mortar as a repair material for damaged concrete structures. This effect has been confirmed by Maltese et al. [3] who have found that the use of a CaO-based expanding agent with a shrinkage reducing admixture allows to obtain mortars less sensitive to drying. The main purpose of the present work was to study whether this effect can be extended to other expansive agents such as those based on Calcium Sulfo-Aluminate (CSA). Indeed, the combined use of CSA and SRA has been found to be successful as patch material in repair work provided that a curing compound is used to prevent moisture loss from the surface [4]. A second purpose of this work was to check whether an early protection from air drying ,as that which would occur in grouting repairing mortar placed into formworks before demolding, can provide sufficient early expansion to compensate the subsequent drying shrinkage. Finally, a third purpose of this work was to check the influence of removing this early protection from air drying as would occur when sprayed mortars on damaged concrete surfaces are exposed to air without any wet curing and any early protection at all.

EXPERIMENTAL: MATERIALS, METHODS AND RESULTS

Two commercial expansive agents were studied : one based on dead burnt CaO and the other on CSA. The expansion produced by CaO or CSA are related to the following chemical processes:

$$CaO + H_2O \implies Ca(OH)_2$$
(1)

 $4\text{CaO·3Al}_2\text{O}_3 \cdot \text{SO}_3 + 6\text{CaO} + 8\text{CaSO}_4 + 96\text{H}_2\text{O} = > 3 [3\text{CaO·Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 32\text{H}_2\text{O}] (2)$

In general the recommended time of wet curing is 1-2 days for cementitious material containing CaO and 5-7 days for cementitious materials containing CSA. This time is related to the different hydration rates of the chemical processes.

The other ingredients used in the study are:

- portland cement (CEM I 42.5 R according to the European Norm EN 197-1;
- natural sand (maximum size: 5 mm);
- polycarboxylate-based superplasticizer;
- Shrinkage-Reducing Admixture based on propylene-glycol ether.

Table 1 shows the composition of the 6 mortars manufactured at a given workability. The liquid-binder ratio was 0.50, where the weight of the liquid includes the amount of the chemical admixtures (SRA and superplasticizer), and the weight of binder includes the amount of the expansive agent (CaO or CSA).

Table 2 shows the compressive strength of the mortars demolded at two days and then cured in the air at 20 °C with Relative Humidity (R.H.) of 60 %. There was no difference in the 28-day strength values of the mortars, all at about 42 MPa. However, the mortars containing SRA had a lower strength (20-25% less) at 1 day with respect to the corresponding mortars without SRA.

The reinforced specimens, manufactured according to the ASTM test method C 878

(75x75x254 mm), were demolded at 6 hours in order to measure the initial length of the metallic bar (5 mm in diameter and 293 in length). Then the specimens were cured at 20 °C in the following three ways:

i) by immersing permanently under water;

ii) by wrapping the specimens with a plastic sheet for 2 days followed by exposure to air (R.H.= 60%);

iii) by immediate exposure to air (R.H.=60%).

Curing procedure *i*) is intended to measure the maximum potential expansion by permanent immersion under water. Curing procedure *ii*) is to determine the behavior of the reinforced specimens according to the realistic demolding at 2 days and then exposure to open air. Curing procedure *iii*) is intended to simulate the behavior of reinforced structures exposed immediately to open air as sometimes occur with sprayed mortars without any protection and wet curing.

The restrained length change of the reinforced specimens was measured as a function of time up to 2 months. The results are shown in Fig.6-10.

Figure 6 shows the behavior of the control mixture and that of the "SRA mortar" following curing procedure *ii*): there was no length change in both mortars during the first two days when the specimens were wrapped with plastic sheet; then, when the specimens were exposed to the air at R.H. of 60%, the "SRA mortar" shrank at a lower rate with respect to the control mortar: about 50% less at early ages and about 30% less at later ages. So, the effect of the chemical admixture SRA used in this work is similar to that recorded by others in the technical literature [5].

Figure 7 shows the behavior of the "*CaO*" mortar when tested according to the three curing procedures: the restrained expansion reached in about two days the level of 800 microstrains under permanent wet curing with little change at later ages; when the specimens are protected from drying by the plastic sheet the initial expansion of 600 microstrains is gradually relaxed by the subsequent shrinkage and it is completely lost in one month; in the absence of the early protection, the initial expansion in the reinforced specimens is only 300 microstrains and it is lost in about two weeks.

The combination of SRA with the CaO-based expansive agent (Fig. 8) gives a synergistic effect with respect to the mortar with only SRA (Fig. 6) or only CaO (Fig. 7). First, the expansion on the "*CaO/SRA*" mortar according to curing procedure *ii*) is the same as that of the same mortar permanently kept under water: the restrained expansion is 800 microstrains at about 2 days regardless of the curing. Second, the shrinkage of the "*CaO/SRA*" mortar after removing the plastic sheet is much less with respect to that of the corresponding mortar with CaO without SRA (Fig. 7); therefore, the initial expansion after the demolding is relaxed by the subsequent shrinkage to a lower extent so that there is still a restrained expansion even after the exposure of the specimen to air with R.H. of 60% for two months. Third, even when the restrained specimens are exposed immediately to the air with R.H. of 60%, the reduction of the expansion due to the subsequent shrinkage is lost only at two months; this means that cracking in the "*CaO/SRA*" mortar would be unlikely: only when the tensile stress, after two months, is higher than the tensile strength of the mortar.

Figure 9 illustrates the restrained length change of the "CSA" mortar according to the

above mentioned three ways of curing. The behavior of this mortar is very different from that of the corresponding "*CaO*" mortar . The restrained expansion of the "*CSA*" mortar permanently kept under water is very slow and it takes about 10 days (versus about 3 days for the "*CaO*" mortar) to reach the maximum value of 600 microstrains (versus 800 microstrains of the corresponding "*CaO*" mortar). The maximum expansion of the "*CSA*" mortar specimens protected by the plastic sheet is only 230 microstrains and it is lost completely in about 1 week by the subsequent shrinkage. Even less effective is the behavior of this mortar when immediately exposed to air (R.H. = 60%): the small restrained expansion of about 100 microstrains is completely lost in about 5 days.

The combination of SRA with the CSA expansive agent (Fig. 10) does not change the restrained expansion compared to the "CSA" mortar (Fig. 9) when the specimens are wet cured under water. However, there is an increase in the initial restrained expansion (400 versus 230 microstrains) due to the addition of SRA when the specimens are protected two days by the plastic sheet: the early restrained expansion of 400 microstrains is completely lost in about one month when the "CSA/SRA" mortar is exposed to air; in the "CaO/SRA" mortar (Fig. 8) the restrained length change of the specimens exposed to the air after a protection of two days is much higher with respect to the "CSA/SRA" mortar, and a restrained expansion of 200 microstrains is still available after two months. Finally, the restrained expansion of the "CSA/SRA" mortar is lost in about three weeks when the specimens are cured immediately in the air with R.H. of 60%.

As far as the combined action of CaO with SRA is concerned, there are two distinct effects as illustrated in Fig. 11:

- the β effect which resultsg in a lower shrinkage due to the expected influence of the SRA on the shrinkage behavior;

- the α effect due to the un expected higher expansion of CaO related to the presence of SRA.

X-ray diffraction analysis (Fig. 12) did not show any influence of SRA on the CaO hydration in terms of the Ca(OH)₂ peaks. The termogravimetric analysis (Table 3), again, does not show any influence of SRA on the amount of Ca(OH)₂. Therefore, presently the increase in the restrained expansion of CaO with SRA cannot be explained. Also unexplainable is the influence of SRA on the restrained expansion is much more effective with the CaO expansive agent (Fig. 8) than with the CSA agent (Fig. 10).

CONCLUSIONS

The combined action of SRA with an expansive agent such as dead burnt CaO or calcium sulfo-aluminate (CSA) increases the restrained expansion in the absence of wet curing. The effect is much more enhanced when SRA is combined with CaO than with CSA.

In particular, the combined action of SRA with CaO will permit the manufacture of shrinkage-free mortars as repair cementitious materials for damaged concrete structures, when they are placed into formworks and exposed to air after two days: even after two

months of permanent exposure to air with R.H. of 60 %, there is remaining restrained expansion that is capable of keeping the mortar under a compressive stress (σ_c).

In repair applications where mortars are sprayed on the surfaces of damaged concrete structures, the mortars based on the combined action of SRA with CaO can keep their advantageous σ_c for more than two months when exposed immediately to air. Under this situation, mortar cracking would be avoided if the tensile strength (f_t) is as high as 2.5 MPa and also higher than the tensile stress (σ_t) in the mortar following shrinkage at later ages.

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MORTAR	CONTROL	SRA	CaO	CaO/SRA	CSA	CSA/SRA
Cement	450	450	450	450	450	450
Expansive Agent			45	45	45	45
Aggregate	1560	1560	1540	1540	1540	1540
Water	220	210	245	230	245	245
SRA		9		9		9
Superplasticizer*	5	6	6	6	6	6

Table 1 – Composition of mortars in kg/m³ at the same workability

(spread table = 50%).

* 20% aq. solution

Table 2 - Compressive strength (MPa) of mortars demolded at 2 days

TIME	CONTROL	SRA	CaO	CaO/SRA	CSA	CSA/SRA
1	25	20	24	20	23	19
3	32	30	32	27	29	28
7	36	38	38	37	34	33
14	40	42	41	39	40	37
28	42	43	43	44	42	41

and then air-cured at 60% and 20°C.

Fable 3 – Percentage	e of Ca	(OH) ₂ in	some	mortars.
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TIME	CONTROL	SRA	CaO	CaO/SRA
1 hour			6.0	6.1
3 hours			7.3	7.0
6 hours	2.8	2.8	10.1	10.3
1 day	11.3	10.6	21.4	21.6



Fig. 1 – Cracks in the repair material and debonding from the concrete substrate adapted from[1].







Fig. 3 – Concrete substrate and reinforcements restrain the length increase of the expanding repair mortar. The repaired portion of the structure accumulates compressive stress (δ_c), adapted from [1].



Fig. 4 – Compressive stress (δ_c) due to the restrained expansion compensates the subsequent relaxation and tensile stress induced by drying shrinkage. The resulting net stress is never higher than the tensile strength (f₁).



Fig. 5 – Due to inadequate wet curing, the compressive stress (δ_c) is very low and then it cannot compensate the subsequent shrinkage: tensile stress δ_t can reach the tensile strength f, and cracking can occur.







Fig. 7 – Influence of the curing on restrained length change of the CaO based mortar.



Fig. 8 – Influence of the curing on restrained length change of the CaO/SRA based mortar.



Fig. 9 – Influence of the curing on restrained length change of the CSA based mortar.



Fig. 10 – Influence of the curing on restrained length change of the CSA/SRA based mortar.



Fig. 11 – Restrained length change in "CaO mortar" and "CaO/SRA mortar" exposed to air (R.H. = 60%) after 2 days of protection by plastic sheet.