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## PHYSICAL AND MECHANICAL SPECIFICITIES OF “TENELIJA” STONE

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### ABSTRACT

Stone “Tenelija” is categorized as oolitic limestone. This stone was used to build a number of constructions in Herzegovina, and one of the most famous is the “Old Bridge” in Mostar. The stone is characterized by its specific physical and mechanical characteristics. Stone “Tenelija” has low uniaxial compression strength, low modulus of elasticity, large porosity, big influence of water on its uniaxial strength, and yet many objects that were built hundreds of years ago, form this rock, still stand. The paper presents the laboratory testing of physical and mechanical characteristics of the samples of various sizes, with all specificities. Also, mutual correlations of the results was analyzed and presented.

Key words: *Physical and mechanical properties, Tenelija, stone*

### INTRODUCTION

Deposit of oolitic limestone (calcarenit) “Mukoša”, located south of Mostar, close to the location of Kadrijevići in the Mostar area (local name is and Bišće polje). “Tenelija” oolitic limestone (calcarenit) is intensively exploited and used in construction as an architectural - building stone of 1550 - ties, in time of Turkey, and then the Austro-Hungarian rule until after the Second World War, when the advanced materials are starting to prevail in construction. Due to the demolition of “Old Bridge” in Mostar, which stood for 427 years there as a monumental building known throughout the world, and was deliberately destroyed in the war, it have been re-tests of physical and mechanical characteristics “Tenelija” for the purpose of rebuilding the “Old Bridge” (figure 2). [1] Tests of physical and mechanical properties of stone samples Tenelija, represent the most comprehensive examination ever made in this stone. Analysis of the results given the professional and scientific explanation to the “Old Bridge” resisted the ravages of time. [2]

### GEOLOGICAL CHARACTERISTIC OF “TENELIJA” STONE

“Tenelija” in deposit “Mukoša” belongs to uppermiocen freshwater sediments. Deposit is built of two types of stone with local name “Tenelija” and “Miljevina”. “Miljevina” is much more present in the

deposit and occupies about 95% of the total mass of rock in the deposit, while the stone “Tenelija” occurs in the context of a complex bank and several thin layers. Under the bank “Tenelija” is “Miljevina” (figure 1). “Tenelija” and “Miljevina” differ considerably, both in the structure, both in terms of the geotechnical characteristics. [3]



Figure 1 Detail from “Mukoša” deposit (photo: K. Mandžić)

The color of “Tenelija” depends on the state in which the sample of the stone is located. When it is taken out of the deposit, the colour of this stone is a light yellow, and when in the wet state it is light brown in color. In areas where there has been a separation of iron oxide, “Tenelija” has a reddish color (the color of rust). Due to the drying stone is of whitish color and with aging rock gets a light gray and gray. Change of colors, evident only in the surface of the blocks, is the result of exposure to the effects of weathering and development of plant organisms (algae). According to the mineralogical and petrographic studies of “Tenelija”, there are disparities in defining their own structure. The most prevalent opinion is that the stone is build from oolite representing alchemical components of micritic and sparitic calcite. [4] Micritic calcite is composed of the carbonate particles of micron sizes (5 microns and less) which arises due to sedimentation of the water and decomposition of solids in the sedimentation basins of carbonate formations. With the investigation of “Tenelija” micro sections, it was found that “Tenelija” consists of oolite, which is spherical in shape and have a diameter of up to 2 mm (figure 2). Oolite, according to theory, the resulting initial floating "nucleus" in the turbulent water, where in the core is a precipitation of particles (carbonates, clastic quartz), which have gradually created crust around "cores". Micro pores are partially filled with micritic cement and in the individual macro pores arising decomposition of the remains of organisms appear. Carbonate content in the sample is more than 95%. Chemical analyzes performed on samples “Tenelija”, using the diffraction of X-rays, have established that all the investigated samples were pure calcium carbonate. According to some authors, stone “Tenelija” represents calcarenite that differ from oolitic limestone by the method of formation. Discussion of this issue is still ongoing between individual researchers. [5]

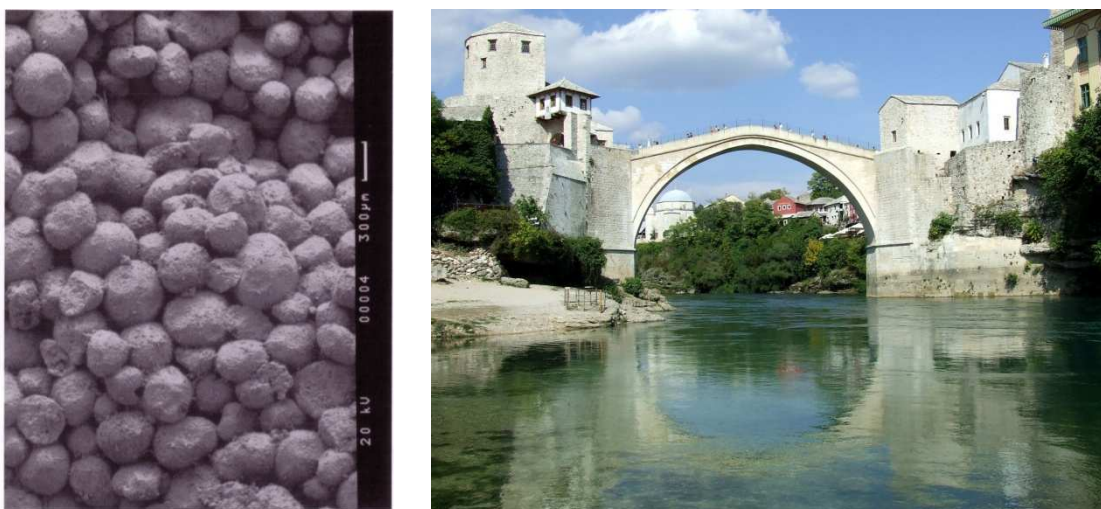


Figure 2 Left; Microscopic view of “Tenelija” composition; [6]  
Right: “Old Bridge” in Mostar [7]

## PHYSICAL-MECHANICAL CHARACTERISTICS TENELIJA

Detailed tests of physical and mechanical characteristics of “Tenelija” were performed in order to determine the properties “Tenelija” as building materials. Tests were conducted on samples of various sizes, according to B. B. (Former Yugoslav standard JUS) [8] and EN (European Standards Norms) standards. [9] Tests were carried on “Tenelija” in two phases. In the first phase, on samples of 10x10x10 cm and 10x10x20 cm and in the second phase, tests were conducted on samples of 5x5x5 cm, 10x10x10 cm and 5x5x10 cm, and tests were carried out according to B. B. standards. In both phases around 170 samples were tested, and the results of these tests are presented in the paper. All samples, which were used in the tests, were selected from different blocks excavated stone, so that the tests carried out are the general representative sample “Tenelija”. Samples were cut circular with diamond saw, by wet process, in the dimensions which are defined by standards. [8]

### UNIT WEIGHT OF STONE "TENELIJA"

Bulk density was calculated on samples of 5x5x5 cm, 10x10x20 cm 5x5x10 cm and, according B.B.030 standards. The dimensions of the samples were measured precisely to the accuracy of 0.01 cm and weight was measured to an accuracy of 0.1 g. Bulk density was calculated as the ratio of the mass weighed and calculated the volume of the sample of tested sample. After that, bulk density was transformed into unit weight of the samples. [8,9]

The results showed a large dispersion of the values of unit weight in testing of one sample size, as a result of the very structure of stone “Tenelija” (figure 3). The mean unit weight of samples 5x5x5 cm  $\gamma=19.19$  (kN/m<sup>3</sup>), samples 5x5x10 cm  $\gamma=19.15$  (kN/m<sup>3</sup>) and in samples of dimensions 10x10x20 cm it was found that the mean value of dry unit weight of stone “Tenelija” is  $\gamma=19.2$  kN/m<sup>3</sup>. The results indicate that there is no significant impact of sample size on values of unit weight. [10]

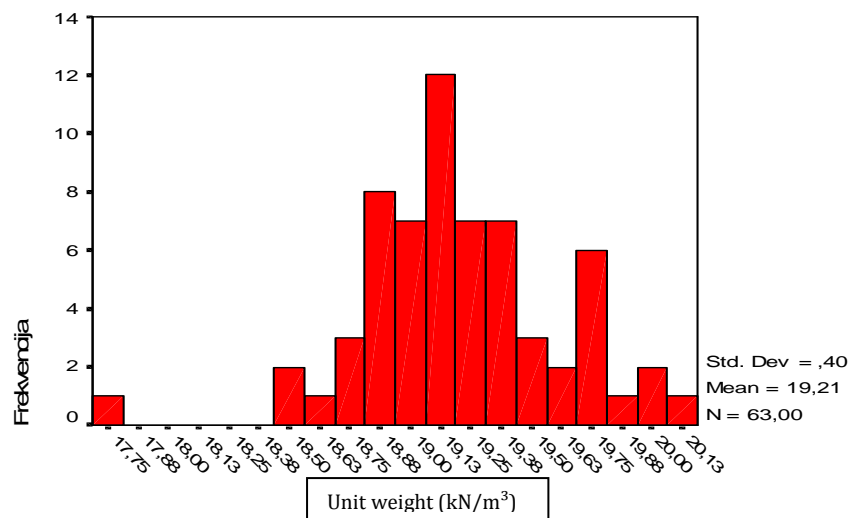


Figure 3 Distribution chart of unit weight (kN/m<sup>3</sup>) for samples 10x10x20 cm [9]

### DETERMINATION OF FROST RESISTANCE

Determination of frost resistance was carried out on samples of 10x10x10 cm [9]. The experiment was carried out so that each sample is subjected to cycles of freezing and defrosting for 25 times. After each defrosting cycle the samples were examined as changes in the surface of sample were recorded. After 25 cycles samples were weighed to determine mass loss and examined to determine the occurrence of any cracks. After 25 cycles of freezing all samples were thoroughly examined and cracks were found that affect the resistant parameters stone. Because of these characteristics it can be

concluded that the stone “Tenelija” is not resistant to frost. For this reason, the “Tenelija”, as construction material, is used only in Herzegovina, where there are no large fluctuations in temperature to the point of freezing. One reason for this behavior, is extremely high porosity values, which is  $n = 25\%$ . This porosity is a consequence of the genesis of the deposit, and allows very rapid infiltration of water in the entire structure of the sample. The investigation determined that the sample  $10 \times 10 \times 10$  cm, when put in the testing dish with constant water level of 2cm, reaches total water saturation after 25 minutes. This happens due to the high capillarity. This is important because stone unit weight is increased and strength is lowered. [11]

## DETERMINATION OF UNIAXIAL COMPRESSIVE STRENGTH

Uniaxial compressive strength was investigated on samples of  $5 \times 5 \times 5$  cm,  $5 \times 5 \times 10$  cm and  $10 \times 10 \times 10$  cm and  $10 \times 10 \times 20$  cm, the press in the measuring range of 1000 kN, with accuracy readings at breaking point of 1 kN. The force at the time of breakage is recorded as the maximum load on the surface of  $10 \times 10$  cm and  $5 \times 5$  cm, as uniaxial strength is the value of the breaking load divided by loading area.

The mean uniaxial compression strength of the samples with dimension of  $10 \times 10 \times 20$  cm is  $\sigma_{ult} = 20.4$  MPa (figure 4-left).

The mean value of the uniaxial compressive strength of the dry sample measuring  $10 \times 10 \times 10$ cm is  $\sigma_{ult} = 23.2$  MPa.

The mean uniaxial compressive strength for samples  $5 \times 5 \times 5$  cm, tested in the dry state is, perpendicular is  $\sigma_{ult} = 21.5$  MPa (figure 4-right).

And the samples  $5 \times 5 \times 10$  cm tests were conducted in the same manner, and the mean value of the uniaxial compressive strength in the dry state is  $\sigma_{ult} = 23.2$  MPa. [11]

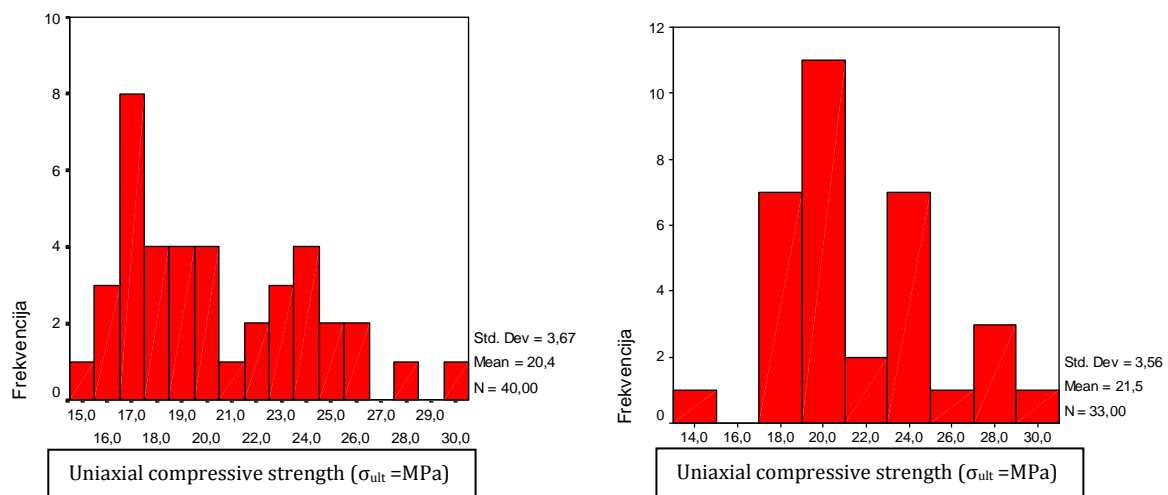


Figure 4 Left: Typical diagrams of distribution of uniaxial compressive strength ( $\sigma_{ult} =$  MPa) perpendicular to the layers of samples  $10 \times 10 \times 20$  cm

Right: Typical diagrams of distribution of uniaxial compressive strength ( $\sigma_{ult} =$  MPa) perpendicular to the layers of samples and  $5 \times 5 \times 5$  cm (right)

One of the objectives of these tests was to determine the potential impact of the sample size on uniaxial compressive strength, due to the various sizes block usage of this stone in construction. Therefore, the tests of different sizes samples have been conducted in an identical manner. All tests were performed on the same equipment (figure 5), and all this is done to reduce the possibility of errors during testing. As shown in the work, for each dimension samples different results were obtained. For samples of dimensions  $10 \times 10 \times 20$  cm, mean strength is  $\sigma_{ult} = 20.4$  MPa and sample

dimensions 10x10x10 cm is  $\sigma_{ult} = 23.2$  MPa. This relationship is characteristic for most rock materials, ie, the strength of the same material is lower in d: h = 1: 2 than in d: h = 1:1 relationship. However, the test specimens of dimensions 5x5x5 cm, where strength is  $\sigma_{ult} = 21,5$  MPa, and samples 5x5x10 cm with  $\sigma_{ult} = 23,2$  MPa, this ratio is different, and “Tenelija” does not behave like other materials. Also, samples of dimensions 10x10x10 cm have higher strength than samples 5x5x5 cm. This shows that the differences in the test results, the various dimensions of the samples, vary in a small range (in some rocks variation can reach 50%), without any legality, on the basis of which it can be concluded that the size of the test sample does not significantly affect the value of “Tenelija” uniaxial compressive strength. This is very important because this stone was used in big blocs for many constructions in geographical region Herzegovina [11].



Figure 5 Left: Typical appearance of the sample after fracture (10x10x20 cm)  
Right: Typical appearance of the sample after fracture (5x5x5 cm)  
(Photo: K. Mandžić)

#### THE EFFECT OF HUMIDITY ON THE COMPRESSIVE STRENGTH

Uniaxial compressive strength ( $\sigma_{ult}$ ) in samples of dimensions 5x5x5 cm, has been tested in dry and saturated samples, in order to determine the impact of water on the value of uniaxial compressive strength. The strength is calculated as the force exerted on the surface of 5x5 cm at the time of fracture. The mean uniaxial compressive strength of samples tested in the dry state is  $\sigma_{ult} = 21.5$  MPa. The samples, which were tested in the wet state, were before carrying out experiments immersed in water for 24 hours, as required by the standard. The samples were completely saturated with water, and when testing, each sample was extracted from the water and directly put under the press after which we performed the experiment. This means that each sample was completely saturated with water during the test. The mean value of uniaxial compressive strength for samples in a saturated state, is  $\sigma_{ult} = 16.8$  MPa.

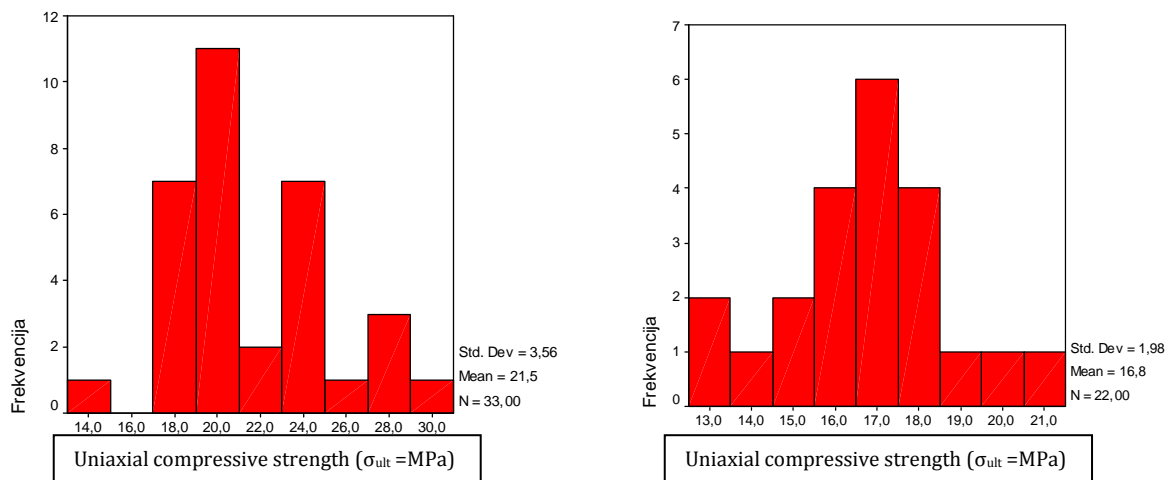


Figure 6 Distribution diagrams of uniaxial compressive strength (MPa) of samples 5x5x5 cm in dry and saturated state

Most of the obtained values of uniaxial compressive strength in the dry state are above 18 MPa, while the samples in a saturated state, most values are under the 18 MPa. Such differences in strength indicate that water has a very significant impact on the strength of “Tenelija” and substantially changes its physical-mechanical characteristics. Since “Tenelija” has a very high value of capillary rising, this saturation effect of water is very important from the point of cracks in structures built of this stone, because they may be due to the decline in the value of strength in the rainy season or, as in the “Old Bridge” in Mostar, when the water level of the Neretva river is high.

In the diagrams of distribution of uniaxial compressive strength, dominant influence of water on the behavior of materials during testing is evident. For testing of dry samples it appears to be three so-called “Mode”, which represent the three influential factors on the uniaxial compressive strength (figure 6). With the increasing strength values, the impact of dominant influential factor decreases. With samples in water saturated state, diagram of the distribution is significantly different (figure 6). There is a clear symmetrical distribution with a single influential factor. Due to the high porosity of the material, water fills all pores and base material which significantly affects the strength. Water acts on the particles by reducing the friction between them, but also affects the particles creating the better connection between them and allowing the better stress transmitting (“homogenized” material). Based on this, it can be concluded that water which saturated “Tenelija” eliminates the influence of other factors, and remains the only influential factor in the strength, but at the same time significantly reduces the value of uniaxial strength of rock material. The influence of water is due to a large porosity ( $n = 25\%$ ), and the possibility of saturation of the sample with water in a very short interval timelines. [12,13]

The samples 5x5x10 cm tests were conducted in the same manner as the samples 5x5x5 cm. The mean uniaxial compressive strength in the dry state is  $\sigma_{ult} = 23.2$  MPa and in a saturated state  $\sigma_{ult} = 18.4$  MPa. In these samples, reduction in strength with the saturation of the sample is observed. [14]

#### THE CORRELATION OF UNIT WEIGHT AND UNIAXIAL COMPRESSIVE STRENGTH

Since the unit weight values did not change significantly with a change in size of the samples, the ratio between the unit weight and the uniaxial compressive strength is detailed in the samples of 5x5x5 cm. (Given the relationship diagrams unit weight in dry and saturated state and uniaxial compressive strength). [15]

The diagram (figure 7) can be seen a lot of dispersion of results, so that we cannot establish a clear correlation between the unit weight of samples in the dry state and uniaxial compressive strength. In the diagram in (figure 9), the dispersion of results is in small boundaries so it can be concluded that with the increasing of saturated sample unit weight the uniaxial compression strength also increases. These results could be due to the action of water in the pores as a temporary binder, by which particles act on each other and getting “stronger” ties for the stress dispersion that resist the action of external forces, i.e., water “homogenized” material.

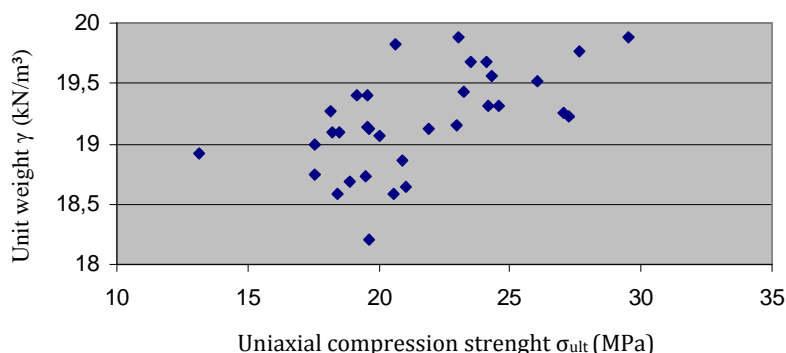


Figure 7 Relations between unit weight of dry sample and uniaxial compressive strength

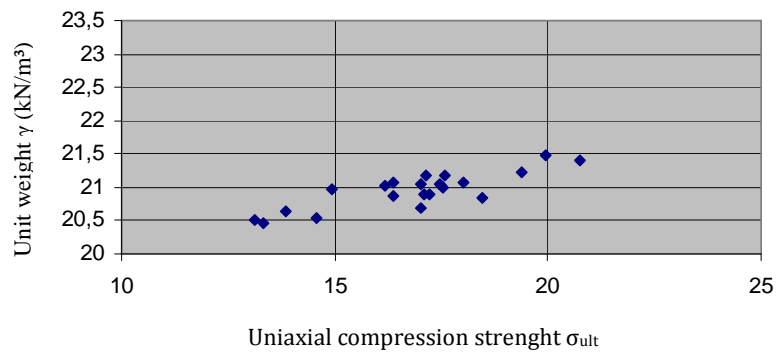


Figure 8 Relations between unit weight of saturated sample and uniaxial compressive strength

## DETERMINATION OF MODULUS OF ELASTICITY

Modulus of elasticity for all samples were determined by measuring the deformability of the sample in the process of continuous load the sample until fracture, and based on the behavior of rock material in the cycle load - relief - load (hysteresis loop).

Elasticity modulus of “Tenelija” is very specific because in the initial stage of compression the material takes loads on account of change of porosity. After the compression is achieved elastic materials behavior starts up to very close to the border of fracture. A small part of the plastic behavior of materials, exhausted after elastic deformation, indicates that the material is in principle behave as brittle material, as has been shown in characteristic diagram of testing. We believe that this compression of the material in the small load operation leads to the compaction of material and reduction of the porosity, reduce the possible influence of water, increases the contact between the particles, which then leads to a kind of the material solidification when in construction.

Modulus of elasticity is determined by calculating the size of the portion of the elastic behavior of rock material, which can also be seen on a given characteristic diagram (figure 9), which is given below.

The mean modulus of elasticity when load on the sample is normal to stratification is  $E = 3822.2$  MPa, and parallel to the stratification is  $E = 3530.2$  MPa (figure 10).

Testing of the material behavior in terms of load-relief (hysteresis loop) with three cycle shows that the material, after passing in areas of the elastic deformation, in relief still acts elastic until almost completely unloaded, while maintaining a very high degree of permanent deformation after repeated cycles, which is shown in a characteristic diagram (figure 11). This is a consequence of the particles compaction process and increase of compactness. [16,17]

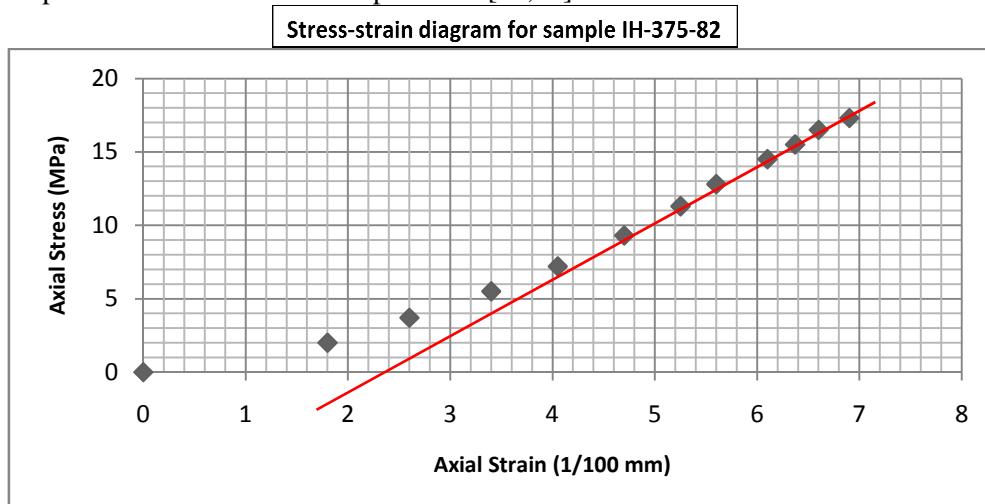


Figure 9 Typical diagram of the stress and strain relationship

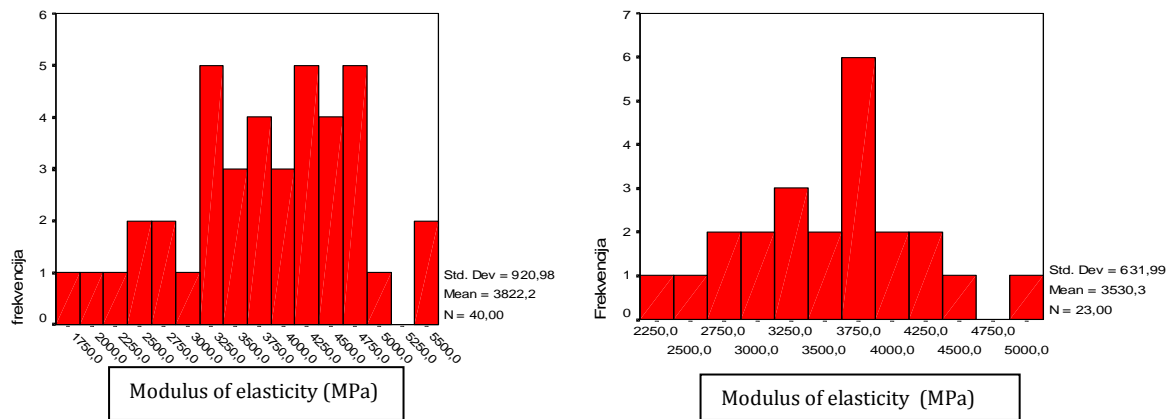


Figure 10 Diagram of modulus of elasticity (MPa) distribution for load vertically and parallel to layering

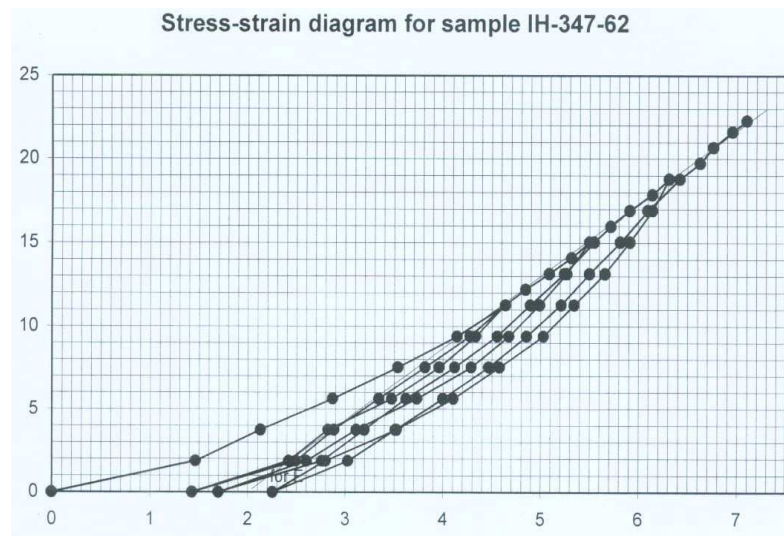


Figure 11 Hysteresis of material behavior with three cycles of load

## DISCUSSION

Tests of some physical-mechanical parameters of rock “Tenelija” give us a set of values and the statistical analysis allows the determination of the mean and range from minimum to maximum value of each parameter. A dispersion of individual parameters results are in a relatively wide range, so the use of the mean value is uncertain if this value is used in calculations, whose results may have relations with the general conditions of structural stability of construction built from this stone. Scattering shows that the frequency distribution does not belong to the classical statistical normal distribution such as Gaussian distribution. Type of value distribution of certain parameters is different and in principle it does not give so-called symmetrical distribution.

Thus, in the testing of compressive strength perpendicular to the stratification of the sample 5x5x5 cm, average strength appears, but in that diagram, this value has the lowest frequency. Modulus of elasticity in frequency diagram shows different behavior in terms of distribution by creating a flattened normal distribution with the load parallel to stratification and asymmetrical distribution with loads perpendicular to the stratification. Diagram stress-strain shows that there is some “compacting” of material during application of smaller loads, and in the diagram load-relief, is shown a high degree of permanent deformation. The correlation of certain parameters showed that there are a number of influential unstated factors that does not allow the establishment of strong correlations of these parameters. Scattering of results in the correlation comparison of parameters is great, so a strong correlation cannot be establish. The correlation parameters, revealed that there is a range of



uncertainty, the source of which remains unknown, and that does not allow (uncertainty) to establish a strong correlation between the examined parameters, as there is presented in books for certain types of rock material.

Testing of the uniaxial compressive strength, present similar dispersion for the sample dimensions 5x5x5 cm, samples 5x5x10 cm and 10x10x10 cm samples. The difference between the mean values of uniaxial compressive strength of "Tenelija", for all tested samples of different sizes, is almost negligible, which is not characteristic of other rock material. Based on these test results of uniaxial compressive strength, it can be concluded that the size of the test sample has no impact on the value of strength.

When examining the relationship unit weight and uniaxial compressive strength, interesting results were obtained. The relationship between unit weight and uniaxial compressive strength for dry samples, presents a large dispersion of results, making it impossible to determine the correlation between these two parameters. However, in examining the relationship between unit weight and uniaxial compressive strength of samples saturated with water, this correlation can be established because the dispersion of the results is negligible. Based on this correlation it can be established that the increase of unit weight increases the value of uniaxial compressive strength. This behavior of the material is the result of its water saturation with water "homogenizing" material and therefore the particles are better connected, and the material resistant to the effects of external loads is different.

## CONCLUSION

Based on these findings can be seen that the stone "Tenelija", in terms of physical-mechanical properties, does not behave like other rock materials.

Therefore, during the construction with "Tenelija" as construction material, one should be particularly careful in determining the parameters for the design.

Because of small influence of sample size on value of uniaxial compression strength, results for the small samples can be representative for larger blocks of this stone. Influence of the water content on uniaxial compression strength can give answer for cracks appearance in construction made of this stone.

These studies help explain, and how the rock material, with such low mechanical characteristics, could be an integral part of the monumental buildings in geographical region Herzegovina.

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