DETERMINAREA DEGRADĂRII BETOANELOR CU AGREGAT DIN CĂRĂMIZI RECICLATE PRIN ANALIZA FRECVENȚEI DE REZONANȚĂ

DETERMINATION OF RECYCLED AGGREGATE CONCRETE DEGRADATION BY RESONANCE FREQUENCY ANALYSIS

KSENIJA JANKOVIC[1]*, SRBOLJUB J. STANKOVIC[2], DRAGAN NIKOLIC[1], DRAGAN BOJOVIC[1] , LJILJANA LONCAR[1]
[1] *IMS Institute, Bulevar vojvode Mišića 43, 11000 Belgrade, Serbia*
[2]*Vinca Institute of Nuclear Sciences, Belgrade, Serbia*

The evaluation of the dynamic modulus of elasticity of twelve different concrete mix proportions as a function of the density and degradations due to freeze/thaw cycles is presented in this paper. Pore system and saturation are the main factors for concrete freeze-thaw resistance. The frequency analysis of ultrasonic waves in concrete after every 25 cycles was done. Dynamic modulus of elasticity was determination by resonance frequency analysis. This parameter is 35-50% smaller for concrete with recycled bricks as aggregate than ordinary concrete. For all concrete mixes dynamic and static (measured by destructive testing) modules of elasticity were compared.

Articolul prezintă corelațiile modulului de elasticitate dinamic cu densitatea şi rezistența la îngheț-dezgheț, pe baza determinărilor efectuate pe douăzeci de compoziții de beton. Factorii decisivi de influență ai rezistenței la îngheț dezgheț sunt porozitatea şi gradul de saturare cu apă a porilor. Modulul de elasticitate dinamic al betonului după 25 cicluri de îngheț-dezgheț a fost determinat prin analiza frecvenței de rezonanță a ultrasunetelor. Betoanele cu agregat din cărămizi reciclate au prezentat valori mai mici ale frecvenței de rezonanță a ultrasunetelor decât betoanele cu agregat natural. Valorile modulului de elasticitate dinamic şi cele ale modulului de elasticitate static (determinat prin încercarea distructivă) au fost anlizate pentru toate compozițiile de beton.

Keywords: *dynamic modulus of elasticity, ultrasonic waves, freeze-thaw resistance, recycled aggregate concrete*

1. Introduction

Nondestructive testing can be used to understand the material properties of structural components without damaging their appearance [1,2]. Among these methods, the impact resonance method is well known and relatively easy to implement for testing the concrete structures. Basically, this method uses mechanical impact to induce a transient stress ultrasound wave into the object from the surface. A transducer next to the impact measures the surface motion which is recorded as a digital time domain waveform. These time-domain waveforms are transformed into the frequency domain by a well-known FFT technique. Frequency peaks in resulting amplitude spectrum can be used to evaluate the integrity of structural components, to estimate wave speed, or to detect flaws in beams and columns, hollow structures, and plate-like structures [3,4]. The integrity of structural members affects their cross-sectional vibration modes and corresponding natural frequencies. The empirical and analytical equations derived from impact-echo method for estimation of natural resonant frequencies of solid members will vary with the shapes of cross-sections of the structural member under examination. The evaluation of the dynamic modulus of elasticity of concrete with recycled bricks as aggregate due to freeze/thaw cycles by resonance frequency method is presented in this paper.

2. Resonance frequency of the concrete beam

2.1. New dynamic models of Bernoulli-Euler beams

Different types of beam theory and resonant methods for non destructive concrete testing are applied mostly in civil engineering and architecture, but in other discipline of science and technology. Thin beams are one of the major structures used widely in micro-electro-mechanical systems (MEMS)[5]. A large number of those applications utilized the dynamic mechanical properties of thin films materials for targeted performance specifications such as those vibration shock sensor, atomic force microscopes and resonant testing method.

The dynamic problems of Bernoulli-Euler beams are solved analytically on the basis of new modified couple stress theory [6,7]. The governing equations of equilibrium, initial conditions and boundary conditions are obtained by a combination of the basic equations of modified couple stress

---

[*] Autor corespondent/Corresponding author,
Tel: +381 11 2653 645, e-mail: ksenija.jankovic@institutims.rs

theory and Hamilton′s principle. According to the basic hypotheses of Bernoulli-Euler beams and the one-dimensional beam theory, the displacement field can be written as:

$$u = -z\psi(x,t)\,, v = 0 \quad w = w(x,t) \tag{1}$$

where *u, v, w* are the *x-, y-,* and *z-* components of the displacement vector, and $\psi(x)$ is the rotation angle of the centrically axis of the beam given approximately by

$$\psi(x) \approx \frac{\partial w(x,t)}{\partial x} \tag{2}$$

For small deformation considered here.
The modified couple stress theory defines the strain energy U in a deformed isotropic elastic material as:

$$U = \frac{1}{2}\int_0^L (EI + \mu Al^2)\left(\frac{\partial^2 w(x,t)}{\partial x^2}\right)^2 dx \tag{3}$$

Where *E* is Young′s modulus of the beam material, *I* is the usual second moment of cross-sectional area, μ is shear modulus, *A* is the cross-sectional area of the beam, *l* is a material length scale parameter and *L* is total length of beam. In general case, the work done by external forces in the form of transverse loading *q(x, t)* is:

$$V = \int_0^L q(x,t)w(x,t)dx \tag{4}$$

And the kinetic energy with $\rho(x)$ is the density of the beam material can be written as

$$T = \frac{1}{2}\int_0^L \rho(x)A(x)\left(\frac{\partial w(x,t)}{\partial t}\right)^2 dx \tag{5}$$

The dynamic governing equation of this beam as well as all possible boundaries.

Conditions can be determined with aid of the Hamilton′s principle:

$$\delta\int_{t1}^{t2}\int_0^L \left[\frac{1}{2}\rho A\dot{w}^2 - \frac{1}{2}(EI + \mu Al^2)(w'')^2 + qw\right]dxdt = 0 \tag{6}$$

Finally, the dynamic governing (equilibrium) equation of the beam in terms of w*(x,t)* is given by

$$\rho A\ddot{w} + (EI + \mu Al^2)w^{(4)} = q \tag{7}$$

The initial conditions read

$$\dot{w}(x,t2)\delta w(x,t2) - \dot{w}(x,t1)\delta w(x,t1) = 0 \tag{8}$$

And the equations

$$\frac{\partial^2 w}{\partial x^2} = 0 \text{ or } \frac{\partial w}{\partial x}\,,\ \frac{\partial^3 w}{\partial x^3} = 0 \text{ or } w$$

Prescribed at *x = 0* and *x = L* as boundary conditions.

Directly applying the new dynamic model and solving equilibrium equation with boundary conditions for a simply supported beam, the fundamental natural resonant beam frequency is:

$$f_{SB} = \frac{\pi}{2}\sqrt{\frac{EI + \mu Al^2}{\rho AL^4}} \tag{9}$$

and for a cantilever:

$$f_C = \frac{(1.875)^2}{2\pi}\sqrt{\frac{EI + \mu Al^2}{\rho AL^4}} \tag{10}$$

The beam with an intermediate support on half length (presented in Fig. 1) for the fundamental resonant beam frequency hold:

$$f_{ISB} = \sqrt{\frac{EI + \mu Al^2}{\rho A^2L^2}} \tag{11}$$

When a material length scale parameter *l* is significant less than characteristic beam thickness, at such time the natural resonant frequency is approximately equal to the values calculated from the classical beam model.

2.2. Determination of dynamic modulus of elasticity

Dynamic Young's modulus of elasticity is calculated by test method for fundamental longitudinal resonant frequency of concrete specimens. The fundamental resonant frequency is determined using the impact resonance method [8].

In the impact resonance method, a suported specimen is struck with a small impactor and the specimen response is measured by lightweight accelerometer on the specimen (Fig. 1). The impactor is made of metal or rigid plastic, the sensor is a piezoelectric accelerometer and specimen support permits the specimen to vibrate freely. The output of the accelerometer is recorded. The fundamental frequency of vibration is determined by using digital signal processing methods or counting zero crossings in the recorded waveform. The fundamental frequency for this mode of vibration is obtained by proper location of the impact point and the accelerometar (Fig. 2).

According to equation 11., the calculate dynamic Young's modulus of elasticity (*E*), from

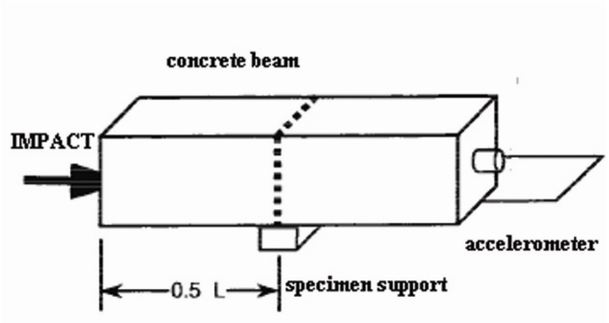

Fig. 1 - Locations of impact, accelerometer and specimen support. / *Principiul metodei analizei frecvenței de rezonanță a ultrasunetelor, cu localizarea impactorului şi accelerometrului pe grinda de beton.*

the fundamental longitudinal frequency (f_{isb}), mass (m) and dimensions (b, h) of cross section of beam (test specimen) as follows:

$$E = \frac{4 \cdot L \cdot m}{b \cdot h} \cdot f_{ISB}^{2} \qquad (12)$$

3. Degradation of concrete

As the temperature of saturated concrete in service is lowered, the water held in the capillary pores in the hardened cement paste freezes and expansion of the concrete takes place. If subsequent thawing is followed by re-freezing, repeated cycles have a cumulative effect. Each cycle of freezing causes a migration of water to locations where it can freeze. The location includes fine cracks which become enlarged by the pressure of the ice and remain enlarged during thawing.

Freezing is a gradual process, partly because of the rate of heat transfer through concrete, partly because of progressive increase in the concentration of dissolved salts in the still unfrozen pore water and partly because the freezing point varies with size of the pore. The larger voids in concrete, arising from incomplete compaction, are usually air-filled, not appreciably subject to the action of frost.

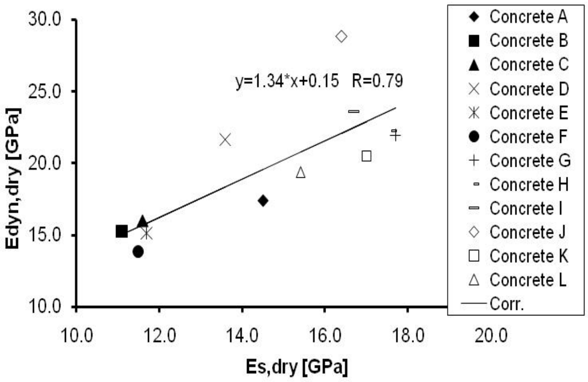

Fig. 3 - Relation of dynamic vs. static modulus of elasticity. *Corelația dintre modulul de elasticitate dinamic şi static.*

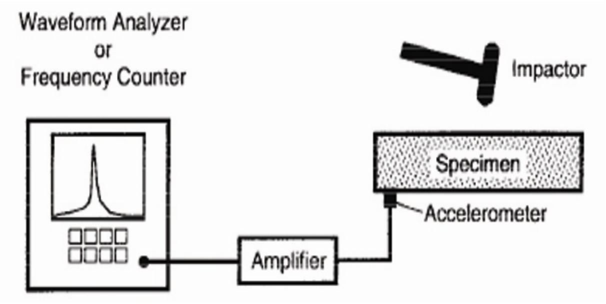

Fig. 2 - Schema of apparatus for impact resonance test method./ *Schema de funcționare a aparatului de analiză a frecvenței de rezonanță a undelor în beton.*

There are two possible sources of dilating pressure. First, freeying of water results in an increase in volume of approximately 9 per cent, so that the excess water in the cavity is expelled [9]. The second dilating force is caused by diffusion of water leading go a growth of a relatively small number of bodies of ice. This diffusion is caused by osmotic pressure brought about by local increases in solute concentracion due to the separation of froyen water from the pore water.

4. Experimental investigation

Experimental work included 12 kinds of concrete consisting of different cement content, type of aggregate and polymer admixture, but with the same consistency [10]. Concrete mixtures were made using ordinary Portland cement (CEM I 42.5R). Six kinds of concrete (A, B, C, G, H and I) had 350 kg/m^3 and six (D, E, F, J, K and L) 250 kg/m^3 cement content. After demolition of masonry structure bricks were crushed and separated into fractions 0/4, 4/8, 8/16 and 16/32 mm. Six kinds of concrete (A, B, C, D, E and F) were made using recycled bricks as aggregate. Other kinds of concrete (G, H, I, J, K and L) were made using combination of river sand and recycled bricks. Concrete mixtures B, E, H and K were modified by 4 % admixture of polymer, while mixtures C, F, I and L were made with 8 % admixture of polymer by weight of cement.

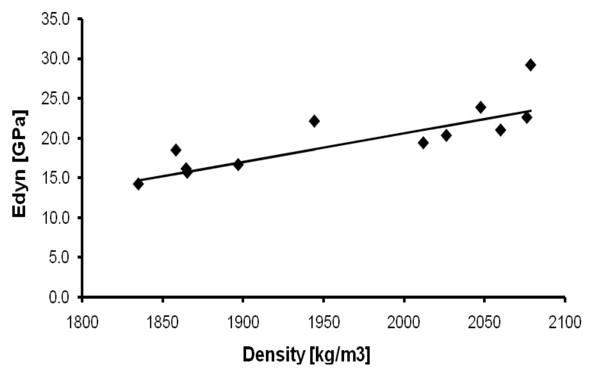

Fig. 4 - Dynamic modulus of elasticity as function of bulk density. / *Influența denistății betonului asupra modulului de elasticitate.*

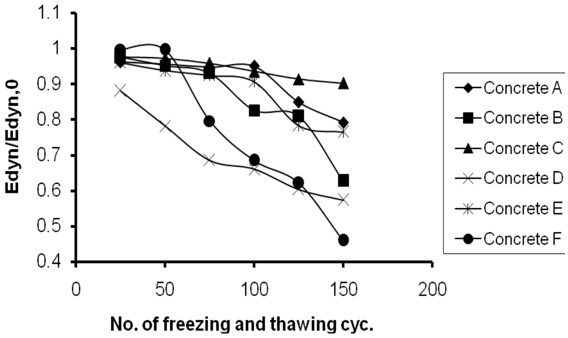

Fig. 5 - Relative dynamic modulus of elasticity of concrete with recycled bricks / *Modulul de elasticitate relativ în funcție de numărul de cicluri de îngheț-dezgheț ale betonului cu agregat reciclat.*

Dynamic modulus of elasticity was tested in dry and saturated state (see 2.2.). This property is 35-50% smaller for concrete with recycled bricks as aggregate than ordinary concrete. Dynamic modulus (Edyn) is greater than static modulus of elasticity (Estat), measured by destructive testing, which was expecting (Fig. 3). Dynamic modulus show a good correlation with bulk density of concrete (Fig. 4). In the Europe, freeze-thaw resistance of concrete was determined by using different methods and time-temperature cycles [11]. In contrast to the destructive testing of resistance to the freezing and thawing [12], in this case is carried out by non-destructive testing method.

One freeze-thaw cycle means that specimens are 4h in the water at temperature 20°C and 4h in the freezing chamber at -20°C. According to Serbian standard after 0, 25, 50, etc. freezing and thawing cycles decrease of dynamic modules of elasticity was tested. Relative dynamic modulus of elasticity (dynamic modulus after n cycles related to initial modulus at 0 cycles) is shown in Figures 5 and 6.

5. Conclusion

This method is intended primarily for detecting significant changes in the dynamic modulus of elasticity of laboratory or field test specimens that are undergoing exposure to weathering or other types of potentially deteriorating influences.

The value of the dynamic modulus of elasticity obtained by this method will, in general, be greather than the static modulus of elasticity. The difference depends, in part, on the strength level of the conrete.

The conditions of manufacture, the moisture content, and other characteristics of the specimens materially influence the results obtained.

Different computed values for the dynamic modulus of elasticity may result from widely different resonant frequencies of specimens of different sizes and shapes of the same concrete.

Therefore, it is not advisable to compare results from specimens of different sizes or shapes.

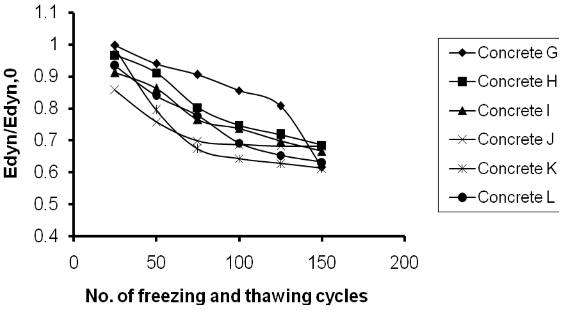

Fig. 6 - Relative dynamic modulus of elasticity ofconcrete with recycled bricks and river sand / *Modulul de elasticitate relativ al betonului cu agregat grosier reciclat şi nisip de râu.*

Acknowledgments

This work was provided under financial support of Ministry of Science and Technological Development, Republic of Serbia.

REFERENCES

1. Z.Dao, L.Xiao-Zhou, G. Xiu-Fen, V.E. Nazarov, and M. Li, Concrete damage diagnosed using the non-clasical nonlinear acoustic method, Chinese Physics B, 2009,**18**,1898.
2. S. Nishibata, T. Watanabe, C. Hashimoto, and K. Kohno, Evaulation of fracture in concrete with recycle aggregate by acoustic emission, International Journal of Modern Physics B, 2006,**20**, 3652.
3. J.J.Wang, T.P.Chang, B.T. Chen, H.C. Lin, and H. Wang, Evaluation of Resonant Frequencies of Solid Circular Rods with Impact-Echo Method, Journal of Nondestructive Evaluation, 2010, **29**,111.
4. K. Byeong-Chan, and K. Jin-Yeon, Characterization of ultrasonic properties of concrete, Mechanics Research Communications, 2009, **36**, 207.
5. S. Kong, S. Zhou, and Zhifeng Nie, The size-dependent natural frequency of Bernoulli-Euler micro-beams, Kai Wang, International Journal of Engineering Science 2008, **46**,427.
6. F.Yang, A.C.M. Chong, D.C.C. Lam, and P. Tong, Couple stress based strain gradient theory for elasticity, International Journal of Solids and Structures, 2002,**39**, 2731.
7. S.K. Park, and X-L. Gao, Bernoulli-Euler beam model based on a modified couple stress theory, Journal of Micromechanics and Microengineering, 2006,**16**,2355.
8. xxx, ASTM Standards C 215-02: Standard Test Method for Fundamental Transverse, Longitudinal, and Torsional Resonant Frequencies of Concrete Specimens, 2002.
9. A.M. Neville, Properties of concrete. Pearson education limited. England 2000.
10. K. Janković, D. Bojović, and D. Nikolić, Some Properties of Concrete Based on Recycled Bricks, Romanian Journal of Materials, 2010, **40**(3), 222.
11. D.Georgescu, A. Apostu, and G. Miron, Experimental research for the evaluation of concrete freeze-thaw resistance, Romanian Journal of Materials, 2010, **40**(2), 122.
12. K. Janković, D. Bojović, D. Nikolić, Lj. Lončar, and Z. Romakov, Frost Resistance of Concrete with Crushed Brick as Aggregate, Facta Universitatis, Series: Architecture and Civil Engineering, 2010, **8**(2), 155.