

# Effects of shrinkage reducing admixture in shrinkage compensating concrete under non-wet curing conditions

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Received 26 March 2004; accepted 23 September 2004

## Abstract

The practice of using expansive agents has been recommended to manufacture shrinkage-compensating concrete provided that an adequate wet curing is carried out. On the other hand, more recently the use of shrinkage reducing admixture (SRA) has been suggested to improve concrete performance in terms of lower risk of cracking related to drying shrinkage.

However, neither expansive agent nor SRA, when used separately, can definitively and safely avoid the risk of cracking caused by drying shrinkage in real concrete structures under the practical conditions of curing on many job-sites.

This paper shows the advantages of the combined use of SRA and CaO-based expansive agent to produce shrinkage-compensating concrete even in the absence of an adequate wet curing.

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**Keywords:** Expansive agent; Shrinkage compensating concrete; Shrinkage reducing agent; Wet curing

## 1. Introduction

Inadequate wet curing of concrete is considered to be responsible for some serious drawbacks. One of these is related to the higher volume of capillary pores ( $V_p$ ) in the concrete cover caused by a lower degree of hydration ( $\alpha$ ) as indicated by the following Powers equation [1]:

$$V_p = 100 w/c - 36.15\alpha \quad (1)$$

where  $w/c$  is water–cement ratio.

A more serious drawback of inadequate wet curing at the early age is the appearance of cracks on the concrete surface [2] when the tensile stress ( $\sigma_t$ ), induced by

restrained drying shrinkage ( $\varepsilon_s$ ) becomes higher than the tensile strength ( $f_t$ )

$$\sigma_t = E \cdot (\varepsilon_s - \varepsilon_c) > f_t \quad (2)$$

where  $E$  is the modulus of elasticity and  $\varepsilon_c$  is the creep strain.

Since the damage related to a higher capillary porosity and that of cracking are both localized in the area of concrete cover, the risk of corrosion of metallic reinforcements increases significantly in concrete structures with inadequate curing due to quicker and easier penetration of  $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{Cl}^-$  and  $\text{H}_2\text{O}$  to the steel reinforcements.

This risk can paradoxically increase in high performance concrete (HPC) structures due to the autogenous shrinkage specially in concretes with  $w/c$  in the range of 0.30–0.40. In these concretes, the rapid development of a very fine pore network within the hydrated

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cement paste occurs and drains water from coarse capillaries. These dry out in the absence of water curing. This phenomenon, called self-desiccation, occurs when the cement hydration progresses because the coarse capillary pores became empty of water just as in an ordinary concrete exposed to drying.

According to Aïtcin [3], autogenous shrinkage does not occur in HPC provided that the formworks are removed as soon as possible and then immediately exposed to water curing for at least one week.

The use of surface reducing admixtures (SRA) has been suggested to reduce both drying and autogenous shrinkage, whereas expansive agents have been recommended to compensate the drying shrinkage of reinforced concrete structures. SRA and expansive agents will be examined in the following sections.

## 2. Shrinkage reducing admixtures

SRA is a chemical admixture (1–2% by mass of cement) based on neopentil glycol,  $(\text{CH}_2)_2\text{C}-(\text{CH}_2\text{OH})_2$ , or other similar products which reduce the drying and/or autogenous shrinkage [4,5]. Fig. 1 shows a typical shrinkage trend after 1 week of wet curing in concretes with a cement content of  $390 \text{ kg/m}^3$  and a w/c of 0.40, with and without SRA. In the presence of SRA ( $4 \text{ kg/m}^3$ ) there is a significant reduction with respect to the reference concrete in the drying shrinkage at 1 month from 0.04% to 0.02%.

Surprisingly SRA does not reduce the water evaporation from concrete when exposed to unsaturated air. Fig. 2 shows a typical weight loss due to water evaporation from concretes with and without SRA, both exposed to the same air conditions ( $\text{RH} = 60\%$ ,  $T = 25^\circ\text{C}$ ).

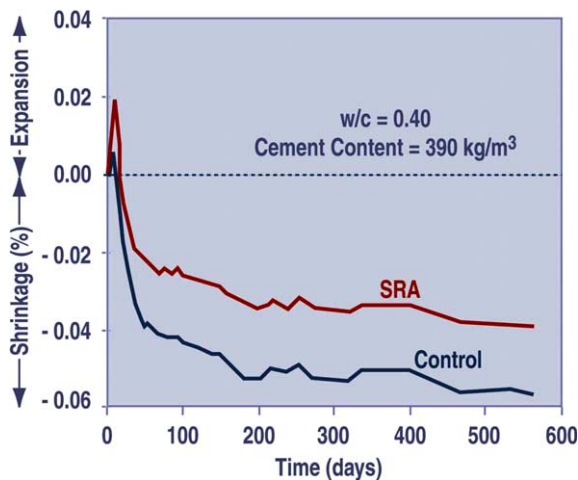


Fig. 1. Length change as a function of time for concretes with and without SRA, wet cured during the first week [5].

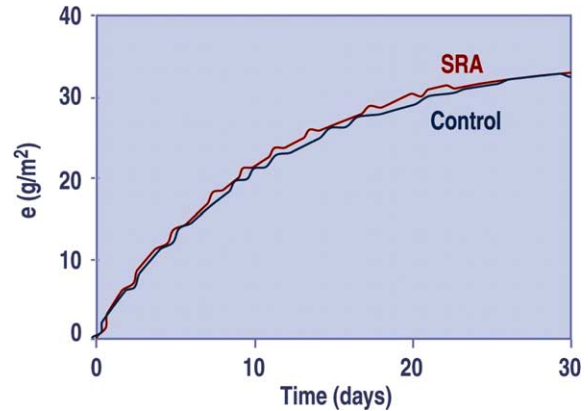


Fig. 2. Evaporation ( $e$ ) of water from concrete with and without SRA.

The effect of SRA on the shrinkage is ascribed [5] to the reduced surface tension of water ( $\gamma$ ). This reduces the capillary tension  $P$  caused by the formation of water menisci developed in capillary pores and responsible for the shrinkage of the cement paste. The capillary tension depends on the surface tension ( $\gamma$ ) according to equation

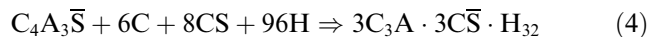
$$P = 2\gamma/r \cos \theta \quad (3)$$

where  $r$  is the pore radius and  $\theta$  the wetting angle.

Due to the dosage of SRA (about  $4 \text{ kg/m}^3$ ) and its price (about 4–5 €/kg in Europe) the extra-cost of  $1 \text{ m}^3$  for the SRA addition is relatively expensive (about 12–20 €/m<sup>3</sup>), because the shrinkage drawback can be mitigated but not completely eliminated (Fig. 1).

## 3. Expansive agents

Expansive agents are special products which can increase the volume of concrete due to specific chemical reactions. There are many families of expansive agents. The most important are based on the formation of ettringite ( $\text{C}_3\text{A} \cdot 3\text{CS} \cdot \text{H}_{32}$ )<sup>1</sup> or calcium hydroxide (CH):



The expansion produced by reaction (4) is based on the transformation of a mixture of sulfo-aluminate ( $\text{C}_4\text{A}_3\bar{\text{S}}$ ), lime (C) and anhydrite ( $\text{CS}$ ) into ettringite, whereas the expansion caused by reaction (5) is based on the transformation of lime into calcium hydroxide.

## 4. Lime versus sulfo-aluminate as expansive agents

The expansion produced by reactions (4) and (5) must occur within a given period of time in a concrete

<sup>1</sup> Cement chemistry symbols are adopted: C = CaO; A =  $\text{Al}_2\text{O}_3$ ;  $\bar{\text{S}}$  =  $\text{SO}_3$ ; H =  $\text{H}_2\text{O}$ .

adequately reinforced, so that the restrained expansion produces a tensile stress in the metallic reinforcement and a compressive stress in the concrete. In other words, a sort of a chemically prestressed reinforced concrete is produced due to the restrained expansion. This can usefully occur only if the expansion process develops mainly after the concrete compressive strength starts to grow and consequently the steel–concrete bond starts to develop. This means that any expansive action occurring too early, in a deformable plastic concrete, does not produce any advantageous compressive stress in the hardened concrete. On the other hand, an expansion occurring at too late ages should be necessarily accompanied by a prolonged wet curing period.

From this point of view the ettringite formation according to the reaction (4) and the CaO hydration according to the reaction (5) appear to be very different. Fig. 3 indicates a typical expansion process as a function of time for two concretes attaining about the same final expansion (1100  $\mu\text{m/m}$  at 1 week) and based on CaO or sulfo-aluminate as expansive agent [6]. The process related to lime hydration occurs within 1–2 days, whereas that based on the ettringite formation needs about 5–7 days to completely develop its potential expansion.

If these two expansion rates are compared with two typical strength developments (cements A and B in Fig. 3), one can conclude that only the ettringite formation agrees very well with both concrete A and concrete B as far as the expansion rate vs. strength development is concerned.

On the other hand, the expansion rate related to lime hydration agrees very well only with the early strength development of concrete A, whereas the concrete B does not develop an adequate strength level in the period of time (0–12 h) corresponding to the main part (about 75%) of the total expansion.

This different behaviour can explain why only the ettringite formation process has been used in manufacturing shrinkage-compensating concretes in the past time when the concretes with 1-day compressive strength

of 5–10 MPa were used. With the advent of the high-range water reducers, concretes, characterized by a strength development like that of B in Fig. 3, can be manufactured and they are compatible with the quicker expansion rate of lime-based expansive agents [6].

The use of CaO-based expansive agents, combined with an early strength concrete (10–20 MPa) like that indicated by A in Fig. 3, is more advantageous with respect to the ettringite-based expansive agent, for the shorter period of wet curing time (1–2 days vs. 5–7 days) needed to completely develop the potential expansion.

## 5. The role of water curing in shrinkage-compensating concretes

Before illustrating the role played by the water curing in the development of the expansion rate it is useful to see how the expansion measurements are carried out according to the ASTM test method 845-90. Fig. 4 indicates the metallic formwork where fresh concrete is placed by embedding a steel bar reinforcement (6 mm in diameter, 280 mm in length). At about 4–12 h when the reinforced concrete specimen, with two metallic plates at the ends, is demoulded (Fig. 4), the initial length of the steel bar is measured and then the reinforced specimen is immersed under water in order to favour the best expansive process as possible. The length-change of the steel bar is then recorded as a function of the curing time. Fig. 5 (curve A) shows the behaviour of a concrete specimen (with the composition shown in Table 1) demoulded at 6 h, immersed under water up to 36 h and then exposed to air with R.H. of 65%. At 30 days there is still a certain level of tensile stress in the metallic bar (and of compressive stress in the concrete) corresponding to the remaining expansion of 100–200  $\mu\text{m/m}$ .

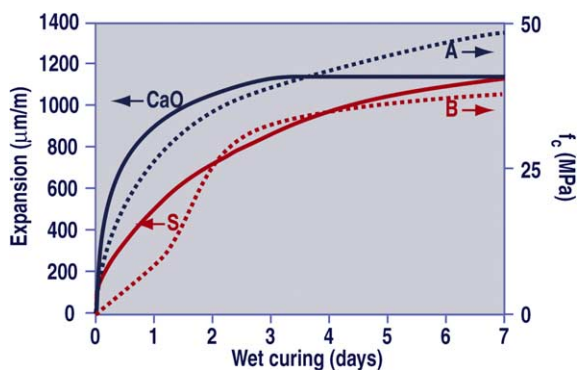


Fig. 3. Restrained expansion and compressive strength ( $f_c$ ) for concretes with CaO or sulfo-aluminate (S).

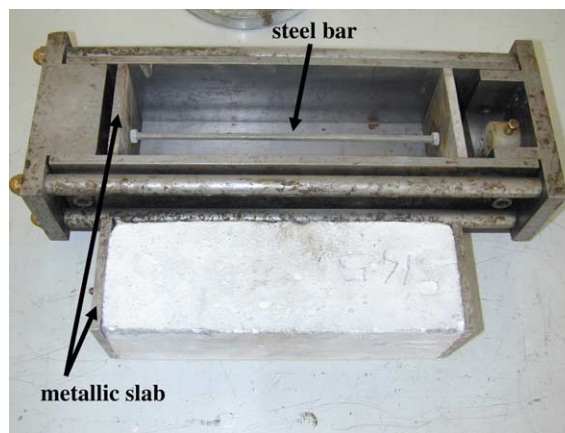


Fig. 4. Formwork for measurement of restrained expansion according to UNI 8148 on ASTM 845-90.

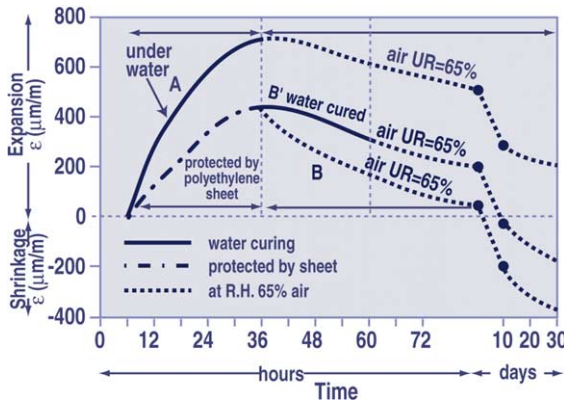


Fig. 5. Length change of concretes (Table 1) cured under water up to 36 h (A) or protected by polyethylene sheet up to 36 h (B) or 60 h (B').

Table 1  
Mix composition and properties of concretes

Ingredient	Composition in mixes*		
	A/B	C	D
Cement (II A-L 42.5N) ( $\text{kg/m}^3$ )	350	350	350
CaO ( $\text{kg/m}^3$ )	35	35	—
Sand (0–5 mm) ( $\text{kg/m}^3$ )	980	980	1015
Gravel (5–20 mm) ( $\text{kg/m}^3$ )	860	860	860
Water ( $\text{kg/m}^3$ )	160	156	156
Acrylic superplasticizer ( $\text{kg/m}^3$ )	3	3	3
Propylen-glycol ( $\text{kg/m}^3$ )	—	4	4
Slump (mm)	180	190	200
Compressive strength (MPa) at			
1 day	16	13	11
3 days	37	36	36
28 days	45	44	43

\* These mixes refer to Figs. 5 and 6.

From a practical point of view the special curing adopted for the reinforced concrete specimen according to the above test method (curve A in Fig. 5) is definitely unrealistic for any reinforced concrete structure except, perhaps, for an industrial concrete floor which could be soaked by water after the setting time. Therefore, this test does not reflect the real curing of reinforced concrete structures which cannot be water-soaked in the period of time corresponding to the expansion process when the concrete is still protected by the form-work.

A more realistic expansion process has been recorded by protecting from drying the reinforced concrete specimen by a polyethylene sheet (from 6 to 36 h) in order to simulate the expansive behaviour of a concrete structure protected from drying by the formwork (curve B in Fig. 5). After removing the polyethylene sheet at 36 h, the reinforced concrete was exposed to unsaturated air (R.H. of 65%) immediately (curve B) or after a water fogging time for 1 day (curve B'). Although the 1 day water fogging treatment improved the behaviour of the shrinkage-compensating concrete, with respect to the same concrete immediately exposed to air, the remaining expansion was completely lost at about 1 month.

Therefore, the performance of shrinkage-compensating concrete based on expansive agents [7–9] does not appear to be successful in practice even with a fogging treatment of the concrete surface just after demoulding.

## 6. Combined use of SRA and CaO-expansive agent

The combined use of SRA and a CaO-based expansive agent was studied in order to check the potential success in producing shrinkage-compensating concrete with a length-change behaviour similar to that of the water cured concrete (curve A in Fig. 5) even in the absence of any type of curing.

The concrete mixture (C) was the same as that shown in Table 1 for mixes A and B except for the presence of propylen-glycol (1.15% by cement weight) acting as SRA. The amount of mixing water was reduced by a volume corresponding to that of SRA.

A reference mix (D), without expansive agent and with SRA (1.15%) was also studied (Table 1).

The expansion of the mix C (with SRA + CaO) and that of the mix D (with SRA) is shown in Fig. 6 in comparison with those of mixes A and B (both with CaO). All the concretes (except mix A) were demoulded at 6 h, protected by a polyethylene sheet up to 36 h and then exposed to air with R.H. of 65%; the concrete A was cured under water from 6 to 36 h according to the test method ASTM 845-90, and then exposed to air at R.H. of 65%.

The behaviour of the concrete C (with SRA + CaO) performs much better than that with CaO only (concrete B) or with SRA only (concrete D).

Surprisingly the expansion caused by CaO hydration in the presence of SRA (concrete C) is very close to that of the concrete A even though no water curing was adopted as that for the concrete A. Moreover, when

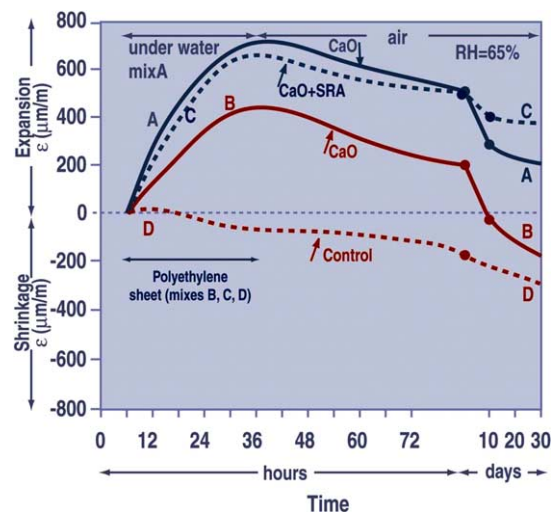


Fig. 6. Length change of concretes (Table 1) cured under water (A) or by polyethylene sheet B, C and D. See table for mix composition.

the polyethylene sheet was removed, concrete C exposed to air (R.H. of 65%) behaves, in terms of length-reduction, much better than concretes with CaO only (A and B). The final result indicates that there is a remaining expansion of about 200  $\mu\text{m/m}$  after about 2 months of exposure to air with R.H. of 65%.

## 7. Conclusions

There is a synergistic effect in the combined use of SRA and a CaO-based expansive agent in terms of more effective expansion in the absence of wet curing and lower shrinkage after removing the polyethylene sheet used to simulate the protection from drying before the demolding on the job site.

These interesting results should be confirmed by using different type of SRA and/or CaO expansive agent. Preliminary results indicate that this synergistic effect does not exist when a sulfo-aluminate expansive agent is used to form ettringite.

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