Advances in Self-Compacting repair mortars with Powder Polycarboxilate Superplasticizers, Expansive Agents and Shrinkage Reducing Admixtures

S. Beraldo[2] , V. Alunno Rossetti[1], P. Corrado[2] , A. Dal Bò.[2], R. Gottardo[2],[1]Università di Roma "La Sapienza", Facoltà di Ingegneria, via Eudossiana, 18, Roma; [2]BASF CC Italia spa, Via Vicinale delle Corti, 21 31100 Treviso - Italy

Shrinkage-compensated self-compacting mortars (SCM) have recently been used to repair structural elements of concrete infrastructures. Due to their great fluidity SCM flow easily through narrow spaces without segregation or blockage, also in locations where vibration is difficult, while securing a high quality surface finish. Because of their lower water demand drying shrinkage is highly reduced as so is the possibility of shrinkage cracking and debonding.

New developed powder polycarboxylate ether polymers (PCE) have been investigated in SCM comparing them to traditional powder superplasticizers based on naphthalene formaldehyde sulfonate (NFS). The new powerful powder PCE ensure excellent flow and flow retaining properties, they allow the reduction of the cement dosage and offer higher strength and reduce shrinkage.

Combinations of PCE, expansive agents (EA) and shrinkage reducing admixtures (SRA) together with low cement content show an additional synergy in terms of long term shrinkage reduction, cracking tendency and bond adhesion, leading to excellent field performances.
Some case histories and typical applications are briefly presented.

1 INTRODUCTION

In a continuous effort to improve existing concrete technologies, the construction industry has recently proposed a number of new approaches to challenge the major shortcomings of repairing material. These include high shrinkage, poor adhesion, low tensile and flexural strength and high slump loss over time.
One of the most spectacular advancement has been the introduction of polycarboxylate ether type superplasticizers (PCE) that allowed not only a higher water reduction[1], but also an increase in the flow and in the workability retention of cement based materials. New self-compacting or high-fluidity concrete have increasingly been used in many different building-sites to achieve a better application and easier use.
After the first development in Japan in 1982[2], the interest in shrinkage reducing admixtures (SRA) has grown in recent years. SRA have shown to be able to reduce drying shrinkage by approximately 20 to

50% and thus reduce cracking, that is the first consequence of shrinkage.

Expansive agents (EA) have been extensively used in the premixed mortars for concrete repair to compensate the plastic and drying shrinkage in order to maintain a tight bond with the substrate and to prevent shrinkage cracking[3]. It is important to provide some type of restraint to the expansion, normally by some form of reinforcement or by applying it to a coarse surface, so that compressive stresses can be built up within the mortar. Then, when subsequent moisture evaporation occurs, compressive stress induced by restrained-expansion will relax due to shrinkage of the mortar. The final result is a dramatic reduction of crack formation and debonding from the substrate.
In the last 30 years millions square meters of damaged concrete have been successfully restored in Italy thanks to shrinkage compensated mortars.

The use of PCE in concrete restoration was initially impossible in pre-packed products like grouts or repair mortars because of difficulties to obtain these admixtures in dry powder form . Only recently powder PCE began to be available in the market, making it easier to produce premixed PCE based repair mortars.

SCM are high flowable mortars that can be placed and compacted into narrow spaces between concrete and formworks or reinforcement bars also in unfavourable geometrical conditions without using any vibration, therefore securing easy application and a high quality finish. SCM are mostly used to repair structural elements of concrete infrastructures, guaranteeing a long-term protection to the embedded steel.

The aim of this paper is to report a comparison between newly developed PCE self-compacting mortars (SCM) and traditional superplasticizers SCM based on naphthalene formaldehyde sulfonate (NFS). Some typical applications are briefly presented.

2 EXPERIMENTAL

Two series of mixes were used:

- standard mortars with different superplasticizers
- mortars with superplasticizers and EA, SRA

2.1 Superplasticizers comparison

A preliminary comparison of different powder superplasticers was carried out using the basic grout composition given in table 1.
Portland cement is a type I 42,5 R type I according to EN 197/1. Silica sand is a natural river sand having a grading according to ASTM C 144-76 in the range size between 0 and 3 mm.

Mortar mixes were prepared adjusting the water to achieve similar initial fluid consistency.
Powder superplasticers dosages are reported in Table 2.

Table 1 - Mix proportion of tested mortar

	Mix A	**Mix B**
Cement	40	34
Silica sand	57,9	63,9
Silica Fume	2	2
Antifoam	0,1	0,1
Total	**100**	**100**

Table 2 – Superplasticizer dosages

	Sample	**Mix n°**	**Dosage**
Naphthalene formaldehyde sulfonate (NFS)	1	A	0,5 %
“ “	2	A	0,7 %
Polycarboxylate ether (PCE)	3	A	0,15%
“ “	4	A	0,20%
“ “	5	B	0,15%

2.2 Test methods

The five mixes in Table 2 were tested for their standard properties according to the following test methods.

Flowability is the most important parameter concerning fresh mortar properties. Flow was measured using EN 13395-2, a method suitable for high flow grouts or mortars that have a maximum aggregate of 4 mm.

Fresh mortar density according to UNI 10859.

Compressive and flexural strength on 4 x 4 x 16 cm prismatic specimens at 1, 7, 28 days according to EN 12190 and EN 196/1.

2.3 Results

Fresh and hardened mortars performances are reported in Table 3 - 4 and figure1.

Table 3 – Fresh mortars properties

Sample	Mixing Water(%)	Flow (cm)				Density (kg/m^3)
		initial	5 min	15 min	30 min	
1	17,6	58	53	45	36	2280
2	16,7	59	50	40	32	2270
3	15,0	62	59	55	50	2290
4	14,5	63	62	59	56	2285
5	14,0	64	62	59	55	2300

Figure 1 – Slump loss over time

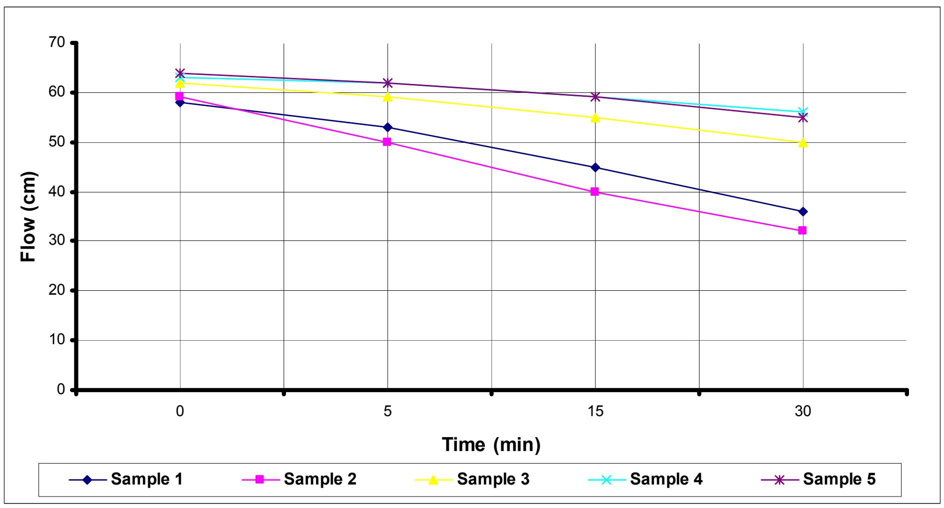


Table 4 – Hardened mortars properties

Sample	Compressive Strength (MPa)			Flexural Strength (MPa)		
	1 g	**7gg**	**28gg**	**1g**	**7gg**	**28gg**
1	34	54	65	6,6	8,2	9,1
2	37	58	69	6,8	8,4	9,5
3	40	65	77	7,2	9,1	9,8
4	41	67	80	7,3	9,3	10,1
5	35	59	71	6,5	8,6	9,4

2.4 Discussion of results

The mixtures using PCE require 20 to 30% of the superplasticizer dosage compared to the mixtures that use NFS due to their higher dispersing efficiency. Slump loss is clearly reduced in PCE mixtures, providing a longer pot life. Compressive and flexural strength are constantly higher in PCE mixtures especially at 7 and 28 days. The addition of PCE allows for a 15% cement reduction without loss of compressive strength compared with NFS mixtures.

2.5 Evaluation of EA and SRA addiction to PCE

Expansive agents (EA) and shrinkage reducing admixtures (SRA) were added to the basic mixture, as reported in the table 5.

Table 5 – Mix proportion of tested mortars

MIX	C	D	E	F	G
Cement	40	40	40	40	40
Silica sand	57,2	57,75	56,25	56,75	55,25
Silica fume	2	2	2	2	2
Antifoam	0,1	0,1	0,1	0,1	0,1
EA	-	-	1,5	-	1,5
SRA	-	-	-	1,0	1,0
NFS	0,7	-	-	-	-
PCE	-	0,15	0,15	0,15	0,15

2.6 Test methods

Tests were carried out to evaluate properties specifically regarding concrete repair, especially cracking and bond adhesion to old concrete. The same water/binder ratio was used in all mixes so that the comparison of results was more coherent.

Drying shrinkage according to EN 12617-4.

O-ring test: cracking tendency was evaluated using a particular ring-shaped specimen which had already been used in several past publications. Due to shrinkage, the mortar ring tends to reduce in diameter, but the steel disk inside prevents this movement and provokes restrained shrinkage. As a result, the material is subjected to stress which causes the mortar to crack.

Triangular test*:* the test determines the susceptibility of the mortars to cracking according to the German standards TP BE-PCC. The method consists of monitoring a mortar in a long triangular prism shaped metal mould. Because of the particular shape of the specimen, the top surface is more exposed, so it is more subjected to drying and shrinkage. At the same time the bottom surface is bonded to the metal mould, which restricts the movement of the mortar and a situation of restrained shrinkage is developed that causes traction stress inside the material and subsequent cracking.

Adhesion bond strength: adhesion was evaluated according to EN 1542 curing at 50% relative humidity and 20°C.

2.7 Results

The results reported in Table 6 and 7 show a clear reduction in shrinkage when PCE is used compared to NFS. Regarding the formulations with PCE, it is evident that the improvement in properties of the mix with EA is about half of that obtained with SRA; the percentage of shrinkage reduction obtained by the combination of both admixtures is higher than that obtained by simply summing up the individual values of each admixture.
EA (mix E) produces a reduction of shrinkage of 10% compared to mix D, SRA (mix F) a reduction of 27,5%. Using the same amount of both the admixtures together (mix G) provides a reduction of 46,1%.
Similar results are obtained in the other tests.

Table 6 – Results (part I)

Mix	**Water (%)**	**Drying Shrink. 28 days (%)**	**Shrink. reduction (%)**	**Shrink. reduction (%)**	**O-Ring test (dbc*)**	**Triangular test (dbc*)**	**Bond strength (MPa)**
C	16	1122	rif	/	17	1	1.4
D	16	1020	9.1	rif.	28	36	1.7
E	16	918	18.2	10.0	54	47	2.0
F	16	740	34.0	27.5	62	54	1.9
G	16	550	51.0	46.1	102	95	2.6

dbc*: days before cracking

To correlate the results of the experiments and the physical-mechanical behaviour observed, we used a method of analysis based on two evaluation factors [5], namely:
• **Cracking Risk Factor**: the ratio between the stress σ_t induced by shrinkage, evaluated as E x ε (Hooke's law: drying shrinkage per elastic modulus) and the tensile strength. Although this factor does not include all the possible variables that contribute to cracking, it includes the most important parameters i.e. drying shrinkage, elastic modulus and tensile strength.
• **Debonding Risk Factor**: the ratio between tensile stress $\sigma_{t,}$ induced by shrinkage, and adhesion. The stress induced by shrinkage is proportional to the elastic modulus; if it is divided by the adhesion

strength it indicates the actual possibility of mortar and concrete becoming detached.

To evaluate the above factors, the “static elastic modulus” and “direct tensile strength” were measured.
Static elastic modulus was determined according to the UNI 6556 standard.
Tensile strength was determined by traction of dog-bone shaped specimens with an automatic tensile testing machine, according to the UNI 6011 standard.

Table 7 – Results (part II)

Mix	Elastic modulus (MPa)	Tensile strength (MPa)	Tensile stress σ_t induced by shrinkage	Cracking risk factor	Debonding risk factor
C	27362	3.6	30.7	8.5	21,9
D	28758	3.9	29.3	7.5	17.2
E	29106	4.1	26.7	6.5	13.4
F	28017	4.0	20.7	5.2	10.9
G	28543	4.1	15.7	3.8	6.0

2.8 Discussion and results

- PCE mixes show lower shrinkage (-9,1%) than equivalent NFS mixes. This is probably due to the effect of polyether side chains which are capable of reducing the surface tension of water in the pore solution of cement paste. It leads to lower internal tension in pore menisci and less associated macroscopic shrinkage. Consequently adhesion is improved and cracking lessened.
- Both expansive agent and shrinkage reducing admixture hinder shrinkage and cracking, as shown by the o-ring, triangular and bond adhesion tests.
- The combination of PCE, EA and SRA create an optimum synergy, providing the best performances in terms of shrinkage and cracking reduction and bond adhesion improvement. The shrinkage reduction value obtained by combining the two additives is higher than the summing up of the values of the two singular additives.
- An analysis of “cracking risk factor” and “debonding risk factor” data shows an interesting correspondence to the results of the cracking tests (O-ring test, triangular test). The laboratory tests show that the low values of “cracking risk facto”r correspond to lower risk of cracking. The most significant example of how a

low cracking risk value corresponds to ideal behaviour is found when SCM is mixed with SRA and EA.

3 THIRD PART: CASE HISTORY

3.1 First commercial products

Five years ago the first cementitious repair mortar and micro-concrete based on combination of PCE, SRA, EA and fibers were introduced in the market with the brand name of Emaco Formula Reodinamico M1 (mortar) and Emaco Formula Reodinamico B1 (micro-concrete). In both formulations, special polymeric fibres reduce the cracking caused by plastic shrinkage during the first hours of setting.
Typical performances of these products are summarise in table 8 by classes of properties.

Table 8 – properties of 2 commercial products

MATERIAL CHARACTERISATION	Mortar	Micro Concrete
Particle size (mm)	0 – 2,5	0 – 10
Chloride ion content EN 1015-17 (%)	< 0,05	< 0,05

FRESH PROPERTIES	Mortar	Micro Concrete
Workability slump flow EN 11041 (cm)	>80	>80
Workability retention (pot life) (min)	>30	>30
Plastic density EN 1015-10 (kg/m^3)	> 2250	> 2300
Air content EN 1015-7 (%)	2	2

ENGINEERING PROPERTIES		Mortar	Micro Concrete
Compressive strength EN 12190 (MPa)	1 days	>30	>30
	7 days	>50	>55
	28 days	>70	>70
Flexural strength EN 197/1 (MPa)	1 days	> 7	>5
	7 days	>9	> 7
	28 days	>11	>9
Restrained Expansion UNI 8147 (%)		>0,04	> 0,04
Drying Shrinkage EN 12617/4 (%)		< 0,04	< 0,04
Bond adhesion EN 1542 (MPa)		> 2,5	> 2,5
Restrained shrinkage/expansion EN 12617/4 (MPa)		> 2,0	> 2,0
Elastic Modulus EN 13412 (MPa)		28	30
O-Ring test (Days before cracking)		> 180	> 180
Triangular test (Days before cracking)		> 180	> 180
Dimensional Compatibility test (Curling – Warping)		Slight warping	Slight warping
Slant shear strength EN 12615		>10	>10
Pull out test on steel bars RILEM-CEB-FIP-RC6-78 (MPa)		>30	>30

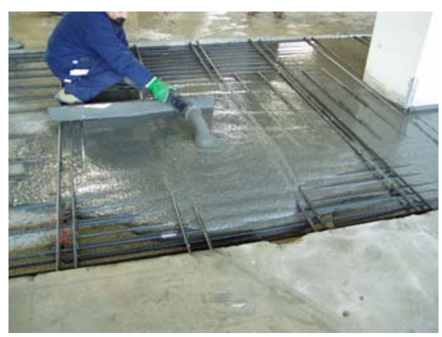
PERMEATION PROPERTIES	Mortar	Micro Concrete
Capillary absorption EN 13057 ($kg \cdot m^{2} \cdot h^{-05}$)	0,06	0,08
Rapid chloride permeability ASTM C-1202	< 900 coulombs (very low)	< 900 coulombs (very low)
Depth of penetration of water under pressure – max penetration EN 12390-8 (mm)	4	5
Carbonation resistance EN 13295 d_k [mm]	0	0

DURABILITY TEST	Mortar	Micro Concrete
Thermal compatibility, Freeze thaw EN 13687-1 (MPa)	>2	>2
Thermal compatibility Thunder Shower EN 13687-2 (MPa)	>2	>2
Thermal compatibility Dry cycling EN 13687-4	>2	>2
Freeze thaw resistance ASTM C-666 (retained % of initial dynamic modulus)	> 95	>95

3.2 Building site applications

Figure 1, 2 and 3 show a typical use of EMACO FORMULA REODINAMICO M1 for structural strengthening of industrial flooring. Vibration is not required and therefore less manpower is needed, reducing dramatically the potential of human mistakes when casting. Bleeding and segregation were not present.

(Fig. 1)



(Fig. 2)

Fig. 1, 2 and 3Workers only need to spread the fresh mortar to ensure the quality of surface finishing.
No cracking or delamination has been observed after 4 years of application.
A smooth and compact surface is still noticeable after a long time. (Fig. 3)

(Fig. 4) (Fig. 5)

Figure 4 and 5
Typical columns jacketing of commercial or residential buildings with EMACO FORMULA REODINAMICO M1. No vibration or compaction is required. A very smooth marble-like skin is achievable.

(Fig. 6)

(Fig. 7)

Figure 6 and 7
Typical structural strengthening of concrete beams in a highway in the tensile zone with EMACO FORMULA REODINAMICO B1. No vibration required. Surface cracking is not present after 4 years of application.

4 CONCLUSIONS

The present article highlights the synergic interaction between these three different admixtures: PCE, EA and SRA.
A balanced combination of these compounds allows excellent performances in terms of shrinkage, adhesion and cracking.
New indicators for assessing long term durability of mortars have been proposed, the “cracking risk factor” and the “debonding risk factor”.
The “cracking risk factor” takes into account the most important parameters concerning cracking: drying shrinkage, elastic modulus and tensile strength.
The “debondig risk factor” evaluates the loss of bond adhesion between the repair mortar and the substrate, loss that compromises irremediably the repair work.
The technical performances and practical applications of two products based on this technology, Emaco Formula Reodinamico M1 and B1, which are already on the market, are briefly presented.

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