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Durability performance of bi-component polymer fibres under creep and in aggressive environments

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Abstract

In tunnel and mining applications spraying of concrete is a well-established and economical alternative to conventional casting techniques. Further time and cost savings are achieved when fibre reinforced concrete is applied. Often steel fibres are used. Corrosion risk, damage of water impermeable films through the stiff fibres and a relatively high fibre rebound are some of the drawbacks of steel fibres.

A suitable alternative may be found in polymer based fibres. Such fibres were thought to bear other problems regarding the long-term application. Especially their performance under permanent load (creep), but also their behaviour in aggressive environment, has been questioned.

A recently developed polyolefin based bi-component fibre was investigated regarding its long-term behaviour. Pre-cracked fibre reinforced square panels were exposed to permanent load and different aqueous solutions (sodium chloride, sodium sulphate, sulphuric acid). Long-term deformation and residual load capacity were determined.

In these laboratory tests it could be demonstrated that for this type of structured plastic fibre neither creep nor the exposure to aggressive underground environments seems to be a limiting factor.

1 Introduction

Fibre reinforced shotcrete has been used since the early 70s with success to secure tunnel vaults (Rose, 1985). Mostly steel fibres are used (Maidl, 1992), because of their wide availability, relative low price and good mechanical properties like tensile strength and elastic modulus. Other fibre types (like high-performance fibres based on polyvinyl-alcohol (PVA), carbon, Kevlar or alkali-resistant glass, etc.) are generally not used because of their relatively high price. Cheap glass fibres are made from non-alkali-resistant glass and hence lead to an insufficient durability. Although their potential was demonstrated on several occasions (Pang and Xu, 2007), many polyolefin-based plastic fibres have insufficient mechanical properties in shotcrete due to a low modulus of elasticity.

At first, the use of synthetic fibres in underground excavations was viewed as problematic, especially with regard to the long-term behaviour in the cracked state (Bernard, 2004a; Gossla and Rieder, 2009; Kurtz and Balaguru, 2000). Unlike steel, polyolefin-based fibres have a tendency for time-dependent deformation (creep) under constant load. However, through the addition of appropriate additives which increase the degree of crystallisation and/or its elastic modulus, creep can be widely reduced. On the other hand, steel fibres in cracked concrete may corrode (Nordström, 2005). Even in this case a need for research is obvious. In particular, only a few long-term experiments on cracked steel fibre concrete in aggressive environments have been documented (Hannant, 1998; Clements and Bernard, 2004; Bernard, 2004b).

Knowledge about the long-term behaviour in an aggressive environment is essential in the discussion of the usability of plastic fibre reinforced shotcrete, unless it is only for a temporary rock protection.

2 Materials and methods

2.1 Studied concrete and fibres

Essentially two different types of concrete (concrete 1/2 in Table 1) were prepared by conventional casting. Concrete 1 was chosen as an adaptation of a simplified formulation of shotcrete while concrete 2 represents a typical in-place concrete.

Table 1 Base concrete mix proportions

	Cement [1)] (kg/m³)	Sand / Gravel (Diameter in mm) (kg/m³)				Water (kg/m³)	w/c	HRWRA [2)] (kg/m³)
		0.4	4.8	8.16	16.32			
Concrete 1	450	1,156	544	-	-	202.5	0.45	4.5
Concrete 2	300	640	320	340	700	150	0.50	1.5

Note: [1)] CEM I 42.5 N [2)] high range water reducing admixture: Sika Viscocrete-2

Different types and amounts of fibres (see Table 2) were added in order to perform the various laboratory tests regarding the chemical resistance and the creep behaviour of fibre reinforced concrete. On the one hand a bi-component polymer based macro-synthetic fibre was studied (Kaufmann et al., 2007). This fibre is polyolefin based and has a structured surface. The fibre dosage ranged from 0.5 to 1 % by volume (9.1 kg/m³). On the other hand a relatively coarse hooked steel fibre was used for comparison.

The proportions of the studied fibre reinforced concrete mixtures are given in Table 3. In order to characterise the rheological properties of the fresh concrete the slump flow in accordance with EN 12350-5 (1999) was determined. In addition, the air content and the density of the fresh concrete were determined according to EN 12350-7 (1999) and EN 12350-6 (1999).

Table 2 Fibre types and properties as used in the tests

Type		Tensile Strength (MPa)	Elastic Modulus (GPa)	Diameter (mm)	Length (mm)
Bico	Concrix ES	625	10.4	0.5	50
Steel	Dramix 80/50	>1,000	210	0.6	50

Table 3 Studied concrete mixtures, fresh properties and test program

	Concrete Type	Fibre Type	Fibre Content (kg/m³)	Slump Flow (cm)	Air Content (%)	Density (kg/m³)	Tests CR = Creep ST = Storage
Mixture 1	Concrete 1	Bico	9.1	54	3.8	2,330	CR/ST
Mixture 2	Concrete 1	Steel	50	53	3.0	2,365	ST
Mixture 3	Concrete 1	Bico	4.55	50	3.7	2,290	CR
Mixture 4	Concrete 2	Bico	4.55	44	1.5	2,414	CR

2.2 Mechanical testing

Square panel tests according to SIA 162/6 (1999) 'Testing of steel fibre reinforced concrete' were performed (Figure 1). This praxis-oriented test is especially suitable for characterising the behaviour of fibre reinforced concrete in tunnel linings or industrial floors under local pressures. The load in this test was applied at the centre of a square panel. The deflection of the panel was measured continuously. The panel had a dimension of 600 × 600 × 100 mm³. The square support had an edge length of 500 mm and the loading rate was 1.0 mm/min. In order to reduce friction, the plates were polished parallel to achieve a roughness smaller than 1/100 mm. This test method is equivalent to EN 14488-5 (2006) and the European Specification for sprayed concrete guidelines (EFNARC, 2000) with regard to test body dimensions and load application. In addition to those tests, the calculated value of the effective flexural strength f_{ctf} is derived as:

$$f_{ctf} = \frac{3\int_0^{w_1} F dw}{n h_0^2 l_f} \tag{1}$$

$$w_1 = (0.07n - 0.10) * l_f \tag{2}$$

Where:

h_0 = height of test panel (100 mm).

n = number of cracks.

l_f = fibre length.

The calculated value of the fracture energy of G_f is determined as:

$$G_f = \frac{\int_0^{4w_1} F dw}{3 n h_0^2} \tag{3}$$

Additionally, the absorption of energy (in joules) is determined, in accordance with the directive EFNARC and EN 14488-5, by integration of the load-deflection curve to a deflection of 25 mm (Equation (4).

$$E_{EFNARC} = \int_0^{25mm} F dw \tag{4}$$

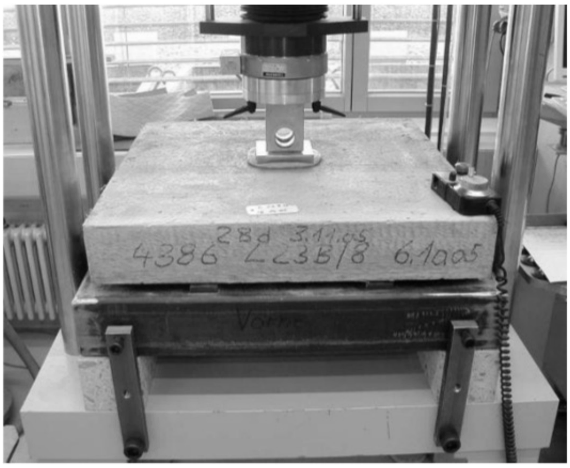


Figure 1 Test arrangement in square panel tests according to SIA 162/6

2.3 Behaviour of square panels under constant load (panel creep tests)

The investigations were carried out in a cracked state. Initial crack widths corresponding to the state of use were generated in an interrupted square panel test (SIA 162/6). At the age of approximately 90 days, the test panels (600 × 600 × 100 mm^3) were loaded while regulating the expansion until a deflection of δ = 2 mm was achieved and then unloaded in controlled manner immediately after reaching this limit.

Then, the specimens were mounted into a frame representing the same test set-up as in the square panel test (central load, square support) were it was possible to apply a constant load. Load application was performed hydraulically via gas expansion vessels, which guaranteed the stability of pressure. The pressure was controlled by pressure gauges and readjusted if necessary. The load level was adjusted according to the test plan reaching 50 or 60% of the load measured at the limit deflection of δ = 2 mm. By means of a dilatometer (having an accuracy of one micron) the deformation as a function of time $\delta(t_x)$ was determined by measuring the distance between two plugs situated at each side of the panel.

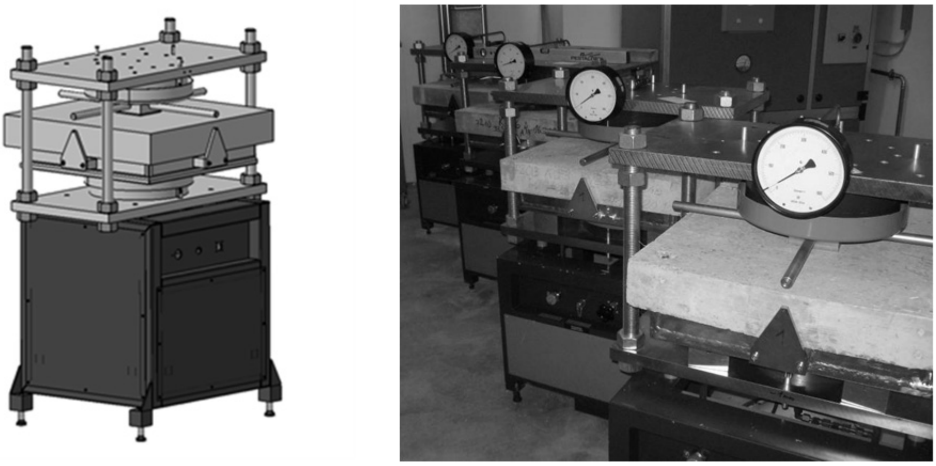


Figure 2 Test arrangement of creep tests on square panels under constant load

In the creep tests on square panels the macro-synthetic bi-component fibre was tested at two different fibre dosages in two different concrete types. The corresponding load-displacement curves of the mechanical testing up to a displacement of 2 mm (SIA 162/6) are plotted in Figure 3.

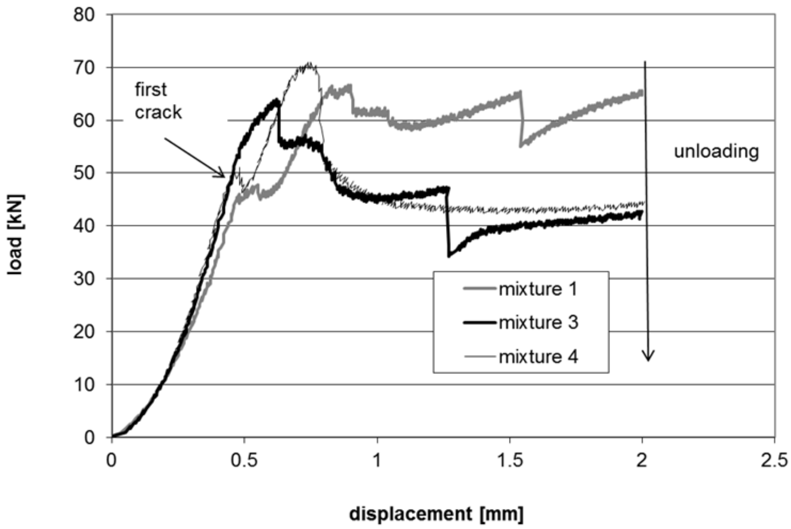


Figure 3 Load-displacement curves (up to limit displacement of 2 mm) of test specimens prior to the panel creep tests (pre-cracking)

2.4 Behaviour in aggressive environments (storage tests)

The chemical resistance of the selected polymer fibres was examined in direct comparison with steel fibres. Two different mixtures (mixture 1 and mixture 2, Table 3) were tested. It has to be mentioned that the diameter of the selected steel fibre is relatively thick compared to the one typically used in shotcrete application (0.35 mm). In order to compensate for the lower number of fibres in the crack a relatively high amount was dosed. For each mixture five square panels were produced.

At regular intervals (Table 4 and Figure 4) the specimens were rinsed with different media (salt solution, sulphate solution, low-concentrated sulphuric acid) or were exposed to free weathering in Dübendorf (Switzerland). For each mixture, one additional specimen was aged in a climate chamber at 20°C/90%RH.

The exposure duration was one year. Thereafter, the residual strength of each specimen was determined in a square panel test (SIA 162/6) to quantify the effect of the chemical load on the mechanical bearing behaviour.

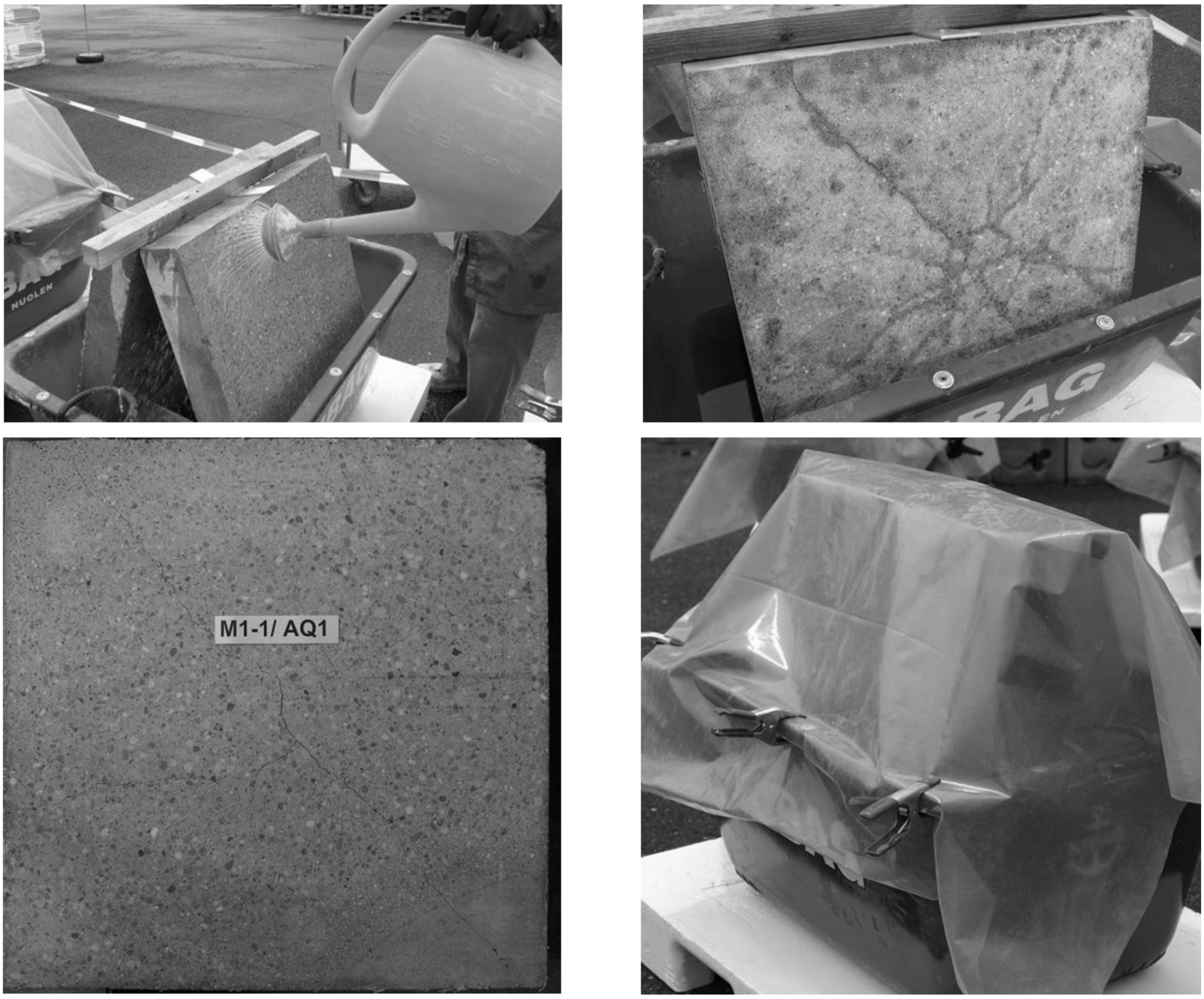


Figure 4 Test arrangement with pre-cracked fibre reinforced concrete panel (600 × 600 × 100 mm³) and application of the different stress media

Table 4 Exposure conditions

Storage 1	Free weathering	Not covered	No medium
Storage 2	3% NaCl – solution	Covered	Weekly, 5 l
Storage 3	4 g/l Na_2SO_4 – solution	Covered	Weekly, 5 l
Storage 4	2% – sulphuric acid	Covered	Weekly, 5 l
Storage 5	Clime chamber 20°C/90%RH	Not covered	No medium

The tests were performed on pre-cracked (with defined crack widths provided) square plates (600 × 600 × 100 mm^3). Pre-cracking was done again in an interrupted square panel tests (SIA 162/6) up to a limit displacement of 3 mm.

After this preconditioning, the obtained crack widths were measured (see Tables 5 and 6). The width of each crack was determined at the centre of the panel and at a distance of 10 and 20 cm from the centre.

Table 5 Crack widths (mm) of mixture 1 with polymer fibres before storage

Position	AQ1		AQ2		AQ3		AQ4	
	No. of Cracks	Storage 1	No. of Cracks	Storage 2	No. of Cracks	Storage 3	No. of Cracks	Storage 4
Centre	1	0.9	1	0.7	1	0.7	1	0.8
10 cm	4	0.55 +/- 0.13	5	0.42 +/- 0.08	5	0.5 +/- 0.12	5	0.36 +/- 0.05
20 cm	4	0.42 +/- 0.10	5	0.46 +/- 0.19	5	0.42 +/- 0.08	5	0.42 +/- 0.04

Table 6 Crack widths (mm) of mixture 2 with steel fibres before storage

Position	AQ5		AQ6		AQ7		AQ8	
	No. of Cracks	Storage 1	No. of Cracks	Storage 2	No. of Cracks	Storage 3	No. of Cracks	Storage 1
Centre	1	0.5	1	0.6	1	0.4	1	0.9
10 cm	6	0.28 +/- 0.13	5	0.36 +/- 0.09	4	0.42 +/- 0.10	5	0.38 +/- 0.08
20 cm	6	0.28 +/- 0.15	5	0.34 +/- 0.05	4	0.38 +/- 0.10	5	0.41 +/- 0.11

3 Results

3.1 Behaviour under constant load

Figure 5 shows the behaviour of three pre-cracked square panels subjected to permanent load. The evolution of the deformation of the indicated mixtures and at the indicated load levels (absolute load in kN, relative load in per cent of the residual load at 2 mm displacement) up to 650 days is plotted. The increase in deformation with time, as a result of the continuous load, is small and there are no critical values reached.

Compared with the load level at the appearance of the first crack (at about 0.5 mm displacement, Figure 3), relatively high load levels (mixture 1: 89%, mixture 4: 42%) can be maintained permanently.

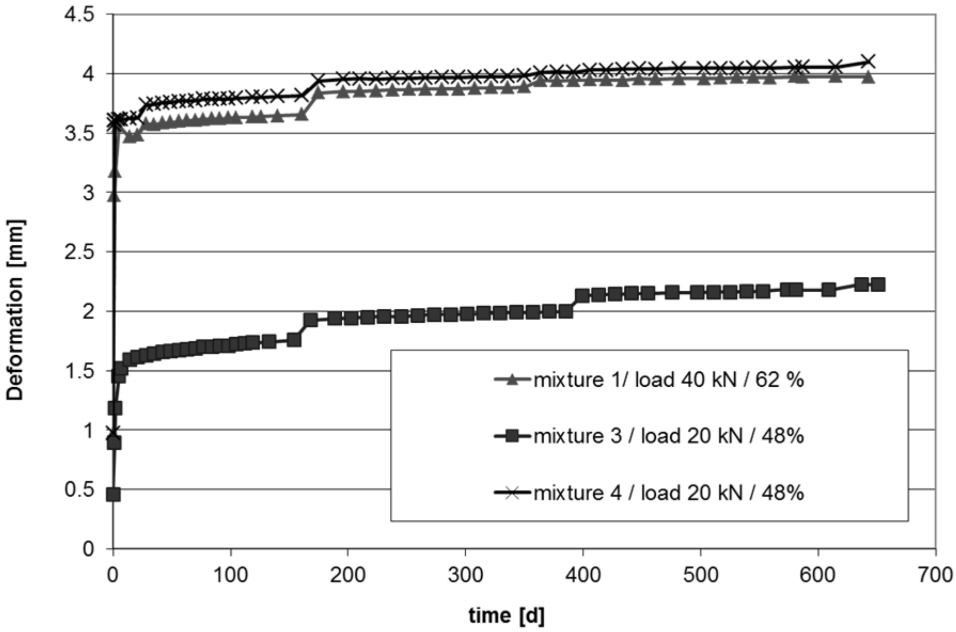


Figure 5 Evolution of the deformation behaviour of pre-cracked square panels under permanent load

3.2 Behaviour in aggressive environments

After one year of exposure all of the steel fibre reinforced concrete panels, even the ones stored in the climate chamber and subjected to free weathering, showed clear signs of corrosion on the concrete surface (Figure 6). These range from clearly visible rust spots (particularly evident for an exposure in a NaCl solution) up to complete dissolution of the fibres in the case of an exposure to a low concentrated sulphuric acid. In contrast, there was no visible alteration observable for the panels made with polymeric fibres.

The corrosion penetration depth seems to depend less on the crack width but rather on how long the aggressive medium was present. At the bottom of the panels where the medium is assumed to remain for a longer time opposed to the top of the specimens where the medium quickly dissipated, a significantly larger corrosion depth (for all cracks) was observed.

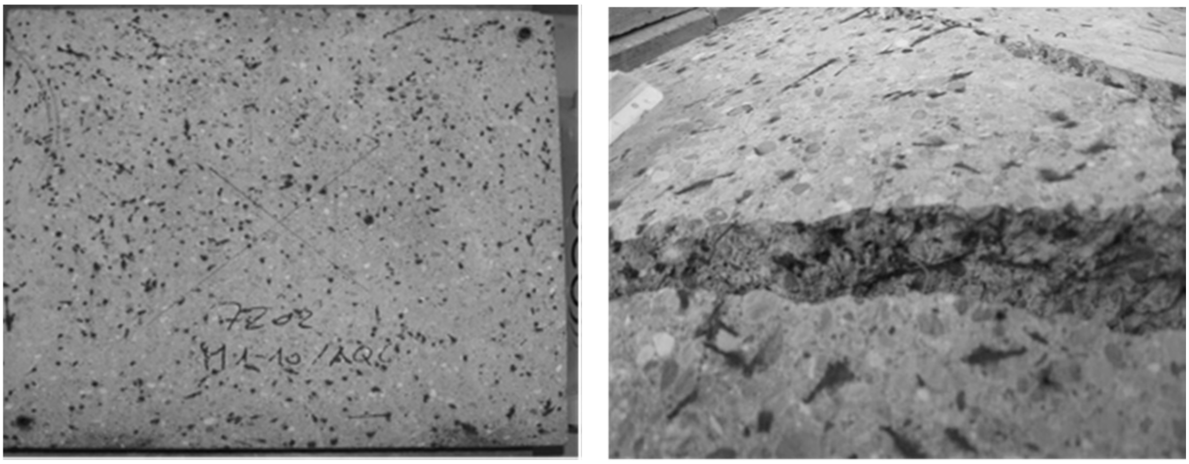
In the case where a low concentrated sulphuric acid (and the same for the sulphate solution) was used, some degradation of the mineral phases of the concrete was observed, especially at the bottom part, where the concrete panels were in direct contact with the wooden frame. The wood is thought to have taken up some of the aggressive medium and hence increased the contact interval.

In contrast, there was no visible chemical degradation of the polymeric fibres observable.

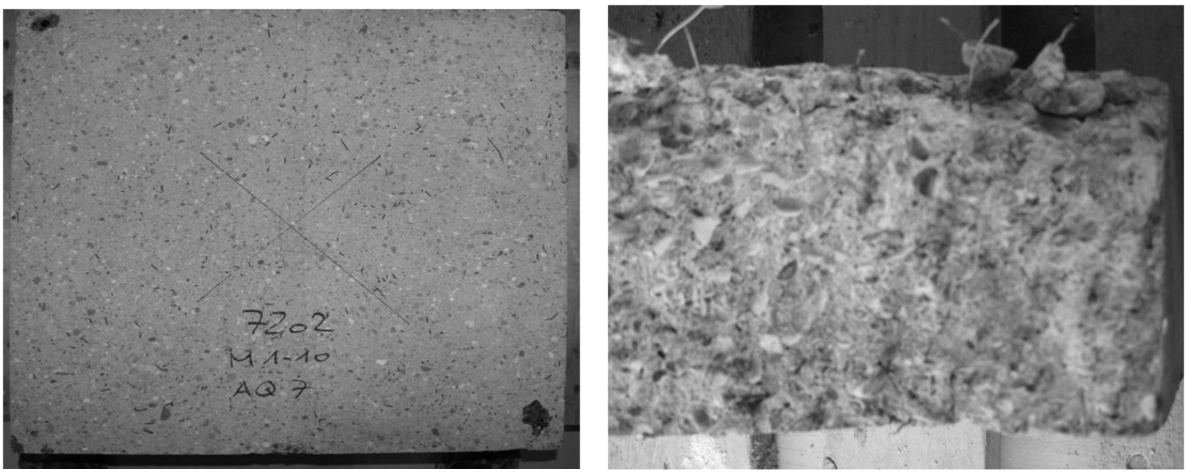
After weathering, the residual strengths were determined in a square plate test according to SIA 162 /6. The obtained load-displacement curves are plotted in Figure 7 and the derived mechanical properties are summarised in Tables 7 and 8.

It is clearly seen in Figure 7 that the post-peak behaviour in the panels with bi-component fibres has improved after chemical exposure. Higher peak loads were achieved after the exposure as well. This can be explained with the greater age of the samples after the exposure. However, at larger crack widths, when exposed to a sodium sulphate solution or a low concentrated sulphuric acid, slightly lower load levels were recorded. This results also in lower fracture energy values (Table 7). It can be assumed that the fibres did not deteriorate, but that the bulk concrete and the concrete at the fibre-interface was weakened by the sulphate attack.

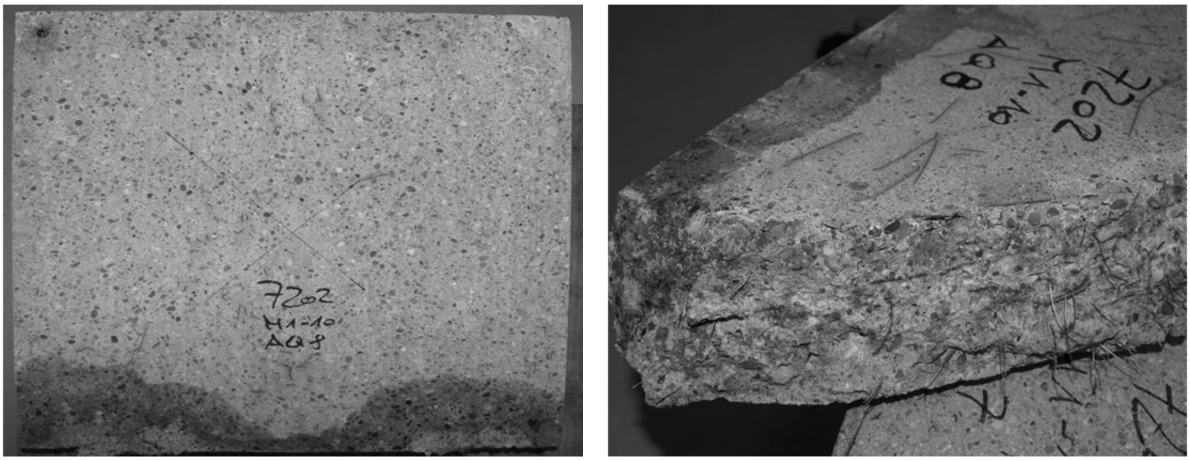
Free weathering: steel fibres => some fibre corrosion (mostly close to the surface)



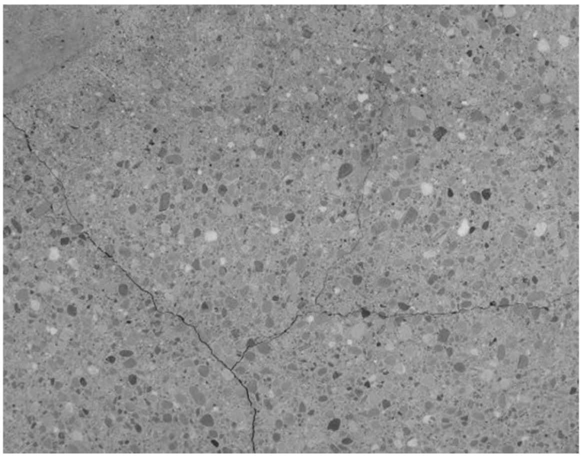
3% NaCl solution: steel fibres => very strong fibre corrosion (also inside the cracks)



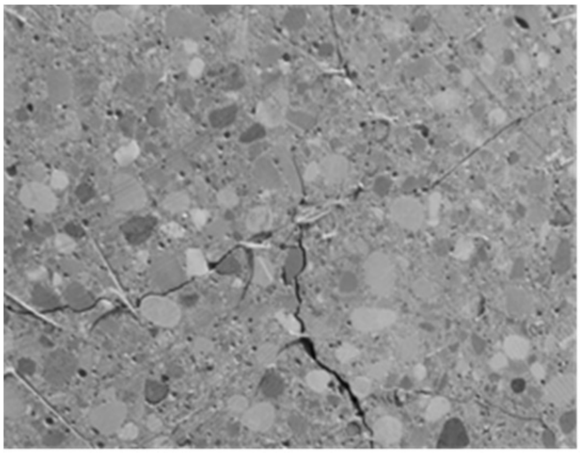
Na_2SO_4 solution: steel fibres => medium fibre corrosion (some inside the cracks)



Sulphuric acid (2%): steel fibres => serious fibre corrosion (also inside the cracks)



3% NaCl solution: polymeric fibres => sound



Sulphuric acid (2%): polymeric fibres => sound

Figure 6 Detailed views of the different panels containing steel or polymeric fibres subjected to different environments after one year of exposure

For steel fibre reinforced panels exposed to thawing-salt (NaCl) solution or diluted sulphuric acids, significantly lower residual peak loads, post-failure behaviour and fracture energy values occur (Figure 7 and Table 8). As a consequence, the originally much better mechanical performance of the steel fibre reinforced concrete (mixture 2) is significantly reduced and falls behind the performance of the polymeric fibre reinforced concrete (mixture 1) when exposed to diluted sulphuric acid and equals the performance of polymeric fibres when exposed to thawing salts.

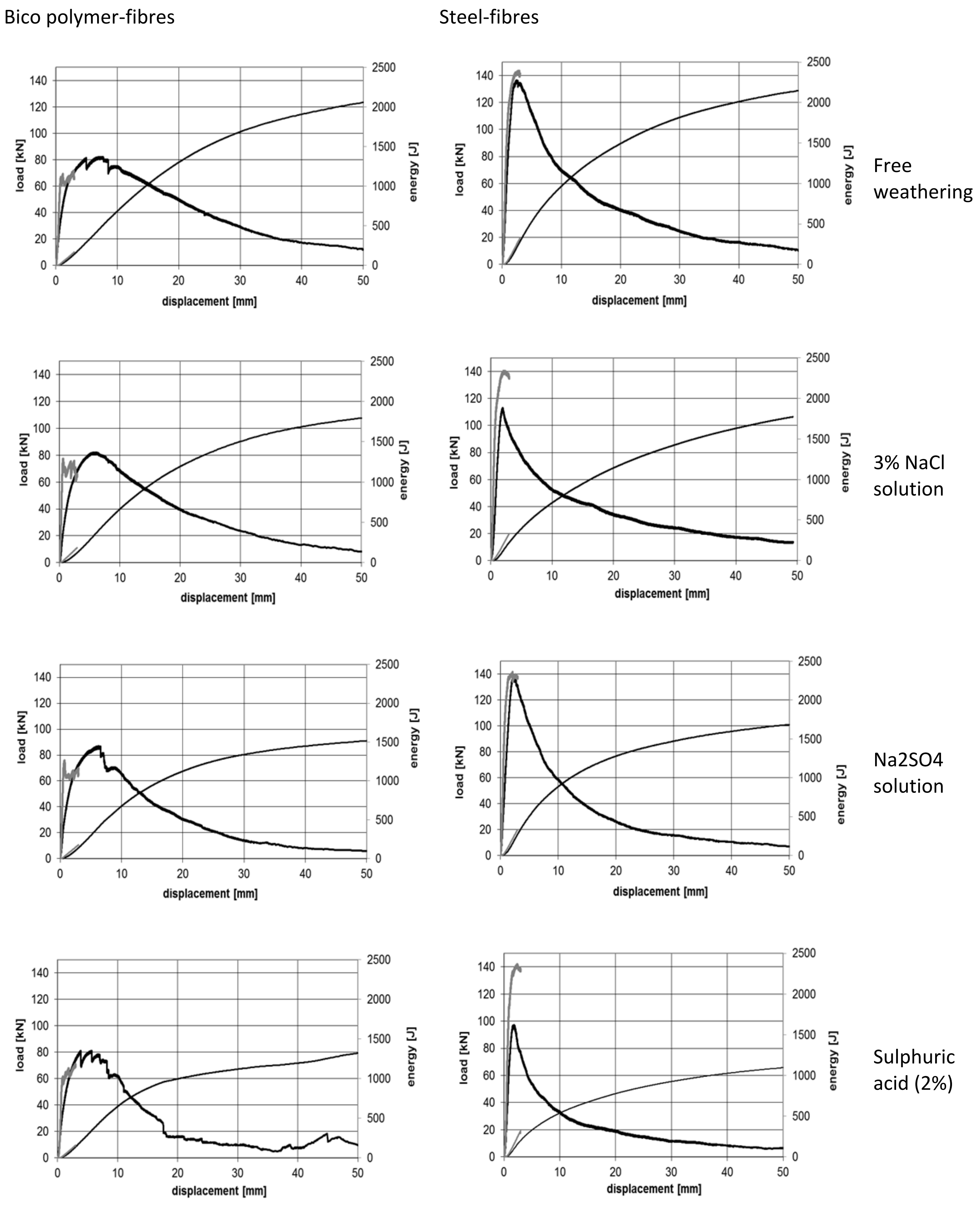


Figure 7 Residual load-displacement (black bold lines) and energy curves (black thin lines) after one year of exposure compared with the initial curves (as obtained during pre-cracking) before the immersion (grey lines)

Table 7 Mechanical results of concrete reinforced with polymeric bi-component fibres in square panel tests (SIA 162/6) after one year of exposure

Bico	Density Before (kg/m³)	Density After (kg/m³)	Peak Load (kN)	E_{EFNARC} (J)	G_f (N/m)	f_{ctf} (N/mm²)
Free weathering	2,325.7	2,363	82.3	1,519	14,929	1.1
NaCl solution	2,345.1	2,348.1	79.7	1,365	12,898	1.04
Na_2SO_4 solution	2,339.7	2,336.8	81.5	1,252	10,905	1.05
Sulphuric acid (2%)	2,326.6	2,314.7	81.1	1,067	9,551	1.01
Reference 20°C/90%RF	2,301	-	78.3	1,236	11,969	1.01

Table 8 Mechanical results of concrete reinforced with steel fibres in square panel tests (SIA 162/6) after one year of exposure

Steel	Density Before (kg/m³)	Density After (kg/m³)	Peak Load (kN)	E_{EFNARC} (J)	G_f (N/m)	f_{ctf} (N/mm²)
Free weathering	2,357.5	2,369.5	136.5	1,674	15,779	1.49
NaCl solution	2,360.9	2,363.9	113.1	1,298	12,115	1.11
Na_2SO_4 solution	2,372.8	2,366.9	138.8	1,387	12,224	1.32
Sulphuric acid (2%)	2,380.8	2,363	119.6	859	7,924	0.79
Reference 20°C/90%RF	2,389	-	144.8	1,715	16,602	1.55

4 Conclusions

Under permanent load the examined polymeric macro-synthetic bi-component fibres showed a slight increase of crack widths in square panel creep tests, but even after a long time the crack widths did not reach critical levels. Permanent loads of more than 60% of the residual load at a deflection of 2 mm, far above utilisation levels, were supported for more than 650 days without significant deformation. At a fibre dosage of 1% by volume (9.1 kg/m³) loads of higher than 70% of the peak load were carried permanently. As a result of the superficial structure and the relatively high (for a polyolefin based fibre) elastic modulus, the bond-creep was reduced.

In experiments on the chemical resistance, the polymeric bi-component fibres proved to be stable, whereas steel fibres even under normal weather conditions, without exposure to de-icing salts or sulphates, revealed significant corrosion. In steel fibre reinforced concrete, after only one year of exposure, this resulted in a significant decrease in mechanical properties, especially in the presence of thawing salts or sulphates.

Acknowledgements

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