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ORIGINAL PAPER

Characterization of the Petrographic and Physicomechanical Properties of Rocks from Otanmäki, Finland

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Abstract Intact rock properties are important for mining and geotechnical engineering because they are important design parameters for tunnels, rock foundations, rock slopes, among others. Some of the properties are also used as input parameters in some rock mass classification systems. Therefore, as rock properties are site-specific, there is need to investigate rock properties at a site especially when such site is used for engineering purpose. This paper documents the petrographic and X-ray fluorescence analyses, and physical and mechanical tests conducted to estimate the physical and mechanical properties of the two rock types (i.e. gabbro and granite) selected from quarries at Otanmäki, Finland. Mineral composition, grain size and chemical composition, water content, porosity, Brazilian tensile strength, uniaxial compressive strength, Young's modulus, and Poisson ratio of the rock types were determined. Both gabbro and granite samples have fine to medium grained texture. The results of laboratory experiments conducted show that rock properties investigated have low to high variability. Simple and multiple regression analyses were performed and useful predictive models for estimating Brazilian tensile strength from physical test results were developed and validated.

Keywords Petrography · X-ray fluorescence · mineral composition · chemical composition · physical properties · mechanical properties

1 Introduction

Physical and mechanical properties of intact rocks have been found useful in rock classification for engineering practice such as slope stabilization works, tunneling construction, design of mining support, mine design and foundation (Wang and Aladejare 2016a; Aladejare and Wang 2018; 2019a). Physical and mechanical properties of rock are important in rock mechanics and mining engineering practice, as they also have effect on major mining operations during excavation and loading of rock fragments (Adebayo and Aladejare 2013). For example, uniaxial compressive strength and Young's modulus are used as inputs in rock mass classification and for estimation of rock mass properties (Bieniawski 1989; Aladejare and Wang 2019a), and tensile strength is an important parameter for determination of the load-bearing capacity of rocks, their deformation, damage and fracturing, drilling, and blasting (Coviello et al. 2005; Dai et al. 2013) among others. In addition, physical properties like water content and porosity have been reported to have influence on the strength and performance of rock properties. Several studies have previously been undertaken to investigate physical properties like porosity and water content (Palchik and Hatzor 2004; Kılıc and Teymen 2008; Gurocak

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et al. 2012; Fereidooni 2016; Zhou et al. 2016). Furthermore, the chemical and mineral compositions in igneous rocks have been found to be useful in evaluating the physicochemical conditions of igneous rocks (e.g., Sarjoughian et al. 2015). The compositions and structures of the various mineral phases (feldspar, amphibole, pyroxene, etc.) can give an idea of the physicomechanical parameters of igneous rocks (Honarmand et al. 2012; Sepahi et al. 2012; Ayati et al. 2013; Sarjoughian et al. 2015).

As a result of the importance of physical and mechanical properties of rock and because of the influence that chemical and mineral compositions of rocks may have on performance of rocks in mining engineering, it becomes imperative to continually investigate rocks. Although similar studies have been carried out by previous researchers (Palchik and Hatzor 2004; Kılıc and Teymen 2008; Gurocak et al. 2012; Fereidooni 2016; Zhou et al. 2016; Aliyu et al. 2019), rock properties are site-specific (Wang and Aladejare 2015; Aladejare 2016, 2019; Aladejare et al. 2020) and they vary from site to site. These variations can be further magnified when empirical models developed for a site are used in another site (Aladejare 2019), leading to discrepancies between estimated property and measured property, especially when empirical equations derived from different rock types and formations are used (Wang and Aladejare 2016b; Kong and Shang 2018; Aladejare 2019). A study conducted by Aladejare and Wang (2017) shows wide ranges in the values of different rock properties reported in literature. The effect of variability on different mining and geotechnical design has been explored in literature (Aladejare and Wang 2017: Aladejare and Akeju 2020). The variability exhibited by rock properties from site to site means that determination of the values of rock properties will be a continuous exercise, especially for deposits which are yet to be fully investigated or reported in literature. Therefore, for a specific site of interest, these properties must be evaluated to determine the site-specific rock properties at such site.

In this paper, gabbro and granite samples were collected from Otanmäki in central Finland. Petrographic investigations were carried out to determine the mineral compositions of the two rock types and X-ray fluorescence (XRF) analysis which is a non-destructive analytical technique was used to determine the elemental composition of the two rock types. A series of physical and mechanical properties including water content (w_c), porosity (n), Brazilian tensile strength (BTS), uniaxial compressive strength (UCS), Young's modulus (E) and Poisson ratio (v) values of the collected samples were measured in the laboratory. Then, assessment and estimation of a mechanical property of the gabbro and granite samples using physical test results obtained from laboratory analysis were performed by regression analysis and verification study was subsequently conducted.

2 Study Areas

2.1 Geographical Description of the Study Areas

The sample materials for this study were picked from two nearby quarries, which are situated in the Otanmäki area, 150 km southeast of Oulu and about 5 km south of Lake Oulujärvi in central Finland. The area hosts Fe–Ti–V ore deposits, which were mined for vanadium, ilmenite, and iron ore from 1953 to 1985. The historical production came from two underground mines, Otanmäki and Vuorokas, totalling about 33 Mt of ore and waste rocks mined with ore reserves of 16 Mt remaining (Sarapää et al. 2015). A Finnish mining and exploration company, the Otanmäki Mine Oy (www.otanmaki.fi), is currently developing the Fe–Ti–V ore deposits in the area with the goal of re-starting the mining activities. Figure 1 is the geographical map showing Otanmäki in central Finland, the location of the sampled gabbros and granites.

2.2 Geology of the Study Areas

The bedrock at Otanmäki area hosts by 2060 Ma old gabbroic intrusions, which contain Fe–Ti–V ore deposits within zones composed of mixtures of gabbro, anorthosite and lensoidal bodies of vanadiferous magnetite-ilmenite-rich ore (Mäkisalo 2019). The gabbro was emplaced into Archean TTG (tonalite-trondhjemite-granodiorite) basement gneisses, but they also share faulted contacts against a nappe structure consisting of 2040–2060 Ma old gneissic A-type peralkaline to peraluminous granites and associated intermediate igneous rocks (Kärenlampi et al. 2019). In their current setting, the rocks in

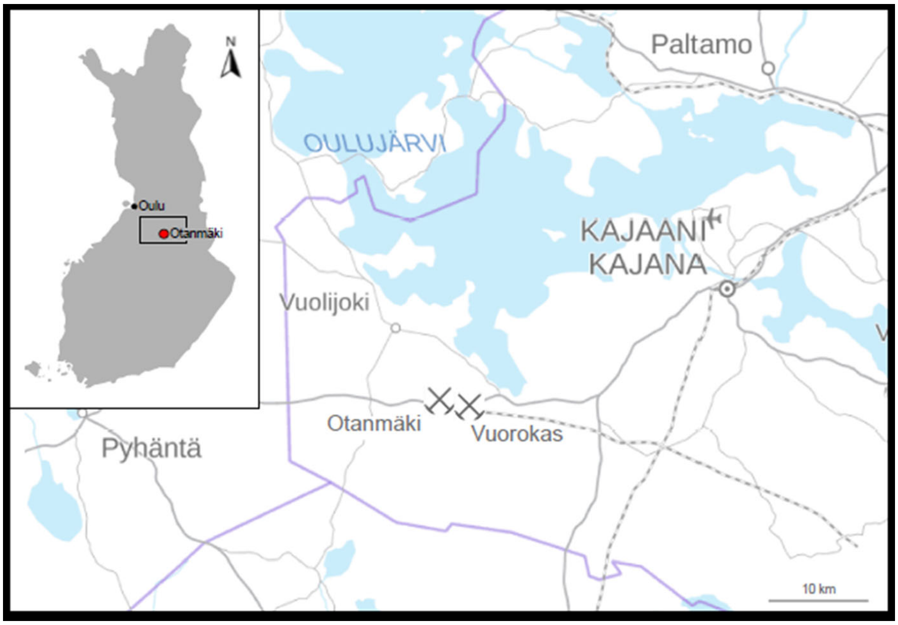

Fig. 1 Geographical map showing Otanmäki in Central Finland, the location of the sampled gabbros and granites

the study area largely reflect the overprinting Svecofennian collisional orogeny (ca. 1900–1800 Ma) during which they were modified by tectonic processes and regional metamorphism in amphibolite facies conditions ($\sim$ 550–600 °C and $\sim$ 4 kbar) (Kärenlampi et al. 2019). Figure 2 is the geological map showing the zones of mineralization of the Otanmäki area.

3 Samples Preparation and Characterization

3.1 Sample Preparation

Rock boulders were sampled from the study areas and brought to laboratory for machining and sample preparation. The specimens for laboratory testing were prepared in accordance with the ISRM (2007) suggested methods (Ulusay and Hudson 2007). Cylindrical specimens were retrieved by coring from the boulders with a Hilti DD 110-W diamond handheld core drilling machine. Figure 3 shows some of the specimen prepared for uniaxial compression and Brazilian tensile strength tests. The specimens for the uniaxial compression tests and Brazilian tensile strength tests were cut and preliminary grinding of the surfaces done with a diamond saw. With the help of a polishing and lapping machine, the cut end faces of the cores were smoothened and made perpendicular to the core axes. Care was taken to ensure parallelism and smoothness of these specimen end faces. The uniaxial compression tests specimens used in this testing had an average diameter of 54 mm and a consistent length to diameter ratio (L/D) of 2.0. The Brazilian tensile strength test specimens had an average diameter of 54 mm and a consistent thickness to diameter ratio (t/D) of 0.5. Irregular rock fragments were also obtained from each rock boulder for determination of physical properties, mineral and chemical composition of the rocks. The samples for petrographic investigations to determine the mineral composition of the rock samples were made into thin sections, prepared perpendicular to the obvious bedding planes.

3.2 Sample Characterization

Polished thin sections were prepared to study the mineral composition of the rocks. The thin sections were examined using a petrographic microscope with transmitted and reflected light capabilities. During the petrographic investigations, the modal mineralogical composition and grain sizes (Prikryl et al. 2007; Zorlu et al. 2008) were determined. In addition, chemical compositions of the rocks were determined by XRF

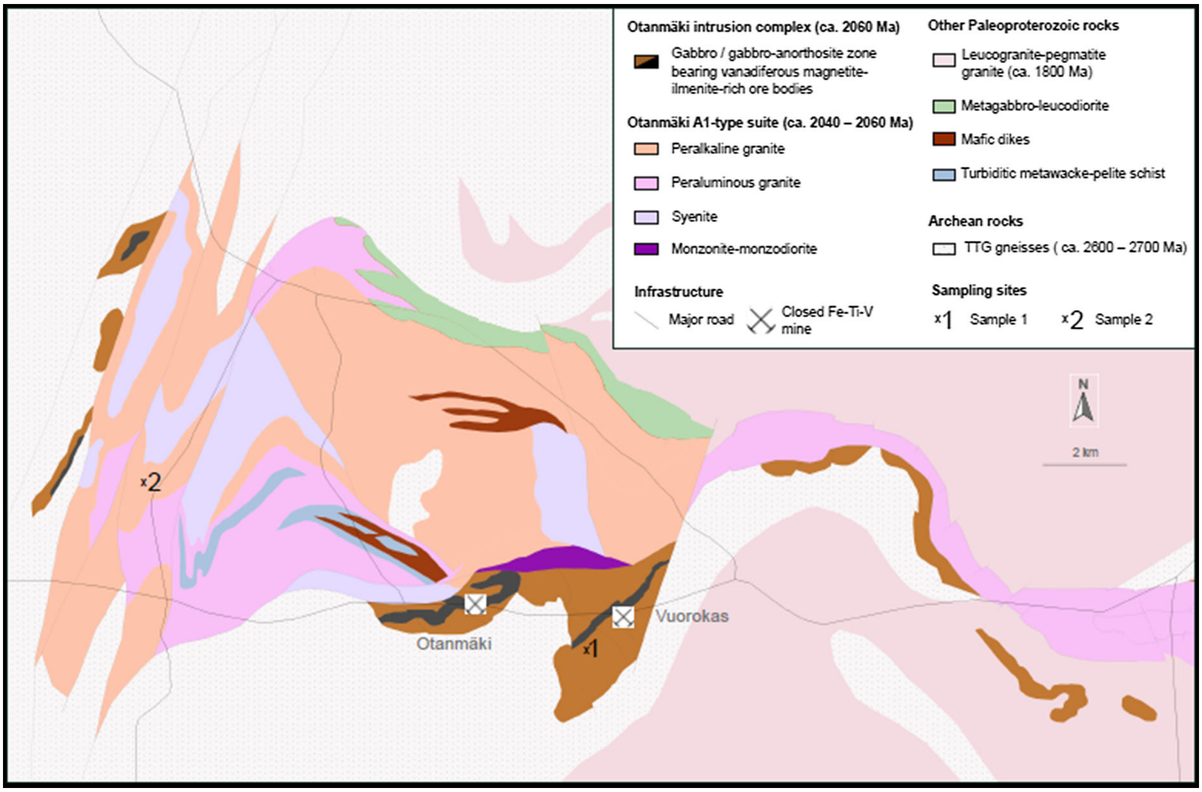

Fig. 2 Geological map of the Otanmäki area showing the gabbroic intrusions and granite mineralized zones (Kärenlampi et al. 2019)

Fig. 3 Core samples of rock for **a** Brazilian tensile strength tests, **b** uniaxial compression tests

analysis using pressed powder pellets and the Bruker AXS S4 spectrometer.

MTS 815 rock mechanics test system was used to perform uniaxial compression tests (see Fig. 4a), and the rock specimens were tested laboratory-air-dry. The test procedure followed was in accordance with ISRM (2007). Representative stress-strain curves of the tested specimens were obtained, from which Young's modulus and Poisson's ratio were calculated in accordance with the ISRM standard. The Young's modulus and Poisson's ratio were calculated between stress levels of 25% and 50% of the ultimate strength.

The indirect tensile strength called Brazilian tensile strength (BTS) was determined by the Brazilian test (Fig. 4b). The NX size drill core specimens were tested according to the suggested methods of ISRM (2007), with the load being applied through two flat steel jaws. The BTS tests are conducted under monotonically increasing load until the specimens failed.

In this study, saturation buoyancy method, suggested by ISRM (2007) is used for measuring the porosity (n) of the rock samples. Weights were measured using a digital balance with a weight accuracy of 0.01%. The water content (w_c) was calculated based on the suggested formula by ISRM (2007), which has been previously used in similar studies (Yao et al. 2016; Masoumi et al. 2017). The change in the mass of the rock samples was used to estimate the water content of the samples at different saturation levels. From each sample, three

Fig. 4 Some of the experimental set-ups for the laboratory testing

(a) Rock specimen held by extensometers for uniaxial compression testing

(b) Rock specimen held by extensometers for Brazilian tensile strength testing

representative specimens were obtained for physical property determination.

4 Test results and analysis

4.1 Thin section, mineral composition, and grain size distribution

Table 1 shows the proportion and grain size range of the minerals present in each rock type. Gabbro is dominated by clinopyroxene (47% by proportion) and plagioclase (43% by proportion), with grain sizes ranging between 2 and 4 mm and 2–5 mm, respectively. There are also relatively small proportion that are hornblende, opaque and other minerals accounting for 10% of the total mineral composition. The grain sizes of the minerals in the small proportion category ranges between 0.5 and 1 mm. The grain sizes of the minerals show that clinopyroxene and plagioclase in the gabbro are of medium-grained grade while hornblende, opaque and other minerals are of fine to medium-grained grade. Granite on the other hand is mostly dominated by K-felspars (50% by proportion), quartz (30% by proportion) and amphibole (10% by proportion) in that order, while opaque and other

Table 1 The mineral composition of gabbro and granite rocks from Otanmäki

Rock type	Minerals	Proportion (%)	Grain size (mm)
Gabbro	Clinopyroxene	47	2.0–5.0
	Plagioclase	43	2.0–4.0
	Hornblende	5	0.5–1.0
	Opaque minerals	2	0.5–1.0
	Other minerals	3	0.5–1.0
Granite	K-feldspars	50	0.5–2.0
	Quartz	30	0.1–1.0
	Amphibole	10	0.1–0.5
	Opaque minerals	5	0.5–1.5
	Other minerals	5	0.5–1.0

minerals account for 10% of the total mineral composition. The grain sizes of the minerals show that K-feldspars, quartz, opaque and other minerals in the granite are of fine to medium-grained grade while amphibole are of fine-grained grade.

Figure 5 shows the microphotographs of gabbro and granite samples from polished thin sections. The gabbro samples are isotropic and are composed of equidimensional euhedral plagioclase laths, subhedral clinopyroxene and anhedral amphibole mineral grains (Fig. 5a,b). The plagioclase exhibited carlsbard twinning with twin lamellae, have medium grains with few visible fractures in the grains. The clinopyroxene grains exhibit cleavages with alteration along cracks in the crystal grains. These alterations were observed to be secondary hornblende, which has replaced primary clinopyroxenes probably after the magmatic crystallization. The grain boundary features between the clinopyroxene and plagioclase are straight, but somewhat irregular due to growth of secondary hornblende. Minor opaque minerals occur as small anhedral to subhedral in clinopyroxene and amphibole. The matrix of the granite rock is characterized by subhedral to anhedral alkali-feldspars (K-feldspar and albite), subhedral to anhedral quartz grains and anhedral amphibole grains (Fig. 5c, d). The alkali-feldspars are brownish-grey, have fractures, exhibit cross-hatched twinning occasionally with straight to sinuous grain boundaries with quartz. Quartz is deformed and exhibits large variations in grain size. The amphibole mineral grains were conspicuous as dark silicates in both plane and cross polar exhibiting sinuous contacts with the alkali-feldspars and the quartz. (Fig. 5d).

4.2 Chemical composition of rocks

Table 2 shows the major chemical composition of gabbro and granite rocks from Otanmäki, which include the statistics of the results in term of minimum and maximum values, range, mean and standard deviation. Comparing the results of gabbro and granite samples, compositions of the gabbro rocks (Table 2) contain lower SiO_2, higher Al_2O_3, MgO, CaO, FeO than those of granite rocks. The compositions of the granite rocks have higher Na_2O, K_2O in addition to SiO_2. The gabbro shows higher average values for Al_2O_3, MgO, CaO and FeO relative to those for the granite because of its mafic compositions. Granite shows higher SiO_2, Na_2O and K_2O values relative to gabbro, reflecting its felsic compositions. P_2O_5 and MnO variations are similar for both rock types, except that in gabbro rocks, there is higher CaO and MgO because of plagioclase enrichment. Lower values of CaO and Al_2O_3 reflect the granite rocks, and high values reflect the gabbro rocks. Fe enrichment is modest in gabbro rocks, with total FeO/MgO values ranging from 0.39 to 0.95 but high in granite rocks from 29.62 to 41.11. Both rock types also contain low TiO_2, but this indicates enrichment, along with K_2O in gabbros and granites. However, the relatively higher K_2O values in granite rocks show that it has more enrichment than gabbro rocks.

4.3 Physical and mechanical properties

Results of the laboratory investigation into the physical and mechanical properties of the rocks are summarized in Table 3. For both rock types, there are specimen that failed in invalid failure modes (Mishra and Basu 2013) and some that were not as smooth and straight as required due to unfavourable drilling conditions. Consequently, uniaxial compressive strength, Young's modulus and Poisson ratio were not calculated for such specimen, and that is the reason the number of data for the three properties are different from the rest of the properties investigated. The variability in the mechanical properties investigated is low with coefficient of variations (COV) of each property less than 20% in all properties for both rock types. On the other hand, the physical properties of gabbro have medium variability with their COVs up to but not more than 50%, while those of granite have high variability with COVs greater than 50%. These classifications are based on a three-tier classification system proposed by Aladejare and Wang (2017).

5 Correlations between physical and mechanical properties

Regression analysis is performed to determine the influence of the physical properties on a mechanical property of rocks in this section. In mining engineering, regression analysis is frequently used to establish

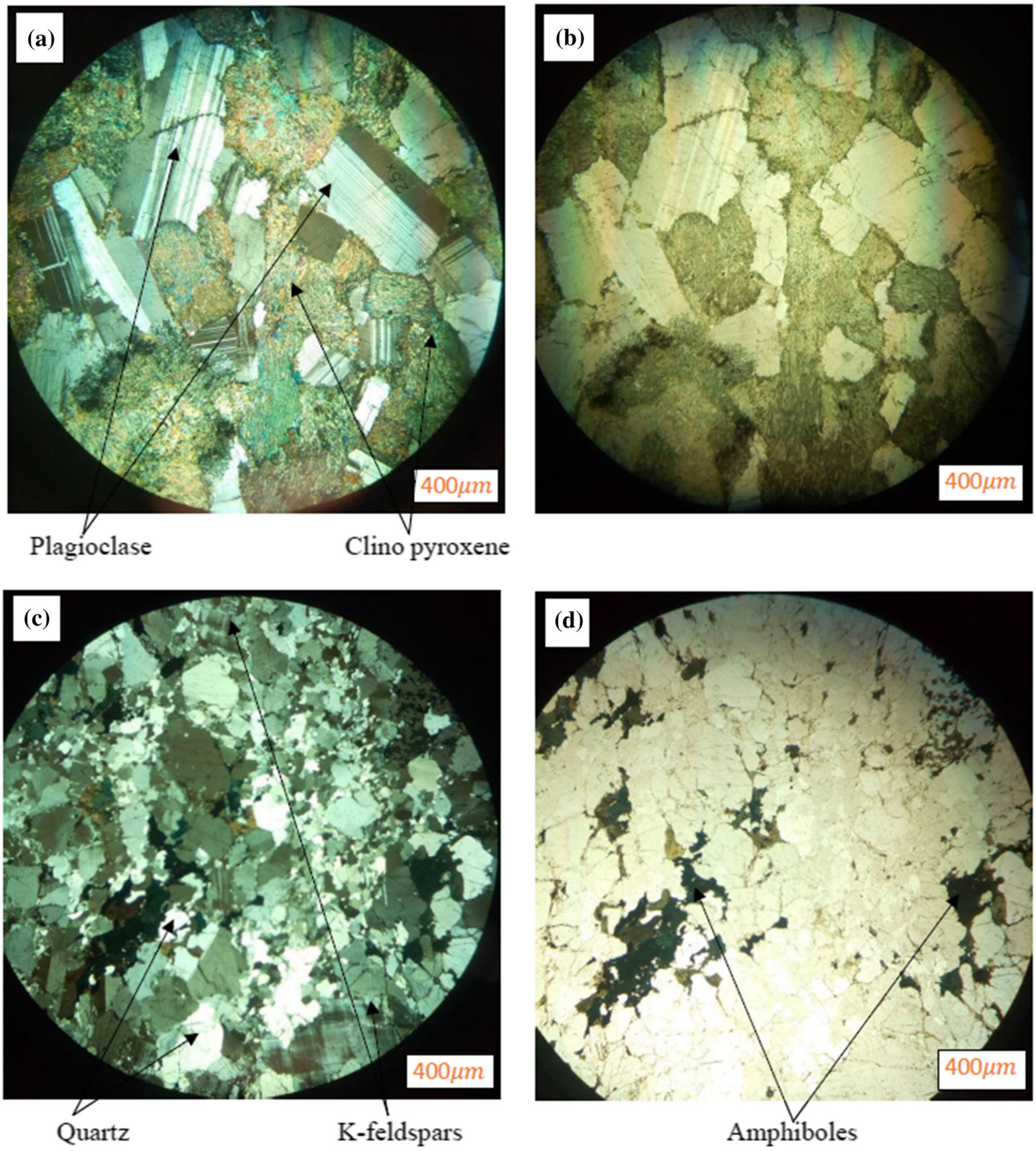

Fig. 5 Microphotographs of gabbro and granite samples from polished thin sections: **a** isotropic gabbro (cross polarized light) composed of plagioclase with characteristics carlsbard twinning and twin lamellae, altered clinopyroxene altered and fine-grained hornblende; **b** isotropic gabbro (plane-polarized light); **c** gneissic granite (cross polarized light) with K-feldspar grains exhibiting crosshatched twinning interspersed with subhedral quartz grains; **d** gneissic granite (plain polarized light)

empirical models among rock properties. In this study, both simple and multiple regression analyses were performed to establish possible correlations between Brazilian tensile strength (BTS) of gabbro and granite and two physical strengths values (i.e. porosity (n), and water content (w_c)), All the data of gabbro and

Table 2 Major chemical composition of gabbro and granite rocks from Otanmäki

Parameter	Number of data	Minimum value	Maximum value	Range	Mean	Standard deviation
Gabbro						
Na_2O (%)	15	2.43	3.45	1.02	2.85	0.26
MgO (%)	15	5.01	8.56	3.55	6.83	1.08
Al_2O_3 (%)	15	15.04	19.59	4.55	17.46	1.25
SiO_2 (%)	15	46.40	48.09	1.69	47.51	0.45
P_2O_5 (%)	15	0.02	0.06	0.04	0.04	0.01
K_2O (%)	15	0.21	0.37	0.16	0.26	0.04
CaO (%)	15	11.71	13.2	1.49	12.53	0.47
TiO_2 (%)	15	0.47	1.02	0.55	0.63	0.15
MnO (%)	15	0.09	0.14	0.05	0.12	0.01
FeO (%)	15	4.80	7.22	2.42	5.97	0.69
Granite						
Na_2O (%)	10	4.63	5.89	1.26	5.00	0.36
MgO (%)	10	0.09	0.17	0.08	0.12	0.02
Al_2O_3 (%)	10	10.92	13.6	2.68	11.87	0.72
SiO_2 (%)	10	63.31	69.61	6.30	67.87	1.90
P_2O_5 (%)	10	0.03	0.06	0.03	0.04	0.01
K_2O (%)	10	3.90	4.80	0.90	4.31	0.24
CaO (%)	10	0.27	0.65	0.38	0.47	0.13
TiO_2 (%)	10	0.27	0.54	0.27	0.39	0.09
MnO (%)	10	0.09	0.12	0.03	0.11	0.01
FeO (%)	10	3.70	5.04	1.34	4.41	0.44

Table 3 Physical and mechanical properties of gabbro and granite rocks from Otanmäki

Parameter	Number of data	Minimum value	Maximum value	Mean	Standard deviation	Coefficient of variation (COV)
Gabbro						
w_c (%)	15	0.01	0.04	0.02	0.01	50.00
n (%)	15	0.13	0.48	0.29	0.10	34.48
BTS(MPa)	15	6.8	12.6	9.88	1.78	18.02
UCS (MPa)	5	294	303	298.8	4.27	1.43
E (GPa)	5	103	108	105.2	1.92	1.83
v	5	0.25	0.29	0.28	0.02	7.14
Granite						
w_c (%)	10	0.02	0.12	0.05	0.04	80.00
n (%)	10	0.29	1.64	0.73	0.43	58.90
BTS(MPa)	10	7.1	12.7	10.41	1.96	18.83
UCS (MPa)	6	228	284	253	23.24	9.19
E (GPa)	6	64	71	66.67	3.01	4.51
v	6	0.27	0.29	0.28	0.01	3.57

granite are also combined to determine the correlation for all data. Test results of uniaxial compressive strength (UCS), Young's modulus (E) and Poisson ratio (v) are not used in the regression analysis because of their relatively limited number (see Table 3).

5.1 Simple regression

n is linearly related with BTS for both rock types when plotted individually as well as when data of both rocks are combined (Fig. 6). The correlation coefficient was found to be high for individual rock type and low for both rocks together (Fig. 6). When w_c was related with corresponding BTS, the correlation coefficient was found to be higher for individual rock types than both rocks together (Fig. 7). For the two rock properties correlated with BTS, the correlations for individual rock types have higher coefficients than when both rock types are combined. The correlation coefficients for BTS versus n and BTS versus w_c are high for individual rock type (with $R^2 \geq 0.81$) but reduced considerably when considered for both rocks together. For both relations, the coefficient dropped from $R^2 \geq 0.81$ to as low as $R^2 \leq 0.35$. The decrease in the correlation coefficient when the test results of the two rock types are combined shows that different rock types behave differently because of the different geological process through which they were formed. Therefore, for regressions that produced high correlation coefficient, it is better they are used for individual rock type and should not be combined for any statistical correlation. From the above analyses, it is noticeable that for gabbro and granite, performances of porosity and water content are reasonably satisfactory in predicting BTS.

5.2 Multiple regression

In rock and mining engineering, multiple regression analysis is popular as it has been used by researchers to establish regression models for the prediction of different rock properties (Gokceoglu and Zorlu 2004; Zorlu et al. 2008; Monjezi et al. 2012; Mishra and Basu 2013). The multiple regression models to predict

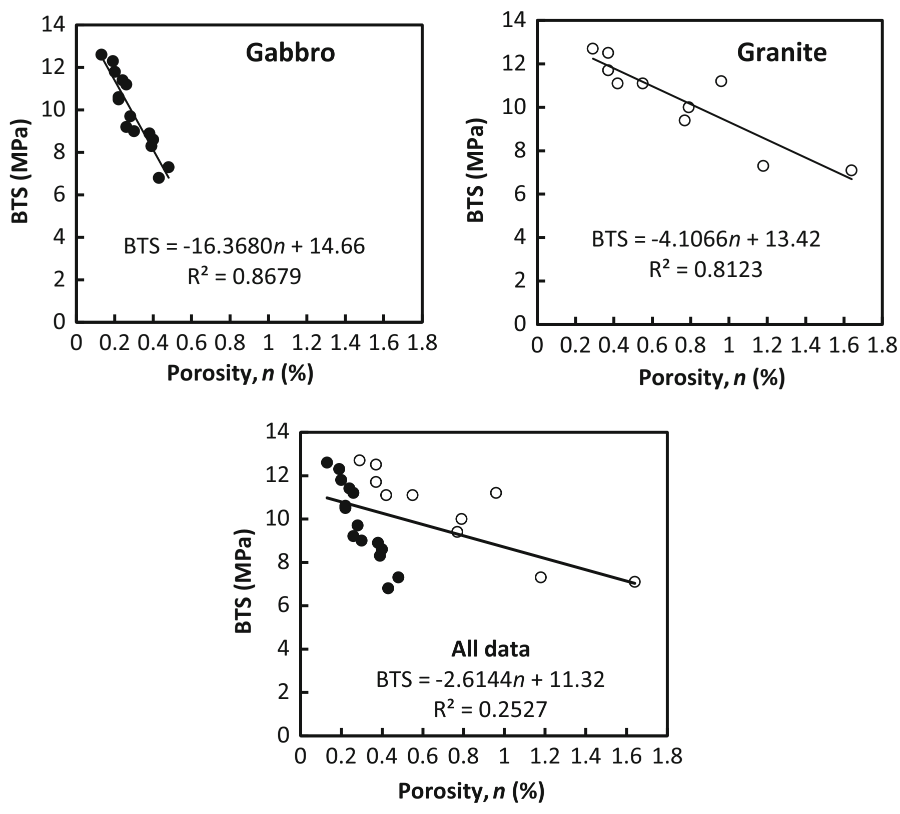

Fig. 6 Simple regression analysis between porosity, n (%) and BTS (MPa)

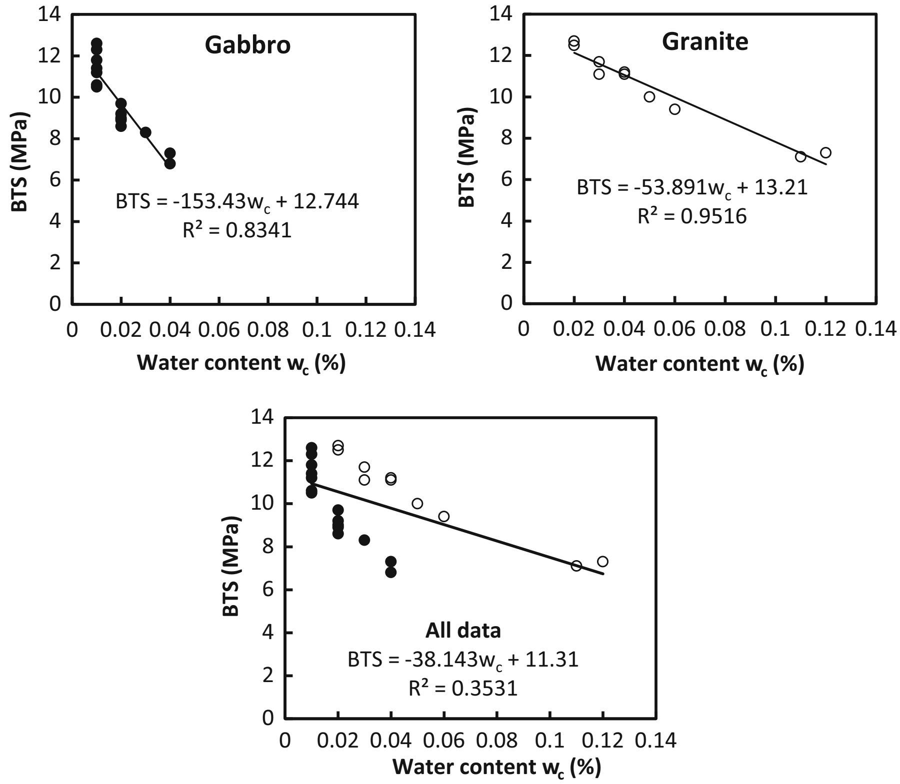

Fig. 7 Simple regression analysis between water content, w_c (%) and BTS (MPa)

the Brazilian tensile strength for gabbro and granite are presented in Eqs. (1), and (2), respectively.

$$BTS = 14.0826 - 10.0094n - 68.5646w_c \quad (1)$$

$$BTS = 13.3499 - 0.7841n - 45.4689w_c \quad (2)$$

The prediction models for the Brazilian tensile strength (Eqs. 1 and 2) are logical, because the variable (BTS) increases as the independent variables (n, w_c) decrease. Strength of rock naturally decreases as porosity and water content increase and vice versa. Multiple regression equation was not considered for combined data of gabbro and granite since simple regressions for such combinations produced weak correlations. Eqs. (1) and (2) are used to estimate BTS from tests results of n and w_c for gabbro and granite, respectively.

The predicted BTS is each case is plotted against the measured BTS as shown in Fig. 8. As can be seen in Fig. 8, the coefficients of correlation of the multiple regressions are higher than those of the simple regressions for each case. Figure 8 also includes the perfect correlation line for each of the cases, and it can be seen that the deviation of the fitted line from the perfect correlation line is minimal in both cases. In the cases investigated in this study, the prediction models from multiple regression are more reliable than the simple regression equations. In addition, the determination of porosity and water content are easy and fast. The tests for their determination can be performed using irregular samples which eliminate the difficulty often posed by the need to have core samples for Brazilian tensile strength tests. Therefore, these multiple regression models can be used to estimate BTS when there is no BTS test result and there is a possibility of performing physical tests to determine the porosity and water content of rock at a site or deposit.

6 Conclusions

Mineral composition, grain size distribution, chemical composition, water content, porosity, Brazilian tensile strength, uniaxial compressive strength, Young's modulus and Poisson ratio of two rock types (i.e. gabbro and granite) were determined, the conclusions

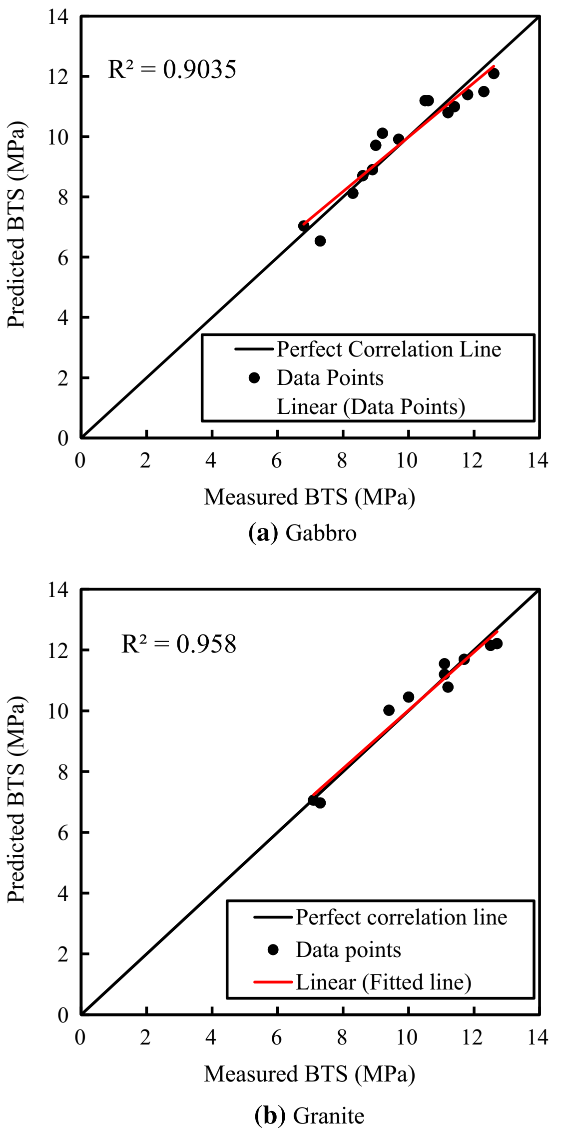

Fig. 8 The relationship between the measured and predicted Brazilian tensile strength values from the multiple regression (Eqs. 1–2): **a** Gabbro, **b** Granite

obtained from the present study can be drawn as follows:

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(a) The petrographic analysis of the rock samples shows that even though gabbro and granite are igneous rocks, there samples consist of different minerals in different proportion. The gabbro is isotropic and have fine to medium-grained texture, composed of euhedral laths of calcic plagioclase with interstitial spaces filled by clinopyroxene, which is replaced by amphibole. The granites have fine to medium grained texture and consists of equigranular framework of quartz and alkali feldspar and dark coloured bands of amphibole, which define gneissic banding.

(b) The chemical composition analysis shows that the gabbro samples have average higher values for Al_2O_3, MgO, CaO and FeO relative to those for the granite samples because of its mafic compositions. Granite have higher SiO_2, Na_2O and K_2O values relative to gabbro, reflecting its felsic compositions. Both rock types show enrichment, though the granite rocks have more enrichment than gabbro rocks.

(c) The results of physical and mechanical tests generally fall within the typical ranges reported in literature for the rock types investigated. However, the physical properties investigated vary significantly with their COVs indicating medium to high variability. On the other hand, all the mechanical properties have low variability as indicated by their COVs. Among the mechanical properties, the Brazilian tensile strength of both rocks has highest variability. The relatively low variability in uniaxial compressive strength, Young's modulus and Poisson ratio compared to Brazilian tensile strength may be a consequence of the small number of compression tests performed.

(d) Multiple regression equations exhibit better predictive performances than simple regression equations for estimation of BTS from rock physical properties. However, there is need for caution when employing the multiple regressions for other sites because of the site-specific nature of rock properties.

(e) Physical test results of different rock types with different geology should not be combined to develop regression models. For the cases investigated, the correlation coefficient of the models reduced considerably when data of gabbro and granite are combined compared to when they are analyzed separately.

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Compliance with ethical standards

Conflict of interest The author declare that they have no conflict of interest

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