Testing of physical and mechanical properties of bricks and mortar in historic structures

Bošnjak-Klečina, Mirjana; Lozančić, Silva

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TESTING OF PHYSICAL AND MECHANICAL PROPERTIES OF BRICKS AND MORTAR IN HISTORIC STRUCTURES

Mirjana Bošnjak-Klečina, Silva Lozančić

Preliminary notes

The requirement to determine the bearing capacity of older brick buildings is being raised more and more frequently. The problem is in defining of inbuilt materials properties. Familiarity with brick material used in their construction is insufficient for the approach to more accurate structural analysis. The biggest unknown is represented by those physical and mechanical properties of brick structures relevant for their bearing capacity against horizontal displacement and bending the compressive strength of mortar, adhesion strength of mortar against horizontal displacement and bending, the tensile strength of wall. These properties, in the function of brick porousness, are its initial capillary absorption and strength. The physical and mechanical properties of bricks from old sacral buildings were tested. At the same time, for the comparison purpose, nowadays materials have been tested too. The possibility and reliability of one method for the determination of the compressive strength of mortar "in situ" have been investigated. The method was proposed 30 years ago in Czechoslovakia, but it remained unknown to wider expert audience. The method is simple, quick and practical. It requires the preparation of very simple equipment for testing and calibration of a greater number of simple laboratory samples and it might be applicable in construction site conditions afterwards.

Keywords: *brick, compressive strength "in situ", mortar*

Ispitivanje fizikalno-mehaničkih svojstava opeke i morta povijesnih građevina

Prethodno priopćenje

Kod starih zidanih građevina sve se češće postavlja zahtjev za utvrđivanjem njihove nosivosti. Problem je u definiranju karakteristika materijala koji je u njih ugrađen. Poznavanje opečnog materijala od kojeg su one izgrađene nedovoljan je za pristup točnijoj proračunskoj analizi. Najveću nepoznanicu predstavljaju ona fizikalno-mehanička svojstva ziđa koja su bitna za određivanje njegove nosivosti na posmik i na savijanje: tlačna čvrstoća morta, čvrstoća prionjivosti morta i opeke pri posmiku i savijanju, vlačna čvrstoća zida. Ta svojstva nadalje su funkcija poroznosti opeke, njezinog početnog kapilarnog upijanja i čvrstoće. Ispitana su fizikalno-mehanička svojstva opeke iz starih sakralnih građevina. Istodobno je radi usporedbe izvršeno ispitivanje na današnjim materijalima. Istražena je mogućnost primjene i vjerodostojnost jedne metode za utvrđivanje tlačne čvrstoće morta "in situ" (predložena je prije 30 godina u Čehoslovačkoj, a ostala je i u širim stručnim krugovima nepoznata). Metoda je jednostavna, brza i praktična, zahtijeva izradu vrlo jednostavne opreme za ispitivanje i kalibraciju na većem broju jednostavnih laboratorijskih uzoraka, nakon čega bi mogla biti primjenljiva u gradilišnim uvjetima.

Ključne riječi: *mort, opeka, tlačna čvrstoća "in situ"*

1 Introduction
Uvod

The need for reconstruction or alteration of specific purpose of brick structures imposed the requirement to test their bearing capacities. The problem with old brick buildings is especially in the defining of the inbuilt materials' properties. Knowing of brick material used in their construction is insufficient for the approach to more accurate structural analysis.

The biggest unknown is represented by those physical and mechanical properties of brickwork relevant to determine its bearing capacity against horizontal displacement and bending strength: the compressive strength of mortar, adhesion strength of mortar and brick against shear and bending, the tensile strength of wall [1]. These properties are further the function of brick's porosity, its initial capillary adsorption and strength.

In order to provide required experimental data, the physical and mechanical properties of bricks from old sacral buildings were tested. Therefore, the required number of samples had been taken from the buildings. For the purpose of comparison, nowadays materials were tested at the same time [2].

The application and reliability of a method [3], completely unknown in our country were investigated too. The method is almost completely non-destructive, it determines the compressive strength of mortar on the spot – "in situ", it was proposed in Czechoslovakia thirty years ago, but it has remained unknown among the wider expert audience. The method is simple, quick and practical; it might have a wide application in the quality assessment of old brick structures. It requires preparation of very simple equipment for testing and calibration of bigger number of laboratory samples and afterwards it could be applicable under construction site conditions.

2 Testing of the brick and mortar properties determined by European standards
Istraživanje svojstava opeke i morta određenih europskim normama

2.1 Testing of the brick properties determined by the European standards
Istraživanje svojstava opeke određenih europskim normama

Under the present research, testing of old and new brick material was carried out in the laboratories of The Institute for Civil Engineering of Croatia, PC Osijek.

The testing has been carried out in accordance with the valid European standards. The samples of old bricks have been taken from three locations: St. Michael's church in Osijek, St. Philip and Jacob's church in Vukovar and Eltz's manor house in Vukovar. The bricks were made in 18th century, most likely in brickyards near the mentioned structures. The samples are shown in Fig. 1. The new brick is solid masonry unit manufactured in a modern Slavonian brickyard. Each testing has been carried out on one sample (according to the standard, one sample represents six bricks at least).

Figure 1 *Tested brick samples*
Slika 1. *Uzorci ispitanih opeka*

Table 1 *Mean values of the bricks' dimensions*
Tablica 1. *Srednje vrijednosti dimenzija opeka*

The marking of building	Length, mm	Width, mm	Height, mm
St. Philip and Jacob's Ch (1)	318	163	81
St. Michael's Church (2)	329,8	163,6	76,7
Eltz's manor house (3)	296,8	141,6	63,3
New brick (4)	251,3	119,7	62,5

Bricks' dimensions. The dimensions of bricks have been determined by measurement according to the norm [4]. Measured were the length, width and height of brick. Here are shown their mean values. Test results are shown in Tab. 1.

Initial capillary water absorption coefficient. The initial capillary water absorption coefficient of the brick wall elements is expressed in kg/m^2·min, as determined by the norm [5]. The quantity of water to be measured is the one absorbed by the brick within the period of 60 seconds. Only the brick's surface that is to be laid into mortar should be sunk into the water. The test results are shown in Tab. 2.

Water absorption. The water absorption is determined by the procedure prescribed by the norm [6]. This test is conducted by sinking of the whole brick into water up to full saturation. The quantity of water absorbed by the brick within 24 hours is measured. The test results are shown in Tab. 3.

The percentage of pores. The percentage of pores in brick elements is determined by the procedure prescribed by the norm [7]. The percentage of pores portion of the brick element is the quotient of the difference between gross and net volume and gross volume. The test results are shown in Tab. 4.

Compressive strength. The compressive strength of brick elements has been tested by gradual increase of the compressive force up to the failure of sample, according to the procedure described in the norm [8]. The tests were performed on a sample made by joining two halves of the same brick. The test is shown in Figures 2 and 3. Results of tests are shown in Tab. 5.

Table 2 *The coefficient of initial capillary water absorption C,* kg/(m^2·min)
Tablica 2. *Koeficijent početnog kapilarnog upijanja vode C,* kg/(m^2·min)

Sample Building	1	2	3	4	5	6	Mean value
St. Philip and Jacob's Ch (1)	2,3	2,3	2,6	2,7	2,2	2,2	2,4
St. Michael's Church (2)	4,7	4,9	5,3	3,7	4,9	5,7	4,9
Eltz's manor house (3)	6,1	4,4	5,1	6,2	5,6	4,3	5,3
New brick (4)	4,8	5,3	5,3	5,4	4,9	--	5,1

Table 3 *Water absorption percentage u,* %
Tablica 3. *Postotak upijanja vode u,* %

Sample Building	1	2	3	4	5	6	Mean value
St. Philip and Jacob's Ch (1)	22,83	19,15	19,04	21,45	21,32	22,3	21,02
St. Michael's Church (2)	24,02	17,22	24,43	24	21,78	19,74	21,87
Eltz's manor house (3)	19,41	20,26	23,23	18,95	22,73	21,42	21
New brick (4)	18,20	18,10	16,03	17,40	17,90	--	17,53

Table 4 *Porosity percentage,* %
Tablica 4. *Postotak šupljina,* %

Sample Building	1	2	3	4	5	6	Mean value
St. Philip and Jacob's Ch (1)	11	7	9	4	6	10	8
St. Michael's Church (2)	7	11	13	14	12	7	10
Eltz's manor house (3)	5	7	7	5	5	5	6
New brick (4)	4,5	4,3	4,1	4,9	4,5	--	4,5

Table 5 *Compressive strength* f, MPa
Tablica 5. *Tlačna čvrstoća* f, MPa

Sample Building	1	2	3	4	5	6	Mean value
St. Philip and Jacob's Ch (1)	11,34	14,38	11,18	10,94	12,26	9,59	11,45
St. Michael's Church (2)	13,42	27,1	13,81	6,3	19,33	23,2	17,2
Eltz's manor house (3)	30,96	16,82	18,44	34,99	28,03	24,11	25,56
New brick (4)	27,8	28,4	30,2	28,2	31,0	--	29,12

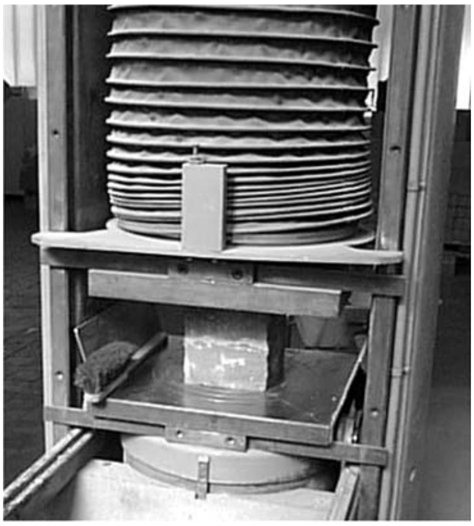

Figure 2 *The brick before failure*
Slika 2. *Opeka prije sloma*

Figure 3 *Compression failure of the brick*
Slika 3. *Tlačni slom opeke*

2.2 Testing of the mortar properties determined by the European standards

Istraživanje svojstava morta određenih europskim normama

The old mortar samples were taken from the 18th century structure located at the Tvrdja in Osijek, built at the same time and with the same material as the observed structures. Because of the difficulties connected with finding the right undisturbed samples the scope of investigation has been limited. The samples were obtained by removing the mortar from the existing building.

Testing has been done according to the European standards [9].

The samples are presented in Figures 4 and 5.

Figure 4 *The samples removed from the building*
Slika 4*. Uzorci izvađeni iz građevine*

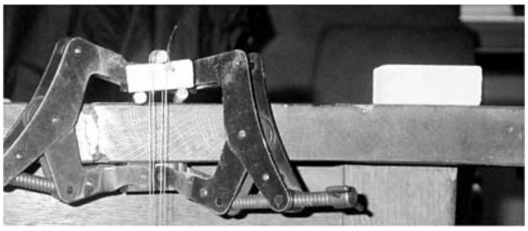

Figure 5 *Samples prepared for testing*
Slika 5*. Uzorci pripremljeni za ispitivanje*

Mortar compressive strength. The compressive strength of mortar has been performed by gradual increase of the compressive force up to the sample failure, as outlined in the corresponding Norm [9].

The measured results are presented in Tab. 6.

Table 6 *The compressive strength* f_{m}, MPa
Tablica 6. *Tlačna čvrstoća* f_{m}, MPa

Sample	1	2	3	Mean value
Compressive strength	0,58	0,52	0,53	0,54

Mortar flexural strength. The flexural strength of mortar samples has been determined by gradual increase of the compressive force up to the sample failure, according to the procedure described in Norm [9]. Results of the tests are presented in the Tab. 7.

Table 7 *The flexural strength* f_{mr}, MPa
Tablica 7. *Čvrstoća na savijanje* f_{mr}, MPa

Sample	1	2	3	Mean value
Flexural strength	0,40	0,38	0,44	0,41

3 The analysis of results
Analiza rezultata

The Brick. For the purpose of easier reference, the following marking is introduced in the drawings bellow: **1** – the brick from Philip and Jacob's Church, **2** – the brick from St. Michael's Church, **3** – the brick from the Eltz's manor house, **4** – the new brick.

The bricks' dimensions. The old brick of the smallest size under present research comes from the Eltz's manor house in Vukovar. Its dimensions (the mean value) compared to nowadays size are 18 % longer and wider, and 2 % taller.

The biggest deviations from the mean value for one sample of old brick are within 6 %. The biggest deviations from the mean value for new brick samples are within 1 %. Fig. 6 indicates the mean value of the brick's dimensions for each tested sample.

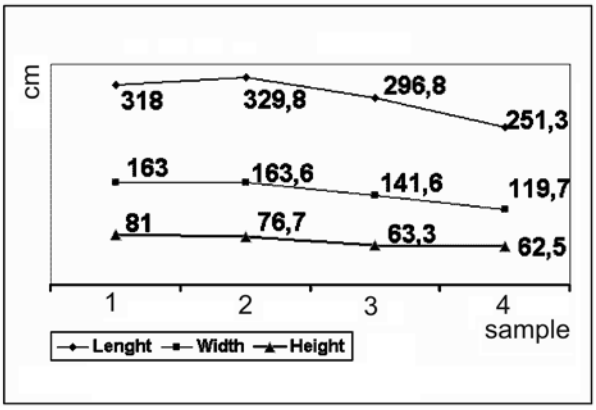

Figure 6 Bricks' dimensions, the mean values
Slika 6. Dimenzije opeka, srednje vrijednosti

The coefficient of initial capillary water absorption. The obtained mean value of the coefficient of initial capillary water absorption for new brick is by 112 % higher than for the brick from the building No. 1; by 4 % higher compared to the results from the building No. 2, and compared to the building No. 3 it is 4 % lower. The highest deviations from the mean value among the old brick samples are up to 12,5 % for the first building, up to 25 % for the second and up to 19 % for the third one. The highest deviations from the mean value among new brick samples are up to 6 %. Fig. 7 indicates the mean value of the initial capillary water absorption coefficient for each tested sample.

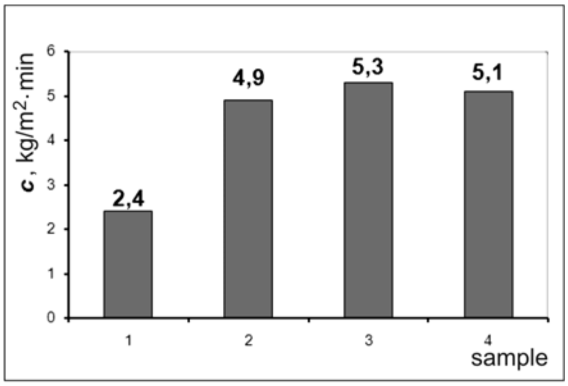

Figure 7 The coefficient of initial capillary water absorption, mean values
Slika 7. Koeficijent početnog kapilarnog upijanja vode, srednje vrijednosti

Water absorption. The obtained mean value of water absorption percentage for new brick is by 17 % lower than for the bricks from the building No 1, by 20 % lower compared to the results from the building No 2 and compared to the building No 3 it is 17 % lower. The highest deviations from the mean value among the samples of old bricks are up to 9 % for the first building, up to 21 % for the second and up to 11 % for the third building. The highest deviation from the mean value among the new brick samples are up to 9 %. Fig. 8 indicates the mean values of absorption percentages for each tested sample.

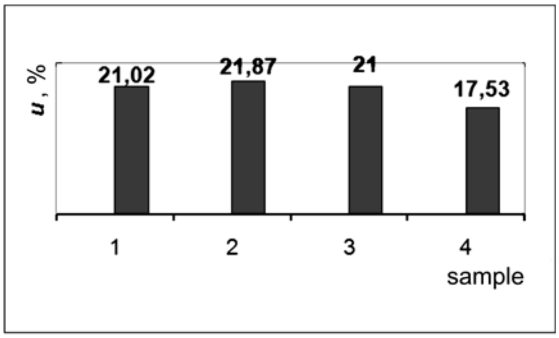

Figure 8 Water absorption percentages, the mean values
Slika 8. Postotak upijanja vode, srednje vrijednosti

The percentage for pores. The obtained mean value of the pores percentage is by 44 % lower than for the bricks in the building No. 1, by 55 % lower compared to the results from the building No. 2, and by 25 % lower compared to the building No. 3. The highest deviations from the mean value within the old brick samples are up to 50 % for the 1st building, up to 40 % for the 2nd and up to 175 for the 3rd one. The highest deviations from the mean value among the new brick samples are up to 9 %. Fig. 9 indicates the mean values of pores percentage for each tested sample.

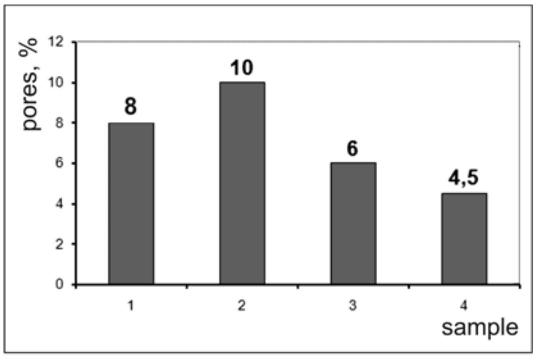

Figure 9 Pores' percentage, the mean values
Slika 9. Postotak šupljina, srednje vrijednosti

The compressive strength. The obtained mean value for the compressive strength of new brick is by 154 % higher than the bricks from the building No. 1, it is by 69 % higher compared to the results from the building No. 2 and compared to the building No. 3 it is by 14 % higher. The highest deviations from the mean value within the old brick sample are up to 25 % for the 1st building, up to 63 % for the 2nd and for the 3rd up to 6.5 %. Fig. 10 indicates the mean values of compressive strength for each tested sample.

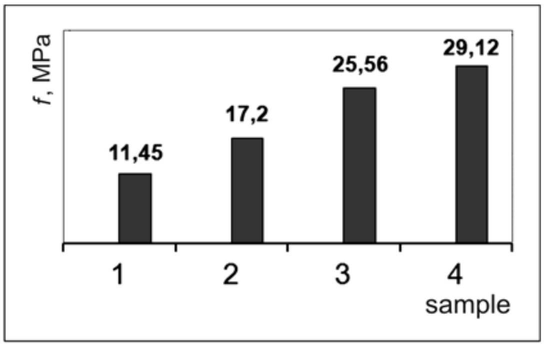

Figure 10 *The compressive strength, the mean values*
Slika 10. *Tlačna čvrstoća, srednje vrijednosti*

Mortar

The compressive strength of mortar. The obtained mean value of the mortar compressive strength was 0,54 MPa, that corresponds to the mortar strength M0,5.

The flexural strength of mortar. The obtained mean value for the flexural strength of mortar was 0,41 MPa, that corresponds to the mortar strength M0,5.

4 The mortar and brick's compressive strength testing by non destructive method "in situ"
Istraživanje tlačne čvrstoće morta i opeke nerazornom metodom "in situ"

To know the compressive strength of the mortar in existing brick walls is as important as to know the compressive strength of bricks. Determination of the compressive strength of the mortar is more difficult because the brick wall contains a relatively thin layer of mortar. Hence, if the sample from the existing building is tested, the thickness of the sample may not exceed the thickness of the layer. The samples are small, their preparation is complicated and test results have great dispersion.

The aim of the present research is to investigate the possibility of application and reliability of one method [3], almost completely non-destructive, to determine the compressive strength of mortar "in situ". The method is simple, quick and practical and it might have a wide application in the quality assessments of the brick structure. The method needs simple equipment (Fig. 11) for testing and calibration of a greater number of simple laboratory samples and after that it might be applicable under construction site conditions.

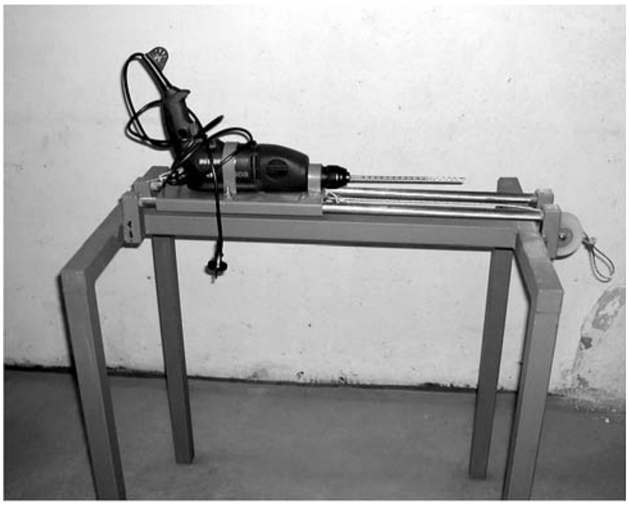

Figure 11 *The equipment for compressive strength testing*
Slika 11. *Oprema za ispitivanje tlačne čvrstoće*

This method measures the penetration speed of drilling into the mortar and it is expected that functional relations between the mortar strength and the penetration speed could be found. Other parameters that could be easily varied: drill rotation speed, drill diameter, application force and by changing them the application field of the method could be enlarged. We may observe some similarities with a few already existing in-situ non-destructive testing methods such as: Schmidt's hammer; Windsor-pin, and for metal hardness tests; Rockwell, Vickers, Brinell. As with these methods, a wide dispersion of results is expected, but also a possibility to determine the regression of dependence of the listed parameters.

To conduct the tests, a device has been constructed according to the original idea [2] (Figures 11 and 12). The device consists of a power drill mounted along the horizontal brackets on a steel support. The test is carried by drilling through the mortar by constant drill rotation speed and force. The constant force is provided by hanging the weights of desired amount on pulley. The power drill slides along the well greased brackets (to decrease the friction at minimum). The depth of the drill's penetration within determined time is measured and so the penetration speed is obtained.

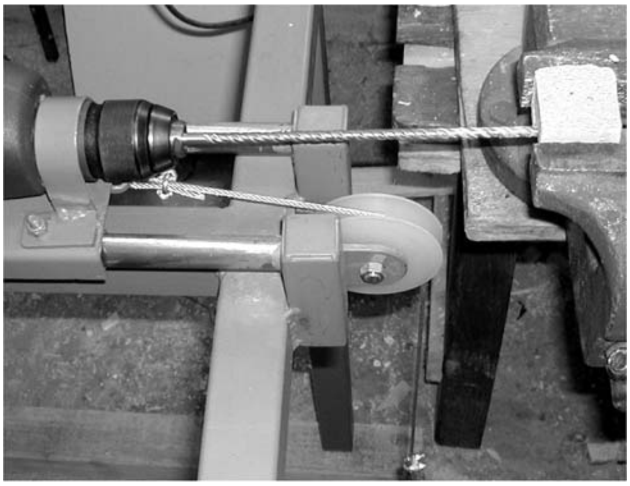

Figure 12 *Mortar compressive strength testing*
Slika 12. *Ispitivanje tlačne čvrstoće morta*

The problem is that the mortar is a non-homogenous material and statistics have to be introduced as mortar samples have great dispersion of results. The tests were carried out on the bricks, as well, as it was expected that they had much more homogeneous structure than mortar.

In order to determine the relationship between the penetration speed and compressive strength, the parallel destructive tests of brick and mortar have been performed at the laboratory of the Institute for Civil Engineering of Croatia, Osijek.

The brick. The tests on bricks were carried out on the samples of two manufacturers and on one sample from the 18th century. Three samples of bricks (six test samples) were tested with the total number of drillings of 90. Each drilling lasted 90 seconds (measured by stop watch), the speed of drilling was 600 rpm, the diameter of the drill bit was 6 mm (drill for concrete, tempered steel tip). The depth of drilling within determined time under constant speed and constant force (penetration speed) was measured for each hole. The results are shown on the two samples of bricks from different manufactures. It is evident (Figures 13 and 14) that the relationship between the applied force and depth of drilling may be determined, and that it is almost linear. The shown penetration speeds for different weights are the mean values of five measurements.

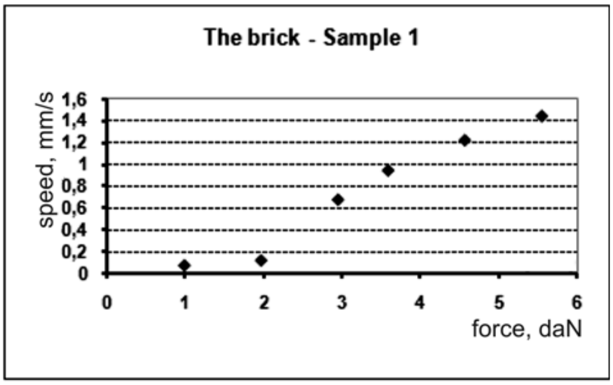

Figure 13 *The brick of strength* 14,50 MPa
Slika 13. *Opeka čvrstoće* 14,50 MPa

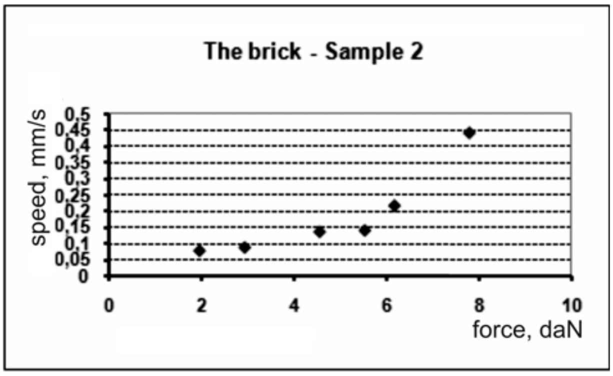

Figure 14 *The brick of strength* 25,00 MPa
Slika 14. *Opeka čvrstoće* 25,00 MPa

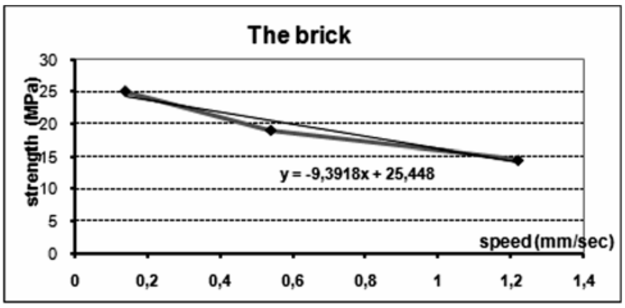

Figure 15 *Relationship between the brick compressive strength and penetration speed*
Slika 15. *Veza čvrstoće opeke i brzine prodiranja svrdla*

If we present the penetration speed for one load and correlate it to a brick strength obtained by destructive tests then we have a situation as shown in Fig. 15 that indicates the relationship between the brick compressive strength and penetration speed under constant force and drill rotation speed for three brick samples of different strengths. It is obvious that the penetration speed is almost linear with the material strength, i.e. the drill penetrates faster into weaker material.

The mortar. The tests were conducted on the mortar samples of compressive strength of 27; 10; 2,8; 1,8 and 0,8 MPa. Eleven mortar samples were tested (thirty three test samples), the total number of drillings being 72. Selected rotational speed of power drill was 600 rpm, the diameter of drilling bit was 6 mm (drilling bit for concrete, tempered steel tip). The expected drill depth was 40 mm. Time was measured for this depth of drilling at constant speed and force for all three holes (the number of holes on one sample was restricted by the size of the sample). It was evident that in tests on the samples of great strength there were almost no differences in the depth of drilling regarding the changes in applied force, while on the samples of compressive strength the samples failed because of their very small tensile strength. On the samples of medium strength, the functional relation of force (the added weight) and drilling time (Figures 16 and 17) may be foreseen. The shown penetration speeds correspond to the mean values in three measurements.

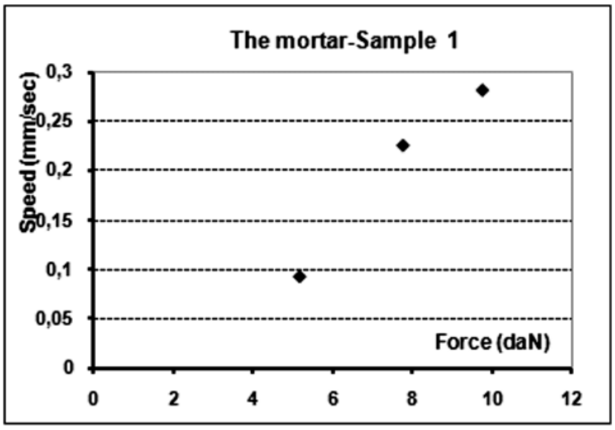

Figure 16 *The mortar of strength* 10,00 MPa
Slika 16. *Mort čvrstoće* 10,00 MPa

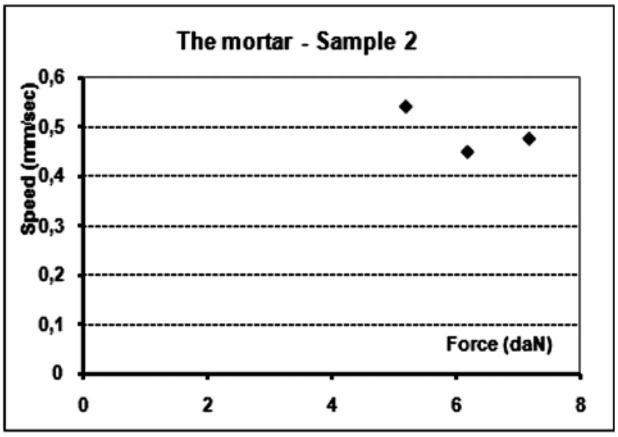

Figure 17 *The mortar of strength* 1,80 MPa
Slika 17. *Mort čvrstoće* 1,80 MPa

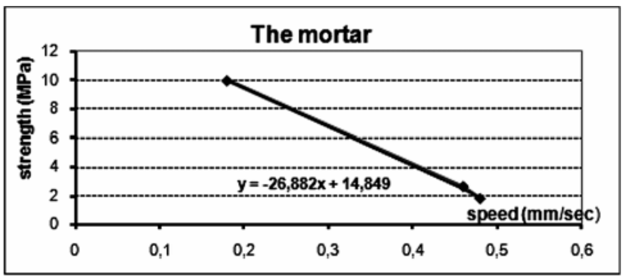

Figure 18 *Relationship between the mortar compressive strength and penetration speed*
Slika 18. *Veza čvrstoće morta i brzine prodiranja svrdla*

Fig. 18 shows the relationship between the mortar compressive strength and penetration speed under constant force and rotation speed for three mortar samples of different strengths. The penetration speed is linearly dependant on the material strength. For higher strength material the drill diameter should be smaller, but the correlation is expected to exist.

5
Conclusion
Zaključak

The brick. In the previous centuries a lot of small brick yards existed which didn't make any arrangements either on the brick dimensions or their manufacture. Also, there were no strict building regulations at that time. Therefore, the physical and mechanical properties of the bricks varied from place to place. The only uniformity existed in the bricks that were made in the brick yards for the army, i.e. the state. It was difficult to obtain the standard quality of the products because of the old manufacturing process. However, the basic physical and mechanical properties of the old and the modern brick are very similar. The presented "in-situ" testing method has shown its applicability in determining the basic mechanical properties. The relationship between the material strength and the penetration speed could be approximated as linear. Prior to its use, the method has to be calibrated by destructive tests on the bricks obtained from the historical buildings. Then it could be used for establishing the material quality on wider wall areas. The investigation indicated the necessity of determining the mechanical and physical properties of bricks for each historical monumental building, as their properties may widely differ.

The mortar. The experimental results of the lime mortar as was used in historic buildings in Slavonia indicated that its average strength was in accordance with today mortar M0,5.

The presented "in-situ" testing method has shown its applicability in determining the basic mechanical properties of mortar. The relationship between the material strength and the penetration speed could be approximated as linear. Prior to its use, the method has to be calibrated by destructive tests on the mortar obtained from the historical buildings. Then it could be used for establishing the material quality on wider wall areas.

Drill tests on brick and mortar by measuring the penetration speed under constant force and drill rotation speed have indicated almost linear relationship between the penetration speed and the material strength. It may be assumed that once the correlation between the penetration speed and strength has been determined by destructive tests the drill tests could be used as a good method for determining the strength variation on a wider wall areas, qualitatively as well as quantitatively.

6
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[7] HRN EN 772-3:2003 Methods of test for masonry units – Part 3: Determination of net volume and percentage of voids of clay masonry units by hydrostatic weighing, (EN 772-3:1998).

[8] HRN EN 772-1:2003 Methods of test for masonry units – Part 1: Determination of compressive strength, (EN 772-1:2000).

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Autor's addresses
Adresa autora

doc. dr. sc. Mirjana Bošnjak-Klečina, dipl. ing. građ.
Sveučilište J. J. Strossmayera u Osijeku
Građevinski fakultet Osijek
Drinska 16a, Osijek, Croatia

doc. dr. sc. Silva Lozančić, dipl. ing. građ.
Sveučilište J. J. Strossmayera u Osijeku
Građevinski fakultet Osijek
Drinska 16a, Osijek, Croatia