CONCRETE DURABILITY AND REPAIR TECHNOLOGY

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ABSTRACT

Properties of shrinkage-compensating mortars for repair work are analysed. Analysis have highlighted how, in order to achieve successful repair of deteriorated concrete structures, strain-induced compressive stress from expansion plus tensile strength of the mortar must be higher than the tensile stress induced by restrained drying shrinkage.

The most widely used shrinkage-compensating mortars do not always satisfy the above mentioned condition since the beneficial compressive stress in real structures is generally significantly lower than the stress value measured in lab tests.

These mortars have high compressive strength and elastic modulus, since they are produced with a large amount of cement. Consequently, 3-month unrestrained shrinkage for these mortars is higher than 1200 μm/m.

As a result of the high shrinkage and elastic modulus, high-strength shrinkage-compensating mortars experience tensile stress capable of promoting cracking of repair material.

Cracks are followed by a loss of bond of the mortar irremediably compromising the success of the repair work.

In order to avoid these problems, selection criteria of repair mortar must be based on tensile strength, on elastic modulus, on drying shrinkage, creep in tension and restrained expansion in real structures. Selection criterion based on the strength properties of the mortar ("*the higher the compressive strength the better the repair material*") is without any technical and scientific basis.

Keywords: Repair material, shrinkage-compensating mortar, drying shrinkage, creep, elastic modulus.

1. INTRODUCTION

Concrete is by far the material which is produced the most in the world. Calculations have in fact shown that each year about one ton of concrete is produced per inhabitant of the planet. There are many reasons for the success of this material including its low cost, easily obtainable ingredients to produce it, and the possibility of incorporating within it waste products from other industrial process. Furthermore, concrete, if well designed, can prove itself to be exceptionally durable with regards to harmful environmental conditions. However, the durability of the "*finished product*" i.e. concrete structures, not only depends on the quality of the mixture, but also on the design, on the constructive details, on the construction methods as well as on the placing, compaction and curing of the mixture on the job-site. Therefore, although it is possible to assert that, in the light of present technological and scientific knowledge, we can easily guarantee durable concrete for over 150 years, durability cannot be guaranteed for concrete structures which in service are subject to static and dynamic loads, weather and environmental effects and impulsive and abrasive actions.

The above-mentioned is indirectly confirmed by the growing incidence of failure in structures due to durability problems: moreover, every year, billions of Euro are spent for the maintenance and repair which is further proof of the existence of numerous unresolved problems regarding durability of real structures.

In recent years, the growing need to maintain and repair structures, has brought about a definite variation in the expenditure for restoration compared to the investment for new structures. It has been estimated that, at present, in Europe (and particularly in Italy) the investments in maintenance and repair work on old structures, represent about 50% of the total expenditure in construction (1). The expenditure for restoration, therefore, has nearly doubled compared to the last decade, when it was seen to be between 25-30% (2). Some estimates have indicated that in 2010 the expenditure for maintenance and repair work will represent about 85% of the total expenditure in the construction field (3). It has been forecast that, in the same year in the USA, 50 billion dollars will be spent for the restoration of deteriorated bridges and viaducts (4).

This information, therefore, indicates a marked increase in repair in recent years and that this trend is likely to continue: bearing in mind what is happening on the stock exchange, we could say that the refurbishing market paradoxically represents a kind of new economy within construction.

The rapid growth in restoration has undoubtedly greatly influenced the market for the products used in maintenance and repair of deteriorated structures, which has literally been inundated by new products. However, this explosion of new products has not only considerably complicated the selection of the most suitable material for the specific repair work, but has helped the circulation on to the market of products which are unsuitable for repair of reinforced concrete structures. The circulation of these products was possible due to the complete lack of norms indicating performance requirements of repair materials.

Without any norms indicating the properties of the products, the producers of repair mortars used different tests to evaluate the performance of their products. However, very often, these tests were arbitrarily modified, frequently showing unrealistic results which exacerbated the confusion of material selection.

The result of this confusion is represented by a series of unsuccessful repair (5-8) having used materials which mainly showed a lack of dimensional compatibility with the substrate represented by the old concrete structure.

The main aim of this paper is to analyse the reasons for these failures with particular reference to the restoration whereby shrinkage-compensating mortar was used. In the European market this mortar represented and still represents (except in Germany) the most widespread type of cementitious material used in repair of reinforced and prestressed concrete structures.

2. SHRINKAGE-COMPENSATING MORTARS

The aim of shrinkage-compensating mortar was to eliminate problems caused by dimensional incompatibility which exists between old concrete substrate and repair material. The reduced tensile strength of cementitious mortars, their low tensile strain and the stress caused by the inevitable restraints of dimensional variations of the restoration mortar, determine cracks in the repair material. These dimensional variations concern:

- elastic strain;
- creep;
- thermal strain;
- drying shrinkage.

Among the above mentioned deformations the shrinkage represents that of major interest for the material used in restoration of reinforced concrete structures. Indeed, the main causes of early failure of repair works are represented by the strain-induced stress from restrained shrinkage. A thorough understanding of the mechanism that control and influence deformations and, hence, its crack resistance property is therefore necessary before selecting repair material.

In short, therefore, the choice of materials to be used in repair cannot be made - as currently happens - on the basis of a compressive strength criterion. On the contrary, the selection as will subsequently be shown, should be made on the basis of physical and elasto-mechanical characteristics that govern the crack resistance properties of the material, which are:

- hydraulic shrinkage;
- elastic modulus;
- coefficient of thermal expansion;

- creep;
- tensile strength;
- bond.

A repair material should be characterized by a reduced shrinkage, coefficient of thermal expansion and elastic modulus equal to or less than those of the concrete substrate, high tensile strength and bond. Concerning creep it is necessary to use a material with a low creep in compression strain but characterized by a high value of creep in tension.

In order to clarify the influence of the above mentioned parameters on strains in a structure which has undergone repair, two cases, which currently occur, will be analysed.

Figure 1 illustrates a column which has been entirely rebuilt using traditional concrete (not shrinkage compensating material) immediately after the removal of shoring and of the mould. After some time, for instance 6 months, the column, due to shrinkage and creep of the concrete, (if it were free to shrink) would undergo shortening. These effects do not involve the adjacent unrepaired columns. However, shrinkage and creep cannot freely occur as they are restrained by the beam that connects the columns. The result of this restraint is represented by the relaxation of the compressive stress, that is a reduction of the compressive load on the repaired column, a part of which would be conveyed towards the other structural elements (Fig. 2).

If the repair work does not affect the whole structural element, but only a limited part of the column (Fig. 3), the compressive load can be considered uniformly distributed in the whole section immediately after the hardening of the repair mortar. Due to the restraint exerted by the substrate and reinforcements on creep and shrinkage of the mortar used for repair, in the initial stage there will be a relaxation of the compressive stress on the portion of the restored column (Fig. 4). Following this relaxation, the concrete of the substrate will be subjected to a higher compressive stress. After this first stage a further restrained shrinkage will determine tensile stress (Fig. 5) in the repair mortar. Tensile elastic stress can be mitigated by the creep (9) in tension (Fig. 6), but when the actual tensile stress is higher than the tensile strength of the mortar, it will crack with a loss of bond from the substrate (Fig. 7). This situation occurs when a common cementitious mortar manufactured with water, cement and sand is used.

In order to solve these problems, shrinkage-compensating mortars have been used for a long time in repair work (10). These prepacked mortars contain, as well as the normal ingredients (water, cement, sand), water reducers, silica fume and expansive agents (11).

The latter represents a type of material based on CaO or on $C_4A_3\overline{S}$ which are capable of expanding in the presence of water in the period of time from the final setting of the cement material and seven days from mixing. At the end of the expansion process, the shrinkage-compensating material exposed to a dry environment (R.H.<95%) shrinks in the same way as a normal cementitious mortar with an equal water/cement and aggregate-cement ratio.

The use of shrinkage-compensating mortar is based on the restraint to the potential expansion caused by the increase in volume of expansive agent (Fig. 8). If the concrete substrate and reinforcements, are able to restrain the expansion from occuring, the repair material will accumulate compressive stress (Fig. 8).

The strain-induced compressive stress from expansion will relax due to restrained shrinkage of the mortar exposed to a dry environment (Fig. 9). Therefore, in order to avoid problems that normally arise in normal cementitious mortars, it is necessary to meet the following inequality:

$$\sigma_c + R_t > \sigma_t \qquad [1]$$

where:

- R_t is the tensile strength of the repair mortar;
- s_c is the strain-induced compressive stress from expansion;
- s_t is the strain-induced tensile stress from drying shrinkage.

An accurate examination of the above mentioned inequality can prove difficult or indeed impossible, but above all and worse still, it can prove to be misleading, as will be clarified later, if we consider that the test results, used by the producers of these materials to determine σ_c and σ_t, are totally unrealistic compared to the values attainable in real structures.

In order to check the inequality [1], one has to quantify s_c and s_t as well as the tensile strength. For the latter properties, procedures provided in Italian and foreign norms can be used, by testing specimens cured for 1, 3, 7 and 28 days.

The data obtained in the early ages (1-7 days) will be used to check [1] when shoring is removed and the repair mortar is exposed to a dry environment, whereas the 28-day tensile strength can be used for long term analysis.

3. STRAIN-INDUCED STRESS FROM EXPANSION

Regarding the evaluation of the strain-induced stress from the expansive agent, a restrained expansion test is carried out (according to the Italian norm UNI 8147) on a prismatic specimen (Fig. 10) of 50x50x250 mm dimensions (76x76x254 mm according to ASTM C878) reinforced in the centre with a 6 mm diameter bar (5 mm in ASTM norm) which is demoulded and submerged into a lime-satured aqueous solution 8 hours after mixing.

The evaluation of the strain-induced stress is carried out by measuring the elongation of the steel bar (e_s). The tensile stress of the steel bar must equal the compressive stress in the mortar:

$$\varepsilon_s = \frac{\sigma_c A_m}{E_s A_s} \qquad [2]$$

where:

A_s and A_m are the steel and cement mortar area, respectively, and E_s[*] is the elastic modulus of the steel.

It is important to highlight that the evaluation of the strain-induced compressive stress must necessarily be carried out by means of a restrained expansion test and not by a free expansion test. In fact, in order to achieve successful repair, it is not the expansion itself that is important, but the strain-induced compressive stress in the mortar. This strain-induced stress strongly depends on the extent of the free expansion, but it is also closely influenced by the elastic modulus, the creep, and the mortar/steel bond when the expansion takes place. This means, for example, that for the same free expansion, mortar with a low elastic modulus and a reduced steel/concrete bond will accumulate a lower strain-induced stress than a more rigid-cementitious matrix. The restrained expansion test, therefore, quantifies the strain induced stress considering:

- the type and the amount of expansive agent in repair mortar;
- the restraint exerted by the steel bar and plate;
- the bond between steel and cement matrix, and the elastic modulus of repair material.

The strain-induced stress when the restrained expansion is 300 μm/m or 900 μm/m is equal to 0.5 N/mm^2 and 1.5 N/mm^2, respectively.

This stress is estimated in ideal, but unrealistic laboratory conditions which are very different to those existing in real structures. The actual strain-induced stress in the structure, in fact, depends on:

- the thickness of repair mortar;
- the surface preparation;
- the percentage of reinforcement and its location;
- the type and amount of expansive agent;
- the storage conditions of bags containing prepacked material;
- the degree of saturation in the concrete substrate;
- the placement methods;
- the curing conditions of repair material.

An analysis of how some of these parameters can significantly modify the results in terms of strain-induced stress from expansion, will follow.

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[*] In specimens manufactured according to the Italian Norm UNI 8147: A_s = 19.63 mm^2; A_c = 2480.37 mm^2; E_s = 210000 N/mm^2.

3.1 Storage of bags containing the prepacked mortar.

The use of bags which are not perfectly impermeable - and/or not properly stored can promote the expansion of the agent in the bag, for instance, due to the transformation of calcium oxide into hydroxide because of the humidity present. Fig. 11 shows the reduction of the restrained expansion values in 6 prepacked products stored for 3 months at 20°C and R.H. 70%.

With the exception of only 2 of the mortars analysed, the other 4 showed a significant reduction in restrained expansion that for prepacked products A exceeded 80%.

3.2 Curing conditions of repair mortar

The evaluation of the restrained expansion in the laboratory is carried out by submerging the mortar samples in $Ca(OH)_2$ saturated aqueous solution. This represents the ideal situation which corresponds to the maximum attainable expansion: the expansion in fact, is promoted by the reaction of the expansive agent with water. However, the lab test conditions are substantially different to those found on the job site, and especially in the repair work of vertical structures which require spraying of the repair material, since wet curing is rarely carried out. The consequence of a lack of a wet protection of the repair mortar is represented by a lower restrained expansion and therefore by a lesser strain-induced compressive stress in the repaired structure.

Fig. 12 shows data concerning restrained expansion for the same shrinkage-compensating mortar cured in different conditions during the 7 days following the placing. As can be observed, without any protection, the shrinkage-compensating mortar possesses a restrained expansion which is equal to about 1/20 of the maximum value obtainable with a wet curing of the surfaces. The use of a plastic membrane or of a curing agent results in restrained expansion values which are sufficiently high, although they are lower than those obtained with a wet protection of surfaces.

3.3 Placement methods

Among the parameters that influence expansion, one must include the mortar/steel bond which depends on the placement method of repair material. Generally, casting results in a more homogeneous mortar, with a smaller amount of macro-defects and voids compared to hand-applied or sprayed mortar. Fig. 13 shows the values of the restrained expansion using spraying, casting or hand-applied placement methods for the same shrinkage-compensating mortar. As can be seen the mortar placed by casting gives the maximum expansion; lower values are obtained for sprayed or hand-applied mortar.

3.4 Surface preparation, thickness of repair material, percentage and location of reinforcements

The restrained expansion measured in the laboratory with the procedure suggested by norm UNI 8147 could be substantially different from the values in service, if in the real structure the restraint of the volume increase is not as effective as the one obtained in the lab specimen. In the laboratory tests, in fact, the mortar expansion is conveyed entirely from the terminal steel plates onto the central bar (Fig. 14), thus guaranteeing the compressive stress on the whole section of the mortar specimen.

However, in a real structure, the strain-induced compressive stress depends on:

- surface preparation;
- thickness of repair mortar;
- presence of reinforcements.

It is obvious that the quantification of the influence of these parameters on the extent of expansion is a rather difficult or improbable operation. However, one can estimate that without reinforcements (Fig. 15a) the compressive stress in the repair mortar attains maximum value at the interface with the substrate and will tend to decrease in the further sections until disappearing completely when the thickness of the repair material becomes consistant. For mortar thickness exceeding 3 cm the compressive stress cannot be guaranteed merely by the restraint exerted by the mortar/substrate bond. In this case, the use of reinforcements in the form of a mesh ϕ_4 or ϕ_5/50mm is required. The mesh must be kept away from the concrete substrate in order to restrain the mortar expansion in the sections which do not benefit adequately from the restraint exerted by the substrate (Fig. 15 B).

It is also difficult to evaluate the influence of the surface preparation on the strain-induced compressive stress in the repair mortar. However, it can be affirmed that the restrained expansion is more effective when the substrate is prepared by water-jet (12) rather than sandblasting or using a jack-hammer (Fig. 16).

3.5 Conclusion on strain induced compressive stress from expansion

To sum up, it can clearly be seen that the achievement of a beneficial compressive stress in real structures heavily depends on a series of operations, including the correct storage of bags of prepacked products, the surface preparation, the correct positioning of the restrained reinforcements, the placement method, and the curing of shrinkage-compensating mortar.

If even only one of these operations is not carried out correctly, the strain-induced compressive stress can undergo a drastic decrease to a point of total annulment.

4. SHRINKAGE IN PREPACKED MORTAR WITH THE EXPANSIVE AGENT

Shrinkage-compensating mortar exposed to a dry environment, shrinks in the same way as a normal cementitious mortar - without the expansive agent - due to the evaporation of water from the cement matrix to the external environment. Because of shrinkage restrained by the substrate and reinforcements, the repair mortar is subjected to a relaxation of the initial compressive stress induced by the expansion. If the restrained shrinkage is considerably higher, the repair material will accumulate a tensile stress. When this tensile stress exceeds the tensile strength of repair mortar it will firstly determine cracks and subsequently will cause the debonding from the concrete substrate.

The relaxation of the compressive stress directly depends on the extent of the hydraulic shrinkage. It would be more accurate to highlight that this relaxation is related to the restrained shrinkage as the repair mortar is stretched with a strain equal to:

$$\varepsilon = S_{UN} - S_R \qquad [3]$$

when:

S_{UN} and S_R represent the free and the restrained shrinkage of the repair mortar, respectively.

The corresponding tensile stress is not immediately calculable, as it depends on the type of restraint (substrate or reinforcement) as well as the creep in tension of the cementitious material. In the event of a restraint of shrinkage exerted only by a symmetrical reinforcement, it can easily be shown that the tensile strength (σ_t) equals:

$$\sigma_t = E_f \cdot \mu \cdot S_{UN} \cdot \frac{1}{1+n\mu} = E_f \cdot \mu \cdot S_R \qquad [4]$$

when : m is the geometric percentage of the reinforcement;
E_s is the steel elastic modulus;
n is the ratio between the steel elastic modulus (E_s) and the concrete tensile modulus (E_{ct}) reduced considering creep.

If the restraint is exerted only by the bond at the interface substrate/mortar, calculation of strain-induced tensile stress from shrinkage would be much more complicated considering that definite information about the degree of restraint exerted by the substrate is not available.

On this subject an accurate estimation of the restrained shrinkage using one of the tests available in technical literature, for example the Ring Test (13), or the German Angle Test (14), could provide useful indications on the tendency of the mortar to crack.

Considering the lack of available results on restrained shrinkage, as well as the inevitable perplexity as to which measuring method would most accurately reproduce the situation found on real structures, and, given that the induced tensile stress in repair material, as highlighted earlier, depends only on restrained shrinkage, one can safely suppose that:

- the total free shrinkage of mortar is restrained(S_{UN});
- the relaxation of compressive stress depends directly on the instantaneous elastic modulus of the mortar;
- the tensile stress induced by restrained shrinkage decreases as the creep in tension increases.

To conclude, one can overcome the difficulty of estimating the tensile stress taking into account not only the unrestrained shrinkage but also instantaneous elastic modulus and the creep of repair mortar.

4.1 Unrestrained shrinkage

A survey of a technical data sheet of proprietary products used in repair shows the total lack of information regarding drying shrinkage of expansive mortars. Therefore, tests have been carried out on unrestrained shrinkage of 6 repair mortars, using procedures suggested in Italian norm UNI 6687. Figure 17 shows the 180-days hydraulic shrinkage (T=20°C, R.H. 50%), and 28-day compressive strength (T=20°C, R.H. 95%). As can be seen, nearly all the mortars analysed show a shrinkage which is over 1200 µm/m, with exception of mortar F where shrinkage is about 800 µm/m.

The analysed mortars show a compressive strength at 28 days higher than 65 N/mm^2.These mortars have been used mostly for repair work since the beginning of the 80s - and unfortunately still today - because generally the criterion adopted for the selection of repair material is based purely on the compressive strength requirement: the higher the compressive strength of the mortar, the better the repair work!!! The high values of compressive strength attained by these mortars come directly from the high percentage of binding material (cement and silica fume). It is easy to determine the cement factor of prepacked products which in most cases is higher than 600 kg per m^3 of mortar (Fig. 18). Therefore, although these repair mortars have low reduced water/cement ratio, their aggregate/cement ratio is lower and, hence, they experience higher hydraulic shrinkage. On the contrary the mortar F, is characterized by a lower amount of cement, higher aggregate/binder ratio and a decidedly lower shrinkage (800 µm/m).

4.2 Elastic modulus and creep

The considerable hydraulic shrinkage is not the only negative consequence that comes from the use of high strength mortars. In fact, high compressive strength generally corresponds to an equally high elastic modulus of the mortar (E). In fact, it depends on the same parameters that influence compressive strength, i.e. the water/cement, the type of cement and curing time.

Figure 19 shows the elastic modulus for six prepacked mortars: the values for all the mortars resulted over 28000 N/mm^2 with the exception of mortar F having an elastic modulus of 24000 N/mm^2.

In short, high strength mortars present two negative aspects: considerable shrinkage and high elastic modulus; both of these aspects determine an increase of the tensile stress of repair mortar.

Unfortunately, the information relative to creep is rather limited. However, it can be said that in similar conditions, a greater creep in tension in the repair material can alleviate the strain-induced tensile stress from shrinkage.

5. SELECTION CRITERIA FOR SHRINKAGE COMPENSATING MORTARS

From the information expanded in previous paragraphs it can be concluded that the selection of shrinkage-compensating mortars must be made on the basis of the physical and elasto-mechanical requirements that allow for the reduction of stress induced by the restrained shrinkage. To sum up, the choice must be directed towards the materials which offer more guarantees in terms of:

- maximization of compressive stress produced by the volume increase of the expansive agent;
- minimization of tensile stress generated by restrained shrinkage.

The analysis carried out in earlier paragraphs have highlighted how high strength expansive mortars do not offer the guarantees for a successful repair since they have:

- an excessive dependancy of the strain-induced compressive stress from expansion of existing conditions on site and in particular on the methods used for curing;
- an excessive amount of binding material compared to the aggregates with consequent high hydraulic shrinkage;
- elastic modulus considerably higher that intensify the tensile stress induced from the restrained shrinkage.

The result of the use of these mortars often consisted in failure of repaired structures characterized by extended crack patterns and debonding of repair mortar from concrete substrate (Fig. 20-24).

In the light of what has been asserted, in Table 1, you will find the selection criteria for shrinkage-compensating mortars to be used in place of the "erroneous" criterion based only on the estimation of the compressive strength.

Performances in Table 1 concern:

- the evaluation of restrained expansion both in water and in air. A minimum value in water equal to 400 μm/m at one day and a value from between 600 and 800 μm/m at 7 days are required. The above mentioned expansion should not exceed 900 μm/m at 28 days; the test should be carried out both on newly produced bags of the prepacked product and on dry material taken from bags that have been stored for 3 months in the open air at a temperature of 20°C and R.H. of 75%. The difference, in terms of restrained expansion between dry material taken from the newly produced bag and that stored for 3 months in bags should be less than 10%;
- the restrained expansion measured on specimens stored in open air (T=20°C and R.H. 75%) should result in at least 200 μm/m at 1 day and not less than zero at 7 days. This requirement is necessary in order to prevent the mortar from undergoing tensile stress in the first days due to shrinkage, before the mortar itself has attained sufficient tensile strength;
- the maximum value allowed for 3-month unrestrained shrinkage is 800 μm/m. This value can guarantee a successful repair only if the repair mortar has a 28-day tensile strength higher than 2.5 N/mm^2 and a 28-day elastic modulus lower than 25.000 N/mm^2. In particular, mortars characterized by a 3-month unrestrained shrinkage lower than 800 μm/m have shown cracks when its elastic modulus was over 25.000 N/mm^2;
- as can be observed, no requirements regarding compressive strength has been included as this property is not considered fundamental for a repair mortar.

Table 2 shows strain-induced stress values from both restrained expansion (s_c) and drying shrinkage (s_t) calculated for a shrinkage-compensating mortar at 1 and 28 days after the exposure to a dry environment.

Stress values were calculated for a repair mortar with a restrained expansion in water (corresponding to a wet-curing for real structures) equal to 400 μm/m. A lower value has been taken into account for real structures protected by a curing compound. No compressive stress is induced in structures without any protection.

Strain-induced tensile stress (σ_t) was calculated from a 3-month shrinkage equal to 800 μm/m restrained only by reinforcements.

Table 2 shows s_t values lower than σ_c plus the tensile strength of the shrinkage-compensating mortar (R_t). Calculations, therefore, seem to confirm indirectly the excellent behaviour shown, by mortars meeting requirements in Table 2 in different repair works.

6. CONCLUSIONS

Properties of shrinkage-compensating mortars for repair work are analysed. Analysis has highlighted how, to achieve successful repair of deteriorated concrete structures, stress from expansion plus tensile strength of the mortar in real concrete structures must be higher than the tensile stress promoted by restrained shrinkage.

The most widely used shrinkage-compensating mortars do not always satisfy this condition due to the reduced value of the beneficial strain-induced compressive stress in real structures compared the stress value measured in laboratory tests. Moreover, these mortars have high compressive and elastic modulus, since they are produced with a large amount of binder. Consequently, 3-month unrestrained shrinkage for these mortars is generally higher than 1200 µm/m.

As a result of the high shrinkage and elastic modulus, the tensile stress in repair material increases. Consequently cracks occur followed by a loss of bond of the substrate compromising irremediably the success of repair work. The present paper provides the selection criteria for shrinkage-compensating mortars and explains why the criterion "the higher the compressive strength the better the repair material" is without any technical and scientific basis.

The correct selection of repair material must be based on the tensile strength, on the elastic modulus, on hydraulic shrinkage, on potential expansion and on the expansion actually attainable for the mortar in service.

The proposed criterion is obviously a starting point to evaluate the actual behaviour of shrinkage-compensating mortars for repair work. Further experimental research would be necessary to analyse deformational aspects of mortar, such as restrained shrinkage and creep in tension which have not been analysed thoroughly in this paper.

7. REFERENCES

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Table 1 - Performance characteristics for shrinkage-compensating mortars for repair work.

PERFORMANCE CRITERIA		1 DAY	7 DAYS	28 DAYS
• Restrained expansion (ASTM C878 or UNI 8147)	In water in air (R.H. 75%)	³0.04% ³0.02%	0.06-0.08% ³0.00%	£0.09%
• Reduction in restrained expansion measured on prepacked material stored 3 months at T=20°C and R.H.=75%	in water	£10%	£10%	—
• Tensile strength (N/mm^2)		1.5	2.0	2.5
• 3-month unrestrained shrinkage (T=20°C; R.H.=50%)	£ 800 · 10^{-6}			
• 28-day elastic modulus	£ 25000 N/mm^2			
• Compressive strength	————			

Table 2 - Compressive and tensile stress induced in a shrinkage-compensating mortar that meets the requirements in Table 1.

CURING	1 DAY			BALANCE		28 DAYS			BALANCE	
	s_c	R_t	s_t			s_c	R_t	s_t		
WET	0.65	1.5	0.54	1.61	●	0.65	2.5	1.5	1.65	●
CURING COMPOUND	0.20	1.4	0.54	1.06	●	0.2	2.2	1.5	0.9	●
NO CURING (R.H.75%)	/	1.2	0.54	0.66	●	/	2.0	1.5	0.5	●

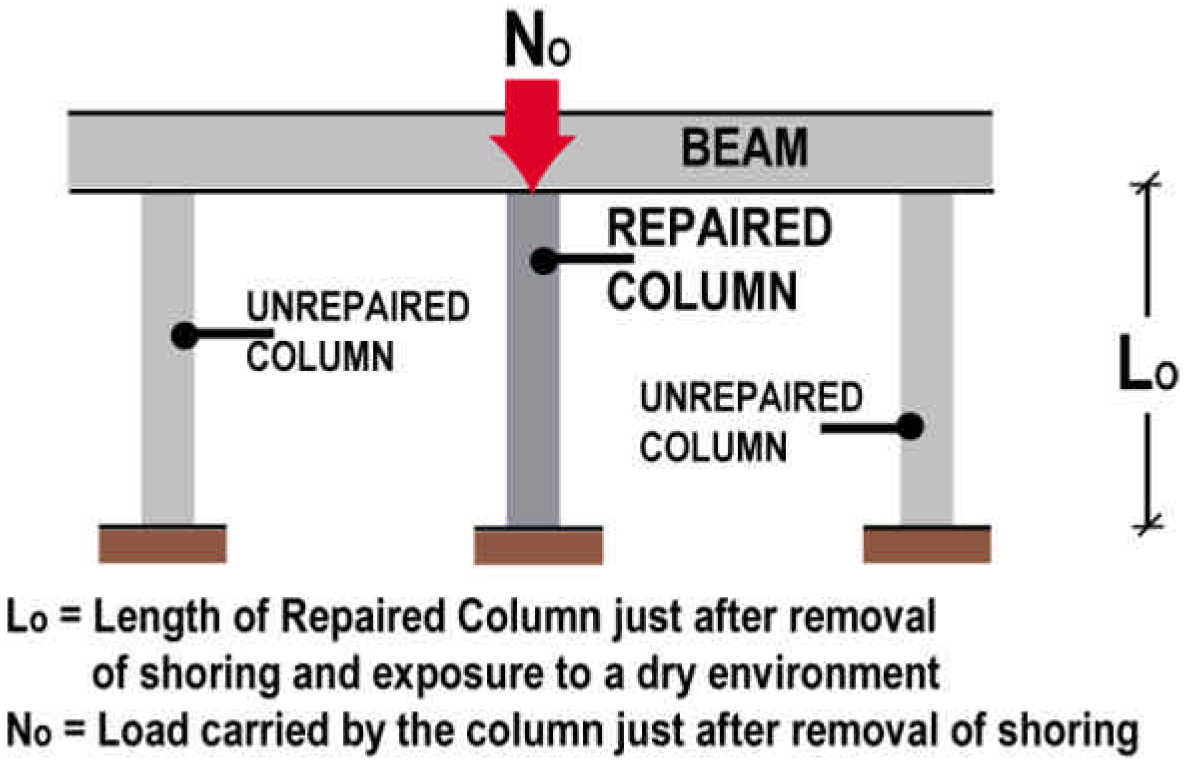


Figure 1 - Load (N_0) carried by the repaired column after removal of shoring.

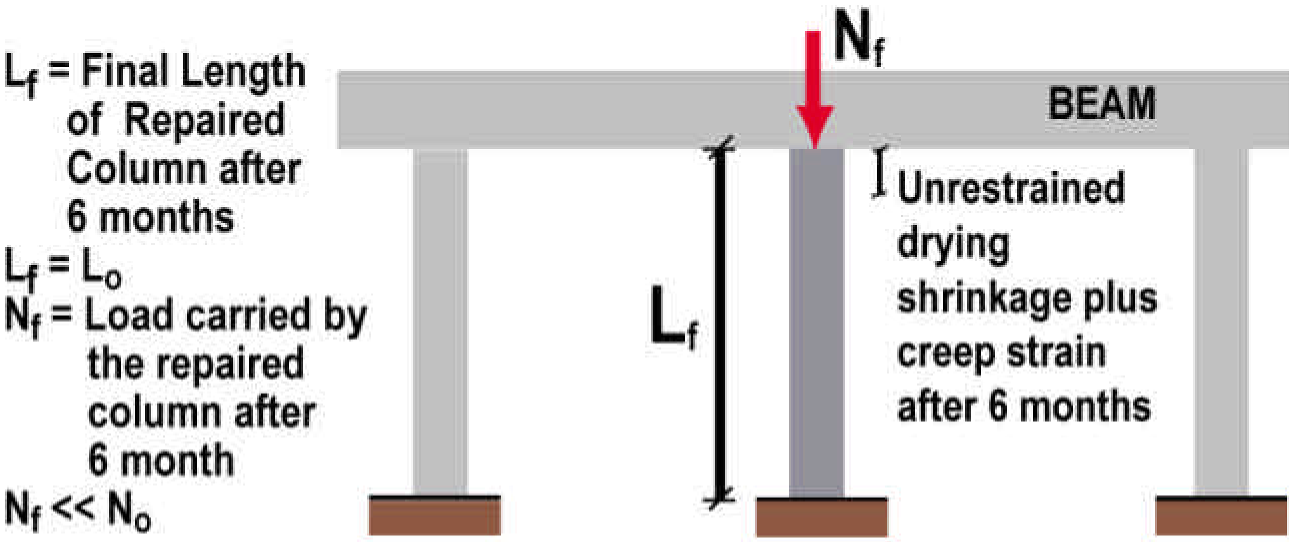


Figure 2 - Load ($N_f <<< N_0$) carried by the repaired column after six months: shrinkage and creep of the repair material restrained by the beam determine a reduction of the compressive load on the repaired column.

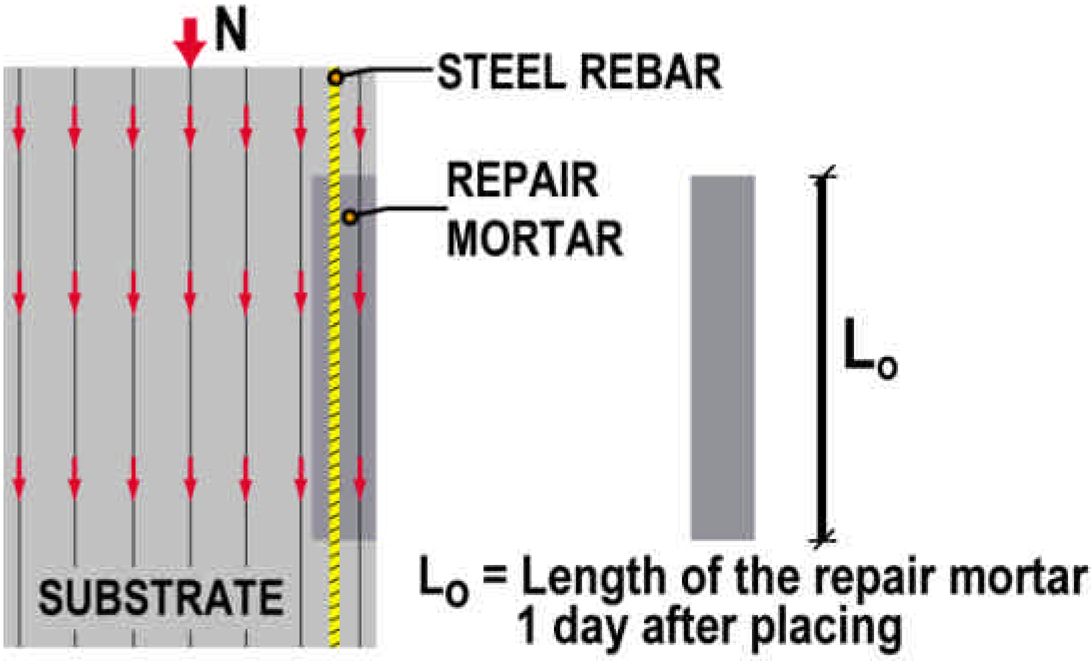


Figure 3 - Repair work affects a portion of the column. One day after placing the hardened repair mortar is exposed to a dry environment.

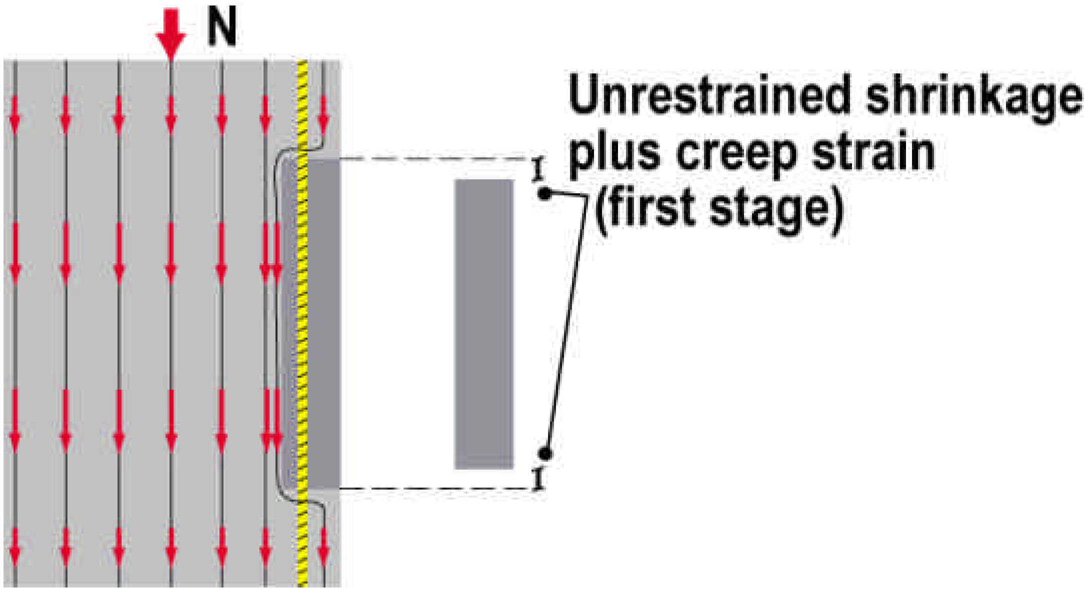


Figure 4 - Restraint exerted by the concrete substrate and the steel bar on creep and shrinkage of repair mortar promotes a relaxation of the compressive stress on the portion of the restored column (first stage).

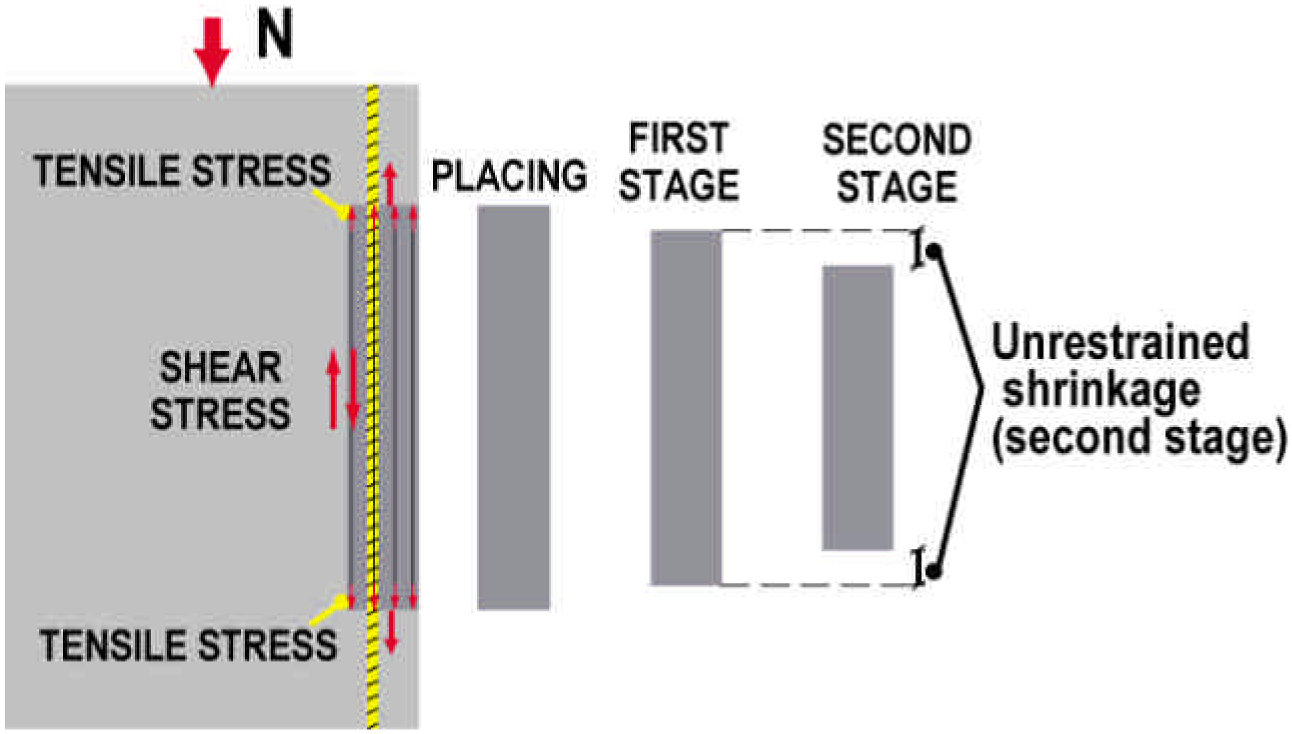


Figure 5 - Further restrained shrinkage induces tensile and shear stress in repair material (second stage).

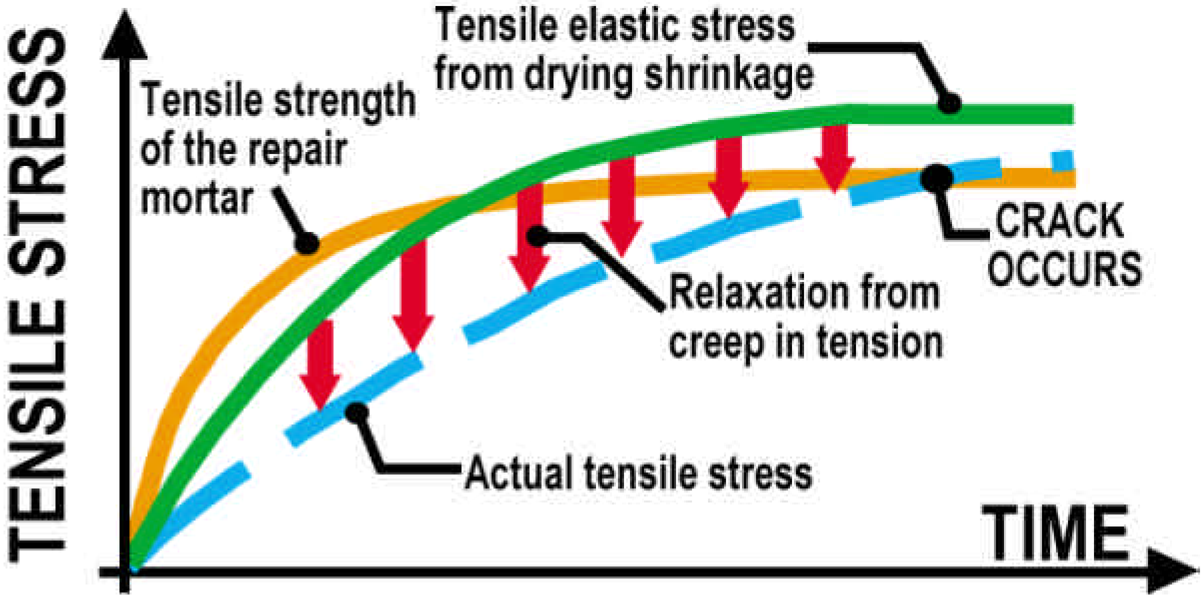


Figure 6 - Tensile elastic stress from drying shrinkage mitigated by creep in tension. Cracks occur when actual tensile stress is higher than the tensile strength of the repair mortar.

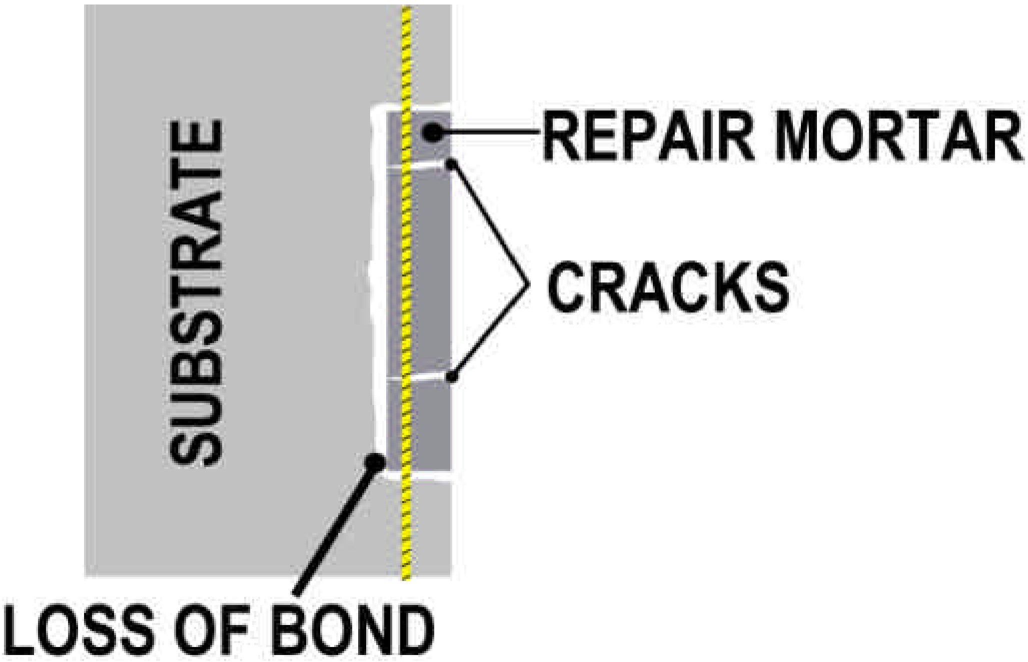


Figure 7 - Cracks in the repair material and debonding from the concrete substrate.

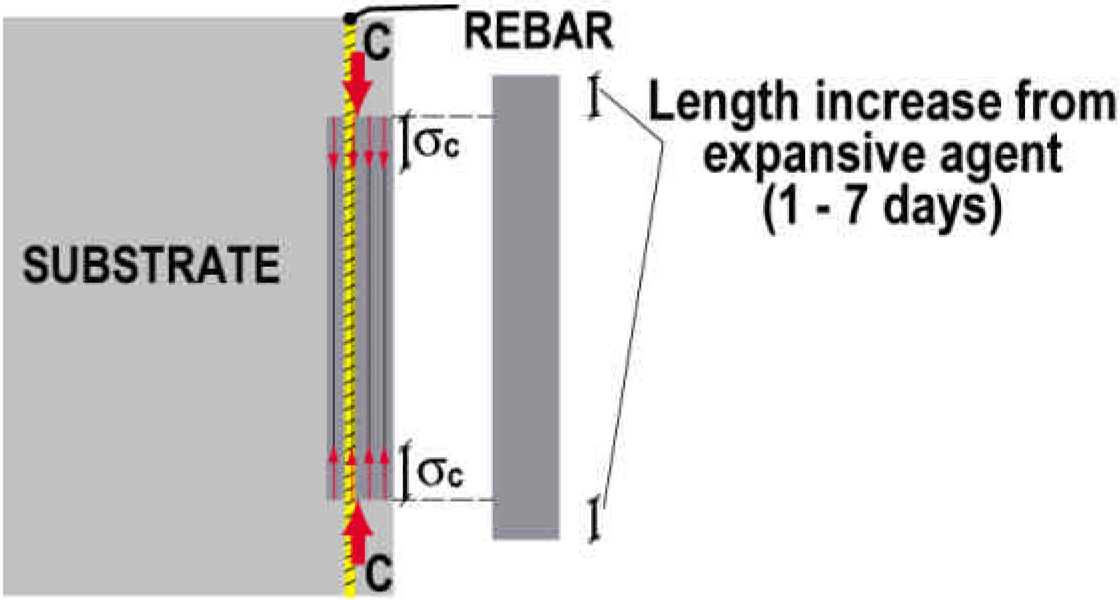


Figure 8 - Concrete substrate and reinforcements restrain the length increase of the repair material caused by the expansive agent. The repaired portion of the structure accumulates compressive stress.

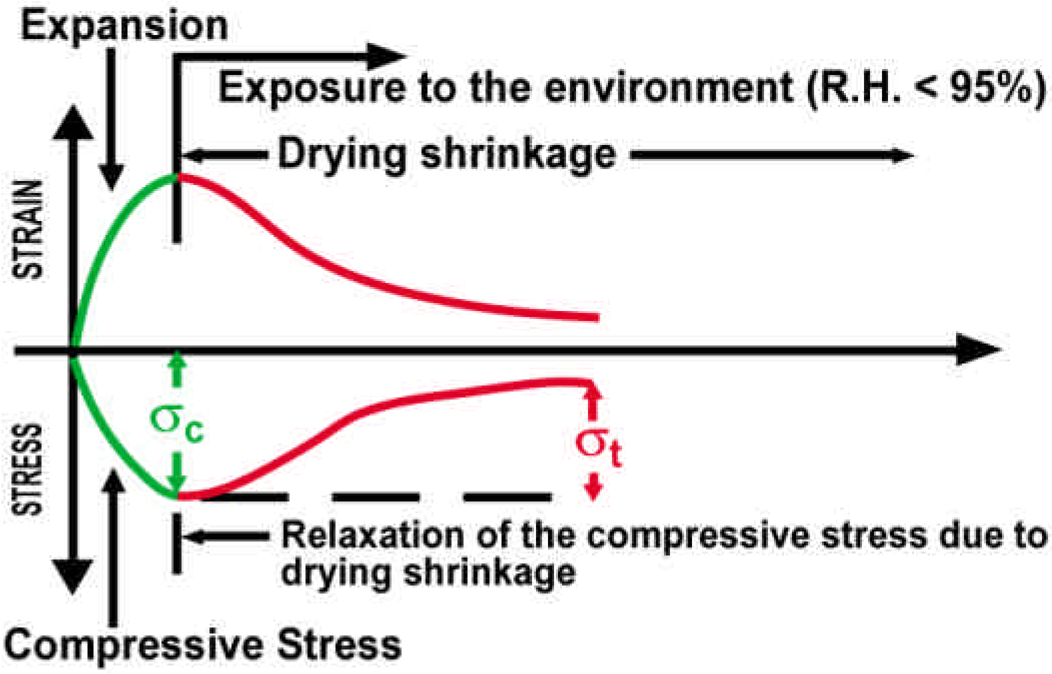
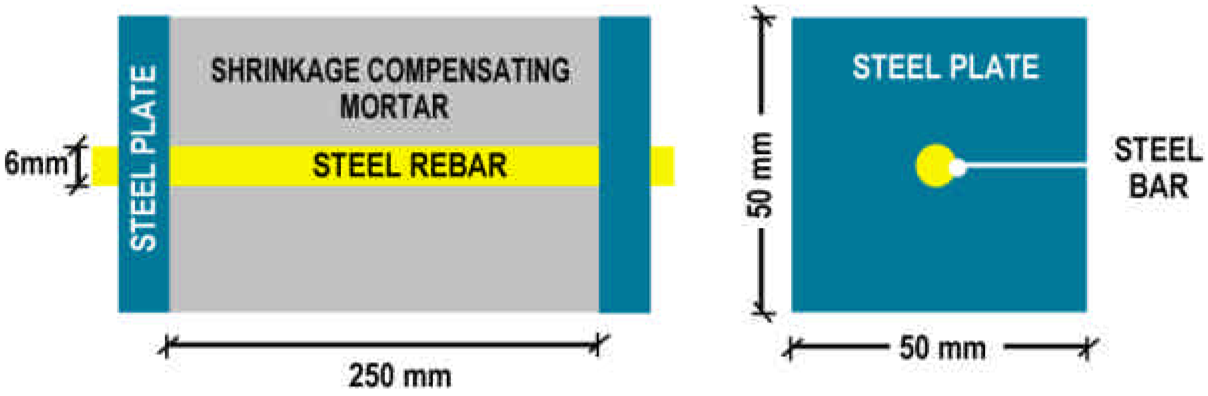


Figure 9 - Strain-induced compressive stress from expansion (s_c) relaxes due to the restraint of shrinkage exerted by the concrete substrate and the steel bar.



- TEMPERATURE : 20 °C
- SPECIMENS DEMOULDED AFTER 8 HOURS
- STORED IN A $Ca(OH)_2$ SATURATED AQUEOUS SOLUTION

Figure 10 - Restrained expansion: lab-test specimen according to Italian Norm (UNI 8147).

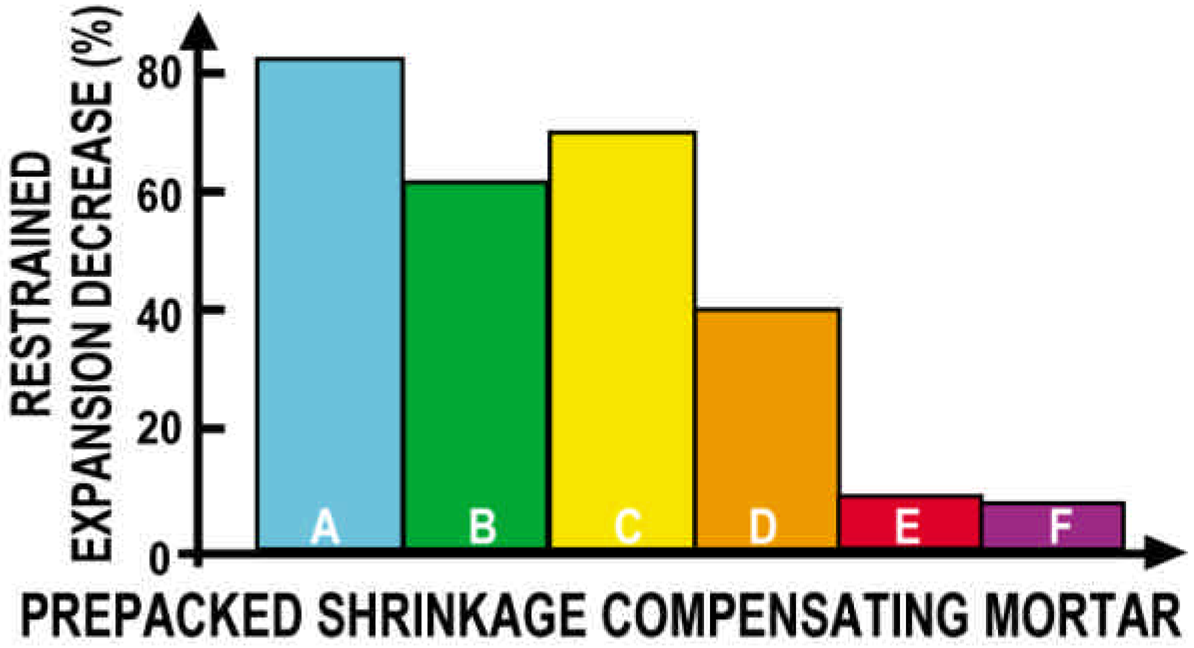


Figure 11 - Reduction in restrained expansion for six shrinkage-compensating mortars stored for 3 months at 20°C and R.H.=70%.

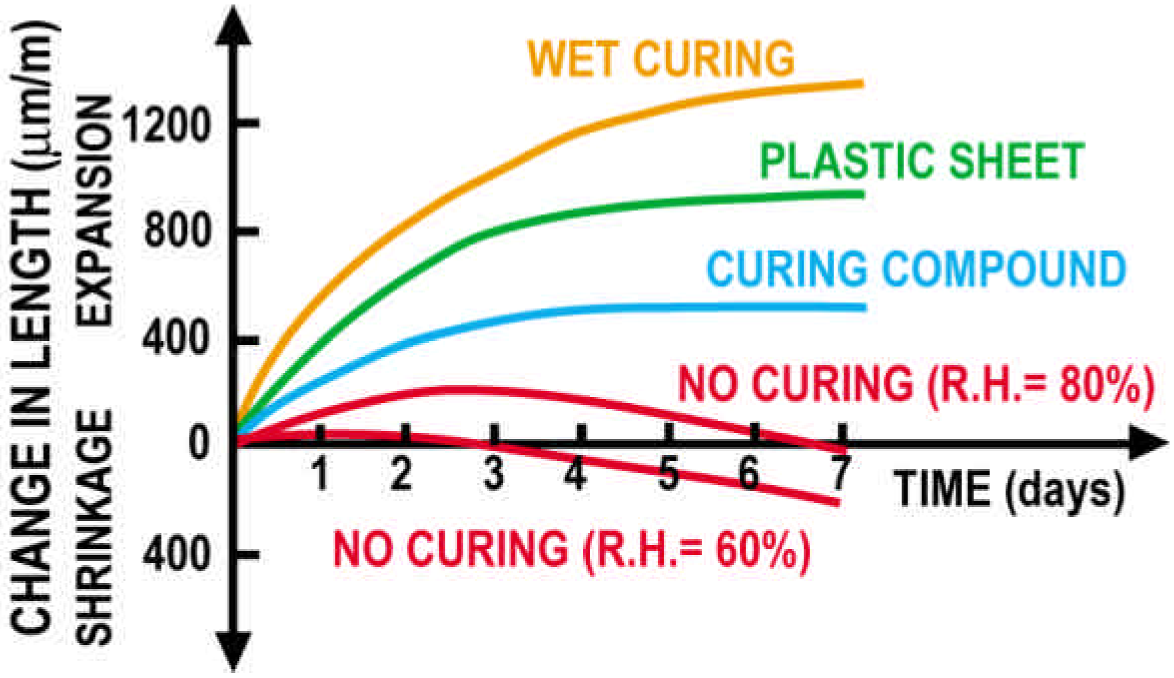


Figure 12 - Restrained expansion of a shrinkage-compensating mortar cured in different conditions during the 7 days following the placing.

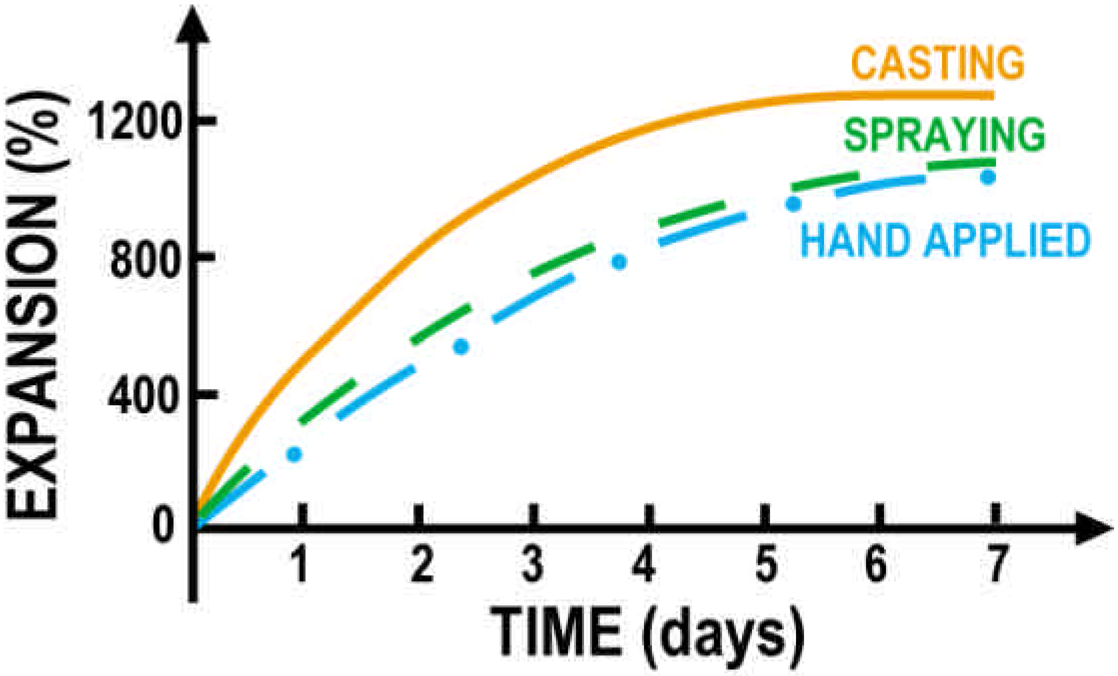


Figure 13 - Restrained expansion of a shrinkage-compensating mortar for different placement methods (casting, spraying or hand-applied).

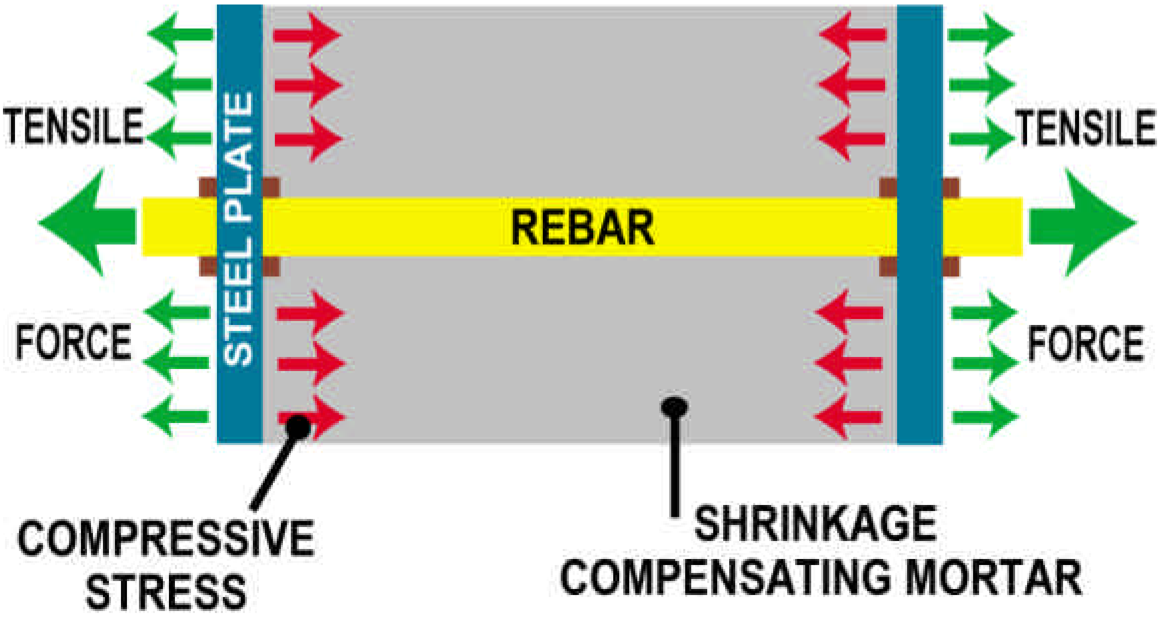


Figure 14 - Lab-test restrained expansion: volume increase of the expansive agent is conveyed entirely from the terminal steel plates onto the central steel rebar.

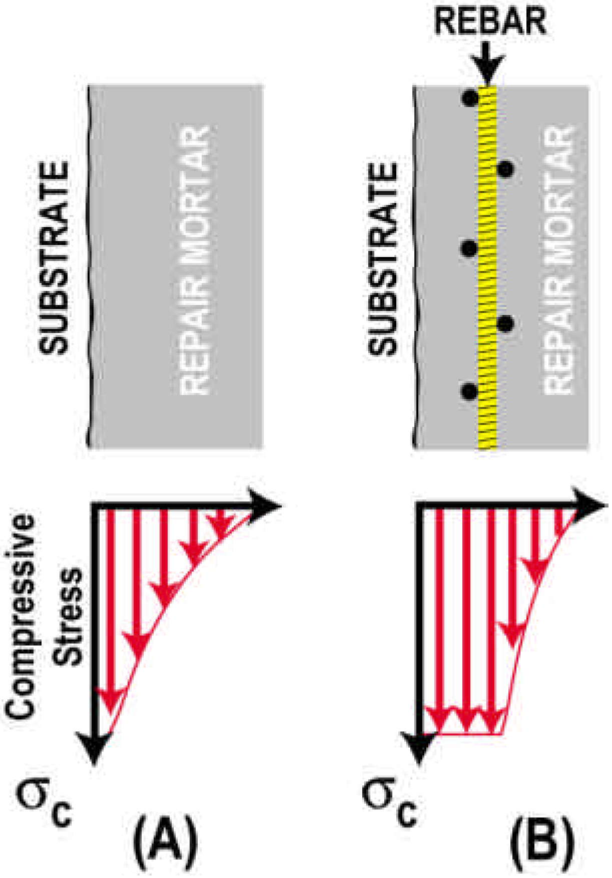


Figure 15 - Strain-induced stress from expansion restrained by the concrete substrate (A) or by the substrate and the steel bar (B).

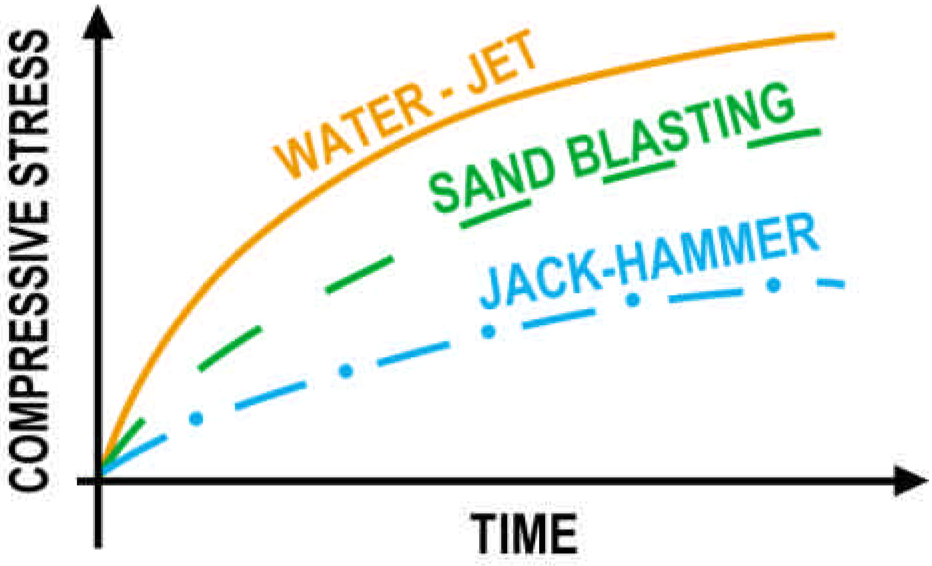


Figure 16 - Strain-induced compressive stress from expansion vs surface preparation.

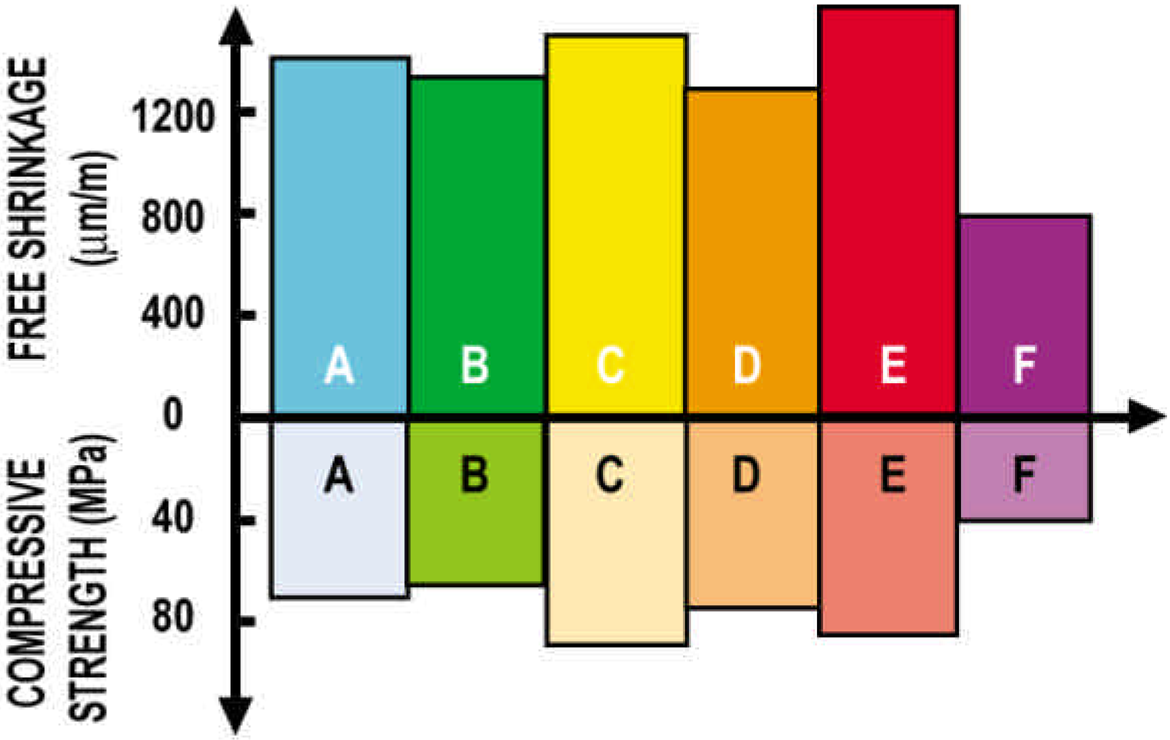


Figure 17 - 180-day unrestrained shrinkage and 28-day compressive strength for six shrinkage-compensating mortars.

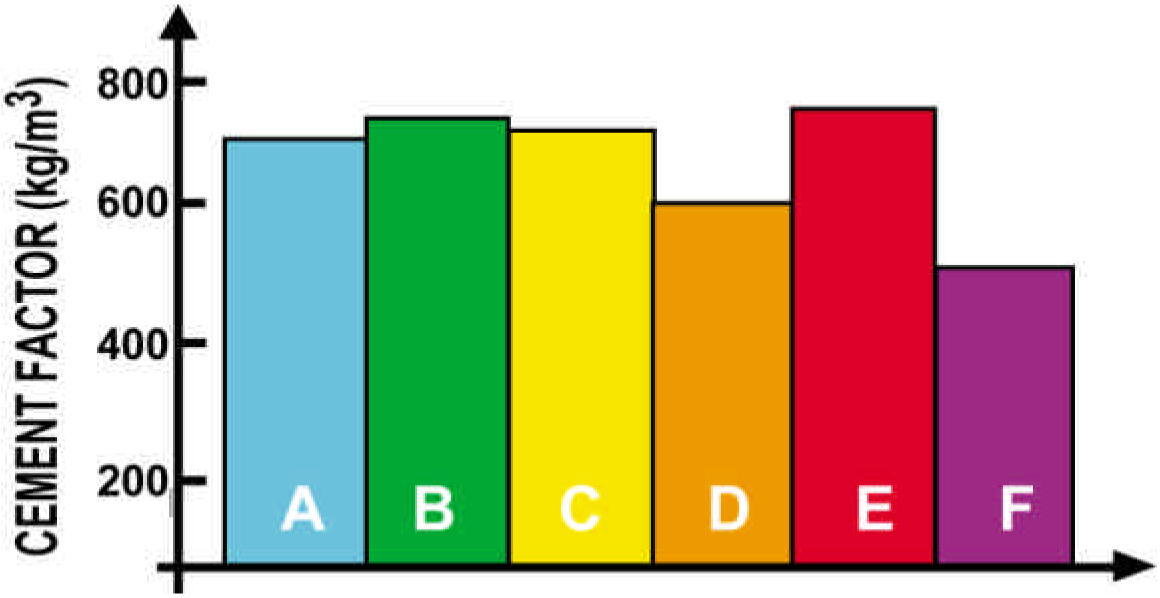


Figure 18 - Cement factor for six shrinkage-compensating mortars.

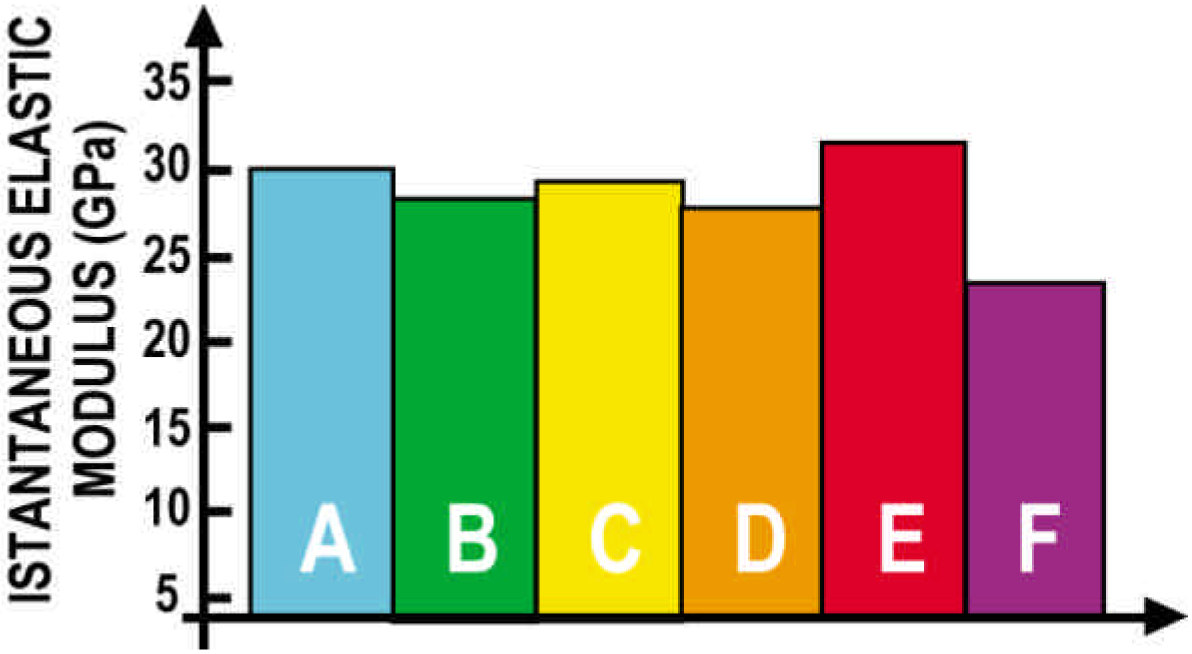


Figure 19 - 28-day elastic modulus for six shrinkage-compensating mortars.

Figure 20 - Crack patterns in a marine structure repaired (on the left) by using high strength shrinkage-compensating mortar.

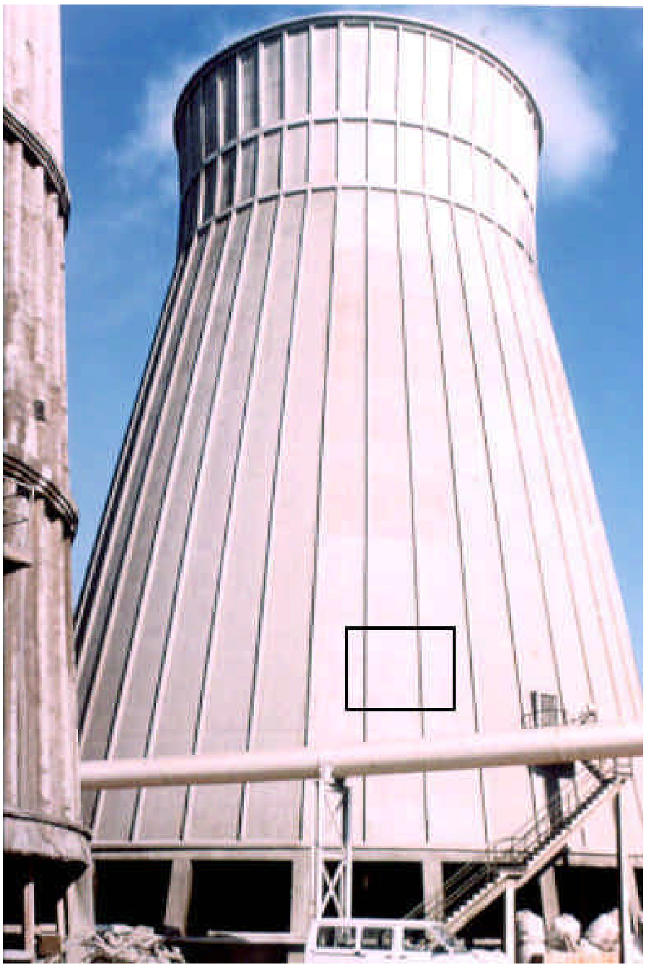


Figure 21 - Surface repair of a cooling tower: 1 year after placing of the shrinkage-compensating mortar.

Figure 22 - Cracks on the surface of the shrinkage-compensating mortar used in repairing cooling tower in Fig. 21.

Figure 23 - Cracks promoted by excessive strain-induced tensile stress from shrinkage in the surface of the cementitious material.

Figure 24 - Cracked enlargement manufactured with high-strength shrinkage-compensating mortar.