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The relationship between compressive strength and sonic velocity depending on moisture content in case of historical masonry

Andras Dormany[1,*], Zoltan Orban[2]

[1]Department of Civil Engineering, University of Pécs, Faculty of Engineering and Information Technology
Boszorkány street 2, 7624 Pécs, Hungary
[2]Structural Diagnostics and Analysis Research Group, University of Pécs, Faculty of Engineering and Information Technology
Boszorkány street 2, 7624 Pécs, Hungary
*e-mail: dormany.andras@mik.pte.hu

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Abstract: Historical masonry structures made from locally available materials such as stone, brick, and mud are an integral part of our cultural identity. Moisture content is a critical environmental factor that can significantly impact the durability and strength of these structures. Moisture ingress in masonry can cause detrimental effects such as decreased strength, increased porosity, and reduced bond strength between the mortar and masonry units. Understanding this relationship is crucial for developing effective conservation strategies and maintenance decisions that can help protect these structures from moisture-related damage. This paper explores the impact of moisture content on the compressive strength of historical masonry structures and highlights the factors that can affect this relationship.

Keywords: historical masonry structures; moisture content; sonic testing; compressive strength

I. INTRODUCTION

1. Water absorption

Historical masonry structures are an essential part of our built heritage and cultural identity. These structures are often constructed using locally available materials such as stone, brick, and mud, which have been exposed to environmental factors for many years. Moisture content is one of the critical environmental factors that can significantly impact the durability and strength of these structures. The effect of moisture content on the compressive strength of historical masonry structures has been the subject of extensive research. Moisture ingress in masonry can occur due to various factors such as capillary absorption, rising damp, condensation, and water penetration through cracks and joints. Moisture content can cause several detrimental effects on the compressive strength of masonry, such as decreased strength, increased porosity, and reduced bond strength between the mortar and masonry units.

Understanding the impact of moisture content on the compressive strength of historical masonry structures is crucial for ensuring their preservation and longevity. It can inform the development of effective conservation strategies and maintenance regimes that can help protect these structures from moisture-related damage. This paper explores the relationship between moisture content and compressive strength in historical masonry structures and highlights some of the factors that can affect this relationship.

The water absorption of masonry structures refers to the amount of water that a masonry unit or mortar can absorb when exposed to moisture for a specified period. This property is influenced by various factors, such as the type and quality of masonry units and mortar, the presence of surface coatings or treatments, and the environmental conditions. The water absorption of historical masonry structures can be measured using various techniques, such as gravimetric analysis, electrical resistance, or ultrasound testing. These methods involve exposing the masonry unit or mortar to water for a specified period and then measuring the amount of water absorbed.

The water absorption of historical masonry structures can have significant implications for their durability and strength. It can also affect the bond strength between the mortar and masonry units and the overall structural integrity of the masonry structure. Therefore, it is essential to consider the water absorption of historical masonry structures when assessing their condition and developing conservation strategies.

2. Compressive strength

Determining the compressive strength of historical masonry structures is a crucial step in assessing their condition and determining their structural integrity. The compressive strength of masonry structures refers to the maximum amount of compressive stress that the structure can withstand without failure. The compressive strength is influenced by various factors, such as the type and quality of masonry units, the mortar type and quality, and the construction techniques used.

The compressive strength of historical masonry structures can be determined using destructive and non-destructive testing methods. Destructive testing involves taking samples from the masonry structure and subjecting them to compressive loads until they fail. The compressive strength is then calculated based on the maximum load that the samples can withstand before failure. However, destructive testing is not always feasible or desirable for historical masonry structures. Non-destructive testing methods, such as rebound hammer tests and ultrasonic pulse velocity tests, are commonly used to determine the compressive strength of historical masonry structures [1]. Ultrasonic pulse velocity tests involve transmitting ultrasonic waves through the masonry structure and measuring their velocity. The velocity is then used to estimate the compressive strength of the masonry structure.

It is important to note that the compressive strength of historical masonry structures can vary significantly within the structure due to variations in the quality and composition of the masonry units and mortar, and the construction techniques used. Therefore, it is essential to take multiple samples and measurements from different locations within the structure to obtain an accurate assessment of the compressive strength [2].

The compressive strength of mortar is established by various standards, such as ASTM (American Society for Testing and Materials) and EN (European Norm) standards. These standards provide guidelines for testing procedures, sample preparation, and calculation of compressive strength. For instance, ASTM C109/C109M-20a [3] provides a standard test method for measuring the compressive strength of hydraulic cement mortars using 2-inch cube specimens. The test involves preparing the mortar specimens with a specific ratio of cement to sand, curing them under specified conditions, and subjecting them to compressive loads until they fail. The compressive strength is then calculated based on the maximum load that the specimens can withstand before failure. Similarly, EN 1015-11:1999 [4] provides a standard test method for determining the compressive strength of cement mortar using prisms with a cross-section of 40x40 mm. The test involves preparing the mortar specimens with a specific ratio of cement to sand, curing them under specified conditions, and subjecting them to compressive loads until they fail. The compressive strength is then calculated based on the maximum load that the specimens can withstand before failure.

It is important to note that the compressive strength of historical mortars may differ from that of modern mortars due to differences in the materials and manufacturing processes used. Therefore, the standards provide guidance for testing historical mortars as well, including recommendations for adjusting testing procedures and interpreting results.

3. Sonic testing

Sonic testing is a non-destructive testing method that can be used to determine the compressive strength of mortar. This method involves transmitting sound waves through the mortar and measuring their velocity. The velocity of the sound waves is related to the stiffness of the material, which in turn is related to the compressive strength of the mortar. The sonic testing involves transmitting sonic waves through the mortar and measuring the time it takes for the waves to travel between two sensors placed on the surface of the mortar. The velocity of the waves can then be calculated based on the distance between the sensors and the time it takes for the waves to travel between them. The velocity is then used to estimate the compressive strength of the mortar. In sonic testing, the velocity of sound waves is related to the stiffness of the material, which is in turn related to the compressive strength of the material. The relationship between velocity and stiffness based on [5] is described by the equation (01):

$$\mathrm{E} = 2\rho V_s^2(1+\sigma) \qquad (01)$$

where E is the modulus of elasticity, ρ is the density of the material, V_s is the velocity of the sound waves, σ is the Poisson’s ratio of the material. This equation shows that as the elasticity of the material increases with the second power of the velocity of the sound.

If the velocity of the waves is known, the compressive strength of the material can be estimated using empirical relationships between compressive strength and velocity that have been established for the material being tested. These relationships are typically established by testing samples of the material in a laboratory using destructive testing methods, such as compression testing, some relevant paper is listed in table 1.

Table 1. *Relevant studies related to Sonic testing*

Reference	***Material***	***Subject***
Luchin et al [6]	Granite wall	Masonry wall characterization
Parent et al [7]	Limestone	Compressive strength by sonic velocity
Butel et al [8]	Stone	Compressive strength by sonic velocity
Elizabeth et al [9]	Masonry	Compressive strength by sonic velocity
Valente et al [10]	Masonry	Detecting voids and cracks

Sonic tomography is a non-destructive testing technique used to assess the internal structure and properties of materials, including masonry structures. The technique is based on the principles of sonic testing, but involves the use of multiple transducers and data processing to generate a 2D or 3D image of the material being tested. The resulting image provides information about the internal structure and properties of the material, such as the location and extent of cracks or voids, and variations in material properties such as stiffness or density. This information can be used to assess the integrity of the material, identify areas of potential weakness, and inform decisions about repair or conservation strategies.

The advantage of sonic testing is that it is a non-destructive method, which means that it does not damage the mortar. It can also be used for the in-situ testing of the mortar, without the need for removing samples from the masonry structure. This is particularly useful for historical masonry structures where removing samples may not be feasible or desirable. However, it is important to note that the accuracy of sonic testing can be affected by various factors, such as the composition and quality of the mortar, the presence of defects or damage, and the environmental conditions. Therefore, it is essential to ensure that the testing conditions are standardized and that the results are interpreted in the context of the specific conditions of the mortar being tested.

II. EXPERIMENTAL PROGRAMME

1. Testing specimens

The aim of this paper was to establish relationship between the moisture content of historical masonry structural elements and their compressive strength. For this purpose, a test programme was carried out taking into account the following aspects:

- testing historical solid clay brick specimens
- usage and testing of lime binder-based mortars
- creating and testing historically accurate solid masonry specimens made with lime mortars mentioned above
- testing the compressive strength of the brick, mortar and masonry specimens with 2 different moisture content (air dry and quasi wet)
- testing the effect of the moisture content on the velocity of sonic waves

The brick specimens were collected from a demolished house built in the 19th century. The size and weight of the brick specimens were measured before the testing. The average size of the bricks was 14,5x30x6,5 cm with relative high error (some brick had 1-2 cm difference from the standard size). For the testing procedure damaged and not whole bricks were filtered and ignored.

The lime mortar specimens were created in the laboratory of the Department of Civil Engineering UP with 40x40x40 mm size. Based on the review book of Attila Déry (Öt könyv a régi építészetről – 5 books about the old architecture) [11] historically accurate Hungarian mortar mixtures were obtained. In table 2 the mortar types and mixtures are listed used in the experimental programme.

Table 2. *The mixture of the tested mortars*

Mortar type	***Binder***	***Sand***	***Water***
FH	1	2	1
AH	1	2	1.1
BH	1	4	1

Three different types of mortars were tested, FH mortar made by quartz sand, AH made by sand with high clay content and finally BH made by mine sand.

Solid clay brick masonry specimens were created with mortars mentioned above and 2 different sample heights in order to find a relationship between sonic wave velocity, moisture content and the number of the mortar joints. For this purpose, 2 different heights of specimens were applied (2 bricks and 3 bricks height).

Sonic testing was carried out before and after soaking the specimens. All the specimens were soaked in water for at least 3 days in order to reach a quasi-wet condition. Before soaking every specimen were weighed to calculate the water absorption. After finishing the Sonic tests, the compressive tests were carried out on each specimen.

2. Water absorption

The water absorption of clay bricks is generally expressed as a percentage of the dry weight of the brick. The American Society for Testing and Materials (ASTM) standard C67/C67M-21 [12] provides a laboratory test method for determining the water absorption of clay bricks. This test involves soaking the brick in water for a specified period and then measuring the weight of the brick after the soaking period to determine the amount of water absorbed. The water absorption of clay bricks can also be measured using non-destructive techniques, such as ultrasound or electrical resistance.

The water absorption of lime mortars is generally expressed as a percentage of the dry weight of the mortar. The water absorption of lime mortars can be determined using various laboratory test methods, such as the ASTM C1585/C1585M-13 [13] test method or the EN 1015-18:2002 [14] test method. These test methods involve saturating the mortar samples with water for a specified period and then measuring their increased weight to determine the amount of water absorbed.

The measured and calculated results of the water absorption tests are discussed in this subchapter. The water absorption value can be derived by the following equation (02):

$$w = \frac{m_{wet} - m_{dry}}{m_{dry}} * 100\% \qquad (02)$$

where w is the water absorption value, m_{wet} is the mass of the specimen after soaking and m_{dry} is the mass of the specimen before soaking.

The tested specimens were soaked for at least 3 days in order to reach the quasi-wet condition. During the soaking great attention was taken for the water amount and level in the wetting boxes, the level of water was above the highest specimen with at least 2-3 cm.

3. Compressive strength

The compressive strength test was performed for each specimen before and after soaking. The test was carried out by Sercomp 7 multi-functional testing machine. The compressive strength CS of the specimens were calculated by the equation (03):

$$CS = \frac{F}{A} \qquad (03)$$

where F is maximum acting load before failure and A is the cross-sectional area of the loaded surface.

4. Sonic testing

The Sonic testing was performed by the ArborSonic testing tool. ArborSonic is sonic tomograph where at most 20 transducers can be installed, the transducers generate waves with 600 Hz frequency. The transducers are nail-like elements, which can be fixed in a hole pre-drilled in the tested material. Due to the relatively small specimen sizes only 6 transducers were used. Data was assessed by ArborSonic software what provides an opportunity to save, download the travel times, calculate velocities and plot images about the tested cross section based on the velocities.

III. Results and discussion

1. Water absorption

A. Brick Specimens

6 clay brick samples were selected and tested during the programme. 3 of them were tested in air-dry and other 3 in quasi-wet condition. The main results such as the average value, standard deviation and coefficient of variation can be found in table 3.

The average mass of the bricks in air-dry condition was 5.79 kg, while the average mass in quasi-wet condition was 6.26 kg. The mass of the tested bricks was increased by an average of 14%, which is a relative high water absorption rate. Also, it can be noticed that the Coefficient of Variation value has changed significantly after soaking (from 0.029 to 0.117).

Table 3. *Results of the water absorption tests on brick specimens*

Property	***Air-dry***	***Quasi-wet***
Average mass [kg]	5.79	6.26
Standard Deviation [kg]	0.167	0.736
Coefficient of Variation	0.029	0.117

B. Mortar specimens

The measured properties of the assessed mortar specimens are shown in Table 4.

Table 4. *Main properties of the tested mortar specimens before and after soaking (in bracket CoV)*

Mortar type	***Average air-dry mass [g]***	***Average quasi-wet mass [g]***	***Average water absorption [mass%]***
FH	102.2 (0.015)	119.5 (0.048)	15.8 (0.260)
AH	88.1 (0.102)	124.5 (0.018)	34.4 (0.329)
BH	93.5 (0.051)	109.0 (0.026)	14.2 (0.271)

Table 4 also shows the main data of the tested mortar specimens related to water absorption. The results suggest that the AH mortar has the highest water absorption compared to the other two types. The data also show water absorption CoV values are relatively high (especially the AH mortar with 0,329). Overall, the FH and BH mortar properties are very similar.

C. Masonry specimens

Table 5 provides information about the average air-dry weight, average quasi-wet weight, and average water absorption of six different types of masonry specimens. The coefficient of variation (CoV) is also given in brackets.

The data reveals that the average air-dry weight of the specimens ranges from 8.94 kg to 16.34 kg. The FH 2 brick height specimens have the lowest air-dry weight, while the AH 3 brick height specimens have the highest. The average quasi-wet weight of the specimens ranges from 10.58 kg to 19.13 kg. The FH 2 brick height specimens have the lowest quasi-wet weight, while the BH 3 brick height specimens have the highest.

The water absorption percentage of the specimens ranges from 16.88% to 18.55%. The AH 2 brick height specimens have the lowest water absorption rate, while the BH 2 brick height specimens have the highest. Interestingly, the FH 2 brick height and BH 2 brick height specimens have the highest water absorption rates despite having the lowest air-dry and quasi-wet weights.

The coefficient of variation for each property varies from 0.032 to 0.098. The lowest CoV is observed for the BH 2 brick height specimens for water absorption, which indicates that the specimens are relatively consistent in terms of their water absorption rate. The highest CoV is observed for the BH 2 brick height specimens for air-dry weight, indicating that there is a high degree of variability in the air-dry weight of these specimens.

2. Sonic testing

A. Brick specimens

Sonic testing was carried out on each brick specimen before loading. Half of the specimens were tested before and after soaking in order to find the sonic velocity change due to wet condition. The test results are given in table 6.

B. Mortar joints of the masonry specimen

Due to the small size of the mortar specimens the application of Sonic test was not possible. Instead, it was carried out on the mortar joints in the masonry specimens. In table 7 the results of this testing are listed.

Table 6. *Results of the Sonic tests on brick specimens*

Property	***Air-dry***	***Quasi-wet***
Average velocity [m/s]	1563	1675
Standard Deviation [m/s]	164.8	279.1
Coefficient of Variation	0.126	0.166

Table 5. *Main properties of the tested masonry specimens (in bracket CoV)*

Masonry type	***Average air-dry mass [kg]***	***Average quasi-wet mass [kg]***	***Average water absorption [mass%]***
2 brick heigh with FH mortar	9.85 (0.098)	11.64 (0.084)	18.30 (0.098)
3 brick heigh with FH mortar	14.66 (0.053)	17.41 (0.039)	18.55 (0.081)
2 brick heigh with AH mortar	10.22 (0.087)	11.94 (0.083)	16.88 (0.066)
3 brick heigh with AH mortar	16.18 (0.056))	19.16 (0.057)	18.44 (0.056)
2 brick heigh with BH mortar	8.94 (0.211)	10.58 (0.208)	18.43 (0.032)
3 brick heigh with BH mortar	16.34 (0.074)	19.13 (0.070)	17.08 (0.070)

Table 7. *Results of Sonic testing on the mortar joints of the masonry specimens (in bracket CoV)*

Mortar type	***Average air-dry velocity [m/s]***	***Average quasi-wet velocity [m/s]***	***Average difference between air-dry and quasi-wet [%]***
FH	617.2 (0.292)	683.5 (0.283)	12.2
AH	785.0 (0.347)	706.0 (0.325)	-10.6
BH	611.6 (0.307)	763.8 (0.292)	25.6

The result of the table shows that the relationship between velocity and moisture content is highly variable. Usually, the average velocities increase with the increasing moisture content except for the AH mortar. The increase of velocity is in range 12 to 25%. Also, the results show that the CoV values are very high for both air-dry and quasi-wet conditions, indicating that the applicability of Sonic testing only for mortar assessment is limited.

C. Masonry specimens

On the masonry specimens another Sonic testing was carried out. The sensors were inserted into pre-drilled holes in the brick in order to find the effect of mortar joint on the Sonic velocity. The results are shown in table 8.

It is clearly seen that the Sonic wave velocity was increased with the moisture content. The difference is very significant, nearly 25% in case of FH mortar, but more than 40% for the other 2 mortar types. Also noticeable that the CoV values are relative high for both air-dry and quasi-wet conditions (but in case of wet medium it is smaller than in air-dry condition).

3. Compressive strength

A. Brick specimens

Before starting the test, each brick was covered with a thin layer of cement mortar in order to create parallel planes and reduce the effect of inaccurate load distribution caused by rough surface. Table 9 provides information about the results of the tested bricks.

The results indicate that the strength of the bricks decreases when they are exposed to moisture with an average of 16%. The coefficient of variation for both air-dry and quasi-wet conditions is relatively low, suggesting that the results are reliable and consistent.

B. Mortar specimens

Table 9. *Results of the compressive tests on brick specimens*

Property	***Air-dry***	***Quasi-wet***
Average strength [MPa]	17.4	14.7
Standard Deviation [MPa]	3.66	3.00
Coefficient of Variation	0.210	0.205

4 mortar specimens were created from each type of mixture for air-dry and quasi-wet condition, altogether 24 pieces. Results are listed in table 10.

Table 10 shows that there were significant differences between the tested mortars regarding the compressive strength of them. The strongest mortar type in air-dry condition was AH with 2.16 MPa, on the other hand the CoV value was the highest as well. The FH mortar had an acceptable strength value with relatively small CoV value. The BH mortar was the weakest with 0.65 MPa, which is considered as extra weak mortar. From the results it is clearly seen that there is an obvious relationship between the compressive strength and moisture content. The strength was reduced by at least 15 % (in case of BH mortar), but for the AH mortar the loss was more than 40%.

Table 10. *Compressive strength of mortar specimens (in bracket CoV)*

Mortar type	***Average air-dry strength [MPa]***	***Average quasi-wet strength [MPa]***
FH	1.42 (0.090)	0.82 (0.058)
AH	2.16 (0.178)	1.74 (0.122)
BH	0.65 (0.121)	0.55 (0.125)

Table 8. *Results of Sonic testing on the masonry specimens (in bracket CoV)*

Masonry type	***Average air-dry velocity [m/s]***	***Average quasi-wet velocity [m/s]***	***Average difference between air-dry and quasi-wet [%]***
FH	676.5 (0.215)	844.9 (0.166)	24.9
AH	650.9 (0.174)	915.8 (0.172)	40.7
BH	633.7 (0.211)	926.4 (0.218)	46.2

C. Masonry specimens

Masonry specimens were created by the collected historical bricks and mortars prepared in laboratory. The aim of this test was to find a relationship between the Sonic velocity and compressive strength of masonry specimen. The compressive strength of the masonry specimens usually reduces by the increased moisture content. Table 11 shows the results.

The results show that the effect of mortar strength to the masonry strength is not significant in case of low strength mortars. The compressive strength of air-dry masonry specimens made by AH and FH mortars are very similar, and the BH mortar made masonry strength is quite close to the AH and FH ones. After soaking the compressive strengths were reduced by range of 11-16%. Noticeable that the CoV value was increased up to 0.334 with increasing the moisture content (change was very significant in case of BH made specimens).

Table 11. *Compressive strength of masonry specimens (in bracket CoV)*

Masonry type	***Average air-dry strength [MPa]***	***Average quasi-wet strength [MPa]***
With FH mortar	5.35 (0.270)	4.73 (0.334)
With AH mortar	5.28 (0.258)	4.57 (0.301)
With BH mortar	4.91 (0.153)	4.22 (0.323)

IV. Conclusions

The aim of the paper was to find a relationship between the compressive strength and Sonic velocity depending on moisture in case of historical masonry compression structural elements. A large number of specimens were created, tested and analysed. Brick specimens were collected from a demolished house from the 19th century, historically accurate mortar specimens were mixed and finally masonry specimens were created.

In the testing programme 3 kind of tests were carried out such as water absorption, sonic testing to measure the velocity and prism test. Water absorption test was done by soaking the specimens at least 3 day long. Sonic test was done by specific tool called ArborSonic. The compressive strength of specimens was measured by Sercomp 7 multi-functional testing machine.

From the results it can be concluded that the water absorption value of the tested brick, mortar and masonry specimens was significantly high (in some specimen it reached 20 mass%), which demonstrates the remarkable compressive strength loss of all the specimens. Due to this fact the loss of compressive strength was remarkable for all specimens. On the other hand, higher Sonic velocities were measured on the specimens after soaking.

Based on the testing programme, if was found that Sonic tests can be a suitable tool to estimate the compressive strength of historical masonry, but a strong dependence was found between the sonic velocity and moisture content. Furthermore, the effect of moisture on sonic velocity was found different than that observed in standard destructive tests. Overall, the compressive strength cannot be determined accurately by the Sonic velocity without knowing the moisture content of the assessed masonry structure.

Author Contributions

A. Dormany: Testing, Data analysis and writing.

Z. Orban: Supervision, Review and editing.

Disclosure Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ORCID

Andras Dormany: https://orcid.org/0000-0002-7944-9219

Zoltan Orban: https://orcid.org/0000-0002-9721-6216

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