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Effect of variations in thermal-curing cycle on the cracking risk of precast segmental tunnel lining

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HIGHLIGHTS

- The effect of thermal curing on precast segmental tunnel lining is analyzed.
- The high strength concrete used was characterized thermally and mechanically.
- The maximum temperatures and rates of heating and cooling are obtained.
- The risk of cracking is evaluated comparing the evolution of stresses and strengths.
- The most appropriate curing cycle for the segment is determined numerically.

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ABSTRACT

This paper analyzes, both experimentally and numerically, the effect of thermal curing on the evolution of temperatures, rate of temperature rise and cooling, stresses and strengths in reinforced concrete elements. It also describes the experimental program carried out to characterize thermally and mechanically the high strength concrete used in the precast segments of the Pajares Tunnel lining. The thermo numerical analysis allows verifying whether a given cycle complies with rules of good practice with regard to maximum temperatures reached within the segment and maximum rates of heating and cooling. The mechanical analysis allows evaluating the cracking risk by comparing the evolution of stress and effective strength at the points of the segments that have higher risk of cracking. The developed computational tool can be used as a virtual laboratory to determine the curing cycle that is most appropriate for each type of segment.

1. Introduction

The mass production of precast members requires the early development of concrete strength, so the hydration of cement is accelerated by heat treatment, allowing the production of a greater number of segments in the same facility. In the case of segments for tunnel linings, this aspect is even more important since the maximum production is usually lower than the capacity of placement of the tunnel boring machines, so that it is necessary to start the production of segments quite before the beginning of the tunnel excavation.

The concrete strength reached at each instant depends on the composition of the concrete, the initial temperature of the mixture and the ambient temperature, as well as the temperatures and periods of curing. The higher the temperature and curing time, the faster the concrete strength develops, which is advantageous for segment handling and for the early prestressing of the elements. However, delayed ettringite formation (DEF) may occur in concretes subjected to prolonged high temperature at early age, which leads to an expansion of the hardened concrete, inducing cracking and the decrease of the mechanical properties [1,2].

Furthermore, storing the elements in the yard as soon as they have been demolded is a common practice in prefabrication plants. Consequently, in winter these elements can be exposed to an intense thermal shock that depends on the outside temperature and the heating conditions used during fabrication [3]. These thermal shocks can weaken the concrete skin and reduce drastically its durability, as a microcracked concrete surface provides a preferential path of penetration to the different aggressive agents to which the element will be later exposed [4].

Concrete standards only provide good practice guidelines for accelerated curing techniques to prevent cracking. For instance, the curing process must begin after the cement has achieved the initial set, and the curing temperature must be raised to maximum and maintained for a certain period, after which it is made to descend gradually.

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Table 1 shows a summary of some good practice guidelines for heat accelerated curing of normal concrete: *MC90* [5], ACI 517 [6], AASHTO [7] and [8], PCI [9] and NPCA [10].

In the curing process of precast and/or prestressed concrete products, all factors (pre-curing period, maximum temperature and heating and cooling rates) are interrelated. A change in one part of the operation may affect the others [6], so that the optimum curing cycle can generally be determined by trial.

In the absence of a general methodology, it is of great interest to have a numerical tool to predict and, if possible, prevent crack formation produced both by the restriction to the thermal deformations and to the DEF, caused by high temperatures at early ages.

For this reason, a numerical tool capable of simulating the thermal and mechanical behavior of reinforced concrete structures from early ages has been developed [11], which takes into account the thermal deformation and autogenous shrinkage produced by the cement hydration process, the evolution of mechanical properties and creep. The characteristics of that numerical model are summarized in Section 4.

The aforementioned computational tool has been used to predict the evolution of temperatures, stresses and strengths inside heat cured segments, allowing the evaluation of their cracking risk. Systematic application of this program for different curing cycles has been used as a virtual laboratory to determine the optimum curing cycle for segments of the type studied herein, in order to make a numerical rather than an empirical adjustment of the temperatures and curing times to meet actual needs.

This paper presents the results of a theoretical and experimental research conducted on concrete with a compressive strength of 105/120 MPa used in the segments of the Pajares Tunnel, connecting Leon and Asturias in Spain. It shows the results of the experimental campaign carried out to determine the effect of heat curing on the mechanical properties evolution of the concrete used. Also, this paper includes the temperature measurements in a cross section of a segment during the whole curing time and compares them with those obtained numerically by the computational tool.

After the thermal model validation, a description of the study performed to analyze the effect of different curing cycles on the risk of cracking is made, and the optimum curing cycle for segments of the type used in the Pajares Tunnel is determined. Also, the reduction in energy consumption that could be obtained from the design of an optimal curing cycle is briefly addressed.

Both the experimental measurements on precast segments of high strength concrete and the parametric study performed constitute the most relevant original contributions of the paper.

2. Description of the experimental program

The experimental program consisted in the measurement of temperatures inside two RC segments with a cross section of 1500 × 500 mm (Fig. 1) during the whole curing time and mechanical testing of the properties of the concrete used, whose mix proportion is shown in Table 2.

The tested segments were A-3-7 of ring number 13235 and A-2-6 of ring 13242, cast in March 2007 at an ambient temperature of 15.5 °C and 12.7 °C respectively and cured at 35.5 °C for 18 and 20 h, respectively.

The temperatures were measured with a data acquisition system of ten thermocouples. One thermocouple recorded ambient temperature near the segment surface, another thermocouple was placed in a specimen located on the segment and the remaining 8 thermocouples were located in a cross section close to the central section, in the positions shown in Fig. 2.

As part of their quality control policy, the manufacturer systematically performs "self-control" compression tests at 7 and 28 days on 150 × 300 mm cylindrical specimens. In addition to these tests, other mechanical tests were performed on specimens subjected to different curing conditions in order to compare the influence of curing temperature on the evolution of mechanical properties.

Some of the specimens were subjected to environmental conditions identical to those of the segments during the entire thermal curing time (at 35 °C) and then they were cured in a chamber at 20 ± 2 °C and RH > 95%. Other samples were cured directly in a moist chamber (20 °C ± 2°, RH > 95%). A series of concrete samples molded with the concrete used in ring number 13235 was left outdoors for the first 16 h and then was cured under the same conditions as the other samples (20 °C ± 2°, RH > 95%).

The number of specimens tested for each segment, the ages at which they were tested, and the type of curing (thermal, at 20 °C or outdoors) are shown in Table 3, where *T* indicates curing time.

Splitting (Brazilian) tensile strength was measured on 150 × 300 mm cylinders, elastic modulus on cylinder samples (100 × 200 mm) and compressive strength on 100 × 100 mm cubic and cylindrical specimens of 150 × 300 mm. 100 mm cubes were used because of the small sample volume. All determinations were performed on sets of three samples, except for the module of elasticity and tensile strength, which were made on two samples.

The standards followed in the tests were: UNE 12390-3 [12] for cube and cylindrical compressive strength, UNE 12390-6 [13] for indirect tensile strength and UNE 83316 [14] for elastic modulus.

The evolution of cement hydration degree was estimated based on the semi-adiabatic temperatures measured in two 150 mm cube samples. Calorimeter calibration and data reduction were performed following RILEM recommendations [15]. Then, the degrees of hydration obtained were adjusted with the expressions presented in Krauß et al. [16].

3. Test results

3.1. Development of mechanical properties

Fig. 3a shows the evolution of the 100 mm cube compressive strength on specimens cured in different ways: thermally, like the segment, at 20 °C and outdoors. As expected, thermal curing accelerates the development of strength: at the output of the curing chamber (19.7 h = 0.82 days), the strengths of the thermally cured specimens were 66% greater than the strengths of the specimens cured at 20 °C, and these were larger than the strengths of the specimens exposed to outdoor temperature, which dropped to 4 °C overnight.

At 28 days, the strength of the specimens cured at 20 °C and exposed outdoors were very similar to the strength of the thermally cured specimens. The results at 7 days had to be discarded due to experimental difficulties.

The cube compressive strengths measured at 91 days were significantly higher than those measured at 28 days. The largest increase took place in the specimens cured at 20 °C, in which the

Table 1
Good practice guidelines for heat accelerated curing.

	Pre-curing period (h)	Maximum rate of temperature rise (°C/h)	Maximum temperature (°C)	Maximum rate of cooling (°C/h)
MC90	$T < 30$ °C during the first 3h $T < 40$ °C during the first 4 h	20	Average < 60 Individuals < 65	10
AASHTO	Between 2 and 4 Ambient temperature 10 °C	Ambient: 22	Ambient: 71	
PCI	After initial set took place (ASTM C403)	Concrete: 20	Concrete: 82	
ACI 517	Between 3 and 5	Ambient: 33	Ambient: 82	39
CIA		Ambient: 20	Ambient: 80	6
NPCA	30 min after initial set (ASTM C403)	Ambient: 22	Ambient: 65	