

On the residual properties of damaged FRC

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Abstract. A discussion on the residual behaviour of Fibre Reinforced Concrete (FRC) is performed based on two selected cases of concrete degradation: the exposure at High Temperatures and the development of Alkali Silica Reactions. In addition, and taking in mind that the failure mechanism in FRC is strongly related with the fibre pull-out strength, the bond strength in damaged matrices was shown concluding that the residual bond strength is less affected than the matrix strength. As the damage increases, the compressive strength and the modulus of elasticity decrease, being the modulus of elasticity the most affected. There were no significant changes produced by the incorporation of fibres on the residual behaviour when compared with previous experience on plain damage concrete. Regarding the tensile behaviour although the first peak decreases as the damage increases, even for a severely damage FRC the residual stresses remain almost unaffected.

1. Introduction

The construction of concrete structures of extended service life represents a key point to improve the sustainability of a country's infrastructure. In addition, the repair and strengthening of existing structures has become an important and urgent issue around the world.

Fibre Reinforced Concrete (FRC) is a high performance concrete particularly efficient for the construction of structures exposed to severe conditions as well as for reinforcement and retrofitting. Fibres incorporation controls cracking processes in concrete, resulting in great improvements of the material toughness and the structures durability. Steel and Polymer FRC have been used for decades in slabs on grade, pavements and bridge decks, tunnels, precast elements among others.

Concrete is a composite material where inclusions of different size and shape, the aggregates, are surrounded by a more or less continuous matrix that acts like a binder. The failure mechanism of concrete is closely related to the initiation and propagation of cracks, coarse aggregates generate weaker zones (interfaces) in which the development of the cracks begins. Furthermore, macrodefects (big pores, air bags) generated during compaction or bleeding may concentrate around the bigger aggregates and also cracks will appear due to differences in stiffness, shrinkage or thermal expansion coefficients between the cement paste and the aggregates. Significant cracking at micro and macro levels can also appears when concrete is exposed to more severe conditions, affecting the functionality and reliability of the structures.

As well as plain or conventional reinforced concrete, FRC can be used in structures in contact with aggressive environments or exposed to severe external conditions that produce damage in the internal structure of the material.



Frequently, for the assessment of the capacity in service or for taking decisions about replacement, reinforcement or repairing damaged structures, the evaluation of the properties of the existing concrete is required. Usually, the evaluation of the structures is made by means of the compressive strength measured on drilled cores; however other properties as stiffness, tensile strength or energy of fracture can change in a very different magnitude. The same may occur with the transport properties.

This paper presents a discussion based on previous works on the residual properties of FRC after severe degradation processes. The exposure at High Temperatures (HT) and the development of Alkali Silica Reactions (ASR) were selected as cases of study; the effect degradation processes on the pull out strength of individual fibres is also considered.

It is known that another very important case of degradation is the bars corrosion in reinforced concrete structures. The incorporation of fibres also can lead to benefits through their effect on the control of crack widths. However, the analysis of this pathology exceeds the scope of this work.

2. Residual properties of damaged plain concrete

There is extensive literature on the behaviour of damaged plain concrete. A summary of the main knowledge regarding the residual properties for the two studied cases is presented.

2.1. High temperatures (HT)

An important case of damage of the internal structure of concrete appears when it is exposed to high temperatures (HT) [1-7]. Initially, the increase in temperature results in the elimination of the pore's water and the consequent contraction of the paste with crack formation. Temperature rise over 500 °C produces non-reversible effects, as the loss of chemical bounded water takes place. Microcracking at the interfaces appears due to differences between thermal dilatation coefficients of paste and aggregates, which increases the size and closeness of the internal cracks.

The alteration of concrete structure affects the failure mechanism, and this is reflected in the shape of the stress-strain curves. In damaged concrete the growth and propagation of matrix cracks starts earlier and there is an important decrease in the period of stable matrix crack growth as the degradation is more severe. In compression, there were reported decreases in ultimate stress, increases in final deformations and rapid and important reduction in Poisson's ratio. The tensile strength shows a great variability, and it is more sensitive than the compressive strength to the changes produced by HT. While damage produces a drop in tensile strength the fracture energy is less affected due to the greater branching in crack propagation in the post-peak regime [3, 5].

Large reductions in ultrasonic pulse velocity and in dynamic modulus of elasticity as temperature increases were observed in HT damaged concrete. The modulus of elasticity was more affected than the compressive strength, thus the residual values of velocity can diminish much more than those corresponding to strength and are very effective to detect damaged zones [4].

The temperature level, the exposure time and the cooling conditions are the main factors affecting the mechanical properties [1, 2]. The type of aggregate represents an important factor meanwhile the type of binder seems to be not so significant. Considerable changes can be produced by moisture content of concrete, in some cases the vapour pressure in the pores increase during heating and spalling takes place. Many times visual inspection showed that specimens exposed to temperatures higher than 500 °C had significant surface cracking, which was more important when they were cooled quickly.

Finally, temperatures lower than 200 °C, do not have a significant effect on the compressive strength, but can affect the transport properties mainly the external layer of concrete, promoting significant changes in concrete durability. In HT damaged concrete the residual velocity and capacity of capillary absorption grew with the crack density until a maximum is reached and then decreased, although the density and width increased. On the other hand the water permeability showed a direct relationship with the level of damage, increasing as the crack density and width increase. It can be mentioned that the transport properties can also be affected by less severe conditions as the presence of microcracking due to drying shrinkage [8].

2.2. Alkali-silica reaction (ASR)

Alkali-silica reaction (ASR) can induce loss in serviceability of concrete structures. ASR occurs in concretes with reactive aggregates, when sufficient alkalis (K_2O , Na_2O), and moisture are available. Different levels of damage and cracking appear in concrete microstructure according to the kinetic of ASR. Rapid reaction rates induce internal stresses at the interfaces and cement pastes, producing micro and macrocracks. On the other hand in concretes with strained quartz, the reactions are localized inside the aggregates in reactive zones (intercrystals), where pore solution can reach. This process takes place very slowly and the attack is not generalized all around the aggregate surface. [9–12].

Usually linear expansions are used to evaluate the material degradation; nevertheless the residual mechanical properties could be different for a same expansion. ASR strongly affects concrete tensile strength and modulus of elasticity. The reductions in compressive strength are always lower than those observed in stiffness, being in some cases compressive strength even not affected.

The failure mechanism of concrete in compression is also clearly affected by ASR. The shape of the stress–strain curves reflects the presence of internal fissures. The growth and propagation of matrix cracks tends to start earlier due to defects produced by ASR. The period of stable crack propagation is less affected than the period of unstable crack growth which is widely extended, showing that the capability of controlling crack propagation decreases leading to premature failure. In tension, the differences in the crack pattern of sound and damaged concretes are reflected in the shape of the load deflection curves, both in the pre- and post-peak regime. Damaged concretes show an increased non-linearity before the peak and a more gradual softening.

Also in this case, the changes on transport properties strongly depend on the characteristics of the crack pattern [8].

3. Residual bond strength of individual fibres in damaged matrix

It is well known that the post peak capacity of FRC depends on the type and content of fibers. The fibers mainly act after a crack appears in the matrix being the pull out the most important mechanism involved. Although fiber – matrix bond increases with the compressive strength, the increments are more significant in the later. This behavior was verified for synthetic macrofibres (M) and hooked-end steel fibres (S) [13].

To study the effect of ASR on bond strength pull out tests were performed. Four mortars with w/c 0.50 were prepared with reactive sand, two incorporated a high content of alkalis (D) and the others were used as reference (C). Reactive and reference mortars incorporating synthetic microfibers were also done with the aim of evaluating if there is any effect in controlling matrix microcracking and consequently in bond strength; they are identified as Cm and Dm. Specimens of 40 x 20 mm section and 70 mm length with a single fibre embedded were used; the bond length was half of the fibre length. In addition, prisms of 25 x 25 x 300 mm were cast to measure the expansions evolution.

Figure 1.a shows the evolution of mortar expansions. Mortars D and Dm that incorporate high content of alkalis show important expansions over 0.6 %. As expected, mortars C and Cm do not expand. Figure 1.b plots the results of bond strength vs. mortar compressive strength obtained with hooked end steel fibres (S) and different types of macrosynthetic fibres (M). It can be seen that mortars D and Dm show a clear decrease in compressive strength, which is slightly lower in the later. However, the variations in pull out strength are significantly lower. In this case, when the matrix is damaged by ASR the mortar compressive strength decreased near 40 %, while the bond strength is only marginally affected specially fibre S.

The same tendency was verified when the residual properties were evaluated in matrices damaged by HT. The variations in compressive strength are usually higher than those observed in bond. In a recent study [14] pull out tests were performed on concrete specimens incorporating steel fibres exposed at 20, 300, 375 and 475 °C; no change in pull-out response up to 375°C was observed, and only a reduction in load capacity of near 20 % appeared for 475°C. The corresponding concrete compressive strengths were 63.7, 55.7, 54.4 and 44.2 MPa respectively.

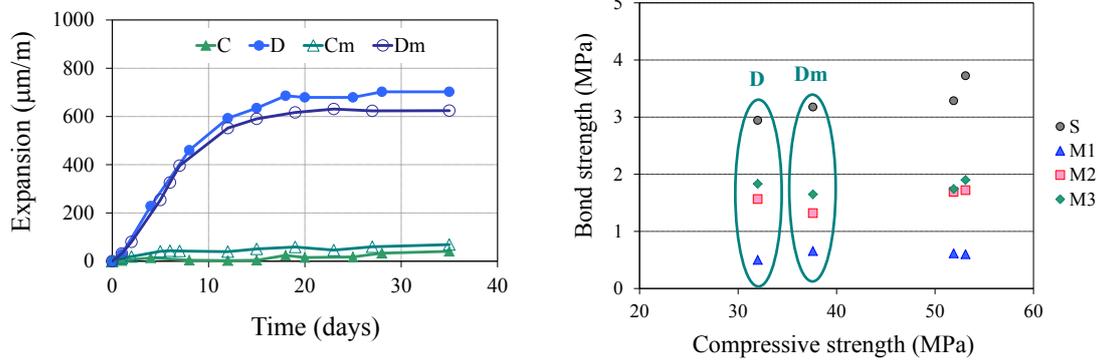


Figure 1. a (left) Evolution of the mortar expansions; b (right) bond strength vs. mortar strength.

4. Residual properties of FRC affected by HT

The residual mechanical behaviour of thermally damaged high strength FRC incorporating different types and contents of hooked end steel fibres were studied [15]. Two exposure conditions were used, 1 hour at 500 °C and 24 hours at 150 °C; reference specimens at 20°C were also tested.

The residual stress strain curves in compression of plain (P) and FRC incorporating 40 kg/m³ (40H) or 80 kg/m³ (80H) of High carbon steel fibres and 40 kg/m³ (40L) of Low carbon steel fibres are given in Figure 2. The axial, lateral and volumetric strains are plotted. It was found that as cracking increases the lateral/axial strains ratio increase at lower stresses and more rapidly.

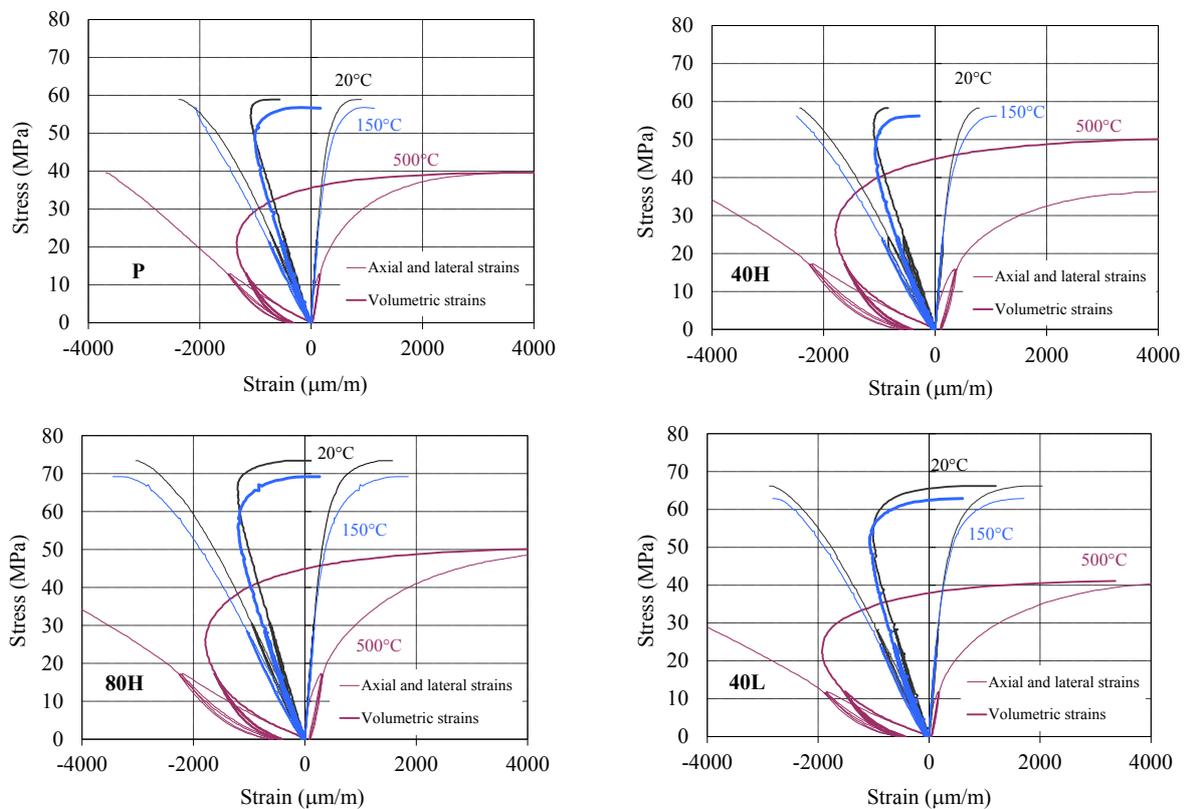


Figure 2. Stress vs. axial, lateral and volumetric strain curves in compression.

Regarding the failure mechanism in compression, Figure 3 presents the initiation stress (f_{init} , associated with the start of matrix cracking), the critical stress (f_{crit} , associated with the onset of unstable crack propagation) which corresponds to the peak volumetric strain [16], and the compressive strength (f_c). It can be seen that these parameters tend to increase as fibre content increases and when High-carbon steel fibres were used. When concretes are exposed to 500 °C, f_{init} and f_{crit} decrease, being the decrease in f_{crit} more significant. This means that, due to the cracking generated by high temperature, the growth and propagation of matrix cracks started earlier. The period of stable crack propagation is reduced and, although the period of unstable crack growth is extended the capability of controlling crack propagation decreases. The fibres increase the load-carrying capacity in post-cracking regime when compared with plain concrete (see P vs. 80H).

Summarizing, FRC follow similar residual compressive behaviour as the plain concrete, but the presence of fibres lead to slight increase in strength and in the stress at which cracks initiate.

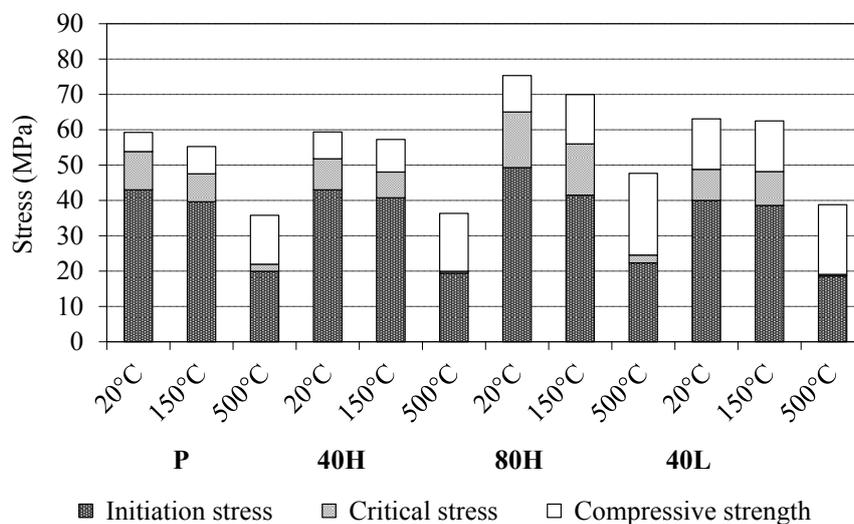


Figure 3. Stress vs. axial, lateral and volumetric strain curves in compression.

The main benefits of fibre incorporation in concrete are related to the tensile behaviour and the corresponding increments in toughness; in this way the characterization of FRC is based on their post peak capacity (residual stress). Thus the study of the post peak loading capacity in damage concrete becomes relevant.

To evaluate the tensile behaviour flexural tests on notched beams were performed. Figure 4 presents typical load – deflection curves in bending. As it was expected, the matrix degradation leads to a reduction of the residual mechanical properties of concrete. It was found that the shape of the load-deflection curves in FRC exposed to 150 °C was similar to the undamaged concrete. The reductions in flexural strength were lower in FRC than in plain concrete, and the post-peak strength was less affected than first-crack strength. For the most severe exposure condition the degradation of the material is reflected by an increased non-linearity of the ascending branch of the curves, nevertheless some FRC still exhibited strengthening type behaviour and kept an almost constant load bearing capacity during the post-peak. Concrete prepared with high-carbon steel fibres tends to show rather higher residual values. Some differences can be attributed to the number of fibres as the low-carbon type has the same aspect ratio but greater length. It is interesting to note that in FRC 40L the post-peak loading capacity was very similar between 20 °C, 150 °C and 500 °C, the degradation specially affects the first crack strength.

Many times Non-destructive tests (NDT) are used for the evaluation of concrete structures. Nevertheless in damaged concretes some particular aspects must be taken into account. In thermally damaged plain concrete, ultrasonic pulse velocity (UPV) strongly differs from the usual values

measured in sound concrete; the UPV method cannot be used to estimate strength but represents a useful tool to identify damaged zones [4]. Figure 5 plots the variation of the static elastic modulus with the compressive strength and the relationship of the static modulus of elasticity with the UPV; the results of concretes P, 40H, 80H and 40L previously presented, exposed to 20, 150 and 500 °C are included. In addition, the residual properties of other fibre concrete exposed to the same conditions are shown, all fibre concretes are identified as FRC. As it occurs in plain concrete, there is not a good correlation between the residual modulus of elasticity and the residual compressive strength in FRC, but concretes prepared with different materials, types and contents of fibres, and exposed to different grades of alteration show a very good relationship between the modulus of elasticity and the UPV.

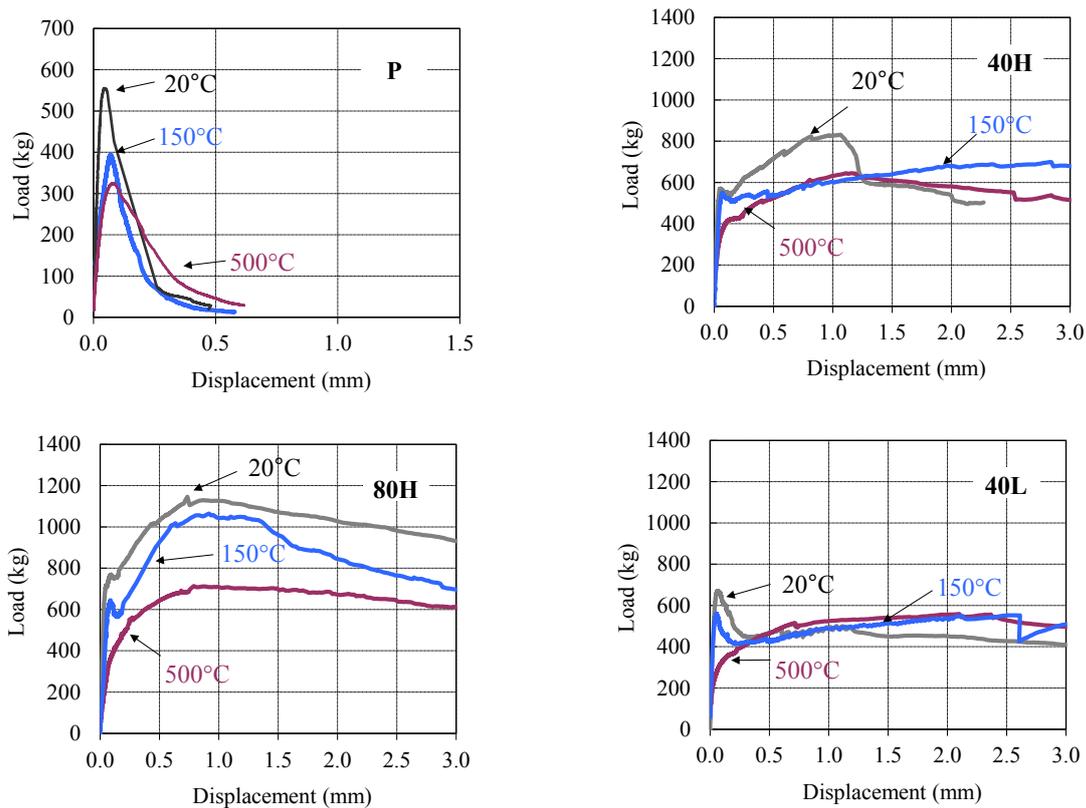


Figure 4. Load - deflection curves on notched prisms.

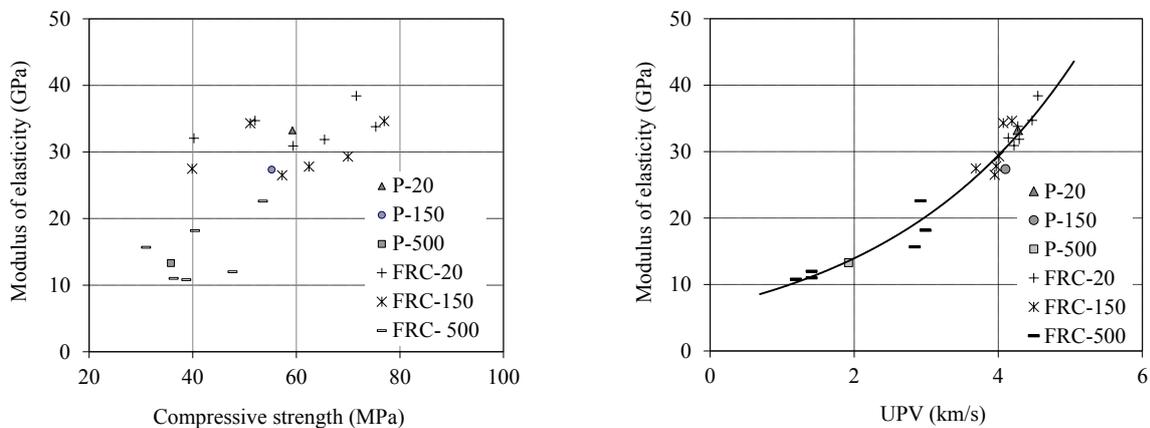


Figure 5. Left: Compressive strength vs. elastic modulus. Right: UPV vs. elastic modulus.

5. Residual properties of FRC affected by ASR

A reference concrete (P) and two FRC incorporating 40 kg/m^3 of hooked-end steel fibres (S) or 3 kg/m^3 of synthetic macrofibres (M) were done. All of them were prepared with similar mixture proportions and incorporate a 19 mm MSA highly reactive crushed quartzitic sandstone as part of the coarse aggregate to promote the development of ASR. The total alkali content in concrete was equal to 4 kg/m^3 (NaOH was added in the mixing water). The expansion along time, as representative of the reaction level, and the compressive strength, the modulus of elasticity and the flexural behaviour, as characteristic residual mechanical properties, were evaluated [17].

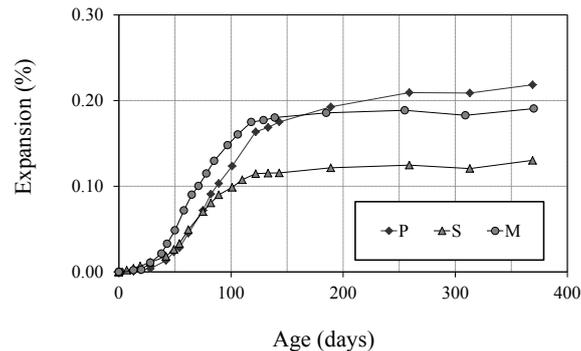


Figure 6. Linear expansions.

The linear expansions of the different concretes are given in Figure 6. A high rate of expansion can be seen until near 150 days and then it markedly decreases, achieving values near 0.2 %. Concrete S shows lower expansions; at one year the expansion is near 0.13 %.

To evaluate the residual mechanical properties compression tests were performed in standard cylinders at different ages from 28 days to 1 year. Test at 28 days were used as a reference value as at that age the ASR was not significant (see Figure 6). Similarly, bending tests on notched prisms were performed at different ages up to 1 year according to the guidelines of the EN 14651 standard [18]; in this case the Limit of Proportionality (f_L , that correspond to the first peak stress, representative of the matrix strength) and the residual stress f_{R3} (that corresponds to the nominal stress for a Crack Mouth Opening Displacement, CMOD, of 2.5 mm) were selected for the analysis.

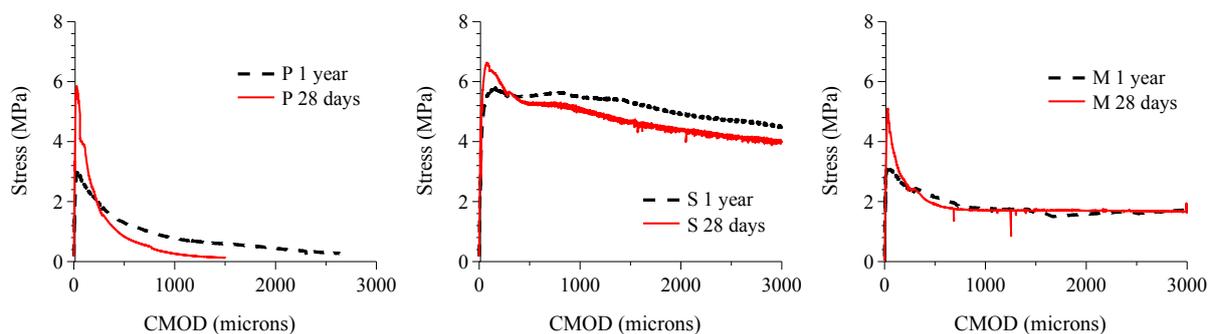


Figure 7. Stress - CMOD curves in bending.

Figure 7 compares typical Stress – CMOD curves of the three concretes at 28 days and 1 year. Each FRC shows a different post peak response, in accordance with the type of fibre incorporated. It can be seen than in plain concrete as the damage increases the softening branch of the curves become more extended, and they even show some residual load capacity. This behaviour is attributed to the possibility of greater branching and meandering of cracks [10]. In concrete M, with synthetic macrofibres, after achieving the maximum value the loads significantly decrease and they remain

almost constant until the end of the test. The steel FRC presents a very gradual descending branch, with high stress values. In both FRC, although the first peak load clearly decreases at 1 year (severely damaged), the post peak loading capacity remains almost constant. It can be mentioned that, an extensive crack pattern was seen in 150 mm side prisms of these concretes [17].

Figure 8 summarizes the effect produced by the cracking developed in each concrete on their mechanical response; the results of compressive strength, modulus of elasticity, first-peak strength (f_L), and the residual strength (f_{R3}) versus measured expansions are plotted. As in damaged plain concrete, in FRC the compressive strength and the modulus of elasticity decrease as the deleterious processes advances; the presence of internal cracking leads to greater reductions in stiffness than in strength [8, 10]. In tension, the strength decreases as the expansion increases but the presence of fibres, particularly the steel ones, improves the concrete behaviour. When the post peak strength capacity is considered a quite different response was found; the residual stress remains almost constant, even for very high expansions. Consequently, FRC incorporating steel or synthetic macrofibres conserve their residual loading capacity when severe ASR damaged has taken place. This is in accordance with previous studies that showed minor changes in fibre-matrix bond strength in mortars affected by ASR [13].

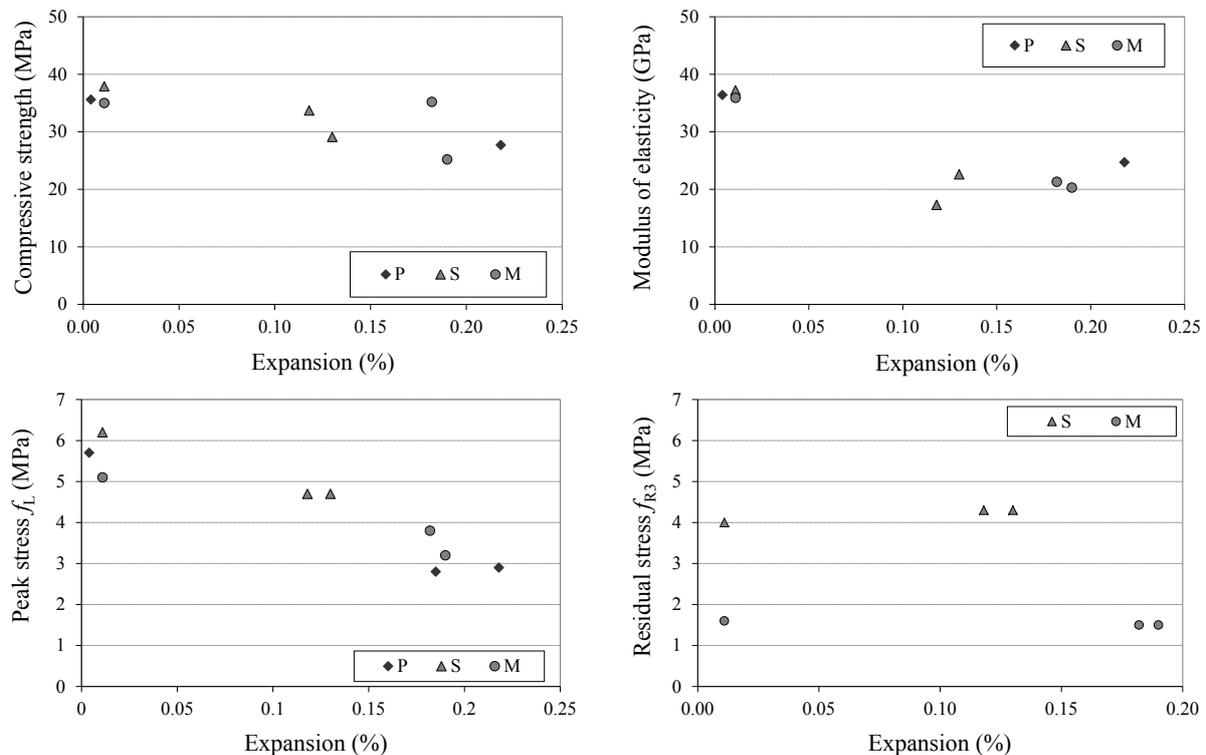


Figure 8. Relationship between mechanical properties and linear expansions: a) compressive strength, b) modulus of elasticity, c) first-peak strength, d) residual stress for a CMOD of 2.5 mm (f_{R3}).

Several codes estimate concrete stiffness from the results of compressive strength. The modulus of elasticity vs. compressive strength relationship proposed by the *fib* Model Code 2010 [19] is represented in Figure 9. The values obtained on concretes P, S and M at 28 days and at 6 and 12 months are plotted. It can be seen that when there is very few cracking, tests performed at 28 days, the measured modulus of elasticity is close to the prediction curve. When concrete is damaged the conventional expressions that estimate the modulus of elasticity from the compressive strength are no longer valid, the experimental values of stiffness are significantly overestimated.

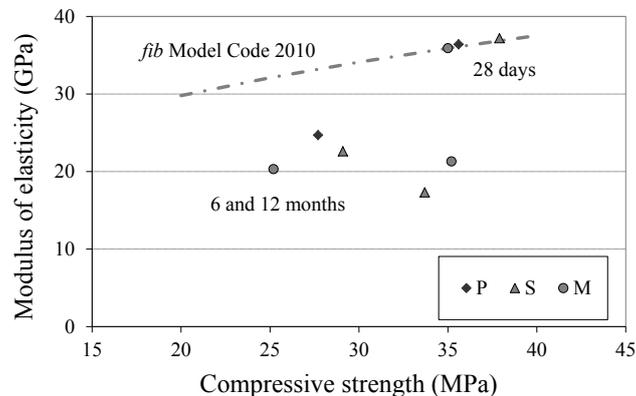


Figure 9. Relationship between compressive strength and modulus of elasticity.

Although the incorporation of fibres does not avoid ASR, some fibres may be useful to reduce in some extent the expansion rate and level, as well as the induced crack sizes [20-21]. Regarding the mechanical performance, it should be emphasized that, FRC maintain their residual properties without significant modifications even when severe matrix damage occurred. Then, the use of FRC is a useful tool to extend the structures service life as they conserve their residual mechanical properties and crack control capacity even if unexpected significant damage processes take place.

6. Concluding remarks

The residual properties of FRC after exposed to different severe conditions have been analysed in this paper, the cases of exposure at High Temperatures and the development of Alkali Silica Reactions were considered. The main findings are pointed as follows:

- No significant differences in the residual behaviour in compression have been found between plain and FRC. The compressive strength is less affected than the elastic modulus and the failure mechanism is clearly affected by the internal damage. The shape of the stress–strain curves reflects the presence of internal fissures, the growth and propagation of matrix cracks tends to start earlier, the period of stable crack propagation is less affected than the period of unstable crack growth which is widely extended, showing a decrease in the capability of controlling crack propagation.
- As well as in plain concrete, the tensile strength decreases as the damage increases but residual post-peak strength capacity due to the presence of steel or macrosynthetic fibres is mainly no modified, even for very severe damage.
- The capacity of FRC to conserve a significant part of its post-peak strength capacity is in accordance to pull out tests of single fibres, which indicate that in damaged concrete the reductions in fibre-matrix bond strength are significantly lower than the decreases measured on the matrix compressive strength.

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