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THE INFLUENCE OF TEST LOCATION, FACE TYPES, AND MOISTURE CONTENT ON THE REBOUND HAMMER TEST OF CLAY BRICKS

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Abstract: *This paper presents laboratory investigations on clay bricks using the Schmidt hammer test to assess their properties. The study includes the standard compression test to establish the correlation between compressive strength and rebound value obtained from Schmidt rebound hammer test. Additionally, the GANN hydrometer is employed as a non-destructive method to measure surface moisture content. The research examines the influence of test location, surface type, surface moisture content, and surface cracks on the rebound value. The findings highlight the significant influence of these parameters on both rebound value and compressive strength. To address these effects, the study proposes empirical equations for estimating compressive strength based on rebound value, accounting for the various factors involved. Overall, this research offers valuable insights into understanding and predicting the behavior of clay bricks.*

Keywords: *Schmidt rebound hammer, rebound value, estimated compressive strength, normalized mean compressive strength, solid clay brick.*

1. INTRODUCTION

The use of clay bricks in construction dates back thousands of years, making them one of the oldest building materials in human history. Even today, many historical buildings in Budapest, Hungary, are over 200 years old and constructed from clay bricks. During the renovation of such historical buildings, it is essential to assess the strength of the brickwork without damaging their architectural beauty and structural integrity. One commonly employed method to assess the strength characteristics of brickwork structures is the rebound hammer test, also known as the Schmidt hammer test. This method is not limited to historical solid clay bricks but can also be applied to modern bricks due to its ease of application and cost-effectiveness. Originally developed to measure the surface hardness of concrete using characteristic curves for specific cube and cylindrical size elements, the rebound hammer test has gained popularity as a non-destructive method for assessing the strength and quality of concrete [1].

While the rebound hammer test has been extensively studied for concrete, there is limited information available for its application in clay brick masonry [[2]-[11]]. Some researchers have demonstrated its usability for clay bricks, but additional considerations are required for honeycomb bricks or hollow block elements to establish a correlation between the rebound number and compressive strength [6]. Different types of Schmidt hammers are used depending on the strength of the bricks being tested. Schmidt hammer type N is suitable for estimating the compressive strength of high-strength bricks, while Schmidt hammer types L and B are used for low-strength bricks [3]. Fódi proposed a modified calculation method using an N-type Schmidt hammer to directly determine the normalized mean compressive strength of bricks [6].

Debailleux and Brozovsky concluded that Schmidt hammer type LB is appropriate for determining the compressive strength of solid clay bricks, but there is disagreement regarding the use of Schmidt hammer type L, which is primarily meant for concrete testing [4]. Henkel [8] and Borosnyoi-Crawley [9] recommend using L and N types of Schmidt hammers for vintage clay bricks, respectively, when the compressive strength is below 25 MPa. To obtain a more accurate estimate of compressive strength for bricks and stone, it is recommended to combine measurements from the rebound hammer test with ultrasonic pulse velocity testing [10].

In summary, the rebound hammer test offers a quick and convenient means of estimating the compressive strength of concrete on-site without destructive sampling. While it has been used for clay brick masonry, further research is needed to establish its applicability and correlation with compressive strength in various brick types. Combining the rebound hammer test with other non-destructive testing methods can enhance the accuracy of assessing the compressive strength of bricks and stone.

Although the rebound hammer provides a quick and inexpensive means of estimating of compressive strength, numerous studies show that rebound readings are sensitive to surface smoothness, age of concrete, moisture content, carbonation, types of aggregates, presence of air voids and steel reinforcement, temperature, and calibration of the rebound hammer [[1]-[10]]. The study carried out on historical solid clay brick indicates that the test locations also have a significant influence on the rebound value due to its size [1]. The rebound values measured on exterior and interior bricks of a wall may significantly vary from each other. Debailleux [4] emphasizes the relevance of considering this variation, when conducting particular assessments of masonry using a Schmidt hammer. As in the case of concrete structures, the test location can be marked easily on the surface of specimen when compared to clay bricks, which is large size and uniform. Because of the size of the bricks, only a limited number of measurements can be taken on a single element. There are no general guidelines for the number of measurement points and their placement within the element. Some characteristic curves are available for brick, which is used Hungary [12] - [14], without a significant modification of the curve developed for concretes [[15], [16]]. If the concrete block recommendation [[1], [17]] is followed, one to three points on a solid clay brick can be measured. Furthermore, there are no standardized characteristic curves or empirical equations exists that relate the rebound value to the estimated compressive strength of clay bricks.

This study investigates the minimum number of tests that should be performed on a single face element, the surface moisture condition, the crack influence, and the need for modification in the calculation of average rebound value while evaluating the application of the Schmidt rebound hammer for the estimation of the compressive strength of solid clay brick elements. In addition, the GANN hydrometer RTU 600 with electrode B60 is employed in conjunction with the rebound hammer test to determine whether it enhances the estimation of compressive strength. By combining these two testing methods, the aim is to investigate whether the measurement of surface moisture content using the GANN hydrometer can provide additional information and improve the accuracy of estimating the compressive strength of the bricks. The main purpose of this combined approach is to evaluate whether the inclusion of surface moisture content data enhances the overall assessment of the bricks' structural properties and quality. By examining the relationship between surface moisture content, rebound values from the rebound hammer test, and compressive strength, it becomes possible to gain deeper insights into the behavior of the bricks and make more informed decisions regarding their structural performance. Ultimately, the goal is to determine whether the incorporation of surface moisture content measurement using the GANN hydrometer improves the estimation of compressive strength when used in conjunction with the rebound hammer test. This information can contribute to enhancing the evaluation and decision-making processes related to the structural integrity and quality of bricks in practical applications.

2. METHODOLOGY

2.1. *Materials*

In this study, we specifically used modern solid clay bricks that were produced in a tunnel kiln in 2018. They were never built into a building but were stored outside for 5 years. These bricks were manufactured using a combination of clay and quartz sand, resulting in a unique chemical composition. The clay component provides the essential binding properties, while the addition of quartz sand adds strength and stability to the bricks.

The manufacturing process of these modern solid clay bricks involves carefully selecting and blending the clay and quartz sand mixture. This mixture is then shaped into brick form using specialized molding techniques. After molding, the bricks undergo a firing process in a tunnel kiln. The high temperatures in the kiln enable the clay to vitrify, transforming it into a solid, durable material. The chemical composition of the clay and quartz sand used in these modern solid clay bricks contributes to their desired properties. Clay, with its fine particles and plasticity, allows for the cohesive binding of the brick material. It provides the necessary plasticity for shaping the bricks during the manufacturing process. Quartz sand, on the other hand, enhances the strength and stability of the bricks. The presence of quartz sand particles adds hardness and resistance to the material, making it more robust and capable of withstanding external pressures. The combination of clay and quartz sand in the chemical composition of these modern solid clay bricks results in a high-quality building material. It possesses the desired characteristics of strength, durability, and stability, making it suitable for various construction applications. Additionally, the careful production process in the tunnel kiln ensures consistency and uniformity in the quality of the bricks, ensuring reliable performance in the built environment.

By using these modern solid clay bricks in our study, we aimed to evaluate their compressive strength using the standard compression test machine and N-type Schmidt hammer [18]. So, six identical solid brick specimens with dimensions of 250 mm x 120 mm x 65 mm, which are the minimum recommended, were chosen for this purpose [19]. However, in compliance with EN 772-1, the standard dimension for the compressive strength test of a solid clay brick is a 100 mm long cube. Therefore, these specimens were cut into two equal pieces using a brick-cutting machine, resulting in each piece measuring approximately 100 mm by 100 mm by 65 mm [[19], [20]]. This was done to investigate the influencing parameters. As a result, we now have a total of twelve specimens, each with two different types of faces – one that is the original and the other that is cut. During the preparation of the rebound hammer test, a thin layer of cement mortar was applied to the top and bottom faces of the specimen, causing it to be slightly taller than the original specimen (65 mm) in height. Six specimens were submerged in water for 48 hours, or until it reached the saturation point, before the test was conducted, to evaluate the influence of surface moisture content on the rebound value. The remaining six samples have also been placed in a lab room with a temperature above 15°C and a relative humidity below 65% for at least 14 days until it fulfills the air-dry condition [19]. For the dry and water saturated conditions, respectively, the physical characteristics of the cut specimen after capping are listed in Table 1 and Table **2**. The specimen names in Table 1 and Table **2** were assigned based on surface moisture content. For air-dry bricks, the names are preceded by a number followed by 'D' to indicate their dry condition. For saturated bricks, the names are preceded by a number followed by 'W' to indicate their wet condition. The numbers represent that the specimens were originally one piece before being cut into two pieces and conditioned to different moisture contents.

Specimen	***Dimension [mm]***			***Dry mass [kg]***	***Dry density [kg/m³]***
	L	***W***	***H***		
1D	100.7	100.1	75.4	1.252	1648
2D	102.2	99.9	79.5	1.294	1594
3D	100.8	99.7	79.9	1.294	1613
4D	101.1	99.5	82.3	1.410	1704
5D	100.3	100.3	81.0	1.320	1621
6D	100.8	99.8	80.9	1.319	1621

Table 1 The air-dry cut specimen physical properties

Specimen	***Dimension [mm]***			***Mass [kg]***		***Air dry density [kg/m³]***	***Water absorption [% by mass]***
	L	***W***	***H***	***Dry***	***Water saturated***		
1W	100.9	100.9	74.6	1.253	1.435	1649	15
2W	100.5	100.3	79.7	1.303	1.502	1621	15
3W	101.4	100.3	79.1	1.321	1.495	1642	13
4W	100.6	100.1	75.5	1.267	1.449	1665	14
5W	98.1	97.1	83.9	1.350	1.538	1688	14
6W	100.3	99.8	78.9	1.320	1.508	1671	14

Table 2 The water saturated cut specimen physical properties

2.2. Testing methods

The most suitable method for establishing the correlation between the compressive strength of bricks and rebound values is to conduct tests using both a compression testing machine and a rebound hammer simultaneously. The apparatus used for this purpose are the N-type original Schmidt Rebound Hammer and the standard compression testing machine.

The rebound hammer test is based on the principle that the rebound of an elastic mass depends on the hardness of the surface against which it strikes. In the case of brick testing, when the plunger of the rebound hammer is pressed against the brick surface, the spring-controlled mass in the hammer rebounds. The amount of rebound is directly related to the hardness of the brick surface [1]. Therefore, the hardness of the brick and the rebound hammer reading can be correlated with the compressive strength of the brick.

The rebound value is read from a graduated scale and is referred to as the rebound value or rebound index. To establish the correlation between the rebound value and compressive strength, a characteristic curve is developed [18]. The rebound hammer test was performed horizontally on all four vertical sides of the specimen. Measurements were taken at three locations on each side: the left edge (L), middle point (M), and right edge (R), as illustrated in Figure 1. Prior to conducting the rebound hammer test, each specimen was positioned in a compression testing machine (FORMTEST ALPHA 3-3000), and a load equivalent to 10% to 15% of the estimated compressive strength was applied. This load was sufficient to prevent any movement of the specimen during the rebound test [1].

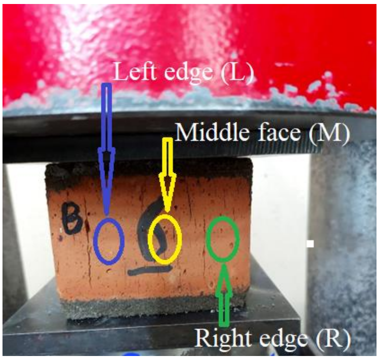


Figure 1 Test locations

Due to the small dimension of length and width, which is approximately 100 mm, it is recommended to take a maximum of three readings on each of the vertical faces that are accessible in the compression testing machine when using rebound hammers. This is necessary because the points of impact on the specimen should not be closer to an edge than 20 mm, and they should be spaced at least 20 mm apart from each other [17]. It is also important to note that the same points on the specimen should not be impacted more than once.

The rebound values are presented in table form based on the location and face types for the purpose of calculating the average value:

(a) All locations (L, M & R) on original and cut faces.
(b) All locations (L, M & R) on the original face only.
(c) All locations (L, M & R) on the cut face only.
(d) Middle face (M) on original and cut faces.
(e) Middle face (M) on the original face only.
(f) Middle face (M) on the cut face only.

When calculating the average rebound value for all locations (L, M & R), the largest and smallest values are excluded, and the average is determined from the remaining values. However, for the middle face (M), the average rebound value is obtained by taking the mean of the results. Subsequently, the correlation between the average rebound value and compressive strength is established using least-square method.

The GANN hydrometer RTU 600, equipped with electrode B60, is a specialized moisture measurement instrument designed specifically for brickworks [21]. It is used to determine the surface moisture content of bricks. The instrument is prepared by calibrating and ensuring its good working condition. The B60 electrode, designed for brickworks, is selected and placed in contact with the clean and dry brick surface. By applying slight pressure, the electrode establishes good contact and provides a moisture content reading displayed on the instrument's digital screen. The measured value can be interpreted by referring to the provided classification or reference values in the GANN hydrometer manual [21], see Table **3**. Multiple measurements are recommended at different locations on the brick surface to obtain a representative average moisture content value. The results are recorded for future reference and analysis, allowing effective monitoring of moisture conditions in brickworks.

Location	***GANN values***	***Classification***
Living area	25-40	dry
	> 40 and <100	semidry
	100-150	moist
Basement	60-80	dry
	> 80 and <100	semidry
	100-150	moist

Table 3 GANN value and brickwork classification

When evaluating the condition and quality of bricks, the surface moisture content plays a crucial role. Moisture levels can greatly influence the structural integrity and performance of the bricks, particularly in areas where moisture can have a significant impact. Therefore, understanding the moisture content is essential for proper assessment [[1], [17], [19]]. In this study, the GANN hydrometer RTU 600 with electrode B60 is employed in conjunction with the rebound hammer test to determine whether it enhances the estimation of compressive strength.

In the case where standard compression tests [19] have been conducted on specimens that are cut from whole units, the normalized strength obtained from the test results for the cut specimens is considered representative of the strength of the entire units from which they were taken. This means that the strength values determined from the tests on the cut specimens can be used to estimate the strength of the whole units. The normalization process takes into account the size and geometry of the cut specimens and adjusts the obtained strength values to reflect the strength characteristics of the original whole units [[19], [20]]. In order to obtain the normalized compressive strength, f_b, the compressive strength of masonry units is multiplied by a shape factor (δ), given in Annex A of EN 772-1 [19], wherein the width and height should be determined in accordance with EN 772-16 [22]. The purpose of this test is to establish a correlation between compressive strength and rebound value with the confidence limit of ±25% [17].

3. RESULT AND DISCUSSION

3.1. Rebound hammer test

The rebound values obtained from the faces of the specimens are summarized in Table **4** and Table **5**, based on the test location and surface type for both dry and water saturated conditions, respectively. In all tables, the labels A, B, C, and D correspond to the four vertical faces of the specimens where the tests were conducted. Additionally, the labels L, M, and R represent the left edge, middle face, and right edge of the test location, as indicated in Figure

1. Furthermore, the dry specimens are represented by numbers followed by the letter D, while the water saturated specimens are represented by numbers followed by the letter W.

Specimen	*Rebound value*											
	Original face						*Cut face*					
	A			*B*			*C*			*D*		
	L	*M*	*R*	*L*	*M*	*R*	*L*	*M*	*R*	*L*	*M*	*R*
1D	47	47	41	44	43	45	42	39	40	34	38	31
2D	35	44	45	39	42	30	28	17	27	36	41	33
3D	47	48	41	45	45	35	35	36	36	37	37	35
4D	45	45	43	45	49	45	35	39	35	30	38	38
5D	47	37	41	48	47	44	35	45	41	37	48	48
6D	42	48	43	46	45	45	35	36	33	33	44	35

Table 4 The rebound value for air-dry specimen

Specimen	*Rebound value*											
	Original face						*Cut face*					
	A			*B*			*C*			*D*		
	L	*M*	*R*	*L*	*M*	*R*	*L*	*M*	*R*	*L*	*M*	*R*
1W	37	43	41	42	39	41	24	31	29	36	39	38
2W	38	43	36	32	39	35	31	35	31	37	37	32
3W	37	39	38	36	44	39	30	33	31	27	32	28
4W	39	40	37	42	40	39	29	35	28	31	37	36
5W	41	36	41	39	39	39	34	38	35	36	41	37
6W	40	42	39	37	41	34	39	39	39	31	38	30

Table 5 The rebound value for water saturated specimen

Based on the data provided in Table 4 and Table **5**, the average value was calculated for each specimen based on face type and test location using the method outlined in section 2.2, and the results are shown in Table 6 and Table **7**.

Specimen	*Average rebound value (R)*					
	Original and cut faces		*Original face only*		*Cut face only*	
	All points (a)	*Middle point (d)*	*All points (b)*	*Middle points (e)*	*All points (c)*	*Middle points (f)*
1D	41	42	44	45	38	39
2D	36	36	40	43	31	29
3D	41	42	45	47	36	37
4D	41	43	45	47	37	39
5D	42	44	45	42	41	47
6D	41	43	45	47	35	40

Table 6 The rebound value for air dry specimen.

Specimen	***Average rebound value (R)***					
	Original and cut faces		***Original face only***		***Cut face only***	
	All points (a)	***Middle point (d)***	***All points (b)***	***Middle points (e)***	***All points (c)***	***Middle points (f)***
1W	37	38	41	41	34	35
2W	36	39	37	41	34	36
3W	34	37	38	42	30	33
4W	36	38	40	40	33	36
5W	37	39	39	38	37	40
6W	38	40	39	42	35	39

Table 7 The rebound value for water saturated specimen

The average rebound value at the middle point on the original face (e) is consistently higher than the values at other test locations, regardless of the moisture content, except for specimen 5D and 5W. This trend is clearly illustrated in Figure 2 and Figure **3**.

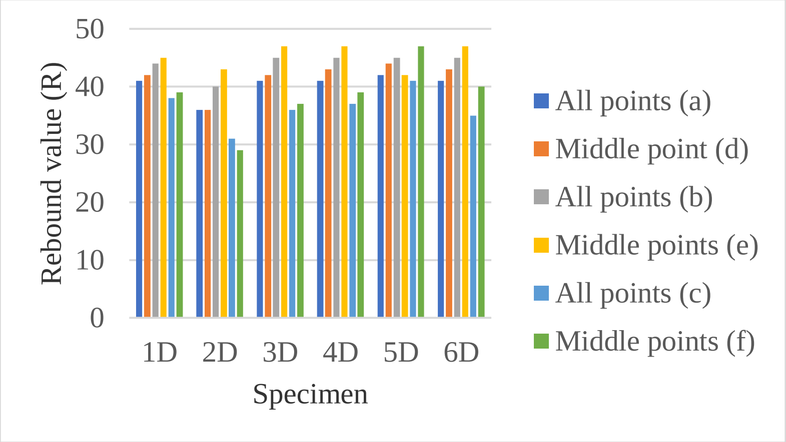


Figure 2 The average rebound value for air-dry specimen

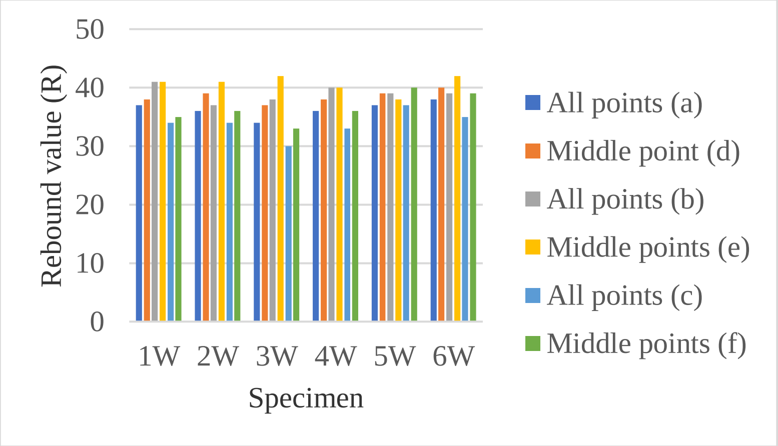
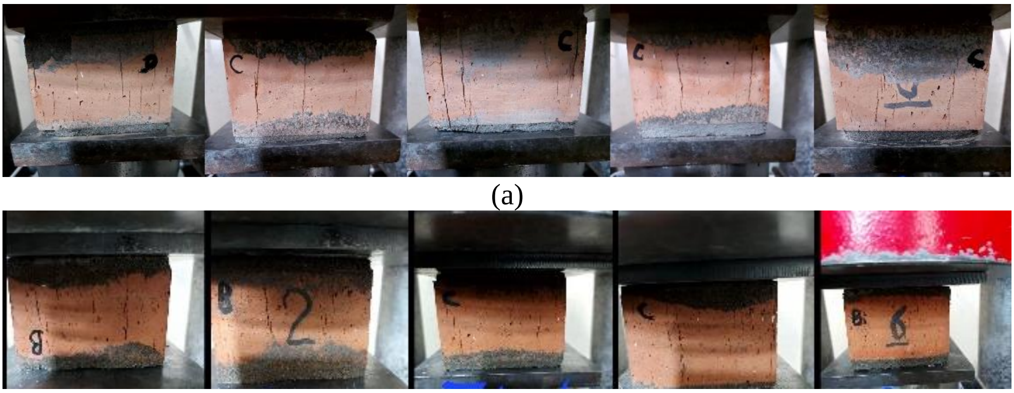


Figure 3 The average rebound value for water saturated specimen

Based on the observations from Figure 2 and Figure **3**, it is evident that the rebound values calculated from all the test locations on the cut faces (c) consistently exhibit the lowest values compared to the values obtained from the middle point on the original faces (e), with a difference of 8–23%. This difference is consistent regardless of the moisture content in the specimen. The primary reason for this significant difference is the presence of cracks on the cut faces, as shown in Figure 4. These cracks on the cut faces negatively affect the rebound performance and result in lower rebound values compared to other test locations.



(a)

(b)

Figure 4 Surface cracks on cut faces of (a) dry and (b) wet specimens

To ensure accurate and reliable results, the influence of surface cracks on the rebound values is taken into consideration. As a precautionary measure, the rebound values obtained from the cut face of the specimens are excluded from the analysis. Instead, the compressive strength is determined based on the average rebound values obtained from the original faces of the specimens.

In order to obtain a representative rebound reading, the test is conducted at all designated locations. This ensures that the measurements capture the overall characteristics of the brick and provide a comprehensive assessment of its compressive strength. By considering both the exclusion of rebound values from the cut face and the inclusion of all relevant test locations, the results obtained from the rebound hammer test can be more accurate and reflective of the true compressive strength of the brick.

To demonstrate the influence of surface moisture content, a comparison was made between the average rebound values of dry and water saturated specimens obtained from all points on the original faces (b). The results indicate that the rebound value of water saturated specimens is consistently 7% to 16% lower compared to the values obtained under dry conditions. This difference clearly highlights the effect of moisture content on the surface of the specimens.

Figure 5 provides a visual representation of this difference.

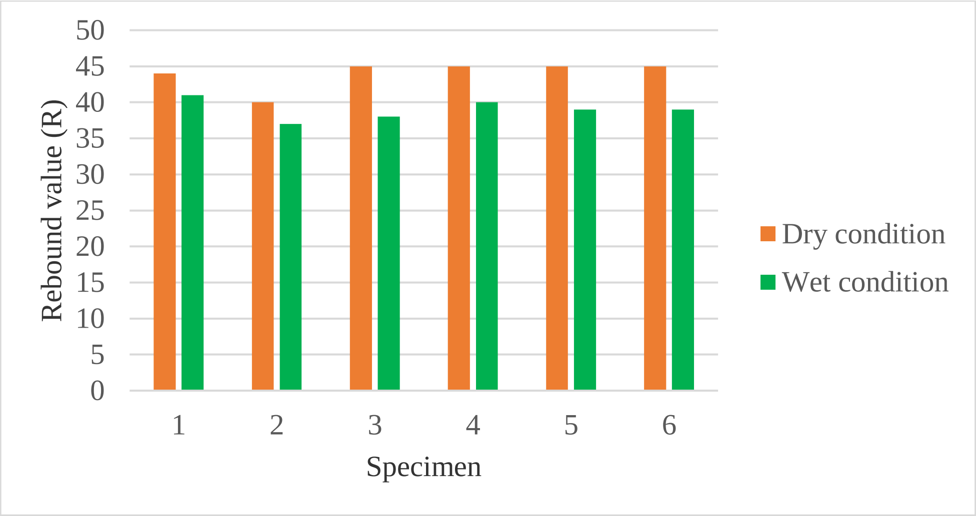


Figure 5 The influence of moisture content on rebound value

3.2. Standard compression test

The standard compression test was conducted on twelve bricks, maintaining a loading rate of 1.8 kN/s [19]. For the water saturated specimens, the surface water was promptly removed using a towel after being taken out of the water and before placing them in the testing machine. After obtaining the compressive strength from the standard compression test, the compressive strength of the cut specimens was converted to the nominalized mean compressive strength of an equivalent 100 mm cube masonry unit, following the guidelines of EN 772-1 [19]. The length and width of the specimens were taken as approximately 100 mm, while the height was maintained as it is to obtain the nominalized mean strength. The test results for the dry specimen are summarized in Table 8, while the results for the water saturated specimen are summarized in Table 9. These tables provide a comprehensive overview of the test results obtained from the standard compression test conducted on the bricks.

Specimen	***Height(mm)***	***Shape factor, δ***	***Compressive Strength, fc [MPa]***	***Normalized mean compressive strength, f_b [MPa]*** $f_b = \delta f_c$
1D	75.4	0.894	30.3	27.1
2D	79.5	0.912	20.0	18.2
3D	79.9	0.914	28.1	25.7
4D	82.3	0.924	28.5	26.3
5D	81.0	0.919	29.6	27.2
6D	80.9	0.918	28.6	26.3

Table 8 Compressive strength for dry specimen

Specimen	***Height(mm)***	***Shape factor, δ***	***Compressive Strength, fc [MPa]***	***Normalized mean compressive strength, f_b [MPa]*** $\mathbf{f_b = \delta f_c}$
1W	74.6	0.891	29.2	26.0
2W	79.7	0.913	31.5	28.7
3W	79.1	0.911	24.7	22.5
4W	75.5	0.895	29.5	26.4
5W	83.9	0.931	29.8	27.8
6W	78.9	0.910	29.1	26.5

Table 9 Compressive strength for water saturated specimen

Despite the high-water absorption capacity of the specimens, as shown in Table 2, the presence of moisture content has not resulted in a significant variation in the normalized compressive strength, except for specimen 2, as depicted in Figure 6. This observation may hold true for the short term; however, it is important to note that prolonged exposure to moisture can have detrimental effects, particularly due to the freeze-thaw effect.

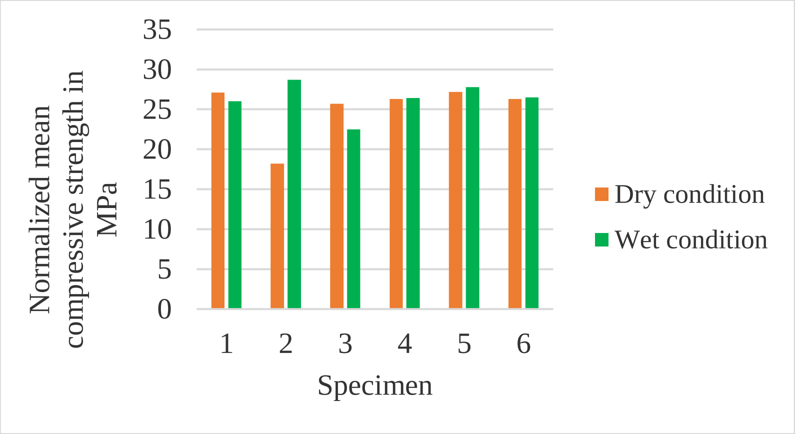


Figure 6 Normalized mean compressive strength, *f_b*

3.3. GANN hydrometer test

The water absorption capacity of the specimens was investigated by immersing them in water for 48 hours, and the corresponding results are presented in Table 2. However, it should be noted that conducting such tests on existing walls at construction sites is impractical. To overcome this limitation, the GANN Test-RTU 600 with electrode B60 is recommended as a suitable apparatus for evaluating the surface moisture content of brickwork. The test results obtained using this apparatus are summarized in Table 10 for dry specimens and Table 11 for water saturated specimens. In Table **10** and Table **11**, the labels A, B, C, and D represent the four vertical faces of the specimens where the readings were taken. These tables provide valuable insights into the moisture conditions of the brickwork using a non-destructive testing approach.

Specimen	*GANN value*					*classification*
	A	*B*	*C*	*D*	*Average*	
1D	74.3	89.5	62.1	68.7	73.7	semidry
2D	76.2	70.6	72.5	74.8	73.5	semidry
3D	80.4	74.4	69.9	83.9	77.2	semidry
4D	99.5	72.8	65.5	81.4	79.8	semidry
5D	95.6	87.1	63.5	73.0	79.8	semidry
6D	81.5	76.6	76.5	69.2	76.0	semidry

Table 10 GANN value and classification for air-dry specimen

Specimen	*GANN value*					*classification*
	A	*B*	*C*	*D*	*Average*	
1W	139.1	145.1	140.3	145.3	142.5	moist
2W	143.3	145.3	141.5	142.2	143.1	moist
3W	141.5	140.5	146.0	149.1	144.3	moist
4W	140.6	145.4	147.6	138.4	143.0	moist
5W	147.4	142.7	139.9	146.2	144.1	moist
6W	145.6	142.5	147.9	141.4	144.4	moist

Table 11 GANN value and classification for water saturated specimen

3.4. Proposed empirical equations

The correlation between rebound number and strength was established using the least-square method, and both linear and power models were developed. These models consider the test location and surface moisture content as additional factors that influence the relationship between rebound number and compressive strength. By incorporating these variables, the proposed equations aim to improve the accuracy of estimating the compressive strength based on the rebound value.

Table 12 provides a summary of the proposed models for the horizontal hammer position, including the equations and their coefficients. Additionally, Figure 7 presents a graphical representation of the correlation between rebound number and compressive strength, showcasing the relationship described by the proposed models.

Model type	*Equation*	*Regression coefficient, R^2*
Linear	$f_c = 1.635x - 46.81$	0.90
Logarithm	$f_c = 69.593\ln(x) - 238.16$	0.91

Table 12 Proposed empirical equations

In Table 12, the symbol "f_c" represents the compressive strength in MPa, while the symbol "x" represents the rebound value.

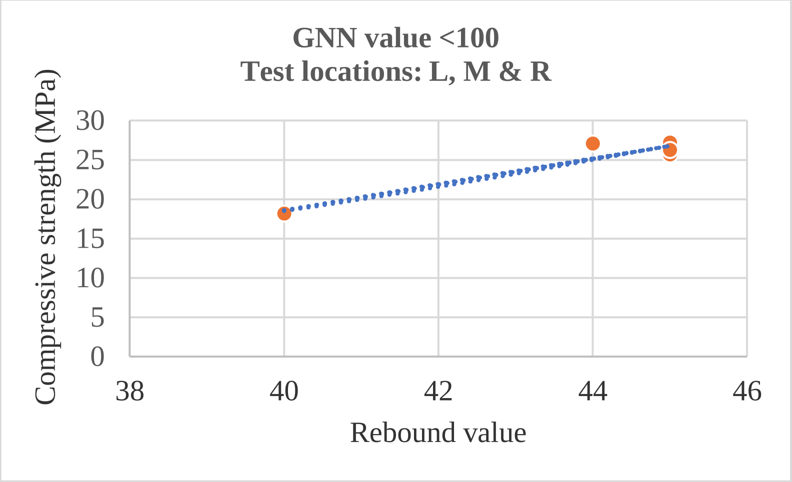


Figure 7 Characteristic curve based on all test locations.

Figure 7 represents the correlation between rebound value and compressive strength for GANN values less than 100 and includes all test locations. It is worth noting that the curves for these functions are nearly overlapped, indicating that they yield similar results within the confidential limit of ±25%. This implies that both functions can be used to estimate the compressive strength based on the rebound value without significantly affecting the accuracy of the estimation. Additionally, incorporating the GANN value in these equations improves the estimation of compressive strength by accounting for surface moisture content.

The incorporation of the GANN value in the equations aims to improve the estimation of compressive strength by considering the surface moisture content as an additional influencing factor. The GANN value provides information about the surface moisture content of the bricks, which can have an impact on their strength characteristics. By taking into account the GANN value along with the rebound value, the proposed equations aim to provide a more accurate estimation of the compressive strength, considering the moisture content of the bricks. This helps in obtaining a more comprehensive understanding of the material properties and allows for better assessment and decision-making in practical engineering applications.

The attempt to correlate the rebound value with compressive strength for the water saturated specimens resulted in a decline curve, which is not practical. Therefore, in this case, a further detailed study is required to develop suitable characteristic curves that accurately represent the relationship between rebound value and compressive strength for water saturated specimens.

4. CONCLUSION

Solid clay bricks were tested in parallel using non-destructive (Schmidt hammer) and destructive (standard compressive strength) methods. The variable values were testing location, surface type and moisture content.

In summary, the findings of this study indicate that the average rebound value at the middle point on the original face (e) consistently shows higher values compared to other test locations, regardless of moisture content, see Table **4** and Table **5**. The presence of surface cracks negatively impacts the rebound performance, resulting in lower rebound values as indicated in Figure **2** and Figure **3**. Water saturated specimens exhibit rebound values consistently 7% to

16% lower than those obtained under dry conditions, highlighting the influence of moisture content on the surface.

Empirical equations have been developed to correlate rebound value and compressive strength, taking into account test location and surface moisture content as additional influencing factors. These equations provide estimations of compressive strength within the confidential limit of ±25%. Thus, the incorporation of the GANN value in the equations resulted a better estimation of compressive strength. However, the attempt to correlate rebound value and compressive strength for water saturated specimens was unsuccessful, indicating the need for a more detailed study to develop suitable characteristic curves specifically for water saturated specimens.

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REFERENCES

[1] **MALHOTRA, V.M., CARINO, N.J.,** Handbook on Nondestructive Testing of Concrete, 2nd ed., CRC Press: New York, USA, 2004, pp. 1_3-13.

[2] **MENGISTU, G.M., GYURKÓ, Z., NEMES, R.,** The Influence of the Rebound Hammer Test Location on the Estimation of Compressive Strength of a Historical Solid Clay Brick, Solids, 2023, 4, 71–86.

[3] **BRENCICH, A., LATKA, D., MATYSEK, P., ORBAN, Z., STERPI, E.,** Compressive strength of solid clay brickwork of masonry bridges: Estimate through Schmidt Hammer tests, Constr. Build. Mater. 2021, 306, 124494.

[4] **DEBAILLEUX, L.**, Schmidt hammer rebound hardness tests for the characterization of ancient fired clay bricks, Int. J. Archit. Herit. 2019, 13, 288–297.

[5] **ROKNUZZAMAN, M., HOSSAIN, M.B., MOSTAZID, M.I., HAQUE, M.R.,** Application of rebound hammer method for estimating compressive strength of bricks, J. Civ. Eng. Res. 2017, 7, 99–104.

[6] **FÓDI, A.,** Effects influencing the compressive strength of a solid fired clay brick, Period. Polytech. Civ. Eng., 2014, 55, 117–128.

[7] **BROZOVSKY, J.,** Implementation of nondestructive impact hammer testing methods in determination of brick strength, Adv. Build. Mater. Sustain. Archit., 2012, 177, 280–285.

[8] **HENKEL, J.,** Evaluation of the quality of historic brickwork, Mauerwerk, 2016, 20, 391–406.

[9] **BOROSNYOI-CRAWLEY, D.,** Non-destructive strength estimation of vintage clay bricks based on rebound hardness in architectural heritage buildings, J. Build. Eng., 2023, 80, 108055.

[10] **ALIABDO, A.A.E., ELMOATY, A.E.M.A.,** Reliability of using nondestructive tests to estimate compressive strength of building stones and bricks, Alex. Eng. J., 2012, 51, 193–203.

[11] **BROZOVSKY, J., ZACH, J., BROZOVSKY, J., JR.,** Determining the strength of solid burnt bricks in historical structures. In Proceedings of the 9th International Conference on NDT of Art, Jerusalem, Israel, 25–30 May 2008.

[12] **DULÁCSKA, E.,JÓZSA, ZS.,BOROSNYÓI, A.**, Strength test of bricks with Schmidt hammer/Téglaszilárdságvizsgálat Schmidt kalapáccsal In: Balázs, L Gy (szerk.) EUROCODE 6 - Téglafalazatok Budapest, Magyarország : Építésügyi Minőségellenőrző Innovációs Közhasznú Társaság (ÉMI Kht.) (2001) pp. 129-132.

[13] **TSZ-01-2013**, Technical Code of the Hungarian Chamber of Engineers, Design principles and recommendations for the assessment of the load carrying capacity of existing buildings/ Műszaki szabályzat – Épületek megépült teherhordó szekezeteinek rőtani vizsgálata és tervezési elvei, Budapest, 2013 (in Hungarian)

[14] **ANTONIO BRENCICH A., DAWID LĄTKA B., PIOTR MATYSEK B, ZOLTAN ORBAN C, ENRICO STER PI D**, Compressive strength of solid clay brickwork of masonry bridges: Estimate through Schmidt Hammer tests Construction and Building Materials Volume 306, 1 November 2021, 124494

[15] **SZALAI K.**, Quality test of concrete/A beton minőségellenőrzése, Magyar Szabványügyi Hivatal, 1982 (in Hungarian)

[16] **E-UT 09.04.11**, Non-destructive testing of concrete pavements and structures using Schmidt hammer and ultrasound/Közúti betonburkolatok és műtárgyak roncsolásmentes vizsgálata schmidt-kalapáccsal és ultrahanggal Útügyi Műszaki Előírás 1999 (in Hungarian)

[17] **EN 12504-2:2012,** Testing Concrete in Structures—Part 2: Non-Destructive Testing—Determination of Rebound Number. European Committee for Standardization: Brussels, Belgium, 2012.

[18] **PROCEQ.,** Original Schmidt Manual of Concrete Test Hammer N/NR—L/LR, Proceq: Zürich, Switzerland, 2002, pp. 8.

[19] **EN 772-1:2011,** Methods of Test for Masonry Units—Part 1: Determination of Compressive Strength. European Committee for Standardization: Brussels, Belgium, 2011.

[20] **EN 771-1:2011,** Specification for Masonry Units—Part 1: Clay Masonry Units. European Committee for Standardization: Brussels, Belgium, 2011.
[21] **GANN**, Operating Instructions of GANN Hydrometer RTU 600, GANN: Stuttgart, Germany, pp. 69.
[22] **EN 772-16:2011,** Methods of Test for Masonry Units—Part 16: Determination of Dimensions. European Committee for Standardization: Brussels, Belgium, 2011.