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Mechanical properties of sedimentary stones in different conditions determined by parametric studies and laboratory tests

A Ph.D. theses booklet

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1 Introduction and objectives

Geology plays primary importance in civil engineering. The type and mechanical properties of soils and rocks have essential effect to perform engineering design and analysis. The elaborate appropriate and cost effective design and/or analysis, the engineers need fundamental and well defined material constants/variables to set up the constitutive equations. The design and/or analytical situations with different type of rocks are rather difficult, because the stones/rocks have double roles in civil engineering, they can use as building materials, but due to excavations one can form an engineering object (e.g. tunnels).

When ones make design/analysis in or on a rock mass as boundary of the engineering objects, it is necessary to know both the mechanical parameters of the intact (non-segmented) rock, as well as the position, formation, and state of the segments. This degree of cracking is also greatly influenced by the appearance of secondary cracks and fractures created during construction, the cause of which is, on the one hand, the result of the construction technique (e.g. new fractures appear as a result of blasting), and, on the other hand, it is created by the stress rearrangement of the formed cavity (based on the scientific literature: excavation we are talking about damage zone and environmental damage zone). It means that the deformation connected material parameters/variables are fundamental to describe the mechanical behavior of stones/rocks based engineering problems. Accurate knowledge of these is essential, especially in the planning of radioactive waste repository. The crack systems, new divisions, and discontinuities created as a result of both original and engineering interventions significantly influence the mechanical properties of the rock mass, so this is currently one of the newest research areas of rock mechanics. The investigation of the deformation theory based rock mechanical problems is the main research area of this doctoral research. More specifically, the variation of the Poisson's ratio as a function of the fragmentation of the rock and the environmental pressure was investigated by virtual tests (parametric studies). Conducting actual laboratory tests, I examined the relationship between the impact resistance and the uniaxial compressive strength of the green sandstone.

The goal of my research is to find a clear connection with the classic rock classification methods, so that the empirical experience and theoretical methods can be connected. With the help of the obtained results, it is also possible to model the environment of the tunnels more precisely.

By using the obtained virtual and laboratory rock mechanical test results and comparing them with international literature data, it is possible to check the formulas for comparing the

existing effects and to make them more precise. On the basis of the experiments, it is expected that new correlations will be discovered - for the given rocks - and new equations will be written that more accurately characterize the behavior of the rocks. By knowing the theoretical and empirical relationships and the segmentation of rock bodies, it is also possible to model the effect of water and temperature on rock. The obtained results are directly useful both in engineering (geotechnical) planning and in the understanding of geological processes. There was a secondary goal in my research, namely, suggests a relatively simple impact energy based in situ test to make correction during excavations if it is necessary.

2 Parametric studies on the Poisson's ratio of rocks

As it was indicated above, I performed virtual tests (parametric studies) in connection with the properties of the Poisson's ratio of the intact rocks. At first a parametric study is elaborated on how the Poisson's ratio of the intact rock depends on the rigidity of the material. In addition, I have investigated the connection between the Poisson's ratio and the Geological Strength Index (GSI), the connection between the Poisson's ratio, the GSI and the confining stress. The section is closed by the research on the theoretical relationship between the confining pressure and Poisson's ratio of intact rock.

2.1 The relationships between Mohr-Coulomb parameters and Poisson's rate value

By the use of existing formulations relations between Mohr-Coulomb parameters and Poisson's rate value could be plotted (Fig. 1.) One can see, that using the applied equations the Poisson's ratio highly depends on the rigidity of the rock material. This non-linear behavior shows that the changing is very sensitive till approximately $R \approx 10$. In case of brittle rocks ($R > 10$) the influence of the rigidity is not so significant. Due to all of these connections the Poisson's rate is equal to 0.5 in case of $R = 1$ (i.e. plastic material). Reaching the maximum rigidity of the rock (i.e. $R = 35$) the minimum Poisson's rate is between 0.02. According to the published data the lowest Poisson's rate is around 0.1.

In Fig. 2 the minimal and maximal Poisson's rate values (v) are plotted in the function of the Hoek-Brown constant (m_i) of the rock. There are only two points out of the line: the shale and siltstone from the list of AASHTO (1989). Note, the Hoek-Brown constant of these types of rock are usually very sensitive.

Comparing the different relationships the best fit curve can be written in function of the rigidity of the rock (R) (it is equal to the Hoek-Brown material constant (m_i), thus $R \approx m_i$,)

i.e.: $\nu = \frac{1}{\sqrt{m_i}+1}$. (1)

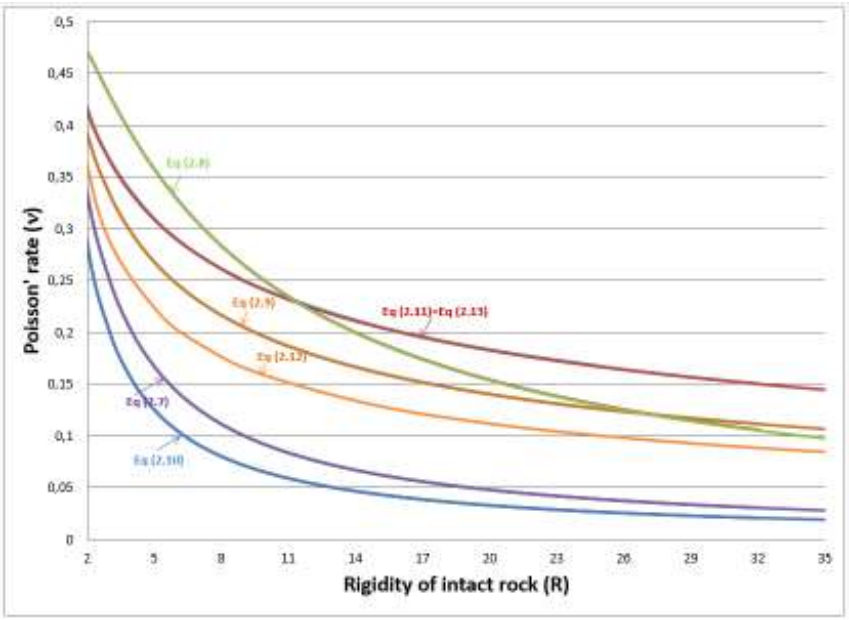

Fig. 1. Prediction of the Poisson's ratio in the function of the rigidity of the intact rock – equations according to Zhang et al (2011).

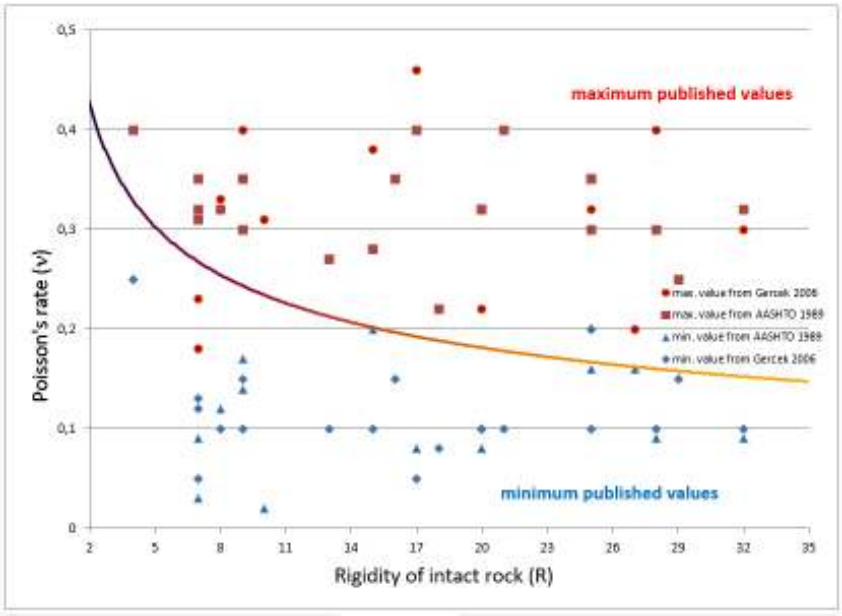

Fig. 2. Plotted maximum and minimum Poisson's rate (ν) of the intact rock in function of the rigidity (*R*) – using the published values of (Gercek 2006) and (AASHTO 1989) and using curve of Eqs. (2.11 & 2.13)

2.2 The connection between the Poisson's ratio, the GSI and the confining stress

The goal of this theoretical research is to determine a simple relationship between the confining stress and the Poisson's ratio value of intact rock. This simple linear relation can be created easily and does not need any other information than the Poisson's ratio of the intact rock without confining pressure ($\nu = \nu_i$) and the transient stress value. It has to be mentioned, that the Poisson's ratio can be differently handled. It can be more accurately described as an elastic deformation parameter that monotonously increases with stress during the compressive processes. According to the experimental results of the international research, different rocks exhibit different behaviors in their Poisson's ratios. In hard rocks, the secant and average Poisson's ratios grow approximately linearly with stress in the main stages of the loading process. However, in soft rocks, these ratios quickly increase beyond the theoretical maximum of 0.5 in the initial loading stage. In that case a bilinear expression can be created, but the determination of the intermediate point is critical in that approximation. The intermediate point is the case where the axial stress reaches 20–30% of the transition stress. If this intermediate point is known a Lagrange or a Hermitian approximation can be applied, as well. In these last cases non-linear approximations are used instead of linear ones.

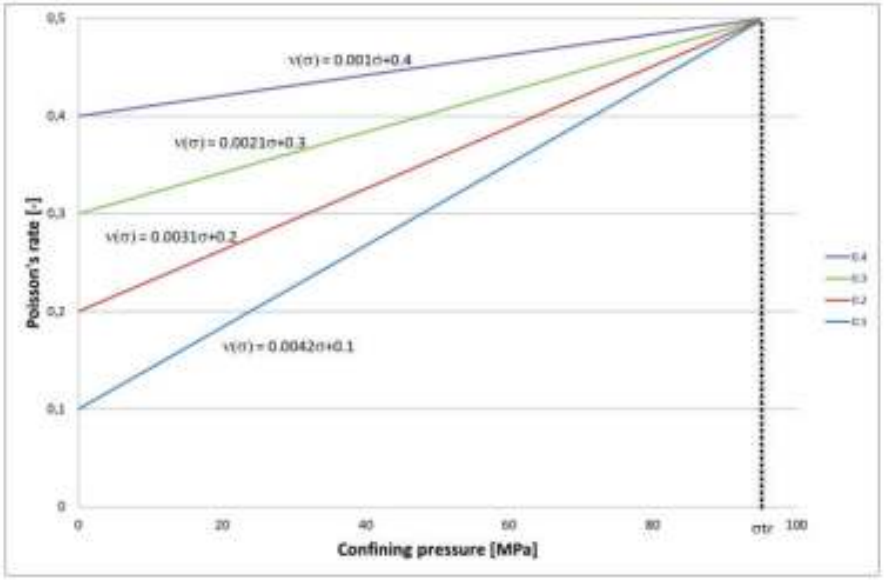

Fig. 3. Changing the Poisson's ratio in case of σ_c=100 MPa and m_i=10 (using Eq.(2.38))

The influence of the confining pressure to the Poisson's ratio values plotted in Fig. 3: the uniaxial compressive strength (σ_c)= 100 MPa and the Hoek-Brown constant (m_i) = 10 in this example. The Poisson's ratios were plotted in the function of confining pressure for ν_i = 0.1, 0.2, 0.3 and 0.4 values of the intact rock at zero confining pressure.

It should be emphasized that this relationship applies to intact rock. In rock engineering practice it is important to know the mechanical parameters of the rock mass (Poisson's ratio, as well). The Poisson's ratio value depends on the rock mass quality. Increasing the quality of the rock mass, the Poisson's ratio is decreasing. The Poisson's ratio also depends on the water content.

2.3 Results of the connection between the Poisson's ratio, the GSI and the confining stress

The results of each equation have been compared in several ways. One of the aims of the study was to determine whether there is any relationship between the Poisson's ratio and the magnitude of the ambient pressure, and how the change in GSI affects the Poisson's ratio. Parametric calculations were performed to see the dependencies of the parameters above.

The Fig. 4. shows Poisson's ratio values for intact rock as a function of σ_3. It can be observed that the results given by each equation, although different in value, behave the same in nature. It can be seen that although there is no constraint on the adapted formulation, it cannot be used in all ranges as it does not give a meaningful result.

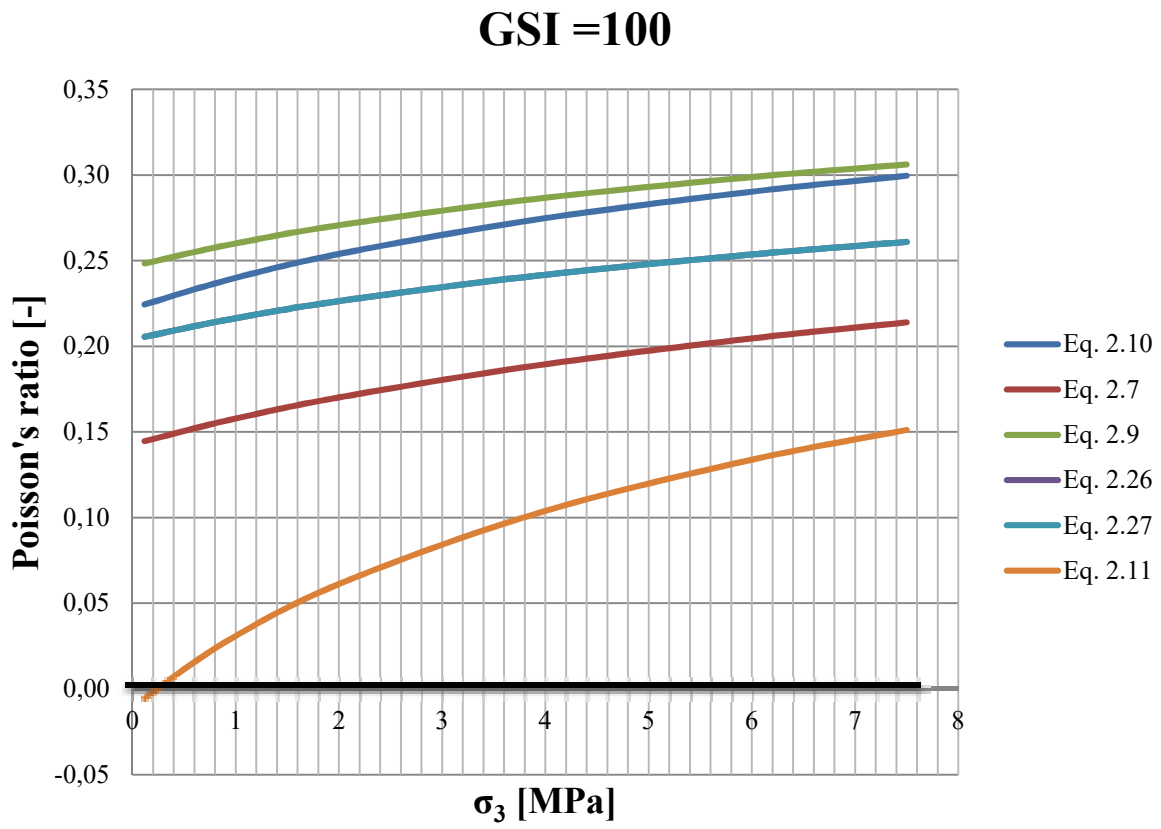

Fig. 4. The results for the intact rock

The following figure (Fig. 5) shows that the value of the Poisson coefficient is not only dependent on the magnitude of the environmental pressure, but is significantly influenced by the fragmentation of the rock. It can be seen that the higher the GSI value of a given sample, the higher the value of the Poisson's ratio will be. The red dots represent the values calculated using each equation. Fitted with these results is a surface that can give a good approximation of the areas between the calculated results.

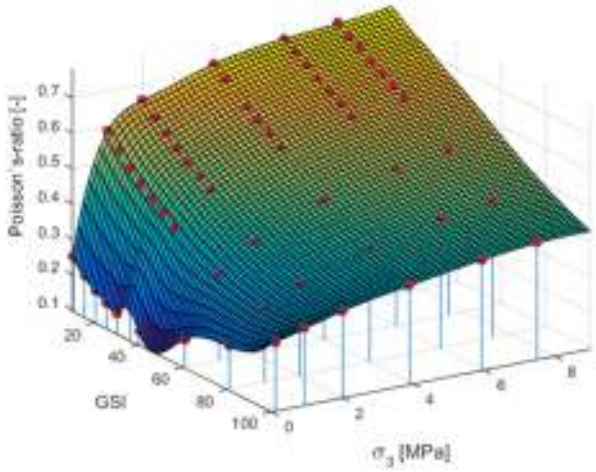

Fig. 5. The results from the Eq. 2.10.a

Based on the results presented above, an interesting correlation can be found between changes in the value of the Poisson's ratio so far considered constant based on the environmental pressure and the GSI value. It is clear that decreasing the GSI value also decreases the value of the Poisson's ratio, while if the value of the σ_3 increases, the Poisson's ratio also increases.

3 Laboratory work based on Charpy impact test

Green sandstone (glauconite sandstone) was investigated in my laboratory impact tests. Green sandstone is a sedimentary rock that typically forms in coastal, shallow sea environments. Its main characteristic is the greenish hue, which is given by the mineral called glauconite. Glauconite is an iron-rich phyllosilicate mineral that often occurs in small amounts in marine sandstones, but is present in significant amounts in green sandstone, dominating the rock's color and characteristics. The formation of green sandstone takes place in a slow sedimentation, oxygen-poor marine environment, usually on continental shelves or in shallower parts of subtropical-tropical seas. Glauconite usually forms in low-energy, stable marine environments where organic matter decomposes between sediment-rich layers and contributes to the growth of glauconite crystals. Green sandstone is fine-grained, but may also

contain coarser grains. In addition to glauconite, quartz, feldspar and lime cement are common in its mineral composition. Glauconite is often greenish, greenish-gray, or olive-green in color, which makes the rock easily recognizable. Sedimentary fabric is typically layered, and the cementation between layers can vary in strength, affecting the porosity and strength of the rock.

3.1 Specimens

When determining the dimensions of the test specimens, I primarily took into account the properties of the sandstone. The goal was to make the dimensions of the test piece as small as possible, so that the size of the grains that make up the sandstone would preferably not affect the fracture to a large extent, and the sample should be considered quasi-homogeneous. The size determined in this way makes it possible to examine the properties of the material during the test in such a way that the possibly different strength properties of the constituent particles do not influence the result. The test pieces are 25x25x60 mm in size, the geometric deviations are less than 1 mm for any size. The standard deviation of the sizes of the individual sides is shown in the following picture: 0.4 mm and 0.5 mm for the two shorter sides, while 0.6 mm for the 60 mm long side.

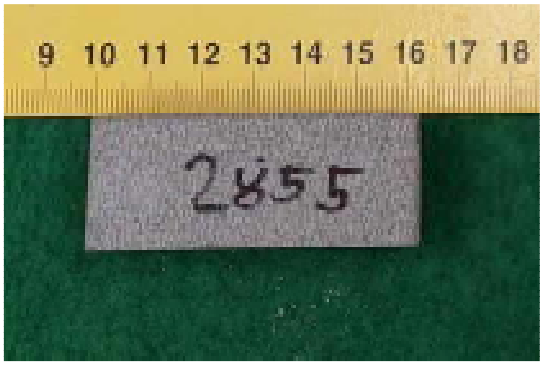

Fig. 6. Green sandstone specimen

Fig. 7. Specimen after the test

Since the temperature and the state of water saturation of the material are the criteria for the load-bearing capacity of rocks and all natural building materials in general, during the tests I tested the specimens in different states of saturation and temperature. That is, air-dry normal temperature (22°C), saturated normal temperature, air-dry frozen and saturated frozen. With these four states, a significant part of the states occurring in nature can be covered, so the test provides information on these states as well.

3.2 Results of the experiments

The obtained measurement results were compared with each other according to several different aspects. My goal is to be able to find a correlation between the impact energy and some property or properties of the sample as widely as possible. Additionally, the secondary goal is to find physical quantities which are fundamental one for daily practice in using rocks. When selecting these physical quantities, I tried to give priority to data that can be easily determined, so that neither special instruments nor complicated procedures are needed for the applicability of the obtained correlation.

Table 1. Average density and impact work values in different conditions

		dry frozen	dry normal	saturated frozen	saturated normal
Density (g/cm^3)	average	2,42	2,41	2,41	2,41
	standard deviation	0,03	0,03	0,03	0,02
Impact work (J)	average	8,63	10,22	10,71	7,55
	standard deviation	2,71	1,84	0,63	2,07

The examined sandstone (Figs. 32-34) is fine-grained and can be considered homogeneous from the point of view of the measurement, as evidenced by the fact that the highest deviation in the density measurement is only 0.03 g/dm^3. (Table 1) In the case of impact work, the standard deviation is already larger, this is partly due to the material of the green sandstone. Since this is a sedimentary stone, the settlement direction of the individual layers could be detected during the measurements, despite the fact that it was not noticeable to any extent with the naked eye. In the case of samples at normal temperature, there is approximately a 35% difference between the impact work of saturated and air-dried samples. In this case, the higher values were obtained during the measurement of air-dried specimens. In the case of frozen samples, this difference was around 24%. Here, on the other hand, the higher impact work values were obtained during the examination of the saturated samples.

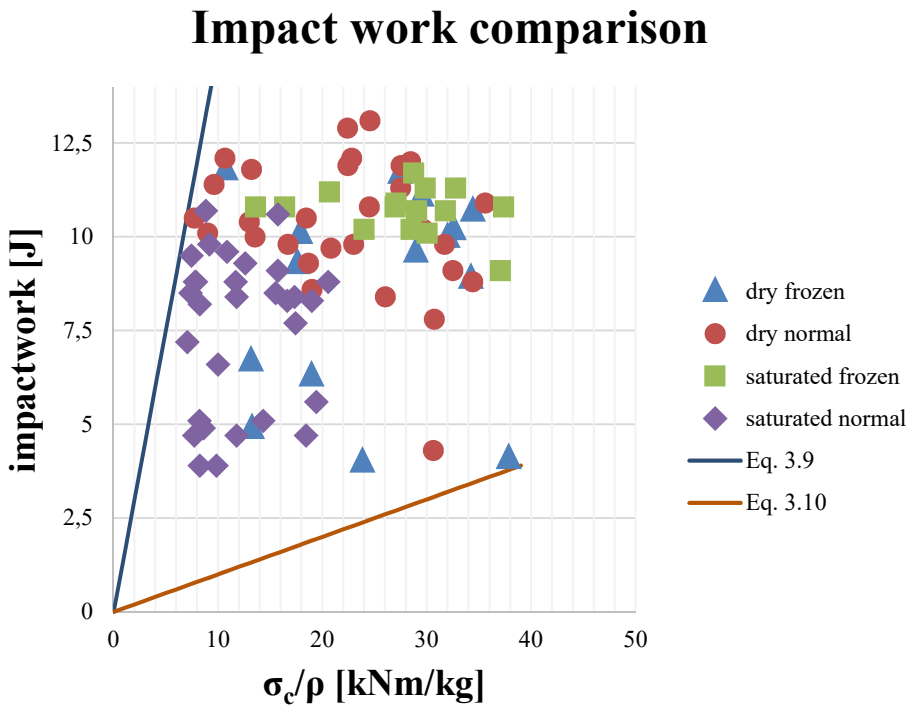

Fig. 8. Impact work comparison

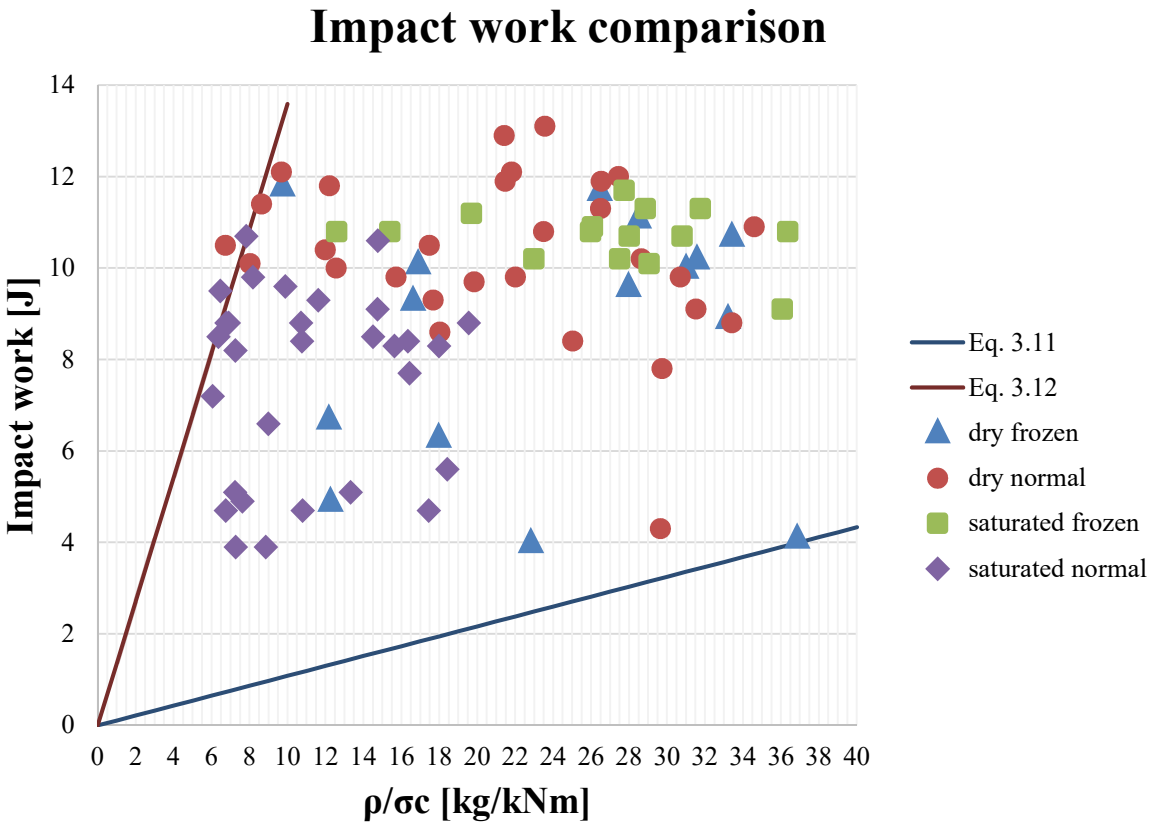

Fig. 9. Impact work comparison

During the evaluation of the measurement results, I obtained the result that, in the case of the examined samples, the value determined by the quotient of impact energy, density and compressive strength has a mathematically well-describable relationship with each other.

In case of the samples, regardless of temperature and saturation state, the impact work values fell within the range bounded by two straight lines (Figs. 8, 9). This makes it possible to obtain an estimated strength value with the help of the tests performed in this way only by determining the density and impact work. Before defining each limit, I used statistical methods to check whether each value was greater than the average minus three times the standard deviation, or if it was smaller than the sum of the average and three times the standard deviation. If a sample does not fit into this range, it cannot be taken into account when establishing the limits. In the case of the examined green sandstone, all measured values were in the appropriate range, so when setting up the boundary curves, it was only necessary to find the straight line that starts from the origin and passes through the two outermost elements of the set of points.

Based on this, if the density divided by σ_c (Fig 8), the upper limit of the values is described by Eq. (2), while the lower limit is given by Eq.(3).

$$\sigma_c = 425 \cdot \rho / W; \quad (2)$$

$$\sigma_c = 32 \cdot \rho / W; \quad (3)$$

here W means impact work, ρ is the density of the specimen, σ_c is the compressive strength of the specimen means.

3.2.1 Elliptic design domain

During the optimal design procedures, one needs elliptic design domain of the data set to provide convexity of the feasible solutions. It also can demonstrate the uncertainty of the data set with this application. In this way the different sets of impact works -UCS data set were used to define this domain. A MATLAB code was written on the optimization principle, that the covered elliptic area should be minimal, while any of the measured points has to be inside the domain (under the ellipse). The following elliptic curves were determined: Fig. 10 all measured specimens, Fig. 11 saturated specimens and Fig. 12 dry specimens, respectively.

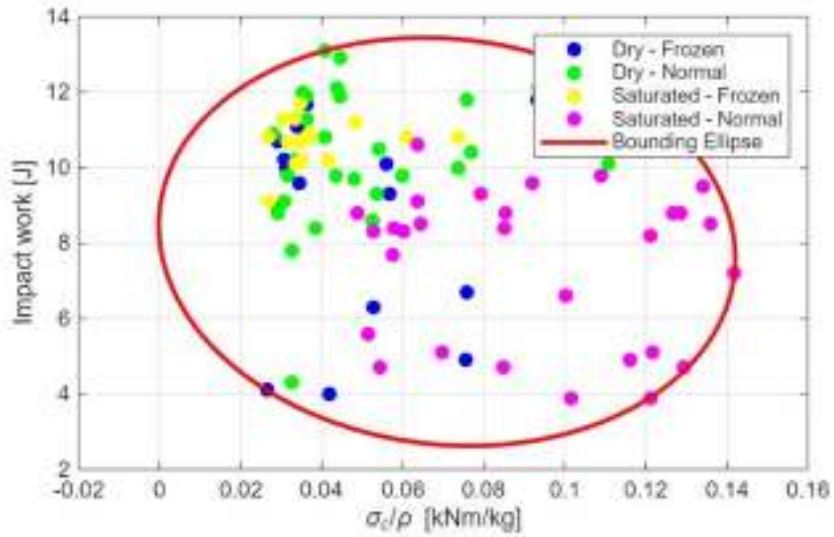

Fig. 10: Elliptic design domain for all points

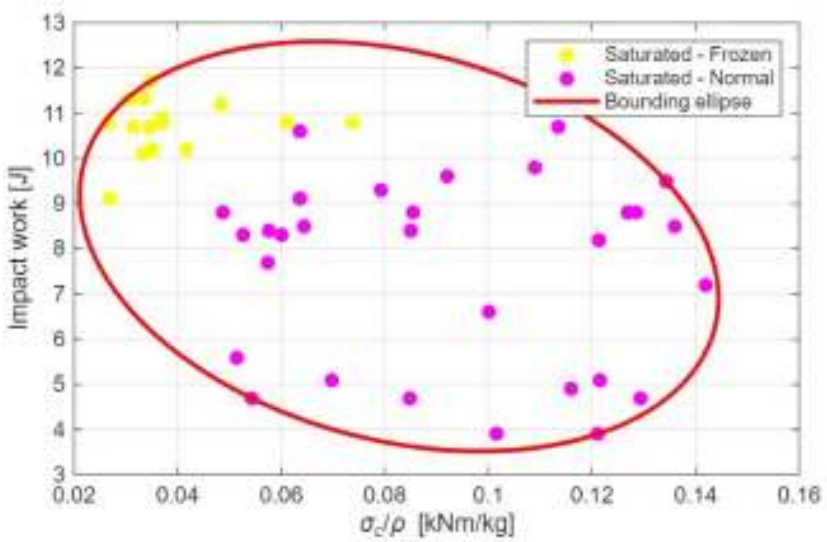

Fig. 11: Elliptic design domain for saturated specimens

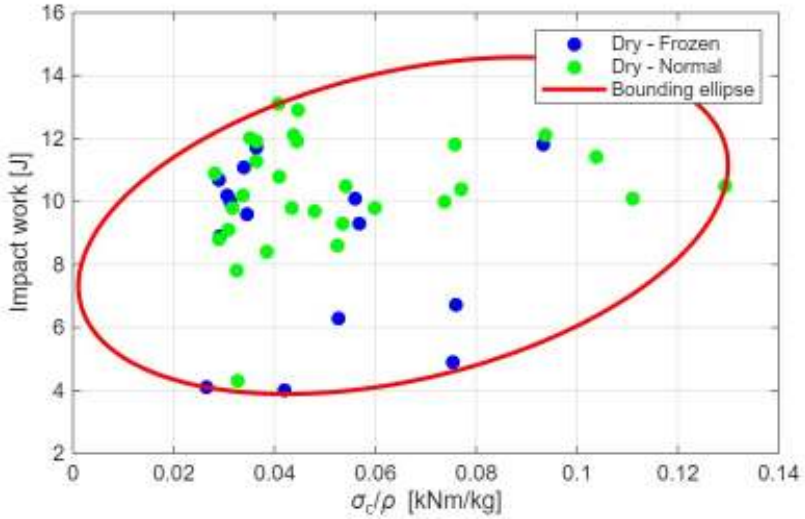

Fig. 12: Elliptic design domain for dry specimens

4 New scientific results, theses

My research works were divided into two main directions. The first one is connected to the virtual test based investigations of Poisson's ratio of rocks and the other one is related to the laboratory tests based researches of the dependence of the impact resistance and the compressive strength of sedimentary rocks with different environmental conditions.

The goal of this first part of the virtual tests based theoretical research was to investigate the possibility: how the Poisson's rate of the intact rock depends on the rigidity of the material. According to the different theories the Poisson's ratio decreasing in case of increasing rigidity. I have also investigated the relationship between the confining stress and the Poisson's ratio value of intact rock and the connection between the Poisson's ratio and the Geological Strength Index (GSI). The relationship between the confining stress and the Poisson's ratio, as a simple linear relation, can be created easily and does not need any other information than the Poisson's ratio of the intact rock without confining pressure ($\nu = \nu i$) and the transient stress value. It has to be mentioned, that the Poisson's ratio can be differently handled. As it was indicated, it can be more accurately described as an elastic deformation parameter that monotonously increases with stress during the compressive processes. As it was known from the literature experimentally was proved by the results of Dong et al. (Dong 2021), different rocks exhibit different behaviors in their Poisson's ratios. In hard rocks, the secant and average Poisson's ratios grow approximately linearly with stress in the main stages of the loading process. However, in soft rocks, these ratios quickly increase beyond the theoretical maximum of 0.5 in the initial loading stage. In that case a bilinear expression can be created, but the determination of the intermediate point is critical in that approximation. The intermediate point is the case where the axial stress reaches 20–30% of the transition stress. If this intermediate point is known a Lagrange or a Hermitian approximation can be applied, as well. In these last cases non-linear approximations are used instead of linear ones.

Thesis I.a:
By the use of parametric study I found that the Poisson's ratio decreasing in case of increasing rigidity. The best resulting formula is:

$$\boldsymbol{\nu = \frac{1}{\sqrt{m_i}+1}}$$

Thesis I.b:
Based on my parametric studies, I found a correlation between changes in the value of the Poisson's ratio so far considered constant based on the environmental pressure (between 0 and 8 MPa) and the GSI value. It is clear that decreasing the GSI value also

decreases the value of the Poisson's ratio, while if the value of the σ_3 increases, the Poisson's ratio also increases.

Thesis I.c:
By the use of parametric study, I found that the Poisson's ratio's value changes suddenly and rapidly (increases) as the environmental pressure (between 0 and 8 MPa) increases, then slows down but does not disappear.

related publications:

Lógó, B. A., Vásárhelyi, B. (2019) "Estimation of the Poisson's Rate of the Intact Rock in the Function of the Rigidity", Periodica Polytechnica Civil Engineering, 63(4), pp. 1030–1037, 2019. https://doi.org/10.3311/PPci.14946

Lógó, B. A., Vásárhelyi, B. (2020) "Parametric Study on the Connection Between Poisson's Ratio, GSI and Environmental Stress", Computer Assisted Methods in Engineering and Science, 27(2–3), pp. 205–217, 2020. https://doi.org/10.24423/cames.287

Lógó, B. A., Vásárhelyi, B. (2022). Theoretical Relationship between the Confining Pressure and Poisson's Ratio of Intact Rock. *Periodica Polytechnica Civil Engineering*, *66*(4), 1114-1121.

Based on the tests performed in laboratory, it can be concluded that the Charpy impact test can also be used on sandstones, based on the measurement results, meaningful and clearly defined correlations can be seen. The lower and upper limits of the range of the measurement results can be determined regardless of the saturation state and temperature. By the use of these relationships it is easy to determine either the compressive strength of the sedimentary rocks based on the knowledge of the impact work or the impact work based on the knowledge of the compressive strength. The latter case can be useful for explosions, since the maximum and minimum required impact energy can be estimated with a simple relationship.

Measurements performed at different temperatures and saturation states showed that the temperature of the sample at temperatures between -12°C and 22°C only minimally affects the result. The water saturation of the sample has a much greater effect on the impact resistance. Due to the ice in the samples, the impact resistance of the frozen, saturated sample either does not change compared to the impact energy of the air-dry sample or increases slightly.

Thesis II.

I have elaborated an experimental program to measure the impact work of green sandstone. By the use of Charpy impact test the compressive strength of green sandstone can be estimated.

related publications:

Lógó, B. A., Vásárhelyi, B. (2025). Estimation of the constitutive relationship between impact resistance and compressive strength in sandstones, *Periodica Polytechnica Civil Engineering 69(3), pp. 944–953, https://doi.org/10.3311/PPci.40270*

Lógó, B. A., Vásárhelyi, B. (2021). Charpy impact test to sedimentary rocks. *In: B. Blachowski and P. Tauzowski (eds.) Book of Abstracts-2nd Workshop on Engineering Optimization, Warsaw* (pp. 89-97).

Lógó, B. ; Vásárhelyi, B. (2022) Charpy impact test to sedimentary rocks, In: Coric, Slobodan; Papic, Jovan (eds.) Engineering problems in soft rocks, Skopje, North-Macedonia: Macedonian Association for Geotechnics pp. 839-844. , 6 p. ISBN 978-9989-2053-4-7

It is important to utilize scientific results. As it was presented in Section 4, these results were used in applications. Additionally, we have investigated what is the effect of the variable Poisson's ratio for the optimal topology.

Related publications:

Lógó, B.A. ; Lógó, J.; Tauzowski P., Blachowski B., (2019) Rugalmas képlékeny anyagú topológia optimálás változó Poisson tényező felhasználásával, In: Baksa, Attila; Bertóti, Edgár; Kiss, László; Szirbik, Sándor (szerk.) XIII. Magyar Mechanikai Konferencia, Miskolc-Egyetemváros, Magyarország: Miskolci Egyetem, Műszaki Mechanikai Intézet pp. 1-1. Paper: 468 , 1 p.

Lógó, B. A.; Bruggi, M.; Lógó, J. (2022) Computational aspect of a reconstruction of heritage structure built as ribbed masonry vaults, In: Ivica, Skozrit; Jurica, Soric; Zdenko, Tomkovic (eds.) 10th ICCSM International Congress of Croatian Society of Mechanics : Book of Abstracts, pp. 189-190.

Thesis III.

In the case of green sandstone, the lower and upper limits between the magnitude of the impact work and the compressive strength can be determined based on the measurement results, regardless of the saturation state and temperature.

Thesis III.a

I defined the envelop boundaries, between 0 and 14 J impact work, belongs to the different saturated state and temperature.

Thesis III.b
In the case of green sandstones, in the range of -12°C and +22°C, in contrast to metals, the value of the impact work is largely influenced not by the temperature, but by the saturation state.

Thesis III.c
I defined the elliptic design domain that belongs to the different saturated state and temperature.

related publications:

Lógó, B. A., Vásárhelyi, B. (2025). Estimation of the constitutive relationship between impact resistance and compressive strength in sandstones, *Periodica Polytechnica Civil Engineering 69(3), pp. 944–953, https://doi.org/10.3311/PPci.40270.*

Lógó, B. A., Vásárhelyi, B. (2021). Charpy impact test to sedimentary rocks. *In: B. Blachowski and P. Tauzowski (eds.) Book of Abstracts-2nd Workshop on Engineering Optimization, Warsaw* (pp. 89-97).

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Lógó, B. A.; Bruggi, M.; Lógó, J. (2022) Computational aspect of a reconstruction of heritage structure built as ribbed masonry vaults, *In: Ivica, Skozrit; Jurica, Soric; Zdenko, Tomkovic (eds.) 10th ICCSM International Congress of Croatian Society of Mechanics: Book of Abstracts, pp. 189-190.*

5 Self publications in the topic of the dissertation

5.1 Journal papers

Lógó, B. A., Vásárhelyi, B. (2019a): Estimation of the Poisson's Rate of the Intact Rock in the Function of the Rigidity, Periodica Polytechnica Civil Engng, 63(4): 1030–1037 https://doi.org/10.3311/PPci.14946

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