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Estimation of the modulus of elasticity for sprayed concrete

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HIGHLIGHTS

- Elastic modulus prediction performed with current equations overestimates the value.
- Adaptation of the Eurocode 2 and EHE-08 equations entails better results.
- Empirical and semi-analytical formulations are proposed.
- Modified equations are validated with results obtained in real tunnels.

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ABSTRACT

The modulus of elasticity is a fundamental parameter for the structural design. It has been studied in the literature and several standards include equations to predict its value for conventional concrete. However, the same is not true in the case of sprayed concrete. This special concrete presents singular characteristics due to the spraying process that must be considered in the prediction of this property. The objective of the present work is to perform an analysis of the modulus of elasticity of sprayed concrete. For that, an experimental program about the mechanical properties of the material was executed. Furthermore, the applicability of formulations available in current codes and guidelines to estimate the modulus of elasticity of conventional concrete is assessed. The analysis conducted provides the basis to adapt these formulations, taking into account the specificities of sprayed concrete. Finally, empirical and semi-analytical expressions are proposed and validated using data from real tunnels.

1. Introduction

Sprayed concrete is a special type of concrete that combines the placement and the compacting of the material in only one process [1], thus reducing the construction time. Recently, high quality sprayed concrete has been achieved by the use of wet-mix process, advances in mix proportioning and the development of alkali-free accelerators [2]. These improvements jointly with the aforesaid advantage increased the importance and the application of sprayed concrete.

The material is widely employed in underground construction, although with little structural responsibility in other applications [3,4]. The consideration of the structural contribution of the sprayed concrete is a growing trend that would increment its use and open other fields of application. Ultimately, it would reduce the thickness of structural elements as well as the execution time and costs for the whole construction. However, to achieve this condition, the structural behaviour of sprayed concrete still needs to be studied in more detail given that its characteristics and properties are different from conventional concrete. These differences are caused by the spraying process, which entails variation of the mix proportion (due to rebound) the higher porosity of the sprayed concrete and also due to the mix designs, which have lower amount of big sizes of aggregates [5,6]. Therefore, fundamental parameters of structural design must be studied considering these differential aspects.

The modulus of elasticity is one of the fundamental parameters in structural design to determinate strain and displacements. This parameter is normally measured through the test of specimens subjected to uniaxial compressive loading [7,8]. Simplified empirical expressions obtained after linear regression of experimental data are also available in codes and guidelines to estimate the modulus of elasticity of conventional, high performance and dam concrete based on the compressive strength of the material [9–12]. Other studies from the literature propose expressions to estimate the modulus of elasticity of sprayed mortar [5]. However, the extrapolations of these expressions to sprayed concrete are not feasible given the differences in the type of equipment used and in the composition of the material due to inclusion of accelerators or bigger aggregate. Therefore, no expression equivalent is available in the technical literature reviewed for sprayed concrete.

The objective of the present work is to perform an in depth analysis of the modulus of elasticity of sprayed concrete and to

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develop formulations to predict this property. For that, an extensive experimental program was conducted simulating, in the laboratory, the spraying process in underground constructions. In total, 32 mixes were tested for compressive strength and modulus of elasticity, among others. The results obtained were used to assess the applicability of formulations available in current codes and guidelines to estimate the modulus of elasticity of conventional concrete. The analysis conducted provides the basis to adapt these formulations, taking into account the specificities of sprayed concrete. Finally, empirical and semi-analytical expressions are proposed and validated using data obtained from real tunnels. The outcome of this study represents a contribution towards the knowledge and the rational use of sprayed concrete. Furthermore, it provides technicians with useful and straightforward formulations that support the consideration of the structural responsibility of the material in the design.

2. Definitions

The modulus of elasticity (E) is defined as the slope of the stress–strain curve (σ–ε) in the elastic deformation region (Fig. 1). According with the scientific literature, two types of modulus of elasticity may be measured: the tangent modulus (E_{ci}) – given by the tangent at a certain point of the curve – and the secant modulus (E_{cm}) – given by the slope of a straight line between the coordinate system origin and a certain point of the curve.

The present study focuses on the secant modulus of elasticity obtained for a stress equal to 30% of the failure stress since this is the parameter usually measured in standardized tests [10–12]. Therefore, from here on the statement modulus of elasticity refers to the secant and not the tangent one.

3. Experimental program

The experimental program was performed in the Laboratory of Technology of Structures Luis Agulló at the Universitat Politècnica de Catalunya (UPC) between May 2012 and June 2013. In this section the materials to produce the mixes and their composition, the spraying process and the test methods considered in the study are presented.

3.1. Materials and composition of mixes

Following the general usage in real construction with sprayed concrete, two different types of cement were considered: CEM I 52.5 R (I) and CEM II/A-L 42.5 R (II). Their main characteristics are presented in Table 1.

Furthermore, 6 alkali-free accelerators were tested (Table 2). The accelerators were divided in three families depending on their characteristics and their affinity. Each family comprised two formulations of accelerators chemically based on hydroxysulphate of aluminium ($Al(SO_4)_x(OH)_{3-2x}$).

As shown in Table 3, three different accelerator doses by cement weight (%bcw) were studied for Family 1 and Family 2: low, medium and high. In the case of Family 3 only two accelerator doses were characterized given the recommendations of

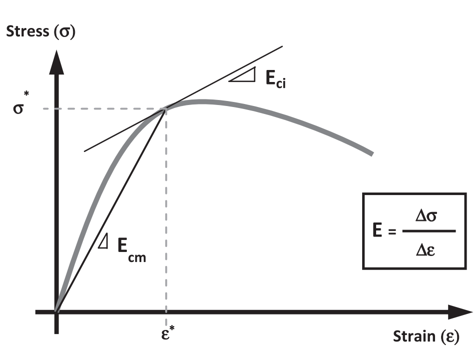

Fig. 1. Stress–strain curve.

Table 1
Cements characteristics.

Cement	I	II
Clinker (%)	98	88
Limestone (%)	–	10
Minor component (%)	2	2
Sulphate, SO_4^{2-} (%)	3.4	3.3
Chlorides, Cl^- (%)	0.04	0.01
Blaine specific surface (CAF-3.1/g)	4600	3900
Soundness Le Chatelier (mm)	0.50	0.50
Initial setting time (min)	110	120
Final setting time (min)	170	180

the supplier. The accelerator content was established for each dose according with the results of the initial/final setting time and the optimal time intervals defined by former studies [13].

The concrete mix emulated the usual composition applied in underground constructions. It was composed by 425 kg/m^3 of cement, 380 kg/m^3 of limestone fine sand (0–2 mm), 900 kg/m^3 of limestone coarse sand (0–5 mm) and 380 kg/m^3 of limestone gravel (5–12 mm) with a w/c ratio of 0.45. Furthermore, the polycarboxylic superplasticizer Viscocrete 5940 was added in a proportion of 1%bcw to increase both the workability and the pumpability of the concrete. The concrete was supplied by the same ready mix plant in charge of producing concrete for the new underground line of Barcelona (Line 9).

The different types of cement and accelerators yield the 32 sprayed concretes mixes summarized in Table 4. The nomenclature defined to refer to the mixes is formed by the name and the dose of the accelerator followed by the simplified indication of the cement type. All terms are separated by the symbol '_'.

3.2. Spraying procedure

All mixes were sprayed with a MEYCO Altera compact wet-mix machine. This machine is an oil-hydraulically driven twin-piston pump that also incorporates a peristaltic dosing unit for accelerators. Furthermore, the equipment includes a 10-m^3/min diesel air compressor responsible for transporting the mix through the concrete circuit.

The mixes were sprayed outdoors. A pumped concrete flow of 4.4 m^3/h (equivalent to 20 strokes per minute) and an air pressure of 4 bars were used. The accelerator-dosing unit allowed a flow between 4.0 and 4.5 l/min depending on the requirements of each mix.

The concrete was sprayed on metallic test panels (500 × 500 × 150 mm) placed at an angle of 20° with the vertical plane, according to the UNE-EN 14488-1:2006 [14]. The distance between the nozzle and the test panels was approximately 1.5 m.

Once the spraying process was finished, the panels were covered with plastic sheets in order to reduce the evaporation of water from the surface. After 24 h, the concrete pieces were unmoulded. First, the test panels were elevated few centimetres using chains attached to a lift truck. Then, they were dumped on wood sticks previously collocated underneath in order to cushion the pieces. After that, the pieces were simply piled together in outdoor conditions and covered by sackings, which were continuously wetted to maintain high humidity conditions.

Next, cores were extracted from the sprayed concrete pieces. These were cylinders obtained by means of an extracting machine with a 75 mm diameter drill. Taking into account this diameter and the minimum distances established by the European standard UNE-EN 14488-2:2007 [15], 9 cores were extracted from each test panel. Then the roughest face of the cores was cut to achieve 150 mm of length and the slenderness equal to 2 recommended by many standards for the compressive strength test [10–12]. To maximize the contact and to assure a good load distribution between the cores and the testing machines, the samples were polished. Then, the samples were maintained in a controlled room with temperature of 20 ± 2 °C and humidity of 95 ± 2% until the age of testing.

3.3. Testing methods

All mixes were assessed for the evolution of the compressive strength and the modulus of elasticity. Furthermore, the porosity was measured since it has a big influence on the mechanical properties of concrete and is highly affected by the spraying process [16].

The compressive strength of the sprayed concrete was evaluated according the European standard UNE-EN 12390-3:2009/AC:2011 [17] through the test of the cores extracted. This test was performed at 1, 7 and 28 days. For each age and mix, six samples were tested entailing a total of 576 measurements.

The modulus of elasticity of the sprayed concrete was evaluated according to the Spanish standard UNE 83316:1996 [7] (Fig. 2). LVDTs measured the displacement between two metallic rings attached to the samples while applying the compressive load cycles. In this case, three samples of each mix were characterized at 1, 7 and 28 days, totalizing 284 tests of modulus of elasticity.