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Durability of a multiscale fibre reinforced cement composite in aggressive environment under service load

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Abstract

The LCPC has developed and patented a new ultra high performance fibre reinforced cement composite (UHPFRCC); the introduction of three steel fibre sizes leads to a multiscale fibre reinforced cement composite (MSFRCC) with multi-cracking and hardening behaviour in uniaxial tension (f_t more than 20 MPa). An innovative test of durability is presented. Pre-cracked thin slabs are damaged by fatigue under loading corresponding to service load (30 MPa in bending test) then maintained under bending at the same level. A part of these slabs undergoes 30 weekly wetting–drying cycles in a chloride solution (NaCl 5%, 20 °C). A reloading to failure is led. One notes an absence of corrosion in the micro-cracked area even for cover lower than 300 μm and a strength increase for pre-damaged slabs by fatigue. Under service load and in the presence of chloride water, a quasi-total recovery of initial stiffness is possible; it is accompanied by an increase of the pseudo-elastic behaviour. The development of a better matrix/micro-fibres synergy and a diffuse micro-cracking explains this result.

Keywords: Durability; Corrosion; Composite; Multiscale reinforcement; Creep; Self-healing

1. Introduction

The ultra high performance reinforced cement composites (UHPFRCC) are constituted of an ultra high performance matrix (UHP) combined with fibres. Increase in the material compactness and its quasi-absence of connected porosity largely improves the transfer properties [1,2]. But for a lot of structural applications, fibre reinforced concretes (FRC) are loaded below the resistance to the first cracking of the matrix that largely limits the appearance of macro-cracks. So, this kind of concrete does not seem to suffer from corrosion of steel fibres, as is in the case of steel bars of reinforced concrete.

The studied material, which is a multiscale fibre reinforced cement composite (MSFRCC) makes it possible to design durable structures, enduring high loading levels, without active or passive reinforcement. Taking into account the hardening behaviour of the composite in uniaxial tension, the structural design should make work the composite at a stress level higher than the uniaxial tension strength of the matrix. That implies a diffuse and multiple micro-cracking. However the strength of the composite depends entirely on steel fibres, which are numerous but which have also different very low diameters (i.e., 40 to 300 μm for the studied material). The composite is thus very sensitive to any phenomenon decreasing the steel fibre section, or their strength. In addition, previous studies on FRC durability are interested mainly in not cracked specimens, or cracked but not loaded ones, which contain seldom more than 2% of fibre reinforcement. This is not a representative of a mechanical behaviour under serviceability load.

Then what would happen if the MSFRCC was loaded at serviceability level in an aggressive environment. This point was not the object of intensive investigations for the new generation of HPFRCC. That is why an innovative test was adapted to the potential applications of the composite. Thin specimens initially damaged in fatigue are maintained charged under flexure. The load level corresponds to a characteristic serviceability stress. At the same time some part of the specimens undergoes weekly

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wetting–drying cycles in a chloride solution. The experimental device description and the presentation of research results precede an analysis of the physical phenomena observed, starting from a previous fatigue study [3].

2. Creep under flexure of the MSFRCC in marine environment

2.1. Material and specimens design

Future industrial application for this material could be thin slabs. So the study was carried with bending tests on panels. The mixing proportions of the composite tested are given in Table 1. The water/binder ratio is equal to 0.16. The volume fraction of reinforcement grows up to 11%. It is composed of three steel fibre sizes: a micro-fibre or steel wool, a straight meso-fibre with 5 mm length, and a twisted macro-fibre of which the length does not exceed 30 mm. The diameter of fibres ranges from 25 to 300 μm (Fig. 1). First matrix and steel wool are mixed dry; water and superplasticizer adjunctions produce a fluid matrix, then meso-fibres are incorporated rapidly before the adjunction of the macro-fibres. The filling of the formworks ($40\times150\times600$ mm) is performed using an external vibration. Twenty-two specimens are produced for bending tests and twelve cylinders 11×22 cm for compressive tests. All specimens are protected from desiccation, and concrete removal happens 48 h later. Two different curing types are set up:

– A half is heat-treated during 4 days at 90 °C in hydrothermal conditions (cellophane film + self-adhesive aluminium foil).
– A half is standard air-cured at 20 °C ambiance.

Then all specimens (prismatic specimens and cylinders) are stored during 180 days at laboratory ambiance (about 50% relative humidity). The upper faces of cylinder and prismatic specimens, which are not plane, are dressed to obtain a constant thickness and inertia.

2.2. Pre-damage and loading device

A building supports during its lifespan a succession of loading cycles, which are more or less important, and which will accentuate its damage (in term of crack opening) and then facilitate migration of aggressive agents (chlorides, sulphates, freezing…). To reproduce such a state of initial damage, the following sequence of first loading is chosen:

– A first quasi-static loading until a stress level corresponding to the characteristic flexural strength under service load: the goal is to initiate micro-cracks.
– A succession of fatigue cycles: bending stress ranges from 10 to 100% of the loading rates previously defined: the goal is here to degrade the fibre–matrix interface bond.

Four point bending tests are monitored by loading measurements. The loading rate is respectively 33 and 42 MPa (flexural stress) for the untreated specimens (NT) and heat-treated ones (HT). The initial deflections range from 0.75 to 0.82 mm for NT specimens and from 0.9 to 1.1 for HT specimens (strains in constant moment zone range respectively from 1.04 to 1.24×10^{-3} and from 1.23 to 1.46×10^{-3}). After the first quasi-static loading, the thin slabs undergo 2500-fatigue cycles. No visible cracking is noted. Among the 22 manufactured specimens, 6 remain virgin of any damage, to be used as control specimens. Compressive characteristic strength averages are respectively 215 and 232 MPa for NT and HT cylinders, 400 days after batching.

A 3-point flexure creep test is performed later (Fig. 2a), in order to control the applied loading rate during all stages. Initially developed by ENTPE (National High School for Public Works) in Lyon, the device is equipped with one hydraulic jack connected to one oleopneumatic accumulator via a three-way valve.

Two creep frames are used (one by type of curing), receiving each one five specimens initially damaged by fatigue cycles. The specimens are piled up one on the other; one intercalates hinges between each slab. An anti-corrosion painting protects frame, jack and hinges. An effort sensor (SENSY 2965 — 100 kN capacity) is inserted between the jack (ENERPAC BS 462252 — 350 bars capacity) and the higher specimen. The applied loading rate induces a strain in the maximum moment zone corresponding to the one produces by the 4-point static bending test. The correspondent stress level is obtained by a finite element analysis of the 3-point and 4-point tests, using the law of mechanical behaviour of the composite.

2.3. Aggressive environment device

For each of the two curings, four different environmental ambiances are applied:

– Control or virgin specimens (3 per series — initials V): they are neither damaged by fatigue, neither charged, nor corroded. They are stored outside the aggressive environment, at laboratory ambiance (temperature of 20 °C ± 2 and relative moisture ranging 50% ± 10).
– Damaged and corroded specimens (3 per series — initials DC.): after fatigue cycles, they are left in aggressive environment, unloaded.

Table 1
Multiscale fibre reinforced cement composite mix design (MSFRCC)

Raw materials		Proportioning mixing
OPC	CPA CEM I 52.5 R	1050 kg/m^3
Sand	Quartz 125–400 μm	514 kg/m^3
Silica fume	Zirconium	268 kg/m^3
Superplasticizer	Polyphosphonate — 30%	44 kg/m^3
Total water		211 L
Steel fibre content		858 kg/m^3

Silica fume/cement	0.255	Superplat/binder	1.02%
Sand/cement	0.49	Density	3
Total water/binder	0.16		

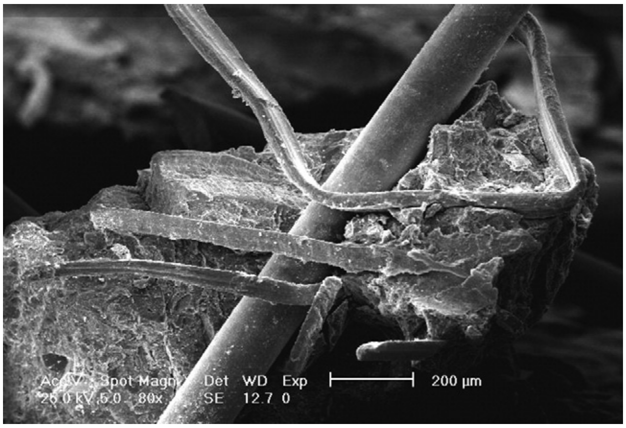

Fig. 1. SEM photograph of MSFRCC reinforcement – macro-fibre embedded by micro-fibres – synergy effect.

– Damaged and charged under flexure specimens (2 per series — initials DF): after fatigue cycles, they are submitted to creep test.
– Damaged, corroded and charged under flexure (3 per series - initials DCF): after fatigue cycles, they are subjected to creep test in aggressive environment.

Each frame thus receives two specimens in higher position, which will undergo only creep (DF), and three specimens in lower position, which will also undergo the effect of aggressive environment (DCF). The remaining place available in the polyethylene container is used for storage of the damaged and corroded specimens (DC) (Fig. 3).

Four hundred litres of NaCl solution including 50 g/L is stored in a first container closed by a lid. Filling and draining a second container are done using a pump connected to the first one. In order to avoid corrosion influence (chloride vapours above the solution), the tended faces of the DF specimens (which were dressed) are covered with a self-adhesive aluminium foil.

2.4. Cycle duration — wetting–drying device

Starting from the study of Hong and Hooton [4], a weekly cycle with 1 wetting day and 6 drying days is adopted. During the drying phases (ambient air at 20 °C and 50% of RH) all the solution are transferred. To accelerate the drying process and to diminish external relative moisture, air is insufflated at the bottom of the container between the lower specimens, using four ventilators (see Fig. 2b). The relative humidity ranges in this area from 50 to 70% depending on the moment of measurement.

To limit the possible plugging of cracks by salt, all the specimens subjected to the wetting–drying cycles were rinsed with clear water after 65, 80 and 142 days. A new solution was made after 153 days. The test is carried out for 210 days, which represents exactly 30 cycles.

2.5. Extensometer instrumentation — measurement control

The instrumentation is composed by 2 load cells and 4 Linear Variable Differential Transformers (LVDT) for the deflection monitoring (2 per creep frame for DF specimens). LVDT extensometers are protected from moisture by a latex sheath, which also includes the steel target of the transducer (see Fig. 2). A heat-shrinkable ring ensures the sealing.

3. Experimental results

The effort is constant for the duration of the test (a reloading is carried out after 10 days). Although the test is not controlled precisely in temperature and relative humidity, the differed strains are greater for the untreated specimens than for those heat-treated (15 and 20% for NT specimens against 11 and 13% for specimens HT). Yet the number of specimens is insufficient to draw any conclusions relating to creep.

After 30 wetting–drying cycles, the specimens are discharged then left at rest 1 week before being reloaded to failure under 4-point bending test. The tests are carried out according to the protocol defined for the static tests [5], at an imposed deflection rate equal to 400 μm/min, 400 days after casting. The deflection is

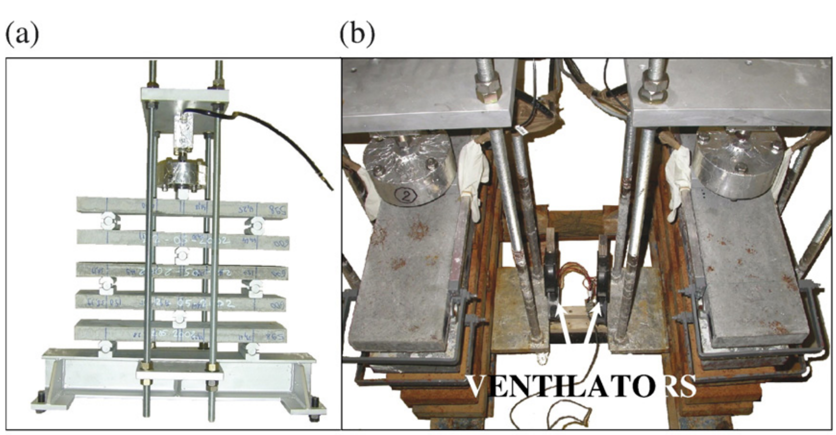

Fig. 2. Experimental creep device. (a) 5 specimens under 3-point bending creep with intercalated hinges, load cell and jack. (b) 2 creep devices in container during drying phase (4 ventilators in dawn position).

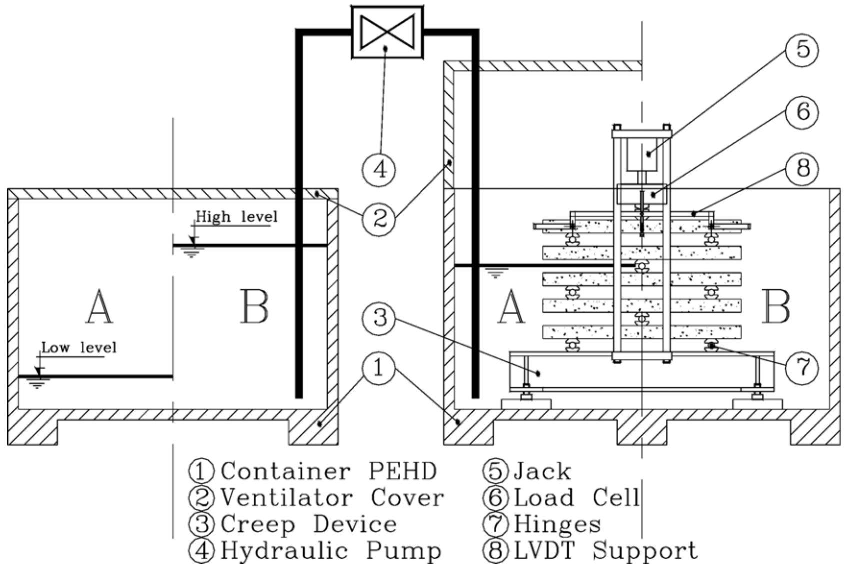

Fig. 3. Global view of the corrosion test with creep device — two containers, on pump and creep device.

measured using a special extensometer, placed on the specimens, designed to eliminate parasitic displacements due to concrete crushing on the level of the hinges.

Figs. 4 and 6 present the average curves of reloading to failure for the two different curings and also for the four environments. All results are summarized in Table 2; tendencies are quite the same for each kind of curing:

- Control specimens have the lower bending strength in term of Modulus of Rupture ($MOR_{NT}=64$ MPa and $MOR_{HT}=67$ MPa) and their Young's modulus is respectively of 53 GPa and of 58.3 GPa for the untreated specimens and for those heat-treated.
- DCF specimens present the highest strength ($MOR_{NT}=73.3$ and $MOR_{HT}=74.1$ MPa). The stiffness of DCF specimens, with $E_{NT}=48.3$ GPa and $E_{HT}=51.6$ GPa (NT and HT), is slightly lower than the virgin specimens.
- DC and DF specimens show similar mechanical behaviours taking into account scattering on material behaviour. Their strength is higher than the virgin specimens: $MOR_{NT}=68.5$ MPa and $MOR_{HT}=72.9$ MPa for DC specimens and $MOR_{NT}=71.3$ and $MOR_{HT}=72.5$ MPa for DF specimens. Their stiffness is clearly lower than the one of the two other series V and DCF. The DC rigidity is initially the same one as the virgin specimens (see Figs. 5 and 7); but it decreases when the tensile bending stress reaches 5 MPa. After 5 MPa, the curve is more and more close to the one of DF specimens. Average rigidity for these 10 specimens is 30 GPa.

The mass variations of specimens are weak, whatever the cure, environment or the applied loading. Thus it is systematically negative for the virgin specimens (−0.07 to −0.16%) and systematically positive for the specimens in the container (above or immersed in the chloride solution; +0.08 to +0.5%). For the two types of curing, DCF specimens are logically those gaining more masses (0.25 to 0.5%). EC specimens gain the less (0.08 to 0.28%) and DC specimens gain 0.17 to 0.33%. Compressive average strength for 400-day specimens is 223 MPa for NT and 247 MPa for HT (characteristic strengths equal to 215 for NT and 232 MPa for HT).

4. Analysis and interpretation

Taking into account the mechanical behaviour scattering of the composite, the results show a similarity of behaviour after 400 days, for the heat-treated specimens and for the untreated ones. For each four environments, the average curve of the heat-treated specimens is slightly higher than the one of the untreated specimens. Only virgin specimens show a notable difference: the end of the pseudo-elastic behaviour intervenes earlier than for DFC specimens (14 against 18 MPa), without resulting in a lower average strength. The influence of heat treatment is weak after 400 days of exposition (Figs. 10–13). The chemical reactions of hydration and pouzzolanicity, initially activated by

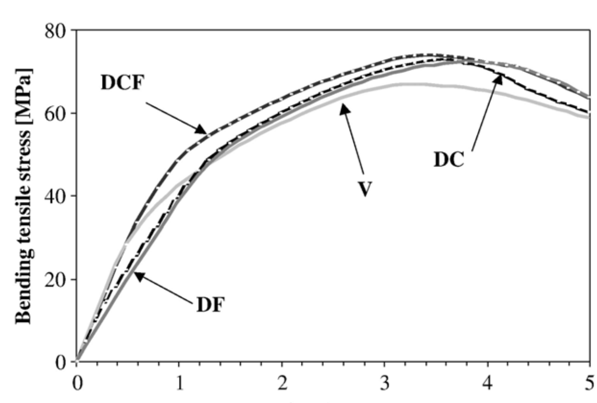

Fig. 4. Stress–deflection average curves – 4 environments – heat-treated specimens.

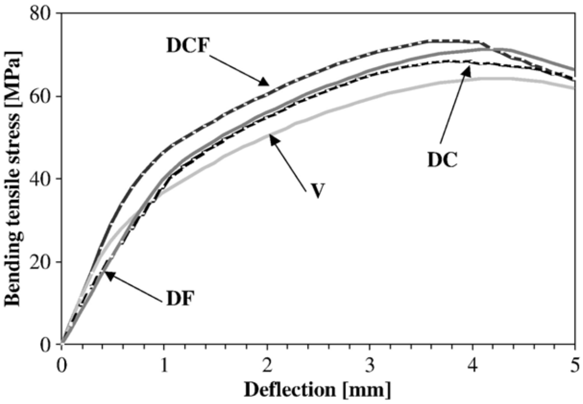

Fig. 5. Focus on stress–deflection average curves – 4 environments – heat-treated specimens.

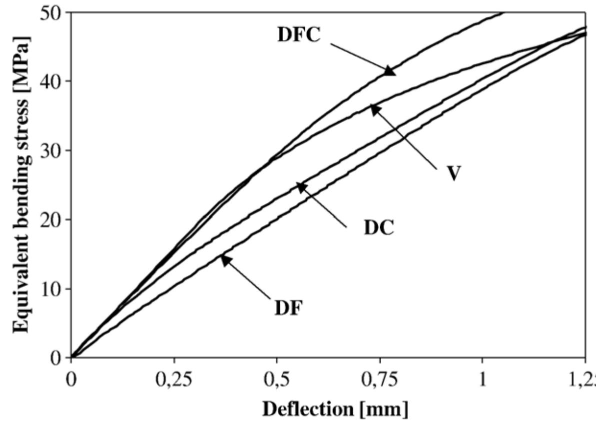

Fig. 6. Stress–deflection average curves – 4 environments – not-treated specimens.

the heat treatment, can reach the same degree of advancement in absence of heat treatment; provided that theses reactions have enough time to develop. This is confirmed by compressive strength (only 12% of variation).

The comparison of the virgin and DF specimen mechanical behaviours shows the two following points:

– The stiffness of specimens pre-damaged by fatigue and then maintained under loading remains clearly lower than the one of the virgin specimens. The pseudo-elastic behaviour is on the other hand increased, and almost linear.
– The maximum strength of DF specimens is slightly higher than the virgin ones.

These conclusions are in perfect agreement with results obtained in a previous study concerning the fatigue behaviour of this composite [3]; especially for specimens having reached 2×10^6 cycles and then reloaded. The gain of flexural strength is explained here by the positive effect of some fatigue cycles at moderate rate of loading. The crack patterns created during the pre-damage stage are positive with respect to the stress concentrations ratio at the fracture tip. The maintained loading at maximum fatigue stress induces a quasi-linear pseudo-elastic behaviour, whereas fatigued specimens behaviour presented a concave part then a convex one. It does not induce any strength loss.

As previously underlined, the behaviour of DC specimens is almost the same than DF specimens. The major difference lies the fact that the DC initial rigidity practically merges with the one of the virgin specimens. For these specimens subjected to the wetting–drying cycles, it seems that a beginning of self-healing of the UHP matrix takes place (Figs. 5 and 7). But as the

Table 2
Experimental set up - mechanical performances - mass variation

Ref.	Batch	Ambiance	Cycles	Loading MP_a	MOR (MPa)	Deflection (mm)	Strain (10^{-3})	Mass (%)
NT 1	1	Air	–	–	57.4	3.72	7.69	−0.19
NT 2	1	Air	–	–	67.2	4.36	11.35	−0.12
NT 3	2	Air	–	–	69.5	4.63	9.92	−0.16
NT 4	1	Air	2500	33.3	70.4	4.11	9.38	0.02
NT 5	2	Air	2500	33.3	72.6	4.42	6.39	0.22
NT 6	1	Chloride	2500	–	67.1	3.79	7.71	0.21
NT 7	2	Chloride	2500	–	72.6	4.49	7.87	0.27
NT 8	2	Chloride	2500	–	68.3	3.69	7.34	0.25
NT 9	1	Chloride	2500	33.3	78.6	4.49	5.61	0.24
NT 10	2	Chloride	2500	33.3	75.6	3.98	7.52	0.50
NT 11	2	Chloride	2500	33.3	68.2	3.59	7.13	0.28
HT 12	1	Air	–	–	80.9	4.01	7.50	−0.07
HT 13	1	Air	–	–	64.1	3.68	8.95	−0.07
HT 14	2	Air	–	–	61.1	3.00	5.43	−0.10
HT 15	1	Air	2500	42	69.9	4.18	8.46	0.28
HT 16	2	Air	2500	42	75.3	3.85	6.80	0.08
HT 17	1	Chloride	2500	–	74.8	3.88	7.35	0.17
HT 18	2	Chloride	2500	–	71.1	3.66	6.70	0.25
HT 19	2	Chloride	2500	–	73.4	3.55	7.01	0.33
HT 20	1	Chloride	2500	42	69.4	3.16	4.35	0.30
HT 21	2	Chloride	2500	42	80.8	3.87	7.50	0.25
HT 22	2	Chloride	2500	42	76.5	4.25	6.71	0.41

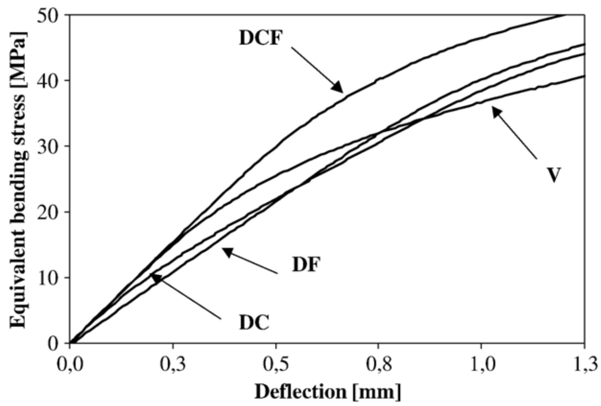

Fig. 7. Focus on stress–deflection average curves – 4 environments – not-treated specimens.

cracks are partially or even completely closed, fault of maintained loading and of the initial fineness of the cracks, the water flow until fracture tip is limited in-depth. Nevertheless, that is insufficient to lead to a total recovery of initial stiffness, the damaged matrix remaining in-depth. It can be noted that the curves diverge for a bending stress approximately equal to 5 MPa, before the ultimate strength of the UHP matrix. The quasi-static bending tests on the plain cementitious matrix [6] showed that the modulus of rupture is equal to approximately 18 MPa.

The fibre–matrix interface remains damaged. Thus the rigidity of the specimens decreases after the rupture in tension of the lately regenerated matrix. This phenomenon takes place around 10 MPa, then DC rigidity approaches quickly the one of DF specimens. One finds the mechanical behaviour such as it was at the end of the damage by fatigue. Thereafter behaviours are similar, in term of stiffness and flexural strength. Modulus of rupture also profits in this case from the beneficial effect of the 2500 cycles of fatigue.

The behaviour of DCF specimens is atypical. On the one hand the modulus of rupture of these specimens is the highest from the four environments tested, and on the other hand the prismatic specimens seem to have found their complete initial rigidity.

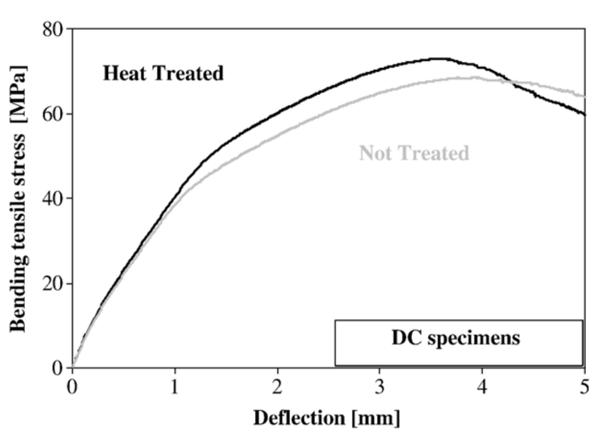

Fig. 8. Stress–deflection average curves — not treated specimens – initial damaged (180 days — 33.3 MPa) versus loading to failure (virgin specimens at 400 days — 64.7 MPa).

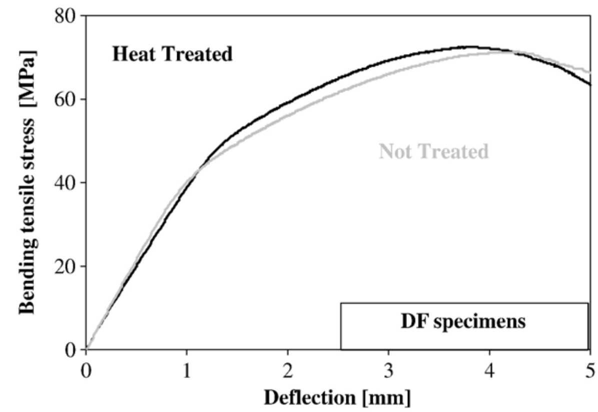

Fig. 9. Stress–deflection average curves — heat-treated specimens – initial damaged (180 days — 42 MPa) versus loading to failure (virgin specimens at 400 days — 68.7 MPa).

- The first point is due to the damage by fatigue and corroborates the strong tendency obtained on DC and DF specimens. Strength is affected neither by the aggressive solution, nor by the maintained load.
- The second point seems to indicate an almost total healing of the initially cracked UHP matrix. The moduli of elasticity are 48.3 MPa (NT) and 51.6 MPa (HT) for DCF specimens, thus slightly weaker than those of the virgin specimens (53 and 58.3 MPa). This self-healing takes place under tensile loading. Moreover, the pseudo-elastic behaviour is from now on more important, which shows a better mechanical efficiency of the micro-fibres as well as a part of the meso-fibres.

Singh made a similar report on thin elements (30 mm) out of ferro-cement [7]. He noted that the pseudo-elastic behaviour and the modulus of rupture increased with time of exposure when the loading rate did not exceed 70% of the ultimate strength of the composite. He concluded that the profits were due to the strength increase of the cementitious matrix and thus the improvement of fibre–matrix bond under loading.

The results obtained on the specimens pre-damaged by fatigue and maintained loaded in aggressive environment are

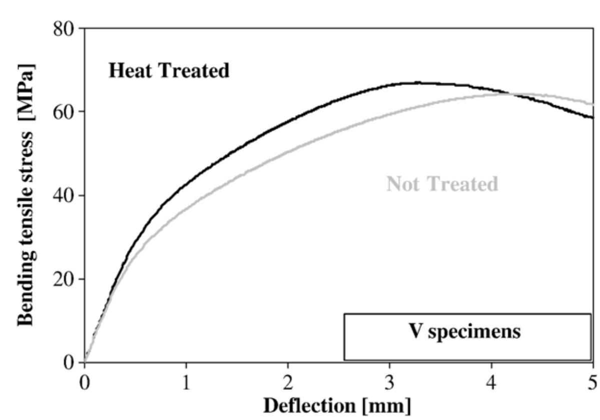

Fig. 10. Stress–deflection average curves — damaged and corroded specimens.

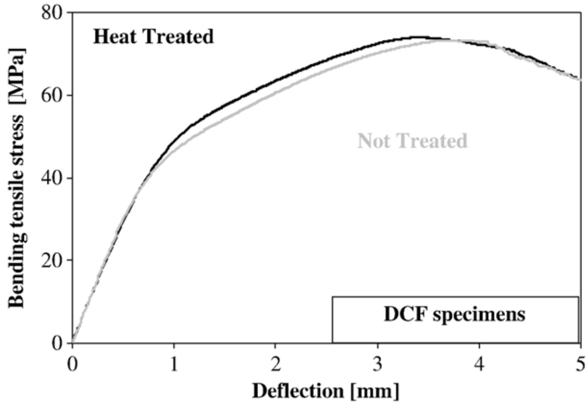

Fig. 11. Stress–deflection average curves — damaged and loaded under flexure specimens.

explained either by a self-healing of the matrix between the lips of the microscopic cracks, or this healing is accompanied by a recovery of the UHP matrix–micro-fibres bond characteristics. For plain concrete (without admixture as silica fume), Jacobsen [8] brings back the case of cylinder damaged and preserved in seawater during 3 years, and which regained their initial mechanical characteristics by self-healing [9]. However it is shown [10] that cylinders charged to 90% of its ultimate compressive strength and 8 h after casting have the same final strength as virgin specimens without early age loading.

For concretes slightly proportioned out of cement and with relatively high water/binder ratio (>0.5), [10] and [11] showed that the healing was much better if the damage intervened early. For these mix designs, the reaction of hydration quickly consumes a great part of cement, and the benefit in term of compressive strength at 90 days is then limited. With 1300 kg of binder and a *w*/*b* ratio of 0.16, we are far from hydrating only one third of cement mass (c.f. [12]). Moreover the loading intervenes 180 days after the slabs casting, some being heat-treated.

In fact, it is clearly established that the autogenous healing of cracks requires before all the presence of anhydrous grains and a contribution of water [13], two conditions fully fulfilled within this study. An air conservation environment has little effect on healing [10] and a permanent immersion is less powerful than a humid atmosphere [14]. According to Neville and Zamorowski, the application of a pressure on the faces of the cracks facilitates the phenomenon of healing. This parameter must be reconsidered: the present study shows improvements of stiffness and resistance even if cracks remain open and solicited in constant tension.

More significant seems to be the crack widths. Basing himself on observations by back-scattered electrons microscopy, Jacobsen highlights the partial filling of cracks exceeding 10 μm [15]. The newly formed hydrated products are mainly calcium silicate hydrates (CSH), with flattened form, as well as crystals of portlandite, as observed by Abdel-jawad, Neville and Vernet [16], and ettringite in smaller quantity. According to him, that explains the partial but never total recovery of compressive strength.

For crack openings lower or equal to 5 μm, the cracks seem completely closed again in secondary electrons microscopy (SEM). However back-scattered electron microscopy shows that the newly formed CHS are less dense than the ones surrounding the virgin matrix. Even healed, the cracks remain zones of weakness, which will be future incipient fractures as Jacobsen and Abdel-jawad observe it. That can explain the difference observed between the rigidities of the pre-damaged and loaded in aggressive environment specimens and the virgin specimens.

In the Jacobsen's study, a concrete with 5% of silica fume addition presents less neoformed products than plain concrete seen previously; the author is unable to explain this phenomenon. If the multiscale composite studied is subject to self-healing, the strong percentage of silica fume does not seem here to disturb this phenomenon. One explanation advanced is the reserve in anhydrous clinkers much higher than the one present in high performance concretes (HPC). With DUCTAL® (HPFRCC developed by French Companies), cracks opening of about 40 μm width are quickly filled by the neoformed hydrates, with the same composition than the initial ones [16]. Self-healing is largely facilitated in the present case by the fitness of the microscopic cracks, initially invisible thus probably lower than 50 μm width. Reinhardt shows that self-healing phenomenon can be extremely fast for high strengths concretes; the filling rate is all the more fast as the cracks are thin [17].

Interaction between self-healing and chlorides flow rate is analysed by Jacobsen starting from a chloride migration test under electrical potential on HPC samples ($w/b = 0.4$). Its specimens are damaged by freeze–thaw cycles [18]. The results show that:

- The Cl^- migration velocity under electrical potential is 2.5 to 8 times faster after the cycles freezing–thawing than for virgin sample. But self-healing is obtained after 3 months in carbonated water observed: migration velocity decreases by 28 to 35% for all samples.
- Even cracks of a 300 μm width see a significant reduction of the water flow.

Thus the very fine crack widths, the large quantity of anhydrous clinkers and the presence of wetting–drying cycles contributed to the phenomenon of autogenous healing for the specimens which were pre-damaged and maintained loaded; the rate of neoformed hydrates explains the increase of the pseudo-elastic behaviour.

Beyond a deflection of 1.5 mm, the strength curves follow the same tendency for all specimens and environments. This last point is explained by the moderate intensity of initial damage imposed on the composite. Figs. 8 and 9 present the initial pre-damaged behaviour and the behaviour at failure of initially virgin specimens (bending tensile stress–deflection curves).

Globally, the loading rates, respectively 33 MPa for NT specimens and 42 MPa for HT specimens deteriorate the macro-fibre interfaces a little; their bond characteristics are not really affected during the pseudo-elastic stage. This type of fibres intervenes relatively late in the cracking process, but gradually, as the state of strain increases. So it is logical that the four curves are similar for all environments. For a specified strain level, the DCF specimens develop a higher strength, a phenomenon that can be explained by the best effectiveness of micro- and meso-fibres and by the synergy between different sizes of fibres.

However the interface of the micro- and meso-fibres is initially damaged as it is shown with the reloading curves of DC and DF specimens in Figs. 5 and 7. It could be expected to see the curves of DCF specimens joining those of DC and DF, when the end of the pseudo-elastic behaviour is achieved. It was mentioned earlier that self-healing does not allow a total recovery of strength. But curves do not converge. Consequently, a partial improvement of the micro- and meso-fibres bond characteristics is required, a phenomenon which is opposed to the beneficial action of fatigue cycles (they induce blunt crack tips, positive in term of crack propagation). For the DCF specimens, a slightly weaker deflection at the maximum peak strength goes in this way. This improvement can have two origins:

– A beginning of fibre corrosion at the fibre–matrix interface; the rust produces an increase in the pressure around fibres and thus an improvement of bond. This process does not confirm the observations reported in the literature dealing with fibre durability in UHP matrix, and the fact that the matrix healing limits the penetration of aggressive agents. Moreover, the microscopic observation of fibres did not make it possible to reveal traces of corrosion, even for cover lower than 500 μm.
– The quality of the fibre–matrix interface was restored (by contribution of external water or water migration initially not chemically fixed by the matrix through the micro-cracking of the interface).

That last hypothesis seems more coherent with Gray's results; they show an improvement of single fibre pullout strength, for fibres loaded beyond the peak shear strength before being water-cured during 90 days [19]. At the time of the third reloading, the maximum effort supported by already tested fibres is higher than what is necessary to pullout fibres conserved under the same curing conditions and first tested at 90 days. The increase in pullout resistance for autogenous healing specimens is higher than the one resulting from the only cementitious matrix curing. The author concludes that fibre interfacial bond heals better than crack inside fractured plain mortars or concretes. These results are in perfect agreement with those presented above which indicate an increase of the fibre interfacial bond healing with the fineness of crack considered.

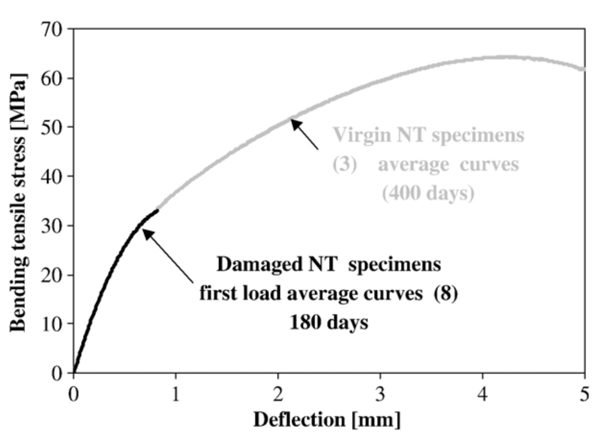

Fig. 12. Stress–deflection average curves – virgin specimens.

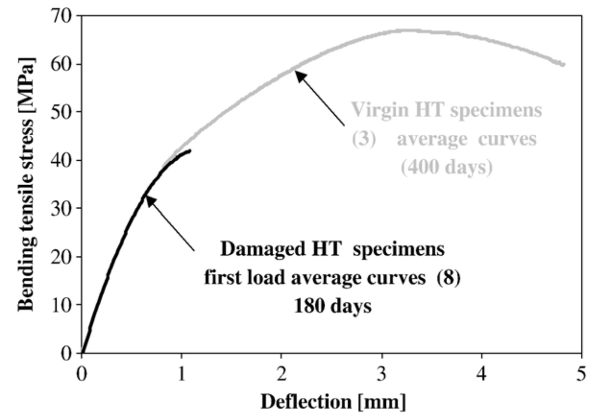

Fig. 13. Stress–deflection average curves – damaged, corroded and loaded under flexure specimens.

For the initial damage conditions, for the loading rate imposed and for the type of aggressive environment selected, we can affirm that the mechanical behaviour of the multiscale fibre reinforced cement composite is not affected by corrosion. Reasons advanced by authors are that the cracks created during the initial damage stage, although maintained open, were healed as early as the first wetting–drying cycles due to the fineness of their cracking patterns.

However the reliability of this test can be questioned; what would have occurred if the temperature, the number of cycles or the loading rate had been higher? As long as the crack openings induced by the fatigue test under service load are limited to the hundred microns (i.e., [3]) and temperature accelerates self-healing, it is reasonable to estimate that the autogenous healing of the matrix will quickly fill cracks partially again, bearing in mind that this discussion deal with monotonous loading.

5. Conclusions

The first question was relative to the evolution of mechanical properties of a multiscale fibre reinforced cement composite (MSFRCC) subjected to an aggressive environment in operating conditions. That led to the development of an innovative corrosion test under loading. The principal characteristics of the test are:

– A specimen geometry for test (thin prismatic specimens), which is representative of the potential structural applications considered. That allows a comparison with previous static and fatigue tests.
– The use of a preliminary fatigue test to control the pre-damage level of MSFRCC specimens. Fatigue cycles allow a better damage of the fibre interface bond compared to a monotonic static test.

– A constant maintained loading on a stress rate representative of the service load, thanks to the use of a creep device under flexure.
– The use of classical LVDT embedded in latex gloves for extensometry acquisition in aggressive environment. Its robustness and its null overcost make that it could easily be reused.

Two series of eleven thin prismatic specimens, with one heat-treated were tested. The main results of the present study are:

– No degradation of the MSFRCC mechanical properties due to aggressive environment. If corrosion takes place, it does not affect the fibres, even the smallest ones and the nearest to the cracks. Otherwise, a strength drop and a stiffness drop would have been noted at least in the first part of the stress–strain curves. This part is in fact dependent on the micro-fibres, which have a very low diameter (it's important to mention that the apparent fibres due to grinding of the compressed face were covered by rust or disappeared).
– The strength increases are to a great extent ascribable to the fatigue cycles. Other contribution is improvement of micro-fibre/matrix synergy. This is coherent with the literature and previous results and reinforces the analysis carried out on the fatigue behaviour of the multiscale fibre reinforced cement composite.
– For specimens pre-damaged by fatigue and stored discharged in chloride solution, as for specimens maintained charged outside the aggressive environment, the mechanical characteristics do not show any evolution. In both case, the autogenous healing does not happen since no sufficient water flow migrates toward micro-cracks (no water or cracks closed again).
– The damaged specimens, maintained loaded and undergoing wetting–drying cycles sees a quasi-total recovery of their initial rigidity (91 and 88.5% for NT and HT).
– The damage level of the fibres–matrix interface bond is unknown. However this interface is certainly partially healed in the case of DCF specimens. This assertion is based on the improvement of the pseudo-elastic behaviour. This increase of the MSFRCC mechanical behaviour in this specific domain is directly associated with the development of a better synergy micro-fibre–matrix.

These results are mainly attributed to the mix design of the UHP matrix and the high volume fraction of the reinforcement; that produces a diffuse micro-cracking pattern and a hardening behaviour. It seems that the very fine crack widths created, allowed a fast self-healing of micro-cracks, limiting the influence of the external environment consequently. The autogenous healing is facilitated by the significant part of residual anhydrous clinkers of the UHP matrix. Our results are thus coherent with the observations reported in the literature – self-healing of fractured UHPC, behaviour of ferro-cements – and coherent with the explanations made concerning the static and fatigue behaviour of the composite. But would repeated cycles of opening–closing of the cracks have prevented healing and thus in the long term allowed the development of a localised corrosion?

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