Calcium Silicate Bricks – Ultrasonic Pulse Method: Effects of Natural Frequency of Transducers on Measurement Results

Jiri Brozovsky

Abstract**—**Modulus of elasticity is one of the important parameters of construction materials, which considerably influence their deformation properties and which can also be determined by means of non-destructive test methods like ultrasonic pulse method. However, measurement results of ultrasonic pulse methods are influenced by various factors, one of which is the natural frequency of the transducers. The paper states knowledge about influence of natural frequency of the transducers (54; 82 and 150kHz) on ultrasonic pulse velocity and dynamic modulus of elasticity (Young's Dynamic modulus of elasticity). Differences between ultrasonic pulse velocity and dynamic modulus of elasticity were found with the same smallest dimension of test specimen in the direction of sounding and density their value decreases as the natural frequency of transducers grew.

Keywords**—**Calcium silicate brick, ultrasonic pulse method, ultrasonic pulse velocity, dynamic modulus of elasticity.

I. Introduction

Modulus of elasticity is one of the important parameters of construction materials, which considerably influence their deformation properties and that can in finished structures show as bending, deviations or shrinkage. It is also one of parameters taken into account when design of the structure is calculated and assessed.

Static modulus of elasticity (Young's modulus of elasticity) can be defined in the area of elastic deformation in accordance with Hook's law as the ratio of normal tension to relative deformation caused by the tension.

Young's modulus of elasticity can be determined by loading test specimen in test press (usually with tension corresponding to 30-40% of compressive strength); the result of the test is usually static elasticity modulus, or, by dynamic non-destructive methods, most usually the ultrasonic pulse or resonance method. The test result is then the dynamic modulus of elasticity. Testing of elasticity modulus by loading test specimens in test press gives real values, however, the disadvantage is high requirements for technical equipment and process of testing compared to measurement with non-destructive test methods. The advantage of non-destructive ultrasonic pulse method is the fact that it can determine the dynamic modulus of elasticity of materials built in constructions

Jiri Brozovsky is with the Department of Technology of Building Materials and Components, Faculty of Civil Engineering, Brno University of Technology, Veveri 331/95, 602 00 Brno, Czech Republic (phone: +420541147513, fax: +420541147502, e-mail: brozovsky.j@fce.vutbr.cz, www.fce.vutbr.cz).

Determination of dynamic modulus of elasticity with non-destructive test methods is use used mostly for concrete, the measurement procedures are stated in many standards, like ISO 1920-7 [12], CSN EN 12504-4 [11], ASTM 597 [10]; however, these do not state the procedure for determination of dynamic modulus of elasticity. Determination of dynamic modulus of elasticity is stated in national standards, like CSN 731371 [13], CSN 731372[14] or in technical literature, for example [1]-[3], [5], [7], [9].

Results of measurement with dynamic methods are influenced by various factors, in particular humidity of material, composition and homogeneity, defects in the inner structure, but they are also influenced by the way of measuring and parameters of testing device. Influence of these factors on measurement results during testing concrete is described in technical literature, for example [4], [6], [8] and standards, for example CSN EN 12504-4 [11]. However, the question is the extent to which these factors influence testing of calcium silicate bricks.

The paper states knowledge about influence of natural frequency of transducers on results of measurement with ultrasonic pulse method for determination of Young's Dynamic modulus of elasticity.

II. Requirements for Measurements of Ultrasonic Pulse Method for Determination of Young's Dynamic Modulus of Elasticity

Generally it is true that natural frequency of transducers for measurement with ultrasonic pulse methods should be selected so that the relation of wave length (λ_L) to the smallest dimension of the test specimen in the direction of sounding (d_{min}) is smaller than 1. Wave length is calculated - refer to (1):

$$\lambda_L = V/f_n \quad (1)$$

where V-ultrasonic pulse velocity (m/s), f_n-natural frequency of transducers (Hz).

This requirement is determined for the reason of elimination of possible reduction of propagation of ultrasonic pulse and it is stated also in CSN EN 12504-4 [11]. The calculation of dynamic modulus of elasticity from measurement by ultrasonic method involves also another parameter, which is dimensionality of the medium - refer to (2):

$$E_U = D.V^2 \; 1\!/\!k^2 \tag{2}$$

where E_U- Young´s Dynamic modulus of elasticity in one-dimensional environment (MPa), *D*-density (kg/m^3), *V*-ultrasonic pulse velocity (km/s), *k*–coefficient of dimensionality of the environment (k=1 for one-dimensional environment).

For reproducibility of test results, i.e. for comparability of determined values of dynamic modulus of elasticity, it is necessary that measurements are carried out in unambiguously defined environment. For measurements on cylinders, cubes, blocks and similar specimens, three types of environment can be defined:

– one-dimensional environment (in accordance from CSN 731371 [13] following condition has to be satisfied: $d_{min} \leq 0.2\lambda_L$);
– three-dimensional environment (in accordance with CSN 731371] [13] following condition has to be satisfied: $d_{min} \geq 2\lambda_L$);
– intermediary environment (environment, which does not satisfy above mentioned conditions).

Ultrasonic pulse velocity in one-dimensional environment V_{L1} is calculated from the ultrasonic pulse velocity in three-dimensional environment (V_{L3}) and from the coefficient of dimensionality (k_3) - refer to (3):

$$V_{L1} = V_{L3}\!/\!k_3 \tag{3}$$

The coefficient of dimensionality k_3 is calculated - refer to (4):

$$k_3 = \sqrt{\frac{1-\nu_U}{(1+\nu_U).(1-2\nu_U)}} \tag{4}$$

III. Test Procedure and Results

Test equipment – the ultrasonic apparatus TICO, accuracy 0.1µs, natural frequency of transducers 54kHz-82kHz-150kHz.

Test specimens – the calcium silicate bricks 290 x 140 x 65mm dried until constant weight; compressive strength 35.7 to 77.4MPa; density 1796 to 1910kg/m^3; number of test specimens in the set-16.

Test procedure and evaluation of measurement results - measurements were taken by direct transmission along the calcium silicate brick in five points of measurements.

Measurement results - the results of measurements and calculated dynamic modulus of elasticity for every natural frequencies of transducers are state in Table I.

TABLE I
Results of Measurements with Ultrasonic Pulse Method

Sp.No	D	V_{54}	V_{82}	V_{150}	$E_{u,54}$	$E_{u,82}$	$E_{u,150}$
Units	(kg/m^3)		(km/s)			(MPa)	
1	1813	3.025	2.917	2.891	16597	15434	15161
2	1828	3.010	2.951	2.936	16566	15919	15763
3	1815	2.985	2.956	2.896	16171	15853	15220
4	1888	3.198	3.165	3.089	19302	18912	18012
5	1870	3.162	3.118	3.055	18702	18187	17453
6	1871	3.113	3.077	2.969	18129	17713	16492
7	1837	3.056	2.984	2.951	17153	16351	15991
8	1822	3.001	2.954	2.927	16416	15907	15611
9	1835	3.045	2.999	2.947	17013	16504	15942
10	1849	3.059	3.037	2.940	17307	17059	15989
11	1849	3.117	3.050	2.968	17968	17199	16289
12	1828	3.038	2.985	2.953	16875	16292	15946
13	1910	3.282	3.225	3.191	20578	19864	19442
14	1851	3.119	3.069	2.999	18001	17436	16644
15	1796	2.945	2.886	2.834	15574	14954	14427
16	1846	3.072	3.004	2.931	17417	16652	15859

Dimensionality of environment for natural frequency of transducers is given in Table II.

TABLE II
Dimensionality of Environments for Individual Natural Frequencies of Transducers

f_n	V_{min}	V_{max}	d_{min}	λ_{Lmin}	λ_{Lmax}	Type ofenvironment
(kHz)	(km/s)]		(m)	(m)	(m)	
54	2.945	3.282	0.066	0.054	0.061	intermediary environment
82	2.886	3.225	0.066	0.035	0.039	three-dimensional environment
150	2.834	3.191	0.066	0.019	0.021	three-dimensional environment

IV. Discussion of the Results

To assess influence of natural frequency of transducers on the results of measurement with ultrasonic pulse method, the differences between ultrasonic pulse velocity or dynamic modulus of elasticity determined by measurement of transducers with natural frequencies 82 kHz and 54, 150 kHz were calculated (reference natural frequency was 82 kHz, because it satisfied the conditions for three-dimensional environment).

Percental differences $\Delta P_{i\text{-}82}$ between ultrasonic pulse velocity or dynamic modulus of elasticity from measurements with transducers with natural frequency 82 kHz and $V;E_u$ from measurements with transducers with natural frequencies 54 and 150 kHz were calculated - refer to (5):

$$\delta P_{i\,\text{-}\,82} = \frac{P_i - P_{82}}{P_{82}}.100 \tag{5}$$

where P_{82}- ultrasonic pulse velocity or dynamic modulus of elasticity at natural frequency of transducers 82kHz; P_i-ultrasonic pulse velocity or dynamic modulus of elasticity at natural frequency of transducers *i*=54; 150kHz

Determined differences are summarized in Table III. Fig. 1 gives comparison of differences between ultrasonic pulse velocity depending on natural frequency of transducers and Fig. 2 gives comparison of differences between dynamic modulus of elasticity depending on natural frequency of transducers.

TABLE III
SUMMARIZATION OF DIFFERENCES V AND E_U FROM MEASUREMENT WITH TRANSDUCERS WITH VARIOUS NATURAL FREQUENCIES

Difere nce	Δ V_{54-82}	δ V_{54-82}	Δ V_{150-82}	δ V_{150-82}	Δ E_{U54-82}	δ $E_{U,54-82}$	Δ $E_{U150-82}$	δ $E_{U,150-82}$
Units	(km/s)	(%)	(km/s)	(%)	(km/s)	(%)	(km/s)	(%)
Mean	0.056	1.85	-0.108	-3.56	625	3.66	-1203	-7.12
Min.	0.014	0.49	-0.074	-2.50	156	0.98	-1679	-5.04
Max.	0.108	3.51	-0.149	-4.89	1221	6.89	-803	-9.76

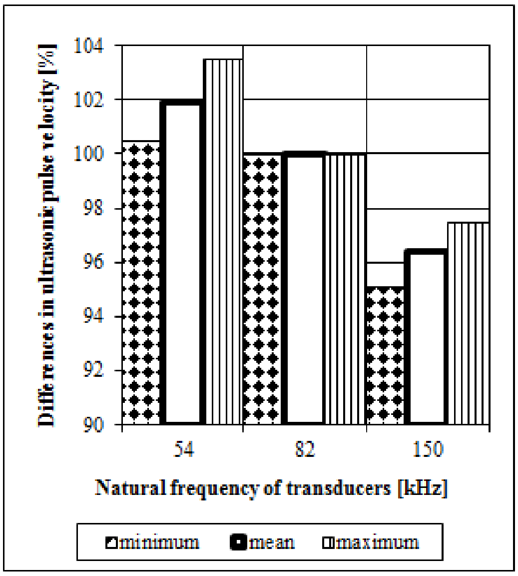

Fig. 1 Comparison of differences between ultrasonic pulse velocity depending on natural frequency of transducers (100%=V_{82})

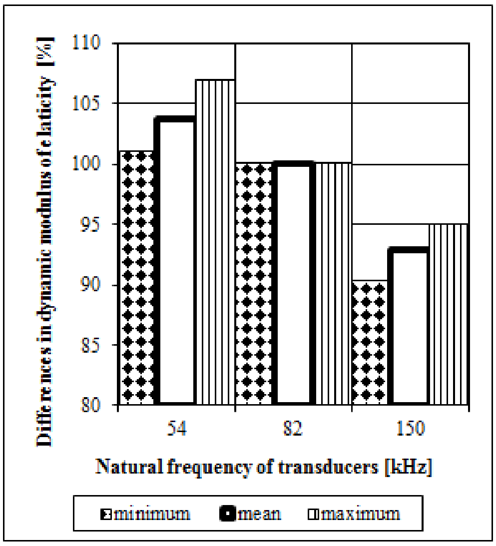

Fig. 2 Comparison of differences between E_u depending on natural frequency of transducers (100%=E_{U82})

Analysis of the knowledge about influence of natural frequency of transducers on results of measurement with ultrasonic pulse method implies that:

– Natural frequency of transducers influences results of measurement with ultrasonic pulse method. The value of ultrasonic pulse velocity and dynamic modulus of elasticity decreases as the value of natural frequency of transducers increases, at the same minimal dimension of the test specimen in the direction of sounding and the same density.
– For calcium silicate bricks with dimensions 290x140x65mm the three-dimensional medium was achieved when measuring with transducers with natural frequencies 82 and 150 kHz, therefore the values of parameters from measuring with ultrasonic pulse method should be theoretically the same. However, in practice, the values of ultrasonic pulse velocity and dynamic modulus of elasticity from measurements with transducers with natural frequency 150 kHz were on average by 3.6 resp. 7.1% lower compared to the values determined by measurements with transducers with natural frequency 82 kHz. This fact can be explained by damping of waves with higher frequencies of transducers travelling on longer distance.
– The highest ultrasonic pulse velocity was observed during measurement with transducers with natural frequency 54 kHz, however, it was not possible to define dimensionality of environments, which is a necessary parameter for calculation of dynamic modulus of elasticity for given smallest size of the specimen in the direction of sounding. Differences between ultrasonic pulse velocity from measuring with transducers with natural frequency 54 kHz were on average by 1.9 or 3. 5% higher.
– For determination of dynamic modulus of elasticity of calcium silicate bricks with ultrasonic pulse method it is necessary to select appropriate natural frequency of transducers based on preliminary measurements, which makes sure that measurements will be carried out in unambiguously defined dimensionality; usually, it is three-dimensional environment.

V. CONCLUSION

The analysis of knowledge about influence of natural frequency of transducers on results of non-destructive testing of calcium silicate bricks with ultrasonic pulse method implied that natural frequency of transducers has influence on the results of measurements and therefore it is necessary to select natural frequency assuring that the measurement will be carried out in the environment with unambiguously defined dimensionality, which enables comparability of results of measurements carried out at different test laboratories. This requirement has to be satisfied every time when the output of the measurement is dynamic modulus of elasticity.

In case the output of the measurement is only ultrasonic pulse velocity it is possible to carry out the measurement with transducers with natural frequencies 50 – 90 kHz; however, to ensure comparability of results of measurements it is necessary to carry out the measurement with transducers with same natural frequency.

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