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PERFORMANCE-BASED PROPOSAL FOR PRECAST SELF-COMPACTING CONCRETE (SCC) SEGMENTS

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Abstract. *Under a PB approach, it is possible to produce tailored materials which should perform according to the specified needs. If focus is put on durability issues, the rational procedure would be to state the required life cycle, i.e., number of years of serviceability with no major maintenance work. This paper deals with the design criteria undertaken to the production of a precast element with a predetermined service life of 100 years. The PB approach requires for the specification and quality control procedures to be harmonised and thus, suitable indicators and subindicators of the required performance have to be selected. The deterioration over time is represented by a service-life model, not discussed in this paper. The requirements for the mix at the fresh state and the effect of the curing regime in a typical precast cycle have not been neglected and thus they contribute to the performance-based requirements. Durability design under a PB approach is a significant step forward to extend service life of precast elements, such as tunnel linings.*

1 INTRODUCTION

The use of Self-compacting Concrete (SCC) in the precast industry has shown a steady increase over the last years, as the advantages are many, such as reduction in manpower, a reduction in noise and vibrations, longer life to moulds and improved finishing characteristics. Nevertheless, the use of SCC for tunnel segments has been limited.

Nowadays, the requirements associated to service life of some underground construction have been extended to 100 years or more and thus, materials used have to be designed and produced accordingly [1]. Common prescriptive indications of Codes and Standard [2], [3] cannot deal with innovative materials and technologies and although there is a trend on shifting toward mixed proposals (prescriptive + performance-based), a lot of work and practical experience is needed for a non-controversial agreement on that matter to be reached.

Performance-based design and characterization is an innovative procedure which first look at the global requirements for the product to be designed. These requirements might be considered in four groups: economical, functional, environmental and social-cultural. For each of these requirements, performance indicators must be defined and then, suitable sub-indicators must be found to refine the performance assessment, as it is shown in Table 1 [4], [5]

General requirements (GR)	***Performance Indicator (PI)***	***Performance Sub-Indicators (PSI)***
Economical	Costs	Direct costs of materials and construction Indirect costs due to the lack of operatibility Indirect costs due to loss of investments during repair Maintenance costs
Functional	Structural stability - Safety	Checking of the structure strength Considerations about a failure that could happen Experience
	Durability	Service life Accidental attacks Environmental conditions Quality control Compatibility
	Execution	Execution control Execution difficulties Perturbations, environnemental impact Safety and health of workers Climatic conditions
Environmental factors	Health & Sustainability	Environmental effects Resources consume Safety of users
Social and cultural	Social perception (public confidence)	Insurance and future liabilities Strength of local economy Improvement of asset values Cultural Heritage

Table 1 : Schema for the performance-based definition including indicators and sub-indicators.

The general criterion described in Table 1 can be specifically applied to the design and characterization of self-compacting concrete (SCC). Self-compacting concrete can be defined as a concrete that does not require other compaction effort than its own weight to achieve full compaction, with no segregation. Its main characteristics (flowing ability, passing ability and stability, i.e. no segregation) are related mainly to the fresh state. Nevertheless, its behavior at the hardened state has to be considered under structural and durability issues [4], [5]. The production cycle has also to be considered as the usual steam curing process might affect long-term properties of the material.

These industrial and technological needs [1], [6] have to be assessed in a quantitative manner and, as a result, suitable sub-indicators associated to specific testing methods have to be chosen or defined. These specific protocols for testing and sampling have to be used for validation or verification the compliance to conformity criteria and then (according to the value obtained) to determine the acceptance or rejection of the material, structural element or structure taken as a sample. At the design stage, only some of the functional requirements can be considered for the evaluation, and among them, only the ones indicated on Table 1 will be included as preliminary validation.

Functional requirement	***Performance indicator (PI)***	***Performance Sub-indicator (PSI)***	***Testing methods (TM)***
No-need for compaction (vibration)	Self-compacting ability –	Slump-flow (flowability) T50 (resistance to segregation)	ASTM C 1611, Test Method for Slump Flow of Self-Consolidating Concrete Visual examination
Precast application	Early-age mechanical properties Low-sensitivity to production cycle	Early-age compressive strength. Low-sensitivity to accelerated curing cycle	EN 12390-3:2000
Suitable structural behaviour	Mechanical strength Stiffness	Compressive strength Static Elasticity Modulus	EN 12390-3:2000 ASTM C469-02e1
100-years service life	Outstanding durability under determined exposure conditions	Durability performance indicators will be addressed according [7], [8].	

Table 2 : Schema for the performance-based definition of Functional requirements including its associated testing methods [7], [8], [9], [10], [11], [12], [13], [14], [15]

2 MATERIALS SELECTION AND CONCRETE PROPORTIONING

There exist different self-compacting concrete types: the powder-type, VMA-type (viscosity-modifier admixture) and the combined type. As the powder-type was chosen, based on the availability of limestone filler in the Spanish market, 63-μm nominal size limestone filler was selected to improve concrete viscosity. Maximum size of coarse aggregate was limited to 12 mm and the flowing ability was assured by a 5th generation high-range water reducer admixture, provided by SIKA Spain.

The effect of the limestone filler on water demand, compressive strength and mix stability was assessed on mortar tests, whose description is beyond the scope of this paper. Nevertheless, it is worth to mention that the nucleation effect of the filler was noticeable, as the increase in the filler-to-cement ration lead to a higher strength for a given water-to-cement ratio, as can be seen in Figure 1. The water-retention capability of the limestone filler selected was also verified.

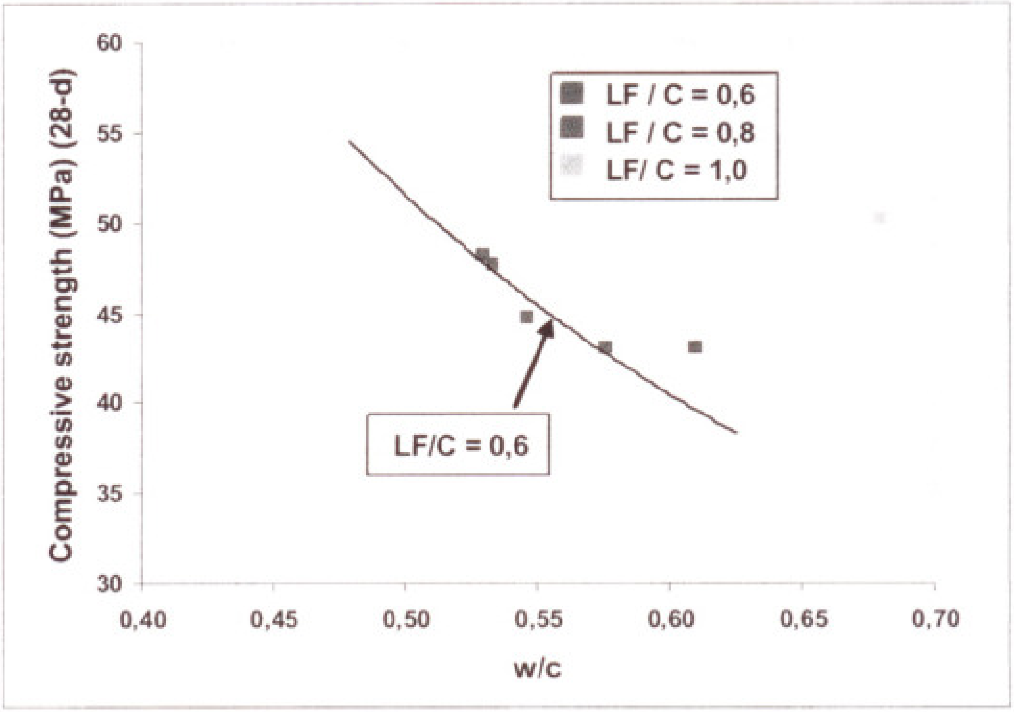

Figure 1: Influence of limestone filler-to-cement ration on the compressive strength of mortars

Concrete mix initial proportions have been selected following general criteria for the powder-type SCC, according to Okamura and Ouchi [16]. The amount of powder (particle size smaller than 0,063 mm, i.e. cement + silica fume + limestone powder) should be about 500-500 kg/m^3, the absolute volume of coarse aggregate between 0.30 to 0.36 m^3, the ratio between sand to mortar volume between 0.55 to 0.60 and the water to powder ratio between 0.95 to 1.05. Using these criteria, trial mixes were prepared and minor adjustments were made (only ***definite mixes*** main characteristics and results are reported in this paper).

As far as the compressive strength of SCC is concerned, two strength classes have been addressed: the 40-60 MPa and 70-90 MPa range. For the former, a CEM I 42,5 R was used while a CEM I 52,5 R + silica fume were combined for the latter. The water to binder ratio was in the range of 0.42 ±0.2 for the 40-60 MPa SCC, while it was kept at a lower value (0.33±0.2) for the high-performance SCC. Water to cement ratio was calculated as follows:

$$\frac{w}{b}=\frac{w}{c+km} \tag{1}$$

Where:

w = water content (kg/m^3)
b = cement content (kg/m^3)
m = mineral addition content (kg/m^3)
k = coefficient (k=1.6 for silica fume)

Mix proportions are indicated in Table 3 for the standard SCC (SCC-I) and the high-performance SCC (SCC-II). Quantities are expressed in kg/m^3, for the aggregates in SSD conditions (Saturated and Surface Dry).

Constituent	SCC-I [kg/m^3]	SCC-II [kg/m^3]
Cement (CEM I 42,5 R)	400	----
Cement (CEM I 52,5 R)	----	500
Limestone filler (0,063 mm)	150	50
Water	175	175
Coarse aggregate (6-12) (crushed)	632	694
Fine aggregate (0-4) (natural)	959	858
Superplasticizer (Viscocrete 3425)	6	----
Superplasticizer (Viscocrete TSG 30)	----	10
Silica-fume	----	45

Table 3: Mix proportions for SCC-I and SCC-II

3 SCC CHARACTERISATION UNDER STANDARD CONDITIONS

3.1 Fresh-state characterization of SCC

Both SCC were tested for their properties at the fresh state. Tests chosen were focused on the assessment of the flowing ability and resistance to segregation using standard equipment, thus, inverted cone and T50 [14] were selected. Figure 2 shows the aspect of the concretes at the end of the slump-flow test (no evidence of segregation neither water bled can be seen in the pictures) while results of both tests are the ones included in Table 4.

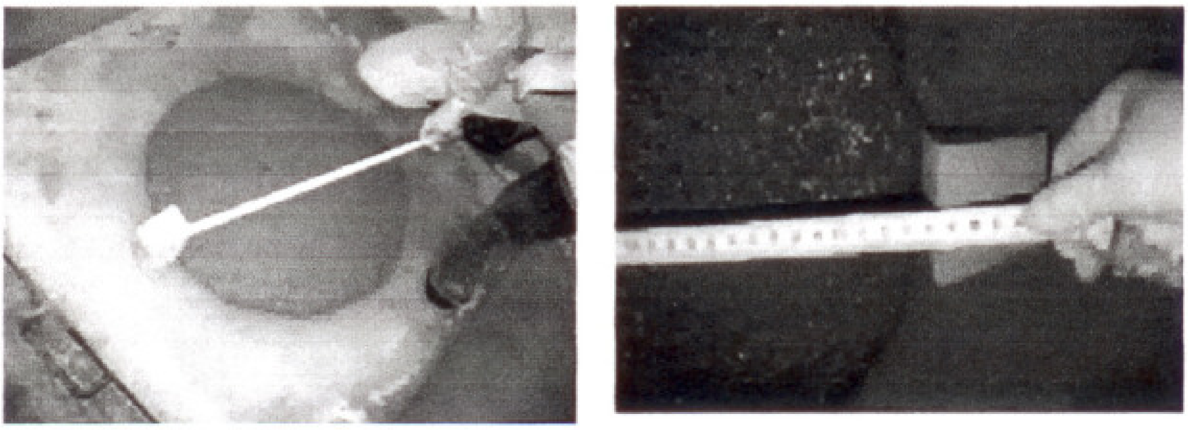

Figure 2: aspect of SCC-I and SCC-II at the end of the slump-flow test

Final adjustment of flowability (slump-flow) and resistance to segregation (T50) would be made for production of concrete at large scale, taking into account industrial requirements at the precast plant. At laboratory stage, both SCC are compliant.

Different moulds were cast and cured under standard and accelerated curing regimes, aimed at assessing the influence of steam curing on the properties of SCC-I and SCC-II.

Mix	*Method*	*Standard Range values*	*Result*	*Compliance*
SCC-I	Flowing ability (PNE 83361) [17]	(mm) 550 < E < 800	670	Yes
	Resistance to segregation	(sec) 2 s < T50 < 9 s	6	Yes
SCC-II	Flowing ability (PNE 83361)	(mm) 550 < E < 800	620	Yes
	Resistance to segregation	(sec) 2 s < T50 < 9 s	7	Yes

Table 3: Mix proportions for SCC-I and SCC-II

3.2 Mechanical performance of SCC

Mechanical performance was assessed by means of the uniaxial compressive strength and Elasticity Modulus. Compressive strength results obtained from at least two samples, at different ages of standard curing are summarised in Table 4 and the evolution of strength with time for both SCC are shown in Figure 3. The 28-days static elasticity modulus was measured according to ASTM C-469 [15], and the results are plotted in Figure 4.

Age (days)	*Compressive strength*		*Elasticity Modulus*	
	SCC-I (MPa)	**SCC-II (MPa)**	**SCC-I (GPa)**	**SCC-II (GPa)**
1	23.9	39.0	-	-
2	40.2	50.3	-	-
7	54.0	70.8	-	-
28	59.9	81.5	37.5 (*)	38.1(*)

(*) individual sample result

Table 4: Compressive strength and static elasticity modulus of SCC-I and SCC-II

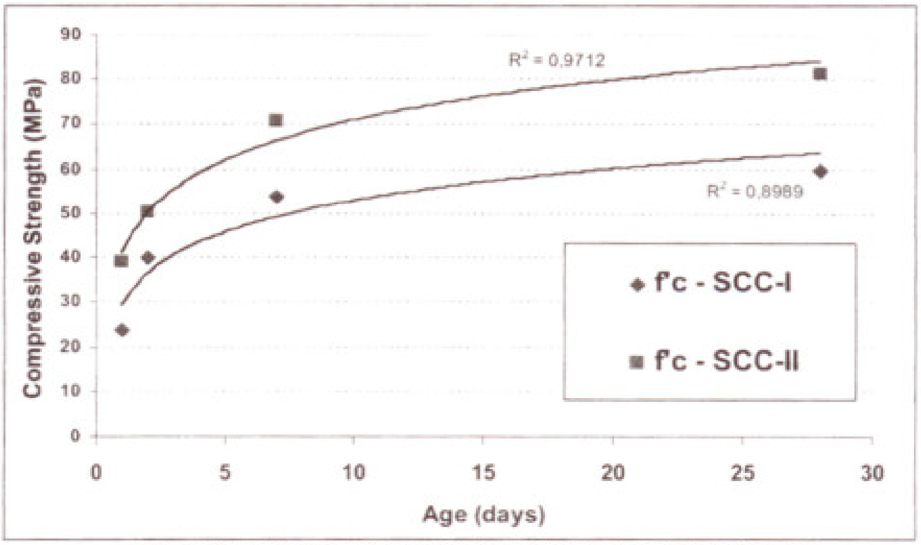

Figure 3: Evolution of compressive strength for standard curing

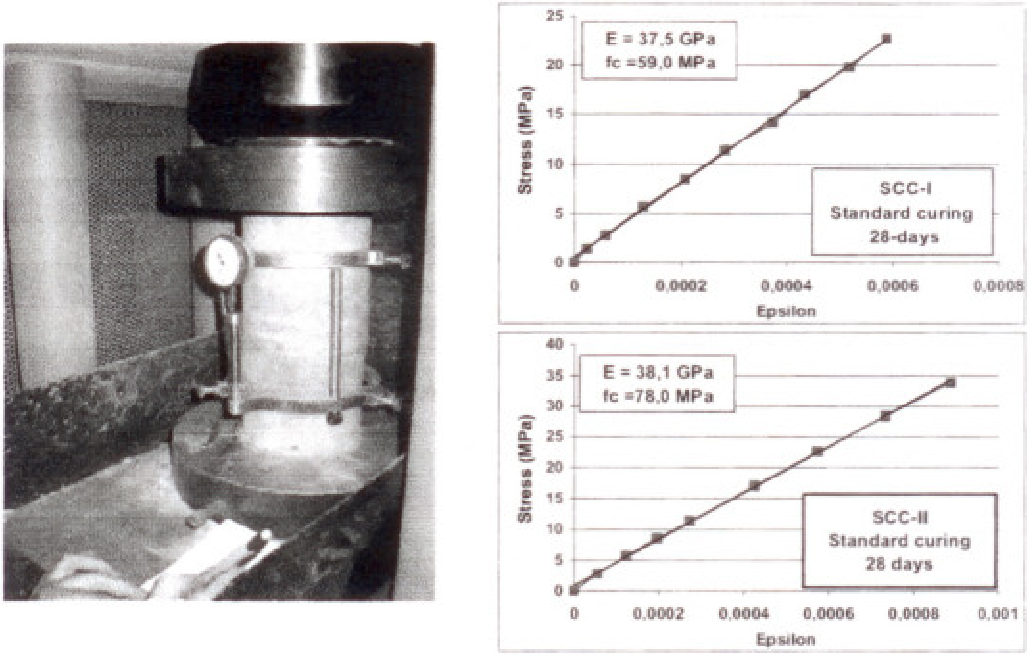

Figure 4: Static Elasticity Modulus for SCC-I and SCC-II according to ASTM C-469

4 ASSESSMENT OF SCC SENSITIVITY TO PROCESS PARAMETERS

The adoption of SCC as the segment structural material requires for some minor improvements in the production control but these efforts are compensated with less requirements in the execution control as fresh-state characteristics of SCC guarantee that neither vibration nor finishing are required, thus reducing the execution control. Safety and health of workers is also improved as the noise level is dramatically reduced.

Nevertheless, the difficulties associated to the introduction of SCC in a standard production cycle, whose duration is closely related to the time required for the concrete to achieve a compressive strength in the range 15-20 MPa, have to be considered as matter of research. Different issues come into consideration, not only the early-age compressive strength but also the sensitivity of SCC to curing cycle.

Striking time is usually shortened by accelerating concrete curing, commonly using a steam-curing cycle. It is known that the acceleration of strength gain leads to changes in concrete microstructure; porosity is coarsened and thus, final strength is reduced. Durability is also related to concrete porosity and thus, IETcc research is focused on this special subject: to determine the effect of accelerated steam curing on SCC durability, as compared to standard curing.

For tunnel segments, steel moulds are closed to the environment, as seen in Figure 5. As a result, concrete shows no exposed surfaces during steam curing and thus, water steam is only used as an efficient manner of heat transfer to the concrete.

A comprehensive testing program has been initiated on a comparative basis, where many samples of different sizes and shapes have been subjected to standard and accelerated curing regimes, as shown in Table 5.

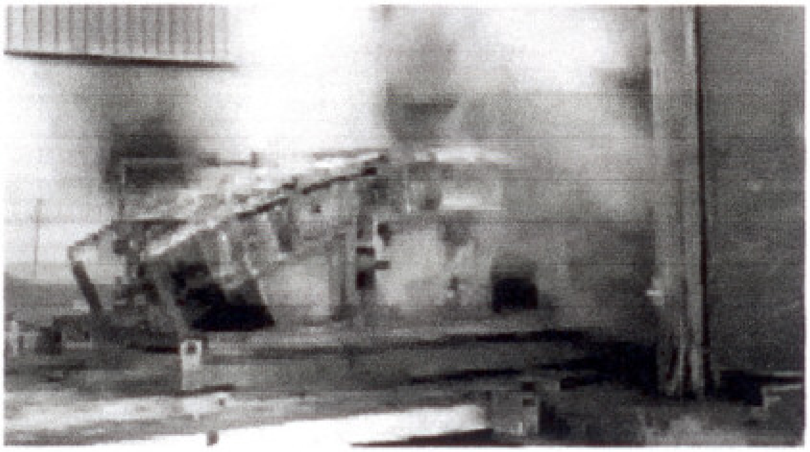

Figure 5: Segment mould entering the steam-curing tunnel

Sample	*SCC – I*		*SCC-II*	
	Standard curing	**Accelerated curing**	**Standard curing**	**Accelerated curing**
150 x 300 mm cylinders	Compressive strength Static Elasticity Modulus	Compressive strength Static Elasticity Modulus	Compressive strength Static Elasticity Modulus	Compressive strength Static Elasticity Modulus
100 x 200 mm cylinders	Compressive strength Durability issues	Compressive strength Durability issues	Compressive strength Durability issues	Compressive strength Durability issues
75 x 150 mm cylinders	Durability issues	Durability issues	Durability issues	Durability issues
150 mm–cube	Early-age strength	Early-age strength	Early-age strength	Early-age strength
Different samples	Visual and /or stereomicroscope	Visual and /or stereomicroscope	Visual and stereomicroscope	Visual and stereomicroscope

Table 5: Testing program scheduled to assess the sensitivity to curing cycle, on a comparative basis

4.1 Finishing and Early Thermal cracking behavior

Finishing characteristics of precast segments is a key issue when aesthetic comes into consideration. The use of a properly designed SCC with a new-generation superplasticizer results in a pore-free surface, even if the mould is non-permeable (steel). The selection of a suitable demoulding agent may also be important to achieve the required surface. Figure 6 shows the quality achieved for standard steel moulds as compared to a conventional concrete.

Surface craking is common in high-strength concrete and can be triggered by thermal gradients associated to the cooling period after steam curing. These cracks, usually harmless due to their width (crack width < 0.2 mm) affect aesthetic of the surface and might act as stress concentrators at later ages.

None of the SCC developed, either standard cured or steam cured have shown any cracks.

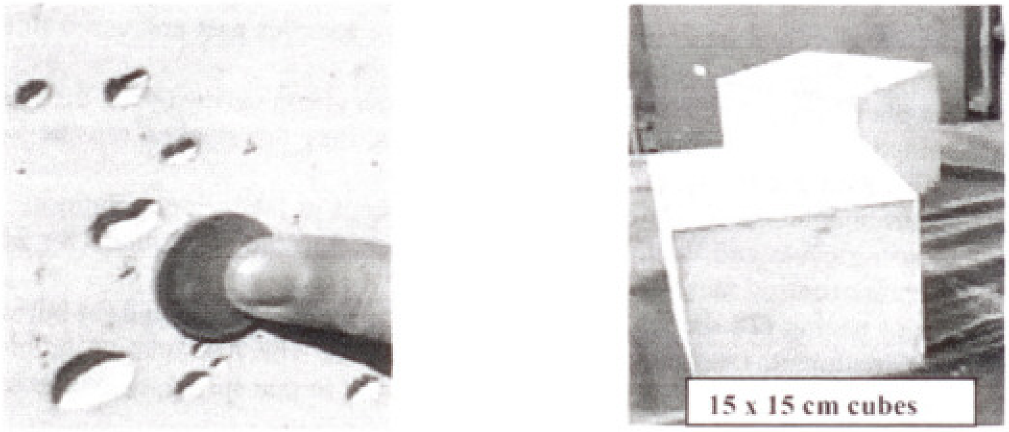

Figure 6: Surface appearance of conventional (left) and SCC (right) concretes

4.2 Mechanical performance

4.2.1. Early-age strength

Compressive strength of SCC was measured at the end of the curing regime, which can be sketched as indicated by a purple arrow in Figure7. Temperatures shown in the diagram correspond to air-temperature.

SCC-II tested reached a compressive strength over 20 MPa, and thus, it complies with the general requirement indicated previously. SCC-I, on the contrary, did not achieve the required strength with the given curing regime. This behaviour can be associated to the use of CEM 42.5 R. Effective curing regime has to be adjusted to the specific concrete used in each case.

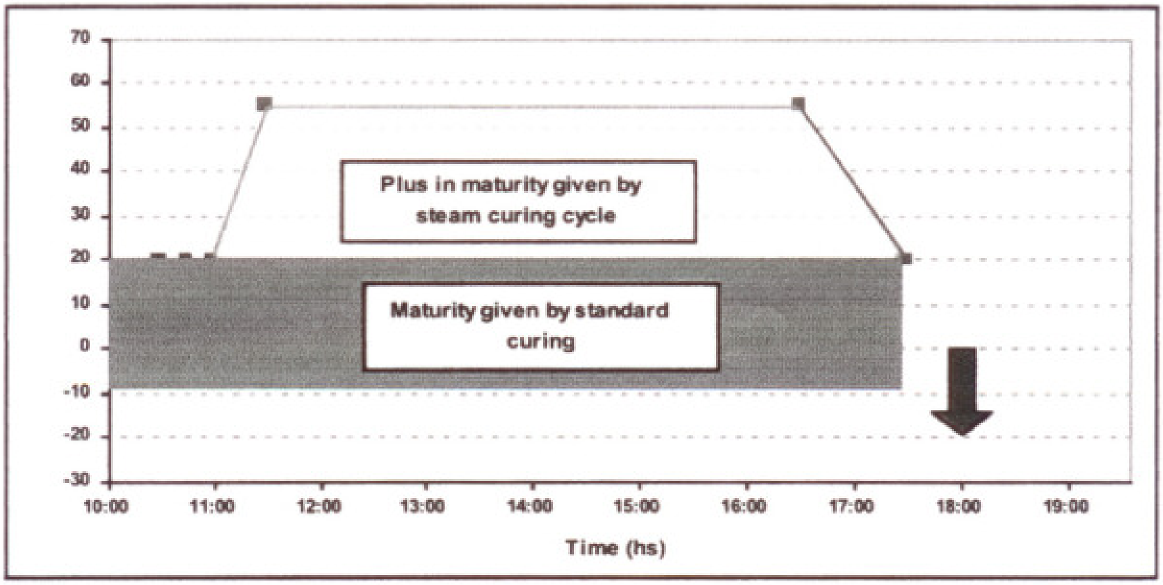

Figure 7: Curing regime used on the tests.

4.2.2. 28-days compressive strength

Taking into account that this research is strongly focused on industrial applications of the materials developed, a special treatment was applied to the samples cast and cured following the cycle described in Figure 7.

At the precast plant, once the elements have finished their steam curing cycle, the segments are then demoulded. After minor conditioning treatments, they are stocked outside with no further curing other than eventual rain.

In order to reproduce these conditions, samples were kept in laboratory conditions for 16 hours after the curing cycle and then, they were left exposed to the atmosphere for 24 additional hours. No rain occurred meanwhile.

Up to the age of testing (28 days), samples were kept protected from sunlight but with no additional curing treatment, i.e., under air-drying conditions. The low relative humidity of Madrid weather cannot be ignored, as 50-70 % RH are usual in late spring, when the samples have been exposed.

After 28 days, 150 x 300 mm cylindrical samples were tested in compression. The results obtained are shown in Table 6. Some of the samples were water saturated during 48 hs. in order to diminish the effect partial drying might have on the compressive strength.

Accelerated curing	SCC-I		SCC-II	
	Air-dried	Saturated	Air-dried	Saturated
28-day compressive strength (MPa)	52,7	53,5	85,2	81,8
Relative strength to standard curing at 28-days	88 %	89 %	104 %	100 %

Table 6: 28-day compressive strength of accelerated cured SCC-I and SCC-II

From the values shown in Table 6, it can be concluded that even after a severe curing regime (steam curing followed by air-curing exposed to the natural atmosphere, sheltered from rain and sun), SCC-II is capable of achieving the same compressive strength as the standard-cured SCC-II. The lower grade SCC-I loses about 11 to 12 % of its 28-days compressive strength, which indicates its higher sensitivity to curing cycle. Remaining samples will be dedicated to further studies, some of them related to the microstructure evolution and other durability related properties, as indicated in previous paragraphs.

5 CONCLUSIONS

Although these conclusions should be take as preliminary, the results obtained up-to-date allow the following remarks to be made:

- Properly selected industrial materials are suitable to obtain SCC in the strength range 50-90 MPa, this situation being beneficial to overall economy of the solution.
- Cement type might play an important role when early-strength is required. The difference between both mixes, higher at early age, is conclusive.
- The new chemical admixture prototype developed by SIKA has shown very good performance both at the fresh and hardened states. Other than being compatible with other concrete constituents, very good response to strength evolution was reached.
- The use of properly aggregate grading and an efficient superplasticizer allowed the w/c ratio to be kept at a very low value without compromising SCC mix flowability.
- The need for an accelerated curing must be determined based on industrial needs. Should this be the case, early-age assessment of SCC has shown low tendency to

surface cracking and very good finishing.
- High early-age strength does not compromise long-term strength as over 80 MPa have been reached.
- SCC-II has shown low sensitivity to curing cycle as far as the 28-day compressive strength is related, even with no post-steam curing treatment. Its influence on durability is still under consideration.

6 ACKNOWLEDGEMENTS

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