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Elastic Wave Velocity Response to Saturation in Rocks: Laboratory Characterization

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Abstract

The propagation velocity of primary (Vp) and secondary (Vs) elastic waves in rocks are crucial for assessment of rock quality and integrity, as well for the estimation of elastic modulus and Poisson's ratio through empirical correlations. Properties such as porosity, density, and moisture content influence both wave velocities and the geomechanical behavior of rock masses. This variability underscores the need to understand the response of Vp and Vs to varying rock saturation conditions. This study evaluates the influence of saturation and physical properties on the Vp and Vs velocities in three lithotypes including: syenogranite (SG), gneiss (GN), and granitoid (GT). Ultrasonic wave velocity measurements were performed using transducers of 250 kHz and 40 kHz were used for Vp and Vs, respectively, under dry and saturated conditions. Saturation was achieved using a vacuum chamber with water immersion for four hours, while drying was carried out in an oven at 100 °C for 24 hours. Physical index tests (porosity and density) were determined. The results showed that wave velocities increased under saturated conditions across all lithotypes, a behavior attributed to pore filling by water and an increase in rock stiffness. This effect was most pronounced in SG, which exhibited the highest average percentage increases (39% for Vp, 26% for Vs), consistent with its higher porosity. In GN, two samples with higher porosity exhibited more expressive increases and lower overall velocity values compared to the others. In GT, the highest Vp values were recorded in samples with the lowest porosity, while the sample with the lowest density presented the lowest wave velocities, despite having porosity comparable to other samples. The findings confirm an inverse relationship between porosity and velocities, and a direct relationship with bulk density, consistent with previous research. Ultimately, this study demonstrated that Vp is more sensitive than Vs to saturation-induced variations.

Keywords

Porosity, Saturation, Ultrasonic pulse velocity.

1 Introduction

Ultrasonic techniques are non-destructive, indirect methods that are easily applicable in both laboratory and field settings, known for their precision and low operational cost. For these reasons, they are widely employed in geotechnical and geophysical applications for the assessment of the physical properties, composition, and density of rocks (Chawre, 2018; Sabri *et al.*, 2025; Viana and Simas, 2024). Elastic waves in solids can be classified into two main types: primary, or longitudinal and compressional (P) waves and secondary or shear(S) waves. P-waves involve particle motion parallel to the direction of propagation, whereas S-waves propagate through shear deformation, with particle displacements perpendicular to the direction of propagation (Kearey *et al.*, 2002).

The measurement of P-wave (Vp) and S-wave (Vs) velocities enables the estimation of parameters such as Young's modulus and Poisson's ratio, as well as the evaluation of rock quality. However, these velocities are strongly influenced by the intrinsic characteristics and mineralogical composition of rocks, including porosity, density, anisotropy, structure, the size and shape of mineral grains, as well as pore fluid content (Chawre, 2018; Figueiredo *et al.*, 2025; Yagiz, 2011; Yasar and Erdogan, 2004). Understanding the behavior of wave velocities in response to these parameters allows for the correct interpretation of test results and a more realistic assessment of the in situ behavior of rock masses. Therefore, aiming to investigate the influence of saturation, this study evaluates the behavior of primary (Vp) and secondary (Vs) wave velocities in rocks under dry and water-saturated conditions, as well as their relationship with physical properties such as apparent porosity and dry bulk density.

2 Materials and Methods

2.1 Materials

This study investigated the behavior of different lithotypes: syenogranite (SG), gneiss (GN), and granitoid (GT). The samples were obtained from rotary core drilling, preserving the diameters corresponding to the drilling crowns used, namely BX (42 mm) for SG and GT, and NX (54.7 mm) for GN. Five specimens of each lithotype were evaluated, as illustrated in Fig. 1.

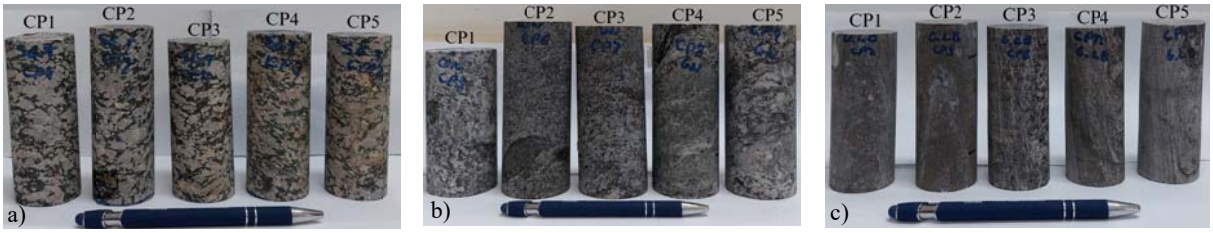


Fig. 1 Samples of SG, GN, and GT. a) Syenogranite (SG); b) Gneiss (GN); c) Granitoid (GT).

2.2 Methods

The physical indices, apparent porosity (η) and dry bulk density (ρ_d), were determined according to the International Society for Rock Mechanics (ISRM, 2007). The elastic wave velocity test, illustrated in Fig. 2, followed the recommendations of theISRM (2014)using 250 kHz transducers for measuring Vp and 40 kHz for Vs. The tests were performed on the specimens under saturated and dry conditions. Saturation was achieved using a vacuum chamber, with the samples immersed in deionized water for 4 hours. The condition was ensured by monitoring the mass of the specimens at hourly intervals until no further variation was observed. Drying was performed in an oven at 100°C for 24 hours.

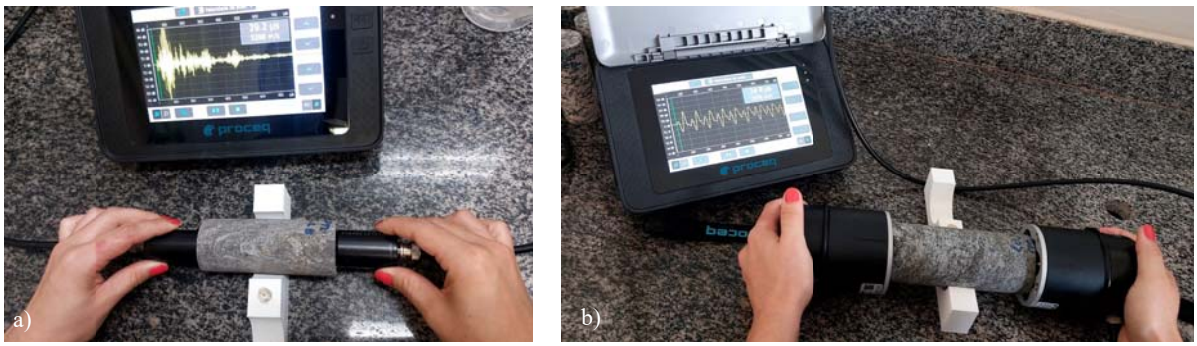


Fig. 2 UPV test. a) Measurement of P-waves. b) Measurement of S-waves.

3 Results and discussion

3.1 Physical Properties

The graph in Fig. 3 illustrates the relationship between porosity and dry bulk density for all specimens.

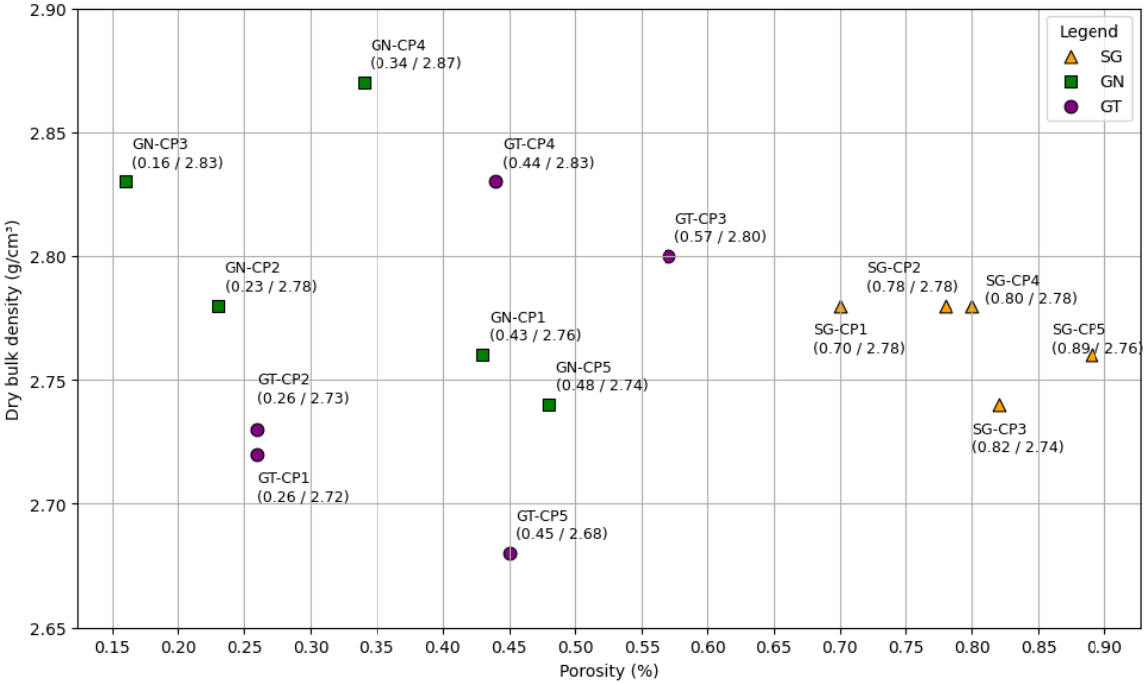


Fig. 3 Results of the physical indices of apparent porosity (η) and dry bulk density (ρ_d).

Based on the analysis of the graph, it is noted that the SG lithotype presented similar physical index results among the samples, indicating that the analyzed specimens tend to exhibit mineralogical and structural homogeneity. In addition, this lithotype stood out for having the highest porosity compared to the others, with an average of 0.80%.

Among the gneiss samples, GN-CP1 and GN-CP5 showed higher η and lower ρ_d values compared with the others, whereas GN-CP2 and GN-CP3 presented the lowest porosities among all samples, of 0.16% and 0.23%, respectively. GN-CP3, in turn, showed an intermediate porosity value but the highest ρ_d among the GN samples. This variability within the lithotype may be associated with the lighter mineralogy observed in GN-CP1 and GN-CP5, while the other samples contain darker minerals (Fig. 1), which results in different physical properties, particularly ρ_d.

Although the granitoid samples exhibit greater dispersion within the dataset, they still show some similarities in their physical indices. Samples GT-CP1 and GT-CP2 presented the lowest porosity values in the group, contrasting with GT-CP3, whose porosity is approximately twice as high. Despite this, GT-CP1 and GT-CP2 presented similar ρ_d values and greater macroscopic similarity. Samples GT-CP4 and GT-CP5 also showed similar η values; however, GT-CP5 stands out for having the lowest ρ_d among all samples. The variability in the physical indices observed in the granitoid may be associated with mineralogical variations between the samples, which presented some visual heterogeneities. These differences, resulting from the presence of distinct minerals or geological contacts, significantly influence the physical characteristics of the material, even though they belong to the same lithotype.

3.2 Elastic wave propagation velocity under different saturation conditions

The graph in Fig. 4presents the Vp and Vs values obtained for all samples under both saturation conditions, as well as the corresponding mean trend lines, which represent the general behavior of these values.

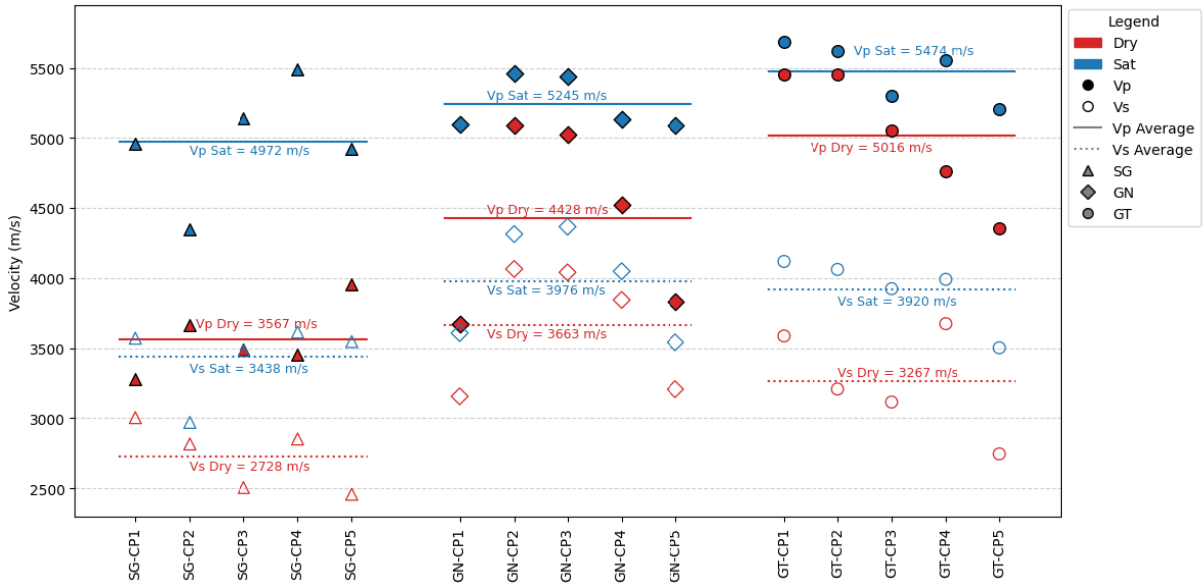


Fig. 4 Results of Vp and Vs under dry and saturated conditions for all samples.

Based on the behavior indicated by the mean value trend lines, a tendency for Vp and Vs to increase with higher saturation levels is observed in all lithotypes. Due to the increase in the rock's compressibility modulus, elastic wave propagation velocity increases as voids become filled with water, especially for primary waves. This behavior has also been reported by Kahraman (2007), Baechle et al. (2009), Uyanık et al. (2019), He et al. (2021), Vukadin, Orešković and Kutasi (2021), Sharo et al. (2022) and Figueiredo et al. (2025).Comparing the mean values under dry and saturated conditions, the percentage increase in Vp from dry to saturated was, in general, greater than that of Vs. The SG lithotype exhibited the highest percentage increases due to saturation, with increases of 39% in Vp and 26% in Vs. The GN lithotype showed an 18% increase in Vp and the smallest variation in Vs, of 9%. The exception was observed in GT, which presented the highest increase in Vs (20%), while its Vp increase was 9%.

In terms of Vs, it is expected that this velocity does not exhibit significant variations with the replacement of pore fluid by water, since fluids do not sustain shear resistance. The effects of saturation on Vs are less frequently reported in the literature when compared to those observed for Vp. Nevertheless, increases in Vs may occur and are commonly attributed to the increase in rock stiffness resulting from the substitution of air by water within the pores, as well as to the characteristics of the pore system, such as pore type, distribution, and connectivity, which may influence elastic wave propagation velocities (Baechle *et al.*, 2009; Uyanık *et al.*, 2019; Vukadin *et al.*, 2021; Yuan *et al.*, 2025).

Regarding the relationship between elastic wave propagation velocity and porosity, an inverse correlation was observed, such that more porous rocks tend to exhibit lower propagation velocities, a trend well established in the literature (Anselmetti and Eberli, 1993; Baechle *et al.*, 2009; Besharatinezhad *et al.*, 2022; Figueiredo *et al.*, 2025; Han *et al.*, 1986; He *et al.*, 2021).This behavior is evident in SG, which presents porosity values approximately twice those of the other samples. In addition to having the lowest average Vp and Vs in both saturation conditions, it was the lithotype that showed the greatest velocity increase with saturation for both Vp and Vs.

With respect to the pairs of samples previously identified as similar in terms of physical indices and macroscopic characteristics, the GN samples demonstrate proximity in velocity values between GN-CP1 and GN-CP5. The Vp values for these samples in the dry condition were close to the Vs values of the other specimens, further reinforcing their distinct behavior. Moreover, this pair presented the greatest increases in Vp and Vs from the dry to saturated states, consistent with the fact that they also had the highest porosities, suggesting the influence of higher pore volumes on wave propagation. Meanwhile, the GN-CP2 and GN-CP3 samples, which had the lowest porosity values, presented similar Vp and Vs in both saturation conditions, and these were the highest values within the lithotype. GN-CP4, with porosity intermediate between the two pairs, presented Vp and Vs values lower than GN-CP2/GN-CP3 and higher than GN-CP1/GN-CP5, reinforcing its intermediate behavior within the lithotype. Additionally, it is observed that the GN-CP1/GN-CP5 pair exhibited the greatest increases

in wave propagation velocity between the dry and saturated conditions. For Vp, this increase was approximately 3.7 times greater than that observed in the other samples, while for Vs the variation was about twice as high.

For the GT lithotype, samples GT-CP1 and GT-CP2, which showed similar physical indices, exhibited comparable Vp values in both saturation conditions, as well as similar Vs under saturated conditions. Furthermore, these samples presented the highest Vp values among all analyzed specimens, even though they did not have the lowest porosities or highest densities. Within this lithotype, GT-CP5 stands out for presenting the largest percentage increase in Vp and Vs from the dry to saturated state. Although its porosity is close to that of GN-CP4 and even lower than that of GT-CP3, its behavior may be associated with its lower bulk density, since this property is directly related to elastic wave propagation velocity, as reported by Anselmetti and Eberli (1993), Uyanık et al. (2019) and Besharatinezhad et al. (2022). Thus, lower density tends to result in lower wave propagation velocities.

It is worth noting that although porosity and bulk density are highly relevant factors influencing elastic wave velocity test results, this method also depends on several other parameters not evaluated in this study, such as mineralogy, pore type, morphology and connectivity, and anisotropy (Anselmetti and Eberli, 1993; Karakul and Ulusay, 2013; Yan and Han, 2016). Therefore, it is not possible to attribute the behavior of the samples in the test solely to the physical properties evaluated here.

4 Conclusion

This study evaluated the influence of saturation on the propagation velocity of elastic waves in fifteen samples of granitic rocks. Additionally, the physical indices of apparent porosity and dry bulk density were determined in order to correlate them with the obtained results. Overall, the results showed an increase in Vp and Vs with saturation for all lithotypes, with this effect being more pronounced for Vp. An inverse relationship between porosity and wave propagation velocity was also observed, as well as the influence of porosity on the increase in velocities from the dry to saturated state, whereas bulk density presented a direct relationship with velocities in specific analyses.

With regard to the lithotypes, syenogranite exhibited a more homogeneous behavior in terms of physical indices, standing out due to its higher average porosity compared with the others. This characteristic was reflected in its lower mean Vp and Vs values, as well as in the highest percentage increases in velocity with saturation. Gneiss, in turn, showed greater internal variability, with samples exhibiting distinct behaviors as a result of differences in physical indices and macroscopic characteristics. The samples with higher porosity presented lower velocities in the dry state and greater increases with saturation, whereas the less porous samples exhibited the highest Vp and Vs values, along with less expressive variations between dry and saturated conditions. The granitoid samples showed greater dispersion in physical indices, indicating less uniform behavior. Although some samples presented high velocities without being associated with the lowest porosities or highest bulk densities, another sample characterized by lower ρ_d exhibited the lowest velocities and the greatest increase with saturation, suggesting that other intrinsic material factors also influence its response.

Therefore, the results demonstrate that porosity and bulk density influence the propagation velocities of elastic waves, particularly in the material's response to variations in the degree of saturation. However, the analysis also indicates that the behavior cannot be explained solely by these physical indices, since other factors such as mineralogy, pore connectivity and morphology, anisotropy, and internal structure are also influential. Thus, the importance of future studies that investigate additional parameters for a more complete interpretation and integration of results is highlighted.

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