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# Effect of different fibres in mitigation of alkali-silica reaction

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ABSTRACT

Alkali-silica reaction (ASR) is a phenomenon that causes irreversible damage to concrete structures. Since 1940, research has continued to investigate the possibility of eliminating these negative effects. The lack of availability of non-reactive aggregates requires the use of reactive aggregates, characterized by satisfactory physical and mechanical properties, with the introduction of innovative solutions to mitigate the effects of ASR expansion. Recently, fibre-reinforcement has shown to be a promising approach, even if the type and the volume of fibres used to reduce, or eliminate, the deleterious effects of expansion are not well established. For this reason, Miniature Concrete Prism Tests (MCPT) were performed on 4 series of expansive concrete prisms without any fibres and with 0.5% in volume of polypropylene fibres, steel fibres, and recycled carbon fibres, respectively. In addition, 4 series of non-expansive mortar prisms, with and without fibres, were tested in bending. As a result, by using recycled carbon fibres a moderate expansion can be observed after 56 days, in contrast to the high expansion of un-reinforced concrete. The same positive effect cannot be observed in concrete reinforced with steel or polypropylene fibres. This is due to the absence of the deflection hardening capacity of the fibre-reinforcement, as confirmed by both mechanical tests on non-expansive mortars, and by the analysis of microstructure on the post-mortem specimens.


## 1. Introduction

The alkali-silica reaction (ASR) is a chemical reaction that occurs in concrete structures when alkalis in the cement mix react with reactive forms of silica in aggregates. The reaction produces a gel-like substance that absorbs water and expands, causing cracking and deterioration of the concrete. The reaction can occur in any cement-based structure, including bridges, dams, and buildings, and can lead to significant damage and reduced structural integrity. As reported almost 90 years ago by Stanton [1], and further by other researchers [234], ASR causes irreversible damage to concrete structures and drastically reduces their durability. Accordingly, preventing the ASR reaction from occurring is important in the design and construction of concrete structures. This is possible by carefully selecting aggregates that are not prone to ASR, using low-alkali cement and properly curing the concrete to ensure that it is adequately hydrated and has sufficient time to gain strength. In some cases, it may also be necessary to treat the concrete with chemical admixtures to avoid that ASR reaction takes place [5].

In situations where the use of ASR-prone aggregates is necessary due to the shortage of non-reactive aggregates, various techniques can be used to mitigate the risk of ASR. The addition of pozzolanic materials [6] or by treating the concrete with a lithium solution [7] can be an effective way to reduce the amount of alkalis available for the reaction and to bind any excess alkalis that may be present. Recently, also the addition of fibres, made with steel or polypropylene, in concrete systems prone to ASR reaction has received a lot of attention. Steel fibres, which are widely used to improve the toughness in bending and tension of concrete manufacts, also have the capability of mitigating the deleterious effects of ASR. Test results presented by Yazıcı [8] indicate that steel fibres not only reduce ASR expansion of mortars (even if it cannot be eliminated completely), but also prevent the loss of mechanical properties, such as strength and toughness, due to ASR. These beneficial effects can be ascribed to the fact that the combination of steel fibres and ASR expansion produces a restraining effect on the concrete structure, as observed by Farooq and Yokota [9]. Giaccio et al. [10] showed that steel fibres were the most efficient for

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the reduction of crack density caused by ASR, followed by concrete with synthetic macrofibres and by concrete with microfibres. However, in all the fibre-reinforced concrete, fewer cracks were found than in reference plain concrete. The tests performed by Hernández-Cruz et al. [11], in which mortars were reinforced by two different polymer fibres (i.e., polypropylene and polymer hybrid fibres) in addition to air-voids distribution, showed a relevant reduction in the expansion, because air voids were filled by ASR gel near the reacting aggregates. A similar behaviour was also observed by Mohr et al. [12], who revealed that thermomechanical pulp fibres were more effective at reducing ASR expansion than kraft pulp and polypropylene fibres. It was shown that the kraft pulp fibres served as a reservoir for alkali–silica gel, potentially minimizing internal expansive pressures.

Nevertheless, in all the previous studies concerning the ASR in fibre-reinforced concrete, only the reduction of expansion with the content of fibres was measured. As it was not correlated with the mechanical properties of FRC, it is impossible to tailor concrete systems with controlled expansion, for instance by using also other types of fibres. Indeed, previous study showed the good mechanical performances of high strength concrete reinforced with carbon fibres [13], and the improvement of strength and microstructure of the cement composites with recycled carbon fibres [14]. Accordingly, due to the concern over sustainability in the construction industry, it could be interesting to investigate new concrete in which recycled carbon fibres (in alternative to the manufactured steel and polypropylene fibres) are added in cement-based systems with and without ASR-induced expansion. This study can be useful when it is impossible to use non-expansive aggregates.

## 2. Materials, mixtures, and experimental methods

### 2.1. Constituent materials

To evaluate the performance of fiber-reinforced concrete (FRC) in reducing the expansion caused by the alkali-silica reaction (ASR) in mortar and concrete mixes containing expansive aggregates, various types of mechanical tests and ASR tests have been performed. There were made with only one ordinary Portland cement (CEM I): CEM I 52,5 R for the mechanical tests and CEM I 42,5 R with a $Na_2O_{eq}$ = 0.9% for both ASR and mechanical tests.

Three different fibres (steel, polypropylene, and recycled carbon fibres) reinforced both expansive potential and non-expansive concretes and mortars. The characteristics of the fibres are presented in Table 1, whereas the morphology of the steel, polypropylene and carbon fibres is shown in Fig. 2.

It is worth emphasizing that, unlike other literature data [14], the analysed carbon fibres from recycling were characterized by a uniform shape and size, smooth surface, free of any defects or products that could remain attached during the recycling process.

As an aggregate, in mortars for mechanical tests, the standard siliceous sand was used according to UNI EN 196–1 standard [15]. For the alkali-silica reaction mitigation test (MCPT), one very highly reactive coarse aggregate [16], was used in the study. The 14-day ASTM C1260 [17] expansion of the mortar with this aggregate was 0.265%, and 365-day ASTM C1293 [18] expansion of the concrete was 0.095%. A non-reactive siliceous sand (14-day's expansion 0.040%) was used as a fine aggregate for the concrete mixtures.

### 2.2. Mixtures

Two groups of cement-based systems were analysed (see Table 2). The first group, composed by four mortars (M1, M2, M3 and M4) was tailored in accordance with UNI EN 196–1 standard [15], with a water to cement ratio equal to 0.5 and with a content of cement of 450 kg per cubic meter. With the exception of M1, the content of fibres was 0.5% in volume in all the mortars, but obtained with the different types of fibres (steel fibres in M2, polypropylene fibres in M3, and carbon fibres in M4).

In the second group, 4 concrete mixtures (C1, C2, C3, and C4) were designed and proportioned for the expansive test, as suggested by AASHTO T-380, [16]. In Miniature Concrete Prism Test (MCPT), the water-to-cement ratio was 0.45, and the cement content was equal to 420 $kg/m^3$. The alkali content in all the mixtures were boosted to 1.25% of the mass of cement. The reactive coarse aggregate consisted of 2–4 mm fraction (11% by mass) and 4–12.5 mm fraction (89% by mass). The fine aggregate (0–2 mm) content was 36%. The content of fibres was similar to that of mortar systems. In particular, C1 was unreinforced, whereas C2, C3, and C4 were reinforced with 0.5% in volume of steel fibres, polypropylene fibres, and carbon fibres, respectively. The superplasticizer was used at 0.5% of cement mass, when polypropylene and steel fibres were introduced in the concretes. It arrives to 1% of cement mass when carbon fibres were used.

The mortars were tested in bending to analyse the mechanical behaviour with and without fibres, and without the expansive phenomenon of ASR. On the contrary, the concretes were used to measure the expansion due to the ASR (with and without the presence of fibres) and to measure the strength in presence of both fibres and expansive phenomenon. To analyse the influence of fibres on ASR expansion, the results of all the tests can be correlated, because in C series and M series the specimens are labelled with a number that represents the same type of reinforcement (i.e., 1 = absence of reinforcement; 2 = reinforced with 0.5 % in volume of steel fibres; 3 = reinforced with 0.5 % in volume of polypropylene fibres, and 4 = reinforced with 0.5 % in volume of recycled carbon fibres).

### 2.3. Specimens and methods

#### 2.3.1. Expansion tests

For the MCPT, the concrete prims shown in Fig. 2a were made with the concrete mixtures (i.e., C1, C2, C3, and C4) and had the dimensions H = 50 mm, B = 50 mm, and L = 285 mm. The prims were introduced in 1 M NaOH solution at 60 °C after one day in moulds and one day in water at 60 °C. As depicted in Fig. 2b, the prisms were monitored for the change of length L1 = 254 mm for a period of 84 days, where a standard duration is 28 days shorter [20].

#### 2.3.2. Bending tests

Three point bending tests (Fig. 2c) were carried out on the concrete prism C1, C2, C3 and C4, at the end of the expansion tests

**Table 1**
Properties of the fibres used to reinforce concrete and mortar.

| Type of fibres | Carbon content (wt.%) | Diameter (μm) | Type of fibres (μm) | Density (g/dm$^3$) |
|---|---|---|---|---|
| Carbon | > 98 | 6.5–7 | 15 000–20 000 | 1600 |
| Steel | < 1, [Fe > 85%] | 200 | 13 000 | 7850 |
| Polypropylene | > 99 | 40 | 9 000 | 910 |

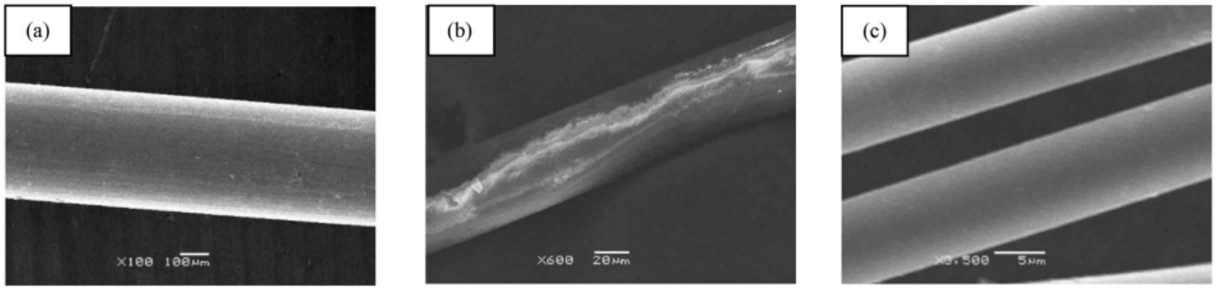


**Fig. 1.** SEM microphotograph of the fibres: (a) steel – scale bar 100 μm; (b) polypropylene – scale bar 20 μm; (c) carbon – scale bar 5 μm.

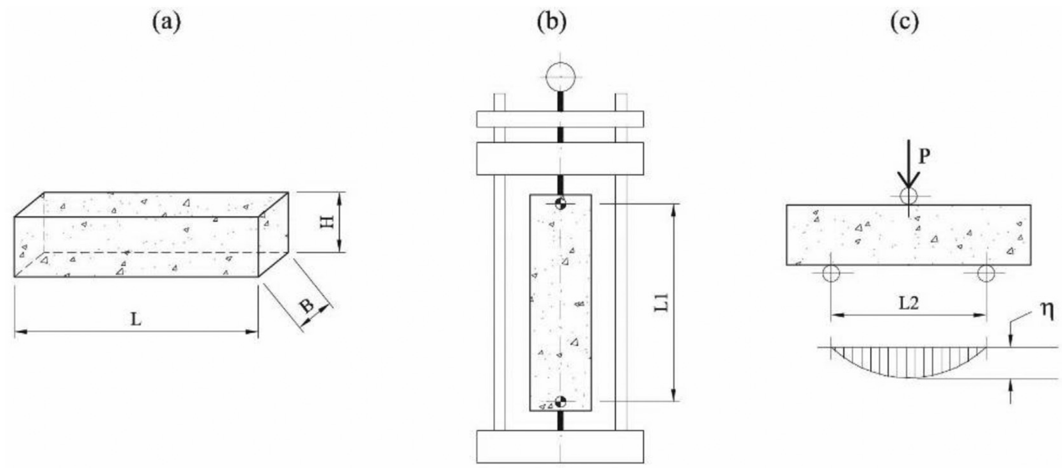


**Fig. 2.** Tests on mortars and concretes: (a) geometrical properties of the specimens; (b) expansion tests; (c) three point bending tests.

**Table 2**
Mortar and concrete investigated in this project.

| | Mortar systems - M series | | | | Concrete systems – C series | | | |
|---|---|---|---|---|---|---|---|---|
| | M1 | M2 | M3 | M4 | C1 | C2 | C3 | C4 |
| Water (kg/m$^3$) | 225 | 225 | 225 | 225 | 189 | 189 | 189 | 189 |
| Ordinary Portland cement (kg/m$^3$) | 450 | 450 | 450 | 450 | 420 | 420 | 420 | 420 |
| CEN sand (kg/m$^3$) | 1350 | 1350 | 1350 | 1350 | – | – | – | – |
| Fine aggregate, 0–2 mm (kg/m$^3$) | – | – | – | – | 643 | 643 | 643 | 643 |
| Coarse aggregate, 2–4 mm (kg/m$^3$) | – | – | – | – | 123 | 123 | 123 | 123 |
| Coarse aggregate, 4–12.5 mm (kg/m$^3$) | – | – | – | – | 1017 | 1017 | 1017 | 1017 |
| NaOH - alkali boosting (kg/m$^3$) | – | – | – | – | 1.9 | 1.9 | 1.9 | 1.9 |
| Superplasticizer (kg/m$^3$) | – | – | – | – | – | 2.1 | 2.1 | 4.2 |
| Steel fibres (kg/m$^3$) | – | 39.3 | – | – | – | 39.3 | – | – |
| Polypropylene fibres (kg/m$^3$) | – | – | 4.6 | – | – | – | 4.6 | – |
| Recycled carbon fibres (kg/m$^3$) | – | – | – | 8 | – | – | – | 8 |

according to AASHTO T-380, [16]. During each bending test, load was progressively increased at a velocity of 0.5 mm/min up to the failure of the prism, by using a load-controlled machine equipped with a loading cell of 50kN.

To correlate the effect of fibre-reinforcement with the expansion produced by ASR, other bending tests were performed in absence of expansive reactions. Accordingly, the prims shown in Fig. 3a were made with the mortar mixtures M1, M2, M3, and M4 as suggested by UNI EN 196–1 [15]. They had the dimensions of H = 40 mm, B = 40 mm, and L = 160 mm. All specimens were tested in three point bending (on a span length L2 = 100 mm) after 28 maturity days. In the mid-span of the specimens through a loading machine an external load P was applied (load capacity of 100 kN). Tests were performed by driving the displacement of the loading cell (i.e., the mid-span deflection $\eta$ in Fig. 2c), whose stroke moved at a velocity of 0.05 mm per minute.

### 2.3.3. Microstructure analysis

Scanning electron microscopy (SEM-JEOL JSM-6460 LV in high vacuum) with an energy dispersive X-ray spectroscopy (EDS) analyser was applied for microstructural analysis. The samples were observed for fracture pattern and fiber interaction with surrounding products of hydration. An aperture of 120 μm and a voltage of 15 kV were applied. The operating distance was 10 mm. Observations were carried out in the magnification range from 60 $\times$ to 3500 $\times$. EDS spectra were collected from more than 25 different places (1x 1 μm$^2$) on each specimen.

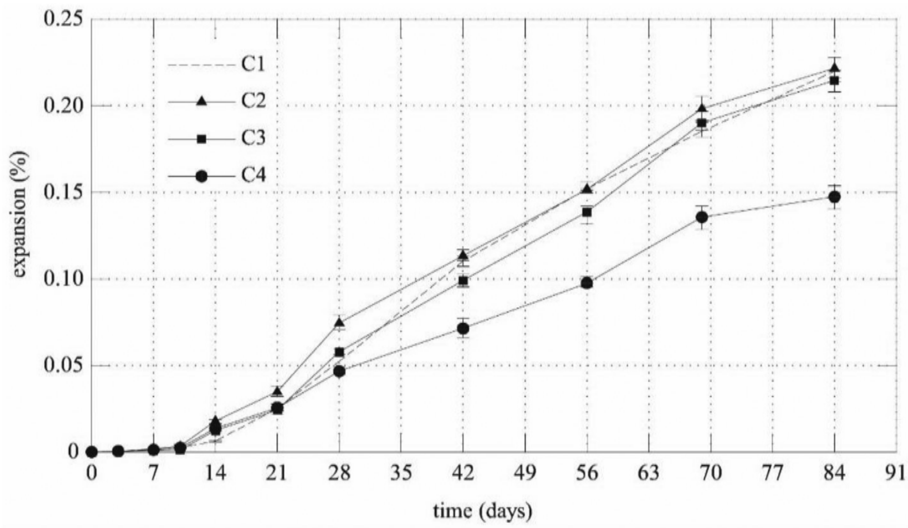


**Fig. 3.** Results of Miniature Concrete Prism Tests (MCPT) after 84 days at 60 °C in 1 M NaOH.

## 3. Results and discussion

### 3.1. Expansion tests

The 84-day results of MCPT are presented in Fig. 3. It is possible to observe that the concrete prisms with carbon fibres (C4) expanded less than those with the steel (C2) and polypropylene fibres (C3). Although the expansion of the reference specimens (C1) without the fibres and the remaining specimens with different types of fibres was similar up to day 28, the expansion rate was markedly slower in the specimens containing carbon fibres. After 56 days of testing, carbon fibre concrete prisms reached an expansion of 0.098% (i.e., they are in the category of moderately reactive composites [16]), whereas the expansion of the remaining concrete specimens was in the highly reactive category, (0.139% in C3, 0.152% in C2, and 0.152% in C1). After 70 days, the flattening of the expansion curve is visible for concrete with carbon fibres.

It should be noted that criteria for characterizing the aggregate reactivity in the MCPT protocol, as well as the criteria to determine the effectiveness of the supplementary cementitious materials in mitigating ASR expansions given in [16], apply to aggregates only. However, they give a general idea of the reactivity of the aggregate and the amount of expansion in FRC.

### 3.2. Bending tests

Fig. 4 shows the typical result of a bending test on fibre-reinforced mortar [19]. On the abscissa, the deflection $\eta$ of the prism (see Fig. 2c), corresponding to the applied load P (on the ordinate), is reported. After the initial ascending branch, the cracking phenomenon can be characterized by the so-called deflection-hardening [20], in which a multiple cracking phenomenon can be observed in the tension zone of the beam. Generally, this behaviour occurs when a suitable content of fibres is used to reinforce the cement-based system. On the contrary, a deflection softening takes the place at the effective cracking of the beams, which reaches the failure conditions only in presence of a single crack.

Therefore, in the case of deflection-hardening, the strength $P_u$ is greater than the load at cracking $P_{cr}$. When deflection softening is present, $P_u = P_{cr}$. Hence, following values of the flexural strength, calculated in the linear elastic regime, can be used to define the type of the load P *vs.* deflection $\eta$ diagram:

$$\sigma_{cr} = \frac{3P_{cr}L_2}{2BH^2} = \text{effective cracking strength} \quad (1)$$

$$\sigma_u = \frac{3\,P_u\,L_2}{2\,B\,H^2} = \text{flexural strength} \quad (2)$$

In particular, deflection hardening exists when $\sigma_u - \sigma_{cr}$ greater than 0, whereas when $\sigma_u - \sigma_{cr} = 0$ (or $\sigma_u = \sigma_{cr}$) deflection softening characterizes the flexural behaviour. The values of flexural strength, measured on both the mortar (M series) and concrete (C series) specimens are shown in Fig. 5a. The highest values of the flexural strength were found for the concrete and mortars with carbon fibres (M4 and C4), whereas the lowest values are obtained in absence of fibres (M1, C1).

Nevertheless, also with steel (M2, C2) and polypropylene (M3, C3) reinforcements, the flexural strength does not differ from that of plain mortar and concrete. It must be remarked that the flexural strength of the mortar (tested without any expansive phenomenon) is more or less similar to that of the concretes used in the MCPT [16]. Nevertheless, in the latter case, $\sigma_u$ is a little bit higher.

Concerning the deflection hardening phenomenon, it is recognizable only in the case of the bending tests on mortars, because both the load P and the corresponding deflection $\eta$ have been measured during in the experimental procedure. As shown in Fig. 5b, only in the case of the carbon fibre-reinforcement (M4), the deflection hardening was observed, whereas $\sigma_u = \sigma_{cr}$ in presence of other fibre-reinforcements, as in the plain mortar M1. Probably, the highest values of $\sigma_u$ observed in the mortar M4 and concrete C4 were due to the deflection hardening phenomenon of the mortars and concretes reinforced with recycled carbon fibres.

### 3.3. Microstructure analysis

As observed in the images obtained from SEM, ASR products with similar morphological characteristics were clearly visible on images (of approximately 70 × or higher magnification – see Fig. 6) of all the specimens of concrete series. In particular, they were situated in the cement matrix, in the air-voids, in the zone between aggregate-cement paste and also at the fibre–matrix interface.

The thickness of the ASR gel on fibres surface was estimated at the SEM microphotographs and the results, illustrated in Fig. 7, are the average of 15 measurements. The thickest layer of ASR gel sur-

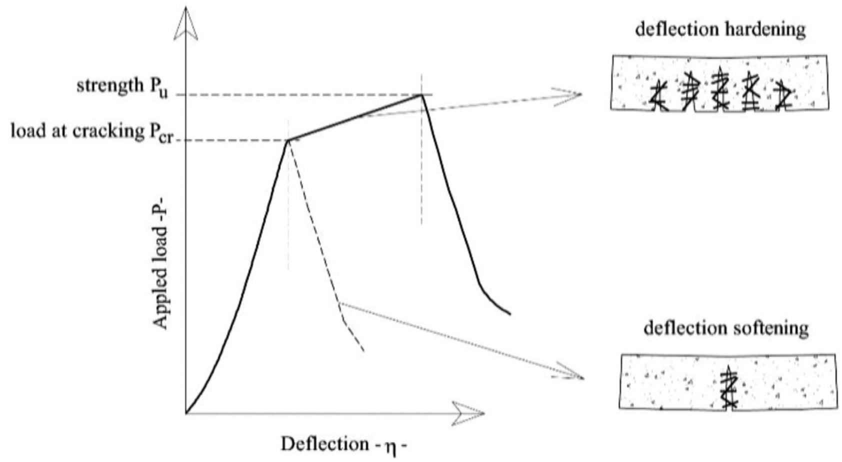


**Fig. 4.** Typical load deflection diagram of three-point bending tests performed on FRC [20].

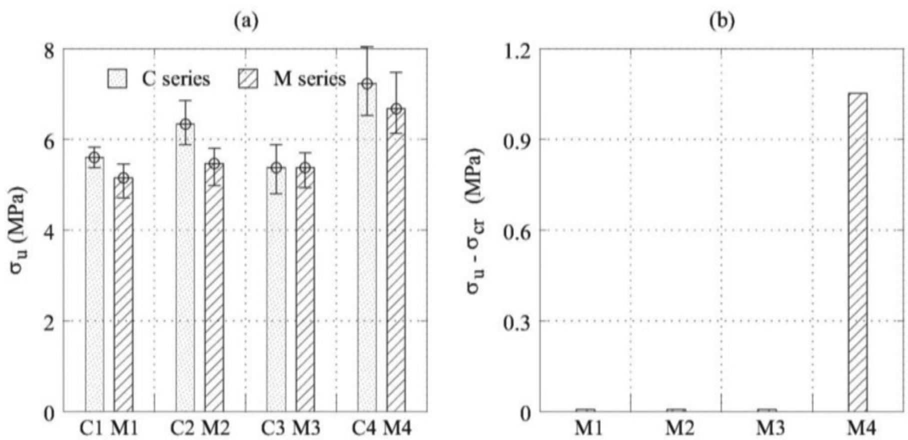


**Fig. 5.** Results of the three-point bending test: (a) evaluation of the flexural strength on both M and C series; (b) quantitative evaluation of the deflection hardening in M series.

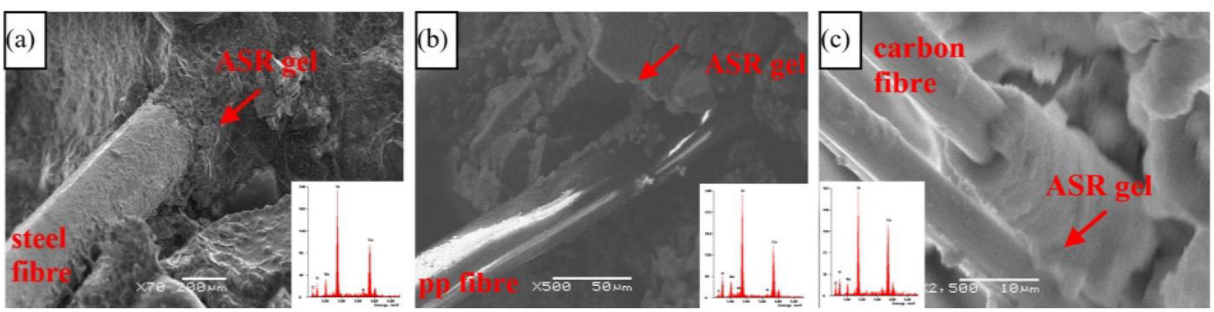


**Fig. 6.** SEM microphotograph of the fibre-ASR gel contact zone in concrete specimens after MCPT and with EDS analysis: (a) steel fibre of C2 specimen; (b) polypropylene fibre of C3 specimen; and (c) carbon fibre of C4 specimen.

rounded the carbon fibres (2.90 ± 0.21 μm), then steel (1.98 ± 0.19 μm), and finally polypropylene (0.96 ± 0.16 μm). It should be noted that the SEM analysis was carried out on the freshly split surface of the specimen, while in the specimens with steel (C2) and polypropylene fibres (C3), a cracked ASR gel was visible, which may indicate variable humidity conditions inside the specimens resulting from the degradation of the microstructure.

## 4. Discussion

As previously mentioned, although the MCPT method does not apply directly to concrete specimens reinforced with fibres, the general tendency of the behaviour of FRC with ASR expansion is clearly visible. The addition of carbon fibres decreased the final expansion about 33%, while it was practically invisible with the other reinforcements. Thus, the expansion of concrete prisms with carbon fibre was at the level of the moderately reactive category and specimens without fibres, or with other types of fibres, were in the highly reactive range.

In practice, in the specimens C2 and C3 there were not a reduction of ASR expansion of concrete specimens, although these results and dependencies differ from those already known in the literature [8 -12,21,22]. This is due to the fact that, although the conducted research was performed according to MCPT method

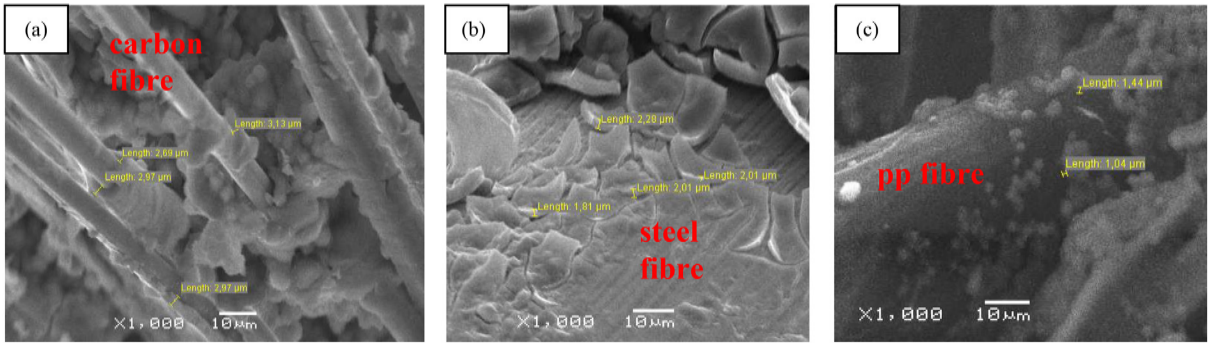


**Fig. 7.** The thickness of the ASR gel shell on the fibres (scale bar 10 μm): (a) steel fibre; (b) polypropylene fibre; (c) carbon fibre.

[16], some modifications were applied to the above research method [8,9,11]. The main difference lies in the composition and size of the tested specimens. Also, the temperature was different from the standard test method. The mortar bar specimens of 40 × 40 × 160 mm were used, [8,9]. A finer sand gradation corresponding to the smallest three aggregate sizes specified by ASTM C 1260 renormalized to 100% and lower temperature (50 °C) were adopted [11].

Moreover, it is known that inclusion of polypropylene fibres increases total porosity of cementitious matrices [23]. Additionally, due to the small cross-section of the specimens, regions with increased porosity could be formed, which could directly create places for the expansion of the ASR gel. Also, previous research [21] were performed on specimens containing from 1% to 7% of steel fibres, whereas in the conducted study the content of fibres was 0.5%. And in similar research [22], when the content of fibres was 0.5% the reduction of the ASR expansion was achieved about 25%. However, in the tests performed by Turanli et al. [21], for the volume of 1% of fibres which reduced the expansion and cracking due to AAR the beneficial effect depended on the curing time.

A detailed analysis of the microstructure of carbon fibres revealed their texture (see Fig. 1). There were no fine particles of different shape and size on the fiber surface as in [14], but grooves of similar widths along the fibre axis of the recycled carbon fibres were found. Probably, this shape improved the bond between fibres and matrix, and the mechanical performances of FRC as well.

In addition, the detailed SEM analysis showed that all types of fibers became an integral part of the cement matrix, and also, as shown in Figs. 6 and 7, the surface of the fibers was surrounded by ASR products. ASR gel was found on the surface of fibres which provides visual evidence that ASR products start to grow around the outer perimeter of the fibers. However, only grooves on the surface of the carbon fibres can be regarded as an additional base for the deposition of ASR products, Fig. 6c. The zone between the ASR gel and the carbon fiber is more compact probably due to the surface of the fibers, which is characterized by grooves that increase the available surface. ASR gel congestion in carbon fibre–matrix interface could increase the pull-out load and debonding toughness, as reported in [24]. The obtained results are in line with previous a study [21], in which the authors proposed that microfibers are more efficient than conventional fibers because their short length allows reactive aggregates to be placed close to the interface, thus affecting early ASR gel formation.

For each type of concrete, the reduction of expansion can be measured with the following equation:

$$\Delta_{exp} = \varepsilon_{concrete} - \varepsilon_{C1} \quad (3)$$

where $\varepsilon_{concrete}$ = expansion measured at a specific day in a concrete specimens (C2, C3, or C4); and $\varepsilon_{C1}$ = expansion measured at the same day in C1. Such value can be correlated with the results of bending tests, and in particular with the flexural strength $\sigma_u$ (Fig. 8a) measured both through the mortar and concrete prisms of M series and C series, respectively. Namely, $\Delta_{exp}$ obtained with each concrete system (i.e., C2, C3 and C4) can be associated to $\sigma_u$ measured on the same specimens and on those of the mortars (i.e., M1, M2, M3 and M4) having the same type of reinforcement (M1 with C1, M2 with C2, M3 with C3, and M4 with C4). As shown in Fig. 8a, it seems that the reducing of expansion (i.e., a negative value of $\Delta_{exp}$) exists only when the flexural strength is higher than a specific value (≈ 6.5 MPa), regardless of the way $\sigma_u$ is measured (i.e., with and without the presence of ASR expansion). Thus, the

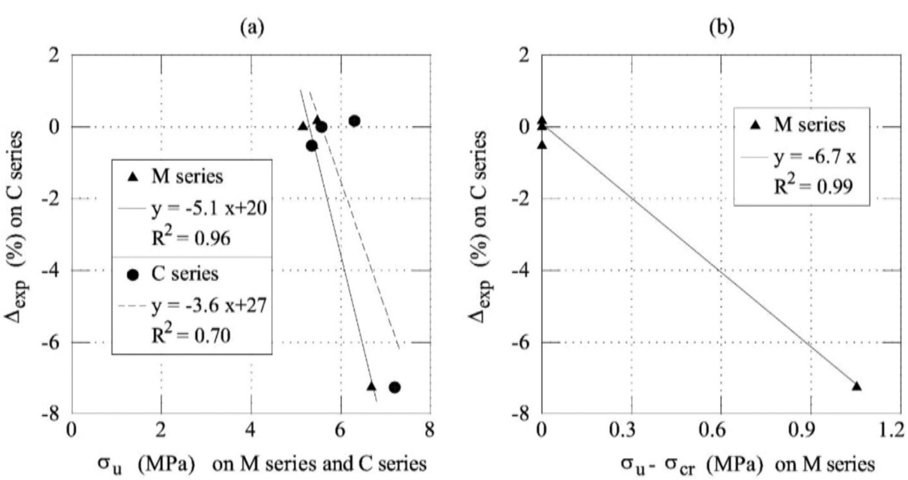


**Fig. 8.** Combining the results of the expansion tests at 90 days and three point bending tests: (a) effect of the flexural strength measured on both M and C series; (b) effect of the deflection hardening behaviour measured on M series.

capability of having a negative value of $\Delta_{exp}$ is an intrinsic property of cement-based system, and in the present research project was achieved only in concretes reinforced with recycled carbon fibres (i.e., in specimen C4).

Although in C2 and C3 the fibre volume fraction of steel and polypropylene fibres is the same of C4, the reinforcement does not have any effect on the mitigation of ASR expansion. Therefore, only carbon fibres may redistribute the local strain caused by ASR expansion throughout the concrete, which can help to reduce the overall expansion of the concrete specimen. Such a redistribution phenomenon produced by the fibre reinforcement is also evident in the flexural behaviour in absence of ASR (see Fig. 4), when multiple cracking phenomenon and deflection hardening occur. Thus, an interesting correlation between $\Delta_{e.}$, measured on concrete systems, and the corresponding strain-hardening phenomenon (herein measured as $\sigma_u$-$\sigma_{cr}$) on the mortar systems with the same type of reinforcement, is shown in Fig. 8b. Only the use of carbon fibres in concrete C4 and mortar M4 seems to improve the bond between the cement paste and the aggregate and help to reduce ASR expansion. It seems possible that the bond between carbon fibres and the gel formed during the alkali-silica reaction (Fig. 6c) may have some potential to mitigate the expansion and cracking caused by ASR.

## 5. Conclusions

According to the tests performed on mortars and concretes, the following conclusions can be drawn:

- The addition of fibres can reduce the expansion of ASR in cement-based systems
- However, for a fixed fibre volume fraction, the capability of the fibres reinforcement to reduce the expansion depends on the type of fibres.
- In this research project, the addition of 0.5% of recycled carbon fibres decreased of about 33% the concrete expansion caused by ASR. On the contrary the same amount of polypropylene and steel fibres does not lead to a significant reduction of expansion.
- Only when FRC shows a deflection hardening, can the ASR expansion be effectively reduced. This occurs in presence of carbon fibres also because the texture of the carbon fibres increases the bond strength.

If the deleterious effect of ASR can be controlled and reduced, reactive aggregate will be used and greener concrete can be tailored (i.e., by eliminating the transportation costs of non-reactive aggregates and by avoiding the depletion of non-renewable natural resources). As this beneficial effect has been obtained with the addition of recycled carbon fibres, future research activities will be devoted to fully understand the specific mechanisms by which this type of fibre reduces ASR expansion.

## CRediT authorship contribution statement

**Daria Jóźwiak-Niedźwiedzka:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Alessandro P. Fantilli:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Kinga Dziedzic:** Methodology, Investigation, Writing – review & editing. **Paweł Lisowski:** Investigation, Writing – review & editing.

## Data availability

No data was used for the research described in the article.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## References

[1] T.E. Stanton, Expansion of concrete through reaction between cement and aggregate, Proc. Am. Soc. Civ. Eng. 66 (1940) 1781–1811.
[2] R.N. Swamy, The Alkali-Silica Reaction in Concrete, Van Nostrand Reinhold, New York, 1992.
[3] M.A.T.M. Broekmans, Deleterious reactions of aggregate with alkalis in concrete, Rev. Miner. Geochem. 74 (2012) 279–364.
[4] E. Garcia-Diaz, J. Riche, D. Bulteel, C. Vernet, Mechanism of damage for the alkali–silica reaction, Cem. Concr. Res. 36 (2006) 395–400.
[5] R.B. Figueira, R. Sousa, L. Coelho, M. Azenha, J.M. de Almeida Jorge P.A.S., C.J.R. Silva, Alkali-silica reaction in concrete: Mechanisms, mitigation and test methods, Constr Build Mater., 222 (2019) 903–93
[6] A.K. Saha, M.N.N. Khan, P.K. Sarker, F.A. Shaikh, A. Pramanik, The ASR mechanism of reactive aggregates in concrete and its mitigation by fly ash: a critical review, Constr. Build. Mater. 171 (2018) 743–758.
[7] M. Kawamura, H. Fuwa, Effects of lithium salts on ASR gel composition and expansion of mortars, Cem. Concr. Res 33 (2003) 913–919.
[8] H. Yazıcı, The effect of steel micro-fibres on ASR expansion and mechanical properties of mortars, Constr. Build. Mater. 30 (2012) 607–615.
[9] S. Farooq, H. Yokota, Residual mechanical properties of steel fibre reinforced concrete damaged by alkali silica reaction and subsequent sodium chloride exposure, Ceram. Int. 48 (17) (2022) 24850–24858.
[10] G. Giaccio, M.E. Bossio, M.C. Torrijos, R. Zerbino, Contribution of fibre reinforcement in concrete affected by alkali–silica reaction, Cem. Concr. Res 67 (2015) 310–317.
[11] D. Hernández-Cruz, C.W. Hargis, J. Dominowski, M.J. Radler, P.J.M. Monteiro, Fibre reinforced mortar affected by alkali-silica reaction: a study by synchrotron microtomography, Cem. Concr. Compos. 68 (2016) 123–130.
[12] B.J. Mohr, K.L. Hood, K.E. Kurtis, Mitigation of alkali–silica expansion in pulp fibre–mortar composites, Cem. Concr. Compos. 31 (9) (2009) 677–681.
[13] N. Lamba, R. Raj, P. Singh, Mechanical response of recycled carbon fibre reinforced polymer fibres in high-strength concrete, Mater. Today:. Proc. (2022), https://doi.org/10.1016/j.matpr.2022.11.
[14] A. Akbar, V.K.R. Kodur, K.M. Liew, Microstructural changes and mechanical performance of cement composites reinforced with recycled carbon fibres, Cem. Concr. Compos. 121 (2021).
[15] UNI EN 196-1, Methods of testing cement - Part 1: Determination of strength, 2016.
[16] ASHTO T-380, Standard method of test for potential alkali reactivity of aggregates and effectiveness of ASR mitigation measures (Miniature Concrete Prism Test, MCPT), AASHTO, 2019, pp. 11
[17] ASTM C1260, Standard test method for potential alkali reactivity of aggregates (Mortar-Bar Method), 2021.
[18] ASTM C1293, Standard test method for determination of length change of concrete due to ASR, 2020.
[19] A.P. Fantilli, F.M. Dehkordi, A two-stage cementitious composites containing recycled steel fibers, ACI Mater. J. 119 (2) (2022) 197–206.
[20] A.P. Fantilli, H. Mihashi, P. Vallini, Multiple cracking and strain hardening in fiber-reinforced concrete under uniaxial tension, Cem. Concr. Res. 39 (2009) 1217–1229.
[21] L. Turanli, K. Shomglin, C.P. Ostertag, P.J.M. Monteiro, Reduction in alkali-silica expansion due to steel microfibres, Cem. Concr. Res. 31 (2001) 827–835.
[22] M.C. Garci Juenger, C.P. Ostertag, Effect of selective positioning of steel microfibres on alkali-silica reaction, Concr. Sci. Eng. 4 (2002) 91–97.
[23] N.P. Tran, C. Gunasekara, D.W. Law, S. Houshyar, S. Setunge, Microstructural characterisation of cementitious composite incorporating polymeric fibre: a comprehensive review, Constr. Build. Mater. 335 (2022).
[24] A. Beglarigale, H. Yazıcı, The effect of alkali–silica reaction on steel fibre–matrix bond characteristics of cement based mortars, Constr. Build. Mater. 47 (2013) 845–860.