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Cracking control of concretes modified with short AR-glass fibers at early age. Experimental results on standard concrete and SCC

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Abstract

At early ages (less than 24 h), cracking can occur in concrete because it can be subjected to dimensional changes, due to shrinkage, can generate loads which are greater than the low strength capacity of the material at this age. This is especially the case in members with highly exposed surfaces, such as floor slabs or precast panels.

As any other cement based composite, Self Compacting Concrete (SCC) shrinks at an early age and can crack when shrinkage is restrained.

One possible solution to reduce the impact of early age shrinkage on concrete durability is to include low volumetric fractions of short fibers in order to control crack growth. To evaluate the cracking control ability of Alkali Resistant (AR) glass fibers in standard concrete and SCC, an experimental program, developed in accordance with the AR-glass fiber producer, was conducted. Two different types of AR-glass dispersible fibers, two concrete compositions and several volumetric fractions of fiber have been studied.

The experimental program included a mechanical characterization of the different concrete compositions (compression and flexural strength tests), free shrinkage tests, with and without air flow over the samples, and double restrained slab cracking tests (Kraai slab modified test).

The results obtained show that the inclusion of low volumetric fractions of the two types of AR-glass fiber under study can control the cracking produced due to very early age shrinkage on both standard concrete and SCC in two different ways: reducing the total cracked area and the maximum length of the cracks. Although, a non-linear dependence of cracked area on AR-glass fiber amount was found. A microscopic study of the cracked surface confirms the favorable effect of the presence of dispersed AR-glass fibers on cracking control.

When standard concrete and SCC results were compared, it was observed that, although SCC drying shrinkage was larger, standard concrete with a similar performance in the hardened state produced equivalent cracking area.

Keywords: Cracking control; Shrinkage (C); Concrete (E); Self compacting concrete; Glass fiber

1. Introduction

Due to its brittle behaviour and low tensile strength, concrete can crack when loaded. The consequences of concrete cracking are aesthetical defects on concrete surfaces, increase of permeability, reduction of mechanical section and reduction of steel reinforcement protection that can compromise concrete durability.

As concrete mechanical capacity increases with age, at an early age, concrete can crack under lower stress because it has lower strength. Immediately after casting, concrete mechanical behaviour is plastic and its stiffness (that can be described by its Secant Young Modulus) and strength are negligible. During setting, concrete stiffness increases and failure strain decreases. After setting, tensile strength increases and failure strain also increases, defining a minimum value for failure strain [1]. At this moment, cracking risk is at a maximum.

A relationship between mechanical properties evolution and degree of hydration has been described through the rate of heat evolution of concrete [2]. As it has been described elsewhere,

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stiffness is the first mechanical property developed, secondly is tensile strength and compressive strength is the last [2,3].

At early ages, concrete can be subjected to mechanical actions derived form shrinkage. Shrinkage produces a dimensional change on concrete and can stress concrete when its displacement is restricted and concrete can not deform freely.

Shrinkage can occur in concrete due to several causes. At early ages (less than 24 h after casting), the main causes are thermal, autogenous and drying shrinkage. In standard concrete, with a water to cement ratio higher than 0.45, drying shrinkage, if drying is allowed to occur, has been described as the most important cause of shrinkage at early ages [1].

Drying shrinkage of concrete depends on concrete properties (composition and casting and curing procedures), shape and exposition of the concrete members and environmental conditions (temperature, relative humidity and wind velocity) [4–7].

As drying shrinkage is induced by the loss of water inside concrete through the members' surface, strain gradients are produced in member sections. Consequently, cracking caused by drying shrinkage initiates from surface areas in contact with the environment [7]. Accordingly, members with large surfaces in contact with an aggressive environment are more susceptible to cracking due to drying shrinkage.

Drying shrinkage has been described to begin even before initial setting time and, therefore, before concrete mechanical capacity has been developed [1]. In order to define the time when tensile stress capacity of concrete begins, the concept of *time maturity zero* has been proposed [8]. It has to be highlighted that this concept does not correspond with initial or final setting time measured using penetration tests (as Vicat needle test).

Creep of concrete has been observed to be beneficial to reduce cracking risk due to the relaxation of tensile stress produced by drying shrinkage at early age [2,3,7]. As creep effects depend on load application time and drying shrinkage can happen at short time after concrete casting, relaxation has to be taken into account to evaluate cracking of concrete at early age.

Summarizing, it can be said that three phenomena are necessary for concrete cracking at early age: a dimensional change (shrinkage), that this deformation produces tensional stress (stiffness) and that this stress is greater than the tensile strength of concrete.

Self Compacting Concrete, also called Self Consolidating Concrete (SCC) is defined as "a concrete that is able to flow under its own weight and completely fill the formwork, even in the presence of dense reinforcement, without the need of any vibration, whilst maintaining homogeneity" [9] and has been described as "the most revolutionary development in concrete construction for several decades" [10].

To achieve a high flowability, the composition of SCC incorporates a high range water reducing admixture (HRWRA), also called superplasticiser. A large amount of fine material, with a particle size under 0.5 mm (cement plus additives or fillers) is included to increase viscosity and, as a result, the resistance to segregation [9–12]. The stabilization time of SCC increases with regard to standard concrete and SCC requires a longer mixing time in order to achieve a homogeneous fresh concrete [13].

The main advantages of SCC, with regard to standard concrete, have been described as faster construction, reduction of in-site manpower, better surface finishes, easier placing, improved durability, reduced noise levels, absence of vibration and safer working environment [9]. The increase of manufacturing and mixing costs of SCC are, therefore, compensated by the advantages achieved [11].

According to the High Performed Concrete (HPC) definition given by Prof Actïn as "a concrete with a high durability due to its low water to fines ratio", SCC can be also denominated as "Self Compacting High Performance Concrete" [12].

The typical dosage parameters of SCC are a cement content of 350–400 kg/m^3, 180–250 kg/m^3 of water, a maximum amount of aggregate of 60% of total volume, filler or additive between 25 and 100% of cement weight and a HRWRA between 1–2% of cement weight [12], and some optimization procedures have been proposed [14,15]. Viscosity admixtures are required to avoid segregation, if filler or additives are less than 50% of cement weight [12,16].

The mechanical properties of SCC, as stiffness and strength, do not differ significantly from the corresponding properties of standard concrete [17,18]. Nevertheless, the higher amount of fine particles increases compacity and reduces porosity, achieving a less permeable and more durable material [19,20].

Several testing methods have been proposed to measure the flowability of SCC [9–11,21], although a minimum spread diameter of 650 mm on a normal slump test is generally accepted to guarantee the filling ability of SCC, if no segregation is observed [9].

Due to the high fines content, SCC may show larger early age shrinkage and creep than standard concretes [9], although some authors reported a similar behaviour [17] and even a lower drying shrinkage at early ages of SCC with regard to standard concrete with similar performance in the hardened state [22]. These discrepancies could be related to the different fines used in each case. In some studies, a delay on the shrinkage beginning of SCC has been reported, produced by its lower bleeding rate and, therefore, lower evaporation rate from the exposed surface members [22].

As any other cement based composite, SCC cracking risk can exist in displacement restrained members, due to drying shrinkage at early ages [22–24].

In order to control cracking of concrete due to drying shrinkage at early ages, two different types of procedures have been proposed:

a) Measures to reduce drying shrinkage, focused on limiting the water loss of the exposed members' surfaces.
b) Incorporation of components to concrete that can control cracking growth, avoiding the propagation of the damages produced in the material at early ages.

The first group of procedures includes the use of curing methods and water retainer or shrinkage reduction admixtures. The aim of these procedures is to reduce tensional stress on concrete until the material develops mechanical strength. In any case, the use of water reduction admixtures should be

Table 1
Standard concrete and SCC reference compositions (without glass fiber)

Components (kg/m^3)/reference concrete	Mixture KR	Mixture SR	AC-REF
Cement CEM I 42,5 R	350	–	350
Cement CEM II-B/M (V-L) 32,5 N	–	250	–
Filler (limestone powder)	–	–	350
Coarse aggregate (4–20 mm)	1144	1320	790
Sand (0–4 mm); natural humidity 11.8%	763	660	–
Sand (0–4 mm); Natural humidity <1%	–	–	650
Water; added (total including sand content)	143 (233)	97 (175)	250 (250)
HRWRA, Glenium C-355	–	–	5.25
W/c	0.66	0.7	0.7
W/fines (cement+filler)	–	–	0.36

minimized because they delay setting time and enlarge shrinkage [1].

The second group includes additives and fibers that, mixed with fresh concrete, provide mechanical capacity to the mixture at early age in order to avoid cracking growth and propagation. These procedures assume that, though shrinkage control methods are applied, cracking risk can not be avoided.

The use of low volumetric fractions (VF) of short fibers has been described as an effective measure for controlling concrete cracking [25–28]. As the amount of fiber incorporated is very low (around 0.1% VF), it can not be considered as a macroscopic mechanical reinforcement, but a local reinforcement.

The efficiency of short fibers on the cracking control of concrete at an early age depends on the fibre shape and dimensions and the ratio between fiber and concrete mechanical properties that varies with time, type of fibers and concrete and environmental conditions.

This paper presents the experimental results of a researching program conducted to evaluate the cracking control ability of Alkali-resistant (AR)-glass fibers in standard concrete and SCC, developed in the Laboratory of Building Materials of the School of Architecture of Madrid, in accordance with the AR-glass fiber manufacturer (Saint Gobain-Vetrotex España, S.A.) [28]. A comparison between standard concrete and SCC cracking performance is also presented.

As far as the authors' knowledge reaches, though some experiences on fiber reinforced SCC have been published [11,29], no studies on cracking control ability of low volumetric fractions of AR-glass short fibers in SCC at early age have been previously described.

2. Materials and concrete compositions

2.1. Standard concrete

Two reference concrete compositions, denominated KR and SR, were designed. The components and dosage of both mixtures are presented in Table 1. No water reducing admixture was used because its inclusion modifies the shrinkage and setting time of concrete [1]. As the sand used had a high natural humidity (11.8%), the water amount that it incorporated was reduced to the water added to the mixtures. The sand was supplied in plastic bags and its natural humidity remained constant. The aggregates, both coarse and sand, were siliceous.

Two types of cement, supplied by the cement manufacturer Readymix-Asland, S.A. and defined according to the Spanish/European standard have been used [30]. Mixture KR incorporates 350 kg of cement type CEM I 42,5 R (rapid hardening) per cubic meter of concrete. This dosage is similar to that usually applied in precast members, as panels or slabs. Mixture SR incorporated 250 kg of cement type CEM II-B/M (V-L) 32,5 N (normal hardening) per cubic meter of concrete and refers to dosages used for cast-in-place surface members, as flooring slabs.

Both mixtures presented a dry consistency in the fresh state (slump < 3 cm).

Reference concrete compositions were modified with low volumetric fractions of two different dispersible Alkali-resistant (AR) glass fibers supplied by the manufacturer (Saint Gobain-Vetrotex España, S.A.). Both AR-glass fiber types are composed of monofilament fibers, have the same dimensions (12 mm long and 14 μm of diameter) and the ability of dispersing homogenously in fresh concrete when introduced in the mixer. Cem-fil Anticrack HD type is supplied dry in paper bags and Cem-fil Anticrack W70 is supplied wet in plastic bags.

Other nominal properties of AR-glass fibers are a Young modulus of 70 GPa and a density of 2.58 g/cm^3.

Table 2 presents the denomination and glass fiber type and amount incorporated to the ten compositions studied. The first letter of the composition's denominations refers to the Reference concrete composition (K or S). As the amount of fiber included was very low (600, 900 and 1000 g/m^3), it had no influence on the fresh state consistency of the mixtures.

Table 2
Fiber modified standard concrete and SCC mixtures. AR-glass fiber type and content (g/m^3) and cracked area results (Kraai slab modified test)

Mixture	Quantity and type of fiber (g/m^3)	Cracked area (mm^2/m^2)	Maximum crack length (mm)
Standard concrete			
KR	–	1254,05	2036 (branched)
KV6	600 [W70 (12 mm)]	410,18	126
KV9	900 [W70 (12 mm)]	378,33	170
KV10 (dry mixture)	1000 [W70 (12 mm)]	970,27	111
KV10 (wet mixture)	1000 [W70 (12 mm)]	1005,16	136
KHD6	600 [HD (12 mm)]	500,37	90
KHD10	1000 [HD (12 mm)]	928,01	128
SR	–	426,90	670
SV6	600 [W70 (12 mm)]	188,18	35
SV9	900 [W70 (12 mm)]	186,46	67
SV10 (dry mixture)	1000 [W70 (12 mm)]	397,62	84
SV10 (wet mixture)	1000 [W70 (12 mm)]	379,72	68
SHD6	600 [HD (12 mm)]	23,61	19
SHD10	1000 [HD (12 mm)]	262,07	98
Self compacting concrete			
AC-REF	–	1302,31	244
AC-HD6	600 [HD (12 mm)]	241,20	115
AC-HD9	900 [HD (12 mm)]	664,35	215
AC-HD9 (2)	900 [HD (12 mm)]	837,50	120
AC-HD12	1200 [HD (12 mm)]	316,57	135
AC-V6	600 [W70 (12 mm)]	365,74	160
AC-V9	900 [W70 (12 mm)]	323,33	120
AC-V12	1200 [W70 (12 mm)]	394,07	80

According to the manufacturer specifications, the incorporation of the fibers in the mixture can be done before, during or after concrete mixing. To facilitate a homogenous distribution of the fibers in the fresh concrete, the fibers have been incorporated in the dry mixture (before water inclusion). Though, one mixture with 1000 g/m^3 of W70 AR-glass fiber was prepared incorporating the fiber after the inclusion of water (wet mixture) in order to check the influence of fiber mixing method on the cracking experimental results.

2.2. Self compacting concrete

A SCC reference composition was designed, according to the typical dosage parameters of SCC described previously. Table 1 summarizes the components and dosages employed in the reference mixture (named as AC-REF). The aggregates, both coarse and sand, were siliceous, supplied dry in plastic bags by Readymix-Asland, S. A. and presented a very low natural humidity (under 1% in weight).

The reference SCC performance in the fresh state was evaluated, measuring the spread diameter on a simple slump test, in order to achieve the minimum diameter required to guarantee SCC flowability (650 mm). It was observed that: (a) the reference SCC achieved 700 mm of spread diameter, (b) no segregation occurred and (c) the coarse aggregate reached the perimeter of the tested sample.

The reference SCC (AC-REF) was modified with low volumetric fractions of the two different dispersible Alkali-resistant (AR) glass fibers described previously for standard concrete. Table 2 presents the denomination of the SCC compositions and glass fiber type and amount incorporated to the reference SCC composition. As the amount of fiber included was very low (600, 900 and 1200 g/m^3), it had no influence on the fresh state flowability of the mixtures.

3. Experimental methods and specimen preparation

A mechanical characterization of the standard concrete mixtures, including compressive and three point bending tests, were conducted at 1, 2–4, 7 and 28 days. A set of two specimens of the reference concretes K and S (without glass fiber) and with 600, 900 and 1000 g/m^3 of Cem-fil Anticrack W70 AR-glass fiber were tested.

On SCC mixtures, a mechanical characterization, including compression and ultrasonic Young modulus tests, were conducted at 1, 7, 14 and 20–28 days on 100 mm standard cubic specimens and 150 × 300 mm standard cylindrical specimens. A set of two specimens of the reference SCC (without glass fiber) and with 600 g/m^3 of Cem-fil Anticrack HD AR-glass fiber were tested. All the specimens, but the ones tested at 1 day, were water cured for 6 days, after being demolded at 24 h.

Non-destructive ultrasonic pulse tests were performed on SCC standard cylindrical specimens, which, afterwards, were tested in compression on an ICON 120 T test machine, to achieve a cubic-to-cylindrical specimens' compressive strength ratio.

Compressive tests were performed on sets of two standard cylindrical or cubic specimens on an ICON 120 T test machine and three point bending tests were performed on sets of two prismatic specimens (400 × 100 × 100 mm) with a span distance of 35 cm on an ICON 2 T test machine. All the specimens, but the ones tested at 1–4 days, were water cured for 6 days, after demolded at 24 h.

Free shrinkage tests were performed on both reference standard concrete and SCC mixtures. Fig. 1 presents the free shrinkage test setup.

Fig. 1. Free shrinkage test setup.

The shrinkage apparatus used consisted on a steel tray with internal dimensions of 500 × 100 × 50 mm and an electronic LVDT connected to a digital register, which records displacement measurements (in mm) every 30 min during the first 24 h. The shorter lateral sides of the tray (100 mm) are removable and have external indentations that remain inside the concrete sample when the tray is filled, acting as anchorages. One lateral was fixed to the tray while the other, which the LVDT is attached, can move freely as the concrete sample shrinks.

To facilitate concrete shrinkage, a demolding agent was applied on all pieces but the external indentations (anchorages).

Although it is not a standard test, this testing method was selected because it records the total shrinkage produced from the first moment, when concrete is cast in the tray, and allows the application of air flow over the sample.

Reference concrete samples where tested with and without air flow produced by a calibrated fan (air velocity of 3 m/s during the first 6 h).

Double restrained slab cracking test (Kraai modified test) [25,28] were performed on concrete samples of both reference standard and SCC compositions with and without different VF of AR-glass fibers, described previously. The cracking test apparatus consists on a wooden mold with internal dimensions of 900 × 600 × 50 mm and a calibrated fan (3 m/s air velocity).

The mold pieces were sealed and waterproofed, to avoid the loss of water of fresh concrete samples. A demolding agent was applied inside the mold.

Galvanized steel U shaped pieces (42 mm width, 35 mm wings, 125 mm length) were attached inside the mold, at 5 cm of the edge, acting as anchorages that restrained concrete displacement in the horizontal plane (double restraint).

Fig. 2 shows the standard concrete specimens preparation for the double restrained cracking test. The slabs were cast in the mold and compacted on a vibrating table, till water appeared on the free surface, before segregation occurs.

The slabs were tested at laboratory conditions (20 °C and 60% RH) and air flow was applied, during the first 6 h, on the free surface with a calibrated fan (air velocity 3 m/s) in order to evaporate all the water exuded due to concrete bleeding [1]. Fig. 3 presents the setup of the testing procedure.

After 24 h, the slabs were demolded and stored at laboratory conditions. The width and length of all cracks that had appeared on the exposed surface of the slab were measured at 7 days of age, using a comparison scale and a ruler, respectively. Although the main cracks were clearly visible on the slab surface at 24 h, the smaller cracks were difficult to measure, as the slab surface was still wet. For this reason, it was decided to settle a measurement procedure, in order to measure all the specimens at the same age. A one week period was selected. As the slabs were demolded always at 24 h, the double displacement restrain system did only apply during this period and a free shrinkage was allowed until the moment the cracks were measured.

In order to facilitate the measurement of cracks, the slabs were divided in eight parts, though the results correspond to the whole slab surface. The cracks measured were marked with ink to obtain a visible cracking map of the tested slabs. The cracked surface was observed using optical devices connected to an image acquisition digital system in order to analyze the relative position of cracks and fibers.

4. Experimental results

4.1. Standard concrete

Fig. 4 presents the compressive strength results of the cylindrical specimens of the reference concretes (without glass fiber) and concretes modified with different amounts of Cem-fil Anticrack W70 AR-glass fiber at several ages. Fig. 5 records the flexural strength results of the same concrete compositions.

Mixtures K achieved a compressive strength of 25 MPa at 28 days, while mixtures type S barely reached 20 MPa. As expected due to the type and amount of cement used, mixtures type K achieved higher strength than mixtures type S, though the difference decreases with age.

Fig. 2. Standard concrete specimen preparation for the double restrained slab cracking test (Kraai modified test).

Fig. 3. Double restrained slab cracking test. (Air flow velocity set to 3 m/s).

The inclusion of low amounts of AR-glass fibers slightly modifies the compressive and flexural strength of the reference concrete compositions. As described in the introduction, the low quantity of fiber incorporated did not produce a mechanical reinforcement of concrete.

Fig. 6 summarizes the free shrinkage test results of reference mixtures KR and SR with and without air flow. An air flow of 3 m/s significantly increased drying shrinkage in both mixtures. Samples tested without air flow produced shrinkage values of 0.05 and 0.02 mm/m (KR and SR, respectively), while shrinkage increased by 6 on samples tested with 3 m/s air flow velocity (0.32 and 0.12 mm/m respectively).

The results obtained from the modified Kraai test of slab cracked area (in mm^2/m^2) and maximum crack length for the different mixtures tested are summarized in Table 2. It can be observed that the values obtained for the reference concrete type KR are around 3 times larger than the values for the reference concrete type SR. In both reference mixture slabs, there were cracks that crossed the slab from side to side.

Figs. 7 and 8 present the results obtained in the double restrained cracking test of mixtures K and S respectively, taking the values of reference concretes as 100%, in order to evaluate the efficiency on cracking control of the different types and amount of fibers included [25]. In all the mixtures studied, the inclusion of AR-glass fibers reduced the cracked area and the maximum crack length.

Mixtures type K modified with 600 and 900 g/m^3 of AR Cem-fil Anticrack W70 glass fiber type produced a reduction of the cracked area of around 70%, while the mixture modified with 600 g/m^3 of AR Cem-fil Anticrack HD achieved a reduction of the cracked area of around 60%. Although, the same mixture with 1000 g/m^3 of both

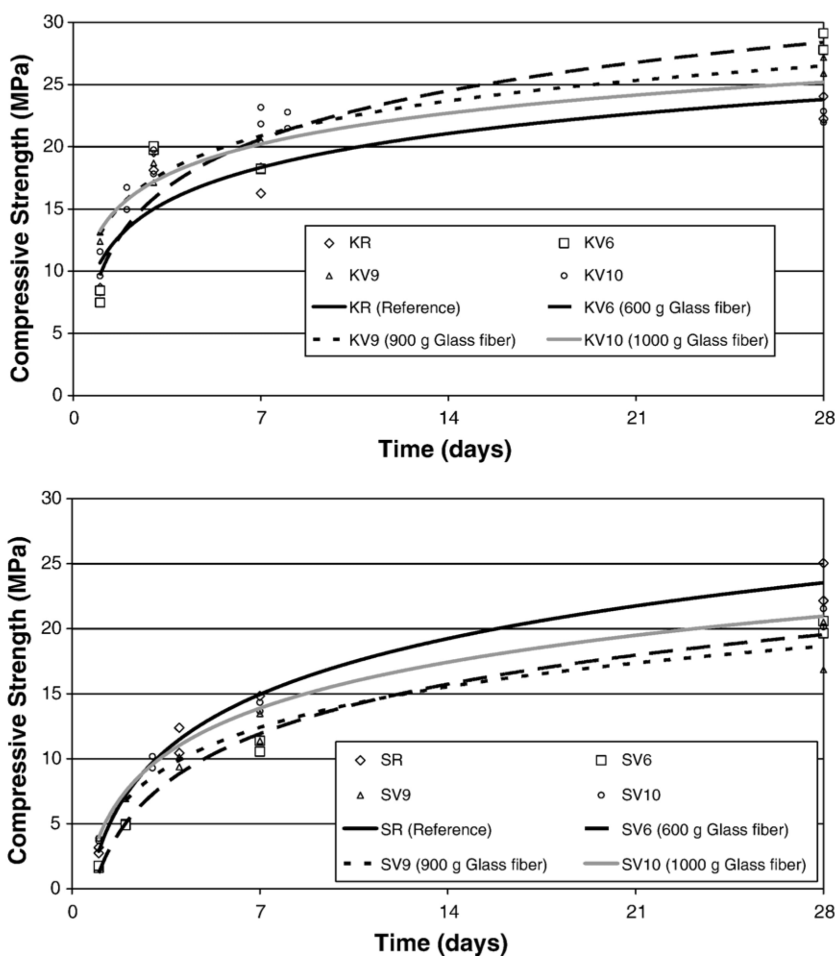

Fig. 4. Standard concrete mixtures K and S. Compressive strength test results (lines correspond to logarithmic approximations).

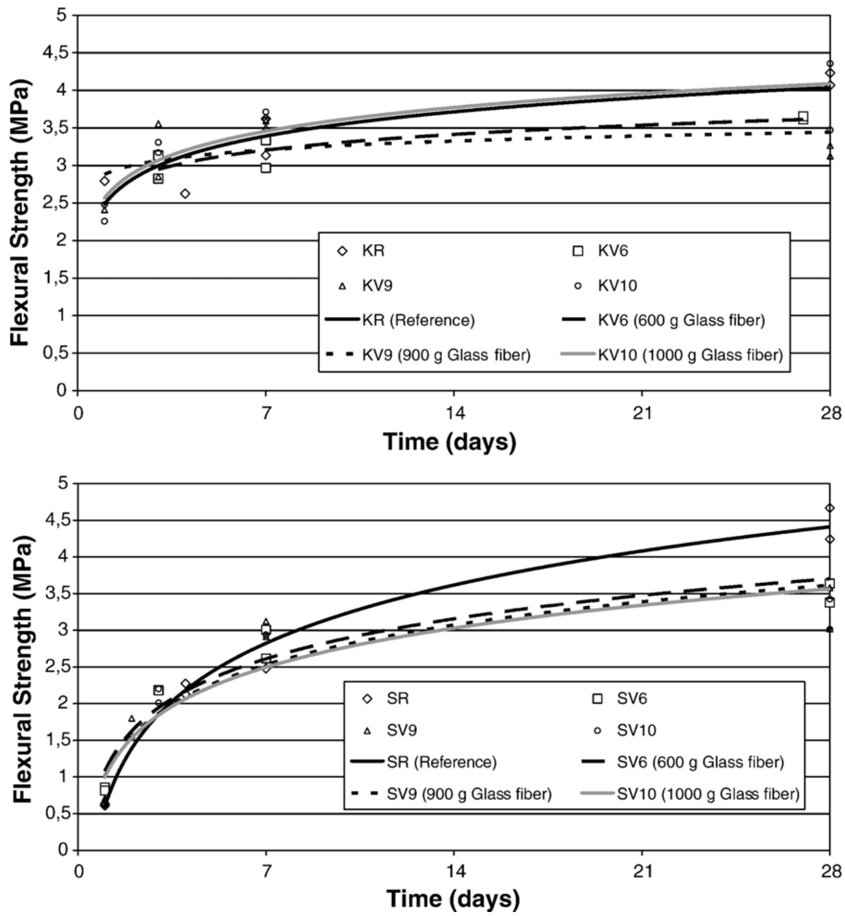

Fig. 5. Standard concrete mixtures K and S. Flexural strength test results (lines correspond to logarithmic approximations).

glass fiber types barely reached a reduction of 20–30%, in all cases a reduction of the cracked area was achieved.

Mixtures type S modified with 600 and 900 g/m^3 of AR Cem-fil Anticrack W70 glass fiber type produced a reduction of the cracked area of around 55%, while the mixture modified with 600 g/m^3 of AR Cem-fil Anticrack HD achieved a reduction of the cracked area of around 95%. As it happened in mixtures K, the same mixture with 1000 g/m^3 of both glass fiber types had shown a loss of effectiveness on cracking control (reduction of cracked area of 10% and 40% for types W70 and HD, respectively).

No difference on cracking control efficiency was observed either when 1000 g/m^3 of W70 type glass fibers were incorporated to the concrete mixing before water was added (dry mixture) or after its inclusion (wet mixture), for both reference mixtures under study.

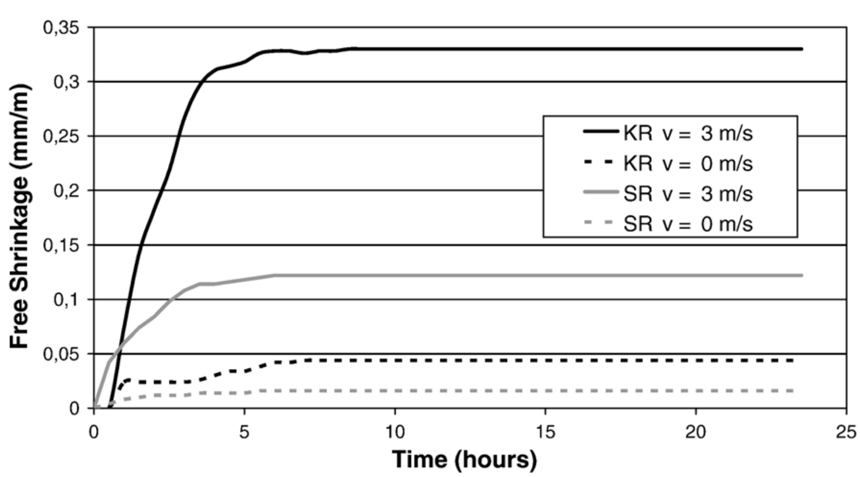

Fig. 6. Free shrinkage test results with and without air flow. Standard concrete mixtures KR and SR.

Independently to the type or amount of glass fiber, the inclusion of glass fiber produced a similar reduction of maximum crack length of around 90%.

Fig. 9 shows the cracked surfaces of tested slabs of concrete mixture type K modified with different amounts of AR Cem-fil Anticrack W70 glass fiber. It can be observed that the cracks did not present any principal direction, which accords with the double restraint of the cracking test.

The tested slabs' cracked surfaces were observed using optical microscopy devices. As it can be expected when short fibers are added to fresh concrete, independently to the constituent material of the fibers [9], two principal types of relative positions between cracks and fibers were observed: perpendicular and parallel.

Fig. 10 presents a micrography of a crack crossed by several glass fibers, perpendicular to the crack edges, which form bridges that limited the crack growth. Fig. 11 shows a micrography of a crack that had grown parallel to a fiber. This pattern was observed mainly on the slabs containing higher amounts of glass fiber.

4.2. Self compacting concrete

Fig. 12 summarizes the compressive strength results of the reference SCC (without glass fiber) and SCC modified with 600 g/m^3 of Cem-fil Anticrack HD AR-glass fiber on 100 mm cubic specimens at several ages. A set of two cylindrical specimens were tested at 28 days in order to obtain a cubic-to-cylindrical specimens' compressive ratio, achieving a value of 0.8. The reference SCC reached a compressive strength of 25 MPa at 28 days. As expected, the inclusion of fiber did not produce significant differences with regard to the reference composition.

The ultrasonic test results are presented in Fig. 13. They were calculated according to Eq. (1) [31]:

$$E_s = \rho \cdot v^2/1000 \qquad (1)$$

Where E_s is the ultrasonic modulus (MPa), ρ is the apparent density (g/cm^3) and v is the velocity of ultrasonic pulse propagation (m/s). The apparent density of SCC was measured, obtaining a mean value of 2.3 g/cm^3.

The inclusion of glass fiber did not modify significantly the Ultrasonic Young Modulus of SCC.

The free shrinkage test results of reference SCC, with and without air flow over the samples, are summarized in Fig. 14. When air flow was applied on the SCC sample, the free shrinkage increased from 0.3 to 0.75 mm/m. It can be observed that SCC shrinkage is several times greater than

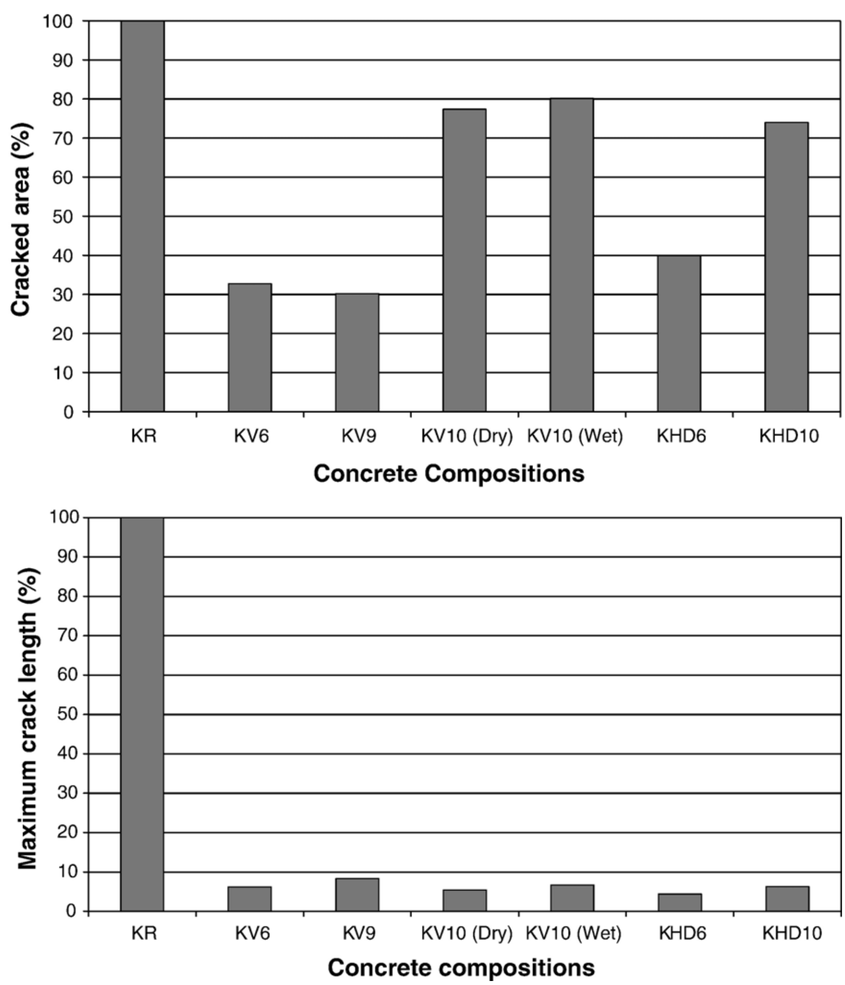

Fig. 7. Double restrained slab cracking test results. Standard concrete mixtures type K (reference concrete = 100%).

the correspondent to standard concrete (mixture KR), though the application of air flow did not increase shrinkage as much as on the standard concrete. A delay on the beginning of SCC shrinkage, with regard to standard concrete, can also be observed.

The results obtained of slab cracked area (in mm^2), cracked area (in mm^2/m^2) and maximum crack length (in mm) for the SCC mixtures tested, with and without AR-glass fiber, are summarized in Table 2.

Fig. 15 presents the results obtained in the double restrained cracking test of SCC mixtures, with and without AR-glass fiber, taking the value of reference SCC (without AR-glass fiber) as 100%, in order to evaluate the efficiency on cracking control of the different types and amount of fibers included.

In all the mixtures studied, the inclusion of AR-glass fibers reduced the cracked area and the maximum crack length. A reduction of 70–80% of the cracked area was achieved for all the SCC compositions with AR-glass fiber, except the mixture with 900 g/m3 of Cem-fil Anticrack HD type. Two slabs were tested with this composition and, in both cases, the reduction reached 40–50%. With regard to maximum crack length, the reduction was between 35–65%, except one of the slabs containing 900 g/m^3 of AR-glass fiber Cem-fil Anticrack type HD.

Fig. 16 shows the cracked surfaces of tested slabs of SCC modified with different amounts of AR-glass fiber. As it can be observed, the cracks did not present any principal direction, which accords with the double restraint of the cracking test used in this study.

Fig. 17 shows a comparison of cracked area and maximum crack length of SCC and a standard concrete with a similar mechanical performance (mixture K) modified with different amounts of both AR-glass fibers under study. SCC and standard concrete without fibers presented similar values of cracked area, though maximum crack length greatly differed. The inclusion of 600 g/m^3 of AR-glass fiber produced a minimum value of both cracked area and maximum crack length. Maximum crack length remains practically constant for larger fiber amounts.

5. Analysis and discussion of results

The reference standard concrete and SCC mixtures designed for the experimental program are similar to those used for precast and cast-in-place plane concrete members that are

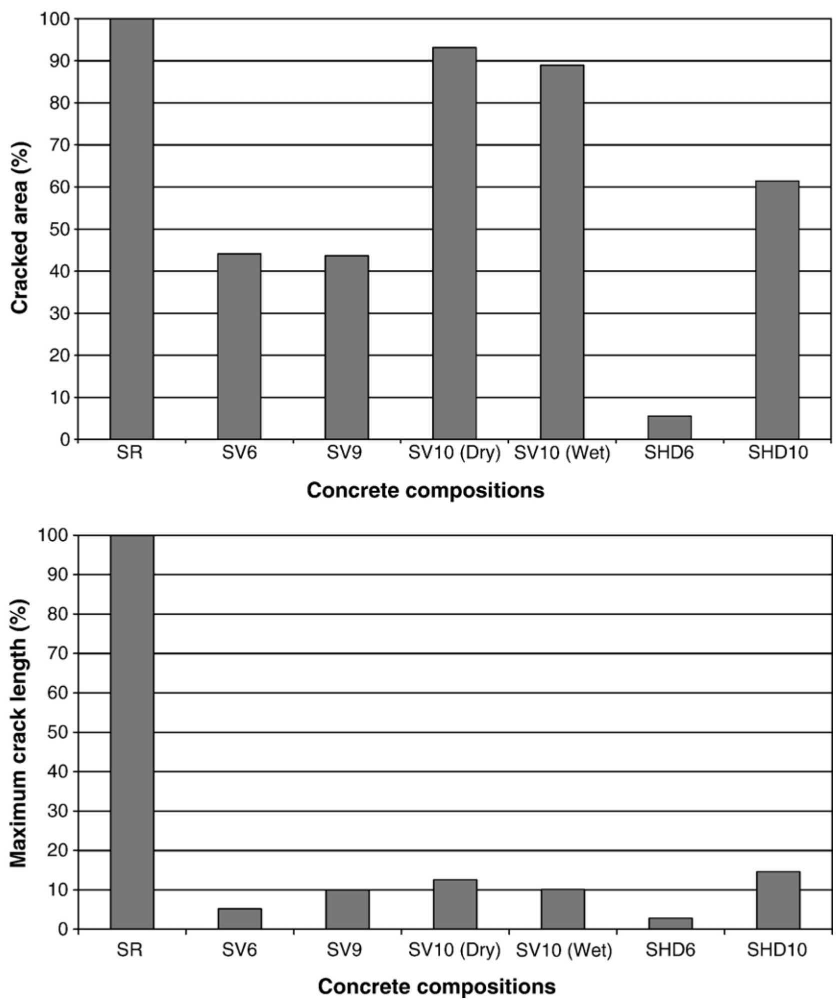

Fig. 8. Double restrained slab cracking test results. Standard concrete mixtures type S (reference concrete = 100%).

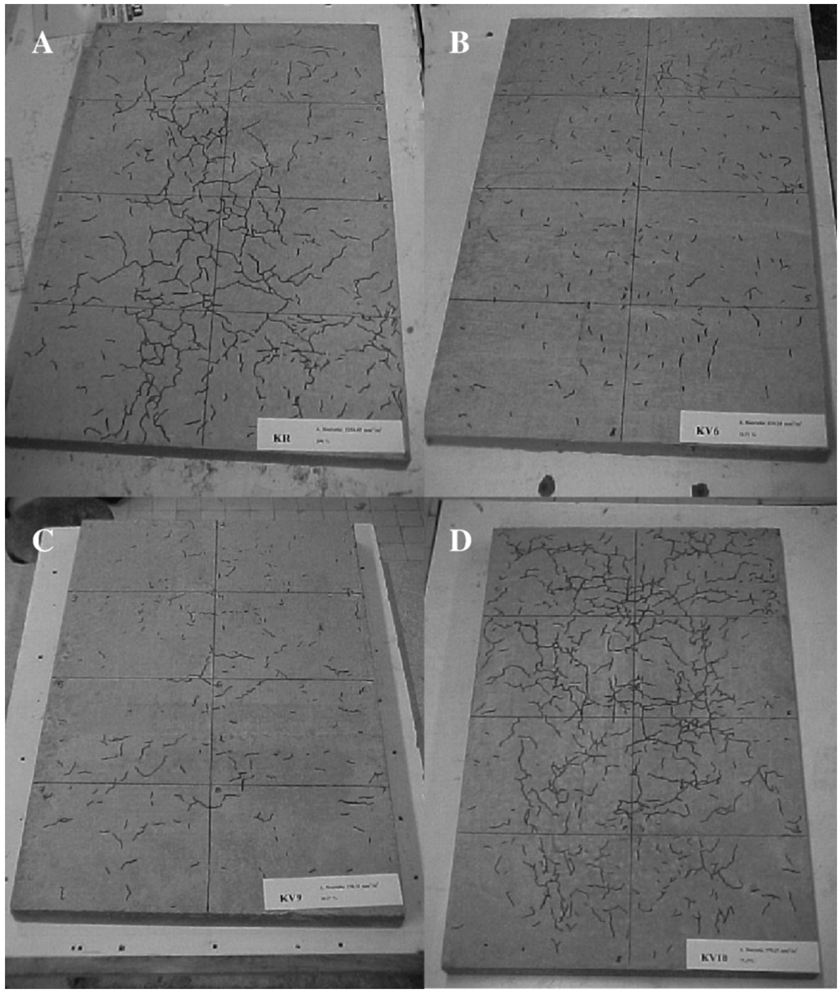

Fig. 9. Slab surfaces after the double restrained cracking test. Standard concrete mixtures K: (A) without glass fiber, (B) 600 g/m^3, (C) 900 g/m^{3}and (D) 1000 g/m^3. (Cracks have been marked with ink for better viewing).

highly cracking sensitive due to drying shrinkage. The inclusion of low amounts of AR-glass fiber did not modify significantly the SCC performance, neither its flowability in the fresh state nor its mechanical properties in the hardened state.

The free shrinkage test results at early age showed a great influence of air flow on drying shrinkage, though the beginning and end of shrinkage remained constant for each concrete type. As the other environmental parameters (temperature and relative

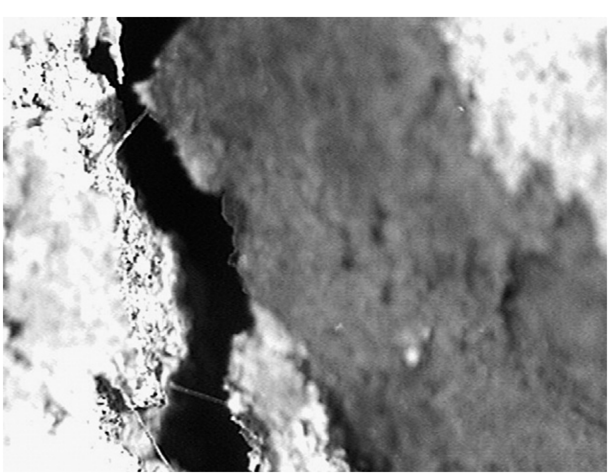

Fig. 10. Micrography of a crack sewed by several AR-glass fibers.

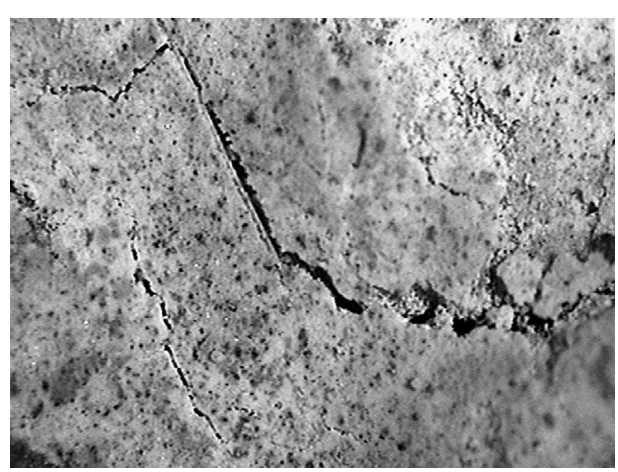

Fig. 11. Micrography of a crack parallel to a glass fiber.

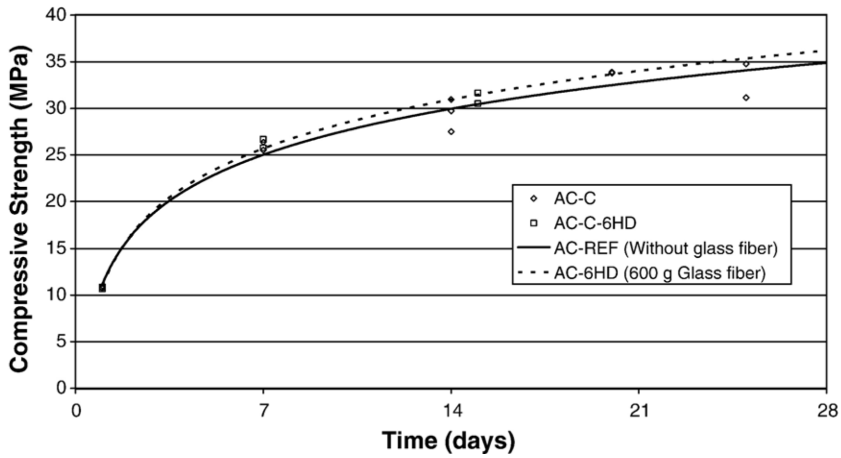

Fig. 12. Compressive strength test results of SCC with and without glass fiber, 10 cm cubic specimens (lines correspond to logarithmic approximations).

humidity) remained constant on both tests, the shrinkage values obtained had to be related mainly to drying, consequently, on the evaporation and, therefore, on the bleeding rate [1].

When compared to a standard concrete with the same type and amount of cement and a similar performance in the hardened state, SCC presented a larger drying shrinkage, independently to air flow velocity, though the increase of shrinkage due to air flow velocity was larger on standard concrete samples. As described in the introduction, SCC may show larger early age shrinkage and creep than standard concretes [9], although some authors reported a similar behaviour [17] and even a lower drying shrinkage at early ages of SCC with regard to standard concrete with similar performance in the hardened state [22]. These discrepancies could be related to the different fines used in each case.

A delay on the beginning of drying shrinkage in SCC samples, with regard to standard concrete, has been registered. This delay has been previously described [22]. As the measured shrinkage depended mainly on water evaporation, due to the free shrinkage test setup, the delay on the beginning of drying shrinkage registered in SCC samples, with regard to standard concrete, pointed to a delay of SCC bleeding.

Although the type and amount of cement used in the reference concrete compositions are different and, therefore, their mechanical properties and free drying shrinkage at early ages greatly differ, the cracking control ability of low amounts of the AR-glass fiber studied is very similar.

The incorporation of 600 g/m^3 of either AR Cem-fil Anticrack W70 or HD glass fiber in any of the reference concrete compositions reduced the cracked area by 50–95%, with regard the reference concrete (without fibers). Larger amounts of fiber did not show an increase of cracking control efficiency. It seems that, independent to the concrete composition, there is an optimum value of fiber amount around 600 g/m^3, for the AR-glass fibers under study.

But the cracked area alone does not describe the level of damage produced by concrete cracking. The maximum crack length measured on the tested slabs was drastically reduced when fiber was incorporated, especially on standard concrete (around 10% of the values for concretes without fibers in all cases).

The double restrained slab cracking test (Kraai slab modified test) shown a good performance as it achieved a high cracking sensitiveness for low variations of fiber amount, allowed the

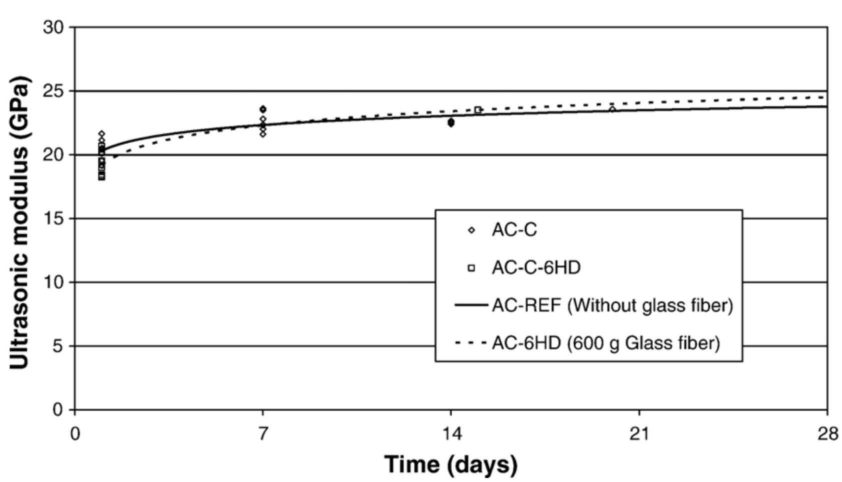

Fig. 13. Ultrasonic modulus test results of SCC with and without glass fiber. (Lines correspond to logarithmic approximations).

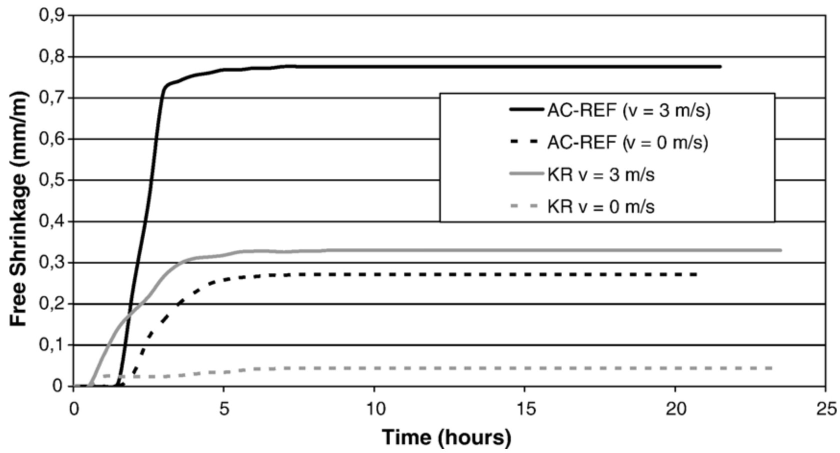

Fig. 14. Free shrinkage test results with and without air flow of SCC and standard concrete (mixture K) at early age (first 24 h after casting).

application of air flow on an extensive concrete free surface and reproduced a restraint of displacement similar to real concrete member casting. The cracking distribution on the slab exposed surface, which did present a random pattern without any principal direction, confirms this affirmation.

The cracking results recorded for SCC slabs modified with both AR Cem-fil Anticrack W70 and HD glass fibers shown a reduction of cracked area and maximum crack length, with regard to SCC without fibers, which proves AR-glass fiber cracking control ability.

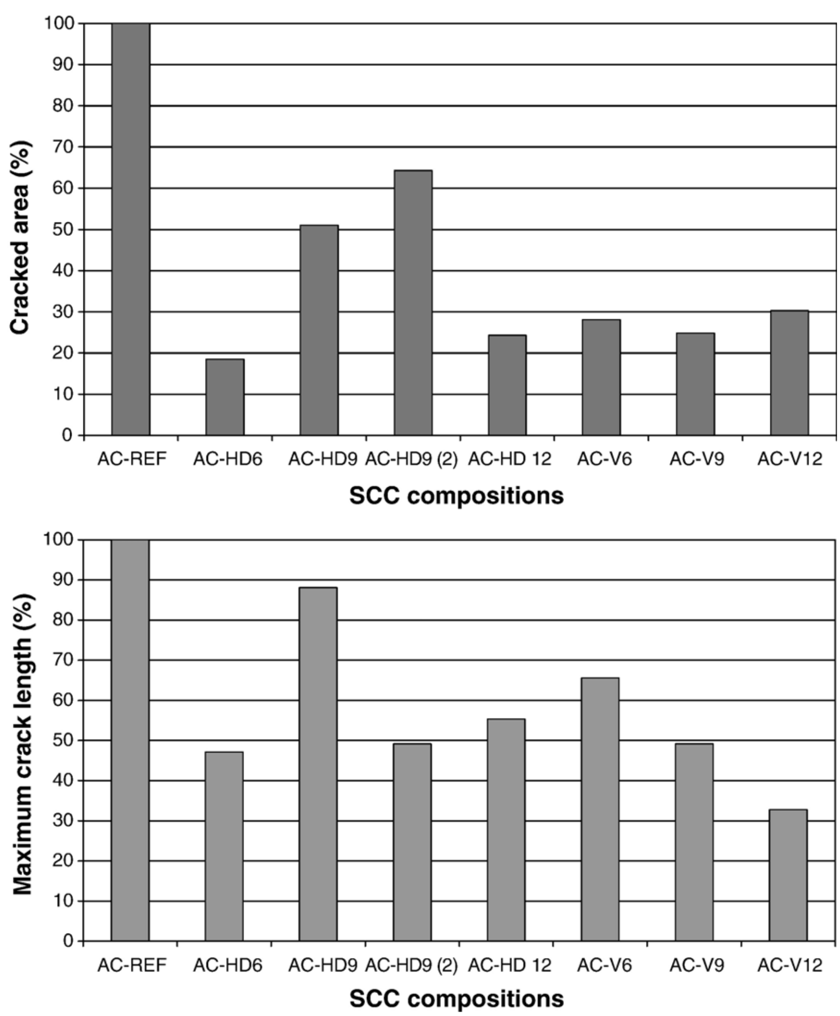

Fig. 15. Double restrained slab cracking test results of SCC modified with short AR-glass fibers (Reference SCC = 100%).

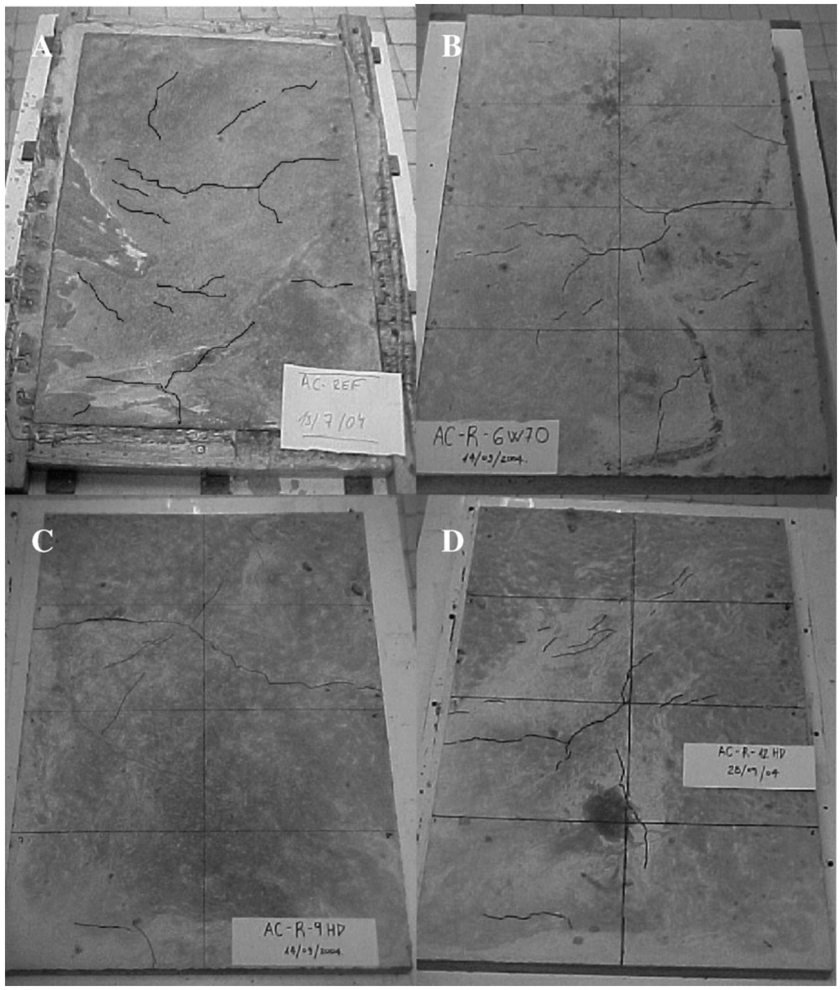

Fig. 16. Slab surfaces after the double restrained cracking test of SCC: (A) without glass fiber, (B) 600 g/m^3 AR-glass fiber type W70 (C) 900 g/m^3 and (D) 1200 g/m^3 AR-glass fiber type HD (Cracks have been marked with ink for better viewing).

The incorporation of 600 g/m^3 of either AR Cem-fil Anticrack W70 or HD glass fiber in the reference SCC composition reduced the cracked area by 70–80%, with regard to the SCC without fibers. Larger amounts of fiber did not show an increase of cracking control efficiency, as it occurred for standard concretes.

When cracking performance of standard concrete and SCC are compared, it can be observed that there is not a linear relationship between drying shrinkage and cracked area. Although SCC specimens shown larger shrinkage, both standard concrete and SCC, with and without AR-glass fiber, presented similar results of cracking area.

It seems that, independently to the concrete composition, for the AR-glass fibers under study, there is an optimum value of fiber amount around 600 g/m^3.

With regard to the maximum crack length, though in standard concrete without fibers is larger than in SCC, similar values were obtained for both compositions when low amounts of both types of AR-glass fiber studied were incorporated. This fact is related to the concept of local reinforcement, because fibers can act as a local reinforcement only after cracking has occurred, when fibers can make use of their mechanical capacity to avoid crack opening and growth, and, therefore, control concrete cracking.

An analysis of the slab cracked surface shown that there are two main patterns of relative positions between cracks and fibers. When the crack appears perpendicular to a fiber, the fiber can act as a local reinforcement, sewing the edges of the crack and controlling crack growth. This situation can explain the concrete cracking control efficiency of the AR-glass fibers studied.

The second pattern corresponded to cracks that grow parallel to a fiber (the fiber is there before concrete cracks). The growth of a crack parallel to a fiber, producing debonding, implies that the bonding strength between fiber and concrete matrix has been overload.

As the fibers were dispersed homogenously and randomized in all directions in the concrete matrix (no accumulations of fibers were observed) and this second pattern appeared mainly in the slabs with 1000 g/m^3, which presented a loss on cracking control efficiency, it can be deduced that both facts, crack pattern and amount of fiber, are related. Further research is needed in order to understand this anomalous behaviour.

6. Conclusions

Two standard concrete and one SCC composition, similar to those used for precast and cast-in-place plane members were

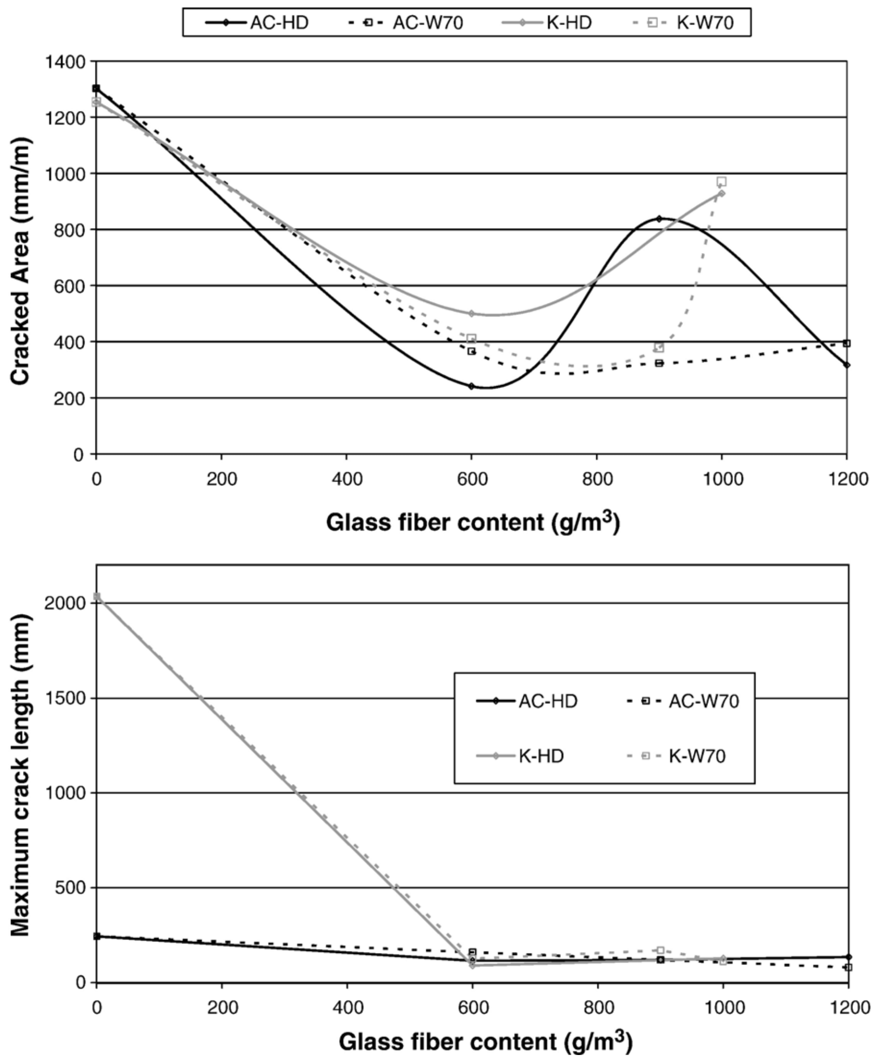

Fig. 17. Comparison of cracked area and maximum crack length of SCC and standard concrete (mixture K) modified with low amounts of short AR-glass fibers.

designed and modified with low amounts of two types of short AR-glass fibers. Although the type and amount of cement used in the reference concrete compositions are different and, therefore, their mechanical properties and free drying shrinkage at early ages greatly differ, the cracking control ability of low amounts of the AR-glass fiber studied is very similar. The low amount of glass fiber incorporated can not be considered as reinforcement and the mechanical behaviour was similar for mixtures with and without fibers.

The inclusion of low amounts of fiber did not modify significantly the SCC performance, neither its flowability in the fresh state nor its mechanical properties in the hardened state.

The inclusion of short glass fibers produced a reduction of the cracked area and maximum crack length measured in a double restrained slab test (Kraai modified test), with regard to concrete mixtures without fibers. Amounts of glass fiber around 600 g/m^3 shown the maximum cracking control ability, but larger amounts did not increase the fiber efficiency. Therefore, there is not a linear relationship between fiber amount and cracking control efficiency.

The SCC composition studied show larger free drying shrinkage at early age than a standard concrete with the same type and amount of cement and similar mechanical performance. A delay on the beginning of shrinkage of SCC, with regard to standard concrete, was recorded and could be related to a delay on SCC bleeding. Though drying shrinkage depends greatly on air flow velocity, no variations on the beginning of shrinkage were observed due to air flow application.

When comparing standard concrete and SCC performance it can be observed that, although free shrinkage greatly differs, the cracking area measured in a double restrained slab test was similar. This fact indicates that, although cracking at early age can happen due to drying shrinkage, both concepts are not linearly related.

The results of maximum crack length pointed out that low amounts of the AR-glass fibers studied can control cracking due to drying shrinkage at early ages, acting as a local reinforcement when concrete cracks.

As it happens with any type of short fibers when added to fresh concrete, two main patterns of relative positions between fibers and cracks were observed. When a crack grows perpendicular to a fiber, its cracking control capacity is high and can limit crack growth. If the crack appears parallel to a fiber, it can progress easier, producing debonding between fiber and concrete matrix.

Further research on the interaction between short fibers and concrete matrix at early age is needed in order to understand the cracking control ability of low amounts of fiber.

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