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COMMENTS ON THE APPLICATION OF THE SCLEROMETRIC METHOD IN THE DIAGNOSTICS OF BRICK MASONRY

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ABSTRACT

The aim of this article is to answer the question about the acceptable range of the sclerometric method as one of the nondestructive tests – commonly used in concrete structures – for solid clay brick masonry structures. The evaluation of suitability for the Schmidt hammer test was based here on the previously conducted experiments and analyses carried out by other researchers, as well as own test results. The presented development focuses on the correlation between the size of a Schmidt hammer rebound and the compressive strength of solid clay bricks. The obtained results from the own test procedure were compared with the findings presented in the literature and also with the mathematical formulae (curves) developed so far.
The article analyzes factors affecting a Schmidt hammer rebound, and the relationship between this mechanical parameter and the brick compression strength, such as: heterogeneity and anisotropy of bricks, the degree of surface corrosion, moisture, type of mortar, size of the element of research and a specimen attachment method.
The summary consists of practical comments on the possibilities of application of the Schmidt hammer test as a supplementary method (in conjunction with other destructive or nondestructive tests) in the brick masonry structure diagnostics.

Keywords: *Brick masonry, Nondestructive testing (NDT), Schmidt hammer test*

1. INTRODUCTION

For decades, in studies connected with the evaluation of the technical condition of structures, the sclerometric method has been used as one of the nondestructive tests (NDT). Tests carried out by means of a sclerometer (also called the Schmidt hammer) are cheap and easy to conduct, they do not require any sophisticated equipment, which enables reaching various structural elements. The sclerometric method is commonly used in concrete structures. Instructions and standards have been developed that allow to evaluate the compressive strength of concrete on the basis of the Schmidt hammer test (PN-EN 12504-2 [1], ASTM C805 [2]). As for masonry structures, the sclerometric method is much less popular, although it should be emphasized that sclerometers for masonry and joint mortar tests have been developed. Moreover, there was issued the instruction RILEM TC 127-MS.D.2 [3], where the principles of conducting sclerometric tests have been provided in relation to masonry structures, and the UIC 778-3R [4] recommendations include curves enabling calculation of test results (hammer rebound numbers) for the strength of masonry and mortar. The above documents are not standards and, hence, the extent of their application is narrow. At the same time, for many years now the research on the applicability of the most popular Schmidt hammers (Types L and N) used in concrete structures in masonry structures tests has been conducted. This type of research has been carried out in, among others, Germany [5-8], Italy [9-11], the USA [9], as well as in Poland [12-13]. The most frequent research objectives were: the estimate of the brick strength, estimate of the joint mortar strength, control of the uniformity of masonry materials, preliminary estimate of the brick masonry strength in the structure,

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control of masonry surface degradation and effectiveness of exercised repairs, evaluation of the scope of influence that unusual circumstances have on the technical condition of masonry structures. The results presented in the subject-matter literature are difficult for direct correlation, due to various procedures for conducting tests and variety of materials. In this article, the analysis has been limited to brick structures, taking into consideration the results of own tests conducted on materials from different historical periods (bricks from the end of the 17th and the beginning of the 18th century – I group, the 19th-century bricks – II group, modern bricks – III group).

2. DESCRIPTION OF THE SCLEROMETRIC METHODS FOR BRICK MASONRY STRUCTURES

Due to the increase of interest in the sclerometric method, several types of Schmidt hammers have been developed – N, L, M and P, each of them in several subtypes distinguished from each other by their impact energy and purpose. For diagnostic purposes, Type N (2,21 Nm) and L (0,74 Nm) hammers, which were developed with respect to concrete tests, are most frequently used. Less popular are hammers designed exclusively for masonry structures such as LB (L with the uniquely shaped impact plunger) or PM (pendulum hammer with regulated energy destined for joint tests) [14].

Functioning of a sclerometer is based on the principle of measuring the surface hardness of material on the grounds of the measurement of the R rebound of plunger mass striking against the tested surface with a particular energy. Because of this operational principle of the device, the result is highly susceptible to a number of factors, such as: the degree of cleanliness and smoothness of the tested surface, occurrence of cracks and scratches, thickness of the tested element, immediate surroundings of free edges, degradation of the element's surface layer material, attachment method and size of the element, specimen dampness, low temperatures, type of research. Prior to taking measurements, it is necessary to eliminate the greatest possible number of factors disrupting measurements, which mostly goes down to choosing the right area of research.

The procedure of testing the masonry structures by application of the N type hammer, proposed in the RILEM TC 127-MS.D.2 [3] instruction, considerably deviates from those specified in standards regarding concrete structures. The fundamental difference of "rebound hardness method" is multiple measuring in one location, and not as in the case of concrete where the distance between the points of successive measurements cannot be shorter than 20-25 mm. The tested brick as well as surrounding bricks and surrounding mortar should be uncracked and dry. The tests are not recommended to be conducted on bricks located near the edges of walls or pillars. Prior to taking proper measurements, the impact plunger is placed vertically to the clean and smooth surface and 3-4 impacts are made aiming at better placement of the impact plunger. Then, without removing the plunger away from the surface, make 10 impacts recording the value of the rebound number R after each impact. Out of 10, choose the 5 highest values whose mean R value and standard deviation constitute the result for a given measurement site.

Despite the fact that there are such instructions as specified above, the most common method remains conducting research in accordance with principles adopted for concrete. This can be justified by low popularization of instructions, inclination to standardize procedure regardless of the tested material or even by the fact that some researchers [15] make use of correlation curves developed for concrete after their previous calibration.

The most popular method to estimate the strength of joints in the sclerometric method is by means of pendulum hammers with regulated impact energy (type PM) [14]. According to the Schmidt hammer manufacturer's declaration it allows to use the same device despite the mortar strength. However, no standardized method of *in-situ* joint test has been published, which forces Schmidt hammers manufacturers to develop their own research procedures and correlation curves. In the end the correlation of results obtained by means of various devices becomes difficult and can lead to unjustifiable final results.

An alternative method to estimate the mortar compressive strength in the brickwall joints by the application of a type N hammer [8] (modification of the classical approach called "penetration method") consists in installation of a steel triangular plate 8 mm thick at the tip of the impact plunger. According to this procedure, we make 10 hammer impacts at one point of joint without removing the plunger from the mortar surface. Because there is no direct correlation between the Schmidt hammer rebound and the mortar strength, the dimension measured during our research is not the rebound number but the penetration depth of the triangular plate into the joint. The test resultant value is the difference in the plate penetration depth between the tenth and first hammer impact denoted as $d_{1\text{-}10}$ [mm]. This value is converted to the mortar compression strength according to correlation provided in the diagram (Fig. 3a).

3. ESTIMATING THE BRICK STRENGTH

In the 70s of the twentieth century J. Olek & J. Śliwiński released an article about N type Schmidt hammer test carried on clay bricks [12]. The tested specimens had been prepared in accordance with the standard PN-68/B-12001 in force at that time (two brick halves joined with cement mortar). The correlation $f_B^*(R)$ as obtained in [12] on the grounds of testing lab specimens has been presented in Fig. 1a. The estimate error value set at 34%; moreover, its percentage share grows with the increase of the rebound number. The study involved only then-produced solid clay bricks.

The test results of historical bricks (18^{th} and 19^{th}-century) and modern bricks produced in accordance with the methods used in the past (handmade bricks) are published in [6]. On the basis of the_correlation between the brick compression strength defined according to German standards (DIN 105 – test on two brick halves joined with cement mortar) and the value of the Schmidt hammer rebound, the correlation curve was suggested (Fig. 1c). Its abscissas constitute the mean R value specified for X (test conducted on heads) and Z (test conducted on stretchers). Schmidt hammer rebounds obtained from the X direction were smaller than in the Z direction, which is related with anisotropic properties of ceramics.

R. Schrank [7] registered hammer respond from the test carried out on 21 brick walls (19^{th}-century) made with lime mortar – Fig. 1b. The bricks compression strength was computed during a destructive test conducted in accordance with standard DIN 105. In order to increase the trust level, the decrease of the function by 28% was suggested –a green curve (all the results on the basis of which the original correlation curve was computed are then placed above it). Such an approach is known from the procedures [14] of estimating the concrete strength, when the_calibration of the correlation curve based on a destructive test of the analyzed concrete is not possible.

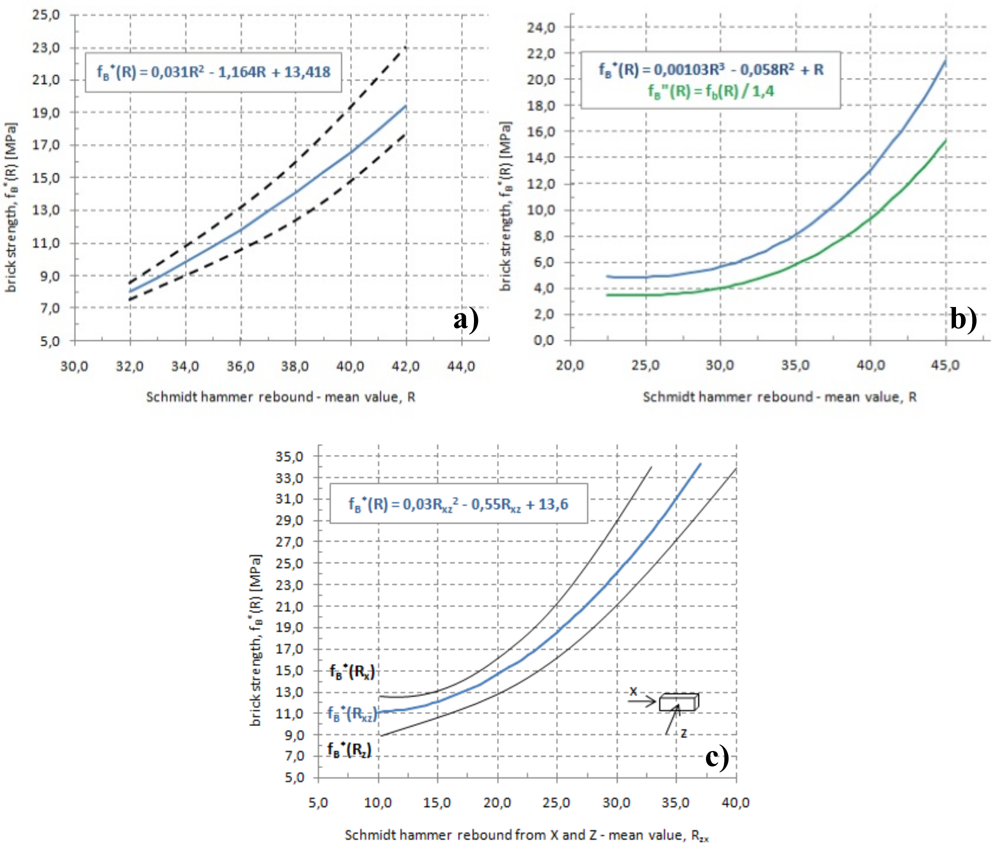

Fig. 1 Correlation curves for N type Schmidt hammer: a) from [12], b) from [7], c) from [6]

In all tests presented above the researchers obtained higher rebound number for higher bricks strength. The correlation curves presented in Fig. 1 are clearly different from one another despite the same type of Schmidt hammer or measuring direction (horizontal) and similar methods of determining the bricks compressive strength (two brick halves joined with cement mortar). This is due to the differences between ceramic materials (anisotropy, inclusions, inside cracks), state of the surface (surface hardness, the degradation of the structure of the brick demolition) as well as different conditions of fastening bricks (bricks in the wall, the sample in the testing machine).

In the authors' own research modern bricks were used, as well as bricks coming from buildings constructed in the 19th century and at the end of the 17th and the beginning of the 18th century. The bricks had been taken out of the masonry in a manner preventing their damage. The sclerometric test was conducted on specimens consisted of two brick halves joined and skinned from top and bottom with cement mortar (1:1) 1 cm thick. After the maturation period, each specimen was placed in a machine for testing compressive strength and compressed with 25 kN force in order to immobilize the specimen; then, the N type hammer was applied to measure the rebound number R at the header and on the cut surface. Following the sclerometric test, the compressive strength was verified by increasing the compression force up until the specimen is destroyed. Two machines differing in weight and dimensions were used – EDU 300 (bigger and heavier) and EDU 40.

The number of modern bricks and of those taken from the 19th century structure, enabled conducting additional tests for the brick compressive strength on core drillings of the 50 mm diameter taken vertically to the stretcher and vertically to the bed joint.

The diagram (Fig. 2) shows obtained correlations between the specimen strength and the rebound number. It can be noticed that there are three concentration areas of results correlated with the period of manufacturing bricks. Specimens made of modern bricks are distinguished by the lowest mean rebound number (irrespective of the tested surface) and, at the same time, the highest mean strength, $f_{B.I}^{*}(38,0) = 24,6\ MPa$. The lowest values of mean strength were recorded for bricks coming from the end of the 17th and the beginning of the 18th century, $f_{B.III}^{*}\ (43,1) = 12,6\ MPa$. Whereas, the 19th century bricks were characterized by the highest rebound number at mean strength values, $f_{B.II}^{*}(53,3) = 18,8\ MPa$.

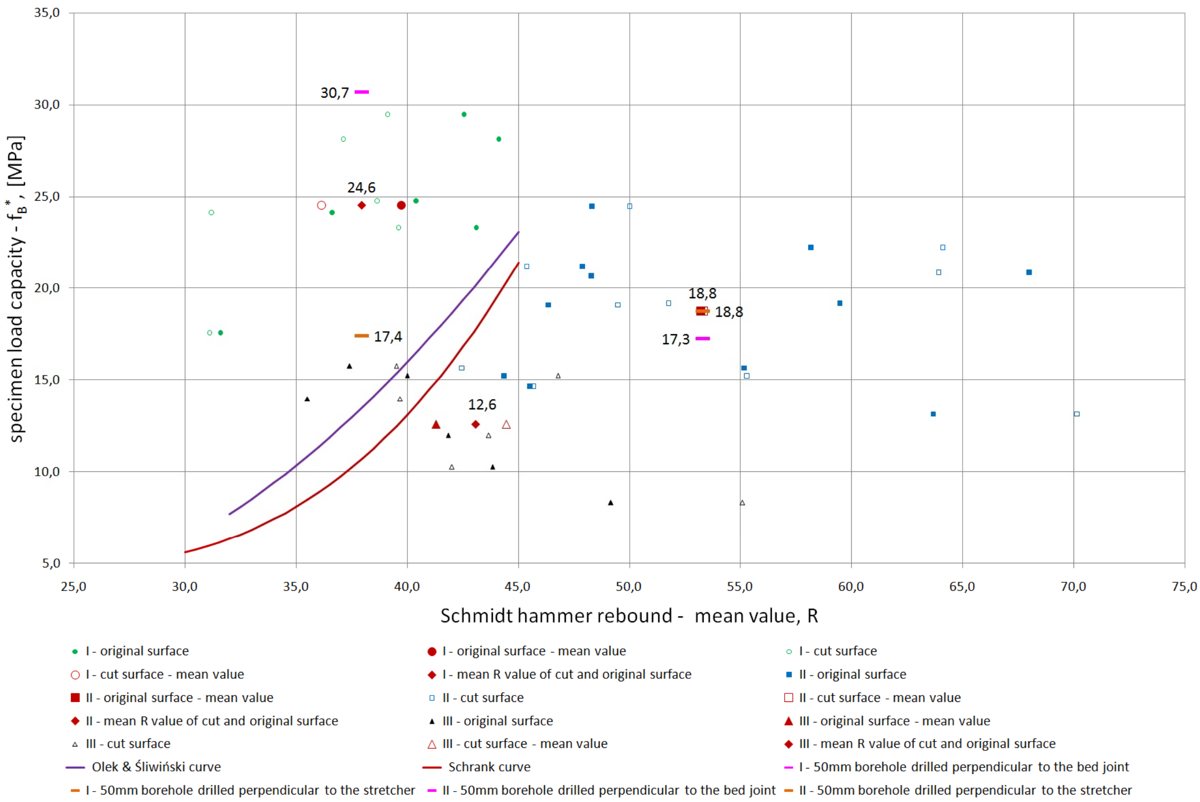

Fig. 2 Test results obtained by authors in comparison with correlation curves from [7] and [12]

When analyzing mean values of the rebound number taking into account the division between cut and original brick surface, it can be observed that modern masonry elements are distinguished by the greatest absolute difference, $\Delta R_I = 3,6$. Greater hardness of the element's outer surface can be explained by temperature distribution in the brick volume during its burning process, which leads to

better baking of clay minerals on their outer surface and, in consequence, its greater hardness. The reverse correlation occurs in the case of bricks from the end of the 17th and the beginning of the 18th century, where the brick outer surface was degraded due to exposure to external environmental factors. As far as the II group bricks are concerned (19th century), mean values of the rebound number are practically independent of the tested surface; however, if we refer to results for particular specimens, it is a group with clearly greatest differences reaching even the value of $\Delta R = 12{,}7$. Such notable differences can result from high dynamics of degradation process, which is typical of buildings' outer brickwalls due to exposure to adverse impact of the environment.
When analyzing statistical parameters (Table 1) it can be determined that the coefficient of variation of the R number mean value obtained by measurement on the brick outer surface (that is in the only feasible manner for *in situ* measurements), for each group of tested bricks, is lower than the variance coefficient of the brick compressive strength from destructive tests.

Table 1 Summary of experimental data

	Mean value		**Standard deviation**		**C.o.V. [%]**	
	f_B^* [MPa]	R	f_B^* [MPa]	R	f_B^*	R
I group of bricks	24.6	39.7	4.2	4.8	17.0	12.1
II group of bricks	18.8	53.2	3.6	8.1	19.1	15.2
III group of bricks	12.6	41.3	2.9	4.9	23.2	11.8

Conducting simultaneous tests on two types of strength machines enabled verification, whether, and if so, to what degree, it affects the value of the calculated rebound number R. In Table 2, results are tabulated showing that tests conducted on the heavier machine generated greater values of the rebound number, even by 24,4% for mean values. It indicates how important it is to properly place the specimen during the sclerometric test.

Table 2 Difference between Schmidt hammer rebound depending on the testing conditions

		I group of bricks	**II group of bricks**	**III group of bricks**
R	EDU 40	24.6	48.0	39.9
	EDU 300	-	59.7	45.9
difference [%]		-	24.4	15.0

Core drilling results have shown considerable discrepancy in brick compression strength depending on the direction of taking a sample. For modern bricks, cylinders bored vertically to the bed joint gave much higher compression strength than cylinders bored vertically to the stretcher, as well as the very results for brick compression tests. It is caused by the technology of masonry elements manufacturing and, thereby, by the internal structure composition. Such tendency was not observed for core samples drilled from the II group of bricks, whose way of forming and firing was different from that used today.
The use of results obtained directly from core drillings made vertically to the bed joint is possible only after previous estimate of correlation between the strength of cores taken in this manner and the brick strength. After such estimate, calibration of the correlation curve seems permissible in the form of vertical translation.

4. ESTIMATING THE MORTAR STRENGTH IN THE BRICKWALL

There are much fewer sclerometric test results for mortar compression strength in brickwall joints published in the literature than tests carried on bricks. The prevailing view is that the research of this type is difficult to be clearly interpreted because of the way how the test is carried out – the registration of the hammer rebound takes place on the outer surface of the wall where the mortar may have different properties than inside the wall. Different mortar properties on the surface of the wall on one side arise due to the process of erecting and repairing brick walls (pointing) on the other hand, the corrosion of joints. That is why these kind of tests can only by carried out in combination with the assessment of uniformity of the mortar in the joint.
In paper [8] a modified N type Schmidt hammer was used for this test, and the detailed procedure with its purpose has been described in point 2. The obtained correlation has been presented in the form of

a diagram (Fig. 3a).The penetration depth for weak lime mortar_(d_{1-10}) was more than 5 mm. There are no other studies comparing the correlation obtained in [8] with any other test results.

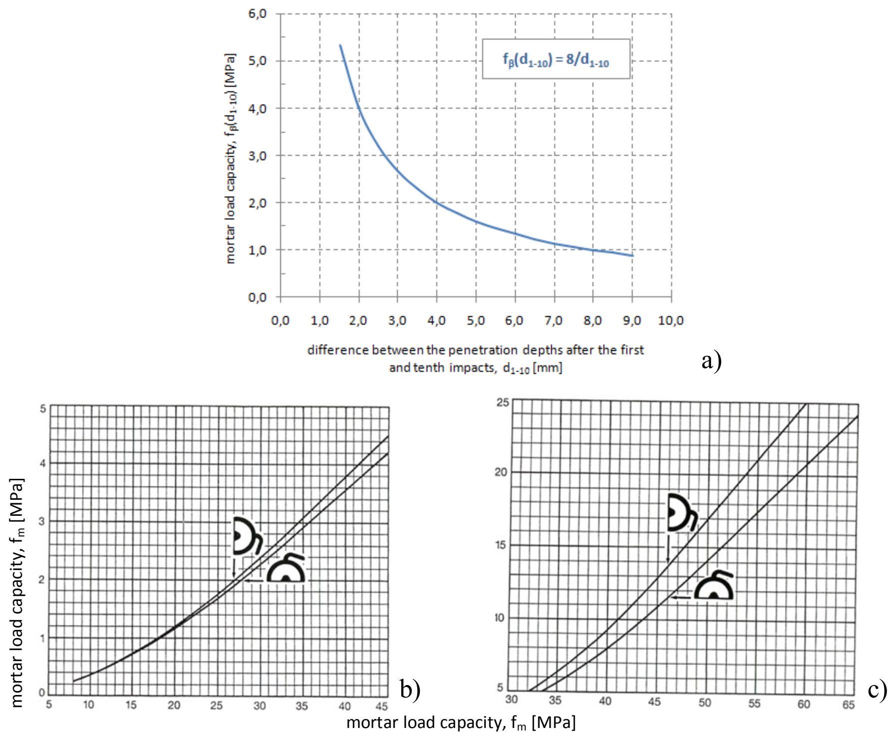

Fig. 3 Correlation curves: a) N type hammer – from [8], b) & c) PM type hammer – from [4]

In the instruction UIC code 778-3R [4], two correlation curves have been published; the first one refers to the cases, where the rebound numbers R are between 8 and 45 (Fig. 3b), whereas the other one – between 32 and 65 (Fig. 3c). The curves relate to tests carried out with the PM type hammer.

5. ESTIMATING THE BRICK MASONRY STRENGTH

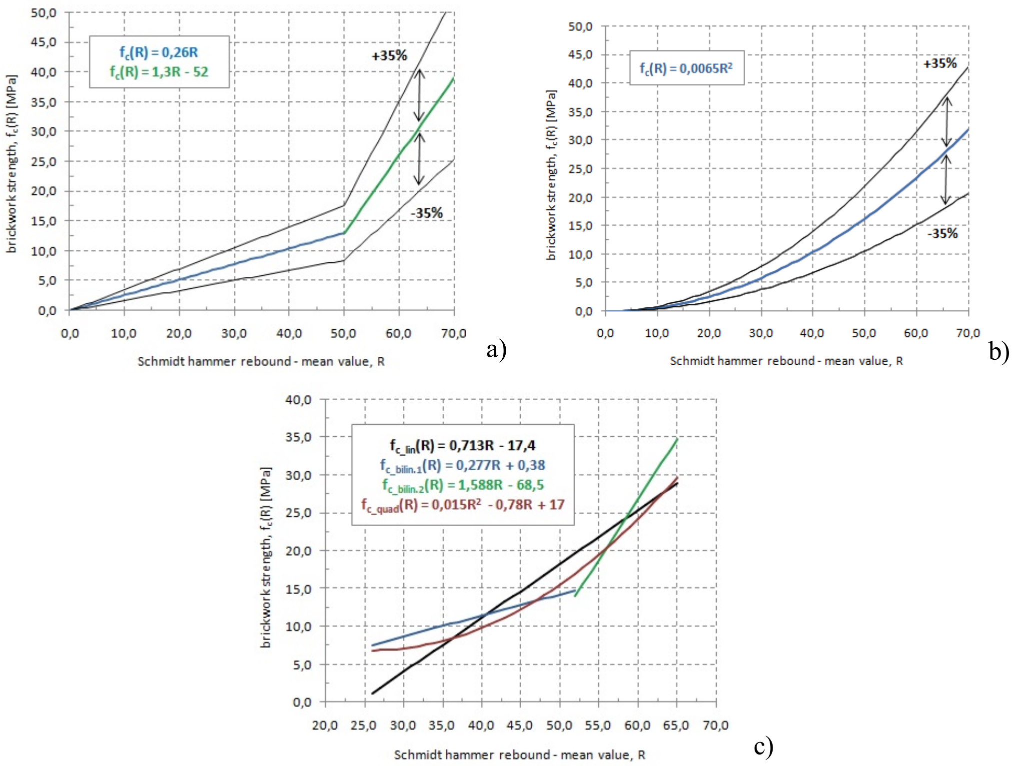

Fig. 4 Correlation curves for N type Schmidt hammer: a) & b) from [4], c) from [9]

In the UIC [4] it is assumed that the test is carried out on the bricks surface of a given brick masonry, and its strength can be computed using one of the two correlation types: the first one has been presented in the form of a bilinear diagram (Fig. 4a), and the other one as a quadratic function (Fig. 4b). The error of this method is estimated in the document at around 35%. It should be emphasized that the UIC recommendations concern brick made engineering structures generally characterized by good quality, and good parameters of the materials.

Three correlation functions have been presented in article [9]: linear, bilinear and parabolic. Correlations have been computed on the basis of data provided by other researchers supplemented by 22 results of two varieties of author's own tests conducted on solid brick masonry joined with cement and lime mortar. Two types of hammers, N and L, were used for the tests, but the final correlation curve was developed for the N type hammer. The obtained Schmidt hammer results (rebound measured on the bricks in the wall) were distinguished by low values of the coefficient of variation – 1,3% for type N and 2,6% for type L. For comparison, during a brick destructive test, the coefficient of variation of 17% was obtained, and around 30% for brick masonry prisms and cores cut out of them.

The compressive strength of masonry can also be estimated indirectly based on the bricks and mortar compression strength, for example, by the application of formulas from standards. The diagrams based on the formula given in PN-EN 1996-1-1 [16] are shown in Fig. 5a.

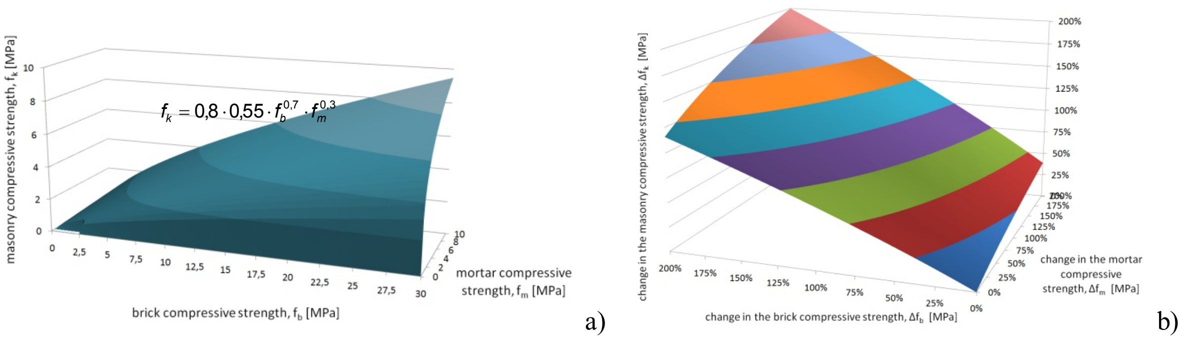

Fig. 5 Impact of the compressive strength of bricks and mortar on masonry compressive strength based on PN-EN 1996-1-1

According to PN-EN 1996-1-1 the f_b value noted in Fig. 5 state for the normalized compressive strength of bricks (tested on whole bricks, taking into account the size effect and humidity) and f_m is the compressive strength of mortar. The graph presented in Fig. 5a shows that it is the bricks strength which has a much greater influence on the masonry strength rather than the mortar strength. If the mortar strength is doubled, the masonry compressive strength increases by just 39%; whereas, if the brick strength is doubled, the masonry strength increases by 116% (Fig. 5b). Due to that fact, it is essential to correctly estimate the brick compressive strength while using this method. It should be also emphasized that in the sclerometric method the error in the assessment of brick strength (see Chapter 3) on the level of 30-40% results in the error of 20-25% in estimating the masonry strength.

6. APPLICATIONS OF THE SCLEROMETRIC METHOD FOR ASSESSING THE TECHNICAL CONDITION OF THE MASONRY

Besides numerous applications of the Schmidt hammer to assessing homogeneity and the strength of masonry materials (brick, mortar) and the walls themselves, there are also sclerometric tests performed to verify the effectiveness of repairs carried out. Examples of that type of tests are shown among others in [17]. The study recorded the size of the rebound number which was measured both on the bricks in the wall before and after the injection, and for different wall drying methods. Simultaneously there were comparative tests carried out on core drillings. Studies described in [17] are an interesting example of who to connect the sclerometric method such as NDT with DT like tests on the samples cut-out of the existing structure. However, there is not enough research of this type to be able to draw practical conclusions of a universal nature.

The application of the Schmidt hammer for tests on masonry structures damaged by the earthquake in Peru are presented in [18]. The decrease in the rebound number was obtained, depending on the degree of damage to the walls. During the research there were observed cracks in the bricks and mortar joints together with loosening of their internal structure.

The sclerometric method was also used to evaluate the degradation of the brick surface in the brickworks exposed to adverse external factors [11]. In the lowest parts of the wall (exposed to humidity etc.) the rebound values recorded on the bricks were lower than in the upper parts.

7. SUMMARY

Using the sclerometric method for the evaluation of uniformity of masonry materials and brickwork is a cheap and quick method. What stands for the heterogeneity measure are the differences in the mean rebound numbers from areas of research within a given structural element. These differences should not be directly equated with differences in the strength of the areas or elements that build them. The results, for example, indicate that the coefficient of variation for N type Schmidt hammer rebounds registered on the bricks in the wall are smaller than those obtained from the bricks compression strength research.

The sclerometric method may be useful for preliminary tests (helpful in choice of places for semidestructive studies or core drillings) and when assessing weak (degraded) bricks in the wall external layer.

The sclerometric method also allows to estimate *in situ* the bricks strength (primary parameter that determines the strength of the wall) on condition that one conducts the relevant comparative studies, which allows correlation curves to be calibrated.

The application of the N type Schmidt hammer for the estimate of the entire masonry strength directly on the basis of rebound numbers is difficult, and the obtained results are debatable.

Correlation curves published in [4] have been developed in particular with respect to strength evaluation of brick arch bridges – the construction of such structures required the best quality products and the need for the periodic internal structure. In case of buildings, the problem is more complex at least due to the use of a wide range of masonry materials and diverse quality of workmanship. To estimate the strength of the brickwall with the sclerometric method, with an acceptable accuracy for engineering purposes, it is necessary to use simultaneously other research methods. As the evaluation based only on the sclerometric method can lead to wrong conclusions.

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