

# SHRINKAGE-COMPENSATING CONCRETES FOR SPECIAL STRUCTURES

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## 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. All these special binders are based on a controlled production of ettringite.

Another effective method to produce shrinkage-compensating concretes, not covered by ACI 223-98 but commonly used in some countries, like Italy or Japan, 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.

Although the actual cause of this synergistic effect has not been completely explained, the use of this technology in construction industry has been increased, in the last five years, particularly in Italy, with very interesting results.

In this work three remarkable examples of special reinforced concrete structures are 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.

## 1 Shrinkage and Shrinkage related cracks

Drying shrinkage is a volume contraction which occurs in the concrete during hardening, caused by moisture loss. If drying shrinkage could take place freely, without any restraint, it wouldn't represent any problem for most structural and non-structural concrete elements. Unfortunately, because of the presence of internal and external restraints (steel reinforcement, linkage with other portions of the structure, subgrade friction in slab on grade, etc.) drying contraction is partially, or totally, hindered and transformed in tensile stresses.

While concrete is a brittle material, drying shrinkage stresses are often large enough to exceed the tensile strength of the concrete, resulting in cracks formation.

Drying shrinkage cracks represent one of the main problems affecting reinforced concrete structures and elements since they are often cause of early deterioration, loss of serviceability or, simply, aesthetic defects formation.

Actually, the formation of cracks nullifies the adoption of a potentially impermeable, low w/c concrete in assuring the required durability of reinforced concrete structures which are exposed to

environmental aggressive agents such as carbonation and chlorides since steel rebars are immediately subjected to corrosion.

Cracks due to drying shrinkage may compromise the serviceability of concrete pavements subjected to heavy traffic loads or special marine or hydraulic constructions which must assure watertightness.

Finally, cracks may represent a concern even if they compromise the aesthetic aspect of not exposed architectural concrete structures.

## **2 Shrinkage-Compensating Concretes**

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 behavior of a shrinkage-compensating concrete is determined 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 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. According to ACI 223R, 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 anticipated shrinkage. This required expansion may be greater than that strictly necessary to offset drying shrinkage if remarkable thermal contractions during service life are expected and need to be compensated.
- c) Estimation of specimen expansion: The ASTM C 878 specimen expansion which is necessary to provide the required member expansion can be easily obtained by using the graph shown in Figure 1, taken from ACI 223-98 and based on data published by Russell

in 1973). The graph gives the relation between member expansion and specimen expansion as a function of 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 ACI 318 (or those of equivalent codes in force in other countries, such as the eurocodes in the European Community) are satisfied. Furthermore, these stresses are normally destined to disappear with time as shrinkage goes on.

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 2 (ACI 223-98).

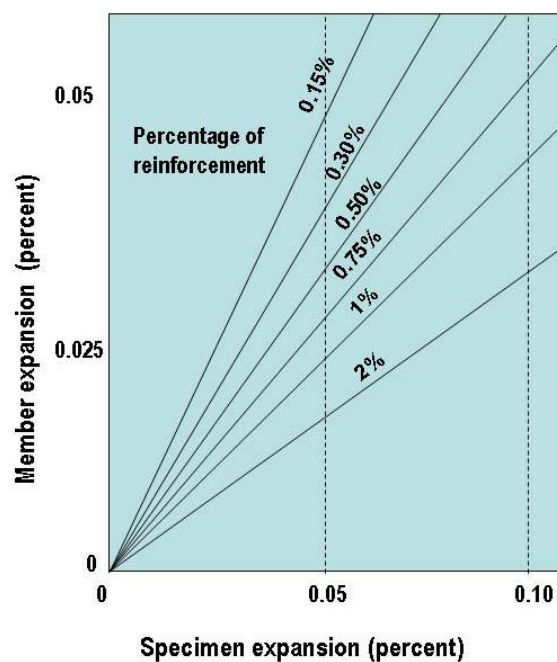


Figure 1 – Member expansion as a function of ASTM C 878 specimen expansion (ACI 223-98)

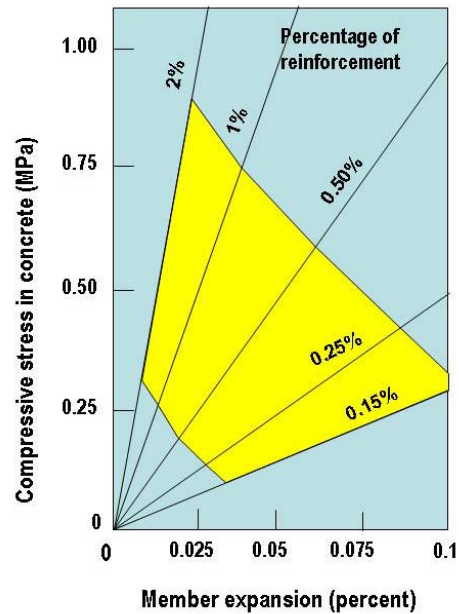


Figure 2 – Concrete compressive stress induced by member restrained expansion (ACI 223R-98)

### 3 Expansive Cementis

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

The first examples of expansive cements were developed in Russia and in France. In particular, in the early 40<sup>th</sup> of the previous century Lossier [3] realized an expansive cement by mixing an ordinary portland cement with an expansive agent, based on calcium sulphate and calcium aluminates, and a stabilizer consisting in blast furnace slag.

The expansion was given by the reaction between calcium sulphate, calcium aluminates and water to form ettringite. The control of the expansion was delegated to the blast furnace slag which gradually substituted calcium aluminates in the reaction with calcium sulphate bringing it to an end. In the following years several expansive cements were ideated most of all based on a controlled production of ettringite.

ASTM C845-90 and ACI 223-98 classify the following three different types of expansive cements:

- 1) type K (Klein cement), containing  $C_4A_3\underline{S}^1$ , calcium sulphate ( $CaSO_4$ ) and free  $CaO$ ;
- 2) type M, produced by blending portland cement with calcium aluminates  $CA^1$  and  $C_7A_{12}^1$ ;
- 3) type S, which contains excess of  $C_3A^1$  and  $C\underline{S}^1$  with respect to that usually found in portland cements.

Among the above listed expansive cements, the most diffused is the type K which can be alternately produced by intergrinding portland cement with a separately burned expansive component or simultaneously burning all components to obtain an expansive clinker.

The expansive reaction which takes place in both cases can be represented as follows<sup>1</sup>:



<sup>1</sup> Cement chemistry contracted symbology: C = CaO, A = Al<sub>2</sub>O<sub>3</sub>, S = SiO<sub>2</sub>, H = H<sub>2</sub>O and S = SO<sub>3</sub>

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 that is needed to offset later drying shrinkage.

Figure 3 shows the effect of various curing method on expansion. Pounding, continuous sprinkling or wet coverings are preferred since adequate water for ettringite formation and expansion is ensured. Other curing methods such as those involving the use of moisture-proof covers can reduce the initial expansion up to 50% with respect to that obtained using methods that provide additional moisture to the concrete. Sprayed-on membranes or other curing compound can be completely unsuccessful if they don't provide a complete coverage of the entire concrete surface and don't prevent loss of moisture for a minimum of 7 days.

An incomplete initial expansion, due to curing deficiencies, is twice negative since final drying shrinkage cannot be offset and considerable amounts of un-reacted sulphate remain in the structure and can produce local delayed expansion in service which can prove disruptive as in the case with external sulphate attack [5].

The strong dependence of expansive cements effectiveness on a continuous wet curing for several days and the danger of possible disruptive later expansion, in the case of deficient curing, are two concerns which have strongly limited the diffusion of shrinkage-compensating concretes in the manufacturing of reinforced concrete structures.

Another disadvantage in the use of sulphate based expansive cements in the production of shrinkage-compensating concretes occurs in the case of simultaneous use of plain and shrinkage-compensating concrete in the same structure. In this case it is necessary to provide two different silos in the batching plant for the two different cement.

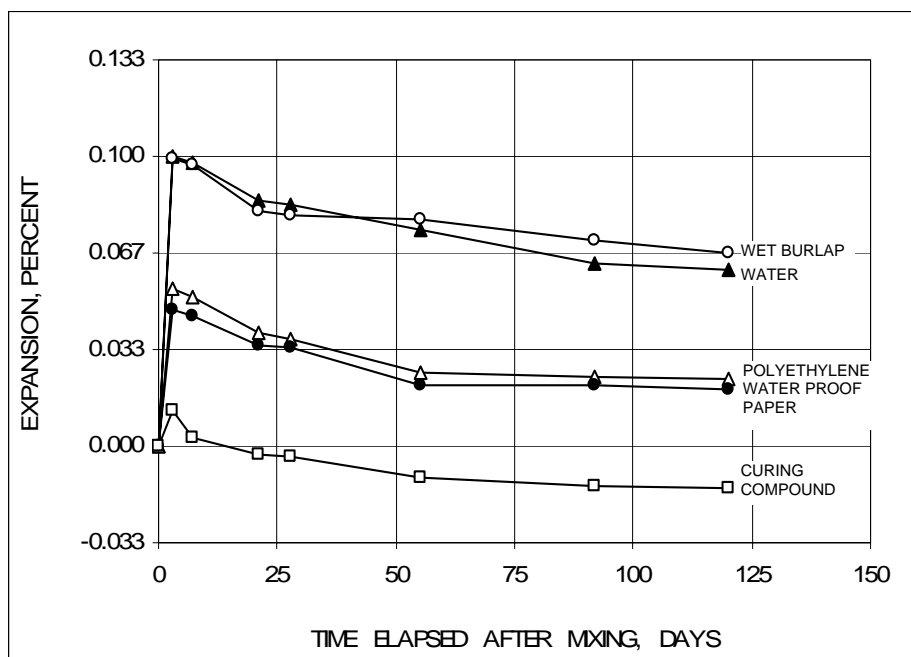


Figure 3 - Effect of different methods of curing on expansion of shrinkage-compensating concrete [2]

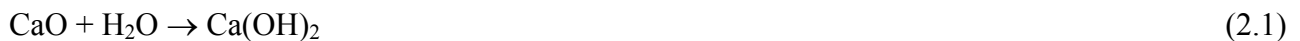
Sulpho-aluminate based expansive external components have been developed in the past, to be added to ordinary portland cement in the manufacturing of shrinkage-compensating concretes. But these expanding agents have not found a large employ since their performance can strongly depend from the composition of the specific cement used.

In fact, the reaction which leads to formation of ettringite involves substances like calcium sulphate and calcium aluminates which are also contained, in variable forms and amounts, in ordinary portland and portland based cements, so that, the amount of ettringite which is formed by a specific amount of an external sulpho-aluminate based expansive component, can be significantly different if one cement rather than another is used.

For the same reason an improper dosage of the external sulphate based expansive component, in relation with the specific cement used, can lead to an unwanted amount of un-reacted sulphate into the concrete.

#### 4 CaO (and MgO) Based Shrinkage-Compensating Concretes

Another method to produce shrinkage-compensating concretes is that based on the expansive reaction which occurs between *lime* (CaO) and/or *periclase* (MgO) and water to produce calcium and magnesium hydroxide according to the following reactions:



Normal CaO and MgO, obtained by burning *limestone* or *dolomite* at a temperature of about 900°C, and used in agriculture or to manufacture *hydrated lime* and *brucite* for masonry mortars and plasters, are not suitable as expansive components. In 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 agent, 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 4 schematically shows the retrained expansion, determined according to the ASTM C 878 test method, in a *dead burnt lime*<sup>2</sup> 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.

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<sup>2</sup> More available than MgO

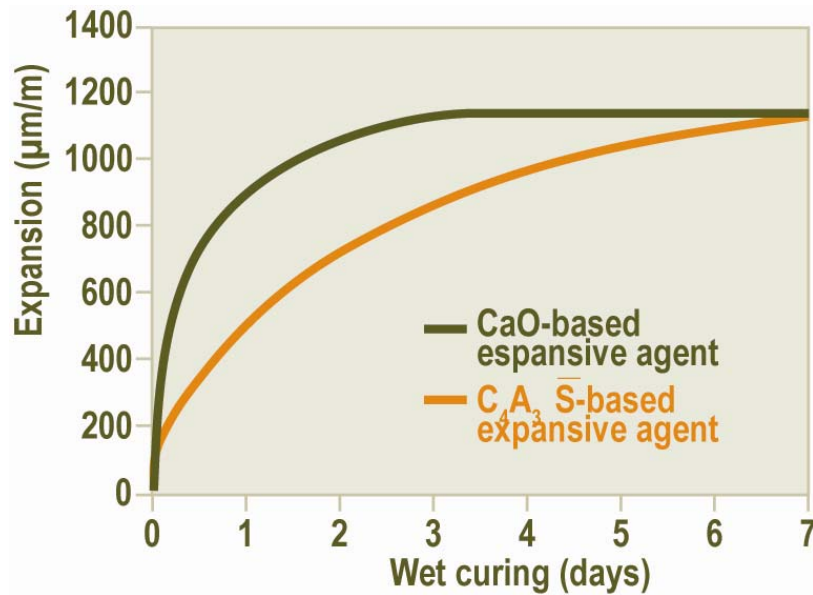


Figure 4 – Schematic behavior of CaO based and  $C_4A_3S$  based shrinkage-compensating concretes

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].

Being sulpho-aluminate expansive reaction 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 and there is a lower risk of the presence of residual un-reacted CaO in the concrete which could cause later expansion.

Although it is possible to directly produce special expansive CaO-based cements (called type O cements) it is generally preferred to manufacture CaO-based shrinkage-compensating concretes by adding an external expansive component 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 used and then, the performance of a certain amount of expansive component doesn't change if one cement rather than another is used.

There are several advantages in the use of an expansive agent instead of expansive cement in manufacturing shrinkage-compensating concretes:

- a) it is possible to optimize the chemical expansion without changing the amount of cement and other raw materials in the concrete, with obvious simplification of mix design procedures;
- b) in the case of simultaneous use of plain and shrinkage-compensating concrete in the same structure, it is possible to use the same raw materials (except for the expansive agent) to produce both the mixes, obtaining more uniformity of performances and rationalizing the production;
- c) the combined use of an ordinary portland cement and a CaO-based expansive agent to produce shrinkage-compensating concretes is generally cheaper than the use of a special sulpho-aluminate based cement.

## 5 SRA and their combined use with CaO base Expansive Components

SRA (Shrinkage-Reducing Admixtures), are generally based on *propylene-glycol ether*, *neo-pentyl glycol* or other similar organic substances, that 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. [6] the effectiveness of SRA must be ascribed to the decrease in the 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 (Figure 5).

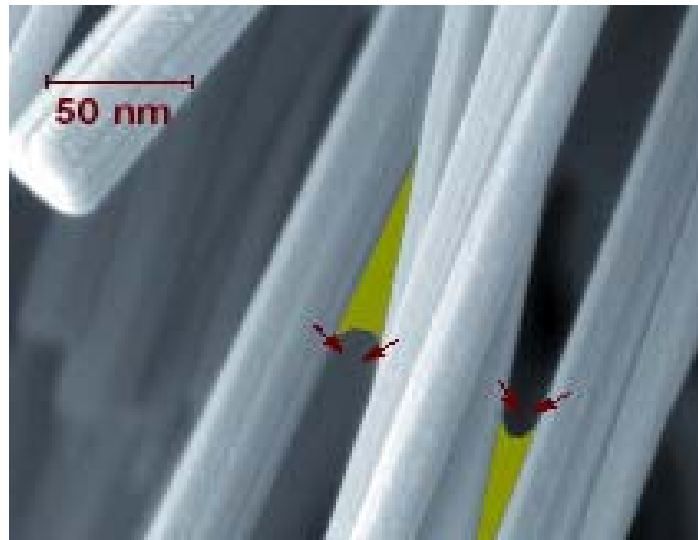


Figure 5 – Water menisci interact with C-S-H fibers determining the shrinkage on cement paste

Recently [7], 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 of 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  $\beta$  effect in Figure 6 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  $\alpha$  effect, which is an increase in the restrained expansion 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 expansive agent needed to obtain a fixed restrained expansion. This reduces the risk of residual un-reacted lime in the concrete.

Furthermore, 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.

The synergistic  $\alpha$  effect in Figure 6 has been confirmed by Maltese et al [8] who have found that the use of a CaO-based expansive agent with a shrinkage reducing admixture allows to obtain

mortars less sensitive to drying. These authors hypothesize that the synergistic effect of the SRA-CaO combination must be ascribed to the massive formation of CaO elongated crystals during the first hours of curing.

The same authors in [9] propose another mechanism of action: since the SRA is an organic hydrophobic molecule, it could reduce the water solubility of CaO, retarding its reaction and, then, increasing the restrained expansion according to Chatterji [10].

Otherwise, Tittarelli et al. [11] have found that SRA doesn't affect the speed of CaO reaction with water.

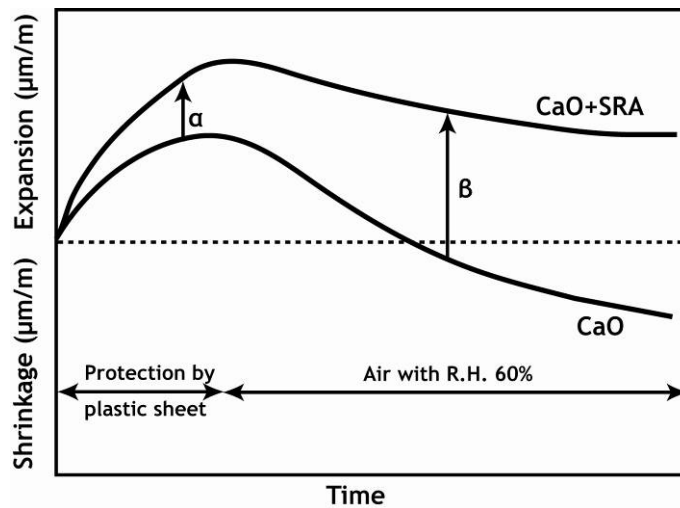


Figure 6 - Schematic view of the influence of SRA on the length change behavior of a shrinkage-compensating concrete

Although this synergistic effect has been confirmed by several authors, the actual mechanism of action needs further investigations in order to be completely understood.

Notwithstanding this lack of knowledge, the use of this technology, in the construction industry, has been growing in the last 5 years with many successful and very interesting results.

In the second part of this paper, three remarkable case histories of special reinforced concrete structures are 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 and thermal conditions.

The difficulties encountered in using this technique, in each case, will then highlight describing the countermeasures which have been taken to overcome them.

## 6 Case History 1 – MAXXI of Rome

The Museum of Arts of XXI century (MAXXI) in Rome was the first relevant Italian construction in which a SRA+CaO-based shrinkage-compensating concrete has been used (2004-2006).

For this very prestigious building, the designers (Zaha Hadid Limited, London, U.K.) had proposed the construction of several architectural concrete walls (20 meters high and 60 meters long) having a sinuous shape and no contraction joints (Figure 7).

A special CaO-SRA based shrinkage-compensating self-compacting concrete (SCC) was studied in order to assure a marble-like look, as required by the designers, even in the presence of a very

congested reinforcement (Figure 8) and, in the same time, to avoid the formation of shrinkage related cracks along the surface.

In order to demonstrate the effectiveness of this type of concrete in offset the formation of shrinkage cracks, its performances were compared to those of an ordinary CaO-based shrinkage-compensating concrete (without SRA) and of a plain SCC mixture without expansive component and SRA.

Table 1 shows the composition of these three SCCs having the same w/c (0.48) and approximately the same cement dosage ( $350 \text{ kg/m}^3$ ).



Figure 7 - View of bent and joint-less walls of the MAXXI, Rome, Italy



Figure 8 – Example of steel congestion in a typical wall of MAXXI, Rome, Italy

Table 1 – Composition of three different SCC

Mix	CaO+SRA	CaO	Plain
Cement CEM II A/L 42.5R (kg/m <sup>3</sup> )*	350	348	347
Limestone filler (kg/m <sup>3</sup> )	150	149	183
Gravel 4-16 mm (kg/m <sup>3</sup> )	847	884	871
Sand 0-4 mm (kg/m <sup>3</sup> )	908	916	903
Water (kg/m <sup>3</sup> )	167	167	166
Acrylic superplasticizer (kg/m <sup>3</sup> )	6.3	6.2	6.3
CaO-based Expansive Agent	35	35	\
Viscosity modifier (kg/m <sup>3</sup> )	4.2	4.1	4.3
SRA	4.0	\	\

(\*) Blended Portland-limestone cement according to EN 167/1

Figure 9 shows the strength development with time of the three compared SCCs (CaO-SRA, only CaO and Plain). The strength of the expansive concretes was higher than that of the plain mix. This is probably due to the consumption of a small part of mixing water caused by the transformation of CaO into Ca(OH)<sub>2</sub> which happens when the concrete is still in the plastic state and to the consequent reduction of the actual w/c.

On the other hand, a slight decrease in the compressive strength of the SRA+CaO mix was recorded if compared to that of the CaO mix due to the presence of SRA as experienced in [12].

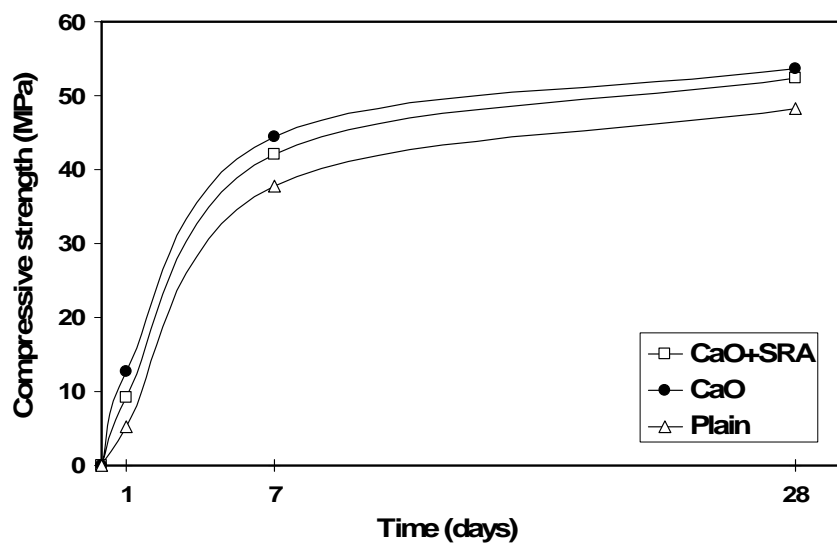


Figure 9 – Strength development of three different SCCs

Although it was specified to protect the concrete surface for at least three days (to assure a correct hydration of the concrete cover) shrinkage compensating concrete was designed in order to warranty a residual restrained expansion of about 200 μm/m even in case of deficient curing consisting in just 24 hours of protection by the formwork.

Figure 10 shows the length change of the reinforced prismatic specimens manufactured with the three different SCCs according to ASTM C 878. Specimens were not put under water for 7 days as specified in ASTM C 878 test method but were protected with a plastic film for just 24 hours (to simulate the protection offered by the formwork) and then exposed to unsaturated air (60% R.H.) at 20°C.

This curing condition was later introduced as “curing method B” in the last version of the Italian standard UNI 8147 in addition to the “curing method A” previously specified, consisting in a total

immersion in water for 7 days as in ASTM C878. Actually, the curing method B appears to be more realistic and similar to jobsite conditions.

Even under these un-favorable conditions of curing, the CaO-SRA shrinkage-compensating concrete performed very well since the restrained expansion after 24 hours of protection with a plastic film was as high as 560  $\mu\text{m}/\text{m}$  and, even after 140 days of exposure to unsaturated air, a residual restrained expansion of about 250  $\mu\text{m}/\text{m}$  was recorded. On the contrary, the conventional CaO-based shrinkage compensating concrete showed a lower initial expansion (at least 320  $\mu\text{m}/\text{m}$ ) which completely disappeared after a week of exposure to air after which, the concrete started to shrink.

Obviously, the plain concrete showed the worst performance reaching a restrained shrinkage of about 550  $\mu\text{m}/\text{m}$  after 60 days when some cracks appeared on the specimen surface.

Comparing the behaviour of the CaO+SRA-based mix to that of the conventional shrinkage-compensating concrete, both the  $\alpha$  and  $\beta$  effect of Figure 6 can be detected.

On the basis of the above results, the customer and the contractor decided to adopt the SRA+CaO-based shrinkage-compensating SCC for the manufacturing of all the architectural concrete walls of MAXXI.

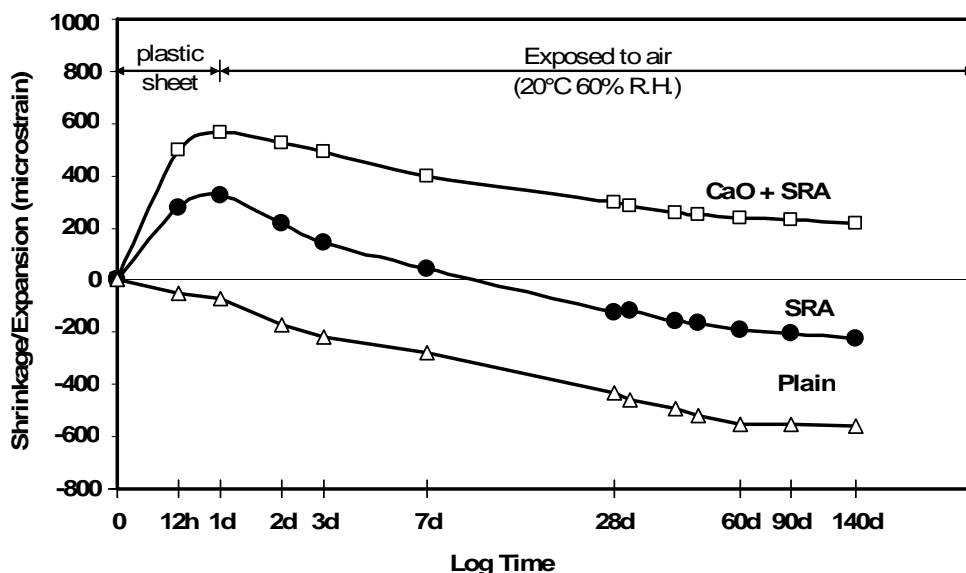


Figure 10 – Length change with time of the three different SCCs

Since it was the first time the contractor used an SCC, it was decided to carry out several field tests, before starting with the manufacturing of the actual walls, in order to optimize all the casting procedures and test the suitability of formwork. It was, then, a good chance to test on a real scale the effectiveness of the expansive technique.

Two field tests were successfully carried out in March and April of 2004 with no cracks formation in two long minor walls of the basement.

A third test carried out in June in order to verify the behaviour of the expansive concrete in the presence of high temperature failed since after two weeks, some cracks appeared on the wall surface. The maximum temperature during the casting operation was as high as 35°C and checking the transport documents of the trucks mixer it was verified that, because of the congested traffic of Rome, the time elapsed between the starting of mixing, in the batching plant, and the casting of concrete into the forms had been in the range of 60-90 minutes, notwithstanding the batching plant were located near the jobsite.

For this reason the cause of the failure was ascribed to a combined effect of the high temperature and of a too prolonged mixing time. This hypothesis was confirmed by laboratory tests in which some ASTM C878 prismatic specimens were manufactured at 20°C (with raw materials kept at 20°C for 24 hours before the use) whereas other similar specimens were manufactured at 30°C (with raw materials kept at 30°C for 24 hours before the use). In both cases, some specimens were put into the forms after 5 minutes of mixing whereas the others were kept in the mixer (in movement) for 60 minutes before casting at the same temperature of manufacturing (20 or 30°C).

After setting time (about 6 hours) the specimens were demoulded and protected with a plastic film till 24 hours, at the same temperature of manufacturing (20 or 30°C). Successively, the specimens were exposed to unsaturated air (60% R.H.) at the temperature of manufacturing (20 or 30°C).

Figure 11 shows the behavior, in terms of restrained expansion or shrinkage, of the various specimens manufactured.

As expected, the specimens manufactured and cured at 20°C performed well showing a residual restrained expansion in the range of 210÷280 µm/m after 28 days of exposure.

The prolonged mixing (at the same temperature of 20°C) caused a decrease of the initial as well as in the residual expansion as reported in [2].

A little higher decrease was recorded in the expansion of the specimens manufactured and kept at 30°C and cast after 5 minutes of mixing. Anyway the behaviour of these specimens can be considered acceptable.

On the contrary, the combination of a high temperature of manufacturing and curing and a prolonged mixing cause a strong reduction in the initial restrained expansion which was completely cancelled after just one week after which the concrete started to shrink.

The problem was not eliminated by increasing the amount of expansive agent au to 45 kg/m<sup>3</sup> so that, being impossible to assure a transportation time lower than 60 minutes, the contractor decided to delay the begin of the main wall construction to the autumn and to stop it during the whole next summer.

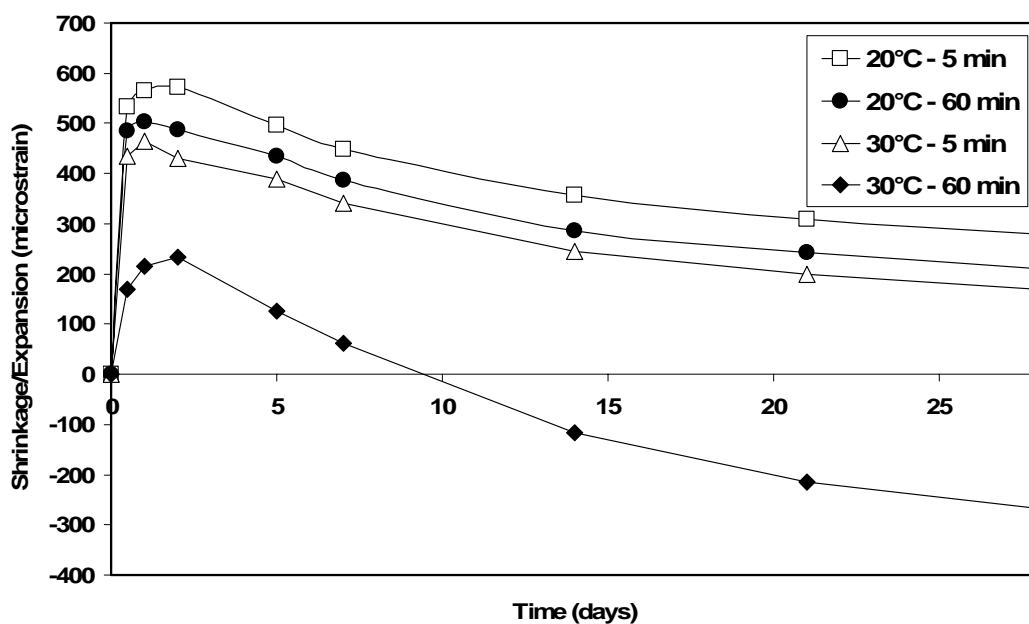


Figure 11 - Restrained expansion or shrinkage in different manufacturing and curing condition

## 7 Case History 2 – Slab foundation of a two storey car park

The second case history concerns the recent construction of the wide slab foundation of a two-storey parking building which will serve a new hospital in the North of Italy.

The designer had specified the construction of a 300 mm thick structural slab on grade, waterproofed of 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, directly trowel-finishing the 300 mm thick structural slab. The request was not easy to be satisfied for the following reasons

a) The foundation has a surface area of about 11.000 m<sup>2</sup> and it was thought 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 place joint-less slabs on grade, where temperature may be subjected to large changes, like in the present case, in areas as large as 650 m<sup>2</sup> separated by construction joints. Always according to ACI 223, 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 steel reinforcement must be stopped beside the joint and the connection devolved to smooth plain dowels or concrete key.

In this case, it was verified that a work crew was able to place and finish up to 500 m<sup>2</sup> a day but the daily joints could not be considered actual “construction joints” according to ACI 223 since they must be crossed by the structural deformed rebars (Figure 12) and so there wasn't any possibility to allow relative displacements among the daily slab sections.

On the other hand, the formation of shrinkage related cracks was not allowed for durability reasons. In fact, the region is frequently subjected to snow or ice formation during winter so that there is a regular use of chloride based de-icing salt on the outside roads. In this situation, the cars entering in the park, transport snow contaminated by chlorides that easily penetrate and quickly corrode the steel reinforcement in the presence of cracks.



Figure 11 – Daily joint crossed by structural reinforcement

b) The placing of the slab had to be carried during summertime (from June to September) in outside conditions and with temperature as high as 35°C. As shown in the previous case history, these conditions are non suitable for the use of shrinkage compensating concretes.

Anyway, it was decided to develop a SRA+CaO based shrinkage compensating concrete, adopting some practical devices which will be explained later.

Table 2 shows the specification for the concrete to be used. According to the European Norm EN 206-1, the class of exposure of this structure is identified as XD3 (pavements of parking areas). For this class of exposure, the use of a w/c ratio not higher than 0.45 and a characteristic compressive strength on cubes not lower than 45 MPa should be used according to EN. 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 30°C) was specified in order to assure an acceptable behavior even with higher temperatures. Table 3 shows the composition and the main performances of the concrete studied.

Table 2 – Specifications of the shrinkage-compensating concrete for the two-storey car park

Exposure class (EN 206-1)	XD3
w/c	≤ 0.45
Characteristic compressive strength (on cubes)	≥ 45 MPa
Consistency class (EN 206-1)	S5 (slump ≥220 mm)
Restrained expansion after 24 hours (UNI 8147 method B) at 30°C of constant temperature	≥400

In order to assure an acceptable expansive behavior, a higher amount of expansive component (45 kg/ m<sup>3</sup>) and of SRA (5 kg/m<sup>3</sup>) was used with respect to the usual dosages of these products.

Figure 13 shows the behavior in terms of restrained expansion or shrinkage of prismatic specimens subjected to different conditions of curing temperature and mixing time.

Table 3 – Composition and main performances of the shrinkage-compensating concrete for the two-storey car park

Mix	(kg/m <sup>3</sup> )
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 compressive strength at 28 d	53 MPa

(\*) Blended Portland-limestone cement according to EN 167/1

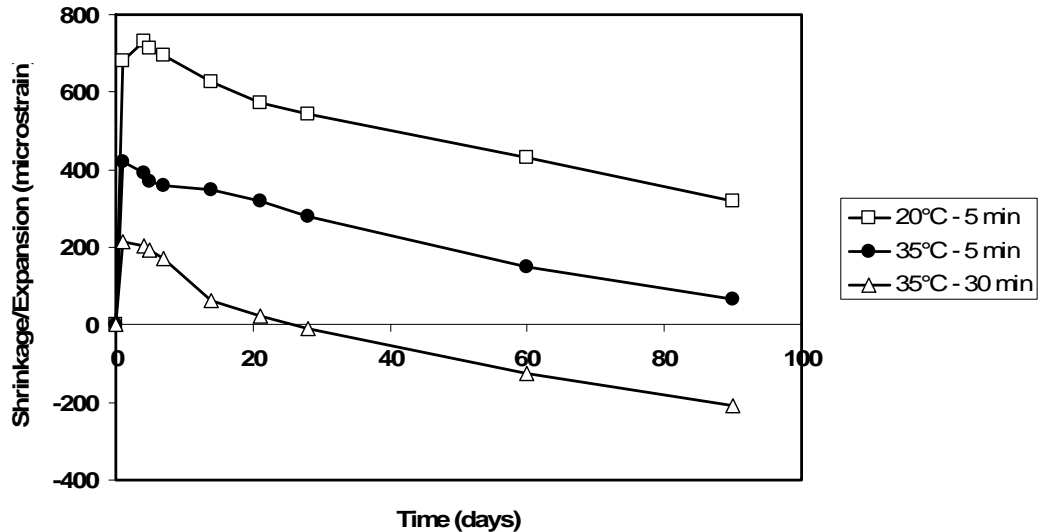


Figure 13 - Restrained expansion or shrinkage in different manufacturing and curing condition

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 trucks to reach the jobsite from the batching plant.

It was found that an acceptable behavior could be obtained even at the temperature of 35°C provided that the time between the first contact of CaO with water and concrete casting could be no longer than 5 minutes.

For this reason it was decided to introduce the expansive agent directly into the truck mixer at the jobsite immediately before the placing of concrete by means of a special automatic silo (Figure 14). 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 14 – Supply of the expansive agent at the jobsite with an automatic silo

## 8 Case History 3 – Navigation lock

The third case here discussed concerns the realization of a navigation lock for small touristic ships.

The lock was constituted by two parallel and twin channels (one for each way of navigation) approximately 90 m long and 12 m wide. The base of each channel was a 2 m thick slab having no joint along the whole surface of approximately 1000 m<sup>2</sup>. The slab had to be placed on a concrete sub-base previously realized with an underwater casting and inside a curtain of steel sheet piles. Since the batching plant was able to produce 500 m<sup>3</sup> a day, it was decided to place the slab in four different layers 50 cm thick (Figure 15).

From a durability point of view, the first three layers have not problems of corrosion since they are permanently under water and don't are in contact with oxygen (exposure class XS2 according to EN 206-1).

On the other hand, the 4<sup>th</sup> upper layer can be periodically in contact with air and oxygen in the case of maintenance procedures which require the emptying of the channel. (exposure class XS3 according to EN 206-1)

In this case, in the presence of cracks on the surface of the 4<sup>th</sup> layer rapid corrosion of steel rebar could then occur. In order to avoid the formation of cracks on the upper surface of the 4<sup>th</sup> layer, it was decided to manufacture it by using a shrinkage compensating concrete. In particular, the three lower layers were manufactured by using an ordinary flowing concrete whereas for the placing of the last layer, a CaO-based expansive agent and a liquid SRA were added to the plain mix. This assured a great uniformity of mechanical characteristics among the various layers.

Like in the previous case history, the placing of this slab had to be executed in summer with relatively high temperature (30°C of max temp.).

The time of transportation was not a problem in this case since the batching plant was located beside the jobsite, but there were other problems related to the massive structure and the consequences in terms of heat of hydration.

For this reason a low heat flowing concrete was developed by using a pozzolanic cement at a relatively low content (360 kg/m<sup>3</sup>) considering the w/c of 0.45 required for durability reasons and the high workability necessary to simplify the placing. It was obtained by using high dosages of an effective acrylic superplasticizer. In order to further delay the production of heat of hydration, a gluconate-based retarder was added.

The same mix was used for manufacturing the shrinkage-compensating concrete just adding the expansive agent (40 kg/m<sup>3</sup>) and the SRA (5.0 kg/m<sup>3</sup>).

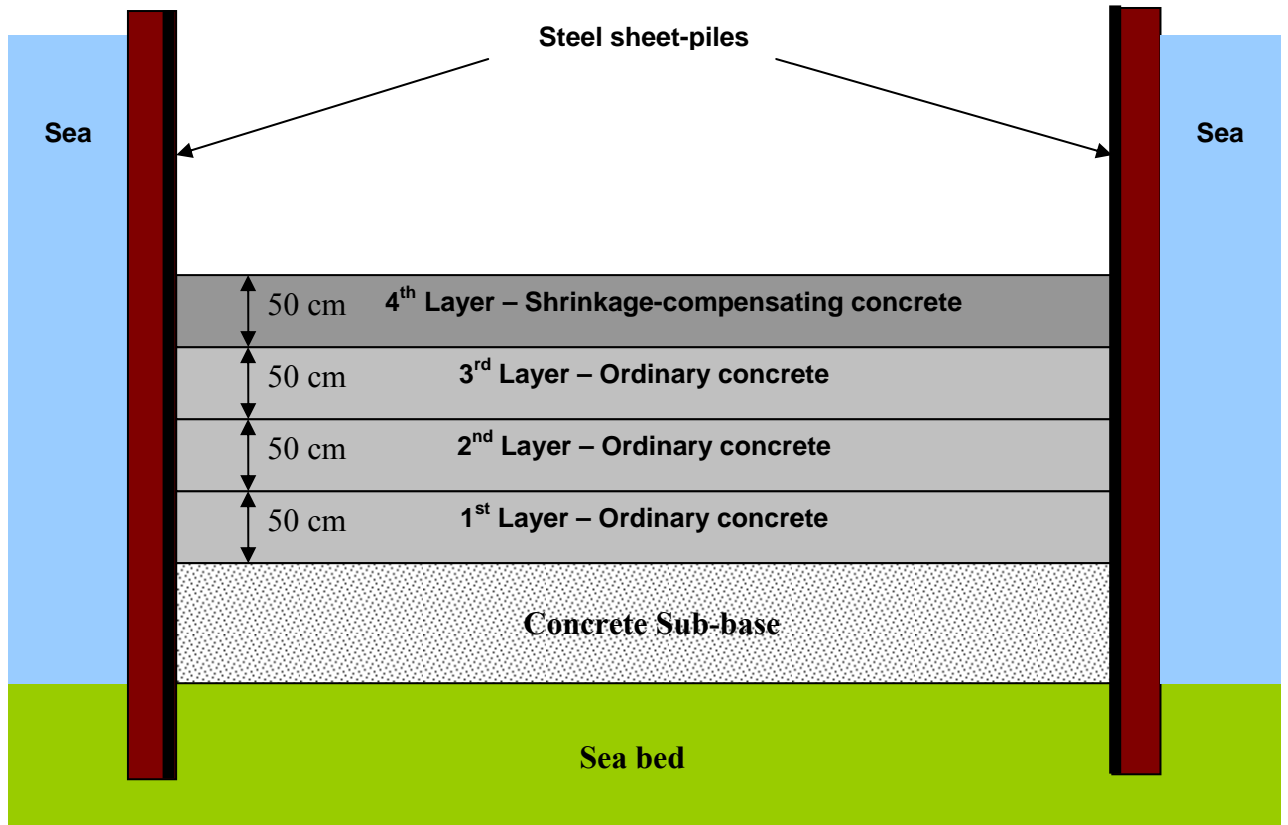


Figure 15 – Schematic section of one of the channels of the navigation lock

Table 4 shows the composition of the two mixes (plain and shrinkage compensating).

Table 4 – Composition and main performances of the plain and the shrinkage-compensating concrete used for the navigation lock slab

Mix	Plain	Shr. Comp.
Cement CEM IVA/P-V 32.5R (kg/m <sup>3</sup> )*	360	358
Gravel 15-25 mm (kg/m <sup>3</sup> )	550	544
Gravel 5-15 mm (kg/m <sup>3</sup> )	550	544
Sand 0-5 mm (kg/m <sup>3</sup> )	922	864
Water (kg/m <sup>3</sup> )	150	152
Acrylic superplasticizer (kg/m <sup>3</sup> )	5.1	5.3
Retarder (kg/m <sup>3</sup> )	1.2	1.2
CaO-based Expansive Agent	\	40
SRA	\	5.0
w/c	0.42	0.42
Slump	255 mm	250 mm
Mean cubic compressive strength at 28 days	61.5 MPa	63.8 MPa

The restrained expansion of specimens kept at 30°C was of 320 µm/m after 24 hours of protection with a plastic film (UNI 8147 method B). This value was considered sufficient because of the great thickness of the concrete member and the consequent low anticipated shrinkage.

A semi-adiabatic test was carried out to verify the rise in temperatures due to the heat development. In particular, a cube with 50 cm of side was cast having all the faces covered by a thick layer polystyrene except for the upper surface which remained exposed to the air put constantly at 30°C

(Figure 16). In this way, the placing of a 50 cm thick layer was simulated and the temperature change with time inside and on the exposed surface was measured.



Figure 16 – Semi-adiabatic test to simulate the placing of a layer of slab.

Figure 17 shows the results of this test. The temperature inside the cube rose up to 55.4 °C after about 40 hours and then decreased to 38°C after 5 days. On the upper exposed surface the temperature rose to 48.6°C and then became in equilibrium with the external air after 4 to 5 days.

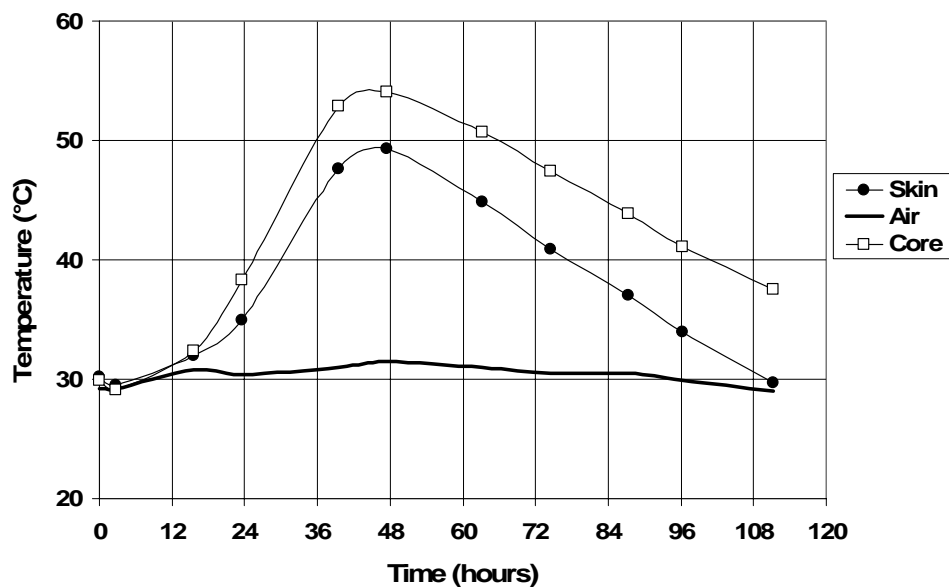


Figure 17 - Temperature change with time in the core and on the exposed surface of a 50 x 50 x 50 cm cube

For this reason it was specify to wait 5 days before placing the 4<sup>th</sup> shrinkage compensated layer of slab. The placing was completed in August without any remarkable crack appeared on the upper surface of the slab.

## 9 Conclusions

Shrinkage-compensating concretes based on the combination of an expansive component containing dead burnt lime and a liquid SRA seems to have several practical and technical advantages with respect to those manufactured with sulphate-based expansive cements according to ACI 223.

This technique has shown, in several practical applications, to be very effective in enhancing the “robustness” of the structure against the appearance of shrinkage relating cracks and in transforming the “potential durability” of a low w/c concrete in the “actual durability” of the structure.

Further investigation are needed to better understand the mechanism of interaction between CaO and SRA which causes the already demonstrated synergistic effect in terms of enhanced initial restrained expansion in the UNI 8147, “method B” test.

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