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ASSESSING MECHANICAL PROPERTIES OF HISTORIC STONE MASONRY: CASE STUDY IN JURDANI (RIJEKA)

Paulo Šćulac [(1)], Josipa Mihaljević [(2)], Ivana Štimac Grandić [(3)], Davor Grandić [(4)]

[(1)] *Assistant Professor, University of Rijeka, Faculty of Civil Engineering, Croatia, paulo.sculac@uniri.hr*
[(2)] *Assistant, University of Rijeka, Faculty of Civil Engineering, Croatia, josipa.mihaljevic@gradri.uniri.hr*
[(3)] *Professor, University of Rijeka, Faculty of Civil Engineering, Croatia, istimac@gradri.uniri.hr*
[(4)] *Professor, University of Rijeka, Faculty of Civil Engineering, Croatia, dgrandic@gradri.uniri.hr*

Abstract

Assessment of mechanical properties of unreinforced stone masonry depends on the material used and the construction techniques applied. In this paper we explore the mechanical properties of stone masonry components on a case study - a more than 200-year-old historical building near Rijeka, which is currently being renovated and repurposed, as part of the ongoing research project on stone masonry in the Kvarner Littoral in Croatia. The stone masonry walls of the case study building were visually inspected, while stone and mortar specimens from the walls were used to determine their mechanical and chemical properties. This case study aims to contribute to a better understanding of the variability of the mechanical properties of stone masonry, especially in traditional buildings in the Kvarner Littoral.

Keywords: Kvarner Littoral, historic buildings, stone masonry, case study, mechanical properties, laboratory tests, earth mortars

1. Introduction

Assessment of the mechanical properties of stone masonry, especially in historic buildings, presents a particular challenge due to the variability of materials and construction techniques. In addition, the construction methods employed by masons vary, which further complicates the assessment of mechanical properties. The primary material – stone, is characterized by considerable regional variation, what can greatly affect their mechanical properties. The second component of stone masonry is mortar and its properties play a crucial role in the overall performance of the masonry (lime mortar is commonly used in historic stone masonry).

The mechanical properties of stone masonry can vary considerably, even within the same country, due to the shape and size of the blocks, the type of stone and the way the blocks are stacked in the wall (typology) which is in fact controlled by the local possibilities of stone supply and the availability of high-quality masons. The properties of mortar, such as the mortar strength, the thickness of the bed joints and possible degradation have a primarily influence on the performance of the stone masonry in an earthquake, rather than the stone blocks of incomparably greater strength [1].

After the 1979 Montenegro Earthquake extensive research on stone masonry, including the testing of masonry walls, was carried out in Croatia [2]. However, the results provided only approximate estimates of the material strengths [3].

In case of listed buildings, destructive testing methods are prohibited, and even non-destructive or semi-destructive techniques are often subject to strict restrictions. On the other hand, for private buildings not subject to listed building control, the investigation process is less restricted, as no cooperation with the heritage authorities is required.

As part of the ongoing research project to determine the material properties of stone masonry in the Kvarner Littoral (Croatia), field and laboratory tests were carried out on masonry components (stone and mortar) of a historic family house in Jurdani near Rijeka. The compressive strength of stone was determined by laboratory tests on 4 test specimens taken from the stone blocks of a partially collapsed

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wall. The mortar was tested using non-destructive and destructive methods. The non-destructive methods, which were carried out in-situ, did not provide any results due to the wear and low strength of the mortar. Using destructive laboratory tests, the flexural strength was determined on 6 specimens from the mortar scraped from the wall, while the compressive strength of the mortar was determined on 12 specimens that remained after the flexural tensile test. The mortar was also subjected to chemical analysis using FTIR spectroscopy.

2. Case study

The building is located in Jurdani, in the vicinity of Rijeka. The year of construction is not known, but the house is displayed on the Second Habsburg cadastral survey from the 1819 [4]. The land lot contains a main building (the case study building) with a former livestock facility situated behind it. The case study building features a rectangular floor plan measuring 11,0 × 6,0 m and comprises of a partially buried ground floor and an upper floor (Fig. 1). The load-bearing walls measure 80 cm at the ground floor and 65 cm on the first floor (including the plaster layer). No iron ties have been detected within the building. The layout of the openings on the front façade is asymmetrical, and their dimensions differ between the ground and first floors, with the ground-floor openings being slightly larger. The building has a gable roof with a ridge height of 6,5 m. However, the roof structure, and consequently also the timber floor structure, have collapsed, so the interior of the building is exposed to weather conditions.

The masonry consists of irregular rubble stone blocks (limestone) of varying dimensions (Fig. 2a)), primarily composed of stone blocks with dimensions of s/h/l = 25/35/40 cm, where s represents the width, h the height, and l the length of the stone block. The largest stone blocks, exceeding 60 cm in length, are concentrated at the corners of the building (Fig. 1b)).

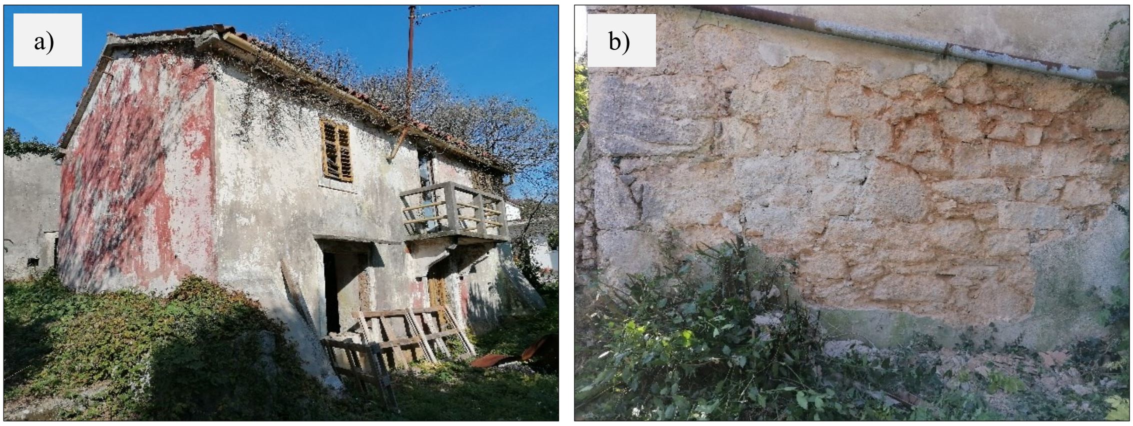

Figure 1. Case study building: a) front façade; b) side view.

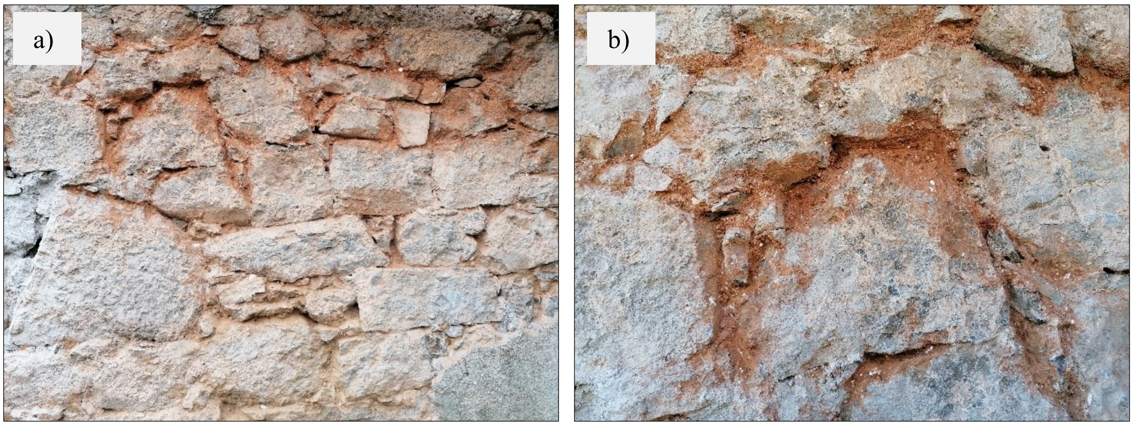

Figure 2. a) Masonry typology; b) detail of earth mortar with lime.

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Non-degraded rubble stone blocks are bonded with a weak mortar. In this case study, instead of lime mortar, an earth mortar with a small addition of lime was observed, as indicated by the presence of white lumps visible in Fig. 2b). The surface layer of the mortar is crumbling. The vertical joints are mostly aligned, while the horizontal joints are discontinuous. Due to large dimensions of the stone blocks, the masonry contains a sufficient number of wedges to ensure the monolithicity of the wall.

3. Material properties of historic stone masonry components

In this section we present results of laboratory tests on stone and mortar specimens performed at the Faculty of Civil Engineering in Rijeka, together with mortar characterization by optical microscope and FTIR analysis, performed by an external laboratory [5].

The original plan was to assess the mechanical properties of the mortar using non-destructive methods, such as the mortar penetrometer or the mortar rebound hammer, but we encountered a mortar that was not lime-based and which was severely degraded in the bed joints near wall surface due to exposure to moisture (Fig. 2).

The mortar penetrometer (Fig. 3a)) measures the response of mortar to needle penetration and correlates it to the mechanical performance of the material, providing information regarding the quality and homogeneity of the mortar [6]. However, the needle penetration depth was so high (Fig. 3b)) that no correlation was possible (i.e. the mortar strength was so small that it was outside the calibration curve).

The mortar rebound hammer (Fig. 3c)) works on the same principle as the concrete rebound hammers: by measuring of the rebound of a spring-controlled mass that strikes a plunger that is in contact with the investigated material [7], except it has a different spring stiffness – the hammer we used may be applied for mortars with strength higher than 1,5 MPa [8]. However, due to low mortar strength the impact plunger just pressed into the mortar (Fig. 3d)), so correlation was not possible.

Figure 3. Application of NDT methods on mortar: a) and b) penetrometer; c) and d) rebound hammer.

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3.1. Mechanical properties of stone

Four stone blocks have been extracted from the neighbouring livestock facility, which is nowadays connected to the case study building (assumed to have been built at the same time since as it is also listed on the cadastral survey [4]). From each block one cylindrical specimen was prepared (Fig. 4), in such a way that the diameter and height match the dimensions prescribed by the Standard [9] equal to 50 ± 5 mm.

The specimens were loaded continuously at a constant stress rate of 1 MPa/s until failure (Fig. 5) according to [9]; the results of uniaxial compressive strength are given in Table 1. Result determined for specimen No. 4 was rejected from statistical analysis due to the large difference in compressive strength (58,6 MPa) and its failure mode during the testing which both indicates probability of the defect in the specimen. The compressive strength values determined in the range of 131,4 MPa to 145,0 MPa (for specimens 1 to 3) correspond to the limestone expected to be built with at the building location.

Figure 4. Preparation of stone specimens: a) stone blocks; b) drilling of cylinders; c) extracted stone cylinders; d) specimens ready for testing.

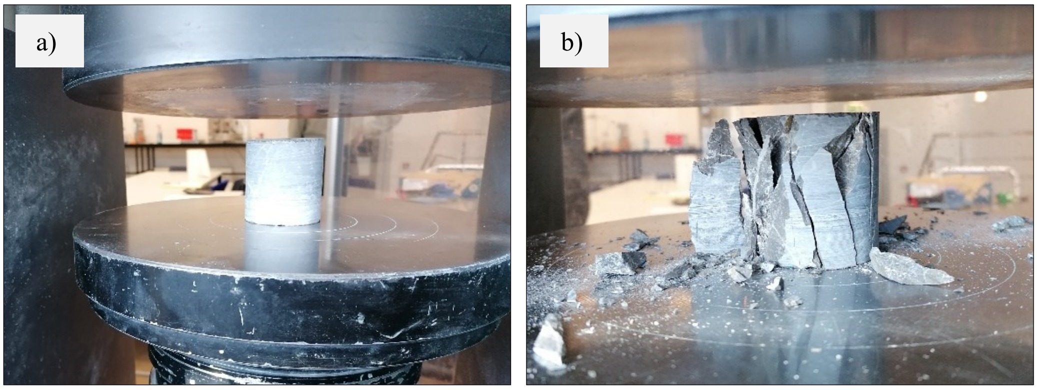

Figure 5. Uniaxial testing of stone cylinders: a) specimen No. 3 before; b) after test.

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Table 1. Compressive strength of stone specimens

Specimen	Height, h (mm)	Diameter, D (mm)	Weight (g)	Density, γ (kg/m^3)	Max load, F (kN)	Strength, f_s * (MPa)
1	53,2	54,2	325	2648	305,1	132,3
2	54,8	54,1	337	2675	333,4	145,0
3	57,7	54,2	355	2667	303,1	131,4
4	62,4	54,1	384	2677	134,6	58,6
Mean value $^+$				2663 $^+$		136,2 $^+$
St. dev. $^+$				14,0 $^+$		7,6 $^+$

* $f_s = 4 \cdot F/(D^2 \cdot \pi)$

$^+$ for specimens 1-3

3.2. Mechanical and chemical properties of mortar

Although the authors did not expected this, based on their previous knowledge on masonry buildings in the Croatian coastal region, after removing the plaster from the ground floor walls of the house in this case study, it was detected that earth mortar had been used (Fig. 2 a)). The similar earth mortar has been observed in another building not fare away from the case study building. There is a high probability that there are many more applications of earthen mortars in our country, but this has not yet been sufficiently researched.

Earth-based mortars (also referred as mud mortar or clay mortar) have been used as filling materials and plasters in adobe, fired brick and stone masonry worldwide [7]. They can be found not only in rural areas but also in European historic centres [10, 11]. Recent restauration works in Scotland have shown that clay mortars are much more common than previously realised [12].

Recent earthquakes revealed that buildings with earth-based mortars behaved poorly, but this shouldn't be attributed only to the mortar but also to the construction techniques. Kumar Bothara et al. [1] report of a large number of destroyed stone masonry buildings with mud mortar located in remote rural areas of India in 2015 Gorkha earthquake. The recent earthquakes in Turkey revealed that earth mortar binders were commonly used in traditional unreinforced masonry buildings in rural areas till 1960s [13, 14]. Kuruscu et al. [13] note that the harsh environmental conditions (freeze-thaw cycles during winter) caused the disintegration of the earth mortars, what significantly decreased the shear capacity of the masonry walls.

Sorrentino et al. [11] and D'Ayala et al. [10] report of performance of historical buildings with mud mortar during the Central Italy earthquakes. As stated in [11], at least until 60-70 years ago,mortar was produced from a soil pit where the excavated ground was mixed with enough water until adequate plasticity was achieved. Cantù et al. [15] report of mortars mixtures consisting of soil and small amount of quicklime (less than 5% of weight) in Cremona. A detailed analysis of earthen mortars in Central and Northern Italy including the petrographic, textural, mineralogical and chemical analysis may be found in [15, 16].

Earth based mortars are regaining its place as building materials for plastering, rendering and repair of earthen walls [17]. In recent studies, the effect of adding fibres or mineral binders as stabilisers was investigated [17], and new methodologies for mortar mix design when adding sand are proposed [18].

Clay mortars are considered to be inferior materials, due to their negligible tensile strength and vulnerability to external conditions (exposure to water). However, the primary function of the mortar is to support the blocks in a masonry wall and to enable a uniform distribution of the compressive stresses and earth based mortars commonly have sufficient compressive strength to conduct this function [12].

Fig. 6 b) presents an image of mortar specimen, which was extracted undisturbed from the bed joints of the case study building, obtained using light microscope with a 10x magnification: it consists of the brown matrix - earth (soil) with a small proportion of lime in the form of white lumps. The admixtures of organic origin (i.e. plant remains) are also visible as black areas in the figure [5].

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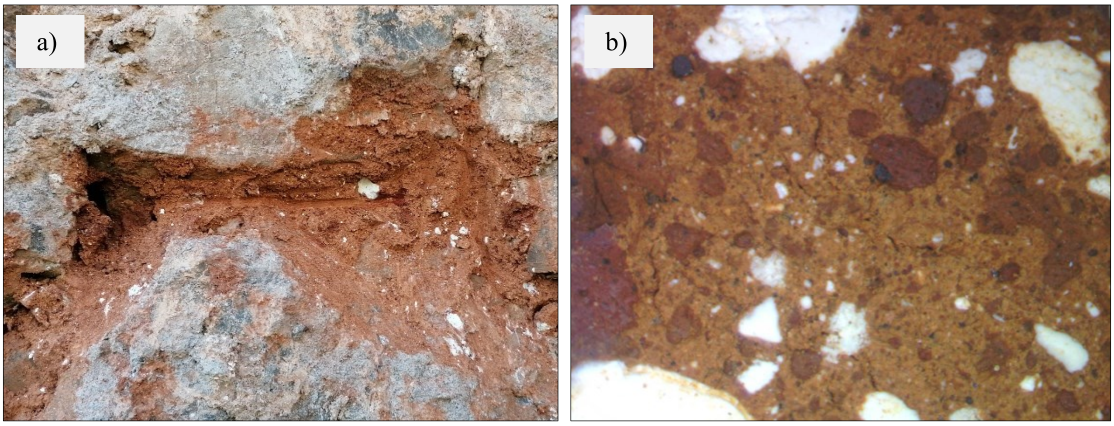

Figure 6. a) Detail of the earth mortar with white lime lumps; b) microscope image of a mortar specimen (10x magnification) [5].

FTIR Spectroscopy was used to identify the composition of the mortar [5]. Two milligrams of both the white lumps as well as the brown matrix were mixed with potassium bromide (KBr) and pressed into pellets. The obtained spectra are the result of the mean value of 20 recorded spectra per sample, with a recording resolution of 4 cm^{-1} in the spectral range from 4000 to 400 cm^{-1}.

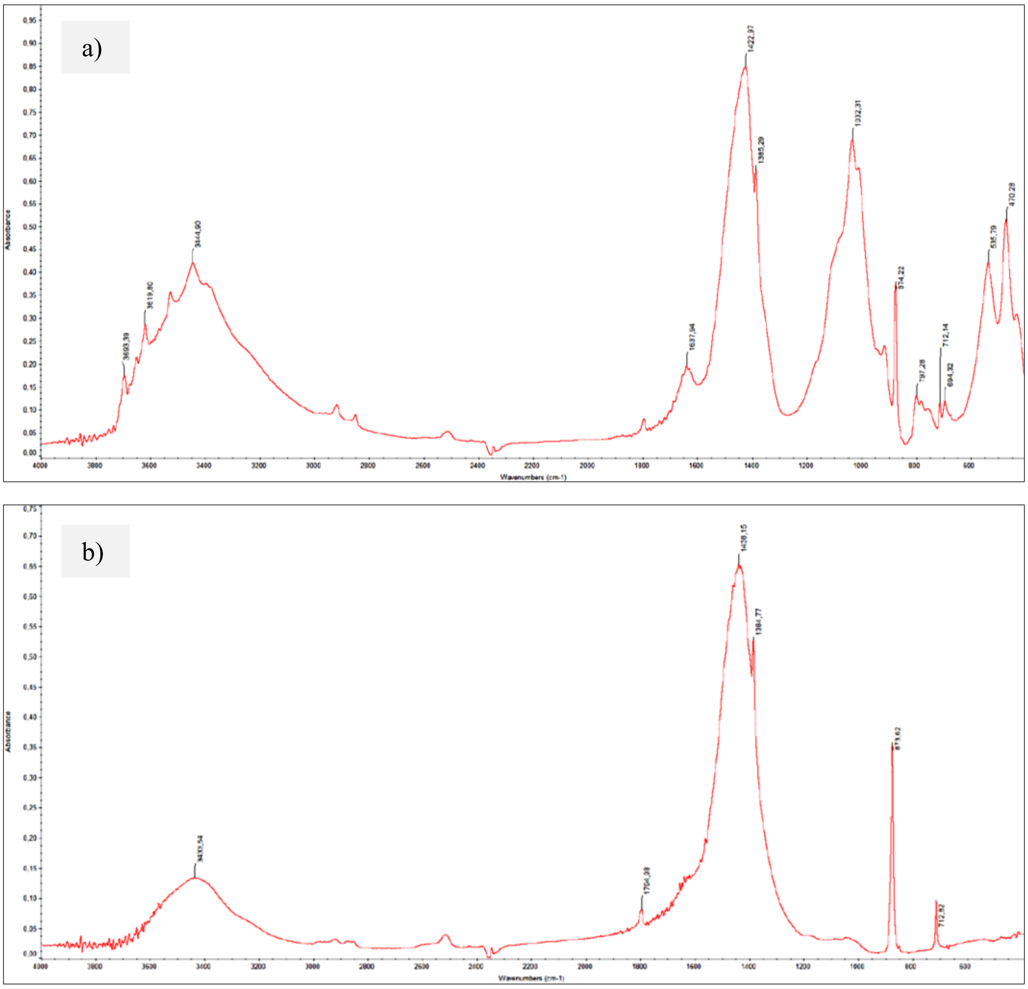

Figure 7. FTIR analysis of mortar: a) brown matrix (soil); b) white lumps (lime) [5].

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The FTIR analysis (Fig. 7) showed that the brown-colored binding matrix consists of minerals typically found in soil (silicates and iron-aluminosilicates such as Illite, Montmorillonite…) and white lime lumps. Additionally, a band at 1385 cm^{-1} is visible in both spectra, indicating the presence of nitrates in the sample. Salts containing nitrates are typically found in buildings in rural areas or tombstones, i.e. in structures that are in direct contact with the soil. Considering that this sample contains a high proportion of the soil, it is possible that nitrates were present from the beginning as components of the soil from which the mortar was made [5].

Since the mortar has degraded, it was possible to extract it from the bed joints in a powder form by simple scratching. The extracted powder was then used to prepare mortar prisms 160 x 40 x 40 mm for flexural and compressive strength testing – enough water was added to ensure good workability (although certain amounts of air pockets were noticed after drying). The metal moulds were filled with mortar in two approximately equal layers, each layer being compacted by 25 strokes of the tamper. The specimens were then stored in polyethylene bags for 7 days and afterwards for another 21 days in laboratory conditions. A total of 6 specimens were prepared (Fig. 8).

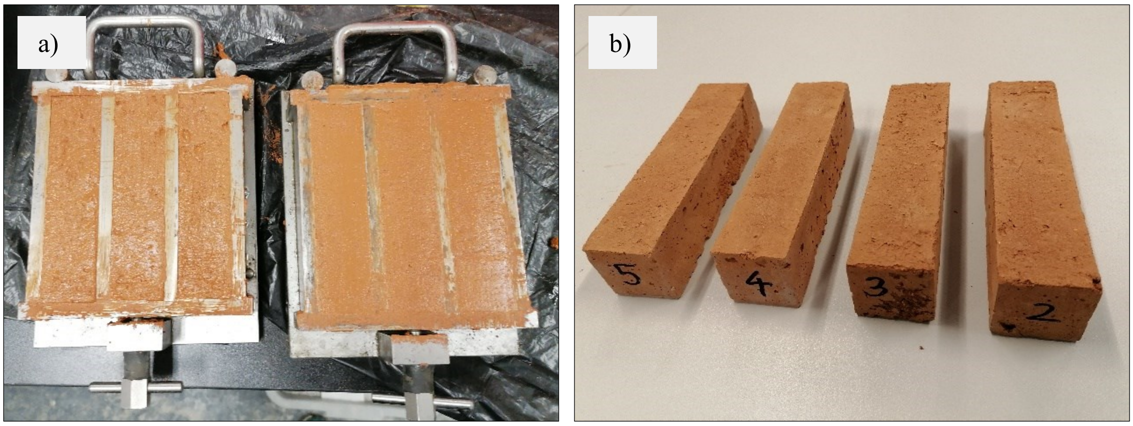

Figure 8. Mortar specimens: a) preparation in metal moulds; b) prisms before testing.

The specimens were tested at an age of 28 days after casting. The flexural strength of mortar was determined by three point loading to failure (Fig. 9) according to [19], and the results are presented in Table 2. The values of flexural strength between 0,18 and 0,3 MPa, with the mean value of 0,26 MPa, are rather low, as expected.

Figure 9. Flexural strength test – three point loading scheme.

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Table 2. Flexural strength of mortar specimens

Specimen	Width, *b* (mm)	Depth, *d* (mm)	Max load, *F* (N)	Strength, f_b * (MPa)
1	39	38,5	100	0,26
2	39	38,3	100	0,26
3	38,6	38,6	70	0,18
4	38,5	38	112,5	0,30
5	38,7	38,2	113	0,30
6	38,6	38,3	103	0,27
Mean value				0,26
St. dev				0,04

* $f_b = 1{,}5 \cdot (F \cdot l)/(b \cdot d^2)$, l =100 mm (distance between the support rollers)

The compressive strength of the mortar given in Table 3 is determined according to [19] on the two parts of the specimens resulting from the flexural strength test (Fig. 10). The average compressive strength of the mortar cubes is 2,36 MPa (standard deviation 0,12). The results are comparable with results reported in [1]: average compressive strength of the mortar cubes 50,8 x 50,8 mm according to ASTM C-109 was 1.73 MPa (CoV 29,2%).

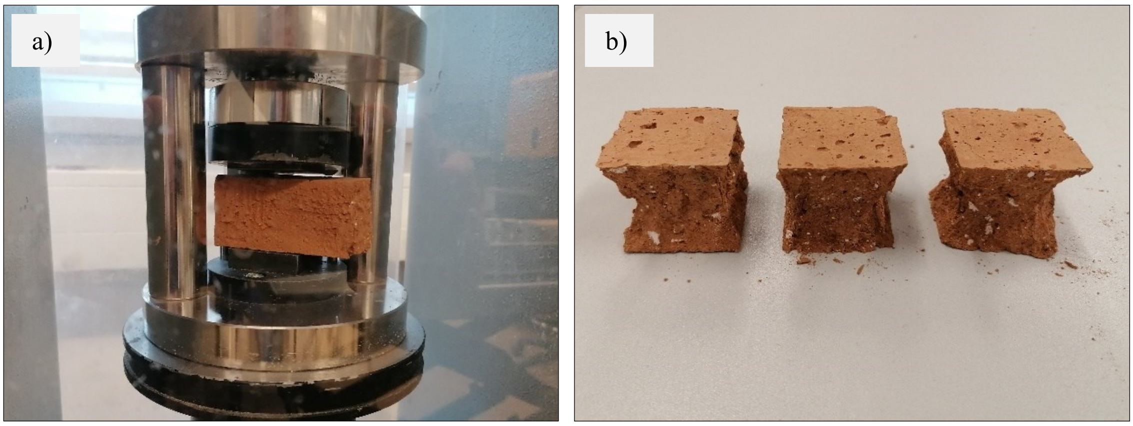

Figure 10. a) Compression test setup; b) hour-glass mortar specimens after testing with visible lime lumps.

Table 3. Compressive strength of mortar specimens

Specimen	Width, *b* (mm)	Max load, *F* (N)	Strength, f_c * (MPa)
1	39	3470	2,22
2	39	3630	2,33
3	39	3710	2,38
4	39	3460	2,22
5	38,6	3670	2,38
6	38,6	3730	2,42
7	38,5	4080	2,65
8	38,5	3620	2,35
9	38,7	3770	2,44
10	38,7	3590	2,32
11	38,6	3630	2,35
12	38,6	3420	2,22
Mean value			2,36
St. dev.			0,12

* $f_c = F/(b \cdot a)$, a =40 mm (bearing plate length)

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4. Conclusions

This paper presents results of an on-site inspection of masonry and laboratory tests on stone and earth mortar from a more than 200-year-old stone masonry building in Jurdani near Rijeka. The selected case study building is a typical rural house in the Kvarner Littoral in Croatia. It is a two-storey building, with ground floor partially buried into the ground.

The on-site examination of the stone masonry walls of the case study building and the laboratory tests led to the following conclusions:

- The walls consist of rubble stone masonry with wedges between the blocks and corner stones of larger size.
- The stone used in the case study building is characterized by the high compressive strength typical for limestone.
- Instead of lime mortar, earth mortar with a small amount of lime added is used (it does not contain sand or gravel).
- The results of the FTIR spectroscopy of the earth mortar indicate that the mortar was made from local soil deposits.
- The earth mortar in the bed joints near the wall surface was degraded due to exposure to moisture, so that the non-destructive testing methods on-site test failed.
- The flexural strength of the earth mortar specimens is low, while the compressive strength is comparable to the compressive strength of lime mortar.
- Earth-based mortars are probably more widespread than may be expected in buildings which are part of the built heritage in the Kvarner Littoral.

The most valuable discovery of the case study presented is the usage of earth mortar in stone masonry, which had not been expected. Although there are numerous researches worldwide related to various aspects of earth-based mortars, this type of mortar has not been sufficiently researched in Croatia. Also, the earth mortar of the case study building is of particular interest because it does not contain sand or gravel, which distinguishes it from the commonly used historic earth mortars in which clay minerals serve as a binder for sand and silt particles.

Since mortar properties have a significant influence on the behaviour of stone masonry during earthquakes, further research is therefore required to determine the mechanical properties of rubble stone masonry in which this type of earth mortar is used.

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