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ELASTIC AND MECHANICAL PROPERTIES OF MRKOTIN GRANITE:
A COMPREHENSIVE LABORATORY STUDY

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ABSTRACT

This study presents a comprehensive laboratory analysis of the elastic and mechanical properties of Mrakotin Granite (MG), a high-quality granitic rock from the Czech Republic known for its strength, frost resistance, and low porosity. A range of experiments was conducted, including porosity and permeability tests, tensile and compressive strength measurements, ultrasonic velocity analysis, and evaluations of both static and dynamic elastic moduli. Results confirm that MG is a highly low-permeability material ($\Phi < 0.9\%$) with high uniaxial compressive strength (UCS ≈ 180 MPa), making it highly suitable for geotechnical and geophysical applications such as hydraulic fracturing studies. Ultrasonic measurements under confining pressure revealed moderate elastic anisotropy at low pressure ($k_a \approx 9\%$), which decreases with increasing pressure ($k_a \approx 3\%$ at 120 MPa), indicating microcrack closure and a transition from crack-dominated to matrix-dominated behaviour. Young's modulus increased by up to 80 % under pressure, and the measured static and dynamic elastic moduli are consistent with reported values for other granitic rocks. In conclusion, Mrakotin Granite demonstrates a highly homogeneous structure, mechanical stability, and excellent elastic properties, making it a promising material for demanding engineering purposes and advanced geophysical research.

HIGHLIGHTS

- Mrakotin Granite shows very low porosity ($<0.9\%$), high UCS (~ 180 MPa), and minimal permeability, ideal for demanding engineering applications
- Ultrasonic tests reveal elastic anisotropy decreases from $\sim 9\%$ at ambient pressure to $\sim 3\%$ at 120 MPa, reflecting microcrack closure processes
- Static and dynamic elastic moduli increase up to $\sim 80\%$ under pressure, indicating significant microcrack influence at low confining pressures
- Results confirm Mrakotin Granite as suitable for geophysical research and hydraulic fracturing studies due to stable elastic and mechanical properties

1. INTRODUCTION

Mrakotin Granite (MG) is a high-quality natural stone from the Czech Republic, renowned for its durability, strength, and medium- to coarse-grained two-mica granite. It is typically light gray in color with a uniform texture, making it ideal for both structural and decorative applications. Despite its high-quality granitic nature, only a few publications have studied

its physical and elastic properties. For instance, René (2000) studied the evolution of the two-mica granites, including the Mrakotin subtype (René, 2000), Gernová (2010) discussed the properties, utilization, and research on Mrakotin-type granite at the Horní Dvorce Quarry (Střejbar et al., 2010). René (2016) examined the two-mica granites in the area between Mrakotin and Rasna (René, 2001). Zel et al. (2020) studied Mrakotin Granite using neutron tomography to analyze its structural properties (Zel et al., 2020), Bankwitz et al. (2004) discussed early cooling and fracturing in Mrakotin Granite (Bankwitz et al., 2004). MG is suitable for various applications due to its durability, strength, and aesthetic appeal. It is commonly used for: Monuments and memorials – Due to its resistance to weathering and elegant appearance; Building facades and cladding – Provides a luxurious and long-lasting finish; Paving and flooring – Ideal for both interior and exterior surfaces; Sculptures and decorative elements – Used by artists for its grain size and polishability; Staircases and countertops – Popular in architecture and interior design.

Due to its physical and elastic properties, MG has also been found suitable for extensive laboratory testing, particularly in studies on the hydraulic fracturing of rocks under triaxial loading. The reason is that the reservoir rocks used in many geothermal

projects, where the hydraulic fracturing method is employed, primarily consist of granite. The high fracture density in these reservoir rocks necessitates an understanding of the rock mass's strength and elastic modulus. However, such research requires a comprehensive understanding of MG's physical and elastic parameters, which are essential for processing and interpreting results from hydraulic fracturing experiments. The knowledge of such parameters is crucial for the interpretation of hydraulic fracturing results, like the velocity model of the specimen under study, interpreting the mechanism of fracturing based on acoustic emission, etc. For this reason, specimens drilled from a $15 \times 15 \times 15$ cm cubic sample underwent intensive analysis, including porosity, hydraulic permeability, compressive and tensile strength, ultrasonic velocity measurements, and both static and dynamic elastic properties.

2. EXPERIMENTAL SETUP

2.1. ROCK DESCRIPTION AND SAMPLE PREPARATION

Controlled laboratory experiments on hydraulic fracturing were carried out on Mrakotin Granite (MG). MG is a two-mica (biotite-muscovite) granite that forms the central part of the Czech branch of the central Moldanubian pluton in the Bohemian Massif, Czech Republic. Its mineral composition includes quartz, feldspars (potassium feldspar and plagioclase), and micas (biotite and muscovite). On fresh fractures, the rock exhibits a white-gray color. The texture of the granite is isotropic and compact. According to granite typology, it is classified as an S-type granite, formed by the melting of sedimentary rocks. The magma likely originated from the melting of Moldanubian paragneiss during their rapid uplift in the final stages of the Variscan orogeny. The exceptional properties of MG, such as its resistance to mechanical wear and frost, make it highly valued. MG is sourced from the area around the village of Mrakotin in the Jihlava district in the Vysočina region of the Czech Republic and is recognised as a high-quality granite renowned for its hardness and durability. This granite has been quarried in the vicinity of Mrakotin near Telč at the quarry Panské Dubénky, Czech Republic. The quarry within the cadastral area of Mrakotin was established in 1863, with additional quarries opened in subsequent years. The MG rock was subjected to intensive study before the preparation of the experiment. A cubic sample measuring $150 \times 150 \times 150$ mm was obtained from a rock block sourced by blasting in the quarry. The cube was prepared by the company Granit Máca Ltd. All samples were cut from this single MG cube, which had an edge length of 15 cm. For all samples, the same Cartesian right-handed coordinate system (XYZ) was assigned, corresponding to the edges of the initial large cube. This was due to the absence of evident structural features such as foliation or lineation.

- A 30 μm petrographic thin section was prepared for analysis under a petrographic microscope.

- For mercury intrusion porosimetry, small cylindrical samples with a diameter of 11 mm and a height of 15 mm were prepared. Two cylinders were simultaneously inserted into the penetrometer, allowing for the determination of pore size distribution, porosity and for evaluation of permeability.
- For permeability measurements, two cylinders with a diameter of 50 mm and a height of 40 mm were prepared to assess hydraulic conductivity.
- For tensile strength determination using the Brazilian test, four cylinders with a diameter of 50 mm and a height of 26 mm were prepared.
- For the uniaxial compression strength (UCS) test and static elastic moduli determination, one cylinder with a diameter of 50 mm and a height of 100 mm was prepared.
- For elastic anisotropy determination by the pulse transmission method under high hydrostatic pressure, a sphere with a diameter of 50 mm ± 0.05 mm was prepared. This sphere was also used for dynamic elastic moduli determination. For ultrasonic measurements at increased pressures, the spherical samples were dried in an oven at 100 °C and coated with epoxy resin to protect the pore space from infiltration by the oil used as a pressure medium during high-pressure measurements. The epoxy resin coating was 0.1 mm thick.
- The measured dry density of the samples was 2.635 g.cm⁻³.

2.2. MERCURY INTRUSION POROSIMETRY METHOD

Mercury intrusion porosimetry is one of the crucial methods for pore network determination in rocks (Giesche, 2006). Porosimetric analysis of a cylindrical sample of granite was done by PASCAL 140 Evo and PASCAL 440 Evo mercury porosimeters (Thermo Fisher Scientific, Germany) in the pore size range of mesopores (2-50 nm in diameter) and macropores (> 50 nm in diameter) in the working size range 7 nm–112 μm . The pore surface (S) and volume (V), and porosity (Φ_{MIP}) are the main textural parameters. Pore size distribution, volume and surface of pores were calculated in software using the Washburn equation with constants as contact angle of 140° and mercury surface tension of 0.48 n/m (Washburn, 1921a, 1921b), and modified equations based on (Wardlaw, 1976; Wardlaw and McKellar, 1981). The principle of measurement consists of the squeezing of mercury into the pores due to increasing pressure and the displacement of mercury as the pressure decreases. The shape of the intrusion/extrusion curve defines the used model for evaluating the pore surfaces (Bernabé and Mainiult, 2015; Scheidegger, 1958).

Some macroscopic properties can be evaluated from the mercury porosimetric data. The approximation of the general permeability coefficient

(K_{Hg}) in m^2 was done from porosimetric data in S.O.L.I.D EVO software using equations (1) (Scheidegger, 1974) and the evaluation (2) (Carniglia, 1986) for tortuosity.

$$K_{Hg} = \frac{\phi_{Hg} \cdot d^2}{16 \cdot t} \quad (1)$$

$$t = 2.23 - 1.13 \cdot V \cdot \rho \quad (2)$$

where ρ = bulk density (2.6104 g.cm^{-3}), ϕ_{Hg} = porosity, d = pore diameter, V = total pore volume, t = tortuosity was obtained by mercury porosimetry.

It should be noted that the bulk density used in mercury intrusion porosimetry is a derived parameter related to the effective pore-accessible volume and does not represent a directly measured physical density. In low-porosity crystalline rocks, this effective density may be slightly lower than the gravimetrically determined dry density, particularly due to the presence of closed pores and the sensitivity of porosimetric calculations to small volume uncertainties.

The filtration coefficient (k_{Hg}) in $m.s^{-1}$ was evaluated by equation (3)

$$k_{Hg} = \frac{k \cdot \gamma}{\eta} \quad (3)$$

where specific gravity of mercury at 20°C $\gamma = 133416 \text{ N.m}^{-3}$, dynamic viscosity of mercury $\eta = 1.55 \text{ e}^{-3} \text{ Pa.s}^{-1}$. The rocks with $k_{Hg} = 10^{-2}$ - 10^{-7} are permeable, collectors, $k_{Hg} < 10^{-8}$ are nonpermeable, insulators.

The drainage coefficient (n_{dr}) is connected with macropores ($V_{>50nm}$ is volume of pores $> 50 \text{ nm}$), which serve as transport pores for liquids. V_{vz} is the total volume of the sample. When the n_{dr} is in the range from 0.2 to 0.4, the material is well permeable, and values < 0.2 are common for poorly permeable materials.

$$n_{dr} = \frac{V_{>50nm}}{V_{vz}} \quad (4)$$

The other factor is the frost resistance (F) of natural stones, which is evaluated on the basis of equation (5) (Maage et al., 1985). There is a necessary percentage of pore volume for pores $r \geq 15 \text{ nm}$ (V_{15nm}) of the total pore volume V obtained by mercury porosimetry. When the values are $F \leq 280$, the material is not frost resistant; $F \geq 310$ is frost resistant.

$$F = \frac{6.2}{V} + 2.1 \cdot V_{15nm} \quad (5)$$

2.3. LOADING SYSTEM

The MTS815 digitally controlled servo-hydraulic system was used for uniaxial loading tests, including the Brazilian test and UCS. A constant loading rate of 10 N.s^{-1} was applied until failure. Two axial MTS extensometers and one MTS circumferential extensometer were attached to the specimen to measure relative deformations. Using the MTS system, the specimen was uniaxially loaded in compression up to peak stress. Loading was controlled

through a linear combination of axial stress (σ) and axial strain (ϵ). Steel loading platens were used to apply compressive force on the rock specimen along its diameter of 50 mm for Brazilian tests. This ensured uniform load distribution on the disc. Cylindrical rock samples with a typical diameter-to-thickness ratio of 2:1 were prepared according to standard ISRM specifications.

2.4. PERMEABILITY MEASUREMENT

Hydraulic conductivity was measured on a cylindrical specimen with a diameter and length of 50 mm using a high-precision Quizix 5000 pump. This setup allows for highly precise measurements of volumetric changes under high pressures, enabling the determination of the filtration coefficient down to the order of $10^{-18} \text{ m.s}^{-1}$. The vertical axis of the cylinder aligns with the Y-axis of the spherical specimen's coordinate system. A steady flow rate method (constant pressure gradient) was applied to determine hydraulic conductivity, assuming the validity of Darcy's law. Upstream and downstream pressures were set at 1.5 MPa and 1 MPa, respectively. Measurements were conducted at an effective confining pressure starting from 3 MPa at a room temperature of 20°C . Distilled water was used as the transport medium. The obtained values were corrected to a reference temperature of 10°C , which corresponds to the temperature of underground water, using Poiseuille's empirical formula. Permeability was then calculated from hydraulic conductivity using the kinematic viscosity of water at 10°C ($1.31 \text{ mm}^2.\text{s}^{-1}$).

2.5. HIGH-PRESSURE MEASURING SYSTEM

Ultrasonic sounding (US) of the spherical specimen was performed using the pulse transmission method in a high-pressure vessel. The technical procedure of the measurement process is described in greater detail by (Lokajíček and Svitek, 2015). The system allows US measurements of a spherical specimen under varying confining pressures, ranging from 0.1 to 120 MPa. A total of 132 regularly distributed points were positioned across the sphere's surface, each spaced 15° apart from its neighbouring points, distributed along meridians and parallels, avoiding the impression of uniform spacing between all neighbouring points. High pressure was applied using oil during the ultrasound measurements. The apparatus is capable of measuring both P- and S-waves (S1, S2 – perpendicularly polarised), employing shear-wave gel on the specimen's surface to enhance contact conditions between the sensors and the specimen. Utilising a recently developed measuring head allowed us to obtain the S1 (faster) and S2 (slower) shear-wave velocity distributions and thus to retrieve a complete elastic tensor accurately. The S1 and S2 wave arrivals are initially picked manually. Subsequently, before the inversion procedure, the software automatically determines the fast and slow shear-wave components based on the picked arrival

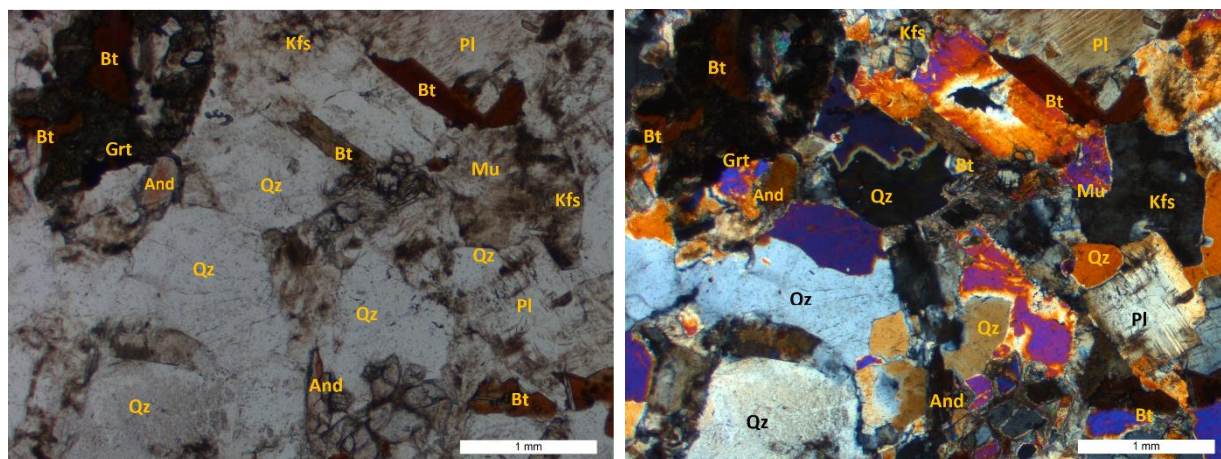


Fig. 1 Petrographic thin sections of the sample illustrating the microstructure of MG. Some grains are marked - Qz (Quartz), And (Andalusite), Bt (Biotite), Mu (Muscovite), Kfs (K-feldspar), Grt (Garnet).

times. We stress that the S1 and S2 describe the faster and slower shear waves for each particular direction and are not directly related to their polarisation. Since we measure the ray (group) velocities but not the phase velocities, we have to recalculate the group velocities to the phase velocities before applying the inversion procedure. Therefore, we construct the wave surface from a dense grid of measured group velocities and by applying a simple transformation, we obtain the corresponding phase velocity surface. This dense grid is constructed from a large number of predefined ray paths connecting source–receiver points distributed over the spherical surface. The phase velocities are then inverted for a full set of anisotropic constants. The whole inversion process is described step by step in (Svitek et al., 2014). Based on the method proposed by (Klíma and Červený, 1973), the complete stiffness tensor was derived in an experimentally chosen coordinate system. This tensor consists of 21 independent parameters. Work (Aminzadeh et al., 2022) introduced a methodology for automatically transforming the obtained stiffness tensor into the material's principal coordinate system, without requiring any prior assumptions. In the cited work, the conversion to elastic parameters was performed only assuming orthorhombic symmetry. In the present study, it should be noted that the full triclinic symmetry was first determined and subsequently transformed into the principal coordinate system at low hydrostatic pressures. At higher pressures, the tensor approaches near-orthorhombic symmetry. Using this approach, it was possible to determine the Young's moduli, shear moduli, and Poisson's ratios in three mutually perpendicular planes of the material.

3. EXPERIMENTAL RESULT

3.1. MRAKOTIN GRANITE THIN SECTIONS

A polished thin section from Mrakotin Granite was prepared, and its composition and structural arrangement were determined. The grains forming the rock mostly do not follow a specific arrangement, and most of them are cracked; small gaps are visible

between the grains. The rock consists of quartz, two types of feldspar: potassium feldspar and calcium-sodium feldspar (plagioclase), two micas: biotite and muscovite, andalusite, many fractured garnets, and a small amount of ore minerals, see Figure 1. Quartz forms grains ranging from 0.15 to 1.5 mm in size, which exhibit visible fractures across their entire length. Feldspar forms grains ranging from 0.2 to 1 mm, which are also fractured; in some grains, plagioclase forms a microcline grid. Quartz appears white to orange in crossed nicols, possibly due to the high thickness of the thin section. Biotite is more abundant than muscovite and is quite easily distinguishable, showing a saturated brown colour in both nicols. Grains ranging from 0.3 to 1.5 mm also contain fractures. Andalusite forms grains ranging from 0.1 to 0.5 mm; it appears pink in plane-polarised light and dark orange in crossed nicols. Garnets are heavily fractured, and their original shapes are not always recognisable; they contain inclusions of other minerals. Its constituent minerals are Plagioclase Feldspar (10-50 %), Potassium Feldspar (K-feldspar) (20-60 %), Quartz (20-60 %), Biotite and Muscovite, combined (5-15 %), Andalusite (up to 0.8 %), and a small amount of accessory minerals: trace amounts of apatite, zircon, monazite, sillimanite, and cordierite.

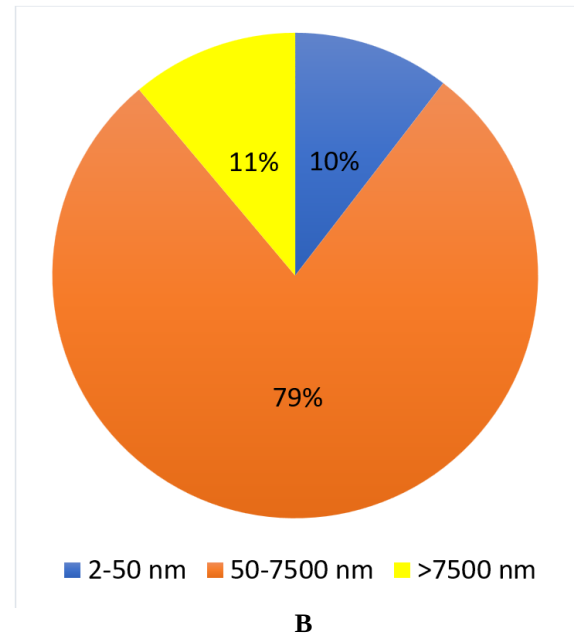
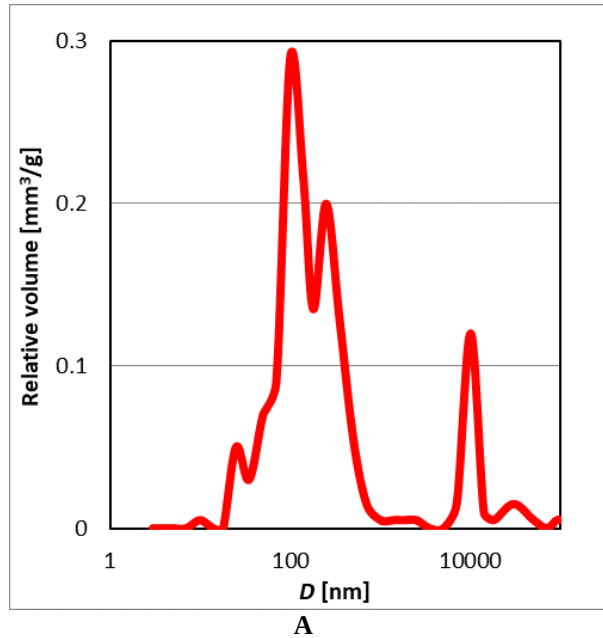
3.2. MRAKOTIN GRANITE TEXTURE

The textural parameters in Table 1, porosity, surface and volume of mesopores and macropores (from 7 nm to 112 μm in diameter) and permeability values are typical for similar raw granitic materials e.g. 0.24 % of fine granulated granite (Řimnáčová et al., 2024), 0.01-9.8 % for granites in the study (Haffen et al., 2017), 0.68 % for granite with similar granularity (Chaki et al., 2008).

Meso and macropores strongly influence the stability and permeability of materials. The pore size distribution of MG determined using mercury porosimetry (Figs. 2 A, B) showed the prevailing content of macropores in the size interval 50-7500 nm. The low porosity (Φ_{Hg}) of the Mrakotin granite

Table 1 Textural and macroscopic properties of MG. V – volume, S – surface of meso- and macropores, Φ_{Hg} – porosity, k_{Hg} – filtration coefficient, K_{Hg} – permeability, n_{dr} – drainage coefficient, F – frost resistance.

V [mm ³ .g ⁻¹]	S [m ² .g ⁻¹]	Φ_{Hg} [%]	k_{Hg} [m.s ⁻¹]	K_{Hg} [m ²]	n_{dr} [-]	F [-]
1.5	0.15	0.39	2.50e ⁻¹⁴	1.91e ⁻¹⁶	0.0015	54.4

**Fig. 2** **A** Pore size distribution of granite obtained by mercury porosimetry, **B** The percentage of volume in pore size classes obtained by mercury porosimetry.**Table 2** Parameters used for evaluating the permeability of Mrakotin Granite (MG) determined by hydraulic conductivity measurements. L – height of the sample, d – diameter, A – contact area, V – volume of water flowed, H – hydraulic gradient, t – time of testing, T – temperature, Const. - conversion factor, k_w – filtration coefficient, K_w – permeability.

L [mm]	d [mm]	A [cm ²]	V [ml]	H [m]	t [min]	T [°C]	Const.	k_w [m.s ⁻¹]	K_w [m ²]
52.44	50.05	19.67424	0.02704	153.1	1482	20	1.67e ⁻⁰⁷	5.3e ⁻¹⁴	5.44e ⁻²¹

reflected the fact that the material had a low content of pores > 7500 nm and low total pore volume (Fig. 2B, Table 1). This makes this kind of granite rock impermeable (low n_{dr} and K_{Hg}) and almost non-porous.

3.3. PERMEABILITY MEASUREMENT

To determine the hydraulic conductivity coefficient, measurements were conducted in a triaxial chamber under a confining and axial pressure of 5 MPa. The inlet pressure to the sample (lower drainage) was maintained at 3 MPa, while the outlet pressure (upper drainage) was kept at 1.5 MPa, ensuring a constant pressure differential of 1.5 MPa throughout the experiment. This corresponds to a hydraulic gradient of 153 m. Assuming laminar flow, the determined filtration coefficient should not depend on the hydraulic gradient. The Quizix 5000 permeameter was used for generating pressure at the lower and upper drainage points, as well as for

measuring and recording pressures and the volume of fluid passed through the sample.

The MG sample represents intact rock without external influences. Table 2 presents the permeability values and the sources used for their calculation obtained by the hydraulic conductivity measurement method. The measurements were conducted at a constant laboratory temperature of 20 °C. The determined hydraulic conductivity coefficient, measured at a constant laboratory temperature of 20 °C, was recalculated to the filtration coefficient at a water temperature of 10 °C.

3.4. MRAKOTIN GRANITE UCS TEST

The uniaxial compression strength (UCS) was carried out by uniaxial loading of Mrakotin cylindrical samples with a diameter of 50 mm and a height of 100 mm. Before the UCS test, the cylindrical sample was ultrasonically sounded along its rotation axis by P

Table 3 Static and dynamic properties of Mrakotin Granite. Φ_w – porosity obtained by water, UCS – uniaxial compression strength, v_p – P-wave velocity, v_s – S-wave velocity, E_s – static Young's modulus, G_s – static Shear modulus, ν – static Poisson's ratio, K_s – static Bulk modulus.

Grain size [mm]	Density [g.cm ⁻³]	Φ_w [%]	UCS [MPa]	v_p [km.s ⁻¹]	v_s [km.s ⁻¹]	E_s [GPa]	G_s [GPa]	ν [-]	K_s [GPa]
0.3 - 2	2.636	0.86	180	4.752	2.784	53.63	22.01	0.21	31.40

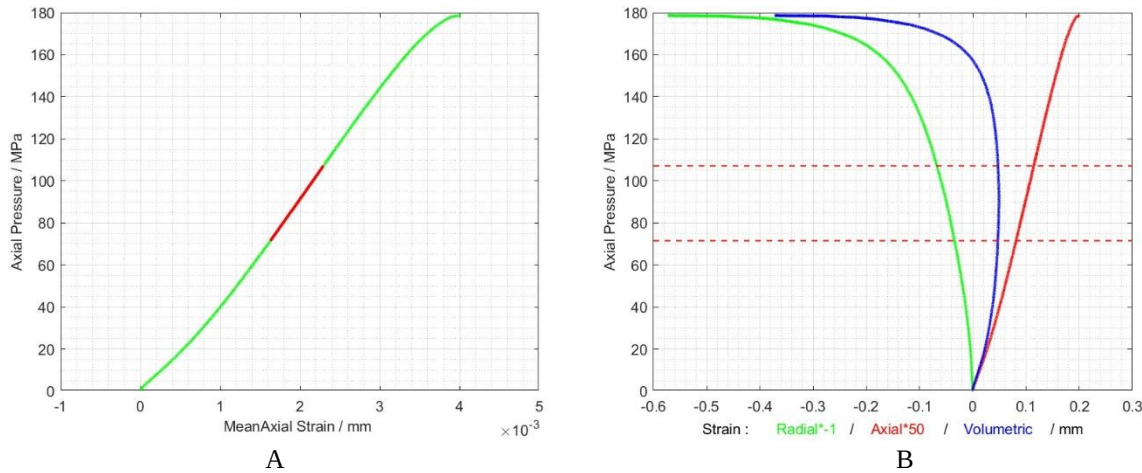


Fig. 3 **A** Axial strain dependence of the Mrakotin specimen is denoted in green. Red line elastoplastic section selected for static and dynamic moduli calculation. **B** Green – radial deformation, blue – volumetric deformation, red – axial strain. The dashed red line indicates the data range selected for calculating the static elastic parameters.

Table 4 Indirect determination of the tensile strength by Brazilian test. h – disk height, D – diameter of the disk, Max F – maximum force, σ_{rtAV} – tensile strength, σ_{rtSTD} – standard deviation of tensile strength.

Sample	h [mm]	D [mm]	Max F [kN]	σ [MPa]	σ_{rtAV} [MPa]	σ_{rtSTD} [MPa]
M2.1	26.31	50.03	19.81	9.572	11.278	1.172
M2.2	26.73	50.04	24.27	11.558		
M5.1	26.85	50.04	24.8	11.758		
M5.2	26.63	50.07	25.59	12.225		

and S Olympus 1 MHz resonant sensors. Cylinder v_p and v_s velocity is shown in Table 3.

The obtained values are presented in Figure 3. For determining these values, two axial extensometers and one radial chain extensometer were used. In Figure 3A we can observe the axial strain behaviour of the sample. The course is quite monotonic and does not show significant deviations. This indicates uniform loading of the sample and low anisotropy. The elastoplastic section (40-60 %) selected for static dynamic moduli calculation is shown in red colour. In Figure 3, the overall load behaviour of the sample along the σ_1 axis over time is shown. The sample displays quasi-linear elastic response, with a gradual elastoplastic response from 10 % to 90 % percentage of the peak axial stress, indicating the closure of all cracks in the range of 0–10 (15) %, which suggests low sample damage. We can classify this Mrakotin specimen into the very high strength group.

In Figure 3B, the axial strain averaged from two axial extensometers is shown. The interval between the dashed red lines in Figure 3B denotes the data range selected for the calculation of the static Young's modulus and Poisson's ratio. Other static elastic

moduli, such as the shear modulus (G) and bulk modulus (K), were calculated using the formulas listed below. The key properties of MG are summarised in Table 3.

$$K = E / (3(1 - 2\nu)) \quad (6)$$

$$G = E / (2(1 + \nu)) \quad (7)$$

3.5. BRAZILIAN TEST

The Brazilian test is an indirect method to determine the tensile strength of a rock specimen. A cylindrical disk is subjected to a compressive load applied diametrically, a tensile stress develops perpendicular to the loading direction, causing the rock to split.

The mean tensile strength was determined to be 11.278 MPa, and the standard deviation is 1.172 MPa.

3.6. SPHERE VELOCITY AND ELASTIC PROPERTIES STUDY

Figure 4 summarises P, S1- and S2-wave velocities distribution at the range of hydrostatic pressure between 0.1 and 120 MPa of hydrostatic pressure. 3D distributions are displayed in equal-area

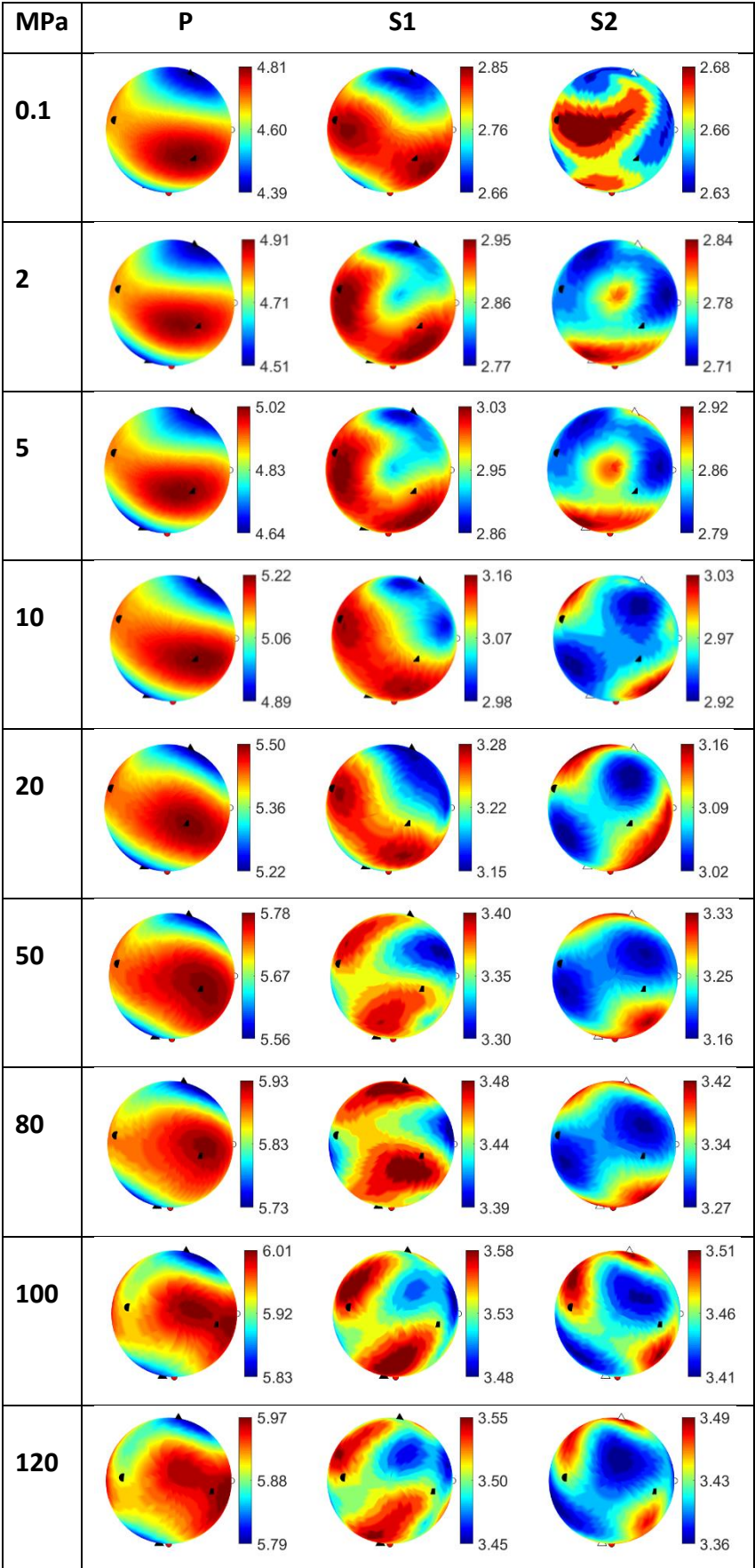


Fig. 4 The phase velocity distribution of the MG sample plotted in the equal-area stereographic projection on the lower hemisphere. From left to right: velocities of the P, S1, S2 waves. The pressure level increases from top to bottom. Stiffness tensor orientation is represented by the black symbols: square – x1-axis (maximum P-wave velocity), circle – x2-axis (intermediate P-wave velocity), triangle – x3-axis (minimum P-wave velocity).

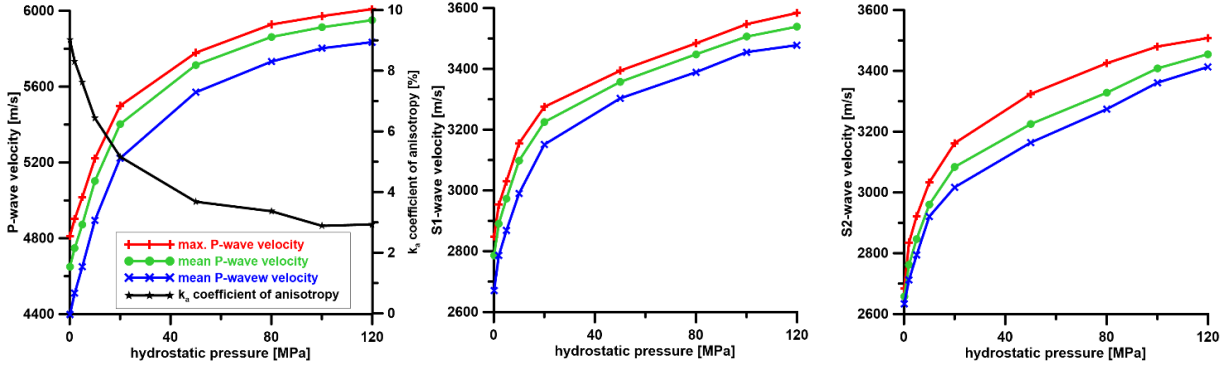


Fig. 5 The maximum, mean, and minimum phase velocity/pressure plots together with the coefficient of anisotropy $k_a = 100 (v_{\max} - v_{\min}) / v_{\text{mean}}$. From left to right: P, S1, S2 waves. The values themselves can be found in Appendix A.

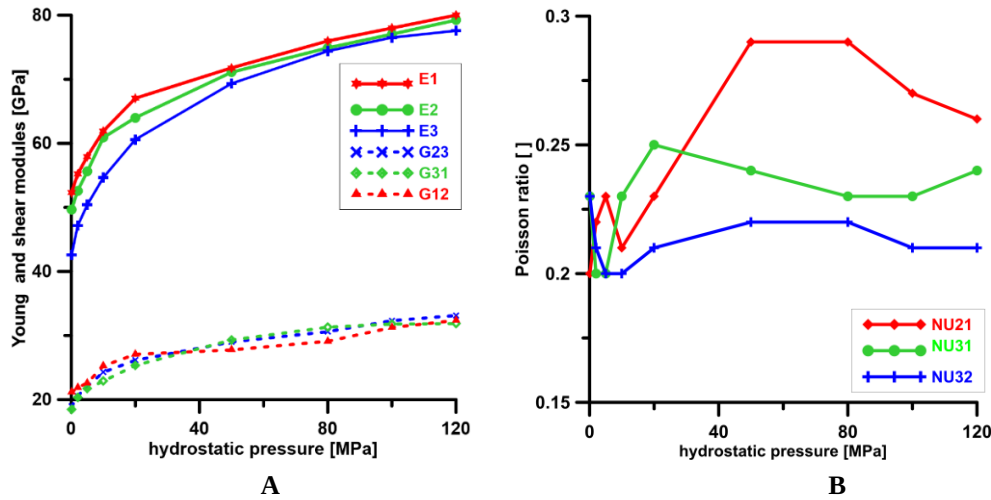


Fig. 6 **A** Dynamic elastic parameters ($E1$, $E2$, $E3$, $G23$, $G31$, $G12$), **B** Poisson constant (NU21, NU31, NU32) in three principal planes for the MG sample. The values themselves can be found in Appendix B.

projection. MG is very compact with low porosity and homogeneous, as at all values of hydrostatic pressure, all velocity isolines are very similar. A similar orientation of material principal directions is denoted by black symbols.

Figure 5 displays the velocity/pressure dependency for three extreme directions together with the degree of anisotropy evaluated in percent, $k_a = 100 * (v_{\max} - v_{\min}) / v_{\text{mean}}$. Velocity dependence exhibits an exponential trend with increasing pressure. At atmospheric pressure, the velocity range of P-waves is in the range 4.4 to 4.8 km.s⁻¹ and the coefficient of anisotropy $k_a = 9\%$; at 120 MPa the P-wave velocity range is 5.8 to 6.0 km.s⁻¹ and $k_a = 2.9\%$ respectively. Similarly, the S-wave dependence shows exponential dependence too. At atmospheric pressure S1-wave velocity range is 2.7 to 2.8 km.s⁻¹ and the S2-wave velocity range is between 2.6 to 2.7 km.s⁻¹. On the contrary, at atmospheric pressure, the pressure S1-wave velocity range is 3.5 to 3.6 km.s⁻¹ and the S2-wave velocity range is between 3.4 and 3.5 km.s⁻¹.

Based on these trends, we can distinguish between microcracks and rock-matrix dominated pressure ranges. In general, the crack closing pressure is estimated as a threshold between non-linear (crack-closing) and linear (rock matrix- dominated) velocity/pressure trends (e.g. (Pros et al., 1998)). For most rocks, it is expected to be within the range of 150–500 MPa. In this work, the maximum applied pressure of 120 MPa was not high enough to lose all the cracks and to reach the linear velocity/pressure trend. For these reasons, we used the anisotropy behaviour to distinguish between the crack- and matrix-dominated pressure regions. However, this change in anisotropy behaviour is related only to the influence of oriented cracks e. g. (Kern et al., 2008). For MG samples, this threshold is between 50 and 80 MPa. Below this level, anisotropy steeply decreases with pressure; then it remains practically constant. The MG sample is practically isotropic at 120 MPa ($k_a = 3\%$), while weakly anisotropic at low pressure $k_a = 9\%$. At a low pressure, when the influence of oriented cracks is significant, the degree of the P-wave anisotropy is about three times higher than at 120 MPa.

Table 5 The elements of the stiffness tensor of the MG sample in its principal coordinate system (all values of elastic constants are given in GPa).

cij	Hydrostatic pressure [MPa]								
	0.1	2	5	10	20	50	80	100	120
c11	61.0	63.2	66.3	71.8	79.7	88.0	92.5	93.6	95.0
c22	57.9	60.5	63.7	69.6	78.0	86.5	90.9	91.6	93.0
c33	50.8	53.7	57.0	63.3	71.9	81.9	87.1	89.0	90.1
c44	18.9	20.6	22.2	24.4	26.3	29.1	30.7	32.3	33.1
c55	18.5	20.4	21.9	23.0	25.4	29.4	31.4	31.9	31.9
c66	21.2	22.0	22.7	25.3	27.2	27.9	29.2	31.3	32.4
c12	17.1	17.9	18.8	20.0	24.1	31.7	33.3	31.7	30.7
c13	18.0	16.1	16.8	20.8	25.3	27.9	28.4	28.7	28.8
c14	0.1	0.6	0.4	-0.8	1.5	-1.6	-1.6	-0.6	-0.7
c15	0.1	-0.1	-0.3	-0.1	0.0	0.2	0.4	0.1	0.2
c16	-0.2	0.4	0.3	-0.2	0.1	-0.1	-0.2	-0.3	-0.1
c23	17.5	16.1	16.3	18.6	22.6	26.6	27.7	26.9	26.8
c24	0.0	-0.2	-0.2	-0.2	0.1	-0.2	-0.3	-0.5	-0.4
c25	0.3	2.0	2.4	2.3	1.9	2.3	1.8	2.2	1.9
c26	0.1	-0.1	-0.1	-0.1	0.4	0.0	0.0	0.0	0.1
c34	-0.1	0.4	0.5	0.6	-0.4	0.5	0.7	0.5	0.4
c35	-0.1	-0.2	-0.1	-0.4	-0.2	-0.6	-0.8	-0.9	-0.9
c36	0.3	-0.5	-0.3	0.7	-1.3	0.4	0.3	0.6	0.3
c45	-0.2	-0.2	-0.1	-0.2	0.4	-0.3	0.0	-0.1	-0.2
c46	-0.4	-1.4	-1.5	-1.3	-1.4	-1.5	-0.9	-0.6	-0.6
c56	0.2	-1.0	-1.0	0.0	-0.8	1.0	0.9	0.8	0.8

3.7. THE DYNAMIC ELASTIC PARAMETERS OF THE MG SAMPLE

The dynamic Young's and shear moduli as well as the Poisson's ratios within the three principal planes of the MG sample are plotted in Figure 6. The three Young's moduli at atmospheric pressure are $E1 = 52.3$ GPa, $E2 = 49.7$ GPa, and $E3 = 42.6$ GPa. When increasing the pressure to 120 MPa, these values climb to $E1 = 80.0$ GPa, $E2 = 79.2$ GPa, and $E3 = 77.6$ GPa, showing an increase of 53 %, 59 %, and 82 % for directions 1, 2, 3, respectively.

The variation of Young's moduli with pressure for the MG sample in Figure 6A shows that $E1$ and $E2$ are very close at atmospheric pressure, while $E3$ is significantly lower. With increasing pressure, all three Young's moduli converge. By increasing the pressure, all these moduli increase in the MG sample due to the crack closure, which makes the material more intact. We can see that ν_{21} (the ratio of ε_1 to ε_2 for the loading applied in direction 2) is higher with respect to ν_{31} and ν_{32} during the hydrostatic stress increase.

4. DISCUSSION

This study provides a comprehensive analysis of the elastic properties of Mrakotin granite (MG) through various laboratory tests, including porosity, hydraulic permeability, compressive and tensile strength, ultrasonic velocity, and both static and dynamic elastic moduli. The findings offer valuable insights into MG's physical and mechanical behaviour,

essential for engineering applications such as hydraulic fracturing and for understanding its response under different loading conditions.

4.1. POROSITY AND PERMEABILITY

MG exhibits low porosity (0.39 % by MIP, 0.86 % by hydraulic conductivity measurement) and extremely low permeability, classifying it as a highly compact and non-permeable material. These characteristics are particularly relevant for construction and hydraulic applications. The measured porosity aligns with values reported for other granitic rocks. For instance, (Giesche, 2006) found that granite porosity typically ranges from 0.5 % to 2.5 %, depending on mineral composition and grain size. (Yu et al., 2014) and (Římnáčová et al., 2024) further observed that exposure to high temperatures increases porosity due to thermal cracking. The low porosity of MG suggests a dense structure with minimal susceptibility to fluid infiltration (Brace, 1980; David et al., 1994).

A comparative analysis of the results obtained from permeability measurements using mercury and water-based methods revealed a discrepancy between the parameters K_w and K_{Hg} . However, the parameters K_w and K_{Hg} were found to be quite similar. This discrepancy can be explained by the differences in methodologies. Mercury porosimetry is designed to measure pore volume and pore size distribution and subsequently calculate permeability, whereas the

water-based permeability method directly measures the ability of the rock to transmit water by creating a steady-state laminar flow. However, this flow does not pass through all pores but only through those that are effective for permeability in the given direction. Additionally, the difference in the wettability of surfaces and molecular sizes between mercury and water also affects permeability measurements. Nevertheless, when accounting for the methodological differences and converting to K_w and K_{Hg} , the parameters show a strong similarity.

Permeability measurements, determined using mercury intrusion porosimetry and hydraulic conductivity tests, confirm MG's classification as non-permeable. This is consistent with findings by (Villeneuve et al., 2018), who reported permeability values in the range of 10^{-9} to 10^{-12} m² for intact granites. Additionally, (Shen et al., 2024) noted that lower porosity correlates with reduced permeability due to limited pore connectivity. (Kang et al., 2019) demonstrated that permeability decreases with increasing burial depth due to compaction and microfracture closure, a trend reflected in MG's results. Temperature plays a crucial role in permeability assessments, as studies by Washburn (1921a) and Scheidegger (1974) indicate that thermal expansion of microcracks enhances fluid flow, a factor to consider when comparing laboratory results with in-situ conditions.

4.2. ULTRASONIC VELOCITY AND ELASTIC PROPERTIES

Ultrasonic velocity measurements under varying pressure conditions provide insights into MG's anisotropic behaviour. Understanding P-wave and S-wave velocities under different confining pressures enables a deeper evaluation of its elastic response and potential engineering applications. A high-pressure ultrasonic method was used to determine the P-wave (v_p) and S-wave velocities (v_{s1} , v_{s2}) at different pressure levels (0.1 to 120 MPa). The results indicate that at low pressure (0.1 MPa), P-wave velocity ranged from 4.4 km.s⁻¹ to 4.8 km.s⁻¹, with an anisotropy coefficient (k_a) of 9%. At high pressure (120 MPa), P-wave velocity increased to 5.8–6.0 km.s⁻¹, with anisotropy decreasing to 2.9%. A similar trend was observed for S-waves, where S1-wave velocity increased from 2.7–2.8 km.s⁻¹ at 0.1 MPa to 3.5–3.6 km.s⁻¹ at 120 MPa, and S2-wave velocity exhibited a parallel trend, increasing from 2.6–2.7 km.s⁻¹ to 3.4–3.5 km.s⁻¹. This exponential velocity increase with pressure highlights the closure of microcracks in the rock structure, characteristic of crystalline rocks (Kern et al., 2008; Pros et al., 1998). The transition between crack-dominated and matrix-dominated mechanical behaviour is evident from anisotropy trends. Below 50 MPa, velocity anisotropy decreases sharply, indicating progressive microcrack closure. Above 80 MPa, velocity trends stabilize, suggesting that the rock matrix controls wave propagation rather than

pre-existing cracks. This aligns with prior studies identifying pressure ranges of 150–500 MPa as the threshold for complete crack closure in granites (David et al., 2012; David and Zimmerman, 2012). From a methodological point of view, the accuracy of the ultrasonic measurements should be briefly addressed. Ultrasonic velocity uncertainty is governed primarily by travel-time picking accuracy. For specimen path lengths of ~50 mm, this corresponds to relative velocity uncertainties of approximately 0.5–1.5 % for P waves and 1–2 % for S waves. The ultrasonic determination yields elastic constants accurate to within a few percent, with absolute stiffness uncertainties on the order of ~1 GPa, which is sufficient for reliable symmetry classification, anisotropy quantification, and pressure-dependent analysis

4.3. DYNAMIC ELASTIC MODULI AND MECHANICAL PROPERTIES

The elastic properties of MG were compared with literature data on other granites. The average Young's modulus for granites typically ranges from 40 GPa to 70 GPa (Villeneuve et al., 2018). MG's static Young's modulus was determined to be 53.63 GPa, fitting within this range. The dynamic Young's moduli at 0.1 MPa were $E_1 = 52.3$ GPa, $E_2 = 49.7$ GPa, $E_3 = 42.6$ GPa, increasing at 120 MPa to $E_1 = 80.0$ GPa, $E_2 = 79.2$ GPa, $E_3 = 77.6$ GPa. This represents a 53–82 % increase in Young's modulus with pressure, confirming that microcracks significantly influence the elastic response at low pressures (Eberhardt et al., 1999). Similarly, the static shear modulus measured 22.01 GPa, whereas the dynamic shear modulus ranged from 21.15 GPa to 18.46 GPa. While discrepancies between static and dynamic elastic moduli are commonly attributed to microfractures, which have a greater impact under static loading conditions (Shen et al., 2024), MG exhibited nearly identical values in both static and dynamic conditions. This aligns with previous findings, where the ratio of dynamic to static moduli varied depending on fracture density and stress state (Kang et al., 2019). The slightly higher dynamic modulus in MG is consistent with other granite types, where microstructural features influence mechanical responses under different loading conditions.

The full stiffness tensor (c_{ij}) was derived from ultrasonic velocity data, revealing that c_{11} , c_{22} , and c_{33} components increased significantly with pressure, consistent with the observed velocity trends. Off-diagonal components (c_{12} , c_{13} , c_{23}) exhibited moderate variations, suggesting that MG maintains a nearly isotropic structure under high pressure. At low pressures, however, these components indicate moderate elastic anisotropy, primarily due to open fractures (Brown and Scholz, 1985). Poisson's ratio remained relatively stable (0.20–0.26) across all pressure levels, reflecting minimal change in deformation behaviour under hydrostatic stress.

4.4. UNIAXIAL COMPRESSIVE STRENGTH AND DENSITY

Uniaxial compressive strength (UCS) is another key parameter in rock mechanics. Granites typically have UCS values between 140 MPa and 220 MPa (Villeneuve et al., 2018), with MG falling within this range at 180 MPa. Regarding density, granite averages between 2.65 and 2.75 g.cm⁻³, with MG slightly below this at 2.636 g.cm⁻³, though still within acceptable limits (Brace, 1965; Carmichael, 2017). The measured elastic and mechanical properties of MG closely align with reported values for other granites, suggesting similar mechanical behaviour, and experimental conditions, including temperature, humidity, and loading rate, can influence test results. For instance, (Yu et al., 2014) demonstrated that increasing temperature leads to a decrease in Young's modulus and an increase in permeability in granites. Consequently, when interpreting experimental results, it is crucial to consider the specific conditions under which the tests were conducted (Paterson and Wong, 2005).

These findings reinforce MG's suitability for engineering applications that require durable, high-strength materials while also highlighting the importance of understanding environmental factors that may influence its mechanical performance.

5. CONCLUSION

The study of MG's sphere velocity properties provides insights into its elastic anisotropy, velocity-pressure dependence, and mechanical behaviour. The key findings are: 1) Velocity increases exponentially with pressure, confirming that microcrack closure dominates at lower pressures, while the rock matrix controls behaviour at higher pressures. 2) Anisotropy decreases significantly above 50 MPa, indicating a transition from crack-dominated to matrix-dominated elastic response. 3) Elastic moduli increase with pressure, with Young's modulus showing a 53–82 % rise, aligning with previous studies on crystalline rocks. 4) MG is nearly isotropic at high pressures ($k_a \approx 3$ %), making it a mechanically stable material for structural and geophysical applications.

Mrakotin Granite exhibits mechanical and elastic properties comparable to those of other granites reported in the literature. Its low porosity and high strength make it a promising material for engineering applications requiring durability and mechanical stability. Future research could further explore the effects of environmental factors on MG's mechanical properties and compare them with granites from different locations.

These insights are crucial for hydraulic fracturing studies, as the rock's velocity behaviour under stress impacts fracture propagation and acoustic emission analysis. Further investigations with pressures exceeding 120 MPa would help clarify whether full microcrack closure occurs at higher confinement levels. The primary objectives of this research,

namely, evaluating the elastic properties of Mrakotin Granite, have been successfully met.

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APPENDIX A.

ULTRASONIC VELOCITIES AND ANISOTROPY PARAMETERS

Hydrostatic pressure [MPa]	P-wave velocity			
	k_a [%]	$v_{\max}$ [m.s ⁻¹]	v_{mean} [m.s ⁻¹]	$v_{\min}$ [m.s ⁻¹]
0.1	9.0	4812	4649	4397
2.0	8.3	4902	4748	4511
5.0	7.6	5017	4872	4649
10.0	6.4	5220	5102	4895
20.0	5.2	5499	5402	5222
50.0	3.7	5779	5714	5570
80.0	3.4	5928	5862	5732
100.0	2.9	5972	5913	5802
120.0	2.9	6009	5951	5835

Hydrostatic pressure [MPa]	S1-wave velocity		
	$vS1_{\max}$ [m.s ⁻¹]	$vS1_{\text{mean}}$ [m.s ⁻¹]	$vS1_{\min}$ [m.s ⁻¹]
0.1	2848	2786	2670
2.0	2953	2891	2786
5.0	3030	2973	2868
10.0	3155	3098	2990
20.0	3275	3225	3151
50.0	3394	3357	3303
80.0	3484	3448	3389
100.0	3547	3506	3455
120.0	3584	3539	3478

Hydrostatic pressure [MPa]	S2-wave velocity		
	$vS2_{\max}$ [m.s ⁻¹]	$vS2_{\text{mean}}$ [m.s ⁻¹]	$vS2_{\min}$ [m.s ⁻¹]
0.1	2683	2658	2634
2.0	2835	2762	2712
5.0	2922	2847	2794
10.0	3033	2960	2921
20.0	3162	3084	3017
50.0	3324	3225	3164
80.0	3425	3328	3274
100.0	3480	3408	3361
120.0	3508	3455	3413

APPENDIX B.

ELASTIC CONSTANTS

Hydrostatic Pressure [MPa]	Young modulus			Poisson ratio			Shear modulus		
	E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	ν_{21} []	ν_{31} []	ν_{32} []	G_{23} [GPa]	G_{31} [GPa]	G_{12} [GPa]
0.1	52.33	49.67	42.58	0.20	0.23	0.23	18.93	18.46	21.15
2	55.21	52.61	47.13	0.22	0.20	0.21	20.54	20.32	21.87
5	57.95	55.60	50.41	0.23	0.20	0.20	22.09	21.70	22.59
10	61.92	60.90	54.66	0.21	0.23	0.20	24.27	22.89	25.25
20	67.04	64.00	60.60	0.23	0.25	0.21	26.14	25.33	27.07
50	71.78	71.10	69.34	0.29	0.24	0.22	28.99	29.30	27.75
80	75.98	74.90	74.40	0.29	0.23	0.22	30.60	31.30	29.10
100	77.99	77.04	76.51	0.27	0.23	0.21	32.32	31.79	31.25
120	80.01	79.23	77.58	0.26	0.24	0.21	33.12	31.86	32.36