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Electrical method to evaluate elastic modulus of early age concrete

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HIGHLIGHTS

- Non-contact electrical method was used to evaluate the development of elastic modulus of early age concrete.
- A general non-linear regression model was used to build up connection between electrical resistivity and elastic modulus.
- The early age hydration process of concrete was investigated.

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ABSTRACT

In this study, the relationship between the modulus of elasticity and the resistivity of concrete was investigated. The resistivity of concrete was measured by newly developed non-contact electrical method and the modulus of elasticity of concrete was measured by echo flying time method. The study focuses on the early age concrete.

It is found that there was a non-linear relationship exists between the modulus of elasticity and resistivity of concrete. It is possible to use the resistivity values to predict the modulus of elasticity for concrete, especially in early stage.

1. Introduction

For the description of elastic properties of stretching or compression, elastic modulus *E*, defined as the slope of its stress–strain curve in the elastic deformation region, is one of the most important properties of concrete. The modulus of elasticity is a measure of the stiffness of materials and is a quantity used to characterize materials. To design concrete structures and ensure their serviceability, the elastic modulus is a fundamental parameter that needs to be estimated accurately.

Ideally, analyzing the load-deformation curve is the most direct method to evaluate elastic modulus of concrete samples under compression. However, from the view of experiment, this testing procedure is much more complicated and time consuming. The workload is heavy.

Try to figure out elastic modulus more convenient, both theoretical and experimental approaches were studied and applied to evaluate the elastic modulus of concrete. In the theoretical model, concrete is assumed to be a two-phase or three-phase system [1–4], which indicates that the elastic modulus can be obtained as a function of the elastic behavior of its components. Nevertheless, elastic modulus is a function of so many parameters, for instance the diameter and volume of aggregate, the elastic moduli of all phases. As a consequence, theoretical models are still too complicated for the practical using. Over the past 30 years, lot researchers have focused on developing a reasonable and feasible model to relate elastic modulus and compressive strength of concrete [5–7]. The predictions of elastic modulus for high-strength concrete [8], high performance concrete [9], stress–strain relation [10] and strain–stress relation [11] of concrete were conducted successfully.

For testing the compressive strength of concrete by compression, even though it is much easier than elastic modulus in practice, amount of samples still need to be prepared. In many researches, electrical method is quite sensitive to monitor the hydration process, microstructure and durability of cement-based materials [12–18]. And the attempt of building up a model to predict elastic modulus and strength of concrete by electrical resistivity has been done [19]. It has been confirmed that the compressive strength can be estimated by the electrical resistivity of

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the sealed cement-based materials [19,20]. The relationship between compressive strength and electrical resistivity of concrete can be expressed in a linear function:

$$f_c = A\rho + B \quad (1)$$

where, f_c and ρ denote compressive strength (MPa) and electrical resistivity (Ω m) of cement-based bulk. A and B are two empirical constants depending on water/cement ratio, cement and aggregate used.

Due to the advantages of electrical method, cheap, sensitive, non-destructive, safe and continuous, it is considered and meaningful to use electrical method to evaluate elastic modulus of concrete.

Without a doubt, the development of electrical resistivity, compressive strength and elastic modulus all depend on the hydration and microstructure formation of cement-based materials. So, in the present work, the objective is to investigate the correlation between the elastic modulus of concrete and electrical resistivity. A general non-linear regression model [21] was adopted and the data were fully discussed to check the feasible of electrical method. Research on the early age electrical property of concrete was carried out by using the non-contact electrical measurement device invented by LI [12]. The elastic modulus was measured by standard compressive test and ultrasonic method.

2. Basic theory

In the previous research, both the development of compressive strength and stiffness of concrete can be expressed in a general degree of hydration-based formulation. For instance, a quite common relation was listed here [22]:

$$\frac{E_c(r)}{E_c(r=1)} = \left(\frac{r - r_0}{1 - r_0}\right)^m \quad (2)$$

$$\frac{f_c(r)}{f_c(r=1)} = \left(\frac{r - r_0}{1 - r_0}\right)^n \quad (3)$$

where r is hydration degree; m and n are exponent parameters depending on type of cement used.

At the same time, electrical resistivity is considered as the fingerprint of hydration process in cement-based materials. The development of electrical resistivity relates with hydration degree in the following way [20]:

$$\rho(t) = \rho_0(t) \cdot \left[V_{total} / \frac{W/C}{D_W} - \frac{D_C - D_H}{D_C \cdot D_H} \cdot r(t)\right]^{s(t)} \quad (4)$$

where $\rho(t)$ is the bulk electrical resistivity; $\rho_0(t)$ is the pore solution electrical resistivity; $s(t)$ is the cementation factor; V_{total} is the total volume of each constituent in the concrete; D_W, D_C and D_H are the densities of the pore solution, cement and hydrates, respectively, and the unit is gram per cubic centimeter; $r(t)$ is the hydration degree of cement paste.

In the view of hydration degree dependent behavior, the correlation between electrical resistivity and elastic modulus can be built up.

A general non-linear regression model [21] was proposed to represent all the building codes' equations as the form:

$$E_c = K(f_c + D)^G + F \quad (5)$$

where E_c and f_c are elastic modulus (GPa) and compressive strength (MPa) of concrete, respectively. K, D, G and F are parameters as intercept.

It is easy to combine Eq. (1) and (5) together to eliminate compressive strength. Then, we can get a new function to express elastic modulus E_c using electrical resistivity ρ:

$$E_c = a(\rho + b)^c + d \quad (6)$$

Parameters a, b, c and d are determined by water/cement ratio, cement and aggregate. For parameter c and d, during the derivation, the parameter A and B would not influence the value of G and F. So, $c = G$ and $d = F$ would not change with type of concrete used, which means c and d must be the constant values.

For parameter c, by the results of empirical formulas provided by some national codes, for instance, the empirical formulas suggested in ACI building code for both normal strength and high strength concrete [23] and European code [24] listed below respectively:

$$E_c = 4.73(f_c)^{0.5} \quad (7)$$

$$E_c = 3.32(f_c)^{0.5} + 6.9 \quad (8)$$

$$E_c = 22(f_c/10)^{1/3} \quad (9)$$

We can conclude that parameter c must be reasonable to choose 0.5 or 0.33 [22] in the new Eq. (6). Otherwise, the correlation between electrical resistivity and elastic modulus would not be close as described above.

3. Experimental methods

3.1. Electrical resistivity method

To measure electrical resistivity of concrete accurately, a non-contact resistivity measurement apparatus was used in the test [12]. The system adopted the transformer principle to avoid error caused by interface between bulk sample and electrode. An induced voltage V on the sample is only 0.1 V, which makes the sample would not be affected by electrical field during the early age hydration process. The volume of sample for electrical resistivity test is 1.4L. During the test, the electrical resistivity data were automatically recorded, and the interval time after a test cycle is 1 min. The whole system was put in a thermo-chamber with a constant temperature at 20 degree same as the curing room. For each sample, electrical resistivity test would last 3 days, starting at the point soon after cement mixing with water.

3.2. Compression test

The compression test was conducted under standard test method for static modulus of elasticity in ASTM C469 - 02e1. The stress/strain ratio of cylinder at $0.4f_c$ was selected as the elastic modulus of sample. For each test, 3 samples were tested by MTS and the average value was used as the real elastic modulus of sample. Though the compression test is the most direct and effective method on testing elastic modulus of concrete, nevertheless, the uniaxial compression test cannot be done at all time slots in the whole 3 days due to the heavy workload and formation of structure in the early age.

3.3. Ultrasonic pulse velocity (UPV) method

The reasons to use ultrasonic pulse velocity method evaluating elastic modulus of concrete is that UPV method can record the velocity of acoustic wave continually and non-destructive. Based on the formula, elastic modulus of concrete would be expressed by the velocity of acoustic wave. This method is a good way to compare with results obtained through electrical method.

In the ultrasonic measurement, a homemade embedded piezoelectric composite was adopted as the ultrasonic transducer [25,26]. When an electrical pulse is applied on the piezo-composite, it starts vibrating and the ultrasonic wave would propagate along the direction of vibration. At the same time, the longitudinal ultrasonic waves would be received by another piezoelectric composite sensor. As long as achieving the longitudinal ultrasonic wave velocity, both dynamic elastic modulus (E_d) and static elastic modulus (E_s) could be obtained.

3.4. Experiments

Ordinary Portland cement meeting the requirement of ASTM type I was used, the density of cement is 3.14 g/cm^3. Sand of 600 μm–5 mm as fine aggregate and artificial gravel of 5–10 mm as coarse aggregate at the saturated surface dry (SSD) were chosen. Three specimens were prepared as shown in Table 1.