USE OF A SHRINKAGE COMPENSATING CONCRETE FOR THE CONSTRUCTION OF A CRACK-FREE SLAB FOUNDATION

Roberto Troli , Giacomo Iannis and Stefano Maringoni

Abstract

Shrinkage-compensating concretes have been extensively used in the last forty years to minimize cracking caused by drying shrinkage in reinforced concrete structures. The first and most diffused system to produce shrinkage-compensating concretes involves the use of expansive cements, according to ACI 223-98, instead of ordinary portland cement. Another effective method to produce shrinkage-compensating concretes, not covered by ACI 223-98, lies in the use of a CaO and/or MgO based expansive agent. This technology seems to be more advantageous with respect to that based on the ettringite formation from an economical as well as from a practical point of view. Recently, the addition of a shrinkage-reducing admixture (SRA) has been found to improve the behavior of CaO based shrinkage-compensating concretes especially in the absence of an adequate wet curing. In this work a remarkable example of a special reinforced concrete structure is presented in which the use of CaO-SRA based shrinkage-compensating concretes was successfully carried out in order to prevent shrinkage related cracks and/or joints excessive opening in the presence of adverse curing conditions which are normally not suitable for the use of this technique.

Keywords

Drying shrinkage. Cracking. Expansive agents. Shrinkage-reducing admixture. Shrinkage-compensating concrete.

Biographical notes

Roberto Troli (troli@encosrl.it) is a research civil engineer and technical director of Enco. He is the author or co-author of numerous papers in the field of concrete technology, chemical and mineral admixtures.

Giacomo Iannis (giacomo.iannis@tecnochem.it) is a civil engineer who since 2006 works in Tecnochem where he is responsible for the repair and consolidation of damaged concrete structures. Since 2010 he also works in the area of energy consumption in the residential buildings

Stefano Maringoni (stefano.maringoni@tecnochem.it) is a building engineer working in Tecnochem Italia where he is responsible for the innovative materials devoted to the repair and consolidation of damaged concrete structures.

1. INTRODUCTION

Probably the use of shrinkage-compensating concretes is the most effective method to eliminate or, at least, minimize the formation of drying shrinkage related cracks in reinforced concrete structures. This technique is based on a volume expansion which is induced in the concrete by a specific chemical reaction whose effects can be adequately designed and controlled by the correct proportioning of the concrete.
Normally the induced chemical expansion occurs during the first 2-7 days being so much faster than the contractions caused by moisture loss. For this reason, in order to be advantageously used to compensate drying shrinkage, the early expansion must be adequately restrained by a proper design and location of the steel deformed bars and/or by other means of restraint. In this way, an early compressive stress is induced in the concrete which will compensate for tensile stresses caused by the subsequent restrained drying shrinkage.
According to the ASTM C 878 test method [1], the expansive behaviour of a shrinkage-compensating concrete is assessed by measuring the length change of a steel rebar embedded in concrete prismatic specimens, demoulded at the setting time (about 6-8 hours after mixing) and kept under lime-saturated water for 7 days. To provide satisfactory shrinkage compensation, the required expansion in the reinforced structural member is recommended to be greater than, or at least equal to, the predicted shrinkage in the member.
According to ACI 223-98 [2], the design of a shrinkage compensated reinforced concrete member must include the four following steps:

a) estimation of the member shrinkage. First of all, a sufficiently reliable prediction of the member final drying shrinkage must be carried out. In this estimation, the effects of member thickness, reinforced amount, relative humidity, concrete composition and type of aggregate must be taken into account;
b) selection of the required member expansion in order to avoid crack formation;
c) estimation of the specimen minimum expansion to provide the required member expansion. It can be easily obtained by using the graph shown in Figure 1.a, taken from ACI 223-98. The graph gives the relation between member expansion and specimen expansion as a function of the actual percentage of reinforcement in the designed member;
d) proportioning of shrinkage-compensating concrete in order to assure the calculated specimen expansion.

The early chemical expansion induces tensile stresses in steel reinforcement. These stresses are generally lower than that allowed for the material if the requirements of national standard codes (or Eurocodes), in terms of minimum steel percentage, are satisfied.
Sometimes, in the case of early heavy loaded structures, the tensile stresses caused by expansion must be considered, in addition to those induced by external loads, in order to verify structural safety. For the same reason, the initial compressive stresses induced in the concrete by the restrained expansion must be added to those caused by eventual early external loads in order to provide proper safety factors in the first period of the service life of the structure. These additional compressive stresses in concrete can be easily determined, as a function of reinforcement percentage and member expansion, by using the graph of Figure 1.b (ACI 223-98).

2.EXPANSIVE CEMENTS

Shrinkage-compensating concretes can be manufactured by using special expansive cements instead of normal Portland cement.

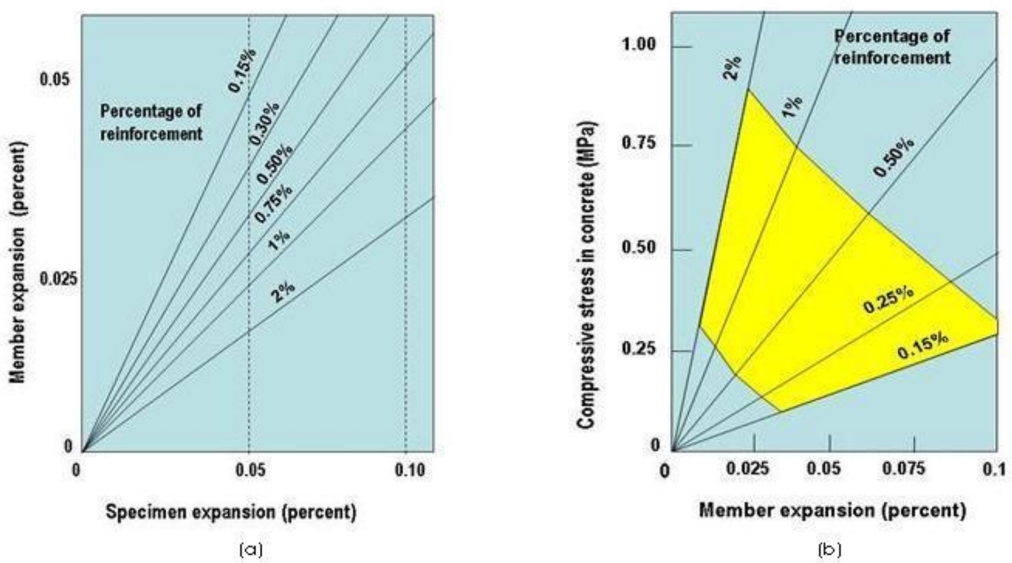

Figure 1 (a) Member expansion vs. specimen expansion; (b) compressive stress induced in the concrete by the restrained expansion (ACI 223-98)

ASTM C845-90 and ACI 223-98 classify the following three different types of expansive cements: type K (Klein cement), type M, and Type S. All these cements base their expansive behaviour on a controlled production of ettringite ($C_3A\bullet 3C\underline{S}\bullet 32H$).

In the case of type K cement the expansive reaction can be represented through the reaction (1) where $C_4A_3\underline{S}$ is the calcium sulpho-aluminate reacting with the calcium oxide (C) and calcium sulphate ($C\underline{S}$) in the presence of water (H):

$$C_4A_3\underline{S} + 6C + 8\ C\underline{S} + 96\ H \rightarrow 3(C_3A\cdot 3C\underline{S}\cdot 32H) \qquad (1)$$

This reaction begins immediately as soon as water has been added to the mix but it takes at least 3 to 7 days to be completed. This assures that the greatest part of the expansion occurs when the concrete is strong enough to interact with steel and generate a restrained expansion.
On the other hand, since the formation of ettringite requires a large amount of water, continuous wet curing for about one week is required to achieve the potential planned expansion. Any deficiencies in the method of curing may reduce the amount of initial expansion.
Another method to produce shrinkage-compensating concretes is based on the expansive reaction which occurs between lime (CaO) and/or magnesium oxide (MgO) and water to produce calcium and/or magnesium hydroxide according to the following reactions:

$$CaO + H_2O \rightarrow Ca(OH)_2 \qquad (2.1)$$

$$MgO + H_2O \rightarrow Mg(OH)_2 \qquad (2.2)$$

Normal CaO and MgO, obtained by burning limestone or dolomite at a temperature of about 900°C, and used in agriculture or to manufacture calcium hydroxide and brucite for masonry mortars and plasters, are not suitable as expansive components. As a matter of fact, in this case, the reactions (2.1) and (2.2) occur too quickly when the concrete is still in the plastic state and therefore no sufficient restraint is offered since the steel-concrete bond is still too weak.
In order to be successfully used as expansive agents, CaO and MgO must be cooked at higher temperatures than 1000°C resulting in “dead burnt lime” or “dead burnt periclase”. Actually, the higher cooking temperature induces a sintering process of new formed CaO and MgO grains reducing their porosity and retarding their reactivity with water. A further retard on hydration can be obtained by reducing the fineness of grains during the subsequent grinding process.
Figure 2 schematically shows the retrained expansion, measured according to the ASTM C 878 test method, in a dead burnt lime-based shrinkage-compensating concrete compared to that of a mix containing a sulpho-aluminate-based expansive system, all other parameter being the

same. The CaO-based concrete achieves the complete expansion in less than 3 days whereas it continues for at least 7 days in the case of sulpho-aluminate based concrete.
The quick expansion induced by CaO obliges to use a rapid hardening concrete in order to better exploit the expansive reaction. Actually, the use of high strength cement class and superplasticizers to reduce w/c can improve the steel-concrete interfacial bond and increase the restrained expansion at the same CaO amount [4]. Since the sulpho-aluminate expansive reaction is quite slower, shrinkage-compensating concretes based on this technique are less sensitive to the above problem. On the other hand, CaO-based shrinkage-compensating concretes require a shorter period of wet curing (about 2 days) in order to achieve the final planned expansion. For this reason, their performances in terms of expansion are less affected by deficiencies of curing.

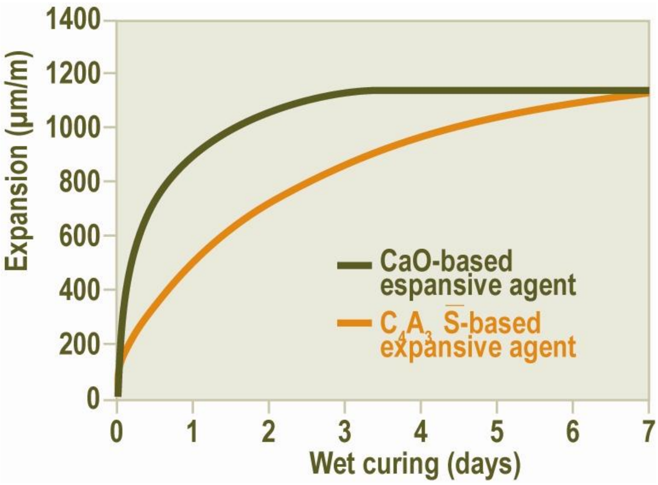

Figure 2   Schematic behavior of CaO based and $C_4A_3\underline{S}$ based shrinkage-compensating concretes

Although it is possible to produce special expansive CaO-based cements it is generally preferred to manufacture CaO-based shrinkage-compensating concretes by adding an external expansive component containing CaO to the concrete made with an ordinary Portland cement. This is possible, from a practical point of view, since reaction (2.1) is substantially not affected by the actual composition of the cement employed and then, the performance of a certain amount of expansive component doesn't change if a cement rather than another is used.

3. COMBINATION OF CaO WITH SRA

SRA (Shrinkage-Reducing Admixtures), generally based on special glycol ethers or other similar organic products, are able to reduce the drying shrinkage of concrete up to 50% if used in 1-2% by mass of cement. According to Berke et al. [5] the effectiveness of SRA must be ascribed to the decrease in the surface tension of water (γ). 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.
Recently [6], the combined addition of a shrinkage-reducing admixture with a CaO-based expansive agent has been found to be very successful in producing restrained expansion in laboratory specimens protected from water evaporation for just 1 day by using a plastic sheet and then exposed to air (60% R.H).
The influence of the SRA on the length change behaviour of a shrinkage-compensating concrete includes two different aspects:

- the β effect in Figure 3 due to a reduction in shrinkage when the concrete is exposed to drying, as expected for the presence of a shrinkage-reducing admixture;
- the unexpected α effect, which consists in the increase of the restrained expansion, which occurs when the concrete is protected from drying, with respect to that obtained without SRA, all the other parameters being the same.

By using a combination of CaO and SRA, then, it is possible to reduce the amount of the expansive agent needed to obtain a given restrained expansion. This reduces the risk of residual un-reacted lime in the concrete.
Moreover, the performance in terms of initial restrained expansion and final restrained shrinkage (or residual expansion), of SRA+CaO-based shrinkage-compensating concretes is less dependant on the curing efficiency so that the practical use of this technique is easier and the results are more reliable.

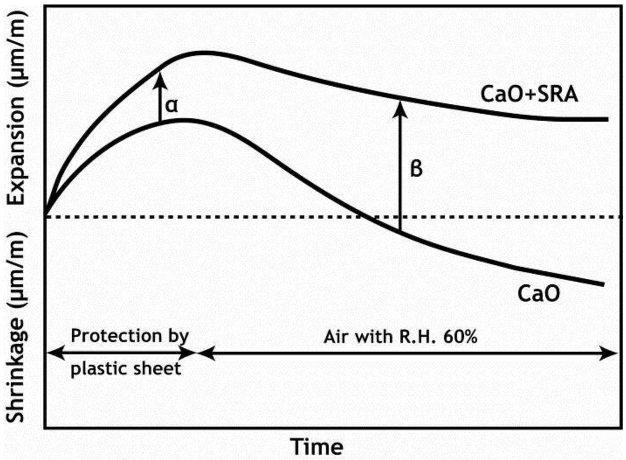

Figure 3 Schematic view of the influence of SRA on the length change behavior of a shrinkage-compensating concrete

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4. CASE HISTORY: SLAB FOUNDATION OF A TWO-STOREY CAR PARK

In this section of the present paper, a remarkable case history of a special reinforced concrete structure is presented where the combined use of a CaO+SRA in a shrinkage-compensating concrete was successfully carried out in order to prevent shrinkage-related cracks and/or joints excessive opening in the presence of adverse curing and thermal conditions. The difficulties encountered in using this technique in a very hot climate will then highlight describing the countermeasures which have been taken to overtake them
For the construction of a two-storey parking building serving the new S. Anna Hospital in Como, according to the original design, it was specified to build a 300 mm thick structural slab foundation, waterproofed, on the upper surface, by a PVC membrane, and covered with a 100 mm thick trowel-finished concrete pavement.
Since the works had totalized a great delay and it was necessary to hand back the whole infrastructure as soon as possible, the contractor asked to abolish the construction of the 100 mm thick pavement and the lay down of the PVC membrane, directly trowel-finishing the 300 mm thick structural slab.
The request was not easy to be satisfied. As a matter of fact, the foundation has a surface area of about 11.000 m^2 and it was conceived by the designer as a monolithic deck without any control joint.
According to ACI 223, by using conventional shrinkage compensating concretes (without SRA) it is possible to build joint-less slabs on grade, in outside areas or where temperature may be subjected to large changes, like in the present case, by placing no more than 650 m^2 of pavement per day, separated by construction joints. These construction joints must be able to allow any relative displacement between two adjacent slab sections, along the plane of the slab. For this reason, the structural deformed still reinforcement must be stopped beside the joint and the connection devolved to smooth plain dowels or concrete keys.
In the present case, it was verified that a work crew was able to place and finish up to 500 m^2 of concrete slab a day but it was not possible to introduce proper “construction joints” between two portions of slab placed in different days, since the actual daily joints must be crossed by the

structural deformed reinforcing bars (Figure 4) and so there wasn't any possibility to allow relative displacements among the daily slab sections.
Moreover, it must be considered that the formation of shrinkage related cracks on the slab surface was not allowed for durability reasons. In fact, the region in which the park is located, is often subjected to snow or ice formation during winter so that the use of chloride based de-icing salts is very frequent on the roads surrounding the car park. For this reason, the cars entering in the building during winter, frequently transport inside water contaminated by chlorides. When the snow melts and drops down on the slab surface, chlorides can easily penetrate and quickly corrode the steel reinforcement in the presence of cracks. Therefore, it was really important to avoid the formation of cracks on the slab upper surface.

Figure 4 Daily joint crossed by structural reinforcement

The concrete placement of the slab was carried out during summertime (from June to September) in outside conditions with temperatures as high as 35°C. In a previous field experience with the use of shrinkage-compensating concrete for the construction of architectural concrete walls 20 meters high and 60 meters long [7] it was found that a combination of high temperatures during placing and long periods of time elapsing between the starting of mixing, in the batching plant, and the casting of concrete into the forms, can strongly reduce the effectiveness of this technique in controlling shrinkage related cracks.
This is due to the strong acceleration induced in CaO hydration by high temperatures so that the expansion takes place too early, when the concrete hasn't still reached the required strength and the steel-concrete bond was not sufficiently high to generate a restrained expansion. The unrestrained concrete expansion doesn't produce any compensation of shrinkage related tensile stresses and so the expansive concrete behaves like a normal one.
It was, anyway, decided to develop a SRA+CaO based shrinkage compensating concrete, adopting some practical devices which will be explained later.
Table 1 shows the specification for the concrete to be used. According to the European Standard EN 206-1, the exposure class of this structure is identified as XD3 (pavements of parking areas). For this class of exposure, the use of a water/cement ratio not higher than 0.45 and a cube characteristic compressive strength not lower than 45 MPa should be used according to the same standard. The specified consistency class was the superfluid S5 according to EN 206-1, in order to accelerate and simplify the placing procedures.
An initial restrained expansion not lower than 400 μm/m in specimens manufactured and stored according to the UNI 8147 method B procedure (but at a constant temperature of 35°C) was specified in order to assure as acceptable behaviour even with higher temperatures. Table 2 shows the composition and the main performances of the concrete.

Table 1 Specifications of the shrinkage-compensating concrete for the two-storey car park foundation

Exposure class (EN 206-1)	XD3
w/c	≤ 0.45
Cube characteristic compressive strength	≥ 45 MPa
Consistency class (EN 206-1)	S5 (slump ≥220 mm)
Restrained expansion after 24 hours (UNI 8147 method B) at 35°C of constant temperature	≥400

In order to assure an acceptable expansive behaviour, a higher amount of expansive component (45 kg/m^3) and of SRA (5 kg/m^3) was used with respect to the usual dosages of these products.
Figure 5 shows the behaviour in terms of restrained expansion or shrinkage of prismatic specimens subjected to different conditions of curing temperature and mixing time.

Table 2 Composition and performances of the shrinkage-compensating concrete

Composition and performances	**(kg/m^3)**
Cement CEM II B/LL 32.5R	360
Gravel 8-25 mm	690
Sand 0-12 mm	200
Sand 0-8 mm	979
Water	156
Acrylic superplasticizer	3.6
CaO-based expansive agent	45
SRA	5.0
w/c	0.43
Slump	230 mm
Mean 28-day compressive strength	53 MPa

In particular, in addition to the specimens manufactured and stored according to UNI 8147 method B some specimens were manufactured at 35°C and stored at the same temperature following, for all the other parameters, the UNI 8147 method B. Part of these specimens were put into the forms after 5 minutes of mixing whereas the others were mixed for 30 minutes before casting being this time that normally employed by the truck-mixers to reach the jobsite from the batching plant.
It was found that an acceptable behaviour could be obtained even at the temperature of 35°C provided that the time between the first contact of CaO with water and the concrete casting could be no longer than 5 minutes. For this reason it was decided to introduce the expansive agent into the truck-mixer at the jobsite immediately before the placing of concrete by means of a special automatic silo (Figure 6). In this way it was possible to carry out the placing of all the slab without any remarkable crack and with no daily joint opening.

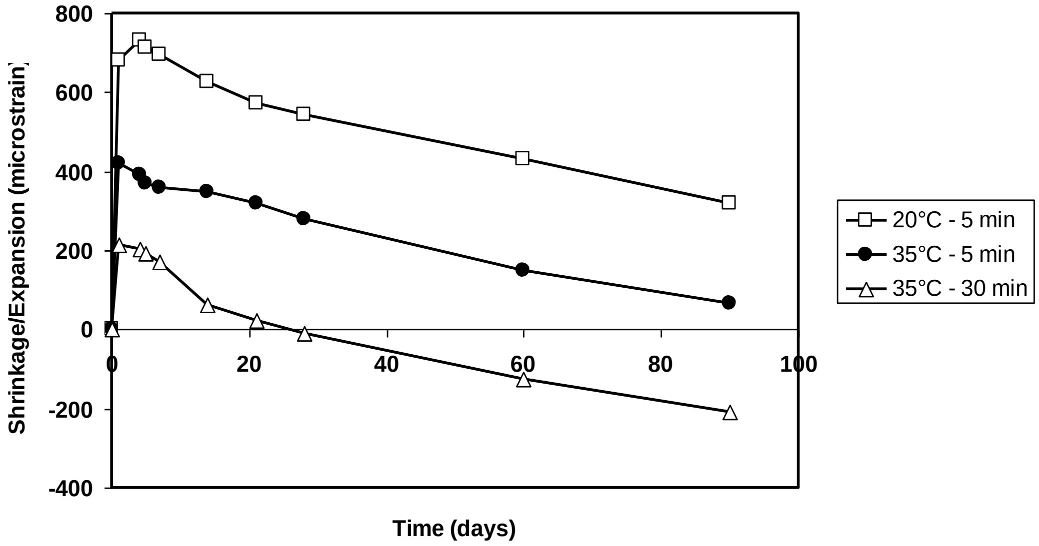

Figure 5 Restrained expansion or shrinkage with different mixing time and temperature curing condition

Figure 6 Supply of the expansive agent at the jobsite with an automatic silo

5. CONCLUSIONS

The use of shrinkage-compensating concretes based on the combination of “dead burnt” lime (CaO) as expansive agent with a shrinkage-reducing admixture (SRA) has several practical and technical advantages with respect to shrinkage-compensating concretes manufactured with sulphate-based expansive cements according to ACI 223.
This technique, was used to successfully place a shrinkage-compensating concrete mixture for 11000 m^2 of a structural monolithic crack-free slab foundation.

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