Third International Conference on Sustainable Construction Materials and Technologies http://www.claisse.info/Proceedings.htm

Use of Non-Destructive Ultrasonic Pulse Testing Methods in Evaluation of Brick Parameters

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ABSTRACT

Currently, building industry uses non-destructive testing methods primarily for evaluation of concrete quality. Efficiency of ultrasonic pulse method (UPM) was proved in order to determine compressive strength of solid bricks (concrete, calcium silicate and burnt ones). Parameters obtained from UPM testing (such as ultrasonic pulse velocity, dynamic modulus of elasticity) are affected by shape/dimension of bricks, their components, and porosity and imperfections of their structure. These factors are variously manifested in test results and calibration correlations elaborated in order to determine compressive strength based on non-destructive testing parameter. In practice, the ultrasonic pulse testing method is utilizable for determination of compressive strength in concrete and lime-sand bricks; calibration correlations feature high consistence between variables (correlation coefficient lies between 0.936 and 0.966). However, above stated factors are subject to accurately defined testing conditions in order to provide reproducibility of test results.

Keywords: brick, ultrasonic pulse velocity, modulus of elasticity, strength, NDT

INTRODUCTION

At the present time, non-destructive testing methods in building industry are mostly used for examination of concrete and reinforced concrete structures; specifically, concerned are hardness test methods (Schmidt impact hammers), local fracture methods (e.g. spine extraction methods), and dynamic methods such as ultrasonic pulse method or resonance method). Aforesaid non-destructive testing methods are used to determine strength of in-built concrete as well as quantity, form and distribution of armature. In sparsely manner, these methods are used in structure defectoscopy or monitoring of in-built concrete uniformity. As for use in concrete and reinforced concrete structures, see technical literature (e.g. Bungey, 1989), (Malhotra, Carino, 1991), (Jones, 1949), (Dufka, Bydzovsky, 2013), along with technical standards (national, European or international ones), e.g. (CSN EN 12504-2, 2002), (CSN EN 12504-4(2005), (CSN EN 13791, 2007), (CSN 731371, 2011), (ASTM C805-08, 2008), (ASTM C597-09, 2009) - concrete, (CSN EN 14146, 2005)-natural stone.

In the matter of other building material of building framework, these methods are considerably less used (except hardness testing of mortar in brickwork bed joints, and testing of solid burnt bricks) because, in particular, there are no usable calibration correlations enabling determination of monitored parameter (e.g. strength) based on non-destructive testing parameter and support by normative documents codified both methodology of testing of its own and procedures of its findings.

Together with steelwork, the ultrasonic pulse testing method is mostly used for evaluation of concrete and concrete structures; in this respect, it serve to both detection of physico-mechanical properties (such as concrete compressive strength, modulus of elasticity) and homogeneity/defects in structures along with crack depths, as the case may be. Also, it can constitute a supporting method with evaluation of concrete frost resistance. Moreover, it is useful to detection of longitudinal wave velocity of ultrasonic pulses in natural stone. See technical standards e.g. (CSN EN 12504-4, 2005 for), (CSN EN 13791, 2007)-concrete, (CSN EN 14579, 2005)-natural stone procedures covering testing and evaluation of test results as to ultrasonic pulse testing method and above material.

As to other material see (Martinček, 1962), (Brozovsky, 2005), (Brozovsky, Zach, 2010) - cements, (Brozovsky et al., 2005)-concrete paving blocks concerning strength detection through the use of ultrasonic pulse testing method.

This paper describes pieces of knowledge, relevant to use of ultrasonic pulse testing method for compressive strength determination of bricks (burnt, calcium silicate and concrete ones).

ULTRASONIC PULSE TESTING METHOD: BASIC CHARACTERISTIC

Ultrasound is created by mechanical particle pulses over 20 kHz. As to building material, probes featuring 40 to 150 kHz are used.

When ultrasonic wave propagates through an environment, particles of the late pulsate in different ways in relation to wave course. Based on that, we differentiate ultrasonic waves to longitudinal, transverse, surface and plate waves. With longitudinal wave, the environment particles pulsate along straight course in the direction of wave propagation.

The ultrasonic pulse passage method is the most widespread one. Its principle can be described as follows: a pulse exciter generates repeated ultrasonic pulse into material; after that, pulses passed through this tested material are sensed in respect of time elapsed during pulse passing through testing base. Testing techniques: direct transmission, indirect transmission and surface sounding. Eq. 1 shows calculation of ultrasonic pulse velocity taking into account time passing through testing base and length of the same as follows:

$$V = \frac{L}{T} \tag{1}$$

Where : *V*-ultrasonic pulse velocity [km/s], *L*-length of measuring base [mm], *T*-transit time [μs].

On the basis of ultrasonic pulse velocity and density, dynamic modulus of elasticity related to the tested material was calculated using relation Eq. 2

$$E_u = D.V^2 \frac{1}{k^2} \tag{2}$$

Where : E_U-dynamic modulus of elasticity [MPa], *V*-ultrasonic pulse velocity [km/s], *D*-density of brick [kg/m^3], *k*-ambient dimensionality ratio, which depends on the minimum specimen dimension and Poisson's ratio.

Ultrasonic pulse method testing is affected by number of factors such as moisture, structural defects of test material, dimension/shape of test sample, sensing probe frequency of its own, as well as means of acoustic feedback between sensing probes and test material. These factors are essential with methodology of particular material tested.

STRUCTURAL CHARACTERISTIC OF PARTICULAR BRICK TYPES

Structure of test bricks – to be particular concrete, calcium silicate and burnt ones – results from used material and manufacturing technology.

a) Concrete bricks: manufactured from mixture of fine and coarse aggregates (D_{max} = 8 mm), cement, water, and admixtures. Compared with common building structure concrete, this concrete contains substantially less mix water; that is why products are manufactured by using of vibrating extruder forming. Owing to used silicate binder, product strength increase in course of time due to cement hydration process. Hardened concrete i.e. concrete brick structure is a conglomeration of aggregates, hardened cement grout and air poruses, see Fig. 1a.

b) Calcium silicate bricks: manufactured from mixture of silica sand, quicklime and water. This mixture is extruded to form products being subsequently placed into autoclave for some time, where – in 16 bar water steam and 195 °C temperature – they harden (i.e. releasing of silicon oxide from sand grains, which react with dry hydrate to create very solid C-S-H phase. Calcium silicate bricks structure is a conglomeration of sand bound by lime hydration products, see Fig. 1b.

c) Burnt bricks: manufactured from brick clay and water, or with addition of grog, fusing material, and lightener in some cases. Depending on water content, these bricks are manufactured by extruding or pressing. The extruding technology is applied mostly to common brick material, while the pressing technology was used in former times with the exception of clinkers. After pressing, bricks are dried up and burnt to get required physico-mechanical properties. Structure of burnt bricks varies, depending upon forming method, drying process and burning. Brick body contains open/closed air poruses along with cracks in varying degrees. See Fig. 1c for extruded brick and Fig. 1d (made in 1899) for pressed one respectively.

Fig. 1a: Structure of Concrete Brick

Fig. 1b: Structure of Calcium Silicate Brick

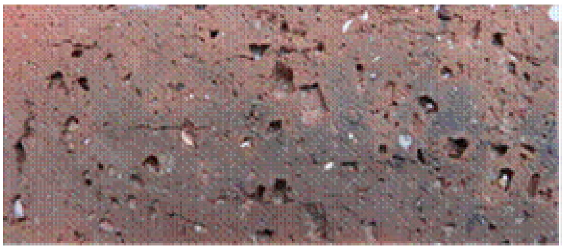

Figure 1c: Structure of Extruded Burnt Brick

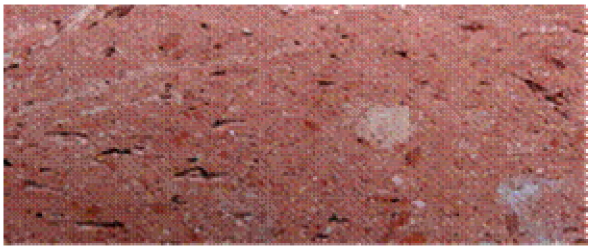

Figure 1d: Structure of Pressed Burnt Brick

METHODOLOGY AND TEST RESULTS

Specimens: Ultrasonic pulse testing was applied to burnt bricks, specifically:

- Concrete bricks: size 240 × 115 × 70 mm; density 2217 to 2305 kg/m^3, compressive strength 45.1 to 77.0 MPa. Specimens were measured at the age 7, 14, 21, and 28 days. Number of specimens in a set tested: 60. To ensure uniform moisture condition, the specimens were stored in environment with $\varphi \geq 95$ % and 20 ± 2 ^{o}C.
- Calcium silicate bricks: size 240 × 115 × 70 mm; density 1744 to 1897 kg/m^3 (number of specimens in a set tested: 50); size 290 × 140 × 65 mm, density 1469 to 1774 kg/m^3, compressive strength 12.7 to 31.1 MPa (number of specimens in a set tested: 40). Before testing, the specimens were dried to constant mass.
- Burnt bricks: size 290 × 140 × 65 mm; bricks formed by means of rigid plastic extruding (marking: "new"), number of specimens in a set tested: 80, density 1469 to 1774 kg/m^3, compressive strength 12.7 to 35.2 MPa. Bricks formed by means of pressing (marking: "old"), number of specimens in a set tested: 50, density 1567 to 1781 kg/m^3, compressive strength 21.9 to 47.0 MPa. Before testing, the specimens were dried to constant mass.

Specimen surface in the point of measurement has to be smooth with no protrusion, unevenness or failure. In case the specimen surface does not meet these requirements, there will be necessary to trim it, e.g. by grinding. Also, the surface shall be free of impurities, contamination or other heterogeneous particles; in such a case, they must be removed before the measurement take place.

Ultrasonic pulse method: Testing was done by means of direct sounding, see Fig. 2. Transit time measurement system: The transit time measurement system function as follows: lengthwise – 3 measuring points; breadthwise – 5 measuring points. All these points were distributed uniformly over the brick measured surface. Natural frequency of probes: 82 kHz to meet the condition $a \geq 1.25\lambda$, (where a represents smallest specimen size at point of measurement, and λ represents wave length). As to bond medium, Sonogel (used in health service) was used. Length of measuring base: measured with an accuracy of 0.1 mm; transit time: measured with an accuracy of 0.1μs. Each measuring point was subject to 3 transit time measurement. Ultrasonic pulse velocity was calculated with an accuracy of 0.001 km/s using equation (1).

Compressive strength: Whole bricks were tested by means of loading up to their failure, according to provisions of CSN EN 772-1 (2011).

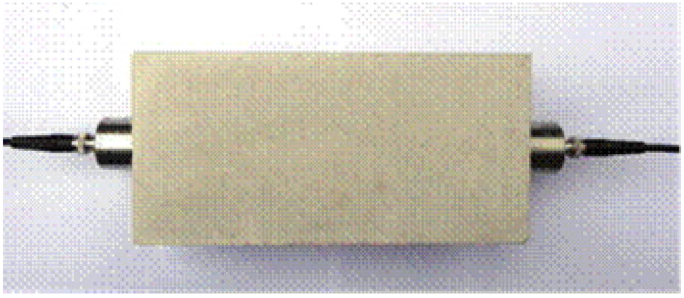

Figure 2. Direct transmission

Test data: See Figs 3a, 3b to 5a, 5b for relation between ultrasonic pulse velocity (dynamic modulus of elasticity in some cases) and compressive strength. For tested bricks, differences ΔV [%] between ultrasonic pulse velocity V (taken from lengthwise sounding) and V (taken from breadthwise sounding. As to reference value – average V of the tasted brick was taken into account). See Fig. 6 for ΔV differences for particular brick types.

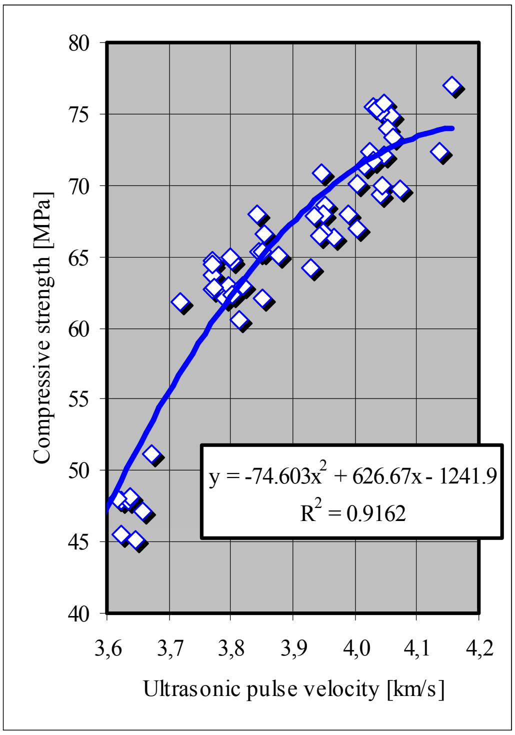

Figure 3a. Ultrasonic pulse velocity vs. Compressive strength – Concrete bricks

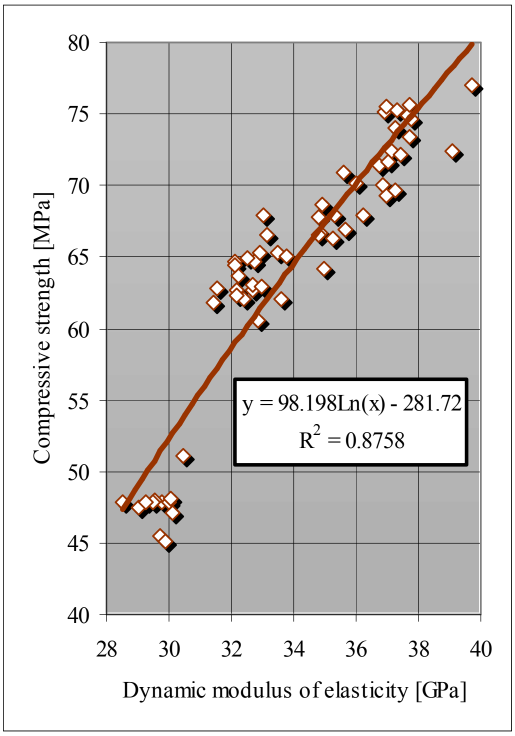

Figure 3b. Dynamic modulus of elasticity vs. Compressive strength – concrete bricks

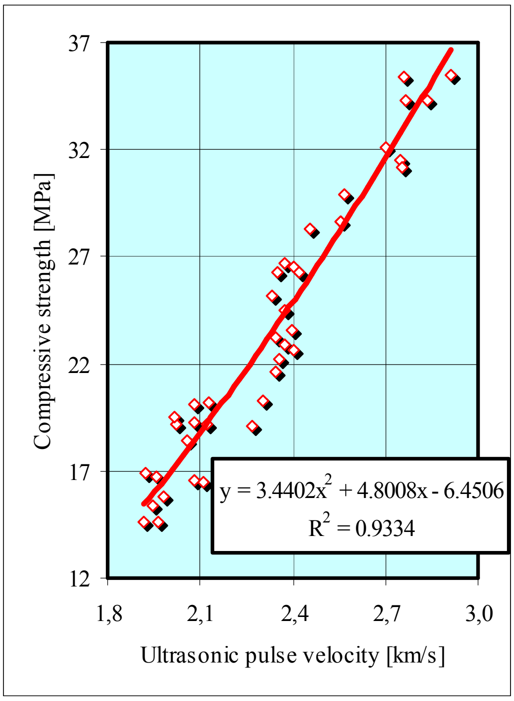

Figure 4a. V **vs. Compressive strength – Calcium silicate bricks (290.140.65mm)**

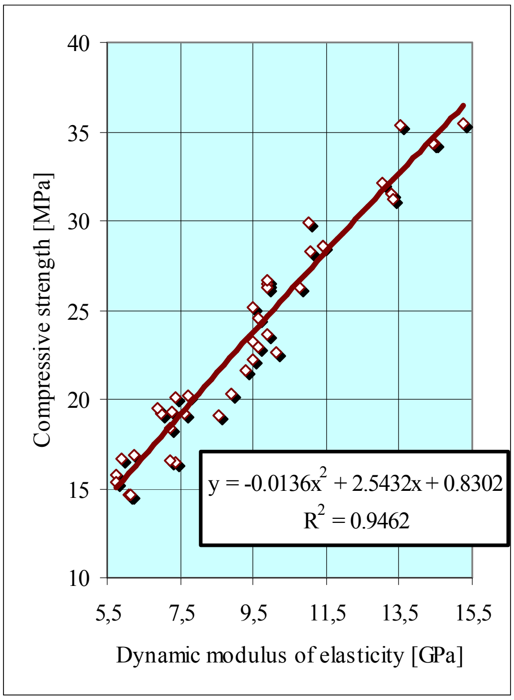

Figure 4b. E_u **vs. Compressive strength – Calcium silicate bricks (290.140.65mm)**

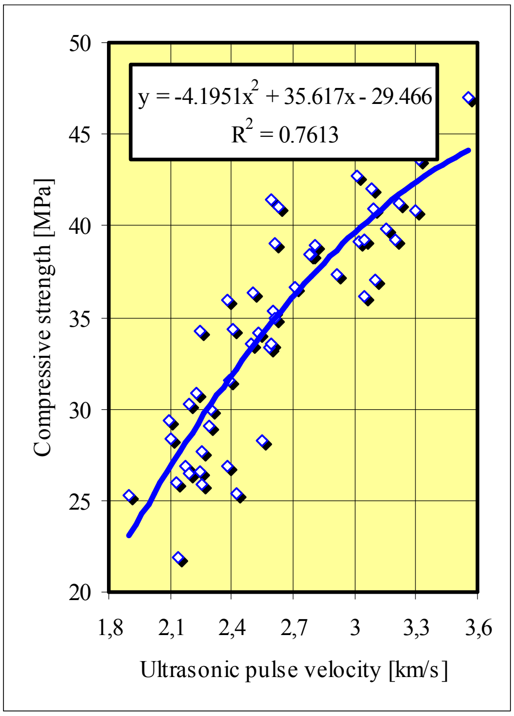

Figure 5a: V **vs. Compressive Strength – Burnt Bricks Formed by Means of Rigid Plastic Extruding**

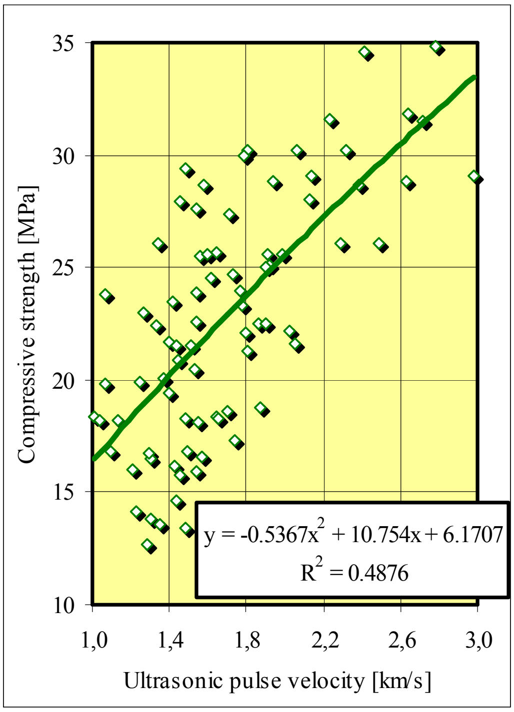

Figure 5b: V **vs. Compressive Strength – Burnt Bricks Formed by Pressing**

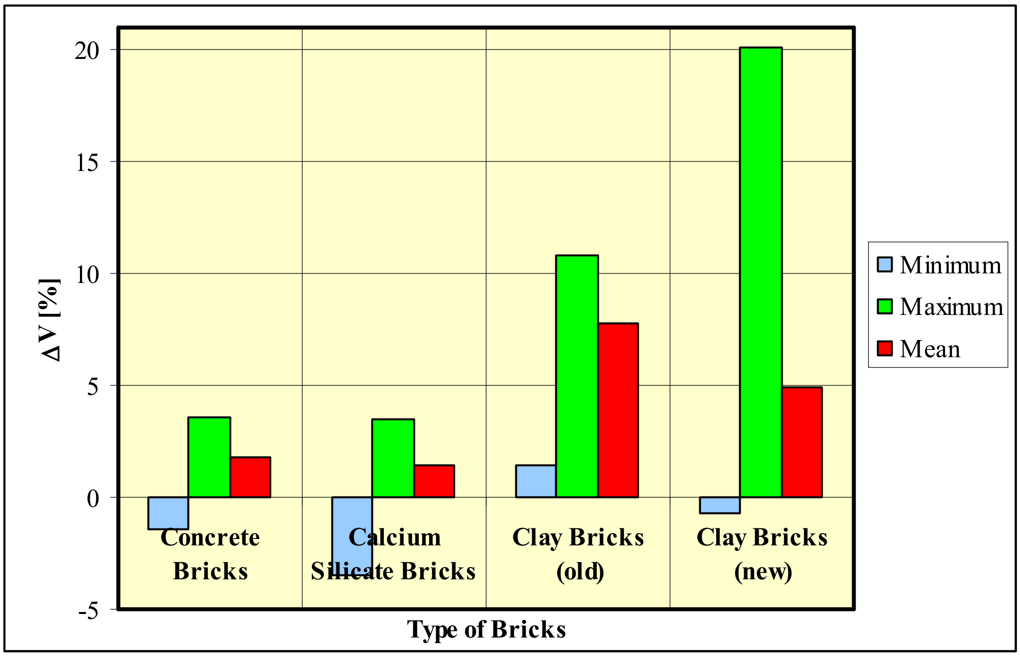

Fig. 6: Differences Between Ultrasonic Pulse Velocity with Lengthwise/Breadthwise Sounding as Determined for Particular Brick Types

Calibration Correlation: Based on test results, calibration correlations (3 to 8) between ultrasonic pulse velocity, dynamic modulus of elasticity and compressive strength in particular brick types were elaborated. Equation symbols: f_c-compressive strength [MPa], V-ultrasonic pulse velocity [km/s], E_U-dynamic modulus of elasticity [GPa].

– **Concrete bricks** (240.115.70mm);

$$f_c = 626.67V - 74.603V^2 - 1241.9 \quad (3)$$

r=0.957; V∈{3.6; 4.2}

$$f_c = 98.198Ln(E_U) - 0281.72 \quad (4)$$

r=0.936; E_U∈{28.5; 40}

– **Calcium Silicate Bricks** (290.140.65mm);

$$f_c = 4.8008V - 3.4402V^2 - 6.4506 \quad (5)$$

r=0.966; V∈{1.9; 2.9}

$$f_c = 2.5432E_U - 0.0136E_U^2 + 0.8302 \tag{6}$$

r=0.957; $E_U \in \{5.8; 15.3\}$

– **Clay Bricks "Old"** (290.140.65mm);

$$f_c = 35.617V - 4.1951V^2 - 29.466 \tag{7}$$

r=0.873; $V \in \{1.9; 3.5\}$

– **Clay Bricks "New"** (290.140.65mm);

$$f_c = 10.754V - 0.5367V^2 + 6.1707 \tag{8}$$

r=0.698, $E_U \in \{1.0; 3.0\}$

DISCUSSION ON TEST RESULTS

On the basis of test result analysis, undermentioned findings relating to efficiency of ultrasonic pulse method for detection in compressive strength of solid bricks (concrete, calcium silicate and burnt ones) were obtained.

Internal brick structure: Ultrasonic pulse velocity is affected by defects in material structure. Concrete bricks consist of aggregates filled with cement grout and poruses (absorptivity < 6%). Calcium silicate bricks are characterized like fine concrete (absorptivity 10 to 15 %). As to burnt brick clinker, absorptivity varies between 11 and 17 %; it contains – together with poruses – also cracks in varying degrees. Cracks are more frequent in bricks manufactured by means of rigid plastic extruding. Test results reflected differences in structure of bricks tested. These differences depend upon kind of the bricks. Structure imperfections manifest themselves mostly in solid burnt bricks and at least in calcium silicate bricks; concerning the last ones, the reason lies in their homogeneity and absence of visible cracks.

Moisture of test specimens: Generally speaking, material moisture impacts on ultrasonic pulse velocity. Water in pore material structure (replacing displaced air) increases ultrasonic pulse velocity, because ultrasonic pulse velocity in water exceeds the same in air 3.5 times). That is why there is necessary to determine unambiguous moisture conditions during testing to ensure repeatability and reproducibility of the measurement. To eliminate moisture impact on test results, both burnt and calcium silicate bricks were dried up; concrete bricks were stored in environment with $\varphi \geq 95$ %.

Shape and dimensions of the bricks: Smallest size of bricks tested: 65 to 70 mm. Ultrasonic pulse velocity depends upon wave length. Wave length ratio to smallest specimen size should be < 1; if it doesn't, ultrasonic pulse velocity decreases. That is why there is necessary to optimize probe frequency in order to ensure reproducibility of measurement results.

Age and composition bricks. Effect of age on clay bricks measurements using ultrasonic pulse method is insignificant, the deciding factors is manufacturing technology (extruded or pressed), internal structure and moisture. When testing concrete and silicate bricks, measurement results can be affected by the composition of raw materials mix and properties of used components.

Calibration correlations between ultrasonic pulse velocity and dynamic modulus of elasticity: As mentioned above, parameters obtained from ultrasonic pulse velocity measurement are affected by shape/dimension of bricks, their components and imperfections of their structure. These factors are variously manifested in test results and calibration correlations elaborated in order to determine compressive strength based on non-destructive testing parameter. Lit. (Janko, 1958) was used for evaluation of these correlations, where coefficient correlation $r \geq 0.85$; however, more suitable are calibration correlations with $r > 0.9$. Based on these above mentioned criteria, practice-utilizable are calibration correlations as elaborated for concrete bricks, see equation (3) and (4), and for calcium silicate bricks see equation (3) and (4); their correlation coefficient lies between 0.936 and 0.966. The correlation coefficient as elaborated for pressed burnt bricks ("old") is 0.873 which means that its usability is critical. Dependence of burnt bricks formed by extruder features low correlation between variables (r = 0.698); that is why the equation elaborated is unusable for determination of corresponding compressive strength. With equal testing conditions, differences in correlation of particular relations are explainable by various structures of particular brick types. Generally speaking of burnt bricks, cracks in clinker does not matter as far as they do not impact upon declared compressive strength adversely. In view of solid burnt brick compressive strength evaluation by means of ultrasonic pulse method, there is considerable impact of amorphous defects in clinker microstructure upon it; this impact is stronger on bricks formed by extruder.

CONCLUSION

Tested by means of ultrasonic pulse method were concrete, calcium silicate and burnt bricks; analysis of test results show that the ultrasonic pulse method is usable in practice for determination of compressive strength of concrete and calcium silicate bricks. Efficiency of it is subject to accurately defined test condition to ensure reproducibility of test results. As to solid burnt brick testing, the ultrasonic pulse method is usable in case the brick clinkers are almost free of defects.

ACKNOWLEDGEMENTS

This work was supported by the Czech Science Foundation: Project P104/12/810 "Study of properties of calcium silicate masonry units by non-destructive testing methods" and the European Union's "Operational Programme Research and Development for Innovations", No. CZ.1.05/2.1.00/03.0097, as an activity of the regional Centre AdMaS "Advanced Materials, Structures and Technologies".

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