V exhibit lower compressive strength at early ages particularly due to the well-known slow hydration kinetics of slag [ATI 09]. These results are in a good agreement with the experimental results of previous studies performed on SCC based on slag cements [PAL 03]. However, at long term (360 days), the compressive strength of SCCs with mineral admixtures exceeds the one of the reference SCC. Particularly, SCC based on CEM III presents the highest compressive strength, 21% higher than the one of the reference SCC at 360 days.

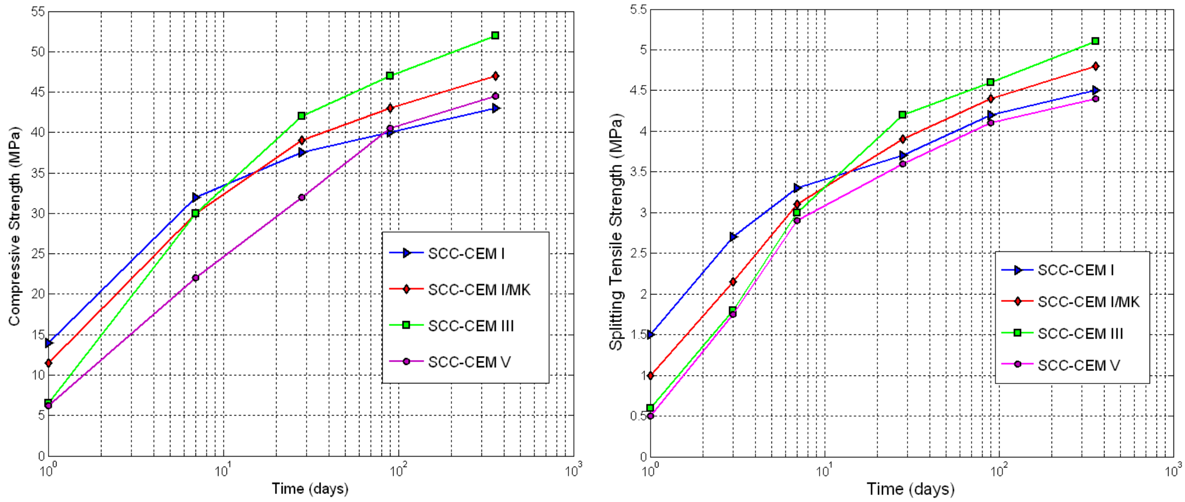

Figure 2. *Compressive strength and Splitting tensile strength of the studied SCCs.*

The tensile strength by splitting test of the studied SCCs measured at 1, 3, 7, 28, 90 and 360 days is shown graphically in Figure 3. This figure suggests that the development of splitting tensile strength is similar to that of the compressive strength. Neville [NEV 96] indicated that there was a direct proportionality between splitting tensile strength and compressive strength of the concrete strength. In other words, while the compression strength increases, the tensile strength also increased at a lower rate.

3.2. Restrained shrinkage and stress calculated in the steel and concrete rings

Figure 4 shows the effect of SCMs on restrained shrinkage due to drying at 40 days. Evaluation of restrained shrinkage by drying in the mixtures shows that the 15% replacing of Portland cement by metakaolin was improved restrained shrinkage. The effect of MK occurs only after 9 days with a slight decrease of shrinkage. In the long term, the presence of MK reduces the shrinkage of SCC-CEM I/MK concrete by 17% compared to SCC-CEM I. This reduction of shrinkage by incorporation of metakaolin can be attributed to the pozzolanic reaction of the metakaolin with calcium hydroxide liberated during the hydration of the cement which can create an additional C-S-H gel and consequently reduction the porosity [KHA 05]. By comparing the development of shrinkage for three types of cements, we find that CEM III concrete has a greater shrinkage by 26% and 21% relative to SCC-CEM I and SCC-CEM V respectively.

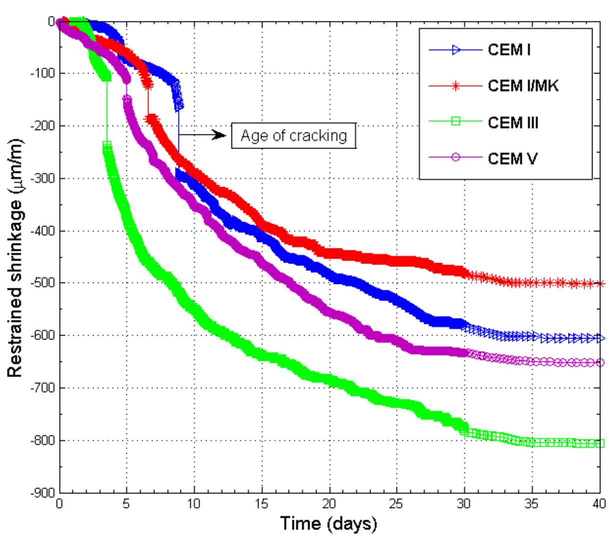

Figure 4. *Development of restrained shrinkage.*

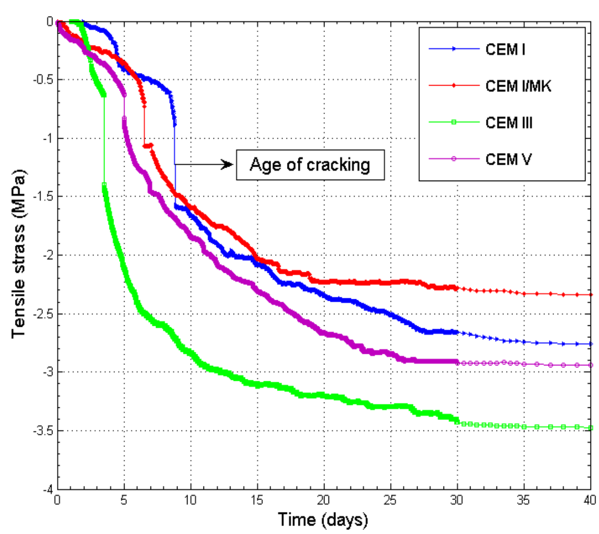

Figure 5. *Development of stresses in the concrete rings.*

The amplitudes of restrained shrinkage in CEM I and CEM V concrete are comparable: -610 µm/m and -650 µm/m respectively at 40 days.

This may be because there is less evaporable water available in the mixtures as hydration and pozzolanic reactions used up significant amount of free water. The shrinkage stresses developed in the interface of the steel and concrete ring is calculated from measure of strain concrete by the gauges. These stresses are calculated according to the equation (6) taking into account the effect of creep deformation. Using the creep deformation (ε_{creep}) obtained in present paper the development of the shrinkage stress with and without creep correction can then be calculated. Figure 5 represents the residual stress calculated with and without creep effect from the deformation of the concrete ring. SCC based on CEM III show greater shrinkage kinetics and low strength at early age compared to SCC-CEM I and SCC-CEM V which causes reach earlier at the threshold of elasticity and therefore crack earlier.

The developments of strain along circle direction at middle location of the inner surface of the steel ring with age for the SCCs are presented in Figure 6. From the results displayed in this figure, first we can observe the strain increases with age after concrete set. The developing rate of circle strain is gradually decreased and the strain achieves a maximum value, finally at certain age then suddenly jumps to a small value. This jump in circle strain indicates shrinkage induced cracking occurs in the concrete ring. Figure 7 show the stresses measured by deformations of the steel ring. In these curves there is the falls stress to almost zero showing age of cracking which is correspond the drop of deformations in Figure 6.

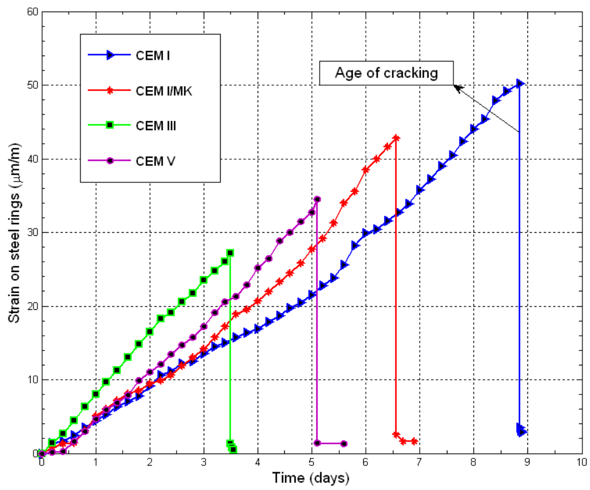

Figure 6. *Development of strain in the steel ring.*

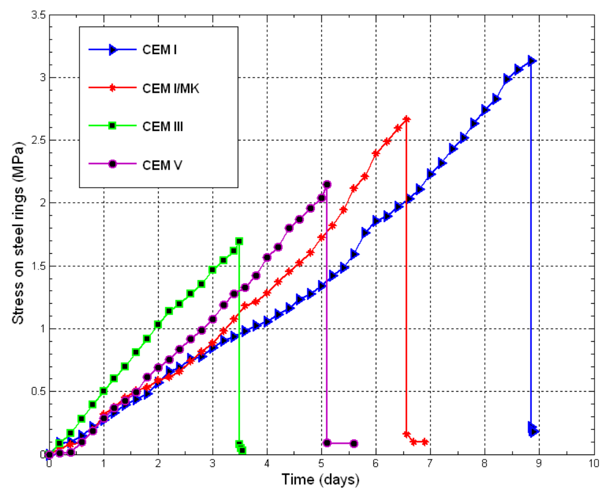

Figure 7. *Development of stress in the steel ring.*

The stress curves of the steel ring show that the SCC based on MK subject to lower stress compared to the reference SCC. However, the interface pressure and the residual stress that developed in metakaolin specimen were slightly lower than the others mixtures. This may be due to lower shrinkage in metakaolin at time of cracking. Indeed the concrete may not result in a uniform deformation of the outside steel ring along its height (Z direction) and as a result, the strain measured at the mid-height of the ring may be higher than the strain that develops at the top and bottom of the ring. By comparing the three types of cements, we concluded that the SCC based on CEM III shows a higher stress in the interface of the concrete-steel ring before cracking due to a greater shrinkage at early age. At the time of crack, the tensile stresses measured in restrained specimens were closed to the splitting tensile strength measured experimentally by cylinders specimens for all of SCCs mixtures. Table 3 shows the tensile strength values at cracking time. These ratios correspond with the values found by [ALT 01]. After cracking, the concrete ring released its stress and then it falls to zero.

Table 3. *Relationship between tensile strength and tensile stress at cracking.*

Tensile stress (Mpa)	CEM I (9 days)	CEM I/MK (7 days)	CEM III (3,5 days)	CEM V (5 days)
experimental (R_t)	3.35	3.1	1.81	2.53
analytical (σ_{crack})	3.1	2.6	1.7	2.15
R_t/σ_{crack}	1.08	1.19	1.06	1.17

3.3. Crack initiation and propagation in concrete rings

Only one crack was developed on the different mixtures and started at different ages: first in the SCC-CEM III, then in SCC-CEM V followed by SCC with CEM I+15% of MK and finally in SCC-CEM I. The age of crack initiation due to the restrained shrinkage can be directly deduced from Figure 6. The values are given in Table 4.

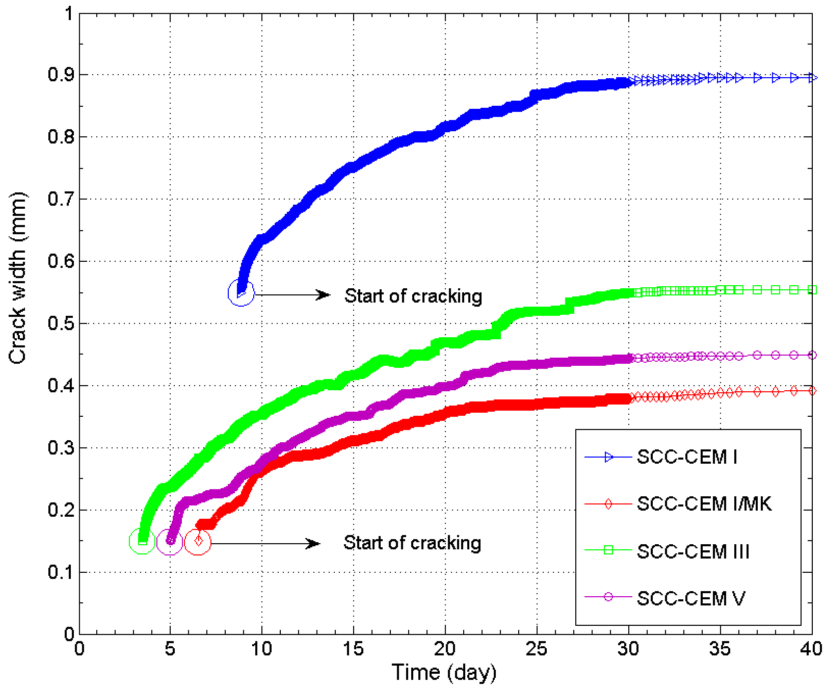

Figure 8. *Measures the cracks width by the crack sensor for the SCC.*

Table 4. *Age of crack initiation and crack width value.*

References	Age of crack (days)	Crack width (mm) at 40 days
SCC-CEM I	8.83	0.9
SCC-CEM I/MK	6.56	0,39
SCC-CEM III	3.5	0.57
SCC-CEM V	5.1	0.46

The initiation point of crack opening was measured by a micrometer microscope. The evolution of the crack width as recorded by the crack sensor is given in Figure 8. This last figure show a limited crack opening in SCCs containing SCMs compared to the reference SCC, a crack width at least 1.58 times lower than the one developed in the reference SCC. Particularly, SCC with metakaolin presents the more interesting behavior with a crack opening 2.3 times lower than the one of SCC-CEM I. This reduction can be attributed to the fine porosity involved by of the use of MK.

4. Conclusion

At present, the economic and environmental contexts are leading precast concrete makers to look for alternative solutions to compensate for the progressive disappearance of CEM I 52.5R cement. In this paper, the effect of composed cements (clinker + slag + fly ash) and partial replacement of CEM I with 15% of metakaolin on the mechanical properties and durability of self-consolidating concrete (SCC) is studied. Based on the findings of this study, the following conclusions may be drawn:

- Replacement of Portland cement by 15% of MK, CEM III and CEM V involves a significant decrease of the compressive strength at very early ages which can be explained by a lower development of the hydrate in early age for the SCC based on mineral additions. This can be linked to their slow hydration kinetics. But at 28 days of hardening, SCC with MK and CEM III exhibits higher compressive strength value than reference SCC. For SCC based on CEM V this increase will start after 90 days.

- At long term and in restrained drying conditions, shrinkage of SCC-CEM V is closed to the one of SCC-CEM I and both are lower than the one obtained with CEM III cement. However, SCC with metakaolin presents the best resistance to restrained drying shrinkage. Substituting the Portland cement by 15% of metakaolin involves a significant decrease on the total shrinkage by 20% at 40 days.

- In restrained and drying conditions, one crack was developed on the different mixtures and started at different ages: first in the SCC-CEM III, then in SCC-CEM V followed by SCC with CEM I+15% of MK and finally in SCC-CEM I, showing the sensibility of SCCs with SCMs to early cracking. However, the crack opening in SCCs with SCMs is at least 1.57 times lower than the one of the reference SCC which presents a very interesting advantage for durability considerations. Particularly, the effect of shrinkage cracking on gas and water permeability in SCC with the considered SCMs should be limited since this last property is directly related to the crack width.

5. References

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