Durability performance of fiber reinforced shotcrete in aggressive environment.

J. P. Kaufmann
Empa, Swiss Federal Laboratories for Materials Science and Technology, Laboratory for Concrete/Construction Chemistry, Duebendorf, Switzerland.

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 fiber reinforced concrete is applied. As consequence of stress at early age due to plastic or drying shrinkage, permanent or cyclic load stress cracks may be formed which then serve as penetration paths for aggressive solutions. The fibers reinforcing and bridging such cracks may be deteriorated and hence lose their potential to bear tensile load and hence lead to a reduction of the mechanical properties of the fiber reinforced shotcrete. The effect of the submerging of cracked shotcrete panels to different aqueous solutions which may be present in tunnels: Sodium salt, sulfate solution, acids or simply ambient wet/dry conditions on their mechanical behavior is shown. A significant drop in the load bearing capacity was observed for some fiber types.

1 INTRODUCTION

Fiber reinforced shotcrete has been used since the early 70s with success to secure tunnel vaults (Rose, 1985). Mostly steel fibers are used (Maidl, 1992). Because of post-crack creep (Kurtz and Balaguru, 2000) the use of synthetic fibers in underground excavations sometimes is viewed as problematic with regard to the long-term behavior. On the other hand, the likely larger deformations for macro-synthetic fiber reinforced shotcrete have been reported to be advantageous in some applications such as ground control in mines and temporary works (Bernard, 2004). Many polyolefin-based plastic fibers have insufficient mechanical properties in shotcrete due to a low modulus of elasticity. However, through the addition of appropriate additives which increase the degree of crystallization and higher stretch levels it is possible to produce polymer fibers with increased mechanical properties. Some of them showed excellent mechanical performance in concrete (Kaufmann et al, 2007).

As consequence of stress at early or later age due to plastic or drying shrinkage, permanent or cyclic load stress cracks may be formed which then serve as penetration paths for aggressive solutions. The fibers reinforcing and bridging such cracks may be deteriorated and hence lose their potential to bear tensile load and hence lead to a reduction of the mechanical properties of the fiber reinforced shotcrete. Steel fibers in cracked concrete may corrode (Nordström, 2005). Very little is known about the behavior of fiber, especially plastic fiber, reinforced shotcrete under cracked conditions. In particular, only a few long-term experiments on cracked fiber concrete in aggressive environments have been documented (Hannant, 1998) (Kaufmann and Manser, 2013) (Clements and Bernard, 2004).

2 MATERIALS AND METHODS

Shotcrete was produced in test gallery Hagerbach (Switzerland) under praxis relevant conditions. A typical shotcrete mix design was used. For this purpose concrete (CEM I 42.5 N: 400 kg/m^3, fly ash 50 kg/m^3, sand 0..1 mm: 116 kg/m^3, sand 0..4 mm: 958 kg/m^3, gravel 4..8 mm: 578 kg/m^3, superplasticizer: Sika viscocrete SC-303 (1.2 % of cement), accelerator: Sika L53 AF (6% of cement), $w/c_{eq} \approx 0.40$) was premixed for 2 minutes and then the fibers were added. Four different polymer fibers (all polyolefin-based, except fiber 2 made of "modified" polyester) were used. As a reference one steel fiber was also studied. Some of the fiber properties as provided by the suppliers (data-sheets) are plotted in Table 1. The steel fiber used in this test was made of ordinary (not galvanized) but relatively high strength steel. Fiber 3 was a bi-component fiber.

The mechanical data (tensile strength and modulus) could not be verified in the scope of this project. Some data is considered a doubtful (fiber 2: strength is given rather unspecified ranging from 400-800 MPa while the modulus is given at exactly 11.3 GPa). Unfortunately, no uniform testing procedure was applied, although such standards exist in the textile sector. No data was available regarding the bond strength to a cementitious matrix which would have allowed an estimate of the utilization ratio (of fiber strength) in the shotcrete.

The fiber content for the polymer fibers was between 5.4 and 8 kg/m^3. A higher dosage (in kg/m^3, not in vol.-%) was used in the case the steel fiber, regarding the fact that polymer fibers (Fiber 3 to 4) have a lower density of a round 0.9 kg/cm^3.The fresh concrete properties are given in Table 2.

Table 1 Fiber properties.

	Fiber 1	Fiber 2	Fiber 3	Fiber 4	Fiber 5
Material	Steel	Polym	Polym	Polym	Polym
Anchorage	hooks	hooks	none	none	none
Surface	fair	struc.	struc.	struc.	fair
App.	round	flat	round	round	flat
Length	35	40	50	54	50
Diameter	0.55	0.88*)	0.5	0.56	0.59*)
Strength	1345	>400	>625	>550	>620
Modulus	210	>11.3	>11	>7.1	>9.5

Length/mm, Diameter/mm, Strength/MPa, Modulus/GPa

*) equivalent diameters

Table 2 Fresh Concrete properties and application parameters.

	A1	A2	A3	A4	A5
Fiber parameters					
type	Fib.1	Fib.2	Fib.3	Fib.4	Fib.5
dosage	35	8	6	6	5.4
Fresh Concrete properties					
Temperature	21.2	19.3	20.4	18.4	19.9
Slump flow	470	600	510	490	470
Air Content	2.3	1.4	4.9	3.9	3.2
w/c	0.46	0.47	0.45	0.46	0.47

The fresh concrete was transported (5 minutes duration) to the spray equipment (Meyco suprema), pumped to the nozzle and finally sprayed. Spraying was by the same nozzleman at generally similar spray conditions (air and pump pressure). The specific spray and pumping pressures are given in Table 2. Square panels were produced by spraying into square casings (area 600x600 mm^2) which were filled to a height of at least 100 mm. After spraying the panels were left in the tunnel environment (10-15 °C) for about 2 days and were then demoulded and finally cut to a height of about 100 mm.

Square panel tests according to SIA 162/6 (1999) 'Testing of steel fibre reinforced concrete' were performed (test arrangement Figure 1). The load was applied at the center of a square panel. The deflection of the panel was measured continuously. The panel had a dimension of 600 × 600 × 100 mm^3. 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 1/10 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. 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 as it is defined in this standard. It should be emphasized that this is in contrast to ASTM C 1550 round panel test, where a larger deflection of 40 mm is applied.

Figure 1 Crack production in interrupted EFNARC square panel test. Test was stopped at a deformation of 3 mm.

The durability experiments 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 120 days, the test panels (600×600×100 mm^3) were loaded, while regulating the expansion, until a deflection of δ = 3 mm was achieved and then unloaded in controlled manner immediately after reaching this limit. Four to six cracks (according the mechanical performance of the fiber introduction) crossing the square panels were introduced. Crack widths were typically in the range of 0.5 to 1 mm at a distance of 15 cm from the center and about 2 mm at the center of the square panels. The panels then were exposed to different storage conditions.

Furthermore, for microscopic analysis after exposure, prisms (600×100×100 mm^3) were cut out of the square panels. Two different cracks, one with a crack width of about 1.2 mm and one with a crack width of about 0.5 mm were introduced in this specimens by means of a three-point bending test arrangement. Five such beams from the five different shotcrete batches were bundled and exposed to the same storage condition.

Square panels and prisms were exposed to the storage conditions according Table 3. They were placed in large containers, one specimen for each kind of shotcrete for each storage condition. Some of the cracked specimens were stored (with introduced cracks) in a climate chamber at 20°C/90%RH (storage 1), others were exposed to the current weather in northern Switzerland (storage 2) and to different solutions. Each specimen was rinsed with five liters of one of the three solutions (always the same) once per week during 1 year. Some of the solution was collected at the bottom of the container and used for rinsing each second time, the other times the solutions were freshly prepared. The filling level of the solutions in the container was not achieving a level to touch the specimens. The containers were covered (except storage 2).

Table 3 Storage conditions.

	St. 1	St. 2	St. 3	St. 4	St. 5
Medium	90% RH	Free weather	NaCl Sol.	Na_2SO_4 Sol.	Sulf. acid
Conc.	-	-	3%	4g/l	2%
Duration	365 d	365 d	365 d	365 d	365 d

Two reference specimens were used. One was tested just before storage started (full testing, no cracks at the beginning of the test). One un-cracked panel (for each shotcrete) was stored in 20°C/90%RH, in order to estimate maturing effects, and tested one year later.

Figure 2 Exposure set-up with application of liquid solutions (top), coverage (center) and different specimens (square panels for mechanical testing and prsims for microscopy, bottom).

One year after the exposure had started, the residual mechanical properties were determined in a square panel test (according to SIA 162/6) and a full load-displacement curve was acquired.

From the prisms smaller pieces were cut (100x100x50 mm^3) and impregnated (under vacuum) with a resin in order to conserve the microstructure and the fiber appearance after the exposure until microscopic analysis could be performed.

3 RESULTS

In Table 4 the maximum load level [kN] as obtained from the load-displacement curves and the rupture energy according EFNARC until a displacement of 25 mm, determined by SIA 162/6 tests of square panels after one year of exposure, are summarized.

Table 4 Mechanical Properties before and after Storage.

Max. Load [kN]					
	A1	A2	A3	A4	A5
REF 109d	77.2	55.8	53.3	46.9	53.4
REF 521d	75.2	51.6	51.3	49.1	59.2
Storage 1	58.5	33.7	53.4	33.1	47.6
Storage 2	53.8	21.8	33.5	43.7	36.7
Storage 3	40.3	27.4	48	43.2	46.8
Storage 4	56.9	33.9	39.2	40.8	46.9
Storage 5	30.8	26.8	44.2	40.3	46.2

Energy EFNARC 25 mm [J]					
	A1	A2	A3	A4	A5
REF 109d	831	446	712	537	785
REF 521d	789	358	660	620	722
Storage 1	590	382	822	559	526
Storage 2	449	310	551	703	546
Storage 3	394	326	673	740	640
Storage 4	508	393	647	578	597
Storage 5	260	271	655	559	600

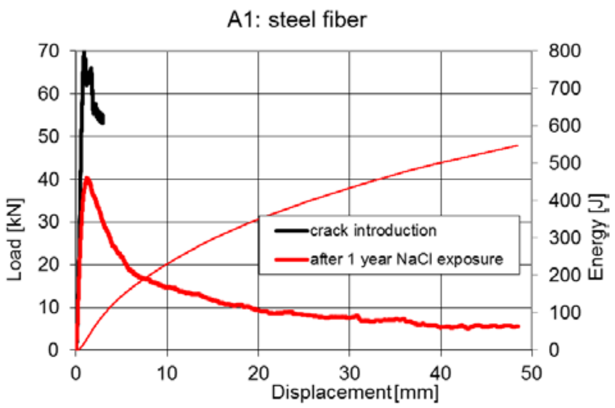


Figure 3 Load displacement curve of steel fiber 1 (A1) after 1 year of exposure to salt-solution (3% NaCl).

In the case of the steel fibers both the maximal load as well as the rupture energy (EFNARC) are reduced for all specimens exposed compared with the non-exposed (non-cracked) references. Surprisingly this even is the case for moderate climate like free weathering or storage in a climatized room (20°C/90%RH). The most significant drop in the mechanical performance is as expected for the treatment with sodium chloride solution (storage 3, Figure 3) and sulfuric (2%) acid (storage 5).

The results for polymeric fibers are quite different for each fiber type. Some scatter in the achieved maximum loads may be due to certain scatter in the shotcrete quality, rather than due to the exposure. Such behavior is not found for the rupture energy data.

Generally there is apparent some minor influence from the storage regime for polymer fibers only. However, the specimen age seems to have some detrimental influence for some fiber types (i.e. A2) which may be attributed to embrittlement (Bernard, 2008). An aging of the concrete might lead to an improved fiber-matrix bond in some cases. When the mechanical properties of the fibers are poor, this may lead to fiber rupture instead of fiber pull-out. Hence no energy is transferred to the shotcrete and the EFNARC values drop.

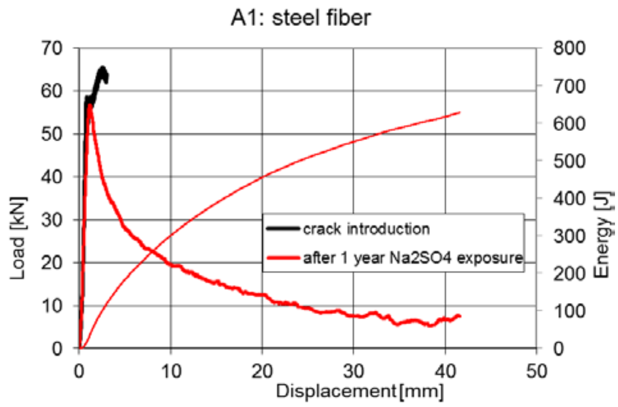


Figure 4 Load displacement curve of steel fiber 1 (A1) after 1 year of exposure to sulfate-solution (4g/l Na_2SO_4).

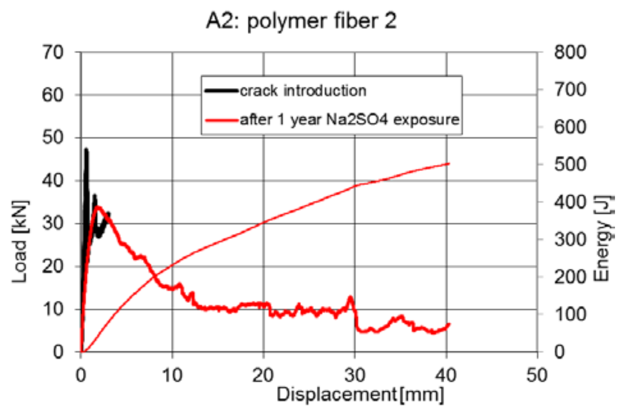


Figure 5 Load displacement curve of polymer fiber 2 (A2) after 1 year of exposure to sulfate-solution (4g/l Na_2SO_4).

As sulfates frequently are present in tunnel environments, for further illustration, in Figure 4-6 typical load-displacement curves after the exposure to a Na_2SO_4-solution are compared with the crack introduction curves (up to a displacement of 3 mm only).

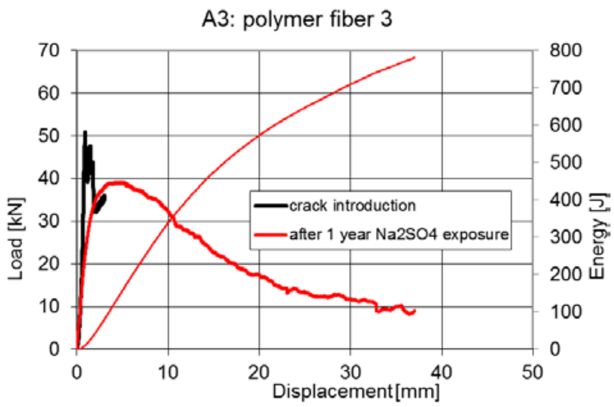


Figure 6 Load displacement curve of polymer fiber 3 (A3) after 1 year of exposure to sulfate-solution (4g/l Na_2SO_4).

The reason for the drop of the mechanical properties for steel fiber reinforced shotcrete is obviously corrosion which can easily be observed on all steel fiber reinforced panels (also storage 1). This is visualized in Figures 7 and 8. Corrosion has not proceeded to the same degree throughout the crack, but is reduced with longer distance from the surface. This was especially the case when the exposure was to a sodium chloride solution (Figure 8).

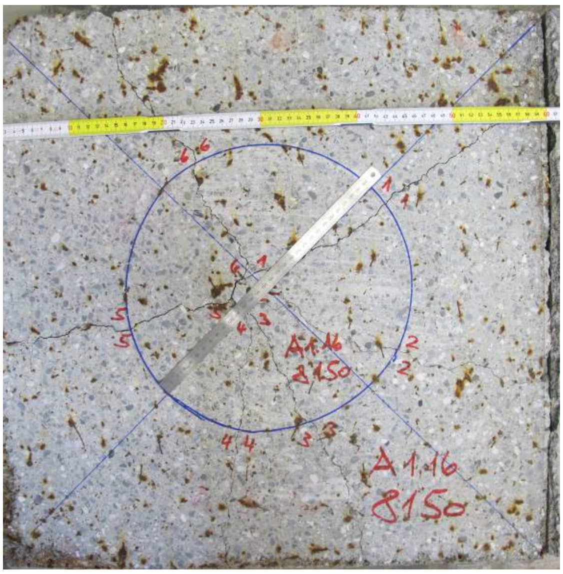


Figure 7 Photo of steel fiber reinforced square panel (A1) after 1 year of exposure to Salt (NaCl-solution: 3%).

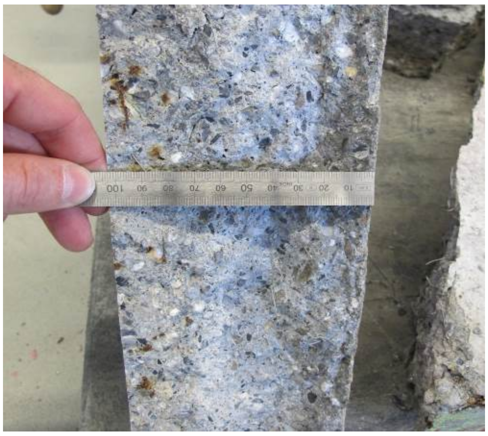


Figure 8 Photo of steel fiber reinforced square panel (A1) after 1 year of exposure to Salt (NaCl)-solution (3%) after square panel testing.

This is confirmed by the microscopic analysis of the pre-cracked prism specimens. While corrosion traces in the case of steel fibers close to the cracks are obvious (Figure 9), no visible deterioration of polymer fibers is observed (Figure 10).

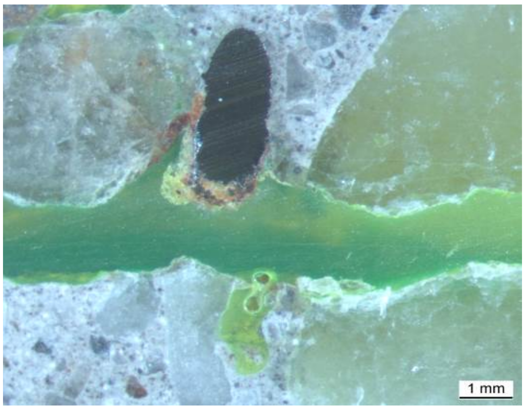


Figure 9 Micrograph of steel fiber near cracks (impregnated for conservation with green resin) at a distance of 35 mm from surface after 1 year exposure in Na_2SO_4-solution (A1).

However, there is no corrosion of the steel fibers found at a certain distance (some mm is sufficient) from the crack (Figure 11). A dense shotcrete layer seems to protect the steel fibers from corrosion in this case. This leads to the conclusion, that un-cracked steel fiber reinforced shotcrete may not be supposed to durability problems. However, cracking is supposed to occur due to one or the other reason anyway.

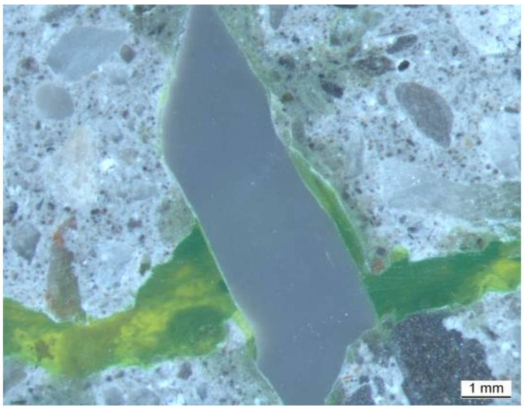


Figure 10 Micrograph of polymer fiber 2 near cracks (impregnated for conservation with green resin) at a distance of 45 mm from surface after 1 year exposure in Na_2SO_4-solution (A2).

Some polymer fibers on the other hand may suffer from damage originating from high pump and spray pressures and hence increased shear forces acting on the fibers during the shotcrete preparation and application. Fibers may fissure or even split completely (polymer fiber A5) along their length (arrows in Figure 12). Figure 12 clearly shows ruptured polymer fibers which are not situated close to a crack. As the ruptured part is filled with cement products, rupture was due to the application (spray) process and not due to mechanical loading of the shotcrete (during pre-cracking for instance). Such rupture, which is along the fibers, however is not critical when the bonding to the shotcrete matrix remains intact.

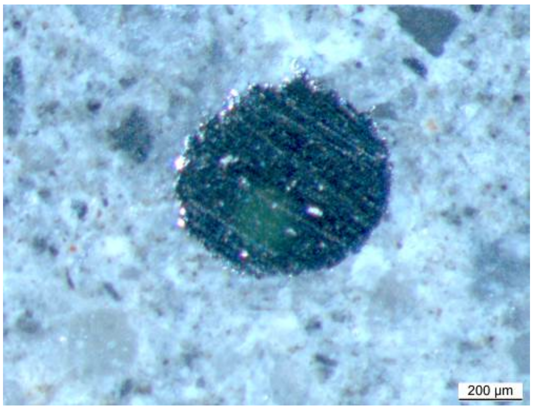
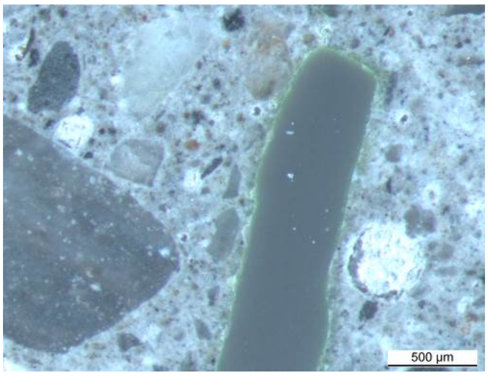


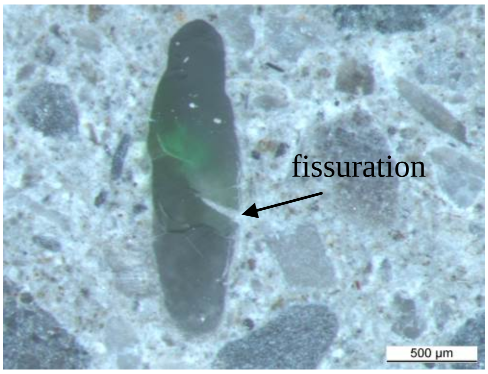
Figure 11 Typical Micrographs of a steel fiber in undamaged shotcrete at a distance of 5 mm from the crack (storage 3).

Polymer fiber (A2)



Polymer fiber (A3)

Polymer fiber (A4)



Polymer fiber (A5)

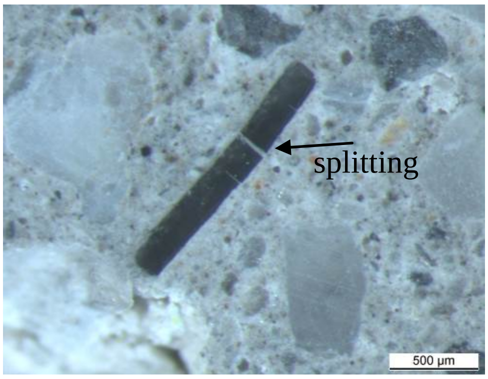


Figure 12 Typical Micrographs of fibers in undamaged shotcrete (storage 3).

4 CONCLUSIONS

In cracked fiber reinforced shotcrete durability problems may arise from an attack of the fibers under tunnel conditions by sulfate and (if deicing salts are used) salt solutions. It was shown that steel fibers in large cracks may corrode leading to a loss of the residual load bearing capacity and hence the post-crack energy. However, un-cracked shotcrete seem to protect the steel fibers at least over certain time.

Polymer fibers generally seem to withstand such durability attacks better and in most cases no significant drop in the residual load bearing capacity is observed. However some degradation of the concrete and/or the fiber-shotcrete interface in case of shotcrete degrading solutions (sulfate, sulfuric acid) was observed.

Furthermore some effects of shotcrete age leading to fiber rupture instead of pull-out can be observed for polymeric fibers of poor mechanical properties. No such effects were found for polymer fibers with enhanced mechanical properties.

ACKNOWLDGEMENT

The authors also would like to acknowledge Test Gallery Hagerbach, Switzerland (V. Wetzig and M. Reinhold) for the shotcrete panel production.

REFERENCES

Bernard, E. 2004. Durability of cracked fibre reinforced shotcrete. In *Shotcrete: More Engineering Developments, Taylor and Francis, London, E.S. Bernard (ed),* p.59–66.

Bernard, E. 2008. Embrittlement of fibre reinforced shotcrete. *Shotcrete*, Vol. 10, No 3, p. 16-21.

Clements, M. ; Bernard, E. 2004. The use of macro-synthetic fiber reinforced shotcrete in Australia. *In Shotcrete: More Engineering Developments, Taylor and Francis, London, Bernard, E.S. (ed),* p.20–22.

Hannant, D. 1998. Durability of polypropylene fibers in Portland cement-based composites: Eighteen years of data. *Cement and Concrete Research*, Vol. 28, No. 12, p.1809–1817.

Kaufmann, J. ; Lübben, J. ; Schwitter, E. 2007 Mechanical reinforcement of concrete with bi-component fibers, *Composites Part A: Applied Science and Manufacturing,* Vol. 38, p.1975–1984.

Kaufmann, J. ; Manser, M. 2013. Durability performance of bi-component polymer fibres under creep and in aggressive environments. *Ground Support 2013, Potvin,Y. ; Brady, B.* (eds), *Australian Centre for Geomechanics, Perth*, p.585-596.

Kurtz, S. ; Balaguru, P. 2000. Postcrack creep of polymeric fiber-reinforced concrete in flexure. *Cement and Concrete Research,* Vol. 30 (2), p.183–190.

Maidl, B. 1992. *Handbook of shotcrete – Handbuch für Spritzbeton, Berlin*.

Nordström, E. 2005. Durability of sprayed Concrete. *Doctoral thesis Luleå University of Technology*, ISSN: 1402-1544.

Rose, D. 1985. Tunnel shotcreting – strength in fibers. *Civil Engineering, New York,* Vol. 55(12), p.62–63.