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Development of a New Nondestructive Method for the In-Situ Determination of Mortar Strength

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Abstract: The determination of the load bearing capacity of masonry in existing structures is not an easy task, even for experienced surveyors. For its assessment, it is necessary to know the compressive strength of the masonry units and mortar. Relatively good destructive and non-destructive methods were developed for the determination of the compressive strength of masonry units. However, mortar compressive strength determination is currently closer to a rough estimation rather than a deterministic approach. All of the currently used methods are either complicated, have a limited application, or are based on the surveyor's experience only. Influence of the human factor on the results of testing is significant. The paper introduces the development of a new non-destructive method, which eliminates the influence of the human factor. The method is supposed to work as quickly and as easily as the Schmidt hammer used for concrete structure surveys. The new instrument was created where the compressive strength of mortar is assessed by hammering a steel bar into a joint with constant energy, while the depth of penetration is measured. The impact energy is provided by a steel spring with a prescribed stiffness, and the loading is provided by an automatic system similar to those used in air-soft guns.

Keywords: mortar; non-destructive testing (NDT); indenter; in-situ; masonry; compressive strength; penetrometer; development; low-strength mortars; innovative

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1. Introduction

The load bearing capacity of masonry depends on the compressive strength of the masonry units, the mortar and their interaction. According to EN 1996-1-1+A1:2012 [1], the characteristic value of the masonry's compressive strength is determined using the following equation:

$$f_k = K \times f_b^{\alpha} \times f_m^{\beta} \tag{1}$$

where f_m is the mortar compressive strength, f_b is the unit compressive strength and K is the material coefficient.

There are relatively good destructive and non-destructive methods for the determination of a masonry unit's compressive strength in existing structures. Nevertheless, in the case of mortar compressive strength, the determination methods are currently closer to a rough estimation, rather than a deterministic approach. The most accurate and also the most used method in Czechia is the drilling method using the "Kučera's drill". This method was designed for mortars with a compressive strength between 1 and 5.2 MPa [2]. However, the greatest effect of mortar strength on the masonry bearing capacity is right between 0.1 and 1 MPa. Figure 1 shows the dependency of the characteristic value of the masonry's compressive strength on the mortar strength, according to Equation (1). The parameters K and f_b, used in the equations were set to 0.55 and 18.5 MPa, respectively. Only f_m was considered as a variable parameter from 0 to 15 MPa. Similar experimental studies were carried out by D. Kasten, in 1994 [3] and A. Costigan, in 2013 [4], where the influence of the mortar properties on the masonry strength was studied.

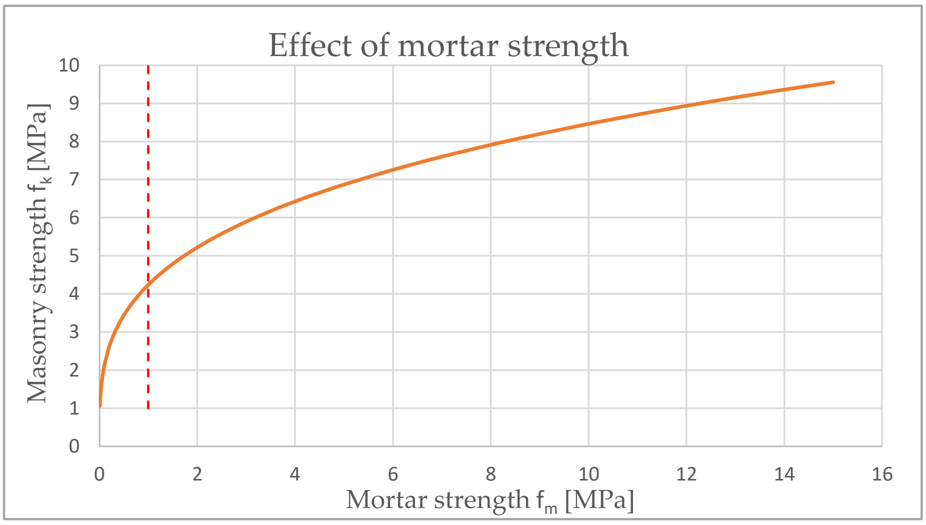


Figure 1. Effect of the mortar strength on the masonry load-bearing capacity according to Equation (1) [1]. Red dashed line highlights the level of compressive strength of 1 MPa.

All of the diagnostic methods currently used in the world, are suitable for mortars with a strength exceeding 1 MPa, and their application is very technically complicated or limited. The first example is the "screw pull-out test" introduced by W.A. Ferguson [5], where a steel helical screw is pulled out from a bed joint by a loading device and the loading force is measured. The procedure is quite complicated and the final result is a shear strength, instead of compressive strength. The second method is the "Windsor pin penetration test" (PPT) [6]. Where a steel pin is penetrated into a bed joint, the depth of penetration is measured and the strength is estimated. This method is limited only to measure the surface and it is quite time-consuming. Another drilling method was introduced by N. Gucci in 1989. The device used in this method is called the "PNT-G" and it measures the amount of energy required to drill a 5 mm deep cavity [7]. It has a good calibration curve and the deviation of the method is very low. However, it can measure only the surface so any deeper measuring in the bed joint is not possible. Furthermore, R. Nogueira, A. Silva and E. Del Monte are focused on the drilling methods, their applications in the diagnostics of buildings and their statistical evaluations [8–10]. A further method is the "torque penetrometric test" (TPT) introduced by D. Marastoni, where the original steel nail with specially shaped teeth is placed in the bed joint and the torque resistance is measured by a dynamometric torque wrench [11]. The compressive strength is determined from the empirical correlation and its range is from 0.34 MPa to 8.55 MPa. However, there is an issue of nail diameter. The most common thickness of the joint is 10 mm and the diameter of the used nail is 9 mm. Finally, the "modified Schmidt hammer" is a method introduced by R. Schmiedmayer in 1997 [12], in which a special plate is placed on the bolt of the hammer and the depth of the penetration is measured. A big disadvantage with this method is the size of the plate. It cannot be driven deeper than 10 mm into the joint.

Furthermore, some penetrometric methods were developed. A team from Italy introduced the "static penetration test" in 2016. Here, a pin is driven into the joint at a constant velocity by a stepper motor controlled by a computer and the test result is the penetration load, as a function of the penetration depth [13]. This solution could provide sufficient data but it is technically demanding, time-consuming and a little bit bulky. Another Italian device was used by D. Łatka and P. Matysek in Poland [14]. The penetrometer RSM-15 is another device, based on the Schmidt hammer where a steel needle is penetrated into the joint [15].

That is the reason why a new method is needed. The new method should be focused on mortars with the lowest compressive strength. It should specify the calculation of historical masonry structures and it can provide greater possibilities for the renovation and expansion of historical buildings.

This article introduces a new diagnostic device, which assesses the compressive strength of mortar, by penetrating a steel bar into a bed joint, while the depth of the penetration is measured. The measurement is not affected by any human factor in any way, and it should be very easy to use, as the Schmidt hammer is for concrete structures.

2. Design and Development of the New Indentation Test Equipment

The new method is based on an archaic method, where a steel bar is penetrated into a bed joint by a hammer and the number of blows needed for a penetration of 5 mm is counted. A penetration depth of 5 mm was found as the most suitable for the determination of compressive strength by the large experiences. The principles of the proposed NDT are similar but the human factor is minimized. A steel spring with a defined stiffness is used instead of a hand hammer. The energy of one blow is defined by spring stiffness k and its deformation y. The potential energy is calculated by the following equation:

$$E_p = \frac{1}{2}ky^2. \tag{2}$$

There is no need to hand load for each blow, that is provided by the automatic loading system used in modern air-soft guns. The mechanism uses an electric motor and gear set with a drive ratio of 18:1. The spring is deformed by y = 62 mm before one blow and the stiffness of the spring is k = 687 N/m. It corresponds to a potential energy of E_p = 1.32 J.

The system was designed for use in the M4 air-soft gun. The gun was purchased and then was completely dismounted, and all parts were measured in detail. The system shown in Figure 2 was designed to fit the measured geometry. The bearing core (5) was fixed onto the metal body of the gun (11) by a bearing nut. The steel indenter (4) moves in the bearing core, following the guide groove. The indenter has a removable spike with a diameter of 4 mm, which is penetrated into the bed joint of masonry. There are many spike lengths for different penetration options. The blow is secured with a steel hammer (2) with a weight of 31.4 g, which is stored in the piston's tube (1). The piston with a hammer is moved by a spring (15) until it bumps into the cylinder (3), where the piston is stopped and only the hammer continues until it crashes into the indenter. The spike of the indenter penetrated the masonry. In order to minimize the human factor in the measuring process, a support system was designed. The support (7) with the plate (14) in the front is secure so that the pressure of the surveyor does not affect the results. The depth of the penetration is measured by a sliding scale placed on the right-hand side of the penetrometer. The scale is connected to the indenter.

The construction of the device allows for a quick and easy replacement of the spring. As the spring guide (9) is placed in the back of the penetrometer, it can be easily removed, and the spring can be replaced by another with varying stiffness. The stiffness of the spring is the main parameter of the mechanism. The proposed potential energy of E_p = 1.32 J is determined for mortar with a compressive strength in the 0–5 MPa interval. However, the use of a stiffer spring could potentially be used to measure stronger mortar.

All original parts were created by CNC Machines, according to the project documentation. A surface treatment system was designed to minimize friction. The components were assembled and the penetrometer testing began. Figure 3 shows the final functional sample of the device and its testing during a structural survey. Testing showed a very simple applicability and long battery durability. The device uses the original NiMh battery supplied with the M4 air-soft gun. The battery has a voltage of 8.4 V and a capacity of 1600 mAh. One full battery cycle is enough for more than 800 blows. The testing process is described step by step in Section 2.1.

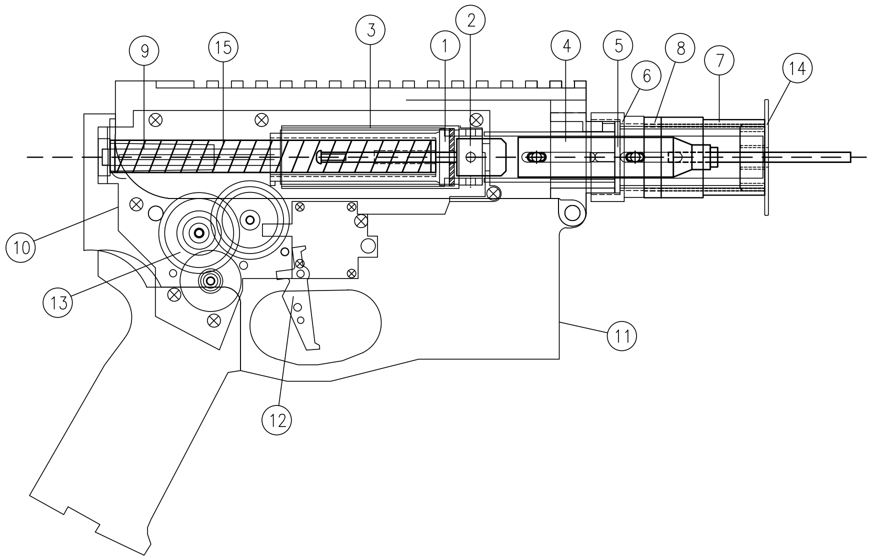
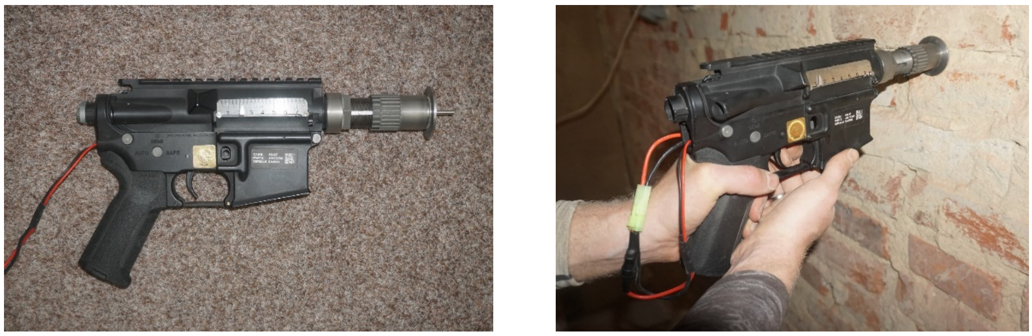


Figure 2. Composition of the proposed device. It consists of the mechanical box of an air-soft gun and additional parts designed for diagnostic purposes. 1—piston; 2—hammer; 3—cylinder; 4—indenter; 5—bearing core; 6—bearing nut; 7—support; 8—arrest nut; 9—spring guide; 10—gearbox; 11—M4 metal body; 12—trigger; 13—gear set; 14—support plate; 15—spring.



(**a**) (**b**)

Figure 3. Pictures of the penetrometer: (**a**) functional sample before testing (**b**) testing of the penetrometer during the structural survey.

2.1. Description of the Testing Process

1. Expose the masonry from the plaster;
2. Scratch the plaster from the bed joint (20 mm);
3. Put the indenter into the bed joint;
4. Screw by support system until the support plate touches the masonry;
5. Set the position to zero on the sliding scale;
6. Press the trigger and penetration begins;
7. Count the number of blows needed for a penetration of 5 mm;
8. Write down the value of one measurement;
9. Set position on the sliding scale to zero and repeat the measurement in the same position (it will provide data from different depths of the joint);
10. Compare the measured values with the calibration relation;
11. Cancel the outliers (for example, using Grubbs' test).

3. Materials and Methods

Validation and testing of the new method were proposed on small piers sized 450 $\times$ 450 mm^2, built from bricks and general-purpose masonry mortar with different compressive strengths.

Initially, the tests were supposed to be focused on mortars with a lower strength than 5 MPa. Many mortar specimens were created and destructively tested according to ČSN EN 1015-11:2020 before the piers were built, and five appropriate mixtures were selected to build ten piers for testing. The mixtures were equally spaced between strengths 0–5 MPa to capture good calibration results. The specimens consist of mortars lime-cement (MLC), lime mortars (ML), and one specimen was created from sand mortar (sand) without any binder. Unfortunately, the absorption effect was underestimated during the mixture selection, which resulted in a significantly higher mortar strength after laying. This effect was described in many publications, e.g., [3,16–18], but in this experiment, it was twice as high. The absorption effect was captured by two types of devices. In the first, the absorption effect was captured in a steel mold (SM) and in the second, the absorption effect was captured in a mold with a brick at the bottom, instead of steel (BM). The results drew comparisons between the standardized method and the specimens laid on the brick, as shown in Figure 4. There is a visible impact of the absorption effect which is more than 100% in a few samples.

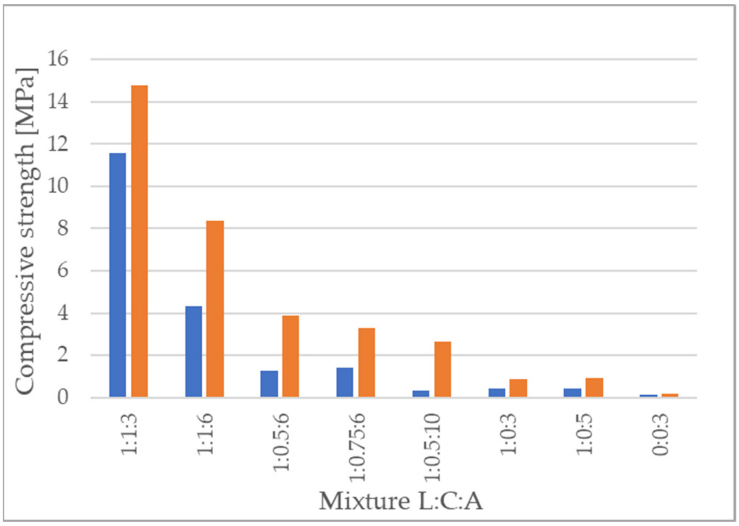


Figure 4. Influence of the absorption effect. Blue values were obtained from the specimens laid in the steel mold and the orange values were influenced by the absorption effect of the bricks.

Mortars used for the final validation are summed in Table 1 together with the mixture ratio, density and compressive strengths of the mortar laid by the two methods.

Table 1. Table of the mortar mixtures and the compressive strength used for the experiments.

Mortar Type	Mixture L:C:A	Density [kg/m^3]	Compressive Strength SM [MPa]	Compressive Strength BM [MPa]
MLC-1	1:1:3	1833	11.59	14.77
MLC-2	1:1:6	1828	4.34	8.35
MLC-3	1:0.5:6	1770	1.28	3.89
ML-4	1:0:3	1658	0.45	0.85
Sand-5	0:0:3	1495	0.16	0.17

From the mortars summed up in Table 1, five pairs of pillars shown in Figure 5, were created. The pillars had a square cross-section of 450 × 450 mm^2 and the height was 600 mm. All of the pillars were built from solid fired-clay CP 20 bricks with nominal dimensions of 290 × 140 × 65 mm^3. Each pillar has its own mortar mixture and for each mixture, two types of specimens (one laid in a steel mold and one laid in the brick mold) were created. These specimens were destructively tested for comparisons with NDTs. Many non-destructive tests were carried out on each pillar. More than 800 tests with the automatic penetrometer were performed to create a statistical database for the possible calibration.

(**a**) (**b**)

Figure 5. Pictures of the samples: (**a**) all 10 pillar samples; (**b**) sample 5A placed in a loading device during the experiments.

4. Validation Results and Discussion

The validation system consisted of mortar compressive strengths tested using a destructive method and the results were compared with those from the NDTs. Each result value corresponded to one testing place in the bed joint of the masonry, where two to ten 5 mm penetration values were obtained. The number of penetrations depended on the bed joint quality. In some testing places, the spike was driven into a gap in the bed joint and the test was terminated. The optimal penetration depth is half of the pillar's thickness, but the actual length of the indenter allows for only a 50 mm penetration (10 measurements). Further testing would be possible after the spike replacement. Each bed joint was tested from all four sides and each bed joint was tested in one to three places.

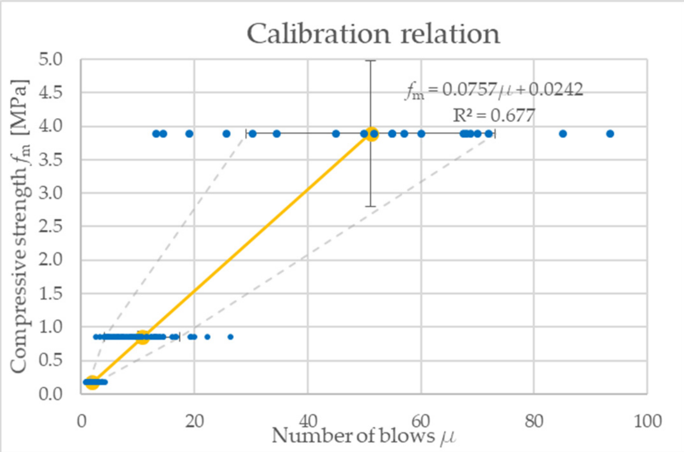
Then, each testing place was averaged into one value and this value was compared with the results from the destructive method. Testing was carried out on piers with MLC-3, ML-4, and Sand-5 mortars. It was not possible to test the first two piers with the penetrometer due to the high compressive strength. For mortar strengths between 5 and 15 MPa, other drilling methods are more suitable.

Figure 6a shows the relation obtained from the results of three pairs of piers with different mortar strength averages. The first mortar had 0.17 MPa, the second pair had 0.85 MPa and the third had 3.89 MPa. There are signalized standard deviations for the number of blows needed for the 5 mm penetration and also for the mortar's compressive strength. The area of the standard deviation is bound by a dashed line. The middle orange line is a curve that was constructed by averaging the results obtained for each mortar type. The curve is almost linear and can be expressed by the following equation:

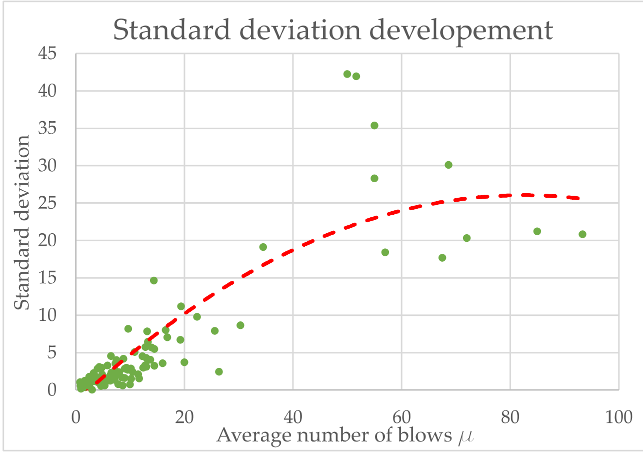
$$f_m = 0.0757\mu + 0.0242 \quad (3)$$

where f_m is the mortar compressive strength and μ is the number of blows needed for the penetration of 5 mm.

With the increasing compressive strength the deviation increases as well, the development of the standard deviation is shown in Figure 6b, where the average number of blows needed for a penetration of 5 mm, is compared to its standard deviation. A measure of dispersion is shown in Table 2. The deviation of the measurement is relatively high but it corresponds to the character of the material. Mortar is not a very compact material and there are many parameters that can influence the results. Examples of these parameters are the porosity of the material, different thicknesses in every joint, the grain size or the loading level. All of these parameters cause a high deviation of the NDT results. Therefore, many values are needed for the evaluation of a proposed method.



(**a**)



(**b**)

Figure 6. Final results: (**a**) calibration curve for the penetrometer, based on the experiments; (**b**) development of the standard deviation associated with the measured values.

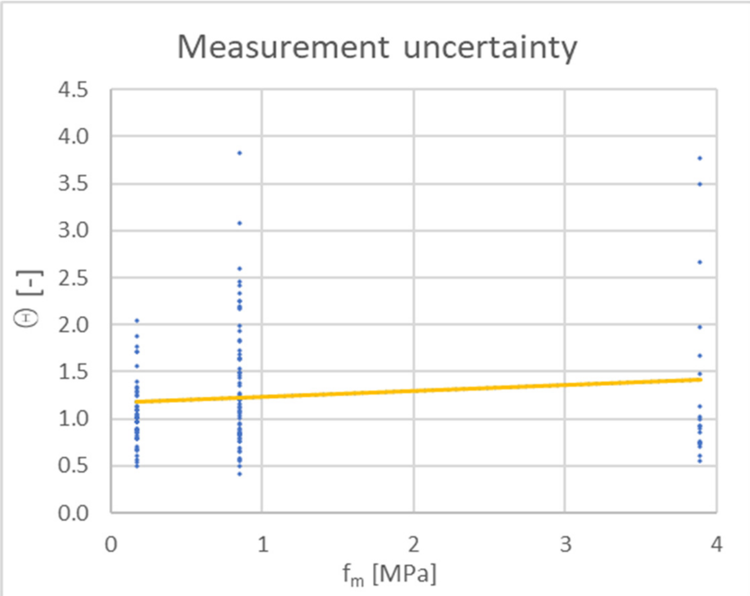
Table 2. Table of the standard deviation and coefficient of variation (CV) of the compressive strength measured by destructive testing and the number of blows μ from the NDT.

Mortar Type	**Compressive Strength BM** $f_{m,BM}$ **[MPa]**	**Standard Deviation** $\sigma_{fm,BM}$	**CV** $V_{fm,BM}$	**Average Number of Blows** μ **[-]**	**Standard Deviation** σ_μ	**CV** V_μ
Sand-5	0.171	0.066	0.386	2.058	0.734	0.357
ML-4	0.852	0.091	0.106	9.958	5.003	0.502
MLC-3	3.890	1.090	0.280	51.764	22.860	0.442

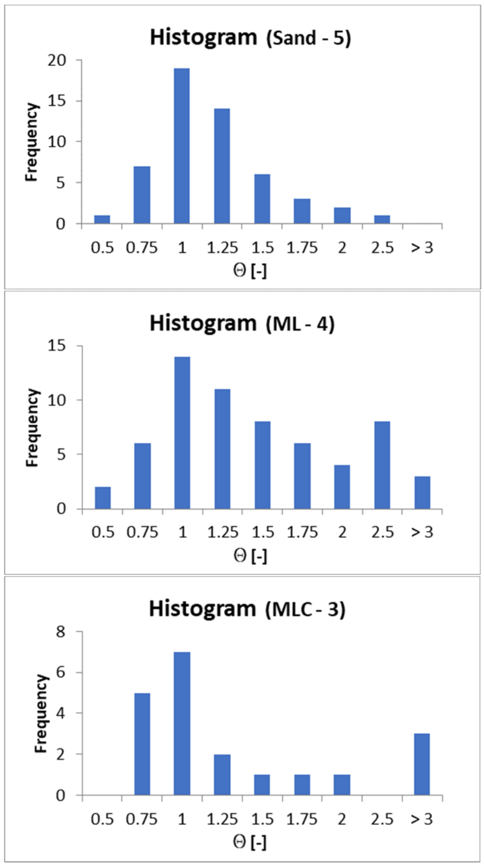
For Equation (3), the coefficient of determination R^2 = 0.677 was manually calculated and it was very low due to the high variations of the destructively determined mortar's compressive strength. Therefore, there was not possibility to separate the variability of the method and the variability of the basic material. The deviation of the measured results for each specimen is described in Figure 7a,b. It is characterized by uncertainty θ calculated as $\theta = f_{m,BM}/f_{m,NDT}$. The basic dispersion parameters of uncertainty are shown in Table 3. Compared to the other NDT methods mentioned in the introduction, the variability of the results is very high. The coefficient of determination (R^2) of R. Nogueira's drilling method, tested on the mortars, ranged 0.9–10.6 MPa, and it was stated as R^2 = 0.9 [8]. It the article of D. Łatka, describing another penetrometric method, R^2 was not mentioned but the differences between the DT and NDT measurements were from 4% to 27% [14].

However, a comparison of the measured results obtained from the mortars, ranged from 0.1 MPa to 3 MPa strength but the mortar ranging between 0.9 and 10 MPa in strength can be misleading. The coefficient of variability of the weaker mortars is usually significantly higher than the stronger mortars [8]. That influences the variability of a measured results.

The measurement was carried out by a prototype of a new device and there are many things that can be improved. First of all, the sliding scale could be replaced by an electric measuring device, which could lead to more accurate results. With more exact measurements there would be a possibility of an inverse evaluation, where the depth of penetration is measured for an exact number of blows (e.g., 10 blows). Further, the length of the spike should be raised, to increase the possibility of measurement at one testing place. The optimal depth of penetration should be 100 mm (20 measurements at one testing place). Lastly, the spring stiffness should be calibrated also for stronger mortars with a compressive strength higher than 5 MPa. These and many more options will be the object of a further research.



(a)



(b)

Figure 7. Measurement of the uncertainty: (**a**) All uncertainties of the results measured by penetrometer and the trend function; (**b**) Frequency of the NDT uncertainty for each mortar type.

Table 3. Dispersion parameters of the uncertainty obtained from the values of compressive strength, determined by NDT.

Mortar Type	Average Compressive Strength by NDT $f_{m,NDT}$ [MPa]	Average Uncertainty μ_θ	Standard Deviation σ_θ	CV V_θ
Sand-5	0.180	1.044	0.340	0.326
ML-4	0.778	0.778	0.379	0.487
MLC-3	3.943	1.333	0.942	0.707

The proposed solution is hard to compare with the destructive or semi-destructive methods, where part of the construction is determined by experiment [19]. However, during the evaluation of heritage buildings, there is usually no other possibility than using NDTs, with a combination of methods, with minimal impact on the structure [20,21]. It can provide data accurate enough for its evaluation. The deviation of the results is the big issue of NDTs and these compare with destructive methods as well. The presented measurement in the research has a higher deviation, compared to the other methods presented in the introduction. It was largely caused due to the character of the tested mortars. The weakest mortars are not very homogeneous and the results of the individual measurements can be very varied, compared to stronger mortars. There should be an established heterogeneity degree as Mr. R. Nogueira obtained in his study [8]. However, for clarification of the calibration curve, the additional measurements have to be obtained. The focus should be on the comparison of the results determined by NDT with those determined by DT, which were obtained from existing structures. Furthermore, a comparison with other methods should be carried out.

The next question is what can influence the NDT results. N. Huber described the effect of residual stress on indentation and hardness testing [22], which can significantly influence the measurement The conditions during the measurement taking for this research, were similar for each sample. However, during real surveys of unknown structures, the situation could be different. The joint thickness has an impact on the NDTs, as described by M. Drdácký [23]. There are many more parameters that can affect the measurements: grain size of the sand, humidity, and, last but not least, the quality of the joint filling. All of this can influence the NDT results, so an accurate determination of the mortar's compressive strength is very challenging, especially on the weakest mortars. Many publications compared different methods [24–26], but only a few of them enabled the evaluation of mortars with a strength under 1 MPa.

5. Conclusions

The study presents an innovative penetrometric device for the in-situ assessment of mortar's compressive strength in existing structures. It focused on the weakest mortars ranging 0.1–5 MPa. The proposed solution is based on the archaic method using a hand hammer, which is replaced by a modern electric device using the constant energy of the blow. The prototype of the device was tested on masonry samples with well-described parameters that were obtained by destructive testing. The calibration relation was derived from the comparison of $f_{m,NDT}$ to $f_{m,BM}$. The observed parameters of the method is the number of blows μ needed for the penetration into the bed joint of masonry, reaching the depth of 5 mm.

Three pairs of masonry samples used for calibration were built from the same type of bricks and the average compressive strengths of three different mortar types were 0.17 MPa, 0.85 MPa and 3.89 MPa. Each mortar type was non-destructively tested by the proposed penetrometer. On each mortar type, the tests were carried out on 20–60 testing places, which consist of 2–10 measurements on one testing position. The variability of the NDT results is significant. The coefficient of variation of the measured uncertainty reaches the values between 0.35 and 0.7, which are much higher than the values obtained by drilling or other methods. However, the difference is caused by the high variability of the basic material, which is in the range 0.106–0.386.

Although the measured results are not very accurate, it could still be used as a useful in-situ method for structural surveys. The proposed technique is suitable, especially for the weakest mortars because it is almost impossible to set its exact strength by common methods. This automatic penetrometer is very easy to use, it could save a lot of time during a structural survey and it helps to evaluate the strength of the weakest mortars, for which no other solution is available.

Further research will focused on improving the calibration relation and comparison of other methods through practical use. The penetrometer will be used during the structural surveys of existing structures and the results will be used for improving the calibration and its accuracy.

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Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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