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Combined Effect of Polymeric Fibres and SAP on the Performance of Repair Mortars

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ABSTRACT

The paper presents performance analysis of fibre reinforced cement mortars modified by two types of superabsorbent polymers (SAP). Comprehensive studies of the mechanical properties, adhesion characteristics and shrinkage progress are accompanied by the microstructural analysis of composites. The effect of SAP water absorption capacities and the size of particles have a strong effect on the mechanical characteristics. Generally the higher absorption leads to the higher reduction in strength. The effect on flexural strength diminishes with the progress of hydration. The effectiveness of SAP for internal curing is evidenced in a reduction of autogenous shrinkage. Microstructural examinations (MIP and SEM) confirmed a negative effect of SAPs on bond between fibres and cement paste.

Keywords: fibre reinforced mortars, SAP, mechanical properties

INTRODUCTION

Although concrete is a very versatile material of considerable durability some defects may arise during its service life. These defects can be of a material (original) nature, for example shrinkage cracks or honeycombing, or may be formed during exploitation due to abnormal loading or corrosive aggression of environment. In order to eliminate these defects or at least to stop the progress of deterioration it is necessary to perform specific “restoration treatments”. One of the key issues to be tackled in any repairs of concrete structures is compatibility of the substrate and repair material (Czarnecki et al., 2006).
The problem is even more acute in the specific climatic conditions (high temperature and/or low humidity), where self-desiccation and excessive drying may take place leading to the disturbance of normal hydration processes (Brüdern & Mechtcherine, 2010), (Esteves, 2010), (Jensen & Hansen ,2001), (Zhutovsky & Kovler, 2010). Adequate strength, good adhesion and reduced shrinkage are of prime importance. Since repair mortars are often applied on the surface of existing materials, usually old and damaged concrete the compatibility of these materials is often very difficult to be achieved (Hannant, 2000).

One of the most common problems in cementitious materials is the shrinkage due to the hydration reaction, which often leads to crack propagation in the early days. This phenomenon is more marked in mortars, which contain fine aggregate and/or that are subject to a rapid evaporation of the water contained in the mix. The use of fibre reinforcement for the improvement of tensile strength has been known for decades and widely published (Hannant, 2000) (Davies, 1993). However, in many occasions such a provision is not sufficient, especially in warm and dry climates. In the attempt to reduce the unwanted effect of self-desiccation the various techniques of internal curing can be applied. One of these, relatively new techniques, is based on use of superabsorbent polymers. The superabsorbent polymers have a very high affinity for water (Esteves, 2010). They can quickly absorb water during mixing and subsequently release it during the hydration reaction. Depending on their chemical composition, cross-linking and external stimuli, different absorption/ desorption characteristics can be achieved. These characteristics, if compatible with the kinetics of the hydration process are responsible for enhanced curing and formation of more uniform internal structure (Jensen et al, 2001) (Klemm et al., 2012)

The purpose of this study was therefore to assess the combined effect of polymeric fibres and the super absorbent polymers (SAP) on the performance on cement based repair mortars. For the purpose of this study two different types of superabsorbent polymers have been selected.

MATERIALS AND MIXES

The studied composites were based on cement classified as CEM I 52.5 N (Lafarge), according to the BS EN 197.1. The monofilament polypropylene fibres used (ADFIL Construction Fibres) were 13-19 mm long, 22μm diameter and density of 910 kg/m^3. This material does not absorb water and it is totally resistant to the action of alkalis. Their melt point is 160° C and the ignition point is 350° C. The fibres were bound in small bundles, which easily dissolved in contact with water after a brief mixing.
Two kinds of superabsorbent polymers were used during the tests. Both proprietary materials are based on acrylic acid. They have the same high relative amount of anionic 127 groups, but the cross-linking density of SAP 1 is higher than that of SAP 2. The first polymer, later called SAP1, was produced by bulk polymerisation technique and required crushing to average size of 586μm (Fig. 1). The second, SAP2 was made using inverse suspension polymerisation and the resulting in spherical particles of average diameter of 324μm.

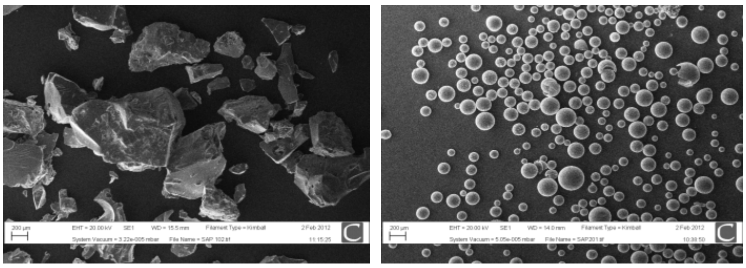

Figure 1. Superabsorbent polymers, SAP 1 (left) and SAP 2 (right)

The study involved seven mortars. A reference1 mortar without superabsorbent polymers and without fibres (REF/-), two mortars characterized by the presence fibres without polymers (R_0.5 and R_0.75), two mixtures containing fibres and SAP1 (S1_0.5 and S1_0.75) and other two mixtures containing fibres and SAP2 (S2_0.5 and S2_0.75).

The compositions of all mortars are presented in Table 1. Tests on mortars were focused on mechanical properties (flexural and compressive strength, autogenous shrinkage and pull-out tests) and microstructural characterisations (MIP and SEM analysis). The compressive and flexural strength were performed according to BS EN 12390-2:2000 and BS EN 12390-5:2000. Mortar prisms 40x40x160mm were made in order to test flexural strength and compressive strength. Experimental tests were performed after 1, 2, 3, 4, 6 weeks of curing. After demoulding (24 hours) the samples were cured in the laboratory in order to simulate the service conditions. The temperature in the laboratory was ranging between 19° and 22°C. Samples for microstructural analysis have been carefully selected from the remains of the prisms.

Table 1. Mix compositions

Mortar	Sand / Cement Ratio	Water/ Cement Ratio	Fibre/ Cement Ratio	SAP_1/ Cement Ratio	SAP_2/ Cement Ratio
R _0,5	2	0.50	0.50%	/	/
R_0,75	2	0.50	0.75%	/	/
S1_0,50	2	0.53	0.50%	0.30%	/
S1_0,75	2	0.53	0.75%	0.30%	/
S2_0,50	2	0.54	0.50%	/	0.30%
S2_0,75	2	0.54	0.75%	/	0.30%
REF/-	2	0.50	0.00%	/	/

Autogenous shrinkage was measured on samples made according to the ASTM C 1696 -09 “Standard Test Method for Autogenous Strain of Cement Paste and Mortar”. The samples in corrugated tubes were stored in the laboratory conditions and tested every day for a month.
Adhesion properties were measured on concrete plates (140x160x40mm)
Thin layers of the mortar (approx. 6 mm) under analysis were put in place and tested after 2, 4, and 6 weeks.

RESULTS AND DISCUSSION

The properties of all fresh mortars were assessed by the flow test according to BS EN 12350-2:2000 and setting times according to BS EN 196 – 3:2005. A thixotropic behaviour of mortars resulting from the presence of fibres has been clearly identified by the flow test.
While the initial diameter measured for all mortars was 100mm, the addition of SAPs slightly increased workability. The use of superabsorbent polymers requires more water. However part of this extra water may not be instantaneously absorbed thus leading to a small increase of workability. After application of 15 beats mortars had a slump flow between 132 – 162mm.
The Vicat test showed that fibres cause a decrease in the setting time while superabsorbent polymers lead to an increase in setting time. The polymers slow down an initial hydration reaction of cement by withholding some of the mixing water. On the other hand, fibres may hinder the execution of the test, resulting in shorter setting times.

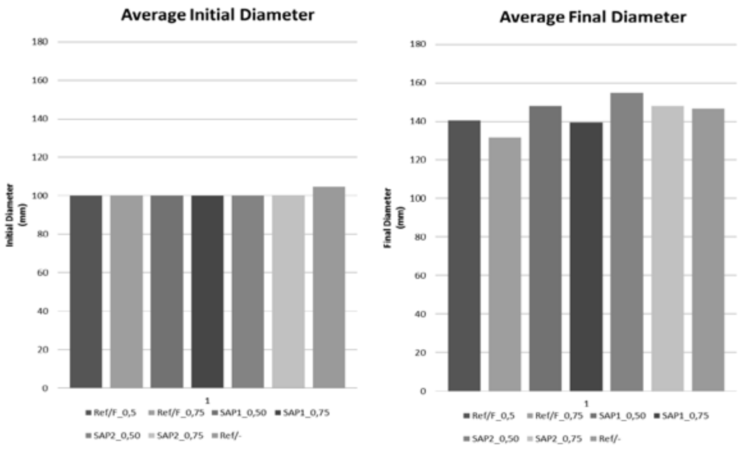

Figure 2. Initial and Final Diameter obtained from the Flow Test.

The Figure 3 shows the flexural strength development over the period of six weeks. The trend lines shown below were obtained from the flexural strength results (min 3 samples) measured at different ages (1, 2, 3, 4 and 6 weeks) on different mortars.

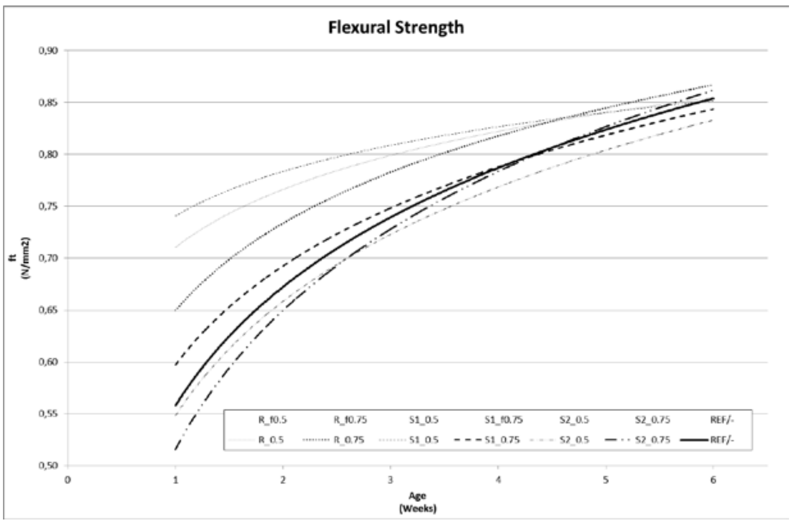

Figure 3. Flexural Strength development

The influence of fibres and polymers clearly decreases over time and although some significant differences can be easily distinguished in very young mortars, after six weeks the results of flexural strength for all samples are comparable (within 5%).

The mechanism of failure of fibres reinforced materials is based on two processes - the tensile stresses are supported by the cement matrix (tensile strength of mortar) before fracture and by the fibres (grip between fibre and mortar) after the fracture. With the progress of cement hydration the tensile strength increases more than a friction between fibres and mortar. This would explain the reduction of the effectiveness of fibres over time.

However an increase in performance due to the use of fibres is clearly evidenced. It can be noted that higher percentage of fibres gives better results on older mortars. Addition of superabsorbent polymers to fibre reinforced mortars has a strong effect on their flexural strength particularly during the first 3 weeks. The highest result was obtained for SAP1 with

0.5% fibres. Increase of fibre content to 0.75% resulted in a decrease in flexural strength below the results recorded for mortar containing 0.75% fibres. The worst result was achieved by using SAP 2 with higher absorption capacity. The effect was even more pronounced in mortars containing higher percentage of fibres. It is possible that the presence of polymers decrease the effectiveness of the fibres by weakening a bond between fibres and cement matrix particularly in the early stages.

The results of the compressive strength development are presented in Fig. 4. The trend lines shown in the chart below were obtained from the measured data on the different mortars (min 6 samples for each result) at different ages (1, 2, 3, 4 and 6 weeks). The addition of fibres and fibre/SAPs leads to a significant reduction of compressive strength. This difference is quite consistent and reaches approximately 18% for FR mortars and even up to 25% for samples containing both fibres and SAPs.

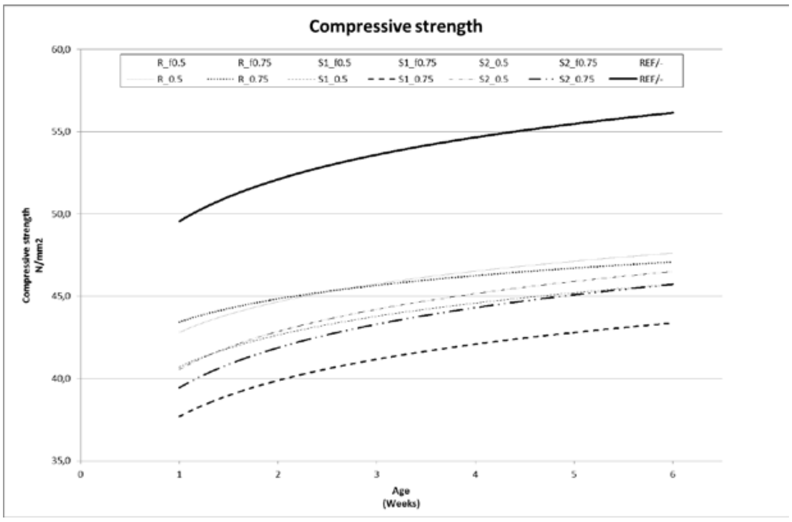

Figure 4. Compressive Strength development

It should be noted that the results obtained for FR mortars (no SAP) are very similar regardless the fibre content. However the higher content of fibres in combination with SAPs gave the lower compressive strength. In fact the lowest value was recorded for S1_0.75 probably use to higher porosity caused by collapsed pores. SAP 1 has lower absorption capacity and may release water faster but forms bigger pores (larger size of SAP particles). The pace of strength increase is very similar for all samples regardless modification type.

In order to assess the suitability of SAPs for internal curing autogenous shrinkage (AS) was recorded for a period of 28 days. It was measured according to ASTM C 1696 -09 on three samples and the average values have been presented in Fig.5. The presence of fibre in cementitious matrices generally ensures a decrease in shrinkage. This has been confirmed by the behaviour of sample R_0.75. A gradual increase of AS after 7 days for sample R_0.5 could be attributed to improper compaction of sample in a corrugated tube. Indeed the results for individual tests were quite inconsistent. The use of superabsorbent polymers in FR mortars reduced the autogenous shrinkage in all samples. The most effective in internal curing was SAP 2 due to its higher water absorption capacities and smaller particles evenly distributed within a matrix. SAP 1 lead to some reduction of AS, mostly visible between 7 and 21 days.

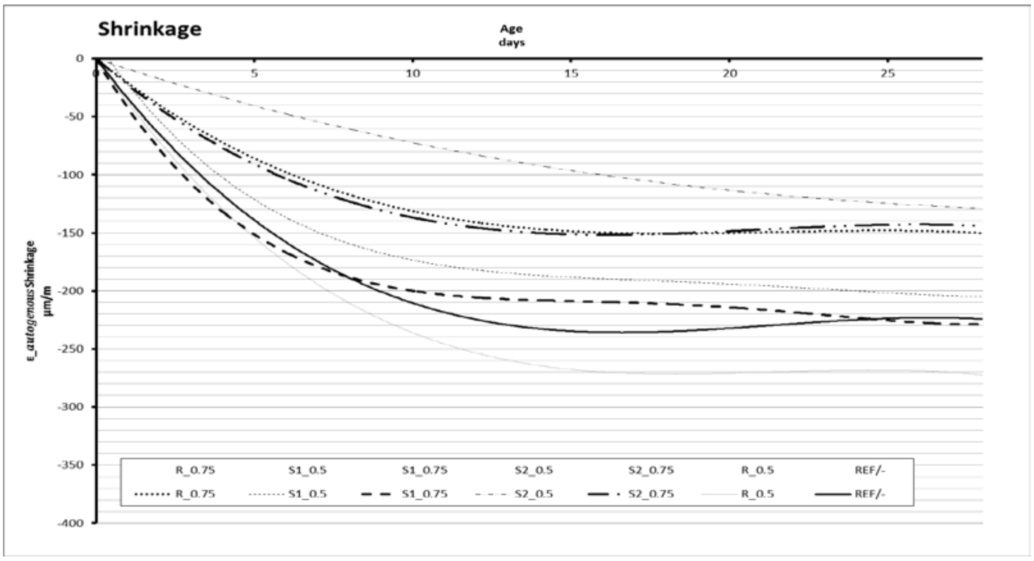

Figure 5. Autogenous Shrinkage development

This reduction ceased to be apparent feature after approximately 28 days. However, it should be noted that the higher fibre content resulted in smaller reduction in AS for both SAP 1 and SAP 2 samples.

Adhesion properties of mortar were evaluated by the pull-out tests. The results are shown in force – displacement curves (Figures 6 – 9). Each graph shows average values measured on the same mortar at three different ages. The reference mortar (no fibres) shows the typical brittle behaviour (Fig 6). After the peak there is a very rapid collapse of the resistance values because nothing binds the mortar after the first fracture, then the test stops for the sudden separation of the mortar.

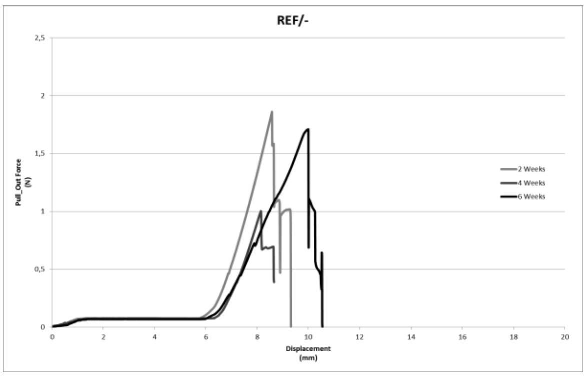

Figure 6. Pull-out test on REF/-

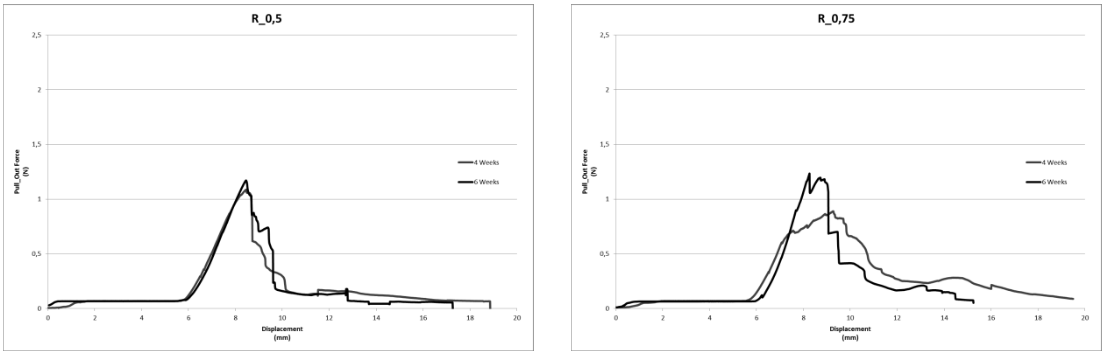

Figure 7. Pull-out test on R_0.5 and R_0.75

Mortars without fibres have the higher values of adhesion but show a brittle behaviour after failure while mortars containing fibres break under lower forces but they have a ductile failure (Fig. 6).

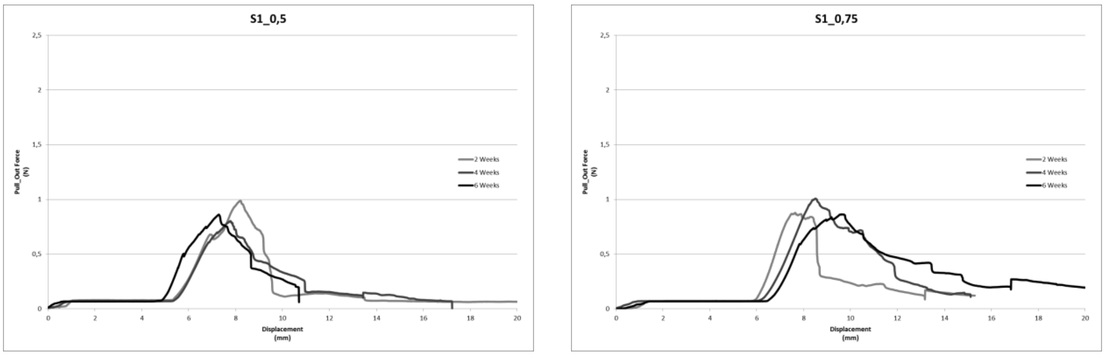

Figure 8. Pull-out test on S1_0.5 and S1_0.75

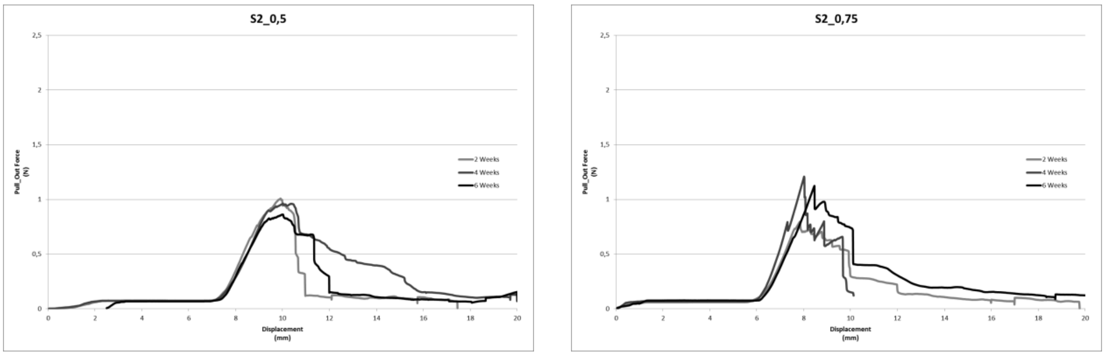

Figure 9. Pull-out test on S2_0.5 and S2_0.75

The graphs show that the part of curve before the failure always has the same gradient regardless of the mortar. This means that fibres and superabsorbent polymers do not change the elastic modulus of mortars.

It is also possible to observe that the increase of fibres from 0.5% to 0.75%, in mortars without polymers, does not involve changes in behaviour during pull-out test (Fig. 7).

Similarly, the presence of SAP 1 does not seem to modify the adhesion of mortars (Fig. 8). However, SAP 2 has some effect on the behaviour of the mortar adhesion. Mortars with SAP 2 have peak values of force similar to the mortars, which do not contain polymers. In this case, the increase in fibres content (from 0.5% to 0.75%) results in a small increase of the peak resistance of adhesion. (Fig. 9)

It should be noted that the results obtained for samples at different ages show a similar trend. This may be due to the small thickness of the mortar layer. It should be pointed out that samples did not undergo any special treatments (no water spaying or polyethylene cover). It is very likely therefore that, after two weeks, most of the water available for hydration reaction evaporated and the performance of mortar cease to evolve. SAPs did not ensure sufficient supply of water to overcome the problem. All graphs show a section characterized by a deformation under constant force. This perfectly plastic behaviour is due to the layer of glue, which connects the test apparatus to the mortar under analysis. The glue also causes uncertainty in the descending part of the stress – displacement curve. Sometime the uplift of metal disc, and then the attached mortar, does not happen all at once. After the failure of the mortar and the extraction of the fibres, it is possible that the metal disc used to transfer stress and the mortar still adhering to concrete plates are still connected by filaments of glue. This can lead to a very elongated final part of the graph. However the part of the graph due to the fibres and the part of graph due to the glue effect can be distinguished by their different inclination. Microstructural characterisation of mortars comprises Mercury Intrusion Porosimetry (MIP) and Scanning Electron Microscopy (SEM) analysis. Samples were tested after 3 and 4 weeks of lab curing. The results are shown in the following graphs (Fig. 10)

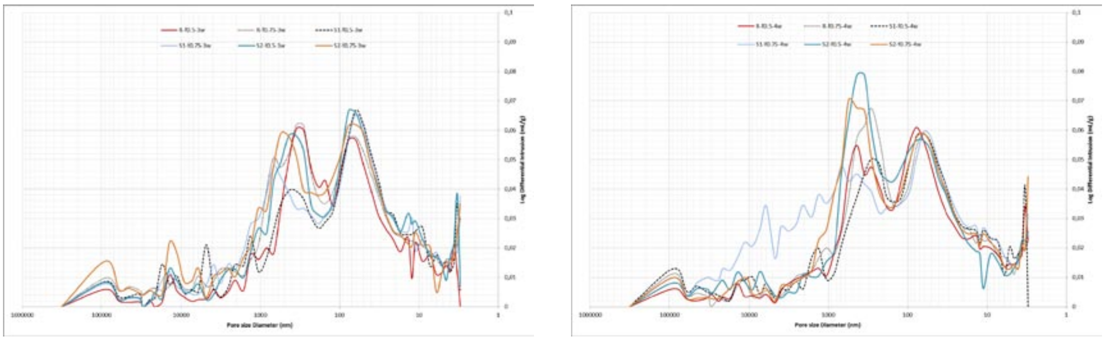

Figure 10. Pores distribution (3 and 4 weeks old samples)

The analyses show that there are not significant changes between the mortars made with different compositions. Bimodal distribution of pores can be clearly identified in all cases.
However, the superabsorbent polymers cause a reduction in the average diameter of pores while fibres cause a rise of diameter of pores (Table 2).
It should be noted that despite the decrease in an average pore diameter in SAP mortars, the increase in porosity could be observed. For the higher fibre content this increase was bigger for SAP 1. More fibres and larger SAP particles facilitated creation of larger pores. On the other hand, the lower fibre content resulted in the higher increase in porosity in mortars containing SAP 2 of higher water absorption capacity. This pattern is valid for both 3 and 4 weeks old samples.
The SEM images of mortars show characteristic features of microstructure including fibre/cement paste interface (Figures 11-12). The reference samples are of a very uniform dense structure although some micro cracks can be identified.

Table 2. Mercury Intrusion Porosimetry data

		Mercury Intrusion Porosimetry						
		Total Pore Area	Median Pore Diameter (Volume)	Median Pore Diameter (Area)	Average Pore Diameter (4V/A)	Bulk Density	Apparent (skeletal) Density	Porosity
		[m²/g]	[nm]	[nm]	[nm]	[g/mL]	[g/mL]	[%]
3 Weeks	R_0,5	9,568	152,2	9,3	39,4	1,8973	2,3150	18,0436
	R_0,75	12,848	266,3	7,4	39,5	1,8648	2,4437	23,6878
	S1_0,5	12,360	108,6	9,1	33,7	1,8980	2,3647	19,7368
	S1_0,75	13,360	224,7	7,5	37,3	1,8740	2,4449	23,3485
	S2_0,5	13,215	132,7	8,5	34,6	1,9075	2,4390	21,7886
	S2_0,75	12,681	212,9	8,0	39,3	1,8218	2,3562	22,6808
4 Weeks	R_0,5	12,521	125,5	7,0	31,8	1,9472	2,4151	19,3727
	R_0,75	12,457	169,1	8,0	35,4	1,8801	2,3712	20,7134
	S1_0,5	13,141	125,6	7,9	32,7	1,9196	2,4180	20,6111
	S1_0,75	13,594	318,4	7,8	39,4	1,7993	2,3696	24,0662
	S2_0,5	11,740	204,0	7,3	39,6	1,9001	2,4380	22,0328
	S2_0,75	13,376	228,4	7,4	36,9	1,8572	2,4096	22,9246

Comparing the fibres extracted from mortars with no polymers (Fig. 11) with those extracted from mortars that contained SAPs (Fig.12) it is possible to see that the polymers reduce the adhesion between the fibres and cement paste.

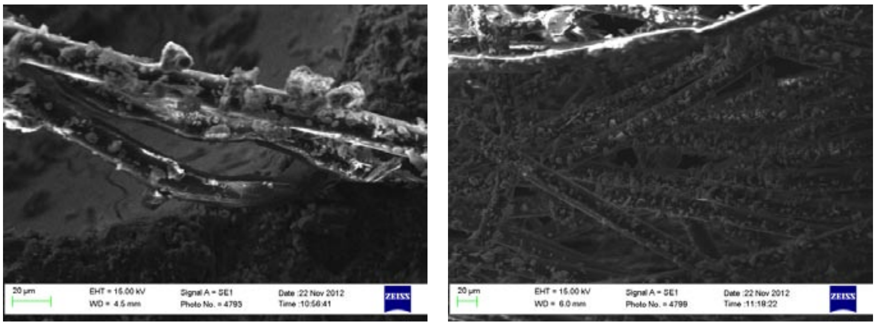

Figure 12. SEM images of R_0.5 and R_0.75 samples

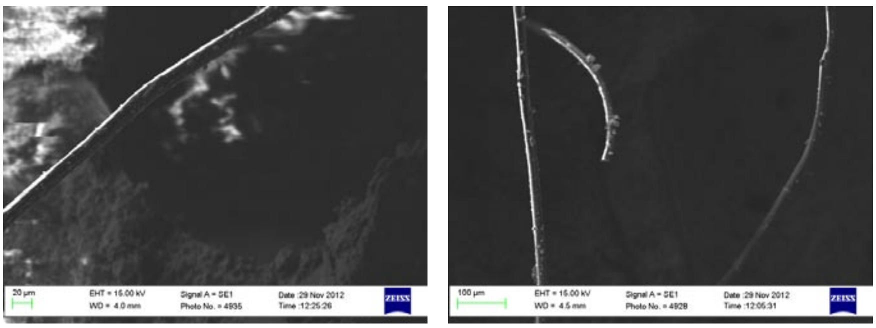

Figure 13. SEM images of S2_0.5 and S1_0.75 samples

Clearly identified crystals of portlandite and other hydrates on the surfaces of fibres are almost not visible on fibres in SAP mortars. Bundles of fibres do not completely dissolve in water before mixing leading to uneven distribution within a matrix. It is possible to identify clusters of interwoven fibres (Fig. 12) particularly in higher fibre content mortars.

CONCLUSIONS

Based on the undertaken experimental investigations it is possible to formulate the following preliminary conclusions:

- Application of polypropylene fibres results in a thixotropic behaviour of mortars. SAPs have a very limited effect on the slump flow. Due to the initial water absorption by SAPs and then its gradual release setting times in SAP mortars are increased. The presence of fibres leads to a decrease in final setting time. This may bring significant benefits in practical applications in construction industry by providing more time for placing and compacting during the first hours after preparation.
- SAPs and PP fibres significantly decrease compressive strength. The effect of polymers is more noticeable in higher fibre content mortars. The water absorption capacity and size of SAP particles is of prime importance. The larger the particles the bigger the pores created by collapsing polymer.
- Addition of fibres increases the flexural strength with a diminishing rate. SAPs in FR mortars may have a strong effect on the flexural strength particularly during the first 3 weeks. The effect is even more pronounced in high content fibre mortars. It is possible that the presence of SAPs decrease the effectiveness of the fibres by weakening the bond between fibres and cement matrix particularly in the early stages as evidenced on SEM images. The effect is greater in mortars with SAP of greater water absorption capacity.
- The use of SAPs in FR mortars reduces the autogenous shrinkage in all samples. The most effective in internal curing is SAP 2 due to its higher water absorption capacities and smaller particles evenly distributed within a matrix.
- The use of fibres reduces the adhesion during pull-out test but leads to a ductile failure. The presence of polymers can reduce the ductility given by the fibres. The elastic modulus of mortars is not affected by fibres and superabsorbent polymers.
- There is a potential benefit in using SAPs in repair mortars however the selection of the appropriate SAP and the PP fibre content is of prime importance. Further comprehensive investigations are necessary to verify the above results.

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