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PROGRESS IN THE TECHNOLOGY OF SHRINKAGE COMPENSATING REPAIRING MORTARS

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SUMMARY

The shrinkage compensating mortars for repairing works may present two drawbacks both caused by the absence of wet curing carried out by the contractor: cracks by plastic shrinkage and partial lost of potential expansion. These two drawbacks can be removed by using plastic fiber to reinforce the cement matrix and a water retention agent to keep the humidity into the mortar.

1. INTRODUCTION

Particularly in the last ten years, premixed shrinkage compensating mortars were used to repair and consolidate reinforced concrete and prestressed reinforced concrete structures.

The shrinkage compensation principle is based on the use of an expansive agent which is able to give rise to a phenomenon called expansion. The expansion is of opposite sign to shrinkage which normally takes place in all concretes exposed to moist unsaturated environments.

The mechanisms of shrinkage caused by hygrometrical variations are first examined and then the progresses in the shrinkage compensating mortars technology are analysed, with particular reference to the solutions of some practical problems in repair field.

1.1 Shrinkage and Crack

The drying of concrete and mortar causes a contraction known as "plastic shrinkage" and occurs when the concrete is still fresh and is in the setting phase [1]. "Hygrometric shrinkage" takes place after hardening of the concrete [2]. While plastic shrinkage occurs normally during the first hours of application, hygrometric shrinkage continues during the whole life of the structures, though its major part takes place fundamentally in the first months.

Both shrinkage phenomena, plastic and hygrometric, are the most frequent causes of cracks in concretes and mortars. In fact, if shrinkage is hampered by the presence of ties (for example the friction between a new repair mortar and the coarse foundation of an old concrete with an exhausted shrinkage), a tensile stress (σ_t) is established calculable by the well known Hooke's equation:

$$\sigma_t = E\varepsilon$$

where E is the modulus of elasticity of the mortar and ε is the shrinkage in the absence of ties.

If the stress generated σ_t is greater than the material tensile resistance (R_t), a crack is ensued (Fig. 1). It is worth precising that, under the same contraction value, the induced stress σ_t is greater the larger the modulus of elasticity. Consequently, with the same contraction value ε, the stress generated in plastic shrinkage is lower than in hygrometric shrinkage. On the other hand, even with moderate values of induced stresses, cracks in plastic shrinkage can be more intense than in hygrometric shrinkage because, before hardening, the tensile resistance, R_t, with which the concrete opposes the stress σ_t is almost nil.

1.2 Plastic shrinkage

To eliminate plastic shrinkage and its consequent cracks which usually occur during the first day, it is necessary to remove the cause which creates the shrinkage itself, that is the water evaporation. Effectively, plastic shrinkage does not manifest itself in mould-protected structures and in structures which are kept moist in the first twenty-four hours. In alternative, cracks caused by plastic shrinkage can be eliminated by consolidating the cementitious matrix with fine fibers (length ≈ 5-10 mm and thickness ≈ 0,01-0,02 mm) which are, generally, of polymers (polypropylene, polyacrylic, etc.). These fibers act by increasing the R_t value till it exceeds the σ_t value. In this case, the addition of the fibers eliminates the undesired consequences (cracks) of plastic shrinkage, but not the plastic shrinkage itself. In other words, while wet curing eliminates plastic shrinkage (ε) and so cancels the induced stress (σ_t), the addition of fine fibers, instead, increases the tensile resistance (R_t) up to values greater than σ_t, which, however, is not modified. It is

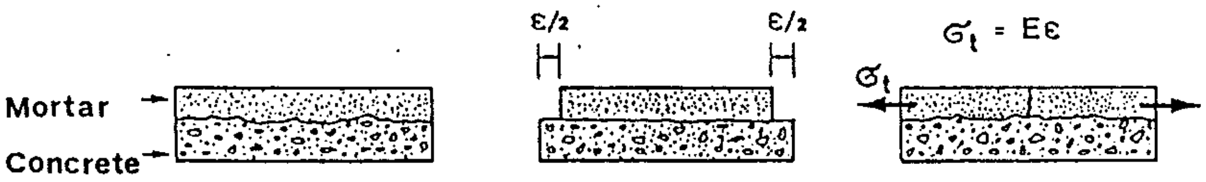

Fig. 1 - Application of a fresh mortar on an old concrete (A). By the effect of shrinkage, the mortar shortens by e if it can move with respect to the concrete in the absence of friction at the mortar-concrete interface (B). The mortar is cracked by the effect of the tensile stress s_t (caused by the hampered shrinkage) when s_t is higher than the mortar strength R_t (C).

evident that the use of fiber reinforced concrete is economically convenient to resolve cracks problem from plastic shrinkage, only for structures of moderate thickness, usually of some centimetres. Effectively the cost per unit surface, derived by the addition of fibers to the whole concrete mixture, increases proportionally with the structure thickness, for example a slab. On the contrary, the cost of evaporation protection per unit surface, whatever the method adopted (evaporating proof membranes, moulds, etc.), does not depend on the structure thickness. It follows that the use of polymer fibers is economically more convenient than evaporation protection usually only for plasters, having thickness not greater than some centimetres.

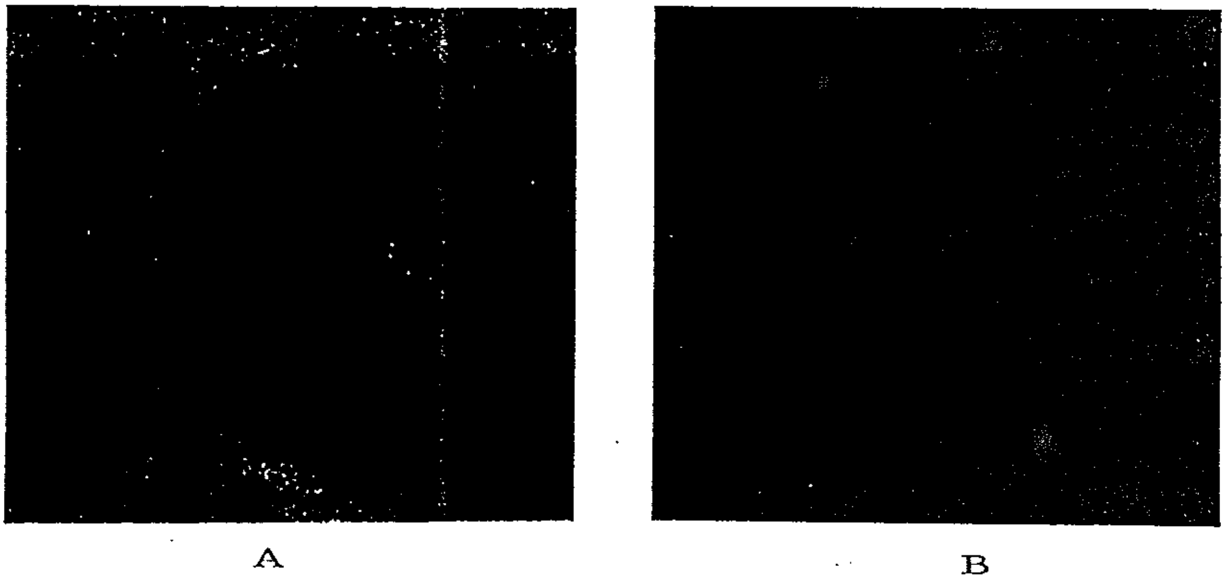

Fig. 2 - Concrete walls covered with mortar A without polymer fibers and cracked by plastic shrinkage, and mortar B with polymer fibers and not cracked.

Fig. 2 shows, as an example, two coatings of a deteriorated concrete wall, effectuated with two mortars both applied by spraying, trowelled and not wet-cured as often happens in the job-site's practice. Mortar A without fibers was cracked during the first twenty-four hours due to plastic shrinkage effect which has induced a stress σ_t greater than the mortar tensile resistance R_t. Mortar B, under the same hygrometric conditions (R.H 40%) was not cracked due to the presence of polymer fibers which have reinforced the cementitious matrix, in such a way, that R_t resulted greater than σ_t.

1.3 Hygrometric shrinkage

Concerning the hygrometric shrinkage, referred to simply as "shrinkage", evaporation protection is not feasible in practice because it would necessitate a very long time and theoretically it would coincide with the life of the structures. Obviously, the problem does not concern structures which, in moist environments,

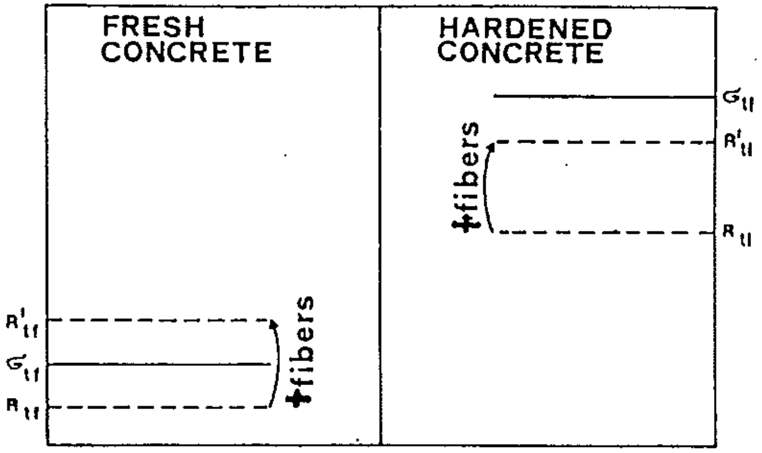

Fig. 3 - For a given shrinkage (e), the induced sti in hardened concrete is much higher than that generated in fresh concrete (s_{tf}). With fibers, R_{tf} becomes R'_{tf} (fresh concrete), and R_{ti} becomes R'_{ti}. In the first case cracks do not appear any more ($R'_{tf}>s_{tf}$); in the latter case cracks are not eliminated ($R'_{ti}<s_{ti}$).

do not undergo shrinkage since water evaporation from the concrete is prevented. Instead, shrinkage is unavoidable in structures exposed to humid unsaturated environments and particularly in those with high surface/volume ratio as in slabs and plasters. It can be minimized (for example by reducing both the water and the cement and by increasing the inert) but cannot be cancelled.

Unlike in plastic shrinkage, the use of polymer fibers in the case of hygrometric shrinkage does not permit, generally, the elimination of cracks. The reason for this different behaviour resides, as already mentioned, in the higher modulus of elasticity of the hardened concrete, to which the hygrometric shrinkage is referred. As a matter of fact cracking of either concrete or mortar by shrinkage effect depends on three factors: shrinkage (ε), modulus of elasticity (E) and tensile resistance (R_t). In plastic shrinkage, moderate tensile stresses are induced for the very low value of E. It is therefore sufficient, through the addition of polymer fibers, to increase slightly the R_t value of the cementitious matrix till it becomes greater than σ_t (Fig. 3). The advantage derived from the addition of polymer fibers, in the case of hygrometric shrinkage, is not sufficient to attain levels superior than σ_t, whose value is high for high value of the modulus of elasticity (Fig. 3). This, naturally, does not mean that the hardened concrete reinforced with fibers - especially steel fibers - does not show particular characteristics (ductility, tenacity, impact resistance), compared to ordinary concrete. The fact remains, however, that it is not possible, with fibers alone, to eliminate induced cracks from hygrometric

So, if the shrinkage reduction attained by the variation of composition is such that it is not acceptable, an alternative is to employ "expansive agents" to compensate it and to release or nullify its consequences. Typical examples of structures where expansive agents are used to produce shrinkage compensating mortars or concretes are reinforced concrete pavements and mortars for repairing deteriorated concrete structures. In these cases, the maximum shrinkage reduction only by means of the concrete composition modification is not sufficient, in general, to withdraw the drawback caused by shrinkage.

For example, in repairing old deteriorated concrete structures, it is convenient to add expansive agents to the mortar in order to avoid either the separation (segregation) at the mortar-concrete interface or the occurence of cracks by the hampered shrinkage effect in the repairing mortar. Fig. 1 schematically shows a freshly applied repairing mortar on an old concrete slab whose shrinkage has been worn out (Fig. 1A); if by the effect of hygrometric shrinkage the new mortar was free to move like in the absence of friction, the situation would be as illustrated in Fig. 1B. This situation would occur on application of the mortar on a very smooth concrete with minimum friction between the two materials. The final consequence would be a separation of the mortar by the effect of its movement with respect to the old concrete. The situation illustrated in Fig. 1C, really, occurs more frequently. The mortar would contract but cannot move freely, due to the presence of friction. Consequently a stress R_t is established which cracks the mortar itself.

2. THE PRINCIPLE OF SHRINKAGE COMPENSATING MORTAR

The shrinkage compensating mortar is based on the following principle: due to the reaction between the expansive agent and the water, the mortar increases in volume after the setting and during the hardening in the curing period. If the mortar is adequately contrasted by reinforcement steel bars, the expansion will cause a compression state in the mortar itself and a tensile state in the rebars in a similar way, though in a very reduced amount, to prestressed concrete. An alternative to reinforcement steels, as opposition to the expansion, could be the external contact with other concrete structures (for example the filling of a hole with shrinkage compensating mortar) or the friction between the coarse support of an old concrete and the new shrinkage compensating repairing mortar, as long as the thickness is limited (1 cm). The shrinkage thus caused, after the wet curing, during the drying of the mortar, simply reduces or cancels the compressive stresses accumulated in the mortar during the initial expansion (instead of inducing tensile stresses which can crack the mortar or cause its separation from the old concrete). Globally, the shrinkage compensating mortar behaves like a "spring", which is charged in the expansion period (wet curing) and is gradually discharged in the successive shrinkage phase (air-drying). The success of the shrinkage compensating mortar depends on an adequate charging of the spring, in order that tensile values which can break the "spring" itself are not reached in the successive discharge phase.

It is worth of note that, frequently, the shrinkage compensating mortar is improperly defined as a "shrinkageless" mortar or as a mortar with "volumetric stability". Effectively, any cementitious material loses humidity and shrinks in a dry environment. What could be done with the shrinkage compensating mortar is to generate an expansion (by a chemical reaction in a wet environment) and to transform it into a compression state (by means of a restraint) in order that the stresses induced from the successive inevitable shrinkage (in the period of dry air exposure) could be adequately compensated by the previous compression.

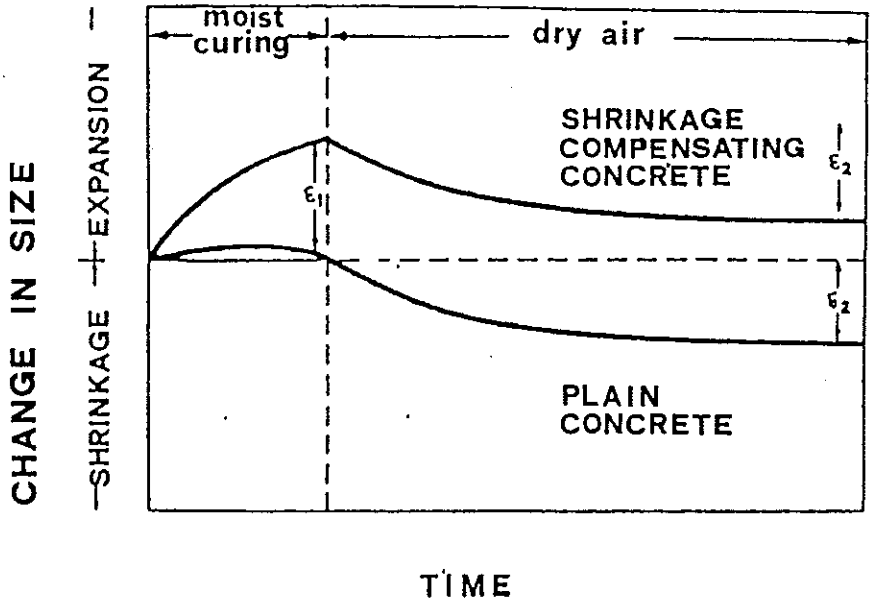

Fig. 4 - Change in length vs. time for plain concrete and shrinkage compensating concrete.

Fig. 4 schematically compares the "change in length vs. time" behaviour of a concrete with an expansive agent to that of a normal concrete. The latter remains stable, or slightly expands, as long as it is protected in the moulds or as long as it is kept wet. Afterwards, it shrinks progressively with time. The concrete with the expansive agent, instead, increases in volume in the wet curing period and undergoes shrinkage on exposure to air. If the two concretes differ only by the presence of the expansive agent, the shrinkage of the shrinkage compensating concrete (recorded from the moment of exposure to air) will be equal to that of the normal concrete. In order that the "strain-time" curve of the concrete with the expansive agent remains, without a net final shrinkage, above the zero-point, it is necessary that the expansion (ε_i) developped during the wet curing is higher than the shrinkage (ε_i).

3. DEFINITION OF EXPANSIVE AGENTS

Expansive agent is defined as a product which causes an increase in volume when reacts with water or with other products eventually present in the cementitious paste. Expansive agents can be divided into two classes (4). Those which cause an increase in volume, only when the concrete is in the plastic state and those which expand even when the concrete is already in the hardened state and has already adhered to the reinforcement steels. Only the second category can be advantageously used in the shrinkage compensating mortars.

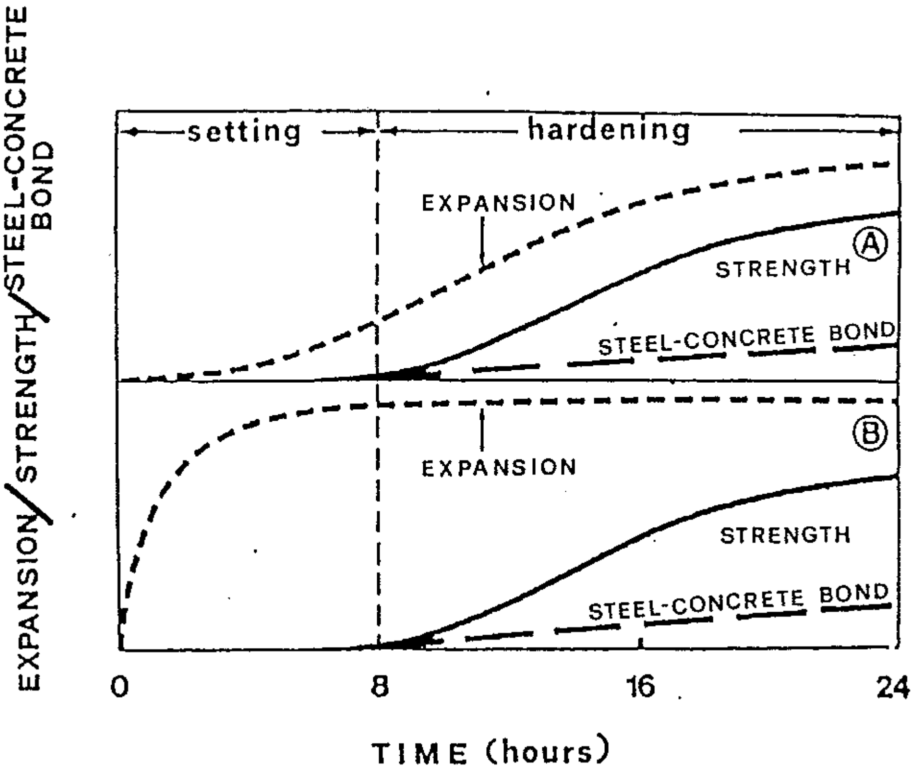

Fig. 5 - Expansion, strength and steel-conrete bond adherence trend for expansive concretes both during setting and hardening (A) and during setting only (B).

Their different behaviour is illustrated in Fig. 5. Zone A shows that the expansion of the concrete begins in the setting period and continues even in the hardening period (when the strength and the steel-concrete bond begin to proceed together at the same rate); the useful part of the expansive process is exactly that one left after the setting period when the concrete is able to adhere to the steels bars.

Zone B of Fig. 5 shows the behaviour of the concrete with an expansive agent, which acts only in the setting period of the cement and therefore is not useful for shrinkage compensating concretes.

3.1 Expansive agent in plastic phase

The expansive agents which use up their actions when the concrete is still in the plastic state and cannot, therefore, adhere to the rebars, are not able to create the coaction states (compression in the conglomerate, and tensile state in the bars) which shall be advantageously used to compensate the hygrometric shrinkage when the structures, in the long run, are exposed to shrinkage when the structures, in the long run, are exposed to drying, that is to contraction.

For example, some powdered amphoterous metals, like aluminium, behave in this manner. They react with water and the lime, produced by the cement hydration, to form a gas (hydrogen):

$$2\ Al_{solid} + 3\ Ca(OH)_2\ _{solid} + 6\ H_2O_{liquid} \Leftrightarrow$$
$$\Leftrightarrow 3\ H_2\ _{gas} + 3\ CaO.Al_2O_3.6\ H_2O_{solid}$$

Since gases occupy a much greater volume than solids and liquids, the reaction (1) with gas evolution (H_2), occurs with an increase in volume. Till the cement paste, into which H_2 is formed, is plastic and easily deformable, the fresh conglomerate swells by the gas evolution. However, as soon as the cement paste begins to harden, the hydrogen evolution is not able to deform either the cement paste nor the concrete. In other words, this type of expansion linked with hydrogen evolution within the concrete ceases when the latter hardens, that is exactly when it should be useful to create the coactions of compression in the concrete and of tension in the rebars.

3.2 Expansive agent in hardening phase

Besides expansive agents which act only when the concrete or the mortar is in the plastic state, there exists another category which acts even when either the concrete or the mortar is hardened. This category refers to different types of expansive agents with various characteristics but anyway they are all useful to shrinkage compensating concrete and particularly to repairing mortars.

The expansion which occurs during the initial wet curing can require a more or less longer time (from 1 day, at least, to one week) depending on the expansive agent used. It is the duty of the producer to draw the attention on the duration of the wet curing, corresponding to the expansive agent used.

Normally, the expansive agents used for the shrinkage compensating concrete are of two types: the first type consists of the oxide of magnesium and particularly of calcium, which increase the volume of the paste by their reaction with water. They are transformed into their corresponding hydroxides as shown in the following reactions:

$$CaO + H_2O \Leftrightarrow Ca(OH)_2 \qquad (2)$$

$$MgO + H_2O \Leftrightarrow Mg(OH)_2 \qquad (3)$$

The second type is fundamentally based on the reaction of a sulphoaluminate of composition $4\ CaO.3\ AL_2O_3.SO_3$ with water:

$$4\ CaO.3AL_2O_3.SO_3 + 6\ CaO + 8\ CaSO_4 + 96\ H_2O \Leftrightarrow$$
$$\Leftrightarrow 3\ (C_3A.3CaSO_4.32H_2O) \qquad (4)$$

The expansive agents based on reaction (2) and (3) react very reaction (4). Other parameters which may influence the reaction kinetics and thus the rate of the expansive phenomenon are the granulometry and the porosity of the expansive agent. Since the reaction which causes the expansion occurs at the water-solid (expansive agent) interface it is evident that, reducing the size of the solid particles of the expansive agent, the surface exposed to the water action is increased and therefore the process is accelerated, reducing thus the time of expansion. Similarly, water penetrates more easily an expansive agent which is in the form of porous granules than when it is of dense and compact granules. The porosity of the expansive agent granules, particularly those based on reactions (2) and (3) can be regulated by the manufacturer through the control of the fusing temperature of the feeding materials (limestone or dolomite). By the effect of sintering, favoured by the high temperatures, a dense and compact product is formed.

So, as one can see, basing on the chemical composition, the granulometry and the porosity of the expansive agent, one can regulate the reaction time needed between the water and the expansive agent present in the concrete or the mortar. Consequently, one may regulate the duration of the expansive process during which a wet curing is necessary. Fig. 6 shows the evolution of expansion of conglomerate with time, using two different commercial expansive agents: the one based on calcium oxide completes its transformation into $Ca(OH)_2$ (that is its expansion) in less than one day. The expansive agent based on the hydration of sulphoaluminate, on the contrary, requires seven days to complete the reaction, causing thus the conglomerate to achieve an expansion level which is comparable to that obtained in one day by the calcium oxide-based expansive agent.

Wet curing is always useful to the cement hydration and to the properties of the cementitious concrete. The longer it proceeds,

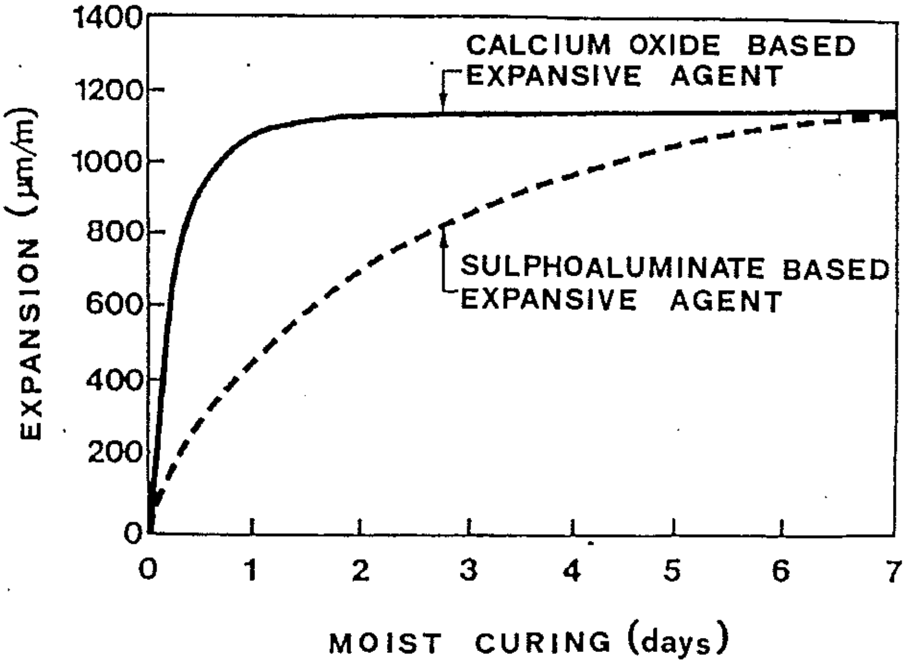

Fig. 6 - Time dependent trend of the expansion during the hardening of two concretes containing two different expansive agents.

the more efficient it is. It is evident that a sharp break in the curing process (for example demoulding after 1 day of placing and without ulterior protection of the exposed surfaces) can significantly limit the expansive process of a shrinkage compensating concrete containing an expansive agent which requires seven days curing. On the other hand, a sharp arrest does not substantially influence the expansion of a shrinkage compensating concrete based on a product whose expansive process exhaustes in one day.

4. CURING AND EXPANSION

One very important aspect in the technology of shrinkage compensating repairing mortars concerns wet curing, which must be absolutely performed in order to permit the reaction of the expansive agent with water, causing thus the beneficial increase in volume. Frequently, the use of an expansive agent is not adequately followed by an initial wet curing. Consequently, the expansion and the derived expected advantages are partly or totally lost.

The importance of curing is illustrated in Fig. 7. It shows the variation of the initial expansion with the curing type. The most efficient curing, as can be observed, is that which contemplates a humidity transport from the environment to the concrete, as it happens with water spraying or the application of wet sheets (curve a). Both operations must be effectuated on the concrete or mortar surfaces, exposed to air immediately after the finishing operation.

Even if the curing accompanied by mechanical protection is less efficient, it is nevertheless appreciable (curve b): in the case of shrinkage compensating concrete casted into porous wooden moulds, it is necessary from time to time to wet the latters, otherwise a water evaporation from the concrete will occur due to drying.

In the case of placing on earth or on hardened concrete, it is necessary to saturate with water the material which will be in contact with the shrinkage compensating concrete, in order to avoid or in any case to minimize the water extraction from the fresh concrete. In the case of concretes placing into moulds, with one side only of the structure exposed (as it occurs in a beam), it is convenient that the protection of the surface exposed to air be performed with wetted or impermeable sheets. If the demoulding must be effectuated before the time needed for the complete expansion, as it frequently happens, it is necessary to complete the curing by wetting and by the application of alternative barriers such as impermeable sheet or evaporating proof membranes (curve c).. Evaporating proof curing applied by the spraying of curing agents is usually less efficient than the mechanical protection.

At last, in the case of a total absence of curing, the expansion evolution strongly depends on the environmental conditions: in very dry environments (R.H $\leq$ 60%), especially if hot and ventilated, the evaporation can proceed so rapidly that the function of the expansive agent is hindered by the lack of moisture in the concrete (curve e). In these conditions, the presence of an expansive agent is useless. Crackings may initiate not only by hygrometric shrinkage effect but also and above all by plastic shrinkage effect. Plastic shrinkage, as already mentioned, can be eliminated only by hindering the evaporation of water. In the case of total absence of curing, but in relatively wet environments, the water evaporation could proceed so slowly that a minimum initial expansion, due to the reaction between the expansive agent and the residual moisture in the concrete, might take place.

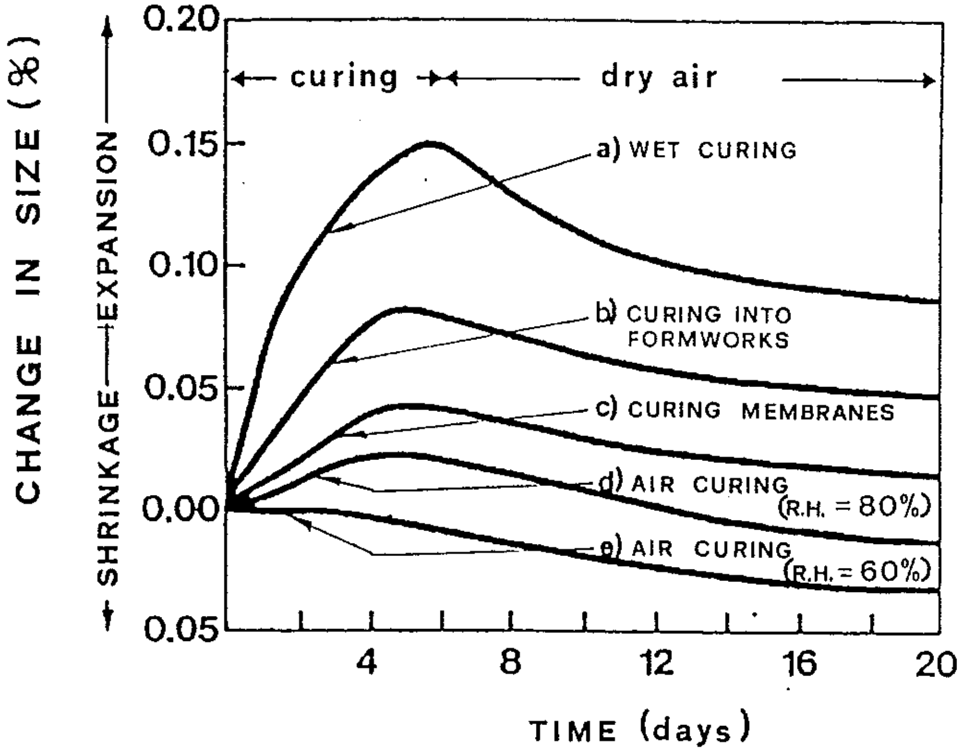

Fig. 7 - The influence of curing on the "change in length - time" curve for a given concrete containing a sulphoaluminate based expansive agent.

It is clear, therefore, that curing operation is essential for the complete realisation of the potential characteristics of the expansive agent. The requirements are, however, cost and engagement on the contractor's side, which can, in such cases, be very burdensome. For example, it is very difficult to carry on for some days the spraying (nebulisation) of water on a precociously unmoulded concrete, with a major part of non-used expansion. The same operation is easier realised on a concrete pavement where, immediately after the finishing, the application of water spraying is possible. More serious, also, is the curing operation with shrinkage compensating mortar applied by sprinkling on concrete walls which need repairs. Since in these cases, curing cannot be initiated before placing, that is after a certain time (1-2 h) necessary for the mortar itself to acquire a certain consistency, it follows that the curing operation, inevitably, involves some obstacles in the site organisations. With the aim to resolve this practical problem on site, some repairing mortars can contain, besides polymer fibers to reduce the plastic shrinkage consequences, some water-retention agents also which have the property to slow significantly the evaporation of the paste water and to preserve the humidity into the mortar, so that the expansive agent can really act even in the absence of an art-rule curing.

5. LABORATORY MEASUREMENT OF EXPANSION AND EFFECTIVE EXPANSION OF COMPENSATING SHRINKAGE MORTAR ON SITE

The expansion of shrinkage compensating mortar or concrete is measured by the method described in ASTM standard C 878. The prismatic specimens of the steel bar reinforced concrete were demoulded after 6-8 hours, when the setting has terminated, and kept under saturated lime water. The relative extension is measured, at different time (from 1 to 28 days), with respect to the original length (before immersion in lime water).

The expansion, thus measured in the laboratory - a very efficient humid curing must be considered - represents the maximum possible expansion. This measurement is prescribed in the standards because of its easy reproducibility. The effective expansion realised in practical conditions is less than that recorded in the laboratory. The difference is higher, the less is relative humidity of the environment in which the real structure is cured.

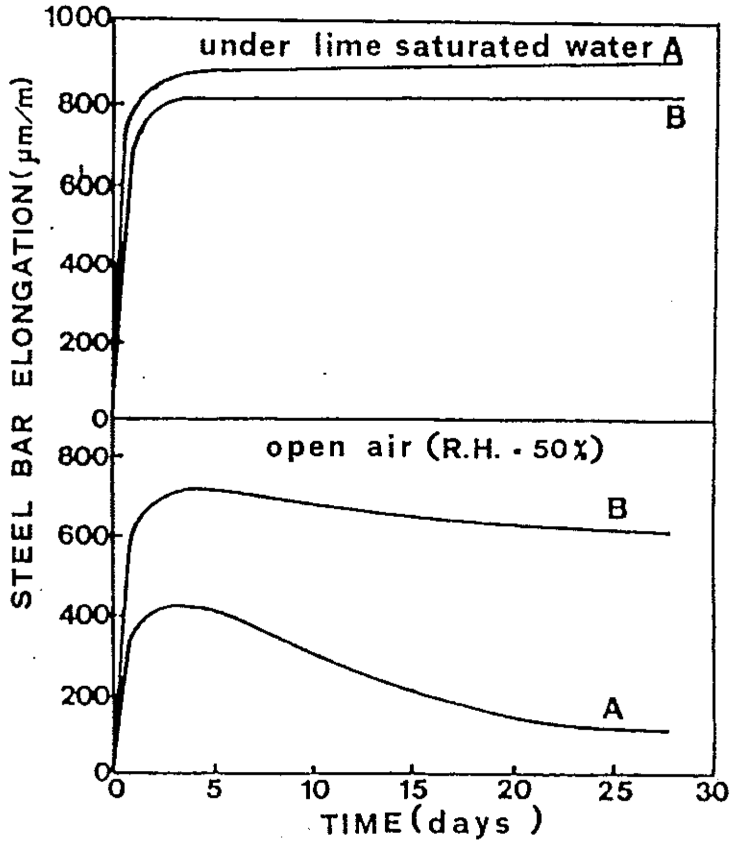

Fig. 8 - "Strain-time" curve according to the original (upper curve) and modified (curve below) ASTM standard C 878 for the dry curing (air with R.H. = 50%) instead of under lime water curing.

The disagreement between the laboratory measured expansion and the actual one on the site is, under certain aspects, similar to that between the laboratory measurement of strength carried out on concrete specimens wet cured and that which is found in the real structure in the absence of a wet curing. Expansion and strength values measured in laboratory should be considered as control data, corresponding to a specified condition. The problem remains however, in real structures and also in absence of curing, of obtaining a value which is as nearest as possible to that found in the laboratory. In other words, a mortar which would expand in laboratory conditions but would not expand in practical conditions, would not be useful for practical purposes.

Fig. 8 illustrates the behaviour of 2 mortars (A and B). They show a very similar behaviour, though they were studied in laboratory (under lime water) and in dry environment (air with R.H = 50%).

Mortars A and B have the same composition and specially the same quantity of expansive agent (4% of CaO). The only difference is that mortar A possess also a "water-retention" polymer, thanks to which, the humidity of the mortar - derived from the water of the paste - is maintained into the concrete even if the sorrounding environment is unsaturated with humidity. The following consequences are deduced:

(a) mortar B can expand more efficiently than mortar A in an unsaturated environment (R.H 50%), when the wet curing, as it often happens in practice, is negligible;
(b) mortar B undergoes a smaller hygrometric shrinkage than mortar A, when the expansion process is ended, by the effect of reduced water evaporation of the material towards the environment;
(c) the sum of the two effects - both beneficials - makes the mortar B more reliable in the practical conditions, since the net result is to conserve the coaction states (compression in the mortar and tension in the steels), even in the absence of curing on the contractor's side.

6. CONCLUSIONS

The shrinkage compensating mortars, widely used from a long time in repairing works, can "suffer", in the absence of an accurate wet curing by the contractor, for the following reasons:

- cracks are induced by plastic ahrinkage;
- the expansion after the hardening is reduced and therefore the hygrometric shrinkage is not fully compensated.

These defects are not easily observed by the tests prescribed by the original ASTM standard. They can be pointed out by modifying the test in such a way as to simulate the practical conditions (R.H $\leq$ 50%). The modification can be effectuated in the following ways:

- by adequately reinforcing the cementitions matrix with polymer fibers in such a way that the tensile strength of the concrete be superior to plastic shrinkage induced stresses;
- by adding a water retention polymer to the mortar in such a way

that, the humidity held into the material, assure not only the hygrometrical conditions for an efficient expansion but also reduce the successive hygrometric shrinkage.

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