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EXPERIMENTAL STUDY ON CRACKING BEHAVIOUR OF FIBER REINFORCED CONCRETES BY RING TEST

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***Abstract*—In this work the influence of different kinds of fibers on Fiber Reinforced Concrete (FRC) cracking behaviour was examined. Several FRCs were prepared by alternatively using steel fibers, polypropilene macro-fibers, glass macro-fibers, hybrid or bicomponent synthetic fibers. The fibers' dosage was always equal to 0,55% by volume. As reference, a mixture with the same mixture proportions but without fiber reinforcement was prepared and tested. Ring test according to ASTM C 1581–04 and free shrinkage test were carried out in the same exposure conditions: 21°C and 50% relative humidity. Moreover, compressive and tensile strengths of FRCs, as well as their elastic modulus, were evaluated on cubic specimens up to 28 days of curing, and, in particular, also at the time of ring cracking. In this way, other important information could be extrapolated by introducing these experimental data in suitable numerical model of the ring concrete specimens available in the literature. This procedure enables to study the influence of the kind of fibers on the potential for early-age cracking of concrete, as well as to identify the effect of tensile creep on concrete cracking. Results obtained showed the effectiveness of the randomly dispersed fibers in counteracting the FRC early cracking.**

Keywords—Fiber Reinforced Concrete, Post-cracking Behaviour, Restrained shrinkage, Ring Test, Synthetic Fibers, Tensile creep effect.

I. Introduction

Concrete cracking at early ages is a significant problem for many concrete structures and in particular, for bridge decks. The presence of cracking can reduce the service life of a concrete structure by allowing aggressive agents to penetrate through it faster in easy ways. This obviously leads to increases in maintenance costs.

Free shrinkage evaluation alone is not enough to determine if cracking can be expected in a structure since concrete creep, stiffness and toughness also influence the potential for cracking. Consequently, it is rather interesting to perform restrained shrinkage tests, such as the ring test according to ASTM C 1581–04 [1]. The testing procedure involves concrete ring specimens restrained by an inner steel ring on which strain gauges are placed to determine the age of cracking, since abrupt changes in the steel strain occur when concrete is cracked.

Moreover, this test could be able to evaluate the viscoelastic behaviour of early-age concretes which strongly influences concrete vulnerability to cracking.

From the literature it is widely recognized that creep and shrinkage are not independent phenomena even if their main causes are completely distinct, mechanical and hygrometric respectively. As a matter of fact, some other effects can play an important role, for example, the drying creep, also called the Pickett effect, which is the increase in creep of specimens when exposed to drying [2]. This phenomenon was recently demonstrated for early-age concrete subjected to tensile load induced in restrained shrinkage tests [3], and its dependence on surface microcracking and stress-induced shrinkage was observed.

In the early days, concrete undergoes very fast and strong changes that make the interpretation of its behaviour complex. For example, in order to measure basic creep of concrete, it is not enough to seal it to hinder water evaporation because sealing cannot eliminate autogenous shrinkage which mainly develops at early age. Concerning with the early-age tensile creep response of concrete, it has been scarcely reported in the literature, primarily because the required experiments are considerably more difficult to perform than those for creep in compression. However, detailed knowledge on the tensile creep behaviour at early ages is important for estimating the possibility of cracking due to plastic shrinkage and thermal stress. Altoubat and Lange [4] showed how creep in compression and in tension are strongly dependent on the age of concrete when it is loaded, in particular within the first 2 days after setting.

According to ACI 544.1 [5], the use of fibers as concrete matrix reinforcement may enhance many properties of concrete including tensile strength, compressive strength, elastic modulus, crack resistance, crack control, durability, fatigue life. In fact, fiber reinforcement has been suggested as an effective method to mitigate early-age cracking in concrete, since fibers increase toughness of concrete, which typically manifests itself by a reduction of crack width and increased energy absorption during failure. In [6], an attempt was made to use ring test to quantify the effectiveness of steel fibers in delaying the age of cracking.

II. Research significance

In this work an experimental campaign was carried out in order to evaluate the viscoelastic behaviour of early-age FRCs, which strongly influences concrete vulnerability to cracking.

In particular, the attention was focussed not only on steel FRC

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but also on different kinds of macrofibers, in order to compare their effectiveness in retarding concrete cracking, also with respect to a reference mixture without fibers.

The time trends of compressive strength, tensile strength, elastic modulus, drying shrinkage were monitored up to 28 days of curing for all the tested mixtures on concrete specimens maintained under the same exposure conditions of the ring test (i.e. 21°C and 50% R.H.).

In this way, it was possible to know the values of compressive strength, tensile strength, elastic modulus, drying shrinkage of the FRC mixtures at the time of cracking of their related ring specimens. Consequently, some other important information could be extrapolated by introducing these experimental data in suitable numerical model of the ring specimens. In particular, the tensile creep effect on cracking behaviour of FRCs could be estimated, which is quite difficult to measure with other experimental equipment. However, tensile creep plays an important role in the viscoelastic behaviour of early-age concretes, which strongly influences cracking appearance, and consequently concrete durability.

III. Experimental campaign

Five different kinds of macro-fibers were compared:

- Hooked steel fibers; the fibers length is 30 mm and their aspect ratio is 48;
- Hybrid fibers, a mix of polypropylene (PP) macrofibres (with a structural function), and fibrillated PP microfibers (with a function of plastic shrinkage reduction); the fibers length is 54 mm and their aspect ratio is 113;
- Bicomponent fibers, with a sheath made of corrugated polypropylene and core made of glass; the fibers length is 50 mm and their aspect ratio is 100;
- Polypropylene Fibers; the fibers length is 50 mm and their aspect ratio is 100;
- Glass Fibers, with a content of ZrO_2 higher than 16% (for avoiding ASR), according to EN 15422 [7]; the fibers length is 36 mm and their aspect ratio is 67.

A. *Concrete mixture proportions*

All the mixtures were prepared with Portland-limestone blended cement type CEM II/A-L 32.5 R according to the EN 197/1 [8], at a dosage of 450 kg/m^3. The inert to cement ratio was equal to 3:1, corresponding to 1350 kg/m^3 of siliceous aggregate (0-8 mm).

Their detailed compositions are reported in Table 1.

The reference mixture without fibers was prepared with a water to cement ratio of 0.65 (corresponding to a water dosage of 290 l/m^3), and, in this way, a super-fluid (slump 200 mm) fresh concrete workability, measured according to EN 12350-2 [9], was obtained.

The same workability (slump 200 mm) was maintained for all the mixtures. When fibers were added, a 30% aqueous solution of an acrylic-based superplasticizing admixture was used, always at the same dosage of 0.6% by weight of cement, in order to compensate the workability loss due to the introduction of the fibers into the mixture.

TABLE I. CONCRETE MIXTURE PROPORTIONS (KG/M^3)

Mixtures	***Ref***	***StFb***	***HyFb***	***BiFb***	***PPFb***	***GlFb***
Water	290	290	300	280	280	290
Cement	450	450	450	450	450	450
Aggregate (0-8 mm)	1350	1350	1350	1350	1350	1350
Water/Cement	0,65	0,65	0,67	0,62	0,62	0,65
Inert/Cement	3	3	3	3	3	3
Superplasticizers	-	2.7	2.7	2.7	2.7	2.7
Steel Fibers	-	40	-	-	-	-
Hybrid Fibers	-	-	5	-	-	-
Bicomponent Fibers	-	-	-	5	-	-
Polypropylene Fibers	-	-	-	-	5	-
Glass Fibers	-	-	-	-	-	15

The water dosage was adjusted to fit the same slump value: in the case of the mixture containing hybrid fibers a little higher water dosage (300 l/m^3) was necessary to achieve the same workability of the other mixtures due to the presence of microfibers besides to macrofibers (see detailed description reported above); while in the presence of either bicomponent or polypropylene fibers a little lower water dosage (280 l/m^3) was enough to achieve the same workability probably thanks to the greater flexibility of these fibers with respect to both glass and steel fibers, which can be responsible for easier concrete flowability. Consequently, also water/cement ratios were slightly different from 0.65 (ranging from 0.62 to 0.67).

Fibers were alternatively added at the same dosage of 0.55% by volume of concrete, corresponding to 40 kg of hooked steel fibers, 5 kg of synthetic fibers and 15 kg of glass fibers, due to their different volumic mass (7.8 kg/m^3, 0.9 kg/m^3, and 2.7 kg/m^3, respectively).

B. *Mechanical characterization*

First of all the mechanical behaviour of FRCs was characterized. Compression tests according to EN 12390-3 [10] were carried out after 1, 7, x (where x is the time of cracking of the relative ring specimen), and 28 days of curing on three cubic specimens (100 mm side). The curing was carried out on the same exposure conditions of the ring specimen, that is 21±2°C and 50±2% relative humidity, in order to better interpret the results obtained from free and restrained drying shrinkage tests. Then, on the basis of the stress-strain curves obtained by compression tests, the chord modulus of elasticity was measured following the method outlined in BS 1881-5 [11], where it is defined as the slope of the stress–strain curve on loading between 1 MPa and one-third of the concrete compressive strength. Also splitting tension tests were carried out at the same curing times (1, 7, x, and 28 days) on five cubic specimens (100 mm side), in conformance with EN 12390-6 [12]; the curing conditions were the same of compression tests.

C. *Concrete characterization under either restrained or free drying shrinkage tests*

Among several specimen geometries reported in the literature for assessing cracking potential, due to its simplicity and versatility, the 'ring test' has become very common over the last 30 years. The major advantage of this kind of test is that it keeps into account all the factors influencing early concrete cracking, i.e. the development of stress, the dimensional changes and the concrete viscous behavior.

In this work, the ring test was carried out following the suggestion of the standard ASTM C 1581–04, however, similarly to previous experimental works [13, 14] some geometry modifications were made: the thickness of the concrete ring (50 mm) used in this work was larger than that suggested by the ASTM standard (38 mm). The height of the rings was 150 mm as suggested by the ASTM standards.

The specimens were cast around a steel ring, using a cardboard tube as an outside mould (see Fig. 1). Immediately after demoulding the external cardboard ring, at the age of 1 day, the top surface of the ring specimens was epoxy-coated. This procedure creates a condition that allows drying just from the outer circumferential surface, since the plastic base automatically seals the bottom surface of the concrete ring. In this way, the only concrete surface in contact with the conditioned environment (i.e. 21±2°C and 50±2% relative humidity), available for free water evaporation, was the external cylindrical surface of the ring.

Two ring specimens were cast for each mixture, but only one of them was instrumented by four strain gauges to determine the first crack, shown by an abrupt loss in compressive strain in the steel tube. The four strain gauges were wired to a data acquisition system. Steel ring strain measurements were monitored from the casting time, having the subsequent readings taken every half-an-hour until the concrete ring cracked.

In addition, prismatic specimens (100 x 100 x 500 mm) were prepared for free drying shrinkage test, according to Italian Standard UNI 6555-73 [15]. In order to have the same ratio of the exposed surface to volume of the ring specimen, the lateral surfaces of the prisms were partially epoxy-coated. After one day of wet curing, the specimens were stored at constant temperature (21±2°C) and relative humidity (50±2%).

IV. Experimental results

A. *Concrete mixture proportions*

Results obtained from the compression tests are reported in Table 2.

On the basis of the water to cement ratio (0.65) and the kind of cement (32.5 R) adopted, the expected 28-day strength for these concretes should be in the range 25-30 MPa. Moreover, the presence of a high amount of fibers could increase this value up to +10%. When the water to cement ratios were either slightly higher (mixture HyFb) or slightly lower (mixtures BiFb and PPFb), the compressive strength values changed as expected.

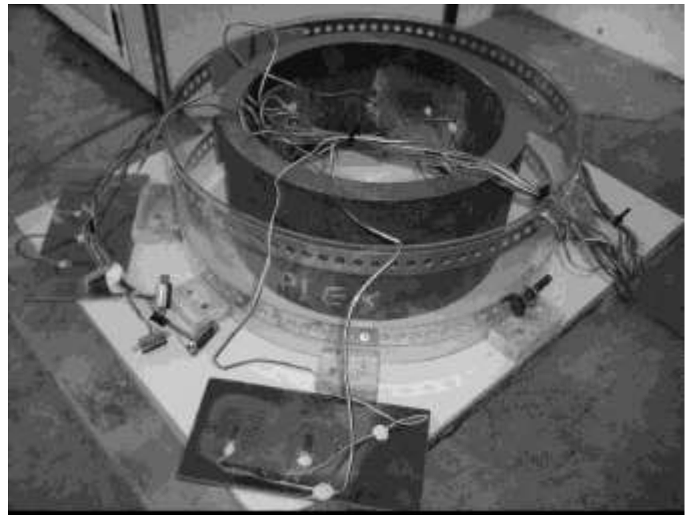

Figure 1. Experimental apparatus used for the ring test.

Also results obtained from splitting tension tests are reported in Table 2, in terms of mean value ± standard deviation (obtained from five specimens for each mixture). The values of the maximum splitting tensile strengths were roughly the same for all the FRC mixtures, except for that prepared with bicomponent fibers. In fact, the post-cracking behavior of BiFb mixture was excellent, with remarkable strain hardening, causing higher tensile strength than that measured in the elastic pre-cracking phase (see Fig. 2, where one load vs. displacement curve was reported for each mixture). The reason probably lies in their optimized geometry (aspect ratio equal to 100), in the scabrous surface of their sheaths, as well as in their cores (characterized by high young modulus).

TABLE II. EXPERIMENTAL RESULTS OBTAINED AFTER 1, 7, 28 AND X DAYS OF EXPOSURE (X = DAYS OF CONCRETE RING CRACKING)

	Mixtures	*Time of exposure (Days)*					
		1	***2***	***4***	***7***	***24***	***28***
Compressive strength (MPa)	Ref	7.43	12.06	-	19.55	-	24.45
	StFb	10.20	-	-	28.91	-	32.12
	HyFb	9.92	-	-	21.62	-	23.90
	BiFb	10.41	-	31.39	36.20	-	38.42
	PPFb	12.00	-	-	30.10	35.24	37.76
	GlFb	11.86	-	-	30.10	32.45	33.31
Chord elastic modulus (GPa)	Ref	2.64	11.27	-	12.67	-	29.83
	StFb	18.32	-	-	32.12	-	42.85
	HyFb	10.79	-	-	21.18	-	34.87
	BiFb	16.07	-	24.56	31.67	-	44.36
	PPFb	22.00	-	-	30.38	40.78	43.56
	GlFb	9.07	-	-	24.24	31.25	33.68
Tensile strength (MPa)	Ref	0.27±0.02	1.18±0.12	-	1.43±0.12	-	1.92±0.18
	StFb	1.12±0.09	-	-	2.04±0.18	-	2.56±0.21
	HyFb	0.67±0.11	-	-	1.63±0.27	-	1.69±0.36
	BiFb	1.07±0.15	-	2.22±0.32	2.63±0.42	-	3.14±0.76
	PPFb	0.80±0.07	-	-	1.69±0.19	2.15±0.23	2.28±0.23
	GlFb	0.87±0.08	-	-	2.06±0.20	2.05±0.22	2.19±0.21

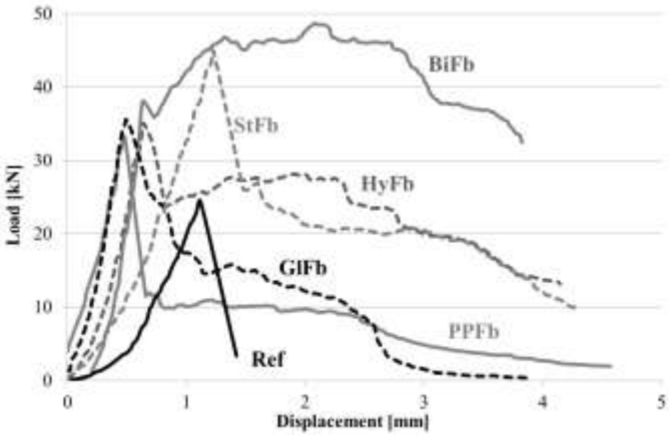

Figure 2. Splitting tension tests after 28 days: load vs. displacement.

Concerning the values of standard deviations, higher dispersion of results was detected for the mixtures prepared with either hybrid or bicomponent fibers, which showed lower degree of homogeneity indeed.

B. *Free drying shrinkage test*

Results obtained from free drying shrinkage tests are reported in Fig. 3.

If compared with the Ref mixture, it is quite evident the effectiveness of whichever kind of fibers used: the 28-day drying shrinkages measured for the FRC mixtures were always lower than 600 μm/m, while for the Ref mixture was equal to 680 μm/m.

The slight differences detected among the various mixtures are under the experimental uncertainty threshold, except for the mixture containing steel fibers, which after 28 days still showed drying shrinkage strain less than 400 μm/m.

C. *Ring test*

Results obtained from the ring tests carried out on the six mixtures are reported in Fig. 4, they are expressed as steel ring strains vs. exposure time. For simplicity, only the values measured by one strain gauge (among four at all) for each instrumented concrete ring has been reported in the Figure 4.

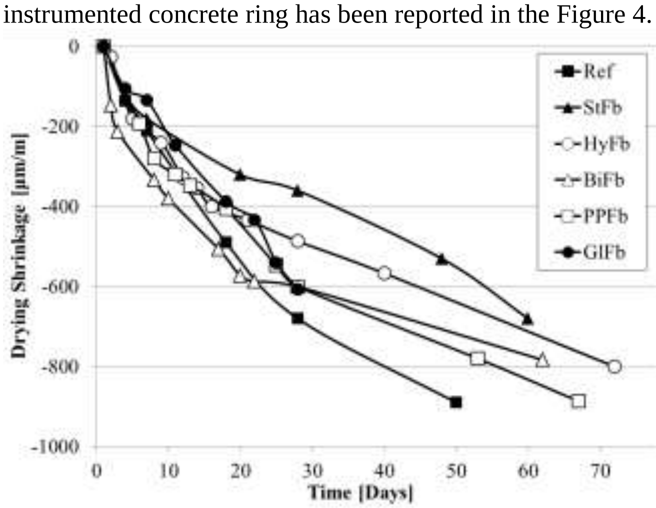

Figure 3. Drying shrinkage measurements vs. exposure time.

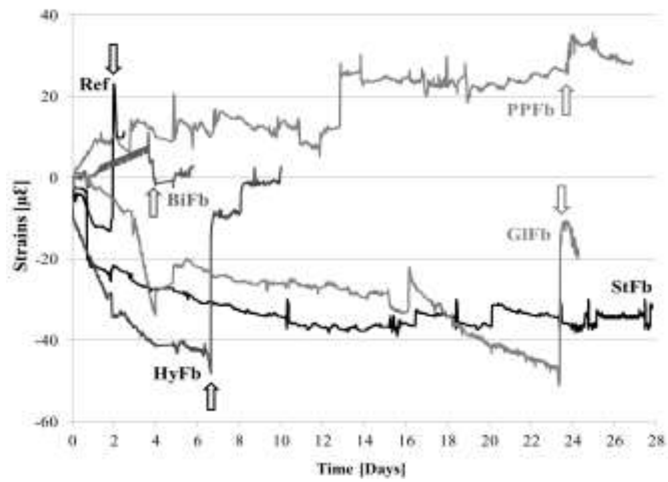

Figure 4. Strains measurements on steel ring vs. time of exposure for the six mixtures (arrows indicate concrete cracking).

A visual inspection of the ring specimens was daily carried out in order to confirm the appearance of cross cracking, corresponding to an energy release, and to a significant jump on the strains measured on the inner steel ring by strain gauges. As outlined before, two ring specimens were prepared for each mixture, of which only one ring was instrumented by strain gauges. However, the visual inspection was carried out on both rings for confirming the time of crack appearance. The difference in time of first macrocracking detected between the two rings related to the same mixture were always short, within few hours.

For the mixtures Ref, HyFb and BiFb the jump confirm the appearance of cross cracking (indicated in Fig. 4 by means of an arrow) is quite evident, and it appears after 2, 7 and 4 days of testing, respectively.

On the other hand, more complicated is the interpretation of the other three mixtures test results. In fact, a series of subsequent jumps were measured, but only after longer time the cross cracking could be visually detected: after 24 days for both PPFb and GlFb mixtures, and for the mixture StFb this cracking wasn't even registered at all, at least during the test period, that was 28 days. The reason could be the formation of many micro-cracks diffused in the volume of the ring specimens, but still not able to coalesce among them to create a visible macro-crack. The mixture StFb was also that showing the lower values of free drying shrinkage strains indeed.

However, the reason for this strong different behavior among the various kinds of fiber used could be the ascribed to a different degree of concrete homogeneity. In fact, for the mixtures HyFb and BiFb, despite of the same level of fresh concrete workability with respect to the other concrete mixtures, a good dispersion of hybrid and bicomponent fibers seemed more difficult to be obtained, due to the particular fiber geometry characteristics. If fibers were not well distributed, the presence of a weak section within the ring specimens without fibers (or with a very low number of fibers) could have been responsible for the early concrete ring cracking detected, just few days longer than that measured for the unreinforced reference mixture (Ref). This lack of homogeneity for the mixtures HyFb and BiFb was confirmed by a visual inspection of the cracked sections of the four ring

specimens (two for each mixture). In all the cases the sections appeared poor of crossing fibers, while in other portions of the specimens the number of fibers was evidently higher. This hypothesis was confirmed also by the higher dispersion of the results obtained by means of splitting tensile test for these two mixtures (see the values of standard deviations in Table 2).
However, in order to better interpret the results of ring tests, the data obtained during the experimental campaign were introduced in numerical models of the ring concrete specimens available in the literature, which are briefly resumed in the next paragraphs.

V. Analytical and numerical models of the ring specimen

In order to describe the behavior of the restrained concrete ring subjected to shrinkage, one-dimensional, two-dimensional and three-dimensional models were proposed in the literature. In particular, the 2-dimensional model is based on the theory of the plane stress state so that the 3-dimensional specimen is studied with a two-dimensional domain. The assumption of plane stress state is justified by the application of a thin layer of form-release agent, which hinders adhesion between steel and concrete. The viscoelastic behavior is considered for the concrete ring while the linear elastic behavior is considered for the steel ring. As in the previous case, under the shrinkage action, the problem is axisymmetric and the only unknown of the problem is the radial displacement of the mean plane of the rings. The solving equation is provided by the local radial equilibrium condition. In this case both radial and circumferential stresses can be calculated as a function of the concrete shrinkage. The mean circumferential stress in the concrete ring, calculated by the strain measured by the strain gauges $\varepsilon^{s}_{\vartheta}$, is given by the expression:

$$\sigma^{c}_{\vartheta\,mean}(t) = -\varepsilon^{s}_{\vartheta}(t)\frac{E_s}{2}\frac{R_2^2-R_1^2}{(R_3-R_2)R_2} \qquad (1)$$

VI. Discussion of experimental results based on ring specimen numerical models

On the basis of the results obtained from the experimental part, the tensile strength of the concrete after a certain curing time can be compared to the circumferential stress induced by drying shrinkage on the concrete ring at the same time, which can be estimated by means of the bidimensional model and the circumferential stress was calculated by the Eq. (1).
Some examples of these comparisons are reported in Figures 5-10, related to the mixture prepared with the various kinds of fibers, and referred to the time of concrete ring cracking (the only exception is Fig. 6, in which the 28-day deadline was chosen, because the StFb mixture was still uncracked at that time). In these figures the circumferential stresses are reported as a function of the circumferential radius, r (mm), which is equal to 152 mm for the external steel ring corresponding to the internal concrete ring, and equal to 202 mm for the external concrete ring (with a concrete thickness of 50 mm).
The circumferential stress can also be theoretically calculated on the basis of the only drying shrinkage effect (without taking into account creep relaxation), by following the model proposed by Hossain & Weiss [16], in which the experimentally measured values of both free drying shrinkage and elastic modulus of concretes must be introduced. The values obtained as a function of the circumferential radius are reported in grey in Figs. 5-10.

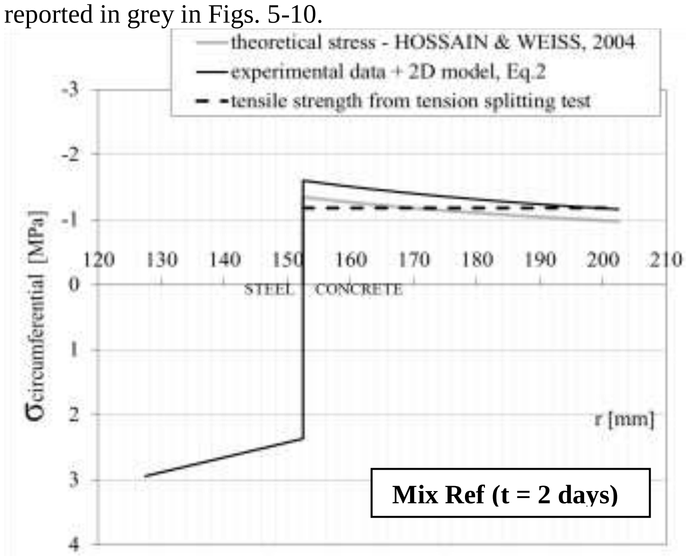

Figure 5. Comparison among theoretical and experimental circumferential stresses for the Ref mixture after 2 days (time of concrete ring cracking).

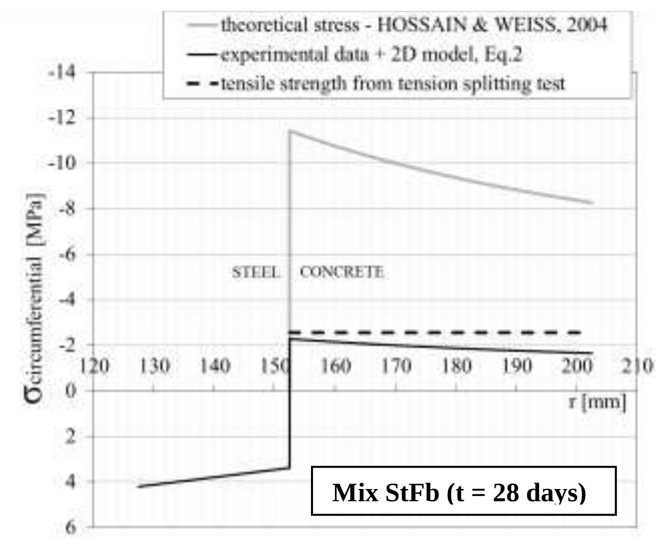

Figure 6. Comparison among theoretical and experimental circumferential stresses for the StFb mixture after 28 days (concrete uncracked).

These values are necessarily different from what can be estimated by introducing in Eq. (1) the mean value of the steel strains, measured by four strain gauges for each mixture (stress values reported in black in Figs. 5-10). The last can be considered the real circumferential stress (including both drying shrinkage and tension creep effects), which develop in the ring specimens.

As it can be seen in Figs. 5-10, the level of the experimental circumferential stresses in the concrete rings are just a little higher than the tensile strengths measured by means of tension splitting test on the material at the same age (dotted line in Figs. 5-10), confirming the visual appearance of cracking for these mixtures. The only exception is the mixture StFb reported in Fig. 6. In fact, by confirming the validity of the approach used, this mixture resulted still sound after 28 days of testing.

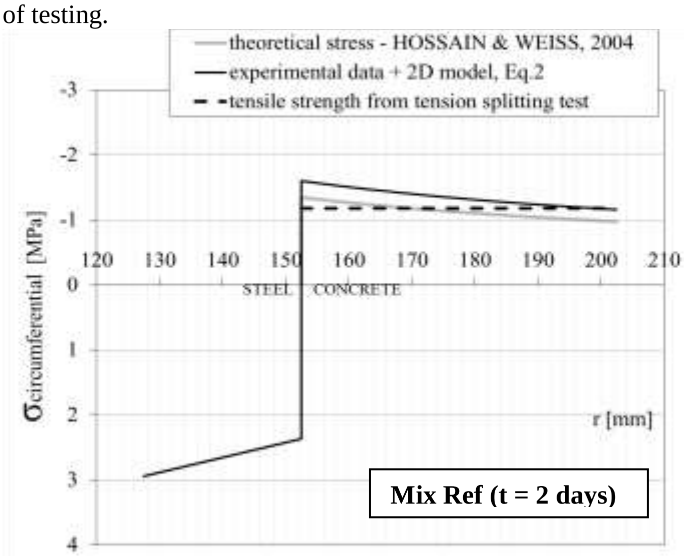

Figure 7. Comparison among theoretical and experimental circumferential stresses for the Ref mixture after 2 days (time of concrete ring cracking).

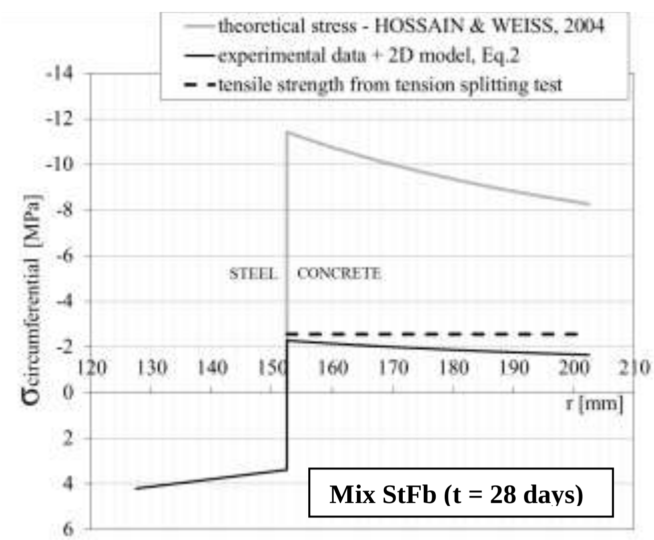

Figure 8. Comparison among theoretical and experimental circumferential stresses for the StFb mixture after 28 days (concrete uncracked).

The remarkable differences between the circumferential stresses calculated by the formula suggested by Hossain & Weiss [16], and the real circumferential stresses in the concrete ring are due to the tensile creep contributions, which can be estimated from there. As you can see by comparing the distance between grey and black lines in Figs. 5-10, the tensile creep contribution grows with increasing time of exposure, regardless the type of concrete. In particular, for the Ref mixture the time of cracking was so short (2 days) that the contribution of tensile creep was negative. The reason probably is that during the first hours after casting, due to the heat of hydration developed by the reaction of cement and water inside the concrete ring, there is a certain thermal expansion of the concrete producing little initial compression of the restrained concrete ring and, consequently, at early age the evaluation of the tensile creep effect through concrete ring test cannot be carried out, since it is affected by too much uncertainty. The maximum value of the creep relaxation under the tensile stress at long ages (after at least 24 days) was detected for the mixture containing polypropylene fibers, followed by that containing glass fibers, and finally by that containing steel fiber (see Figs. 9, 6 and 10, respectively). These results are consistent with increasing values of the fiber elastic modulus: 2 GPa for PP fibers, about 80 GPa for glass fibers, and around 210 GPa for steel fibers. Probably, the lower is the elastic modulus of the fiber used, and the higher is the creep of the FRC mixture under tensile stress.

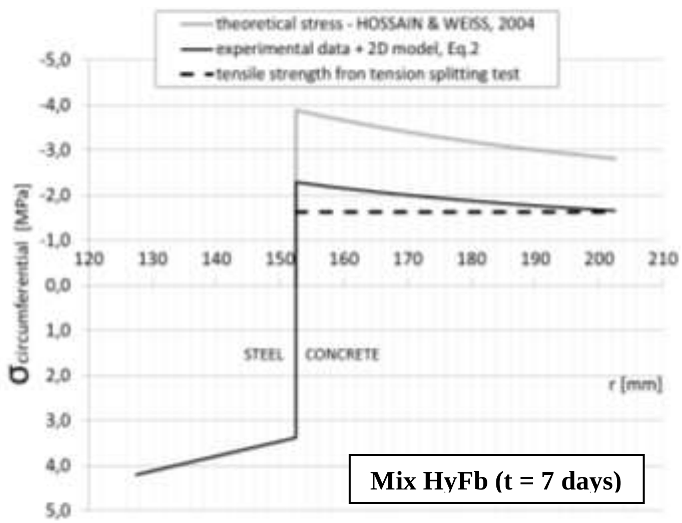

Figure 9. Comparison among theoretical and experimental circumferential stresses for the HyFb mixture after 7 days (time of concrete ring cracking).

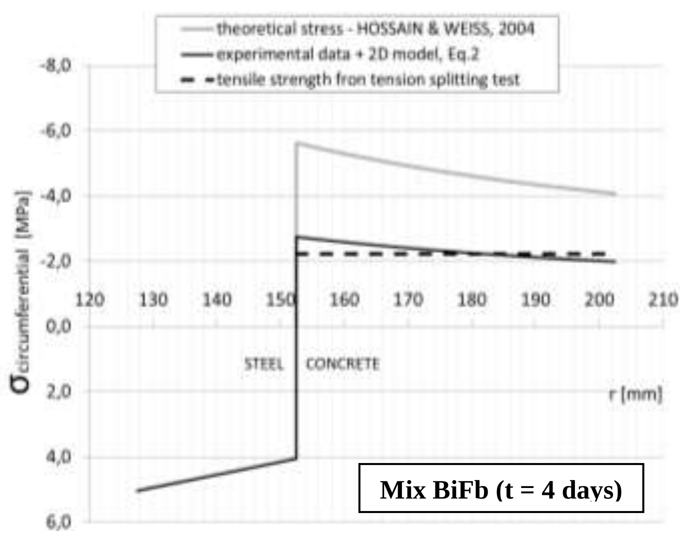

Figure 10. Comparison among theoretical and experimental circumferential stresses for the BiFb mixture after 4 days (time of concrete ring cracking).

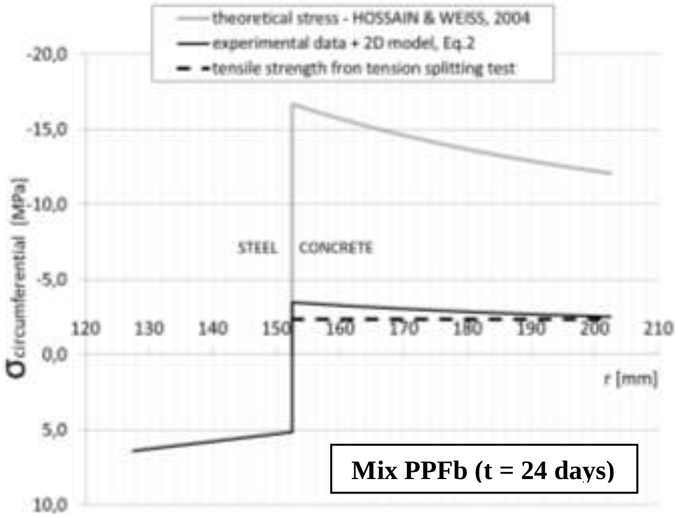

Figure 11. Comparison among theoretical and experimental circumferential stresses for the PPFb mixture after 24 days (time of concrete ring cracking).

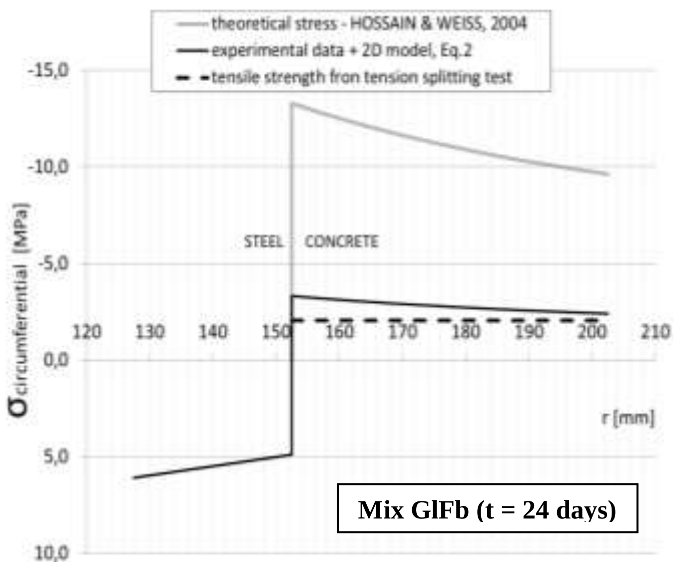

Figure 12. Comparison among theoretical and experimental circumferential stresses for the GlFb mixture after 24 days (time of concrete ring cracking).

VII. Conclusions

Based on the results of this experimental investigation, the following conclusions can be drawn:

- the addition of macrofibres, whichever the type, showed to be effective in reducing drying shrinkage of FRC, as well as in retarding concrete cracking;
- the only mixture showing an evident strain-hardening after cracking was that reinforced by means of bicomponent fibers (characterized by a rough PP sheath and high modulus glass core);
- however, concerning the results drawn from the ring tests, the addition of bicomponent fibers, as well as hybrid fibers, wasn't so effective as expected, likely due to a bad dispersion of these kinds of fibers within the cementious matrix, as confirmed by the high standard deviations of the splitting tensile test results;
- in particular, on the basis of ring test results, excellent behaviour under restrained shrinkage was obtained when either steel, or polypropylene or glass fibers were used, with a strong delay in the appearance of macro-cracking of concrete; at least concerning the mixture containing polypropylene fibers the reason probably lies in a positive effect of the remarkably creep relaxation under the tensile stress caused by restrained shrinkage;
- finally, this experimental procedure proved to be able to study the influence of the concrete mixture composition on the potential for early-age cracking of concrete, as well as to estimate the value of the tensile creep function coefficient; even if, the conclusions gained concerning this last aspect need further data for validation.

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