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Experimental investigation of the sonic velocity in historical masonry walls

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ORIGINAL RESEARCH PAPER

ABSTRACT

The structural assessment of historical buildings poses a significant challenge for engineers. However, when it comes to historical structures, more commonly used and reliable destructive testing may not always be viable. Instead, non-destructive testing has gained prominence, encompassing techniques like the Schmidt hammer test, georadar, and sonic-based tests.

In this paper, the viability of employing sonic testing on historical masonry structures was investigated. This study involves using the measured sonic velocities to identify voids and solid parts within masonry walls. In addition, the purpose is to determine the compressive strength of both mortar and brick constituents and to analyze the effects of moisture and compressive stress on the propagation velocity of waves.

KEYWORDS

historical masonry, compressive strength, sonic test, moisture

1. INTRODUCTION

1.1. Sonic testing

Sonic testing represents one among the viable non-destructive techniques for assessing the strength characteristics of historical masonry. This method involves transmitting sound waves through the tested material and measuring their velocity. The velocity of the sound waves is related to the density of the material, which in turn is related to the compressive strength of the brick or mortar [1]. In the context of masonry structures, sonic testing encompasses the transmission of sonic waves through the masonry material, followed by the measurement of the duration it takes for these waves to traverse the space between two sensors inserted on the surface of the brick or mortar. Subsequently, the velocity of the waves can be computed by considering the distance separating the sensors and the time required for the waves to make their journey between them. The relationship between velocity and density [2] can be described by Eq. (1):

$$E = 2\rho V_s^2(1+\sigma), \tag{1}$$

where E is the Young's modulus of elasticity; ρ is the density of the tested material; V_s is the velocity of the sound waves; σ is the Poisson's ratio of the material.

Sonic tomography stands as a non-destructive testing method applied for evaluating the internal structure and characteristics of various materials, including masonry structures. This technique builds upon the fundamental principles of sonic testing but employs multiple transducers and advanced data processing to produce either two-dimensional (2D) or three-dimensional (3D) representations of the material under examination. The resulting images provide valuable information about the internal structure and properties of the material, for instance the location of cracks or voids, and variations in material properties such as density or compressive strength [3]. Utilizing this data allows for the evaluation of masonry

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integrity, the detection of potential weak points, and the formulation of informed choices regarding repair or preservation strategies.

Sonic testing offers the benefit of being a non-destructive technique, ensuring that the material being examined remains undamaged. Additionally, it proves valuable for in-situ assessments of masonry, particularly in the context of historical structures where extracting samples may be impractical. Nonetheless, it is essential to acknowledge that the precision of sonic testing may be influenced by several factors, including material composition, quality, the existence of defects or damage, and prevailing environmental conditions. Due to these uncertainties the sonic methods should be combined with other non-destructive tests in order to provide more reliable data to determine the compressive strength of the masonry components [4, 5].

1.2. The effect of moisture on sonic velocity and compressive strength

The moisture of masonry can have a significant impact on its compressive strength [6] and excess moisture in masonry can lead to a variety of problems, including reduced strength and decreased durability.

When masonry units absorb moisture, they can undergo physical and chemical changes leading to expansion, swelling, additionally excessive moisture can decrease the bond between the masonry units and mortar.

This study was carried out to find the correlation between compressive strength and sonic velocity in historical masonry [7]. The test results show that increased sonic velocity was dependent on moisture conditions. That means while the compressive strength decreases due to moisture, the sonic velocity can be higher than it was under dry conditions. This led us to the conclusion that an accurate estimation of compressive strength cannot be made without measuring the moisture content of the tested material.

2. EXPERIMENTAL PROGRAM

2.1. Aim of the program

As highlighted in the introduction, the assessment of mechanical properties in historical masonry structures through sonic testing necessitates careful consideration of numerous factors, like the density of the material, moisture, compressive stress, and number of mortar joints. The aim of this experimental program is to enhance the understanding of how these influences are altered when conducting tests on historical masonry structures, considering their non-homogeneous nature. Additionally, the aim is to establish the correlation between sonic velocity and the compressive strength of historical bricks and mortars.

2.2. The testing samples

The testing program was carried out on historically accurate samples which were reconstructed and tested for two different moisture conditions (air-dry and wet) and two other conditions based on normal stresses (non-loaded and preloaded). To ensure the historical accuracy of the study, the solid clay bricks were collected from a demolished residential house built in the 19th century and three different lime mortar mixtures were used.

The reused bricks were measured before testing, the size and mass determined by the regulations of EN 772-16:2011 [8] and EN 772-13:2000 standards [9]. The bricks, on average, measured 14.5 × 30 × 6.5 cm, but there was a relatively high degree of variability, with certain bricks deviating by 1–2 cm from the standard size. The damaged bricks were filtered and ignored during the testing program.

Lime mortars were created according to Attila Déry's book on historical construction materials [10]. The mortar types and mixing ratios are listed in Table 1.

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

Solid clay brick masonry samples were created for two different samples heights (two bricks high with one horizontal mortar joint and three bricks high with two horizontal mortar joints) using the mortars previously mentioned. In addition to these smaller samples, a masonry wall (1.1 m long, 1.1 m high and one brick thick) was created using BH mortar to test the behavior of the sonic waves on a larger scale. The second aim of the masonry wall was to analyze the void detecting capabilities of the sonic device. For this purpose, hidden voids were purposely created when building the wall. The location of the hidden voids and the solid parts of the wall is presented in Figs 1 and 2.

Table 1. Mixing ratio of tested mortars [5]

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

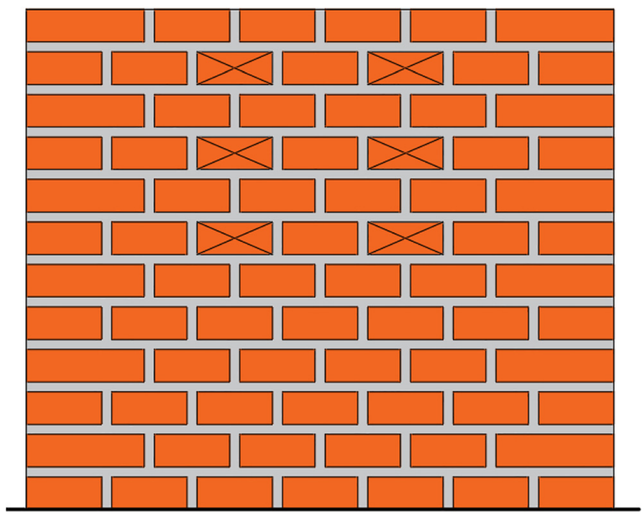

Fig. 1. Illustration about the masonry wall elevation view (voids are marked with X)

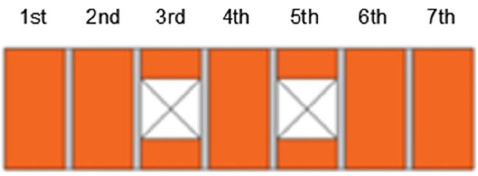

Fig. 2. Illustration about the masonry wall, horizontal view (voids are marked with X)

2.3. Water absorption

Typically, the water absorption of clay bricks is represented as a percentage of the brick's dry weight. The American Society for Testing and Materials (ASTM) standard ASMT C67/C67M-23A:2023 [11] offers a laboratory test procedure for assessing the water absorption of clay bricks. Lime mortar's water absorption is typically quantified as a percentage of its dry weight. Various laboratory test methods, including the ASTM C1585-20:2020 [12] and EN 1015-18:2002 [13] procedures, can be employed to ascertain the water absorption of lime mortars. These tests entail saturating mortar samples with water for a specified duration and subsequently measuring the increment in weight to determine the absorbed water content. The water absorption value can be derived by the mass incensement after saturation divided by the dry mass.

The water absorption value can be derived by the following Eq. (2):

$$w = \frac{m_{wet} - m_{dry}}{m_{dry}} \cdot 100\%, \tag{2}$$

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

The tested samples were soaked for at least three days to reach the saturation point. Special attention was taken to ensure the water level was 2–3 cm above the largest sample. Each sample was measured after soaking and the water absorption was calculated. Both mortar and brick samples reached 14% water absorption, which is considered saturated.

2.4. Non-destructive tests

2.4.1. Sonic tests. Sonic testing was performed using the ArborSonic testing device [14]. ArborSonic is a sonic tomography where up to 20 transducers can be installed, generating waves at the 600 Hz frequency. The transducers are nail-like elements, which can be inserted into holes drilled in the testing material. Due to the relatively small sample sizes only six transducers were used (three on the top and three on the bottom) fixed in the bricks and another six were fixed in the horizontal joints of the small samples. Sonic testing was carried out for each joint under non-loaded and preloaded conditions (20 kN preloaded caused an average 0.44 MPa compressive stress) using an Instron 5595 multifunctional testing machine. It was possible to apply ten transducers fixed horizontally in the brick wall (5 in each side of the wall) functioning as a tomography sonic test. The transducers were installed similarly like single brick testing. The transducers were inserted based on the following: 3–3 transducers were in the middle bricks (3rd, 4th and 5th) and 1–1 in the bricks at the end of wall (1st and 7th brick). The test was repeated in different height providing possibility to take data from solid cross section and cross section with voids as well. Data was mapped using ArborSonic3D software for saving and downloading the travel times, calculating velocities, and plotting images of the tested cross section based on the velocities.

2.5. Standard compressive strength tests

2.5.1. Compressive strength of mortar. The compressive strength test was performed for each sample depending on the moisture condition (air-dry and wet), using the Sercomp 7 multi-functional testing machine. The compressive strength of the samples was calculated using the standard EN 1015-11 [15], by dividing the ultimate compressive force with the loaded surface area.

2.5.2. Compressive strength of brick. The compressive strength test was carried out according to standard EN 772-1:2011+A1:2015 [16]. For this purpose, every brick was covered with a thin mortar layer on top and bottom to reduce inaccurate load distribution during testing. The compressive strength can be calculated by dividing the ultimate compressive force by the loaded surface area and multiplying with size factor.

3. RESULTS AND DISCUSSION

3.1. Non-destructive tests

3.1.1. Sonic test. Before performing the compressive strength tests, sonic testing was carried out on the mortar joints of the masonry samples (mentioned in section 2.4.1). Table 2 presents the measured sonic velocities in each mortar type depending on the actual normal stress on the sample for air-dry condition.

The data shows that the sonic velocities of all mortar types increased in the preloaded condition for air-dry samples. This indicates that preloading has a positive effect on velocity. When comparing different mortar types, mortar type AH exhibits the highest velocities under both non-loaded and preloaded conditions. This suggests that mortar type AH has a higher compressive strength compared to other mortar types BH and FH. The average sonic velocity

Table 2. Sonic velocities of the tested mortar joints for normal stress, air-dry condition

Mortar type	Non-loaded, 0 MPa, (m s^{-1})	Preloaded, ~0.44 MPa, (m s^{-1})
AH	961.3	1,237.8
BH	692.9	1,041.2
FH	832.3	1,148.8

value increased by 28.7%, 50.2% and 38.0% for AH, BH and FH respectively.

The same results are listed in Table 3 for the saturated condition.

The sonic velocities of all mortar types increased in preloaded condition when saturated. In this case, it is not so obvious which mortar type has the strongest compressive strength, indicating that moisture increases the uncertainty for estimating the compressive strength based on sonic velocity.

The results of the sonic testing of bricks are listed in Table 4.

In this case, the velocities decreased by around 10% when moisture was increased. The coefficient of variation is very similar in both cases.

The effect of mortar joints on the velocity of sonic waves was tested according to section 3.1.1, the results are presented in Table 5.

Horizontal section views made by the ArborSonic3D software are shown in Figs 3 and 4. Figure 3 shows non-solid section with two voids with dimensions of 15 × 15 cm. The images taken from the sonic device provide helpful information about the location and size of both the voids (black zones where the sonic velocities are low) and the solid parts (white zones where the sonic velocities are high), which can be easily identified. However, in Fig. 4 the black circle in the middle of the solid cross section is not a real void, but is a plotting bug caused by the phenomena of wave velocity changes within a heterogeneous material. The vertical joints were made using BH mortar that has different material properties from the brick, meaning the sonic velocity is reduced every time the wave crosses a joint (as presented in Table 5). The inclined wave path (which crosses six joints) has a lower velocity than the others, which is shown as a black circle plotted in the middle of cross section. In Table 6 the velocity changes are presented depending on the number of crossed joints.

Table 3. Sonic velocities of the tested mortar joints for normal stress, saturated condition

Mortar type	Non-loaded, 0 MPa, (m s^{-1})	Preloaded, ~0.44 MPa, (m s^{-1})
AH	907.0	1,162.7
BH	881.8	1,152.4
FH	791.6	1,364.9

Table 4. Sonic velocities of the tested brick samples in air-dry and wet condition

	Air-dry velocity (m s^{-1})	Wet velocity (m s^{-1})
Average value	2,201.100	1,971.600
Standard deviation	362.900	307.600
Coefficient of variation	0.165	0.156

Table 5. Sonic velocities depending on the number of mortar joints

Mortar type	Velocity in case of 1 joint (m s^{-1})	Velocity in case of 2 joints (m s^{-1})	Velocity change (%)
FH	694.4 (0.116)	526.8 (0.098)	24.1
AH	644.5 (0.100)	589.8 (0.080)	8.5
BH	597.8 (0.160)	484.8 (0.120)	23.3

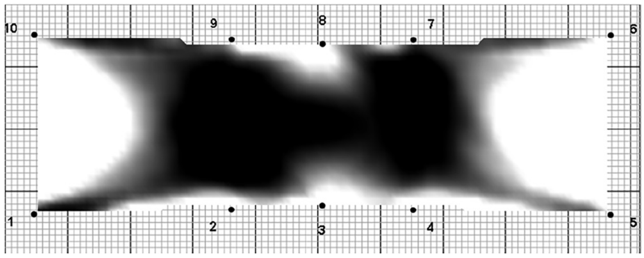

Fig. 3. Section view of the masonry wall plotted using ArborSonic3D (non-solid section)

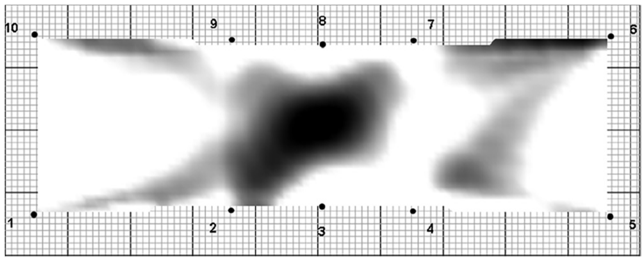

Fig. 4. Section view of the masonry wall plotted using ArborSonic3D (solid section)

Table 6 shows that the sonic velocity of the brick is very close to the value that was presented in Table 5, indicating that the mechanical properties of the bricks in the wall should be similar to the bricks that were tested independently. The velocity loss after each joint is around 20%, so similar to that shown in Table 6. This decrease in velocity allows us to write a logarithmic equation, as it is shown in Fig. 5.

The correlation with Fig. 3 is more than 0.968, which means that there is nothing in the cross section, which causes velocity loss except the mortar joints, so the cross section is solid. The correlation for the non-solid cross section is only 0.639 what is a significant difference. The curves are crossing each other in one point because there is a solid section between the voids.

3.2. Compressive strength tests

Based on section 2.4 the tests were carried out and the results were calculated. Tables 7 and 8 show the results of the calculated compressive strength values of the tested samples with different moisture level. The results of the compressive strength values of the different mortar types were published in [5].

According to the test, there is a strong connection between moisture and compressive strength of the tested samples. For mortars, there was a strength decrease 42, 19 and 15% for FH, AH and BH respectively and for bricks it was 20%.

Table 6. Sonic velocities depending on the number of crossed joints

Number of crossed joints	0	1	2	3	4
Average of sonic velocity (m s^{-1})	2,250.0	1,643.5	1,261.2	1,146.0	1,070.5

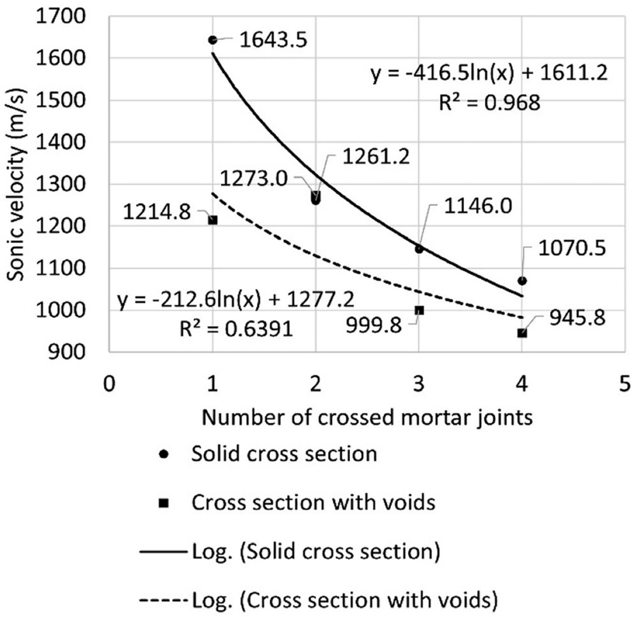

Fig. 5. Sonic velocities depending on the number of crossed joints

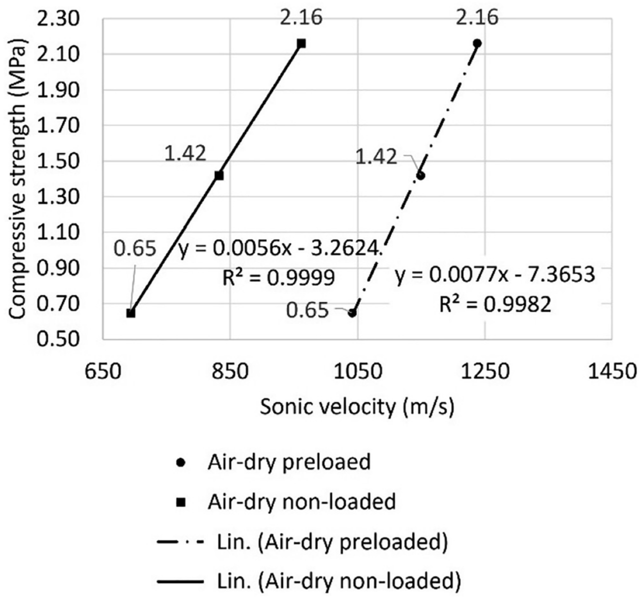

Fig. 6. Correlation between sonic velocity and compressive strength of mortars in air-dry condition

Table 7. Compressive strength of the tested mortar samples under air-dry and wet conditions (in brackets the Coefficient of Variation (CoV)) [5]

Mortar type	Average air-dry strength (MPa)	Average -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. Compressive strength of the tested brick samples under air-dry and wet conditions [5]

Property	Air-dry	Wet
Average strength [MPa]	12.6	10.1
Standard Deviation [MPa]	0.91	1.53
CoV	0.07	0.15

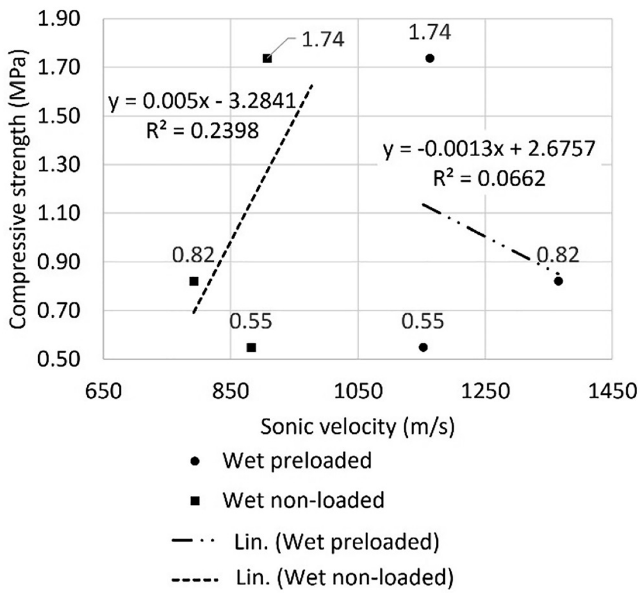

Fig. 7. Correlation between sonic velocity and compressive strength of mortars in wet condition

3.3. Relation between compressive strength and sonic velocity

The results of the mortar test are presented in Figs 6 and 7, where air-dry and wet mortar strength is compared with sonic velocity values for non-loaded and preloaded conditions.

Figure 6 shows that the correlations for both air-dry conditions are almost perfect (R^2 is 0.999 and 0.998 respectively), at the same time the correlations for wet results can be considered as weak (for both non-loaded and loaded) see in Fig. 7. Especially in the wet preloaded case ($R^2 = 0.066$). it can be seen, that there is a reverse relation between sonic velocity and compressive strength which is not realistic. Due to the small number of samples for this analysis, the correlation values should be considered approximate results.

The results of the correlation analysis for brick are presented in Figs 8 and 9. The correlation in case of preloaded condition for air-dry samples is very good (more than 0.99),

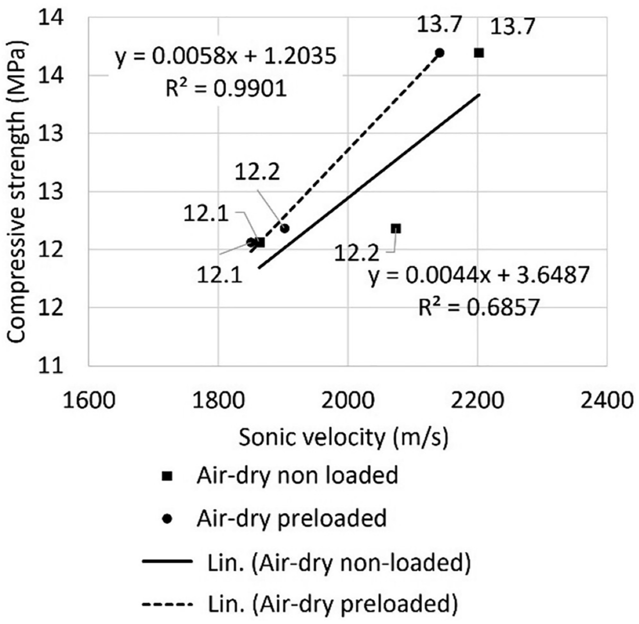

Fig. 8. Correlation between compressive strength of bricks and sonic velocities, air-dry condition

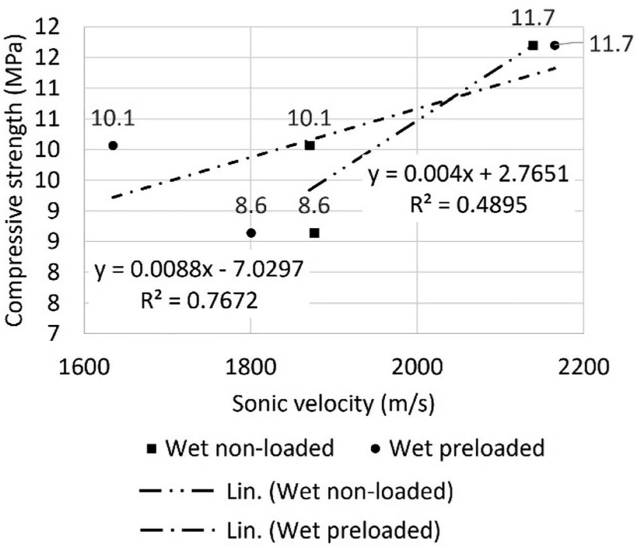

Fig. 9. Correlation between compressive strength of bricks and sonic velocities, wet condition

but with the wet samples this value is much lower at 0.49, at the same time the correlations for non-loaded condition for both air-dry and wet can be considered weaker (0.68 and 0.77).

4. CONCLUSION

In this paper, the applicability of sonic testing was examined for historical masonry structures. One of the main objectives of the paper was to investigate the relationship between the compressive strength of masonry elements and the propagation velocity of sonic waves. For this purpose, a testing program was carried out, testing the mortar and brick alone, and a masonry wall.

Previously, it has been documented that there is a strong connection between the moisture of the tested material and the propagation velocity of sonic waves. In the experiments, this phenomenon was studied concerning compressive strength. Based on the results, the compressive strength of the tested materials can be determined by knowing the velocity of the sound waves and the moisture content. The tests showed that moisture reduces the strength of masonry elements while increasing the velocity of sound waves.

Another important objective was to establish the applicability of sonic testing for non-homogeneous materials like masonry. Mortar joints made from different materials have different properties from the bricks, causing a decrease in wave velocity at each joint. The decrease in velocity varies depending on the number of joints, and a good correlation can be described with a mathematical equation, in the case of solid sections, while the relationship is significantly weaker for sections with voids.

The third aspect considered was the effect of compressive stress on wave velocity. The tests on mortar samples clearly demonstrated that under load, the mortar exhibited a higher wave velocity compared to its unloaded state.

This study illustrates that sonic testing could be useful for determining the compressive strength of masonry structures, determining solid parts and locating voids. The velocity of sound waves is clearly influenced by the moisture and compressive stress of the tested material, and further investigations are needed to gain a more precise understanding and mathematical description of these factors.

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