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Ultrasonic evaluation of mechanical properties of concretes produced with high early strength cement

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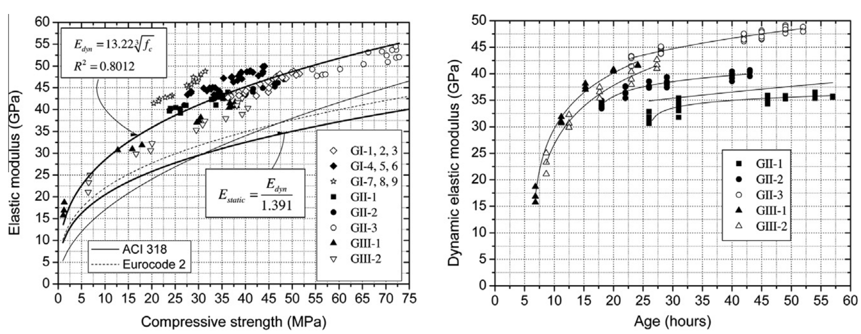
HIGHLIGHTS

- Ultrasonic tests have been widely applied to characterization of concrete.
- Aggregate size and proportion of materials were variables in this study.
- Elastic modulus of concretes is evaluated through ultrasonic tests.
- A good correlation between elastic modulus and compressive strength was obtained.
- Significant increase in elastic modulus occurred in the first 24 h.

GRAPHICAL ABSTRACT

A very good correlation between dynamic elastic modulus and compressive strength was achieved. Additionally, results showed that significant increase in elastic modulus and compressive strength occurs in the first 24 h for concrete produced with high early strength cement.



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ABSTRACT

This paper evaluates the use of ultrasonic tests for the characterization of mechanical properties of concretes produced with high early strength cement. Aggregate size and proportion of materials were the variables analyzed. Ultrasonic tests were performed from early hours up to 28 days after their production and a very good correlation between dynamic elastic modulus and compressive strength was achieved. The results also show the elastic modulus and compressive strength of the concrete produced with high early strength cement significantly increased in the first 24 h.

1. Introduction

Concrete is an excellent material to resist compression stresses generated by gravity loads. Its main mechanical property is the compressive strength, addressed in most concrete standards (ACI318 [1], Eurocode 2 [2], ABNT NBR6118 [3]). The compressive behavior of concrete is also defined by the elastic modulus that influences the stiffness of concrete elements. Several studies have highlighted the importance of the knowledge of the elastic modulus for the evaluation of the behavior of concrete elements in service conditions (Yildirim and Sengul [5], Yazdi et al. [6]). In the past, the specification of elastic modulus was not common in building requirements; however, this scenario has changed. According to Carmichael [4], the constant pressure exerted by

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the market for the construction industry to provide shorter schedules leads to the premature removal of concrete forms before concrete has been properly cured. Therefore, some concrete manufacturers have provided concretes of specified compressive strength and elastic modulus. The concern about the durability and deformability of concrete elements has led to efforts toward the development of studies for a better understanding of their mechanical properties.

Some codes have addressed a relationship between elastic modulus and compressive strength, in which the elastic modulus (E) is estimated from the compressive strength of concrete (f_c) for evaluations of serviceability limit states. ACI 318 [1] considers elastic modulus dependent on the concrete density (ρ) and compressive strength, see Eq. (1), whereas, according to Eurocode 2 [2], the elastic modulus is defined only from compressive strength, see Eq. (2).

$$E = 0.043 \times \rho^{1.5} \times \sqrt{f_c} \tag{1}$$

$$E = 22,000 \times \left(\frac{f_c}{10}\right)^{0.3} \tag{2}$$

where E is the static elastic modulus in MPa, ρ is the unit weight of the concrete in kg/m^3 and f_c is the specified compressive strength in MPa.

Such equations do not compute the composition of concrete. Eurocode 2 [2] agrees the elastic deformations of concrete largely depend on its composition (especially the aggregates). The high influence of the aggregate type on the elastic modulus of concretes was evaluated by Beushausen and Dittmer [7], Beshr et al. [8] and Wu et al. [9]. The prediction of elastic modulus from compressive strength has been proposed by several standards, therefore, this relationship has been the focus of several studies, such as those conducted by Yazdi et al. [6], Wang and Li [10] and Demir and Korkmaz [11]. Another interesting aspect explored by Wang and Lee [12], Conrad et al. [13] and Han and Kim [14] is the influence of aging on the elastic modulus, since it can be directly related to the removal of concrete forms.

In general, compressive test is the common procedure for the evaluation of the elastic modulus and compressive strength of materials. ASTM C469 [15] describes the conventional static method for the experimental determination of those mechanical properties. Differently from compressive strength, elastic modulus is not so easy to be measured in such tests, due to issues related to test procedures, as misalignment of the specimens with the center of the loading machine, misalignment of the transducers with longitudinal axis and irregularities at the top and bottom faces of the specimens, which cause stress concentration. Such issues lead to a high dispersion of elastic modulus results, as observed by Haach et al. [16].

Non-destructive tests (NDTs) have been used for the evaluation of material properties (McCann and Forde [17], Bore et al. [18] and Ferreira and Jalali [19]), as they do not damage the sample under testing and enable repetitions in the same sample at different times. According to ACI-228.2R-13 [20], NDTs can be applied for quality control, troubleshooting problems in new and old constructions, evaluation of conditions of older materials for rehabilitation purposes and quality assurance of repairs.

The ultrasonic pulse velocity (UPV) method has been widely applied for the characterization and quality monitoring of concrete structures (Philippidis and Aggelis [21], Panesar and Chidiac [22], Lai et al. [23]). According to Malhotra and Carino [24], it is a truly non-destructive method, as it uses mechanical waves and results in no damage to the concrete element under testing. The principle of the UPV method is based on the dependence of the speed of propagation of stress waves (v) on the density (ρ) and elastic constants of the solid (elastic modulus, E and coefficient of Poisson, μ), see Eq. (3) for isotropic materials.

$$v^2 = \left(\frac{E}{\rho}\right)\left(\frac{1-\mu}{(1+\mu)(1-2\mu)}\right) \tag{3}$$

An interesting characteristic of the UPV method is it can be applied to very early-aged concrete (Trtnik and Gams [25], Sharma and Mukherjee [26]). The technological control of concrete in the early ages is one of the concerns of several civil engineering works, as construction of roller compacted dams, application of shotcrete and production of precast concrete elements, in which the application of high early strength cement to the production of the concrete is very common. In precast industry, it is applied to optimize the productivity and anticipate tasks, like prestress transference and demoulding of elements. Therefore, tests are mandatory for a proper characterization of the concrete being applied. In some cases, the use of dry concretes hampers the molding of concrete specimens due to the low water/cement ratio. In this context, the UPV method can be a reasonably accurate, reliable, and directly applicable in situ alternative for the characterization of concretes. Besides, ultrasonic tests provide an easier and economic estimation of the compressive strength variation over time during the construction of certain special structures where the early compressive strength is a concern.

This paper evaluates the use of ultrasonic tests for the technological control of concretes produced with high early strength cement. An experimentally based analysis of elastic modulus of different concrete compositions through ultrasonic tests is provided. Concrete specimens were tested from early hours up to 28 days after production. A discussion on the correlation between compressive strength and elastic modulus is also addressed.

2. Experimental program

The performance of distinct concrete compositions was evaluated by an enlarged experimental program composed of static and ultrasonic tests conducted on cylindrical specimens.

2.1. Material properties

Portland cement, sand, two types of gravel and a commercial policarboxylate superplasticizer were used for the preparation of mixtures of concretes. The cement used was Portland type III with high early strength specified according to ASTM C150 [27]. The sand has 2.4 mm maximum size and 1.95 fineness modulus, in accordance with ABNT NBR 7211:1983 [28], see Fig. 1. Gravels A and B, used in the study, have 12.7 mm and 9.6 mm maximum size and fineness moduli of 6.84 and 6.43, respectively. Table 1 shows some physical properties of the materials.

Fourteen concrete mixtures divided into three groups were specified by proportions of Portland cement, sand and gravel, see Table 2. In the first group, the mixtures were defined through a 51% constant dry mortar ratio, three different slumps (100 mm, 150 mm and 200 mm) and three different binder/aggregate ratios (1:3.5; 1:5.0 and 1:6.5). The second and third groups were defined according to the concrete mixtures used in some precast industries. The use of dry concretes with very low slump and water/cement ratio is very common when the extrusion system is applied as a manufacturing method for the construction of some precast elements, as hollow-core slabs. Therefore, the definition of the mixtures of the second group was based on three different binder/aggregate ratios (1:3.5; 1:5.0 and 1:6.5) and a 50 mm slump. The focus of the third group was on the evaluation of the concrete mixtures at a very early age. In the second and third groups, the dry mortar ratio defined by Eq. (4), shown in Pereira de Oliveira et al. [29], was kept equal to 55%. The standard procedure described in the ASTM C192 [30] was applied to the mixtures.

$$D(\%) = \frac{1 + \text{sand}}{1 + \text{sand} + \text{gravel}} \tag{4}$$

2.2. Test specimens

Cylindrical specimens of 100 mm diameter and 200 mm height (height–diameter ratio of 2:1) were molded according to ABNT NBR 5738:1994 [31] and kept in the laboratory environment for one day. They were then removed from the molds and immediately stored in a moist chamber for curing until the age of testing.