



# Effects of Fibres on the Flexural Behaviour of Sound and Damaged RC Beams

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**Abstract.** The incorporation of fibres in Reinforced Concrete (RC) beams controls the width and evolution of cracks leading to positive effects on the durability of the element. The study of damage processes in concrete and their effects on the residual properties represents a key point related to the service life of RC structures. The contribution of fibres on the bending behaviour of sound and damaged RC beams was investigated. In order to use alkali silica reaction as a damaging tool, RC beams with and without fibres and reactive aggregates were subjected to service loading conditions during eight months in an environment with high humidity. The evolution of deformations and the distribution and propagation of cracks were recorded. As reference, similar RC beams without reactive aggregates were also evaluated. After the treatment, all RC beams were loaded up to failure. The free expansion, the compressive strength and the bending residual capacity of plain and fibre concrete were measured on companion specimens for material characterization. The effect of both fibres and alkali silica reaction on bearing capacity and ductility of RC beams were analysed. Results showed that alkali silica reaction damage provokes a significant reduction of RC beam ductility, while the flexural strength is preserved.

**Keywords:** Alkali silica reaction · Crack control · Flexure · Reinforced concrete · Steel fibres

## 1 Introduction

Alkali Silica Reaction (ASR) represents one of the processes of degradation of concrete that generates most interest. Much progress has been made in terms of minerals and causes that produce ASR as well as in the criteria and methods of evaluation and prevention. Nevertheless, there is not much work on the development of ASR under load [1–6] and even less under tensile loads. However, considering that the presence of cracks substantially affects concrete permeability and water is essential for the ASR, it is possible to infer that the kinetics of the reaction should be related to the evolution of tensile cracking.

Fibre Reinforced Concrete (FRC) is a high-performance material with great possibilities for structural design as seen in the *fib* Model Code 2010 [7]. The incorporation of fibres into concrete controls the propagation of fissures and increases residual capacity and toughness. In addition to FRC traditional applications such as floor slabs or tunnel lining, the combined use of FRC y Reinforced Concrete (RC) structural elements improves shear resistance allowing the reduction of conventional steel bars and improves steel-concrete bond, then, reductions in anchorage length are possible. In addition, as fibers control crack width they give important benefits in terms of the extension of service life. Many papers confirm that the use of steel fibers reduces cracks width and spacing [8–10]. In a study on steel FRC elements loaded under uniaxial tension, increases in toughness and reductions in crack spacing were found [11]. Although when combined with conventional reinforcements, fibers do not significantly increase flexural strength and ductility in Ultimate Limit State [12] there are benefits in Service Limit State referred to the control of cracks and deflections, as they enhance the transfer of tensile stresses from the reinforcements to the concrete. The synergy between this mechanism and the FRC residual tensile capacity reduces the width and spacing of cracks. Finally, although the presence of fibres does not prevent the ASR, it reduces the expansions; mainly in the case of steel ones [13]. As a part of a research project on the advantages of using FRC for the extension of the service life and durability of the structures, this paper shows the effects of fibres on the development of ASR in RC beams subjected to long-term loads.

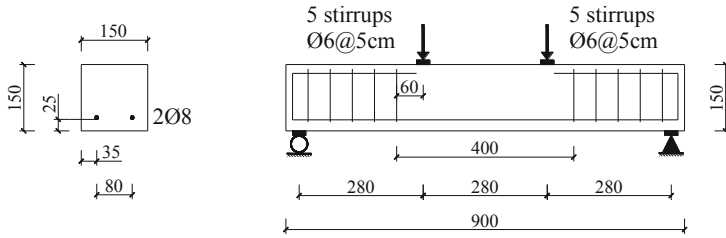
## 2 Experimental Program

Four different types of concrete were used: two incorporating non-reactive aggregates and two with potentially reactive coarse aggregates, and, in each case, one without fibres and the other with steel fibres. Four RC beams, one for each concrete, were subjected to service loads. Twin beams were also cast and they remain unloaded and exposed to the same environmental conditions.

### 2.1 RC Beams

Beams of  $150 \times 150 \times 900$  mm including two 8 mm diameter steel bars as main reinforcement ( $\rho = 0.53\%$ ) and 6 mm diameter stirrups (spaced 50 mm) were cast. They were loaded using 4 PB configuration on a span of 840 mm; Fig. 1 shows the geometry and load configuration adopted. Tensile and compression deformations were continuously recorded by mechanical extensometers.

The study was carried out in a temperature controlled chamber ( $23 \pm 2$  °C) and, to promote ASR all samples were covered with wet cotton cloths and then were isolated by a plastic film and remain in that condition during all the creep test; in addition, water was periodically injected (see Fig. 2). The beams were demoulded at 24 h and moist cured (as described) for 7 days. Then, they were removed from the bags, instrumented, wrapped again with humid cloths and plastic film and loaded by a lever system. Unloaded reference RC beams also remain in the same conditions. The RC beams



**Fig. 1.** Geometry and reinforcement details of the RC beams (in mm).

remain during 8 months under loading and then they were tested in bending up to failure using the same loading configuration.



**Fig. 2.** Load RC beams (left) and reference unloaded ones (right).

## 2.2 Concretes Mixture Design and Properties

Two plain concrete (R, P) with similar mixture proportions, w/c ratio 0.42;  $380 \text{ kg/m}^3$  of ordinary portland cement ( $\text{Na}_2\text{O}_{\text{eq}} 0.73\%$ ), natural siliceous sand (fineness modulus 2.07) and granitic crushed stone of 19 mm maximum size were done. To promote ASR, 40% of the coarse aggregate was replaced by a very reactive quartzitic sandstone in the first of them (R) and NaOH was added in the water to achieve a total alkali content in concrete equal to  $4 \text{ kg/m}^3$ . Two FRC, one reactive and the other non-reactive (FR, FP), were prepared adding  $40 \text{ kg/m}^3$  of low carbon hooked ended steel fibres to the same matrices (R, P). The slump was  $170 \pm 20 \text{ mm}$  on concretes R and P and  $90 \pm 20 \text{ mm}$  when fibres were incorporated.

In addition to RC beams, three  $70 \times 70 \times 300 \text{ mm}$  prisms to measure the evolution of the length variations, six  $100 \times 200 \text{ mm}$  cylinders to evaluate the compressive strength and the modulus of elasticity (only in R and P concretes) and six  $75 \times 105 \times 430 \text{ mm}$  prisms to characterize the flexural response were cast.

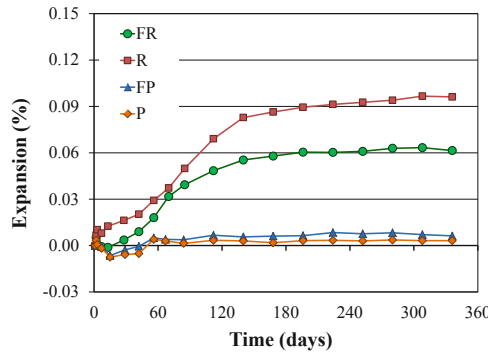
All the specimens were compacted by external vibration and protected to prevent water evaporation. Both RC beams and the rest of the specimens were demoulded after 24 h, covered with wet cotton cloths and stored in plastic bags. Throughout the study the ambient temperature was maintained at  $23 \pm 2 \text{ }^\circ\text{C}$ .

At 7 days RC beams were loaded in the frames as already described. Simultaneously, the compressive strength and the modulus of elasticity and the flexural behaviour of each concrete were evaluated on three cylinders and three notched prisms respectively. Bending tests were performed following the general guidelines of EN 14651 [14, 15]. The rest of the cylinders and prisms were tested at the end of the experience (near 9 months) in order to evaluate the impact of the ASR on the mechanical properties of the concrete.

### 3 Results

#### 3.1 Plain and FRC Properties

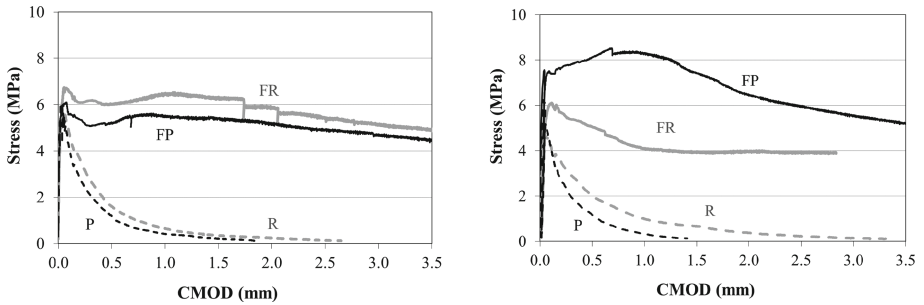
Figure 3 shows the linear expansions measured on  $70 \times 70 \times 300$  mm prisms of each concrete. It can be seen that after near 3 months R and FR show expansions greater than 0.04%, while in the reference mixtures (P and FP) the dimensional changes did not exceed 0.01%. It can be seen that ASR expansions are smaller in FRC; although the incorporation of fibres cannot inhibit ASR, it leads to some benefits such as a decreases in expansions and, even more important, reductions in the width and length of cracks [16].



**Fig. 3.** Evolution of expansions (FR: reactive FRC; R: reactive concrete; FP: non-reactive FRC; P: non-reactive concrete).

Figure 4 shows typical stress-CMOD curves of each concrete at 7 days and 9 months. The effect of ASR damage on the mechanical behaviour of plain and FRC is clearly appreciated when compared the post-peak responses.

The average results of compression and bending tests at both ages are given in Table 1. As it can be seen, no great differences in the mechanical properties at 7 days are present, indicating that ASR damage has not yet occurred at that age. On the contrary, at later ages there is a significant decrease in compressive strength and especially in the elastic modulus of concrete R.



**Fig. 4.** Stress – CMOD curves on notched prisms at 7 days (left) and 9 months (right) (FR: reactive FRC; R: reactive concrete; FP: non-reactive FRC; P: non-reactive concrete).

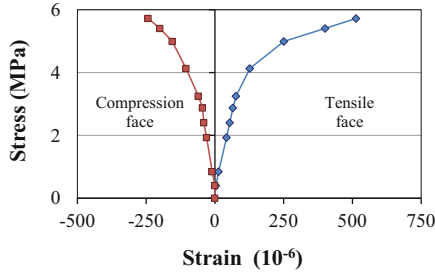
**Table 1.** Mechanical properties of concretes (CV between brackets).

Concrete		R	FR	P	FP
Fibre content (kg/m <sup>3</sup> )	Age	0	40	0	40
$f'_c$ (MPa)	7 days	42.5 (4)		44.5 (4)	
	9 months	32.2 (18)		47.8 (6)	
E (GPa)	7 days	38.5 (4)		40.2 (4)	
	9 months	19.3 (20)		38.5 (3)	
$f_L$ [MPa]	7 days	5.5 (3)	6.9 (3)	5.8 (6)	6.3 (4)
	9 months	4.4 (12)	5.1 (1)	6.2 (9)	7.8 (11)
$f_{R,1}$ [MPa]	7 days		5.8 (6)		5.1 (17)
	9 months		4.1 (31)		7.6 (12)
$f_{R,3}$ [MPa]	7 days		5.6 (4)		5.0 (12)
	9 months		3.2 (28)		6.1 (8)

Regarding the bending behaviour, reactive concretes (R, FR) evidence the internal damage in a lower initial slope (due to internal cracking) when compared to the one observed in concretes P and FP, a reduction in the first peak load and, in the case of plain concrete, an increase in the softening branch. In FR the first peak, the maximum and the residual loading capacity decrease, however, it conserves a residual stress near 4 MPa. The comparison against P and FP is difficult since the crack opening before testing in FR and R prisms is different than zero (i.e. samples are pre-cracked by ASR).

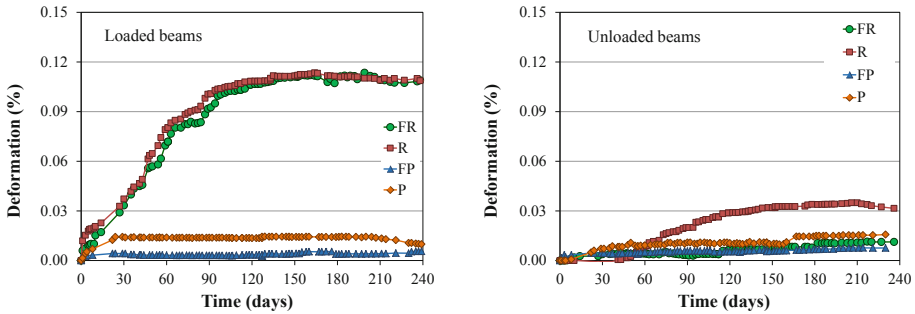
### 3.2 Instantaneous and Creep Behaviour of RC Beams Under Loading

Once placed in the frames, RC beams were loaded measuring tensile and compression deformations in the middle third. Considering that the ultimate estimated load in bending would be between 50 and 65 kN, 24 kN were applied enhancing the development of flexural cracks as in SLS condition. In every case, when the load exceeded 18 kN (near tensile stress 4 MPa) a clear deviation from the linear behaviour was observed during initial loading, indicating the presence of cracks (see Fig. 5).



**Fig. 5.** Example of instantaneous deformations of a beam during the loading process.

Figure 6 shows the evolution of deferred deformations measured on the tensile face of loaded and unloaded RC beams. It can be seen that the specimens incorporating reactive aggregates (R, FR) show a clear increase in the deformations; no great differences between specimens with and without fibres can be detected. Nevertheless, in the case of beams which are not subject to long-term loading (and therefore are not pre-cracked), slight expansions (<100 microstrains) product to a high humidity environment appeared in three cases while in concrete R the expansion growth from about 45 days indicating the presence of ASR.



**Fig. 6.** Evolution of deferred deformations on loaded (left) and unloaded (right) RC beams (FR: reactive FRC; R: reactive concrete; FP: non-reactive FRC; P: non-reactive concrete).

After 5 months under loading a survey of the RC beams surface was performed. In R and FR gel points were observed together with several cracks of approximately 0.05 mm width in the R beam. The crack widths were much smaller in FR being necessary to moisten the specimen surface to see the cracks. It must be noted that not only the expected vertical cracks were found but also cracks with different orientations. Only very small cracks (thickness  $\ll$  0.05 mm) were detected in concretes P and PF which cannot be easily differentiate to those produced during loading (see Fig. 7).



Fig. 7. Appearance of the surface of loaded R and FR beams at the age of 5 months.

### 3.3 Residual Bending Behaviour of RC Beams

Figure 8 presents the load-deflection curves of RC beams after creep test, both that loaded and those that remained unloaded. In addition, Table 2 shows some cracking characteristics measured on the surface of damage beams (R, FR) at 9 months and the main flexural test results evaluated both in terms of bearing capacity and ductility.

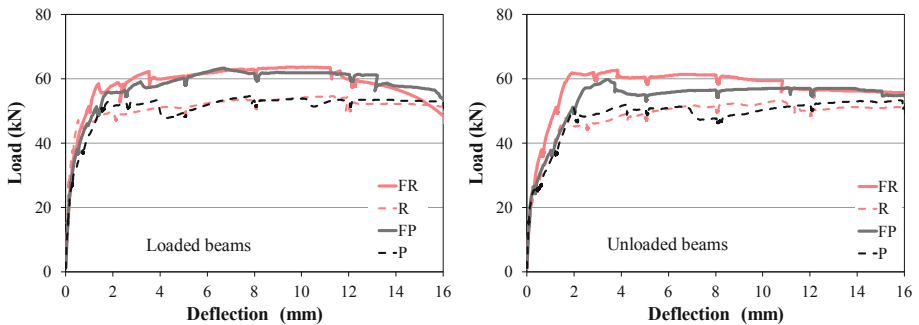


Fig. 8. Load-deflection curves of RC beams after creep test. Left: creep loaded beams. Right: beams that remained unloaded (FR: reactive FRC; R: reactive concrete; FP: non-reactive FRC; P: non-reactive concrete).

Regarding loaded beams, it can be observed that the typical flexural failure expected for under reinforced beam section (i.e. rebar yield before the concrete in the compression zone reached its maximum usable strain,  $CC$ ) was observed only for RC beam without alkali silica reaction. In fact, both FR and R showed a flexural collapse characterized by rebar failure. This aspect can be also observed in Fig. 9, where the final crack patterns of FR and FP beams are shown and compared. In addition, in case of fiber incorporation, crack localization after rebar yielding was observed as expected [17]. This underlines that the damage due to alkali silica reaction changed the mode of failure of the beam, leading to a significant reduction of beam ductility, relative ductility (RD) equal to 0.72 and 0.63 for R and FR beam, respectively. RD was evaluated as  $(\delta_{\max}/\delta_y \text{ of FR})/(\delta_{\max}/\delta_y \text{ of FP})$  for concretes with fibers and  $(\delta_{\max}/\delta_y \text{ of R})/(\delta_{\max}/\delta_y \text{ of P})$  for concretes without fibers. The reduction of ductility was even more pronounced in the FRC beam as a consequence of the crack localization due to fibers. In terms of

**Table 2.** Survey of cracks before testing in concretes affected by ASR and the results of flexural tests on RC beams.

Concrete		Before testing		Results of flexural tests						
		Crack density mm/mm <sup>2</sup>	Crack width mm	Type of flexural failure	P <sub>max</sub>	ΔP <sub>max</sub>	δ <sub>y</sub>	δ <sub>max</sub>	δ <sub>max</sub> /δ <sub>y</sub>	RD
					kN	%	mm	mm		
Loaded	FR	0.029	0.07	RF	63.6	16	1.86	11.7	6.29	0.63
	R	0.023	0.20	RF	54.6		2.07	15.5	7.51	0.72
	FP	–	–	CC + CL	63.3	16	1.92	19.3	10.05	
	P	–	–	CC	54.6		1.90	19.8	10.42	
Unloaded	FR	0.026	0.05	CC + CL	62.7	18	1.90	20.0	10.54	0.99
	R	0.011	0.01	CC + CL	53.1		1.76	17.3	9.85	0.94
	FP	–	–	CC + CL	59.8	15	1.90	20.2	10.63	
	P	–	–	CC	52.1		1.96	20.6	10.51	

Type of flexural failure: *RF*: rebar failure due to crack localization; *CC*: concrete crushing without crack localization; *CC + CL*: concrete crushing with crack localization.

P<sub>max</sub>: Maximum load.

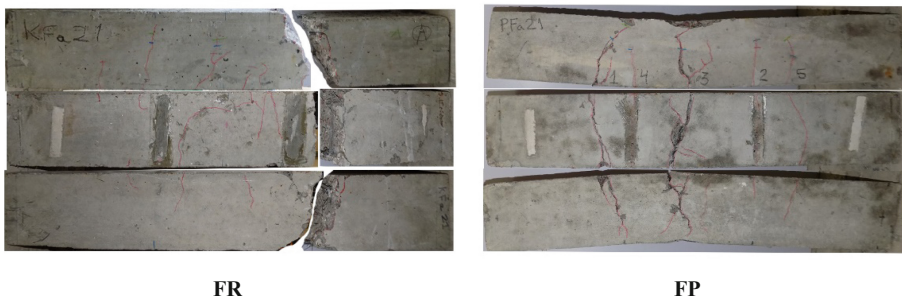
ΔP<sub>max</sub>: Increase in load due to fibre incorporation.

δ<sub>y</sub>: Net mid-span deflection at rebar yielding.

δ<sub>max</sub>: Maximum net mid-span deflection.

RD: Relative ductility of damaged concrete (R/P; FR/FP).

bearing capacity, it can be observed that the damage due to alkali silica reaction does not reduce the flexural bearing capacity. This is due to the fact that the main parameter influencing the flexural bearing capacity of RC beams is the rebar amount and position, while the concrete compressive strength (which is affected by alkali silica reaction, Table 1) has a secondary role.



**Fig. 9.** Final crack pattern of loaded beams after testing: FR (left) and FP (right).

Concerning unloaded beams, it can be underlined that all beams showed a flexural failure characterized by concrete crushing after rebar yielding (no rebar failure was

observed). However, the presence of either fibres or alkali silica reaction damage led to a premature crack localization, which is not generally observed in under reinforced beams under flexure. Since this crack localization did not affect the beam ductility, the overall ductility of the different beams resulted comparable. In fact, RD is equal to 0.99 and 0.94 for R and FR beam, respectively. This small reduction of beam ductility in the unloaded specimens damaged by alkali silica reaction is probably due to the low mechanical properties of concrete in the compression zone. Finally, the maximum bearing capacity seems once again to be not affected by alkali silica reaction damage.

## 4 Conclusions

The influence of alkali silica reaction damage on the flexural behaviour of RC beam with and without fibres was studied by means of an experimental program on small beams subjected to service loads or not. Based on this experimental program, the following conclusions might be drawn:

- With the selected materials and proportions, a concrete was achieved where the damage caused by ASR was manifested for the times of the proposed research; after a month the signs of reaction were already evident. From that period, the standard prisms showed expansions that exceeded 0.04% and the ASR was also manifested in the RC beams.
- The flexural behavior of RC beams damaged by alkali silica reaction is different considering loaded or unloaded beams. In fact, alkali silica reaction effects are more severe in service loading condition.
- Alkali silica reaction damage significantly affects the ductility of RC beams, due to premature crack localization after rebar yielding. This effect is even more pronounced in case of fibre reinforced concrete.
- The alkali silica reaction damage (corresponding to a reduction of 25% of concrete compressive strength) does not clearly affect the flexural bearing capacity of RC beams.

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