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Maturity method to predict the evolution of the properties of sprayed concrete

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HIGHLIGHTS

- The maturity method estimates the strength of concrete during construction.
- This method is not currently used for sprayed concrete.
- New maturity curves and equations are proposed.
- An adaptation of the maturity method is proposed to be used for sprayed concrete.

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ABSTRACT

The maturity method provides a simple approach for assessing the strength evolution of concrete. Although it is already used in the precast industry, no reported applications with sprayed concrete may be found in the literature. Such concrete presents singular characteristics due to the spraying process and, in some cases, due to the introduction of accelerators that modify the kinetics of cement hydration. Consequently, the traditional equations that relate the evolution of mechanical properties and the maturity index might not apply in this case. The objective of this study is to adapt the maturity method to sprayed concrete. An experimental program was conducted with 24 concrete mixes sprayed in laboratory and tested for the evolution of temperature and compressive strength. An alternative equation was proposed to relate the maturity index and the mechanical properties. Subsequently, finite element models were developed to generalize the maturity curves considering the local design parameters.

1. Introduction

The maturity method provides a relatively simple approach for assessing the in-situ strength evolution of concrete during construction. It relies on the measured temperature history of the concrete to estimate the maturity index that is then related with the strength development during the curing period. For each concrete mix composition, the relationship between a mechanical property and the maturity index can be established via trial mixes subjected to controlled conditions.

The method has been widely used in applications such as concrete pavements or precast concrete to improve productivity by, for instance, minimising the curing time [1–4]. However, according to the literature, there have been no reported examples of applications with sprayed concrete. This special type of concrete is pumped and sprayed over vertical or top surfaces, resisting the self-weight and the loads applied as soon as the element is executed. In some applications, accelerators are added to the mixture in order to speed up the setting and the short-term evolution of mechanical properties. For that reason, the early strength control is a key element that might affect the productivity and the safety in the worksite [5,6].

The maturity method, adapted to this particular form of concrete construction, would help engineers decide when the construction advance could be done safely. Furthermore, it would be a helpful alternative to the two traditional tests used to measure the compressive strength evolution of the sprayed concrete at early ages – the penetration needle test and the stud driving method [7]. In that sense, the time to obtain results and the number of people working under a risky condition in a poor environment (i.e. tunnelling) could be reduced [8].

Several reasons explain the difficulties associated with the implementation of the maturity method for the quality control of

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sprayed concrete. On one hand, the conventional equations used to relate the evolution of mechanical properties and the maturity index might not apply to mixes with accelerators. On the other hand, changes in the characteristics of the support over which the material is sprayed may affect the heat transfer of the concrete layer [9,10]. Therefore, the calibrations of the maturity index for a certain condition might not be generalized to the high variability of conditions found in practice.

The aim of this study is to propose a methodology for the quality control of sprayed concrete based upon the maturity method that overcomes the difficulties mentioned previously. Accordingly, an experimental programme was conducted involving the spraying of 24 different concrete mixes, which were then characterized for the evolution of temperature and compressive strength. The relationship between these two parameters were used to propose an alternative equation that relates the maturity index and the evolution of mechanical properties for sprayed concrete with accelerators. Subsequently, an approach using finite element models (FEM) was developed with the aimed of adapting the maturity curves obtained in laboratory to the local conditions (such as layer thickness and the type of ground support) found in the worksite. The theoretical and empirical findings are presented, culminating in a description of the proposed in-situ application.

2. The maturity method

The Nurse-Saul function (Eq. (1)) is commonly used [1] to assess the maturity index (M), taking into account the evolution of temperature (T) over time (t) and the datum temperature (T_0). This last parameter, which is equal to $-10\,^{\circ}\mathrm{C}$ in different studies [1], represents the minimum temperature that permits the chemical reaction of cement hydration.

$$M = \sum_0^t T - T_0 \cdot \Delta t \tag{1}$$

This index M may be related to the compressive strength (S) using the Plowman's logarithmic equation [11]. This presents two parameters, a and b, that are the strength for maturity index equal to 1 and the slope of the line, respectively. The relationship between both these parameters shown in Eq. (2) gives the maturity curves.

$$S = a + b \cdot \log(M) \tag{2}$$

The latter is capable of estimating the strength evolution of conventional concrete as observed in various studies [1,12]. However, sprayed concrete often has particular characteristics that are not considered in Plowman's equation. The addition of accelerators – very common in sprayed concrete for tunnelling applications – changes the chemical reactions produced during the hydration of cement [13,14]. These chemical changes alter the development of the mechanical properties of the sprayed concrete at very early ages, which consequently requires a modified relationship between the compressive strength and the maturity index.

Moreover, maturity curves are based upon pre-determined calibrations of the time-temperature-strength relationship development, determined in laboratory tests. These conditions, however, are different from those found on a construction site, particularly in tunnelling applications. Consequently, maturity curves for sprayed concrete are usually obtained experimentally by spraying in the laboratory moulds with a thickness of 150 mm as described by the standard UNE-EN 14488-2:2007 [7]. In underground construction, the thickness of concrete is chosen due to structural reasons – the weaker the ground support, the thicker the lining (considering the same concrete compressive strength). Furthermore, the ground support in a tunnel has different thermal and mechanical properties than a metallic mould used in a laboratory. These variations cause changes in the evolution of temperature inside the concrete, and therefore variations in the maturity curves, due to heat transfer between the different materials.

This heat transfer, governed by a diffusion phenomenon, is the exchange of energy through the boundary between two systems. When an object is at a different temperature from another body or its surroundings, heat flows until the body and its surroundings reach the same temperature. Heat transfer always occurs from a region of high temperature to an adjacent region of lower temperature, as described by the second law of thermodynamics [15]. In the case of underground construction, thermal conduction is the fundamental heat transfer mode that occurs between the concrete and the ground, whereas convection is the one that occurs between the concrete and the atmosphere. This phenomenon is different in the specific case of spraying into a mould (Fig. 1).

An experimental programme was designed to consider this phenomenon and propose a methodology to perform the maturity method on the sprayed concrete. This involved tests in laboratory conditions to obtain the maturity curves and finite element modelling in order to adapt these curves to the real conditions.

3. Methodology

This section presents the materials to produce the mixes and their composition, the spraying process and the test methods considered in the study. It also explains the FEM developed in order to generalize the experimental results to the real case conditions.

3.1. Materials and composition of mixes

The cements CEM I 52.5 R (CEM I) and CEM II/A-L 42.5 R (CEM II) were used in the study. Their main characteristics are presented in Table 1. The high proportion of clinker of CEM I allows quick setting of the concrete and, therefore, a high compressive strength at early ages. Although it is still used in sprayed concrete, the European tendency is to favour blended cements for environmental reasons. In order to reduce the CO_2 emissions during the production of cement, several European countries apply cements

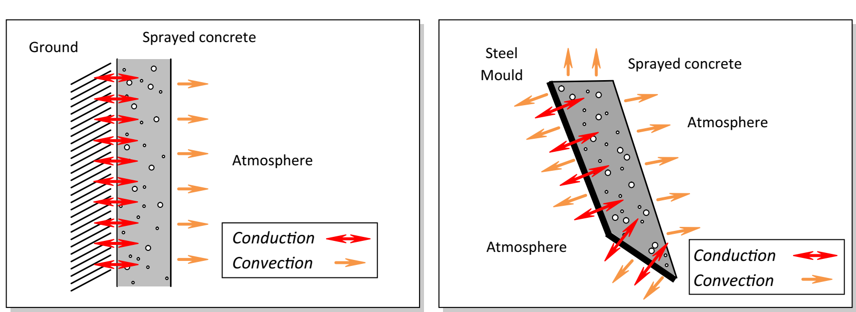

Fig. 1. Heat transfer modes in a tunnel (a) and for a sprayed mould (b).