Assessment of Materials for Concrete Surface Repair Based on Cracking and Debonding Risk Factors.

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ABSTRACT

Frequent failures occur in many concrete repair works and a large number of pre-mixed repair products and systems available on the market call for a critical revision of the technologies involved in order to guarantee adequate durability of repaired concrete surfaces.
Seven of the most frequently used pre-mixed repair mortars available on the Italian market have been tested according to the recent EN 1504 European Standards on "Products and systems for the protection and repair of concrete structures", and by using other specific test methods.
The objective was to evaluate the durability of concrete repair work through laboratory and field tests that quantify the parameters most likely to influence performance.
Cracking risk factor and debonding risk factor have been proposed as performance evaluation indexes. Correct understanding and awareness of these two factors can help design engineers to choose a repair system with a reduced risk of failure.

KEYWORDS
Concrete repair; Performance oriented test; Cracking risk factor; Debonding risk factor.

INTRODUCTION

Results of repair works, which, to a large extent are concrete surface restoration by means of cementitious mortars, have evidenced, all over the world, many cases of early degradation in repaired structures and have brought to light the inadequacies of both some materials used and some application procedures (the latter will not be dealt with in this paper).
It is evident that the choice of the repair products becomes a moment of paramount consequence, as well as the definition of their appropriate requirements and performances. Unfortunately the designer has to face a difficult task: to deal with a market over-flooded with proprietary restoration products, whose properties, as specified in the technical sheets, not always are pertinent for their successful application. Most industrial pre-mixed cementitious mortars found on the market are in effect characterized by formulation criteria (cement mixes, size of aggregates, additives) whose main purpose is to facilitate use - even by non- skilled operators - and to shorten the time it takes to carry out the work.
Although these features can be important, products for maintenance must primarily offer effective performance in avoiding the main problems: **craking and debonding** of the newly applied products.
The increasing focus on this type of work and related problems, has resulted in the drawing up of the EN 1504 Standards *"Products and systems for the protection and repair of concrete structures"*, which gives appropriate guidance for the restoration process development and general principles and

methods. The EN 1504 Standards also gives a broad guide for selecting the relevant properties of the materials and a range of test methods and specific requirements for each repair system.
It is nevertheless opinion of the present authors that, especially for the cementitious products, widely used in Europe, neither the Standard nor the producers do give sufficiently clear criteria about the properties essential to get good performances in the repair work.
Aim of this experimentation (Bettosti et al. 2001) was the identification and assessment of the properties most likely to influence the end performance (reliability and durability without cracking and/or debonding) of concrete surface restoration by means of premixed cementitious mortars. To these properties the designer should refer to specify and choose the repair products.
Beyond single properties of the mortars (strength or shrinkage or adhesion to substrate), combined parameters are believed to be possible solutions of the problem. As an evaluation tool *cracking and debonding risk factors* are proposed as an example, whose evaluation should give design engineers the possibility of a correct choice of the products with a reduced risk of failure.

REQUIREMENTS OF CEMENTITIOUS MORTARS FOR REPAIR

Various causes of incompatibility between repair materials and concrete substrate, leading to failures, have been identified, in particular dimensional, chemical, electrochemical and permeability aspects, as pointed out by several authors (Emmons et al. 2000) (Emmons & Vaysburd 1997) (Rizzo & Sobelman 1989) (Morgan 1996).
Researches conducted throughout the world have shown that it is mainly the dimensional aspects, including shrinkage, thermal expansion coefficient, elastic modulus and creep, that determine the behavior of the maintenance work over time. A marked difference within these dimensional parameters can negatively affect mortar and concrete substrate interaction in various ways, the most frequent being cracks on the new material, that can easily be detected on the surfaces after repair work has been carried out. Cracking alone often triggers a whole series of additional problems; the onset of cracking in fact (of various size and extension) accelerates normal degradation processes.
The main type of dimensional incompatibility and the cracks that ensue is shrinkage. Of the various types of shrinkage (thermal, plastic, drying, carbonation and autogenous), the most critical for repair mortars are plastic and drying shrinkage.
Plastic shrinkage, due to rapid loss of water by the fresh mortar, can easily cause crazing or cracking of the repair mortar. Sometimes this is not a real problem, unless there is the possibility of formation of white salts deposits on the fracture rims, due to liquid water migration. This type of defect can be avoided by applying on site correct procedures against water loss.
Drying shrinkage is mainly due to water loss from capillary pores of the cement gel. When shrinkage (ε) is mechanically restrained (by steel reinforcement or rough non-shrinking old concrete substrate) tensile stress **(σ_t)** is generated, that can be calculated with the Hooke equation:

$$\sigma_t = E \cdot \varepsilon$$

in which E is elastic modulus of the mortar.
This stress, even if somewhat attenuated by the creep of the applied mortar, increases with the shrinkage and if it grows higher than the tensile strength of the material **(Rt),** it makes the mortar crack. The second possibility is that the above-mentioned stress, acting parallel to the old/new interface, overcoming the adherence can causes the debonding.
The scope of this experimentation is to identify the parameters that are most likely to influence the durability of concrete surface repair mortars, especially towards cracking and debonding, by application of advanced testing methodologies, comparing the results of tests on the products with the performance in tests simulating field application.

EXPERIMENTAL

Materials

Seven pre-mixed mortars were tested, the most popular on the Italian market for concrete surface repair, identified as: TH – KE – MP – TO – WB – SI – MA.
The proportions indicated in the respective technical sheets were used to prepare the mortar mixes, and the consistency was subsequently verified according to the Italian Standard UNI 7044 - Spreading test.

Methods of testing

The experimentation was developed in two test series:

1. Application of UNI Italian Standard testing methods, to define the general features and quantify the properties stated in the technical forms;

- *Initial and final setting time* according to UNI 7132 standards.
- *Workability(flow) and loss of workability over time* according to UNI 7044
- *Capillary absorption* according to UNI 10859.
- *Fresh mortar density* according to UNI 8995 standards.
- *Compressive and tensile strength* on 4 x 4 x16 cm prismatic samples, at 1, 7, 28 days to UNI 196-1.
- *Static elastic modulus* according to UNI 6556.
- *Tensile strength* according to ASTM C 190-85.
- *Adhesive bond strength:* good adhesion of repair mortar to the concrete support is essential to offset interface shear stress caused by shrinkage or thermal effect. Carried out according to UNI EN 1542 applying the mortar onto a R_{ck} 25 concrete slab and pulling out cores across support and mortar.
- *Drying shrinkage* according to EN 12617-4.

2. Performance oriented dimensional compatibility standard and non standard tests:

- *O-ring test*: the test determines the susceptibility of the mortars to cracking, using a particular ring-shaped sample that accelerates cracking. Due to shrinkage, the mortar ring tends to reduce its diameter, but the steel disc inside offsets this reduction and provokes a situation of restrained shrinkage. As a result, the material is subjected to stress which causes the mortar to crack. This test method is not standardized, however, it is commonly used in research laboratories and in scientific studies.
- *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 thin triangular section prism-shaped sample composed of a metal mould that acts as a support to the mortar in it. The mortar prism tends to reduce its size in a diversified way and in proportion to its section; this reduction is greater in correspondence with the top surface than on the bottom. The metal mould however offsets this reduction and develops a situation of restrained shrinkage that causes a tensile stress inside the material and subsequent cracking.
- *Dimensional compatibility test*: determines the susceptibility of mortars to warping or downward curling in job site non-controlled conditions, especially suited to detect the occurrence of shrinkage or expansion (Emmons et al. 2000). A thin prism-shaped sample is cast in a form on which bottom a perforated metal sheet acts as support and restraint to shrinkage or expansion. Unlike the drying shrinkage test, the movements that occur even within the first hours after setting can be detected.
- *Concrete cavity filling*: the purpose of the test is to verify the ability of a product to repair surface cavities. The support is a 49 x 39 cm concrete cube with R_{ck} 40 and 21.5 Ø cm cavity of 2 cm in depth at the center of every face. The mortar is applied in two stages: initially only the cavity is filled; subsequently a layer of mortar is applied to the entire surface of the

sample. The work is monitored, and any cracks that form during the following 180 days are recorded.

TEST RESULTS

Standard tests

The results of the **standard tests** are summarized in Table 1, also showing the mixing water content.

Table 1 – Physical and mechanical properties of the mortars

SAMPLE	MIXING WATER, %	SETTING TIME, min		WORKABILITY, INITIAL AND IN TIME , Flow %				CAPILLARY ABSORPTION at 24 h, g/cm^2
		Initial	Final	0 min	5	10	15	
MP	15,0	20	25	60	58	50	0	0,18
MA	17,6	230	295	90	77	72	70	0,36
TH	10,8	35	44	40	35	30	0	0,09
KE	15,2	16	28	73	60	58	55	0,39
SI	17,0	291	630	69	60	45	40	0,09
TO	16,0	75	135	40	32	30	20	0,38
WB	14,0	10	12	36	0	0	0	0,72

Table 1 – Physical and mechanical properties of the mortars (continued)

Sample	Density Kg/m^3	Compressive strength MPa			Tensile strength MPa	Elastic modulus MPa	Bond strength MPa	Drying shrinkage (µm /m)
		1 day	7 days	28 days				
MP	1960	35,3	48,0	59,60	4,38	22762	0,70	1637
MA	2128	25,5	54,0	62,10	3,78	24785	2,75	648
TH	2165	17,6	48,8	52,3	3,80	26805	1,70	1052
KE	2041	11,4	34,1	41,3	3,17	20895	0,81	1427
SI	1908	18,5	37,5	42,0	3,23	19615	0,94	1602
TO	2116	11,3	37,6	45,3	3,73	23316	1,92	1462
WB	2137	15,7	32,4	42,8	3,07	27217	1,40	1390

Discussion of standard test results

Workability and setting time
Water was added to each repair mortars according to their technical data sheet recommendations, leading to different workability and loss of workability over time. After mixing, some products (WB, TO, TH) had very dry consistency with somewhat rapid loss of workability (WB), while others revealed better workability which was maintained for a longer period of time. No relationship can be observed between mixing water and workability. Two products can be classified as rapid setting type (MP and WB).

The rapid loss of workability is related to the low initial and final setting time as in the case of WB. It must be pointed out that higher initial workability with loss coming about gradually makes the mortar easier to apply so that some common application errors can be avoided, such as excess addition of water, poor compaction on the concrete substrate (and consequently poor adhesion), or the need to use small quantities of product for each mix.

Capillary absorption
All the hardened mortars have low capillary absorption; the value of WB alone distinguishes itself from the average. In general all the samples have low capillary absorption if compared with that of most rendering and plastering mortars. This is a good requirement in terms of improved durability.

Density
The values of the various products are appreciably different, going from the lowest value of 1908 g/l to the highest value of 2185 g/l. This difference (about 15%) can be mainly attributed to the air entrained during mixing (a difference of about 7.5 % by volume).

Mechanical strength
All the materials exhibit far higher performance than the EN 1504-3 standards for structural (R4 >45 MPa and R3 >30 MPa) and non-structural repair mortars (R2 >20 MPa and R1 >10 MPa).
We do not consider this parameter very important as regards repair work durability, for reasons of compatibility with a support generally less strong.

Tensile strength
The values of all the mortars are quite similar.

Elastic modulus
The values go from 22882 MPa to 32355 MPa. Basically they are all close to the typical values of average concrete and similar to those of a normal structure in reinforced concrete that needs to be repaired. If these conditions were to be guaranteed, any stress on the new to old interface or any uneven load distribution due to deformation of the whole structural member, could be avoided.

Adhesion
The adhesion values are quite different in all the products tested; they go from a minimum of 0,70 MPa to a maximum of 2,75 MPa. Three products do not reach the minimum values required by the EN 1504-3 standards for non-structural mortars (R2-R1 >1 MPa). And only one product (MA) is also able to comply to the EN 1504-3 standards for R4 structural mortars (>2 MPa).

Drying shrinkage
In all the materials, except MA, drying shrinkage is over 1000 µm/m, in some cases (MP, SI) it is over 1500 µm/m.
These very high values cause high risk of cracking according to the International Concrete Repair Institute (International Concrete Repair Institute 1996) classification.
One has to observe that the shrinkage values result from different consistencies as a consequence of the instructions coming from the data sheet of each single product. If it would be used the water required for equal workability, differences in shrinkage would be further emphasized.

Relationship among data
The tested products can be different in many ways: type and dosage of cement, admixtures, additions, aggregates utilized; as a consequence also the properties of the mortars after mixing and hardening, among which entrained air content, can be and are different. So an attempt to find relationships among

the properties has failed: for example the mortar TH has a minimum mixing water, maximum density and minimum absorption; the mortar SI has a maximum mixing water and minimum density but a minimum absorption; the mortar MA has a high density and the maximum compressive strength but also the maximum mixing water.

Discussion of performance related test results

The results of the performance oriented tests and dimensional compatibility tests are summarized in Table 2, together with the shrinkage values.

Table 2 – Dimensional compatibility tests

Sample	O-Ring Test (days before cracking)	Triangular Test (days before cracking)	Curling (+) warping (-) after 60 days (mm)	Concrete pit cracks development (days)	Drying shrinkage (µm /m)
MP	7	7 (debonded)	-18	6	1637
MA	No cracking	No cracking	+11	No cracking after 180 days	648
TH	No cracking	No cracking	-11	24	1052
KE	29	24	-12	14 – 21	1427
SI	25	31	-12,5	14	1602
TO	28	24	-8	35	1462
WB	28	10 (debonded)	-13	21	1390

The analysis of the results leads to the following observations.

O-ring test
Very clear results emerged from this test that has proven to be very selective: only the 2 mortars with lowest drying shrinkage (MA, TH) did not crack. All the others crack within a period of one month. The material quickest to crack (MP) is also the one with the highest shrinkage.

Triangular test
The results of this test are similar to those of the previous test: only 2 low shrinkage materials (MA, TH) do not crack. Two of the others, besides cracking even resulted debonded from the support (MP, WB), while the remaining are cracked in various ways.

Curling/ warping test
All the materials revealed pronounced shrinkage warping, except MA with initial expansion curling and subsequent low shrinkage. Of the other materials, MP was found to have the greatest warping, followed at a distance by SI and WB. This property is in very good agreement with shrinkage data..

Concrete cavity (pit)
Over a period of 35 days all the repair mortars cracked, except MA. MP is the first material to crack and partially detach from the support, followed by the other materials that all cracked, except MA. Also this property is in good agreement with shrinkage data.

PARAMETERS FOR PERFORMANCE PREVISION

Even if the drying shrinkage has proven a good correlation with performance oriented tests as previously said, the authors feel that some combination of properties, instead of a single property, could perhaps be useful as a parameter to foresee and specify materials performance.
As for a first attempt two combined factors have been defined:

- **cracking risk factor**: ratio between the stress σ_t induced by shrinkage (evaluated as $E \cdot \varepsilon$) and the tensile strength of the mortar. 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**: ratio of tensile stress σ_t induced by shrinkage and adhesion, supposed to be related to the actual possibility of mortar debonding from concrete.

Table 3 – Cracking and debonding risk factors

Sample	Tensile strength (MPa)	Adhesion (MPa)	Tensile stress σ_t induced by shrinkage (MPa)	Cracking risk factor (σ_t/ Tensile strength)	Debonding risk factor (σ_t/Bond strength)
MP	4,38	0,70	37.3	8.5	53.2
MA	3,78	2,75	16.1	4.2	5.8
TH	3,8	1,70	28.2	7.4	16.6
KE	3,17	0,81	29.8	9.4	36.8
SI	3,23	0,94	31.4	9.7	33.4
TO	3,73	1,92	34.1	9.1	17.8
WB	3,07	1,40	37.8	12.3	27.0

Table 3 illustrates tensile strength, the bond strengths and the values of stress σ_t induced by shrinkage, that determine the "cracking risk factor" and the " debonding risk factor.".
Table 4 illustrates the values of the above-mentioned factors in comparison with the performance oriented tests. An analysis of these data shows that a good correspondence can be noticed between both factors and O-Ring test, triangular test and curling and warping test.
Work is in progress for the definition of new suitable combined factors, taking into account also the creep behaviour of the various tested products, not measured during this experimentation.

Table 4 – Comparison among risk factors and performance oriented tests

Sample	Cracking risk factor	Debonding Risk Factor	O-Ring Test (days before cracking)	Triangular Test (days before cracking)	Pit Test (days before cracking)	Curling (-) or Warping (+)
MP	8,5	53.2	7	7 (debonded)	6	-18
MA	3,6	5.8	No cracking	No cracking	No cracking	+11
TH	7,4	16.6	No cracking	No cracking	24	-11
KE	10,4	36.8	29	24	21	-12
SI	9,7	33.4	25	31	24	-12,5
TO	9,1	17.8	28	24	35	-8
WB	12,3	27.0	28	10 (debonded)	21	-13

Examination of the results shows that the proposed factors are broadly correlated with the measured properties; the best relationship can be observed between Debonding Risk Factor and Pit test results, shown in Fig.1; the MA sample values are not reported because of the non-numerical value, even if the correlation is very good (because no cracking corresponds to the minimum value of the factor).

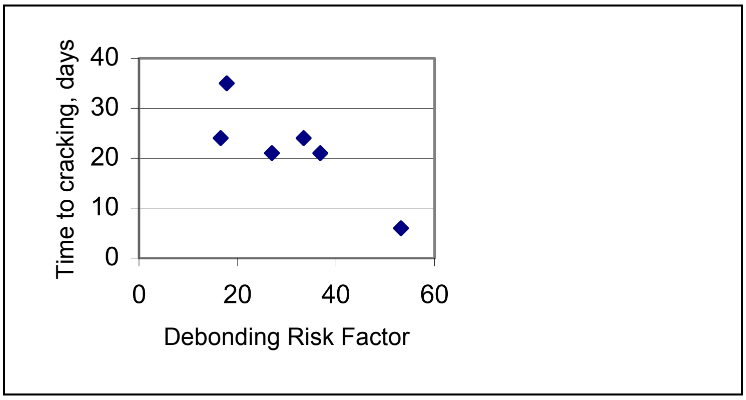

Figure 1 - Time to cracking in the pit test as a function of Debonding Risk Factor

CONCLUSIONS

The assessment of the technical data provided by the producers of the seven commercial products examined, the most popular in Italy, has shown that in most cases the specified characteristics are not necessarily related to the final performances of the products, especially to avoid the main problems of cracking and debonding, main requisites for attaining successful repairs and their durability.
The results emerged from the standard tests on the properties, show that the mortars can be different in many aspects; no relationships among various properties have been identified.
The results on performance oriented tests have also shown great differences among the tested mortars, that in some instance show very unsatisfactory behavior.
There is therefore a need of more precise information on performance, which might be mandatory when the market will fully accept UNI EN 1504.
To foresee the performance on the basis of standard test data, evaluation factors obtained by combining different properties could be very useful: the *cracking risk factor* and the *debonding risk factor* have been proposed and evaluated in comparison with performance tests results.

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