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Vibration-based nondestructive testing as a practical tool for rapid concrete quality control

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HIGHLIGHTS

- Study related to vibration-based non-destructive testing for QC/QA of concrete.
- A correlation of dynamic E-modulus and compressive strength was identified.
- NDT were useful to track the evolution of static and dynamic E-modulus in time.
- A relationship of expected E-moduli from measurements at earlier ages is proposed.
- Proposed predictive correlations include compressive strength to dynamic E-modulus.

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ABSTRACT

This paper involves a practical approach to perform quality-control/quality-assessment of concrete using vibration-based NDT. The first component is the analysis of compressive strength and dynamic E-modulus of concrete samples from various construction projects. The second component involves continuous measurements of E-Moduli as a function of curing time in laboratory-controlled specimens. The experimental program allowed proposing a correlation to predict the expected static and dynamic E-modulus at 28 days from their measurement at any instant of the curing process. A similar relationship is proposed to predict compressive strength at 28 days based on the dynamic E-modulus measured at earlier ages.

1. Introduction

The quality control (QC) and quality assurance (QA) of concrete is very important in the construction of reinforced concrete structures. Traditionally, the axial compressive strength (f_c) is the engineering property most commonly used for QC/QA assessment of concrete. The most common approach used to assess the compressive strength of concrete is to collect concrete cylinder samples from a project and measure this property through simple compression tests as outlined in the ASTM Standard C39 [1]. For structures under construction, the samples can be prepared using the fresh concrete being delivered to the project. For existing structures, this approach would require coring concrete specimens which may induce damage to the structure. Furthermore, for both cases, a large number of samples would be required to reliably estimate the concrete strength as concrete conditions are expected to vary greatly not only based on inherent variability between the different concrete batches delivered to a project, but also variability associated to external factors such as differences in concrete placement conditions, vibration, water/cement (w/c) ratio, curing conditions, and boundary conditions. Thus to obtain a reliable assessment of the compressive strength of the concrete placed in a structure using compressive tests usually requires a very large number of samples. Direct measurement of the in situ strength of concrete with destructive tests is usually expensive and time consuming.

An alternative approach that has become more popular is the use of some direct compressive testing complemented with modern non-destructive tests (NDT). This is the main focus of this paper, specifically the use of vibration-based NDT methodologies to carry out QC/QA of reinforced concrete structures. Although

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the NDT methodologies discussed in this paper cannot measure mechanical properties of concrete directly, they are useful for the indirect estimation of elastic mechanical properties of the concrete such as the strength and the elasticity modulus (E-modulus). The most remarkable advantage of the NDT techniques involved in this study is that they offer the capability to measure rapidly and cost-effectively the concrete of most or the whole structure, thus allowing a QC/QA assessment of the concrete used in the structure under actual in situ conditions.

The paper presents vibration-based NDT of concrete from two experimental programs. The first experimental program involved a comparison of impact vibration NDT results with results from direct compression tests. This comparison was done for 245 concrete cylinders obtained from various construction projects in the city of Lima, Peru. The second experimental program involved continuous ambient vibration monitoring of a concrete specimen from initial placement as fresh concrete until completely hardened at 28 days of curing. This second component is based on tracking the evolution of the E-modulus of the concrete as a function of curing age. The results obtained from both experimental components support the notion that vibration-based NDT tests can be a valuable approach to complement direct compressive testing of concrete samples commonly used for QC/QA of construction of concrete structures.

2. Mechanical properties commonly used in concrete QC/QA

Before discussing the NDT methods it is useful to review the main mechanical properties commonly used when performing QC/QA of reinforced concrete structures. The main structural contribution made by the concrete in a reinforced concrete structural element is its strength and stiffness under compression. A schematic stress–strain curve for concrete is shown in Fig. 1(a). It can be seen in this curve that the behavior of concrete under axial compression has a small portion where the behavior can be considered linear elastic, but for the most part the behavior is considered non-linear. The peak of the curve is often used to determine the compressive strength of the concrete (referred herein as f_c). The level of axial strain when the peak compressive stress is reached is usually between 20,000 and 30,000 $\mu\varepsilon$ [2]. In terms of E-moduli or stiffness it is common to use one of the following: the initial tangential E-modulus (E_t), the secant E-modulus (E_s), and the chord E-modulus (E_{chord}). The definition of these three E-moduli is presented graphically in Fig. 1(b). The initial tangential modulus (E_t) is the slope of a line drawn tangent to the initial linear portion of the stress–strain curve [3]. The secant modulus (E_s) is defined as the slope of the line that goes from the origin to the point in the stress–strain curve corresponding to a compressive stress equal to 0.4 f_c [2]. Finally the chord modulus (E_{chord}) is defined as the slope of the line that connects the point of the stress–strain curve that has an axial strain level equal to 50 $\mu\varepsilon$ with the same point used to determine the secant modulus (i.e. point with stress equal to 0.4 f_c) [3].

The use of NDT vibration-based experiments for purposes of QC/QA of concrete can be done by comparing mechanical properties (i.e. different E-moduli) from traditional compressive tests on concrete cylinder samples with corresponding values obtained from measurements of NDT vibration-based tests. As described later in this paper, the compressive tests were used to determine the compressive strength (f_c) and the different types of E-modulus of the concrete in a direct form. The procedure for the QC/QA of the concrete based on vibration-based NDT tests is presented based on determining the dynamic E-modulus from impact resonance tests [4]. This paper also presents NDT evaluations of concrete using the E-Modulus measurement based on the Ambient Response Method (EMM-ARM) [5]. This second NDT technique has the advantage that it can be used to track the evolution of the E-modulus of the concrete as a function of curing time. The applicability of this second NDT test towards the QC/QA assessment of concrete is also assessed and discussed.

3. Experimental program

The experimental program presented in this paper has two main components. The first component entailed a detailed evaluation of the feasibility of using impact resonance NDT for QC/QA of plain, unreinforced concrete. This was done by comparing the NDT based test results with direct measurements of the mechanical properties of unreinforced concrete samples from compression tests. The second experimental component involved the evaluation of the mechanical properties of a fresh concrete mix as a function of curing time. This section describes the main experimental methods used in this study, which are shown schematically in Fig. 2.

The first experimental component entailed the direct measurement of the mechanical properties of plain, unreinforced concrete cylinders samples was done by mean of compressive tests, as shown schematically in Fig. 2(a). Compressive tests in 245 samples were carried out at the structures laboratory at the Pontificia Universidad Católica del Perú (PUCP). The concrete samples came from dozens of projects within the city of Lima, Peru therefore representing a wide variety of concrete mix designs and curing conditions and ages. The compression tests were carried out in general accordance with the standard test method described in ASTM C39 [1]. All concrete cylinder samples were plain, unreinforced concrete with a standard 0.15 m diameter and a 0.30 m height. The cylinders were tested using neoprene end caps as per specifi-

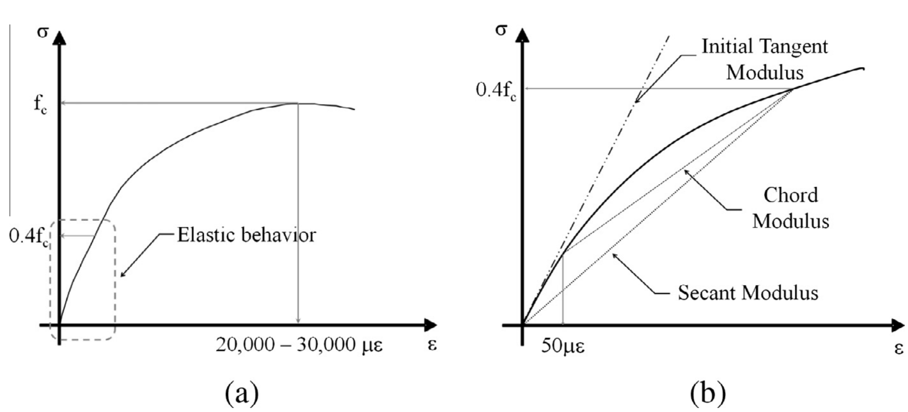

Fig. 1. Stress–strain curve of concrete under compression: (a) curve until maximum strength; and (b) detail of elastic modulus calculation.