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A new dynamic testing method for elastic, shear modulus and Poisson's ratio of concrete

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HIGHLIGHTS

- The position to paste strain rosette for dynamic test of concrete was determined.
- Steady-state excitation method was used and was proved reliable by static experiment.
- "Mode shape coefficient" for concrete was proposed.
- Formula of first-order torsional frequency of free slab was derived.
- Dynamically measured concrete properties follow the relationship given by $E = 2G(1 + \mu)$.

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ABSTRACT

In this work, an energy-based method was used to derive the correlation between concrete shear modulus and torsional frequency of free slab based on first-order torsional mode shape of free slab. The relationship between dynamic elastic modulus of concrete and first-order bending frequency of free slab was also obtained. According to stress and strain analysis of first-order bending mode of concrete cantilever slab and the physical relationship between stress and strain under state of plane stress, the dynamic method for testing Poisson's ratio μ of concrete was proposed. For the concrete with a compressive strength of 22.6 MPa, a transient excitation method was used to determine its dynamic elastic modulus E and shear modulus G; and a steady-state sine excitation method was used to determine its dynamic Poisson's ratio μ. The results of dynamic test showed that the ratio of shear modulus G and elastic modulus E is 0.403; elastic modulus E, shear modulus G and Poisson's ratio μ, follow the relationship given by $E = 2G(1 + \mu)$.

1. Introduction

High-performance concrete is widely used in civil engineering. In concrete structure engineering, elastic modulus and Poisson's ratio are the two significant parameters [1]. However, very few studies have been focused on shear performance among dynamic properties of concrete [2] and dynamic Poisson's ratio [3]. Square plate torsion and beam bending methods at dynamic and static states were used to measure shear modulus of five-layer lauan plywood. The method was proved to be valid by finite element method [4]. To determine Young's and shear modulus of concrete materials at a high temperature, Bahr et al. [5] applied impulse excitation method to determine characteristics of concrete elastic materials with effect of high temperature. Based on that, a new equation for concrete elastic materials at high temperature was proposed. Majid et al. [6] analyzed the relationship between dynamic and static elastic modulus of coir concrete beam specimens based on mechanical dynamics and experiments of damping ratio and natural frequency. The results indicated that this kind of concrete has high damping ratio and low dynamic and static elastic modulus. When coir fiber has a length of 5 cm and a content of 5%, the coir concrete material would have better characteristics. In order to improve elastic modulus of concrete, Azenha et al. [7] measured elastic modulus of concrete specimens during hydration period by a vibration method. During the test, acceleration signal was real-time monitored on the free end of concrete cantilever specimen with a length of 450 mm. Using natural excitation technique, the first-order resonance frequency was distinguished to prove the reliability of the new method. Wen et al. [3] analyzed dynamic Poisson's ratio and strain–stress relationship of concrete based on a three-axis dynamic compression test in 2000. This work

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applied energy method to derive relation between first-order torsion frequency and shear modulus according to torsion vibration of free plate with rectangular section. Thereinto, vibration coefficient depends on the ratio of plate width and length. It can be calculated by kinetic and potential energy related to vibration [8].

For free beam, the relation between elastic modulus and first-order bending frequency has analytic solutions [9]. However, it would be modified when used for free slab. Simulation calculation for concrete with compressive strength of 30 MPa was conducted to derive the modified equation for elastic modulus test. The equation was proved to be suitable for concrete with compressive strength of 20 MPa, 40 MPa, etc.

This work aimed at proposing principle and method of testing concrete dynamic Poisson's ratio based on stress and strain distribution of first-order bending mode of cantilever slab and the physical relationship between stress and strain under state of plane stress, dynamic method for testing Poisson's ratio of concrete was proposed. Particularly, the correct positions to stick stress rosette were determined. Achieved by steady-state sine excitation, the method proved that the test of dynamic Poisson's ratio was conducted based on first-order bending mode shape of cantilever slab. Furthermore, four-points static bending test was conducted to verify it. Therefore, it could be recognized that the dynamic method for testing Poisson's ratio of concrete proposed in this work has adequate basis and its data was credible.

In order to indicate the dynamic method for measuring elastic modulus E, shear modulus G and Poisson's ratio μ and its validity, the concrete with compressive strength of 22.6 MPa was then used to test for dynamic elastic modulus, shear modulus and Poisson's ratio.

2. Testing principles

2.1. Dynamic elastic modulus

For free beam, first-order bending frequency f_b has the following relation with elastic modulus E [9]:

$$E = 0.9462\rho l^4 f_b^2/h^2$$

This equation is suitable for the slender bard with a large length-thickness ratio l/h. For the bar with small length–thickness ratio, the elastic modulus can be expressed as follows:

$$E = k\rho l^4 f_b^2/h^2$$

Considering slab specimens with length–width ratio of 2–8 and width-thickness ratio of 4, 6 and 8, "solid 45" element was applied in ANSYS program to conduct simulation of concrete with compression strength of 30 MPa (set parameters as: $E = 30$ GPa, $\mu = 0.18$, $\rho = 2400$ kg/m^3). According to the computation, k value depends on the length–thickness ratio of the bar so that the calculated k value was conducted with optimization regression analysis by least square method. Therefore, k can be expressed as follows:

$$k = 0.9462\left(1 - 0.08641h/l + 6.9420h^2/l^2\right)$$
(Correlation coefficient R=0.9997, n=21)

The above equation has a high accuracy. e.g., for concrete with compression strength of 30 MPa free bar 640 mm × 160 mm × 40 mm, the calculated and regression values were very close (0.9678 vs. 0.9667) with a difference of 0.1%. In addition, regression equation of k is verified to be suitable for concrete with compressive strength of 20 MPa, 40 MPa etc. by simulation. Therefore, for free-slab specimen, concrete elastic modulus has the following relation with the first-order bending frequency:

$$E = 0.9462(1 - 0.08641h/l + 6.9420h^2/l^2)\frac{\rho l^4 f_b^2}{h^2} \quad (1)$$

In Eq. (1), the length–thickness ratio of free slab is considered to modify equation of free beam theory, thus increasing the measurement accuracy of dynamic elastic modulus by free slab specimen. Therefore, based on Eq. (1), dynamic elastic modulus of concrete could be calculated if first-order bending frequency of free board is measured.

2.2. Dynamic shear modulus

Wang et al. [8] applied first-order torsional frequency of free plate to test shear modulus of metal, glass and timber according to first-order torsional mode shape and energy method in 2014. The method was here applied on concrete with compressive strength of 30 MPa to derive mode shape coefficient γ for shear modulus test of concrete with compressive strength of 30 MPa, based on first-order torsional mode shapes of free slab with different length–width ratios computed by ANSYS program with aid of optimization principles (See Fig. 1).

For concrete, first-order torsional frequency f_t was used to calculate shear modulus as follows:

$$G = \frac{\pi^2 (l/2)^2 b^2 \rho f_t^2}{\gamma \beta h^2} \quad (2)$$

where, $\gamma = 7.4248(1 - 0.0451b/l + 0.1814b^2/l^2)$ (Correlation coefficient $R = 0.99998$, $n = 7$, $l/b = 2 \sim 8$); $\beta \approx \frac{1}{16}\left[\frac{16}{3} - 3.36\frac{h}{b}\left(1 - \frac{h^4}{12b^4}\right)\right]$.

Simulating calculation indicates that Eq. (2) applies for concrete with compressive strength of 20 MPa, 40 MPa, etc.

2.3. Dynamic Poisson's ratio

The ratio of transverse and longitudinal strain (ε_y and ε_x) varies with the distance x from clamp edge, according to stress and strain data of concrete with compressive strength of 30 MPa cantilever slab in first-order bending mode by ANSYS (see Fig. 2). The corresponding stress component σ_y also varies with x. There exists a position x_0 to make σ_y change sign, in other words, from positive to negative or from negative to positive. From another perspective, this indicates that around position x_0 there exists some area of unidirectional stress state $\sigma_y \approx 0$.

For loaded concrete cantilever slab in the state of plane stress, its physical relationship between stress and strain can be expressed as:

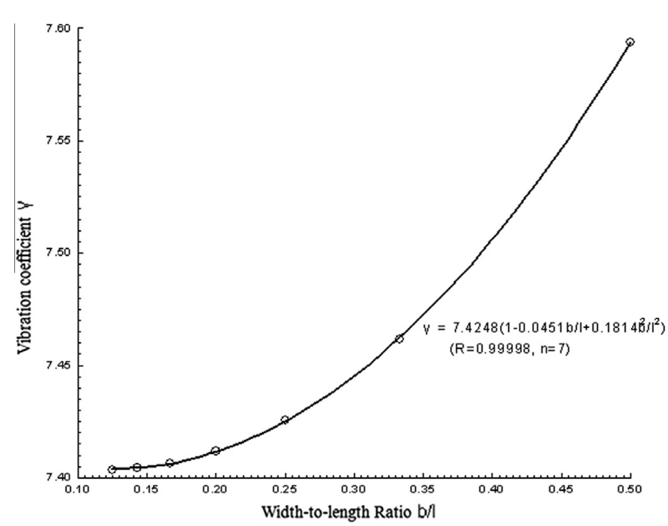

Fig. 1. Mode shape coefficient curve of concrete with compressive strength of 30 MPa.