Estimation of Mechanical Properties of Granitic Rocks and Gabbro from Ultrasonic Velocity in Northern Thailand

Sathit Kanthata *, Kannipa Motanated and Chanawut Sooksabai
[a] Department of Geological Sciences, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand.
*Author for correspondence; e-mail address: sathit.k@cmu.ac.th.

ABSTRACT

Uniaxial compressive strength (UCS) test is a fundamental and widely used technique for evaluating the mechanical properties of rocks for engineering purposes. However, the UCS test is destructive. This research proposes the use of non-destructive ultrasonic techniques, which send ultrasonic waves through the rock core samples, to quantify rock mass physical properties, such as density and porosity, as well as rock quality index. The cylinder core samples from Tha Khao Plueak, Chiang Rai province, were petrographically identified as monzogranite, syenogranite, and gabbro and those from the pre-construction phase of the water diversion tunnel project in Mae-Taeng, Chiang Mai province were identified as biotite granite, pegmatite, and aplite. Thus, the rock samples are divided into granitic rocks and gabbro. The correlations between P-wave velocity and density and between P-wave velocity and porosity are linear ($R^2 = 0.5691$) and inverse exponential ($R^2 = 0.6255$), respectively. The diagram developed by Uyanik et al. (2019) to determine RMR values from ultrasonic velocities can be utilized to identify the quality of these granitic rocks and gabbro. The association between uniaxial compressive strength (UCS) and P-wave velocity, on the other hand, is unidentified, and more research into the relationships between mineral composition, mineral orientation, and ultrasonic velocity is highly encouraged.

Keywords: ultrasonic velocity, density, porosity, UCS, RMR

1. INTRODUCTION

The ISRM [1] standards suggest straightforward methods for testing or measuring rock mass parameters such as uniaxial compressive strength (UCS), density, and porosity, which are important rock properties. UCS test is a fundamental and widely used technique for analyzing critical rock properties for engineering purposes. In addition, the UCS value is also a key factor in determining the mechanical rock mass ratings, which is an index of rock mass quality used for the design and construction in rock proposed by [2]. However, the UCS test is destructive because the axial stress is applied until the rock sample experiences failure.

The ultrasonic techniques are non-destructive tests used in rock mechanics. Factors that influence pulse waves, the ultrasonic longitudinal (V_p) and shear wave (V_s), velocities are density, porosity, grain size, weathering, and joint properties ([3-4]). Previously, many researchers have proposed equations to express the correlations between UCS, porosity, void ratio, and RMR of granitic rocks, sedimentary rocks, and plutonic rocks (Table 1). This study is aiming to investigate the correlations between the pulse waves and mechanical properties of granitic rocks and gabbro as well as the possibility of utilizing a non-destructive test instead of a destructive UCS test.

2. MATERIALS AND METHODS

The rock samples used in the study are from two locations including Tha Khao Plueak sub-district, Mae Chan district, Chiang Rai province and Mae-Taeng district, Chiang Mai province. Samples from the pre-construction phase of the water diversion tunnel project in Mae-Taeng district, Chiang Mai provided by Right Tunnelling Public Company Limited were petrographically analyzed by DGS-CMU* lab; they were fine- to coarse-grained granites and classified as biotite-granite, pegmatite, and aplite. Table 2 summarizes the rock types, sample numbers, and sampling locations. The length-to-diameter ratios of all sample cores are between 2-2.5:1. Before performing the ultrasonic wave measurements and the UCS tests, the cylindrical samples' surfaces were smoothed using a rock grinding machine.

Table 1 Regression equations proposed in previous studies

References	Equations	Rock types	Unit of V_p, V_s
Tugrul and Zarif [5]	$UCS = 35.54V_p - 55$	Granitic rocks	km/s
Sousa et al. [6]	$UCS = 0.004V_p^{1.247}$	Granitic rocks	m/s
Vasconcelos et al. [7]	$UCS = 0.0407V_p - 36.31$	Granite	m/s
Mishra and Basu [8]	$UCS = 0.087V_p - 355.8$	Granite	m/s
Goh et al. [9]	$UCS = (2.55 \times 10^{-5})V_p^{1.7658}$	Granite	km/s
Uyanik et al. [10]	$UCS = 6.6V_p^{1.5}$	Sedimentary rocks	km/s
	$n = 31V_p^{-2.14}$		km/s
	$n = 28.6V_s^{-4.1}$		km/s
	$e = 32.5V_p^{-2.16}$		km/s
	$e = 30V_p^{-4.1}$		km/s
	$V_p = 1.72V_s - 0.5$ [for RMR]		
Rahman and Sarkar [11]	$UCS = 5.0952V_p^{1.8671}$	Plutonic rocks	km/s

Table 2 Rock samples description

Observed rock types	Sample number	Locations
Granite	Gr01, Gr02, Gr03, Gr04, Gr05, Gr06, Gr07, Gr08, Gr09, Gr10	Tha Khao Plueak sub-district, Mae Chan district, Chiang Rai province
Gabbro	Gb01, Gb02, Gb03, Gb04, Gb05, Gb06, Gb07, Gb08, Gb09	
Biotite-Granite,	MTMG02, MTMG03, MTMG10	A pre-construction survey of water diversion tunnel project in Mae-Taeng district, Chiang Mai province
Pegmatite,	MTMG04, MTMG08	
Aplite	MTMG05	

*Department of Geological Sciences, Science, Chiang Mai University

2.1 Petrography

The rock samples were prepared into thin-sections and analyzed under a crossed-polarizing microscope. The amounts of primary minerals are determined by an automatic swift point counter by counting the mineral that appears at the crosshair point—400 points per thin-section. Furthermore, the amount of each mineral is calculated into percentages.

2.2 Density and Porosity

The rock samples were dried in an oven at 105 °C for 24 hours to determine their dry weight (W_{dry}). The dry samples are then entirely submerged for a day in pure water and kept in a vacuum cell for another 12 hours. The saturated samples were submerged in water to measure their saturated weight (W_{sat}).

Porosity is unitless; it is the ratio of the void volume in rock to the total volume. Low porosity is characteristic of hard rocks, especially intrusive igneous rocks. However, the severely deteriorated rock shows more voids and porosity density.

When V_{total} is the total volume of core barrels and γ_w is a pure water density, which equals 1 g/cm^3, rock density (ρ) and porosity (n) are calculated as follows.

$$Density\ (\rho) = W_{dry} / V_{total} \tag{1}$$

$$where \quad Void\ volume\ (V_{void}) = [(W_{sat} - W_{dry}) / \gamma_w] - V_{total}$$

$$Porosity\ (n) = (V_{void} / V_{total}) \times 100\% \tag{2}$$

2.3 Uniaxial Compressive Strength

The uniaxial compressive strength (UCS) of each rock sample was determined by subjecting it to incremental axial loading (P) on the sample's face area (A) at a relatively stable rate using a Universal Testing Machine (UTM). The UCS of the test sample is calculated as follows.

$$Uniaxial\ Compressive\ Strength\ (UCS) = P / A \tag{3}$$

2.4 Ultrasonic Velocity

The OYO sonic viewer model 5217A with an accuracy 0.2 μs and measuring range of 20 μs–50 ms was used in the direct method of ultrasonic velocity testing [1] based on wave travel time including the longitudinal or P-wave travel time (t_p) and the shear wave or S-wave travel time (t_s). When D is the distance from the transmitter to the receiver, the pulse waves pass the sample. The following equations are used to calculate velocity:

$$P\text{-}wave\ velocity\ (V_p) = D / t_p \tag{4}$$

$$S\text{-}wave\ velocity\ (V_s) = D / t_s \tag{5}$$

2.5 Rock Mass Rating

Geomechanical classification of rock mass called Rock Mass Rating (RMR) is based on the following parameters: UCS, rock quality designation (RQD), joint spacing, condition and orientation of discontinuity, and groundwater condition. This study followed the method proposed by [10] to estimate RMR from RQD, UCS, V_p, and V_s (Table 3).

Table 3 Rock classification according to mean values of mechanical and physical properties of rocks

RQD[12]	RMR[2]	UCS (GPa)[13]	V_p (km/s)[14]	V_s (km/s)[10]	Description
0-25	0-20	< 0.025	< 3.125	< 1.0	Very Poor
25-50	20-40	0.025-0.05	3.125-4.0	1.0-1.7	Poor
50-75	40-60	0.05-0.1	4.0-4.5	1.7-2.2	Fair
75-90	60-80	0.1-0.2	4.5-5.25	2.2-3.0	Good
90-100	80-100	> 0.2	> 5.25	> 3.0	Excellent

3. RESULTS AND DISCUSSION

3.1 Petrography

The samples from Tha Khao Plueak sub-district, Mae Chan district, Chiang Rai province were petrographically classified as felsic and mafic plutonic rocks (Fig. 1). The felsic plutonic rocks show non-porphyritic texture, crystal size ranges from 0.50-2.00 mm. The main mineral components are 38.50-55.10% quartz, 25.80-38.50% alkali feldspar, and 17.40-31.00% plagioclase. Minor minerals are biotite, zircon, and opaque minerals, such as monzogranite and syenogranite. Mafic plutonic rocks were classified as gabbro. The main mineral components are 50.60-79.40% plagioclase, 19.10-44.80% pyroxene, 0.00-6.90% olivine. Minor minerals are opaque minerals. The mafic texture shows cumulus characteristics, assembled crystals of plagioclase, clinopyroxene, orthopyroxene, and olivine, and between cumulus minerals are hornblende, plagioclase, and micro-clinopyroxene.

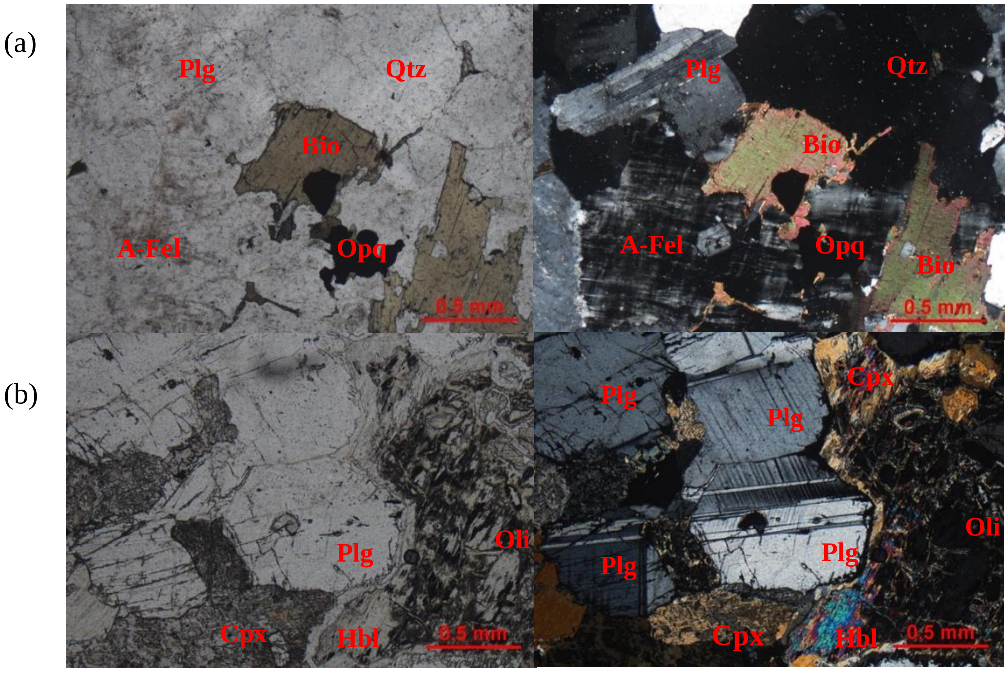

Fig. 1 Felsic (a) and mafic (b) plutonic rock form Tha Khao Plueak sub-district, Mae Chan district, Chiang Rai province under a polarizing microscope, normal light (left) and light passed between the polarizer and analyzer (right). (Qtz = Quartz, Plg = Plagioclase, A-Fel = Alkali Felspar, Bio = Biotite, Opq = Opaque mineral, Cpx = Clinopyroxene, Oli = Olivine, and Hbl = Hornblende)

The samples from Mae-Taeng district, Chiang Mai province had been analyzed by DGS-CMU lab during the pre-construction phases of the water diversion tunnel project. They were petrographically classified as felsic plutonic rocks, namely biotite-granite, pegmatite, and aplite (Fig. 2). The biotite-granite or monzogranite is coarse-grained, mainly composed of 37.75% quartz, 23.50% potassium feldspar, 14.75% plagioclase, and 22.25% biotite. Trace minerals such as muscovite, apatite, and zircon account for approximately 1.75% of the mineral component. The main mineral crystals are 0.25-4.00 mm in diameter and show seriate texture. Pegmatite or alkali-felspar-granite shows coarse to very coarse crystalline structures and is composed mainly of 45.50% quartz, 38.00% potassium feldspar, and 16.50% of minerals such as muscovite, plagioclase, tourmaline, garnet, and topaz. The crystal sizes are ranging from 1.25-15.00 mm. Aplite is non-porphyritic and primarily composed of 39.75% quartz, 31.75% potassium feldspar, 16.75% plagioclase, 8.75% muscovite, and 3.00% trace minerals including biotite, tourmaline, apatite, and zircon of 0.10-1.25 mm in width.

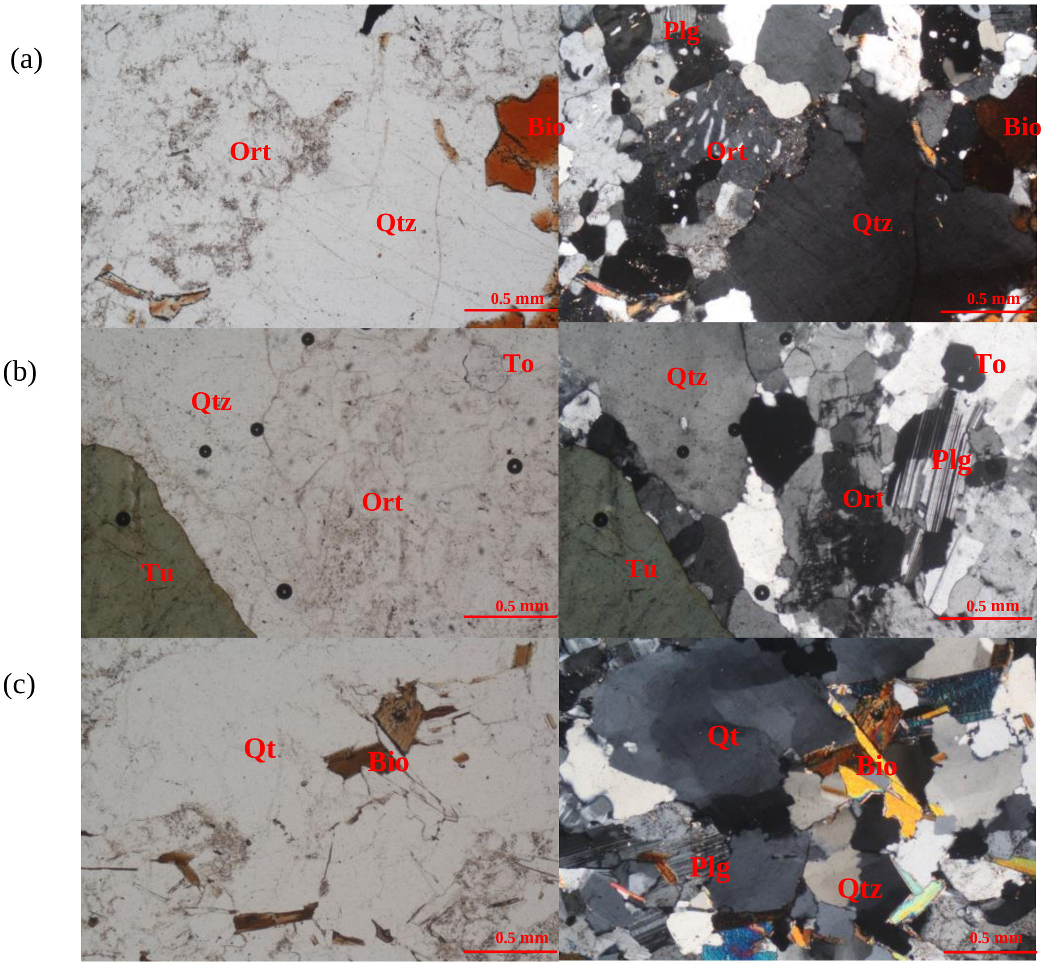

Fig. 2 Biotite-granite or monzogranite (a), Pegmatite or syenogranite (b), and Aplite (c) from a pre-construction survey water tunnel in Mae-Taeng district, Chiang Mai, by Right Tunneling Co., Ltd.under a polarizing microscope, normal light (left) and light passed between the polarizer and analyzer (right). (Qtz = Quartz, Plg = Plagioclase, Ort = Orthoclase, Bio = Biotite, To = Topaz, and Tu = Tourmaline)

3.2 Density and Porosity

The density of the granitic rocks varies from 2.56-2.71 g/cm^3, and that of gabbro varies from 2.72-3.02 g/cm^3. P-wave velocity ranges from 3.44 to 7.29 km/s. A linear correlation between P-wave velocity (V_p) and density is shown in Fig. 3.

The porosity values of gabbro and granitic rocks are 0.03-0.10 and 0.03-0.45, respectively. Fig. 4 compares the relationship between porosity and P-wave velocity from this study with those from [10]. The data points in both Fig. 3 and 4 are clustered into two groups based on the rock types. Gabbro has higher porosity and lower porosity than granitic rocks and results in higher P-wave velocity.

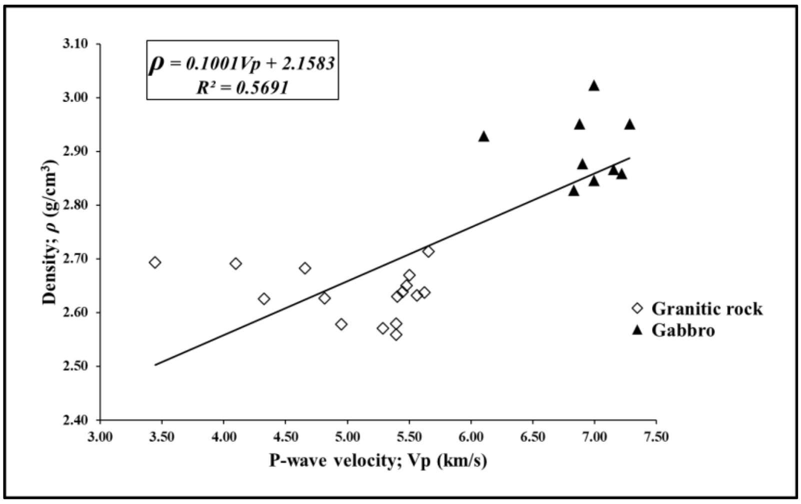

Fig. 3 The relation between density and P-wave velocity.

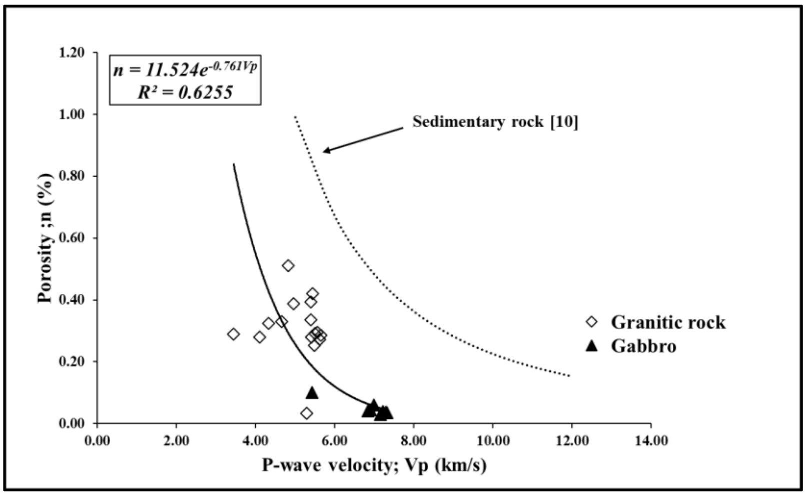

Fig. 4 Comparison of correlation between porosity and P-wave velocity.

3.3 Uniaxial Compressive Strength

The UCS values of granitic rocks and gabbro are 39.85-151.50 MPa and 38.82-144.95 MPa, respectively. Fig. 5 shows the relationship between UCS and P-wave velocity from this study with those from the previous studies.

3.4 Rock Mass Rating

Fig. 6 plots P-wave and S-wave velocities of the granitic rocks and gabbro on the published novel diagram of [10] to determine RQD and RMR values from ultrasonic velocities of this study. The red lines are wave velocity ratios (V_p/V_s) of 1.5, 2, and 2.5. Dispersion of data is around the wave velocity ratio line of 2.29.

3.5 Relationship between Density, Porosity, UCS, RMR, and Ultrasonic Velocities

From Fig. 3, P-wave velocity increases with density. There is an inverse exponential relationship between porosity and P-wave velocity (Fig. 4). The trend of the relationship is similar, but the equation of the relationship is different from that of the sedimentary rocks [10]. The relationship between UCS and P-wave velocity of this study is unidentified, which significantly differs from the relationship reported in the previous studies (Table 1 and Fig. 5). This is likely because the rock types and mineral composition of the earlier published studies and of this study are different. From Fig. 6, increases in ultrasonic velocities lead to increases in rock qualities.

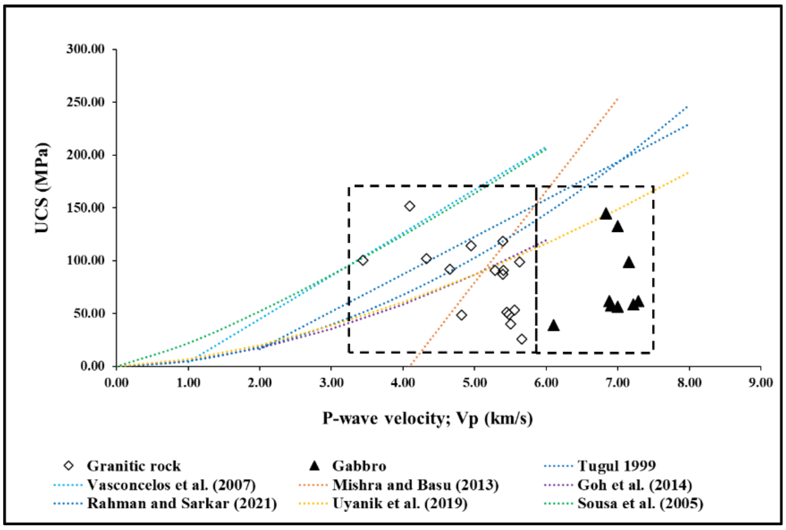

Fig. 5 Correlation of uniaxial compressive strength with P-wave velocity

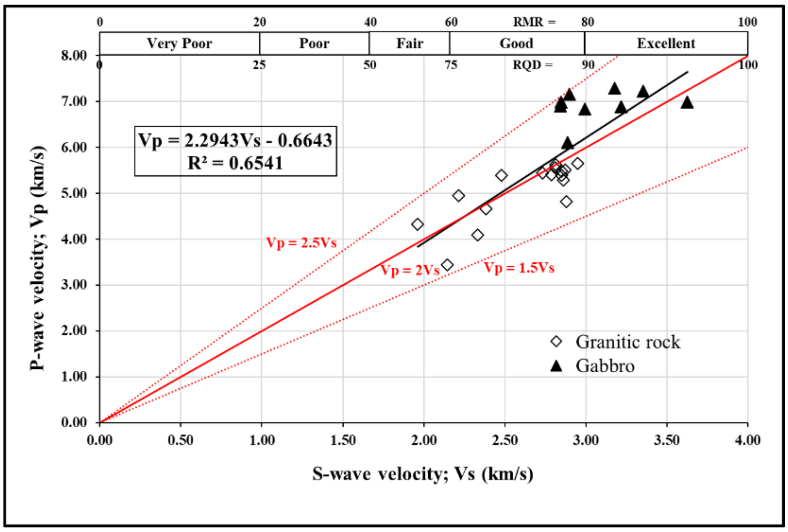

Fig. 6 Estimation of rock quality as rock mass rating (RMR) from P-wave and S-wave velocity (modified from [10])

4. CONCLUSIONS

This study demonstrated the use of ultrasonic velocity as P-wave to estimate the physical properties including density and porosity in granitic rocks and gabbro (Figures 3 and 4). The UCS of either rock cannot be determined from the P-wave, but the data from the two rock types are clustered into two groups due to their difference in P-wave velocity (Fig. 5). This is because some of the factors that affect the rock UCS do not have the same effect on P-wave velocity. From Figs. 3 and 4, it could be inferred that P-wave velocity is density- and porosity-dependent. However, the rock UCS is not solely affected by P-wave velocity but also by other parameters such as mineral type and grain size, shape, and orientation. The diagram of [10] for predicting RMR values using ultrasonic velocities can be utilized to identify the quality of granitic rocks and gabbro from the northern Thailand area (Fig. 6).

Previous studies such as [5-11] showed that there are empirical correlations between the properties of rocks and ultrasonic velocity. However, we do not propose estimating mechanical characteristics and UCS of granitic rocks and gabbro using solely P-wave velocity. We strongly advise more research into the association between mineral composition, mineral orientation, grain boundary type, grain boundary shape, and others with ultrasonic velocity.

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