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DETERMINING THE STRENGTH OF SOLID BURNT BRICKS IN HISTORICAL STRUCTURES

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ABSTRACT

Burnt bricks lined with mortar were among the materials used in the construction of historical load-bearing structures. The need to know the strength characteristics of masonry material arises during repairs of historical structures and their subsequent static securing. These can be investigated either by sampling a masonry specimen, or the employment of non-destructive testing methods. With destructive testing that involves removal of a sample from the structure, the structure being tested could be damaged by the removal of a whole brick. When determining the strength by using just a small test sample extracted from the masonry (brick cutouts, or 50 mm diameter drilled cores) the problem is insufficiently accurate conversion rates for the compression strength of a small masonry test specimen, and for overall brick compression strength. For non-destructive testing it is necessary to have a calibration relationship between the parameter from non-destructive testing and strength. Solid burnt bricks sized 303(290) × 145(140) × 70(65) mm are the most widely used building material in brick masonry buildings in the Czech Republic. Both load-bearing and non-bearing structures have been built from these bricks. The load-bearing structures mainly involve extra bearing masonry and ceiling vaults.

The article presents findings involving the utilization of non-destructive testing methods – hardness measurement methods and dynamic methods for determining the compression strength or tensile bending strength of solid bricks. Of the hardness measurement methods, the Waitzmann hardness tester (impression method) was used, while the ultrasonic pulse method (direct and semi-direct transmission) was the dynamic method employed. The article also states the required calibration relationships between the non-destructive testing parameter (the β ratio for hardness measurement methods, and ultrasound pulse velocity for the ultrasonic pulse method) and brick strength, and the evaluation carried out on their usage in practice. It further presents a comparison of ultrasonic pulse velocity depending on the technique of transmission).

STRENGTH CHARACTERISTICS OF SOLID BRICKS

Two documents published at the turn of 19th century have contributed to the development of masonry construction in the present territory of the Czech Republic, namely the Building Regulations [9] of 1787, and the Patent of 1819, licensing subjects to manufacture bricks [5]. The Patent [5] also established the dimensions of solid bricks to 303 × 145 × 70 mm. In 1864, new Building Regulations were issued, which established the dimensions of bricks to 290 × 140 × 65 mm (in some cases 220 × 105 × 50 mm). These Building Regulations specified also the requirements for strength characteristics of solid bricks. Fig. 1 below summarizes brick specifications from 1870 to 1945.

Interval: 1870 to 1900		
Brick Type		Minimum compression strength [MPa]
Sintered brick ("tuhovka")		Only quality requirements, such as "very firm" and "perfectly weather-proof" (darker colour, sintered material, sharp edges, high-pitched sound when struck), were specified,
Common brick	Class 1	20
	Class 2	14
	Class 3	8

Early 20th Century		Regulations of 1931	
Brick Type	Minimum compression strength [MPa]	Brick Type	Minimum compression strength [MPa]
clinker, clinker brick, vitrified brick	30	clinker, clinker brick, vitrified brick, channel brick	60
superior brick	26	hard stock brick	30
common brick	20	tough brick	15
horizontal coring block	17	common brick	7.5
common solid brick	10		
hollow clay block	8		
Regulations of 1944			
Brick Type	Minimum compression strength [MPa]	Brick Type	Minimum compression strength [MPa]
clinker	55	facing brick	15
vitrified brick	35	common brick 150	15
hard-burnt brick	25	common brick 100	10

Table 1: Strength parameters of bricks over various manufacturing periods

NON-DESTRUCTIVE METHODS USED FOR BRICK TESTING

In the course of its history, solid brick manufacturing technology underwent considerable development: in processing of brick clay from stamping, through pressing, up to the current manufacturing technology that uses drawing; in drying from air-drying up to the current industrial drying-plants with their various drying media. Similar progress took place in baking of brick products.

Manufacturing methods had impact both on the product quality and on the crock structure. Crock of solid bricks is fine-grained with considerable porosity. Besides, the crock contains defects such as cracks, various inclusions (e.g. grains of burnt limestone, grains of grogs, and so on). These defects can – to a certain extent – influence both the results of non-destructive method measurement and the strength characteristics of the bricks. As stated in the author's works, crack occurrence in the crock is higher for solid bricks manufactured by drawing technology (industrial production of bricks since the beginning of the 20^{th} century) than for bricks produced by pressing. According to the technical standards, cracks in the brick crock are not regarded as a flaw unless reducing strength.

However, both cracks and other brick crock defects influence the non-destructive testing parameter in various ways. This is most markedly demonstrated for ultrasonic pulse velocity and natural frequencies in resonance method measuring. Because of that, it is problematic to use calibration formulae elaborated for bricks produced by drawing technology, listed e.g. in [1], for determining strengths of bricks in historical objects that were built from pressed bricks.

Non-destructive methods for testing solid burnt bricks inbuilt in a structure are not codified in the Czech Technical Standards. The Czech Technical Standards include above all non-destructive tests of concrete, and further – in a limited scope – testing of building stone or wood. Therefore, there are also no calibration formulae for solid bricks to determine brick strength using the non-destructive testing parameter. Methods used for concrete testing, which are also backed by the Czech Technical Standards, specifically: scleroscopic methods of testing - CSN 73 1373[3], EN 12504-2[7], and ultrasonic pulse method - EN 12504-4[8], were chosen for non-destructive testing of solid bricks.

Test procedures were modified for the purposes of testing solid bricks in structures.

The article quotes testing results for burnt solid bricks produced by pressing within the period from 1840 to 1900, which were sampled from five different objects in the Czech Republic. The tests were performed partly by scleroscopic methods, partly by dynamic methods. Scleroscopic methods included Waitzmann's scleroscope, Schmidt impact hammer types LB and L, and boring method according to the Technical and Test Institute for Construction ("TZUS"). Ultrasonic pulse method was used as dynamic method. For the selected methods, calibration formulae for determining brick strengths using the non-destructive testing parameter have also been elaborated. Test results for solid bricks manufactured in the period 1930 to 1940 were also used to compare the boring method results.

Scleroscopic Testing Methods

Tests by Waitmann's scleroscope were performed on 70 bricks. For the TZUS boring method, comparison of results of tests performed on two types of bricks with strengths calculated according to the calibration formula delivered by the manufacturer with the test equipment is quoted. Measurement by Schmidt impact hammers types N and L was performed on a set of 24 bricks sampled from one object, and comparison of Schmidt impact hammer type L applicability to determination of strengths of bricks inbuilt in structure is included.

Waitzmann hammer

Waitzmann's scleroscope method counts among impression methods. It is in principle a follow-up of the POLDI hammer designed for steel hardness determination. It is based on measurement of impression produced by insertion of a punch with defined shape – see Figure 1 – in the inspected material and in a comparison bar with defined strength of 700 MPa. The force for punch insertion is produced by means of a mallet and it is not constant, but depends on the impact force. The non-destructive testing parameter is the ratio β, which is the ratio between the dimple detected on the steel comparison bar and the dimple on the foil put on the tested brick surface – it is calculated according to Formula 1. The impact force must be such so as to produce a dimple with diameter ca 2 mm on the comparison bar. An advantage of the Waitzman's scleroscope in comparison with hardness drop testers is automatic elimination of the impact attenuation.

$$\beta = \frac{d_1}{d_2} \cdot \sqrt{\gamma} \tag{1}$$

Where:

d_1 – dimple diameter on the reference bar (mm)

d_2 – dimple diameter on the paper foil (mm)

G – ratio between actual steel hardness of the reference bar and nominal steel hardness (700 MPa)

Schmidt impact hammer, types LB/L

The Schmidt impact hammer method counts among the rebound methods. The method is based on material hardness determination, in the case in question the hardness of brick crocks. During the test, the hammer punch is hurled with defined energy by means of a spring and the instrument dial indicates the rebound value, which depends on the material hardness - i.e. also on its strength. Schmidt impact hammer, types LB/L, has the initial impact energy of 0.735 N.m. The difference between types LB and L rests in the punch ending; the LB type has a spherical ending (it is designed for ceramic material testing) and the L type punch ending has a lens shape (it is designed for concrete testing). Schmidt impact hammer, type LB, is represented in Figure 2.

TZUS drill (Figure 3)
This is a boring method. The principle of the test consists in determining depth of a bore in material at a defined number of revolutions. To ensure reproducibility of results, the drill is equipped with a spring to produce constant thrust of 150N. This device was developed for determination of compression strength of masonry bed mortar and for determination of compression strength of solid burnt bricks inbuilt in masonry. For masonry testing, the number of drill revolutions is 40. The compression strength of bricks is determined from the established depth of bore according to the calibration formula delivered by the device manufacturer (TZUS - Technical and Test Institute for Construction, Prague).

Figure 1. Waitzmann Hammer

Figure 2. Schmidt Impackt Hammer typ LB

Figure 3. TZUS drill

Ultrasonic Pulse Method
Ultrasonic pulse method tests were performed on 70 bricks. The method's principle consists in sending repeated ultrasonic pulses in the material by means of a pulse generator and subsequent sensing of pulses passing trough the material inspected. The transit time of their

front edge from the sending probe to the sensing one, i.e. the time needed to go through a certain distance, is traced. Ultrasonic pulse velocity is calculated from the ultrasonic pulse transit time and the known trajectory. Use of the ultrasonic pulse method to determine physico-mechanical properties of material is conditional upon the need to establish the appropriate calibration formula between ultrasonic pulse propagation velocity and the parameter traced (e.g. strength). The ultrasonic pulse velocity is calculated from relation (2) as per EN 1504-4 [8]:

$$V = \frac{L}{T} \quad (2)$$

Where:
V ultrasonic pulse velocity (km/s)
L length of measuring base (mm)
T transit time (μs)

METHODOLOGY OF TESTING

The testing equipment, sample preparation and testing itself were performed in accordance with the provisions of EN 12504-2[7], CSN 731373[3] (scleroscopic methods) and EN 12504-4[8] (ultrasonic pulse method). The particulars of measurements and their interpretations for the individual methods are described below:

Scleroscopic testing methods

- Number of measurements per one sample – min. 24 (Schmidt impact hammer, Waitzmann's scleroscope) – min. 10 (TZUS drill)
- During testing, the samples were loaded to ca 10% of their assumed strength.
- Measurement in the test area are deemed valid if 20 (Schmidt impact hammer, Waitzmann's scleroscope) and 8 (TZUS drill) measured values of non-destructive testing parameter are valid. Values are deemed valid if they do not differ from the average value by more than 13.5% (Schmidt impact hammer, Waitzmann's scleroscope) and 15% (TZUS drill).

Ultrasonic pulse method

- Ultrasonic probes (natural frequency: 82 and 100 kHz) were situated in two positions: against each other – so called Direct Transmission, or one of them round the corner – so called Semi-direct Transmission, see Fig. 4 and 5.

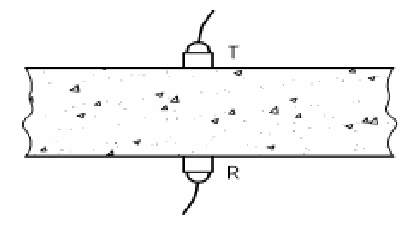

Figure 4. Direct Transmission

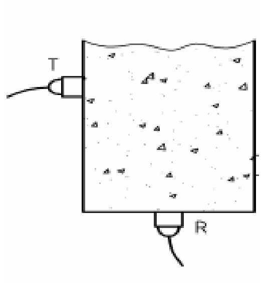

Figure 5. Semi-direct Transmission

- For each sample, 10 (direct transmission) and 8 (semi-direct transmission) measurements were performed.
- Ultrasonic pulse velocity for direct transmission and semi-direct transmission, and the average ultrasonic pulse velocity from all values measured for a brick were calculated.

Brick strengths

Compression strength (all samples) and flexural strength (70 bricks tested by Waitzmann's scleroscope and ultrasonic pulse method) were tested on the bricks by destructive testing.

Compression strength was determined according to EN 772-1[6] and flexural strength by procedure according to CSN 722605 [2].

TEST RESULTS

Test results for solid bricks from the period 1840 to 1900 by Waitzmann's scleroscope and ultrasonic pulse method are given in Figures 6a., b. and 7a., b. Comparison of ultrasonic pulse velocity for different ways of transmission is shown in Figures 8a., b.

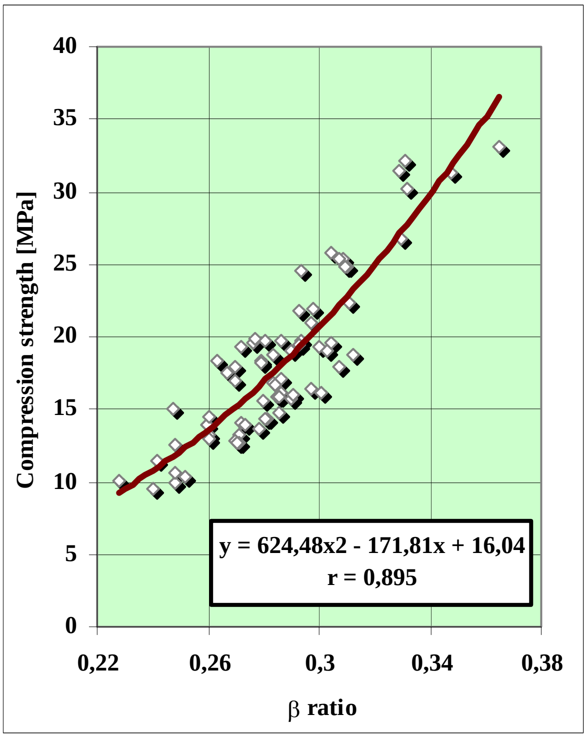

Figure 6a. Compression strength from Waitzmann's scleroscope testing

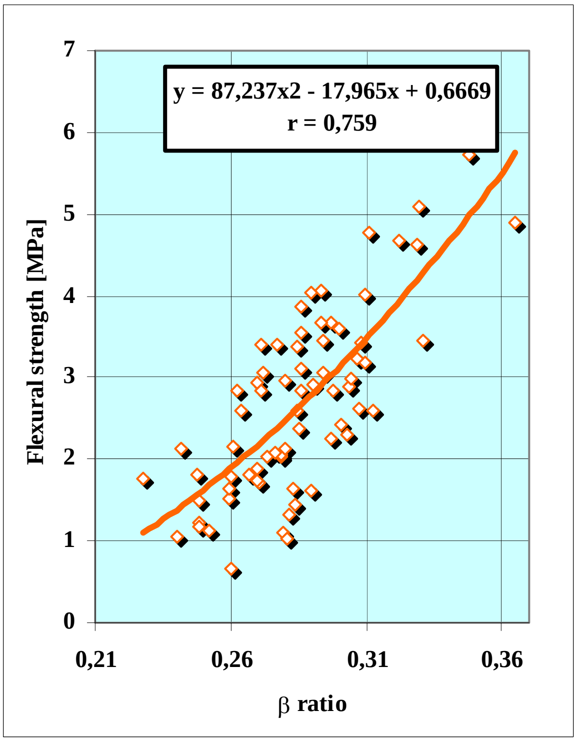

Figure 6b. Flexural strength from Waitzmann's scleroscope testing

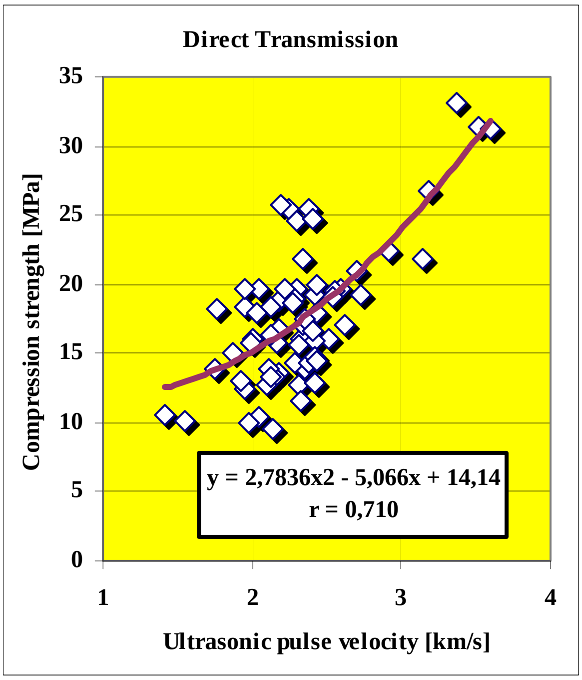

Figure 7a. Relation between compression strength and ultrasonic pulse velocity

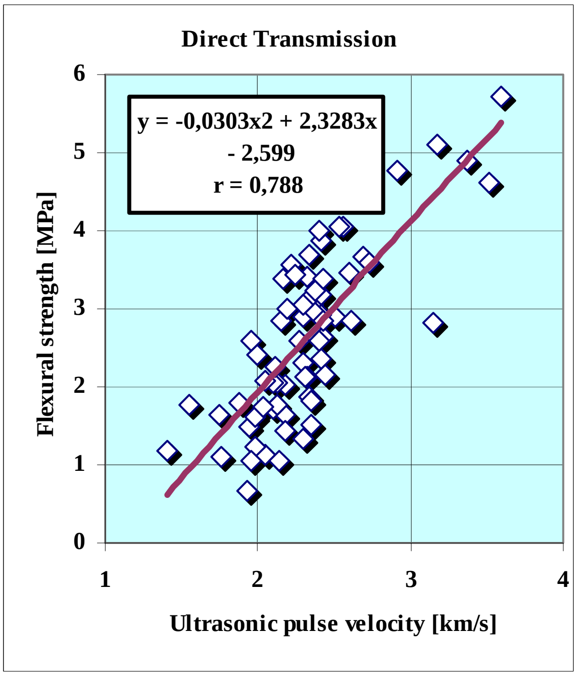

Figure 7b. Relation between flexural strength and ultrasonic pulse velocity

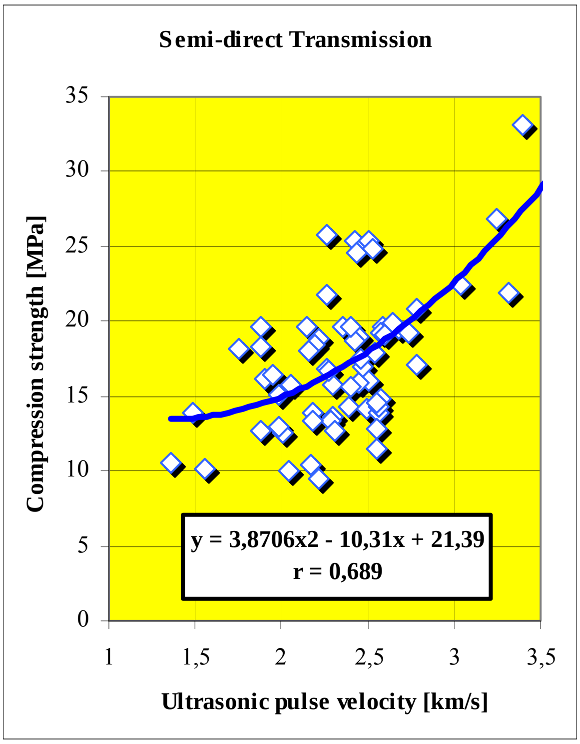

Figure 7c. Relation between compression strength and ultrasonic pulse velocity

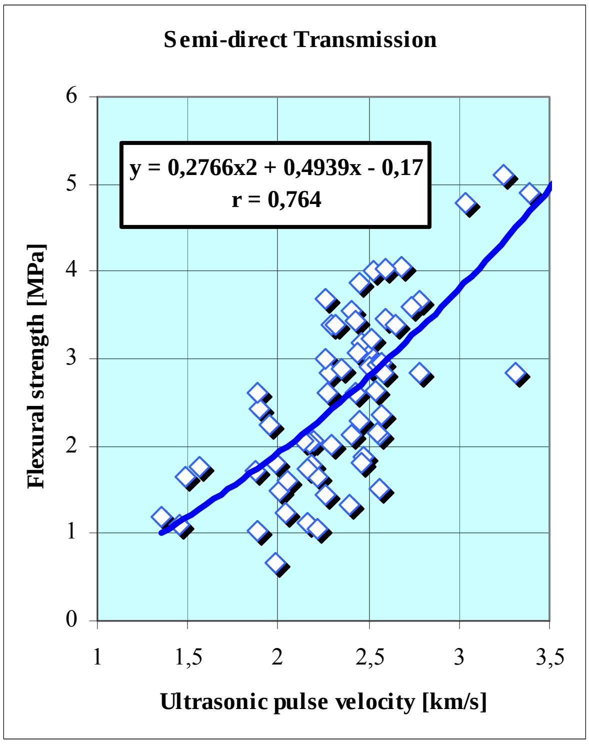

Figure 7d. Relation between flexural strength and ultrasonic pulse velocity

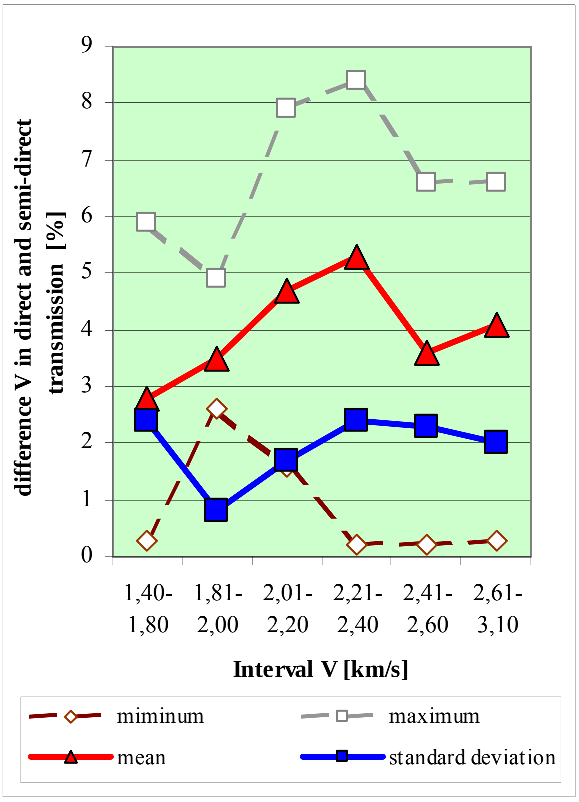

*Figure 8a. Comparison of differences **V** for different ways of transmission*

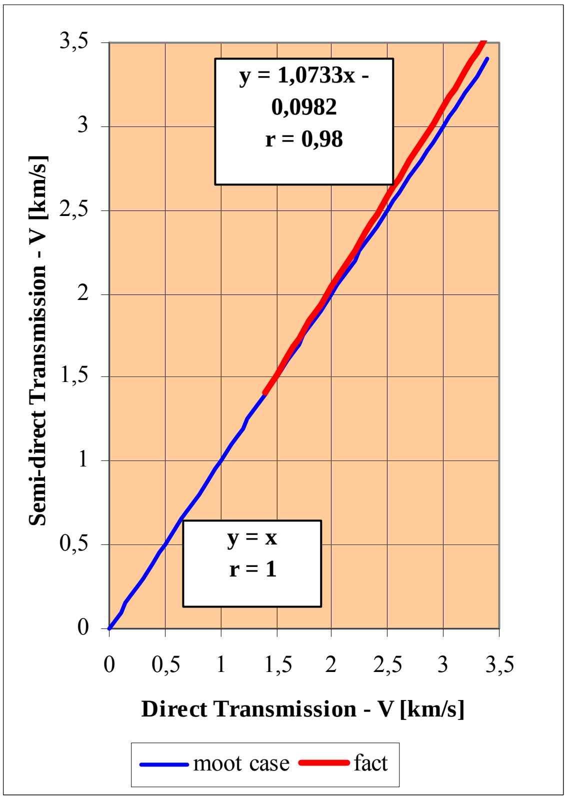

*Figure 8b. Comparison between theoretical and actual **V** relations for different ways of transmission*

Comparison of measurements by Schmidt impact hammer type LB and L is shown in Figure 9. Comparison of calibration strengths compiled from the tests of two sets of solid bricks from different production periods with values calculated for established depth of bore according to the calibration formula of the TZUS drill manufacturer is shown in Figure 10.

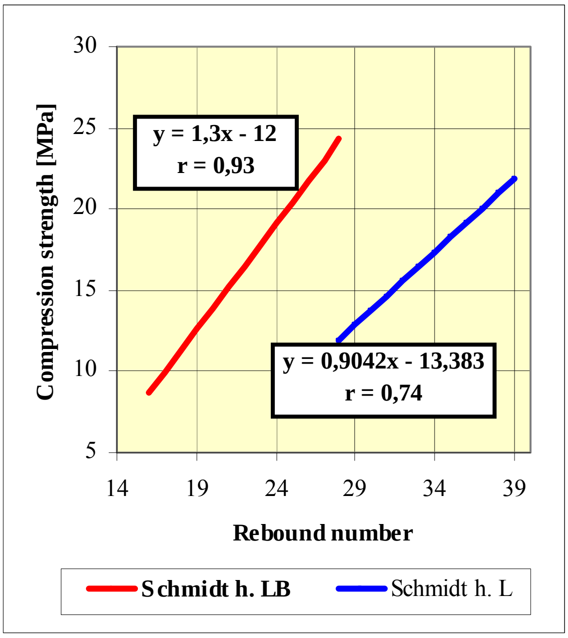

Figure 9. Comparison of measurement results by Schmidt impact hammer types LB and L

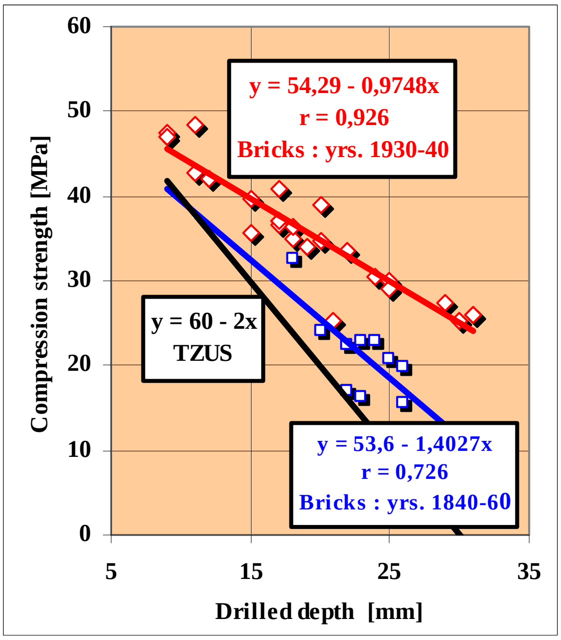

Figure 10. Comparison of strength measurement results by TZUS drill

CALIBRATION FORMULAE

Based on test results, calibration relations between non-destructive testing parameter and brick strength were elaborated by means of the least-squares method.

Waitzmann's Scleroscope

- Compression strength

$$f_{bc-W} = 624{,}48\beta^2 - 171{,}8\beta + 16 \quad r = 0.895 \quad \beta \in \{0.2200;\ 0.3700\} \tag{3}$$

- Flexural strength

$$f_{bf-W} = 87{,}24\beta^2 - 17{,}96\beta + 0{,}66 \quad r = 0.759 \quad \beta \in \{0.2200;\ 0.3700\} \tag{4}$$

Ultrasonic Pulse Method

Direct Transmission

- Compression strength

$$f_{bc-U} = 2{,}7836V^2 - 50{,}66V + 14{,}1 \quad r = 0.710 \quad V \in \{1.4;\ 3.1\ \text{km/s}\} \tag{5}$$

- Flexural strength

$$f_{bf-U} = 2{,}3282V \ - 50{,}0303V^2 - 2{,}59 \quad r = 0.788 \quad V \in \{1.4;\ 3.1\ \text{km/s}\} \tag{6}$$

Semi-direct Transmission

- Compression strength

$$f_{bc-U} = 3{,}8706V^2 - 10{,}316V + 21{,}39 \quad r = 0.689 \quad V \in \{1.4;\ 3.1\ \text{km/s}\} \tag{7}$$

- Flexural strength

$$f_{bf-U} = 0{,}2766V^2 + 50{,}4939V \ - 0{,}17 \quad r = 0.764 \quad V \in \{1.4;\ 3.1\ \text{km/s}\} \tag{8}$$

Rebound and Boring Methods

The elaborated calibration formulae are only for study purposes. They were used on the one hand to evaluate applicability of Schmidt impact hammer types L and LB for determining brick strengths, on the other hand to attest practical applicability of general calibration formula for the TZUS boring method.

Schmidt impact hammers

$f_{bc-LB} = 1{,}3R - 12 \ \ r = 0.93$ (9a); $f_{bc-L} = 0{,}904R - 13{,}38 \ \ r = 0.74$ (9b)

TZUS boring method

$f_{bc-TZUS} = 60 - 2D$ (10a); $f_{bc-1840} = 53{,}6 - 1{,}403D \ \ r = 0.73$ (10b)

$f_{bc-11930} = 54{,}3 - 0{,}975D \ \ r = 0.93$ (10c)

CONCLUSION

Scleroscopic Testing Methods

Compression strength

- Waitzmann's scleroscope - impression method (Waitzmann's scleroscope) is applicable without any problems for determination of compression strength of solid bricks in a structure. Calibration formula (3) for compression strength is characterised by high closeness of correlation, correlation coefficient r = 0.895. (From the practical application viewpoint, calibration formulae with correlation coefficient r > 0.85 are seemed as appropriate.)
- Schmidt impact hammer type LB – seems to be very appropriate method for determination of compression strength of solid bricks. The elaborated calibration formula (9a) is characterised by high closeness of correlation, correlation coefficient r = 0.93. However, the information capability of the calibration formula is still limited, as it was elaborated based on tests of bricks from one manufacturing plant and a relatively low number of samples.
- Schmidt impact hammer type L (designed for concrete testing) – its use for brick testing is very problematic because the scleroscope punch shape is not appropriate for brick crock testing. This is also obvious from the comparison performed (see Fig. 9). There is indeed a relation between scleroscope rebound and compression strength, however, the correlation coefficient of the calibration formula equals to r = 0.74, which means that it is inapplicable from the practical viewpoint.
- Boring method (TZUS drill) - results of compression strength testing by TZUS boring method vary quite significantly as follows from the comparison given in Figure 10. The calibration formula was elaborated by the manufacturer for bricks produced by drawing and, therefore, it is unsuitable for bricks produced by pressing technology. The depth of bore is influenced by the crock structure, which shows more defects for standard quality bricks than for bricks produced by pressing. As is obvious from Figure 10, boring method can be used for bricks from historic buildings on condition that the necessary calibration formula for determination of compression strength for solid bricks from the depth of bore has been be elaborated.

Flexural strength

Relation between non-destructive testing parameter and flexural strength was determined only for the set of bricks tested by means of Waitzmann's scleroscope. The tests indeed established relation between flexural strength and the ratio β, but the closeness of correlation is insufficient from the viewpoint of practical use of the calibration formula (r = 0.759). This can be explained by the fact that tensile strength is more influenced by crock defects (cracks, grog grains, anomalies from processing) than compression strength.

Ultrasonic Pulse Method

The use of ultrasonic pulse testing method for determination of strength of solid burnt bricks is not unambiguous. Relations between ultrasonic pulse velocity and compression strength or flexural strength were indeed found for the tested set of bricks, but these relations have correlation coefficients 0.69 to 0.79, which means that they are unsuitable for practical use. Higher correlation coefficients are shown by calibration formulae for determination of flexural strength, which can be explained by higher correspondence of flexural strength, same as ultrasonic pulse velocity, to defects in crock structure.

It follows from the authors' measurement results given in [1] that ultrasonic pulse method is applicable to testing bricks from a specific brick factory if the crock shows minimum of defects.

When measuring masonry in structures, it is often impossible to perform measurements by direct transmission (except when testing pillars and/or walls near openings); however, these measurements can be performed by semi-direct transmission. It follows from the performed comparison of results of measurement by direct transmission and semi-direct transmission that, while we do receive different values of ultrasonic pulse velocity, these differences fluctuate in the range from 3 to 5%, which can be seen as marginal from the practical viewpoint.

ACKNOWLEDGEMENTS

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