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Depth variations as effective indicators for strength variation of Najran granites, Najran region, Saudi Arabia

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Igneous rocks of various types are used for various purposes; however, their use as building stones for construction is ubiquitous due to their durability, hardness, appearance, and availability. This study thoroughly examines the impact of the petrographic and physico-mechanical characteristics of Najran granite on the rocks strength with depth variation. In this study 55 granite samples were acquired from various localities in the Najran area, and the various properties were analyzed including petrophysics, and geo-mechanics in reference to various burial depths of 0, 5, 10, 20, 25, and 30 m. Experimental models were constructed to delineate the link the burial depth and mechanical attributes, and then four specimens with different burial depths validated the experimental models. The results depict the direct relationship of mechanical attributes of rocks (i.e., SDI, Brazilian strength, uniaxial compressive strength (UCS), and tensile strength) with increase in burial depth. As the specimen depth increases from 0 to 30 m, the SDI, Brazilian strength, UCS, and tensile strength also increases from 98.67%, 16.65, 132, and 10.82 MPa to 99.76%, 20.46, 187, and 15.33 MPa, respectively. Moreover, the p-wave also increases with the increase in depth, indicating low porosity, voids, and high density. This observation is also confirmed by the low water absorption that decreases with depth as well. Analyses of XRF data also considered the mechanical reasons for the strength with burial depth effects; findings suggested a direct relationship between burial depths and UCS values and inverse relationship with quartz content. For a better knowledge of the granites throughout the region, it is

Abbreviations: Vp dry, Dry primary wave velocities; Böh, Böhme abrasion test; Brazil str, Brazilian strength; ISI, Impact strength index; UCS, Uniaxial compressive strength; σt, Tensile strength; Ab, Water absorption; BG, Black Granite; XRF, X-Ray Fluorescence.

advised to carry out comparative studies on other granites in Saudi Arabia and create a comprehension model using numerical simulation.

KEYWORDS

granite, depth impact, Najran area, mechanical properties of rocks, physical properties of rocks

1 Introduction

The differences in the inherent characteristics of the mineralogical composition and texture of rocks are closely related to their mechanical features and chemical signatures. The term texture ferrered in the literature as linkages among the rocks fabric, mineral grains, shapes and sizes (McPhie et al., 1993; Bucher and Frey, 1994). Both the texture and mineralogy, which are the intrinsic properties, can assess the geomechanical aspects of the rock (Lindqvist et al., 2007; Sajid and Arif, 2015). A number of researchers (Tugrul and Zarif, 1999; Pomonis et al., 2007; Sajid and Arif, 2015) have related the mechanical properties to petrographic characteristics. The mineralogical and chemical investigations are considered to be very important especially when bseing used for construction purposed. Researchers have studied the granites of the different regions with respect to mineralogical and geomechanical properties (Wulff et al., 1999) Changes in mineralogical and chemical compositions have a prominent effect on the geotechnical characteristics of the granites; numerous researchers have worked on granite on physical and chemical variations and their comparison with changes in the engineering behavior of the granites (Ali and Yang, 2014; Ali et al., 2020; Evans and Pomeroy, 1966). Several researchers have shown an inverse relationship between the strength of granite and the degree of alteration. Previous researches also show that the geotechnical strength of granites is greatly affected by variations in their mineral and chemical compositions, and the various researches have been conducted on the subject matter and study these properties from different aspects, including exposure to weathering, clay mineralogical alteration, changes in texture, etc (Coggan et al., 2013; Sousa, 2013; Hu et al., 2014; Rigopoulos et al., 2014; Basu et al., 2009; Tugrul, 2004; Sajid et al., 2014).

The study under investigation lies between 45° 1′15″ and 45° 09′E longitudes and 19° 01″ to 19° 5′30″ N latitudes in the city of Najran (Figure 1). The city of Najran is located along Wadi Najran and serves as the region's administrative and commercial hub. The Najran basin is located towards the extreme southwest of Saudi Arabia, where its boundaries are marked by the arid Empty Quarter in the east, the Asir Region on the west, Ar-Riyadh City on the north, and the Republic of Yemen on the south (Figures 1A–C). It is a huge area with a population of over 450,000 people and covers around 359.9 km^2. The basin has a great similarity with other basins in Saudi Arabia that have attracted significant development over the past 3 decades. There are some archeological sites in the study area, although it is primarily a sector of agriculture in the Najran.

The mining sector and usage of rock as a building material have increased steadily recently as part of Saudi Arabia's 2030 program. The mining industry is now regarded as the third pillar of the economy of a nation and the primary means of revenue. Naturally derived stones are primarily utilized for ornamentation and flooring (Hecht et al., 2005). Stone tiles are preferred and installed for floor covering purposes based on their mineral composition as well as their physical and mechanical characteristics. Individuals walking on floors are the most prevalent source of floor wear because of the friction created by the contact of the surface with the floor.

Granite is one of the oldest and most durable construction materials available, and it will outlast the structure in which it is used. It has become the material of choice for today's luxury houses and companies due to its enduring beauty and the fact that no synthetic material can yet equal its elegance and performance. Granite is a popular choice for kitchen and bathroom countertops. Countertops, cashier desks, storage, seats, and tables are all frequent uses for granite tiles with a thickness of 20–50 mm.

The following points can be gleaned from the above-mentioned works: (1) The majority of research looked at how intrinsic microstructure (such porosity, minerals, or particle size) and extrinsic engineering environments (like temperature, stress or fluid) affect the strength of the rock. The impact of the geological effects in form of structure or depth) on microstructure, on the other hand, has received little attention. (2) Microstructure knowledge is useful for strength prediction models. Petrography and other studies of thin-sections are undertaken on various samples when utilizing the model for uniaxial strength and grain size, for example. However, rock specimens are sometimes difficult to come by in deep rock engineering procedures, which restrains the use of models of prediction.

To correlate or establish a relationship among strengths and depths can provide a way forward for engineering techniques. Lanaro et al. (2009) investigated the depth variability of UCS on intact Toki granite and discovered that granite UCS is highly related to depth. Zhou et al. (2010) examined the influence of basalt burial depth on its mechanical properties and attributes of deformation. Sedimentary rocks, on the other hand, show different diagenetic patterns than magmatic rocks. In coal-measured layers, sedimentary rock has received little attention. Moreover, the micro-mechanisms that underpin the influence of depth on rock strength must be investigated further. A number of tests were carried out on samples gathered from the Huainan coalfield at various burial depths in this research. The link between rock strength and burial depth was investigated along with data from used for micro-mechanism among these properties.

For civil engineering projects, compressive strength is the most imperative quality of any building stone. The UCS is a measurement of how much weight a stone can withstand before being crushed and, consequently, its strength (Karaman and Kesimal, 2014). When stones are used as external pavements or masonry load-bearing buildings, this feature is especially essential. The resistance of pressure applied to a single point, causing deformation, is demonstrated by the splitting tensile strength test of the rocks.

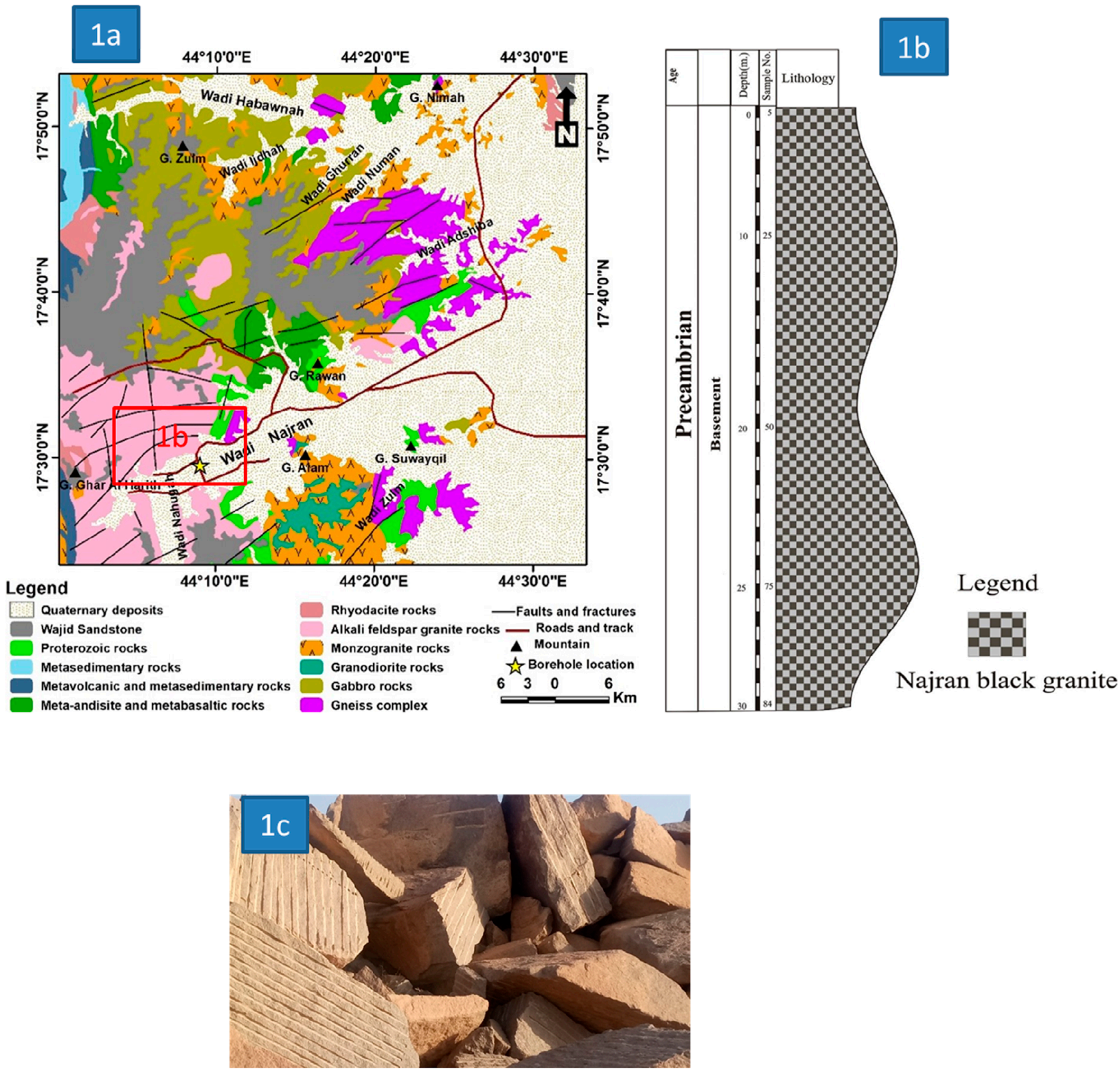

FIGURE 1
(A) Geological map of the area under research, **(B)** lithological log for the studied section in Najran area, field phots illustrating the site under study, **(C)** field photo for the site (after Abd El Aal et al., 2023).

2 Geological setting

In this study, pre-Cambrian igneous rocks are examined, followed by layered Mesozoic rocks from the Cambrian-Ordovician period (Wajid sandstone) and bedrock of the Tertiary age (Sable, 1985). The area under investigation lies at the southern edge of the Arabian Shield (AS). The Pre-Cambrian basement rocks in the AS are made up of metamorphosed, interlayered volcanic, and ancient metamorphosed sedimentary rocks. The Precambrian to Cambrian Gabro to Syenite igneous rocks intruded on these rocks. Volcanic rocks in the area range in texture from andesite to rhyolite, agglomeration to thick, massive flows to lithic tuff. Sandstone, conglomerate, graywacke, shale, and limestone are all interlayered with sedimentary strata in various ways. The basement rocks are not encumbered by unconsolidated alluvial, aeolian, or Cambro-Ordovician Wajid sandstone, according to Abd El Aal and Nabawy (2017). The Wajid sandstone is eroded at the western Najran, leaving only isolated buttes where the bedrock has been retained.

3 Materials and methods

The methodology includes both field work and laboratory analysis. In order to investigate the granitic rocks in depth along the foot slopes and surface area of Najran, detailed field investigations were performed. The samples were collected from one location (Bir Askar Najran Granite-from Bin Hirkil company) in the Najran region. During the fieldwork in the study area, 84 rock samples were obtained from various grey granites in the Najran region.

3.1 Laboratory tests

In order to determine the strength of a rock samples, several geomechanical tests were performed. The experimental standards of ISRM (2007) were employed for the testing of uniaxial compression (UCS) of 5 by 5 cm (Figure 2). The loading rate was balanced between 0.5 and 1.0 kN/s. The elastic characteristics of solid rocks are related to their tensile strength (t). Greater tensile strength is necessary when employing rocks as face stones (Benson et al., 2007). The assessment of slake durability is a valuable instrument for determining the toughness of the stone or rock. The ISI (impact strength index) is a straightforward and quick tool for the investigation of materials' pulverizing behavior (Sharma et al., 2011). The ISRM (2007) method was employed to measure these geomechanical characteristics.

The Brazilian test is one of the most frequent procedures for determining tensile failure strength (indirect tensile strength test). A compression force on a rock sample in a disc shape is exerted in a uniaxial test setup, causing a field of tensile stress of a homogenous nature (ISRM, 2007). For dry and water-saturated cores and slabs, the Vp is determined as reported by Abd El Aal et al. (2020) and Salah et al. (2019). The primary wave velocity is quantified using the timing of the pulse arriving first spotted by a monitor as accurately as 0.01 s.

Since there is a dearth of information about the indirect granitic rock tensile strength analyses, the identified values, according to Siedel and Siegesmund (2014), are between 3.6 and 19.1 MPa. The resistance of rocks to mashing is an indication of their hardness that is determined primarily by their internal rock fabric and composition (Siedel and Siegesmund, 2014). Rock wear abrasion was measured using the Böhme abrasion testing method. A 50 cm^2 rock specimen is pressed onto the mashing wheel with a specific weight and then pulverized with a specified average. Microscopic investigations have been carried out to properly identify the textures, mineral make-up, micro-fractures, and harmful materials of the samples tested, as well as to precisely anticipate the character of the rocks during or before the application in construction.

Finally, for determining the major and trace elements, X-ray fluorescence analysis (XRF) is a method for qualitative and quantitative analysis of elements using secondary X-rays generated by X-ray irradiation of a sample. XRF can quickly and precisely analyze the elemental composition of a large number of samples non-destructively. In addition, XRF is an essential analysis method for environmental analysis (Stallard et al., 1995) and research and development of materials and products because sample preparation is simple and the analysis accuracy is high (Ida et al., 2005). When the analyte is irradiated with X-rays, the inner shell electrons of the atom are excited and emitted, creating a hole in the inner shell. When the outer shell electrons move in the hole of the inner shell, the energy corresponding to the difference in the level of the electron energy of the element is emitted as an electromagnetic wave in the X-ray region and is called a fluorescent X-ray. Because the fluorescent X-ray spectrum is obtained from an intrinsic element, the element constituting the sample from the spectrum can be qualitatively analyzed. In addition, since the intensity of fluorescent X-rays is proportional to the concentration of elements in the sample, quantitative analysis is possible based on the intensity.

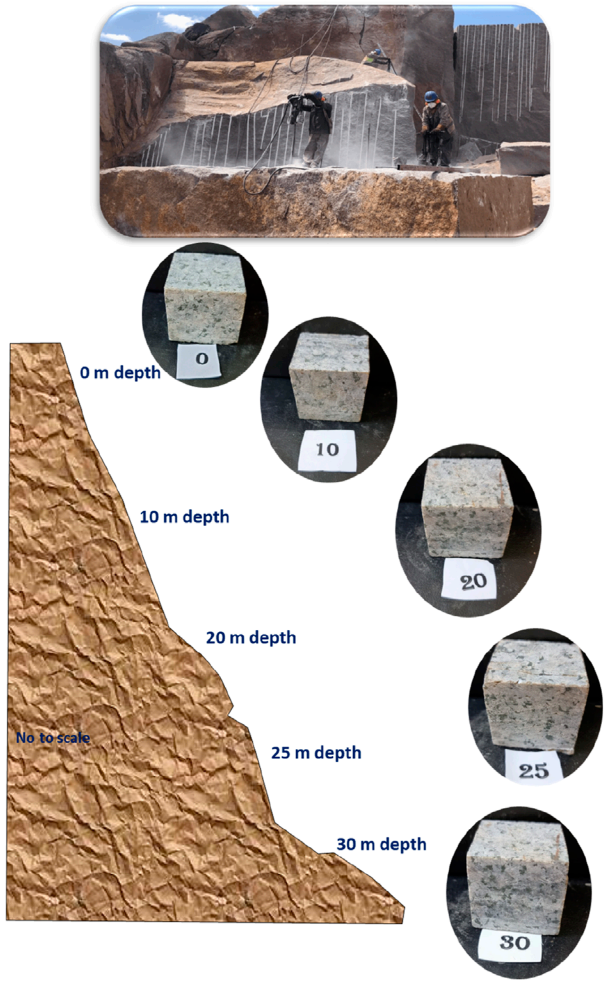

FIGURE 2
Schematic diagram and photos Najran granite, and photos of sample preparation.

4 Results and discussion

4.1 Petrographical characteristics of Najran Black granite (NG)

Petrography is so important to classify rocks. The detailed investigation of microscopic features, i.e., mineralogical composition and texture, can pave the way to predict the physico-chemical and mechanical properties of rocks (Quick, 2002).

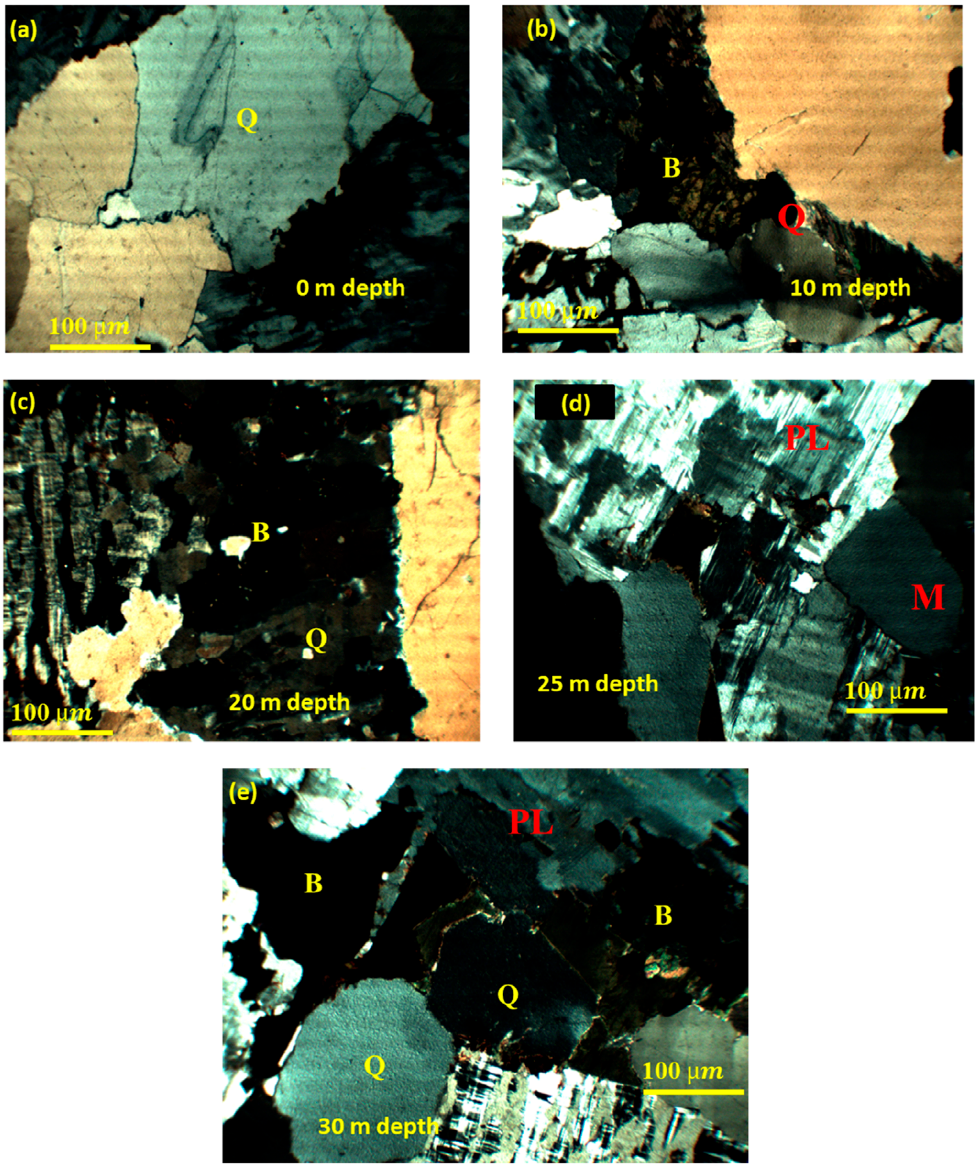

FIGURE 3
Micrographs of the analyzed Najran Black granites (NG) exhibit: **(A)** heavy microcracks of quartz "Q" in deformed grains of plagioclase (PL) at 0 m depth; **(B)** partially altered plagioclase "Pl" and minute biotite aggregates **(B)** incorporated by the coarse grain of microcline perthite (M) at 10 m depth; **(C,D)** interlocking quartz grains at 10m and 20 m depth respectively (Q) with sharp boundaries and minute grains of biotite **(B)** within grains of microcline perthite (M), and **(E)** quartz grains at 30 m depth (Q) with sharp boundaries and high content of biotite grains.

The petrographic study is performed through the study of thin-sections under a polarized light microscope to determine the chemical and depositional makeups of the rock along with its mineralogy (Hussain et al., 2023). The area under investigation comprises granite rocks (granitoids), which are categorized into one categorie, and their details are as follows:

Najran granite is a weathered, black, and rough stone with a range of textures, including perthitic, and in the color range of black to buff. Despite the higher properties of electrolytes, they consist of accessory minerals such as biotite and hornblende, with the dominant mineralogy being feldspars, plagioclase, quartz, and riebeckite. Alkali feldspar is typified by orthoclase, microcline, orthoclase perthite, and microcline perthite, with crystal shapes ranging from anhedral to subhedral. Orthoclase perthite and microcline perthite constitute about half of the composition of the rock, while orthoclase and microcline comprise about 20% of the composition. The difference in diameter of the perthite is marked by flaky, string, and vein types (Figures 3A, B). At places, the crystals of orthoclase perthite and microcline perthite are bisected by sodic narrow rims of plagioclase and exhibit lamellar twinning. The abundance of quartz makes a rock composition of about 25%–55%, and it is of two types. The first type comprises euhedral to subhedral areas marked by rare undulose extinction (Figures 3C–E). The other type consists of crystals of fine size and has a micrographic texture. The composition of about 2%–10% of the rock is mainly albite plagioclase, occurring in crystal shapes ranging from euhedral to

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TABLE 1 Mineralogical composition (Major and trace elements) for investigated samples of Najran Black granite.

Depth in (m)	Al_2O_3%	BaO%	CaO%	Cr_2O_3%	Fe_2O_3%	K2O%	MgO%	MnO%	Na_2O%	P_2O_5%	SO3%	SiO_2%	SrO%	TiO_2%	Total%	Loi%
0	17.33	0.08	2.59	0.07	6.43	4.27	3.93	0.23	4.06	0.32	0.2	54.82	0.04	1.07	99.49	1.06
10	15.84	0.08	1.28	<0.01	6.55	5.66	0.07	0.09	4.68	0.03	0.02	68.88	0.01	0.38	100.7	0.01
20	12.98	0.04	0.73	<0.01	7.22	5.32	0.07	0.06	4.25	0.01	<0.01	72.02	<0.01	0.31	99.85	0.12
25	13.25	0.04	0.64	<0.01	7.99	5.44	0.07	0.05	4.32	<0.01	<0.01	72.92	<0.01	0.26	100.55	0.09
30	10.49	0.08	1.74	<0.01	8.33	5.72	0.09	0.12	4.29	0.05	0.03	67.44	0.01	0.48	100.6	0

TABLE 2 Average values of the physical and mechanical properties of the tested Najran Black granite samples at selected depths.

Type	Depth in M	Fe^2O^3	P Wave wet (Km/s)	P Wave dry (Km/s)	Water absorption "sw" (%)	Bohme ($cm^3/50\ cm^2$)	Brazil str. (MPa)	TS (MPa)	SDI%	ISI%	UCS (MPa)
Najran Black granite	0	6.43	5.23	4.32	0.993	9.93	16.65	10.82	98.67	85	132
	10	6.55	5.67	4.54	0.893	8.93	17.32	11.89	99.02	82	145
	20	7.22	5.98	4.87	0.628	7.28	18.55	12.79	99.27	77	156
	25	7.99	6.21	5.33	0.546	6.55	19.43	14.35	99.44	75	175
	30	8.33	6.34	5.76	0.519	5.43	20.46	15.33	99.76	76	187
Average	—	7.30	5.89	4.96	0.72	7.62	18.48	13.04	99.23	79.00	159.00

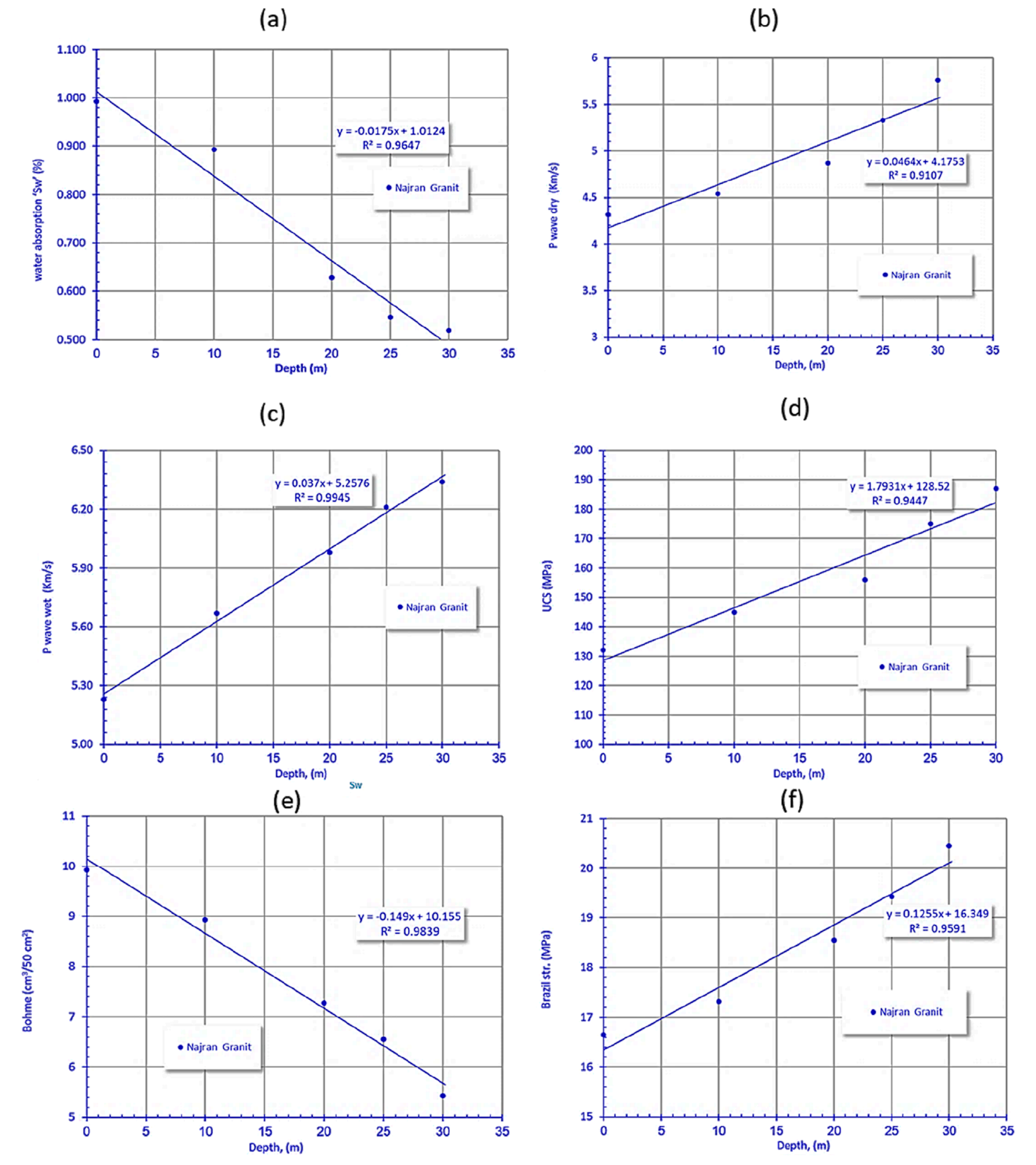

FIGURE 4
Plots between **(A)** depth and water absorption; **(B)** dry P wave; **(C)** wet P wave; **(D)** unconfined compressive strength "UCS" (MPa); **(E)** Bohme abrasion test "Böh" ($cm^3/50\ cm^2$); and **(F)** Brazilian strength (MPa) (Note R^2 refers to calculated correlation coefficient).

subhedral in lamellar and twinning form. Similarly, 4%–12% of the composition of the rock is made up of Riebeckite, which is present in crustal shapes ranging from subhedral to anhedral and prevails mostly in pleochroic. At places, it is speckled and corroded by iron oxide and transforms into epidots.

4.2 Mineralogical composition of Najran Black granite

Variations in the micro-components of the granite can impact the type of fracture and the strength of the granite. For this purpose,

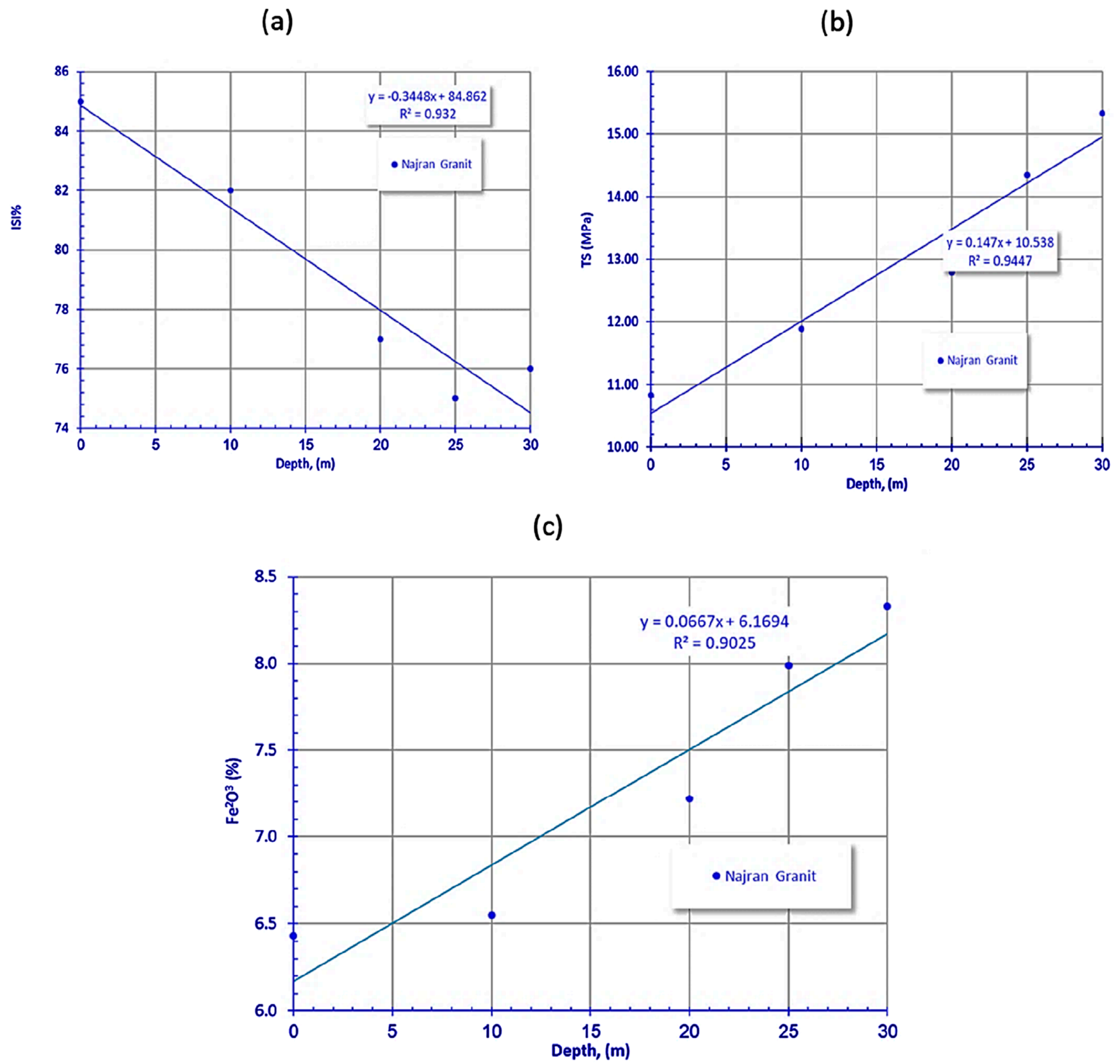

FIGURE 5
Plots between **(A)** depth and impact strength index "ISI" (%); **(B)** tensile strength "TS" (MPa) and **(C)** Fe_2O_3 content (%) (Note R^2 refers to calculated correlation coefficient).

three locations characterized by varying patterns of failure were chosen for XRF of the rock's surface of fracture. The elemental chemistry of BG at the study location is mainly comprised of O, Fe, Mg, and Si, with minor constituents of K, Ca, Al, and other elements. The granite's predominant composition is quartz with an abundance of feldspar, followed by mica. The mineral composition and microstructure of a rock are closely linked to its macro-mechanical properties (Table 1). Since the prevailing microstructure of the specimen is minute, its composition is a single entity, and at the macroscale, it seems to have higher resistance and strong mechanical properties. Conversely, granite possesses a level of discreteness that causes the generation of fractures resulting from the variation in composition and prevalence of impurities (Table 1).

4.3 Impacts of depth variations on physical properties of Najran Black granite

4.3.1 Water absorption (Ab %) ASTM C20-00 (2015)

Salah et al. (2019) found that water absorption (Ab percent) and rock characteristics are strongly connected variables. The average porosity of 0.72 percent is generally considered to be in the modest porosity range. It ranges from 0.993% at surface level to 0.519% at 30 m of depth (Table 2). The recorded values of porosity suggest that the porosity range of the studied rocks is extremely porous to highly compact based on the classification scheme of Moos and De Quervain (1948). Because the porosity value is low, the water

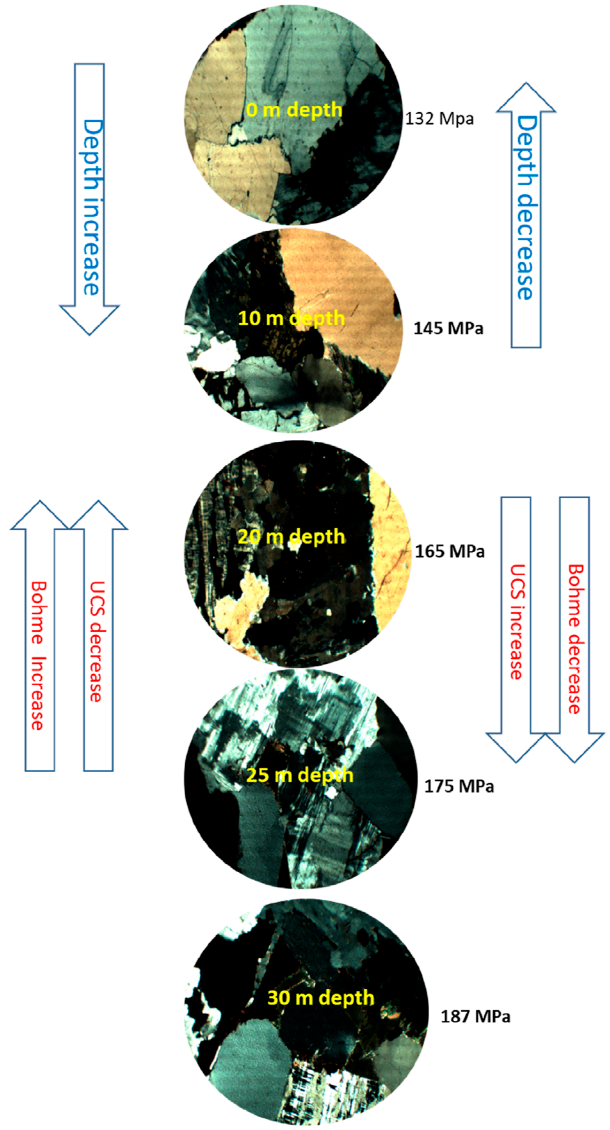

FIGURE 6
Sketch summarizing the Influence of depth on the mechanical aspects as well as the factors controlling the strength of the Najran Black granite.

absorption is likewise low, with an average value of 0.72 percent for all samples taken along the depth. This reflects the direct relationship or link between porosity ranges and water absorption: as one increases, the other increases, and *vice versa*. Similarly, Zada et al. (2023) indicated that water absorption is a direct indicator of permeability, which would affect the pathways for fluid movement and influence the rock fabrics in sedimentary rocks.

4.3.2 P-wave velocity (Vp) measurement

Since this is a simple and nondestructive measuring tool to use, the current measurement of pulse waves is more commonly employed not only in laboratories but also on site. Its applications are ubiquitous in various engineering projects in mining, civil, construction, and geotechnical fields, as described in the studies of Kahraman et al. (2008), Sharma and Singh (2008), and Sharma et al. (2011). The degree of danger zone produced around underground openings and tunnels can be predicted using VP methodologies, as well as the deformation and tension of the rock mass (Kahraman et al., 2008; Sharma and Singh, 2008). This measurement technique is employed for assessing the rocks' weathering condition, and its degree of rock weathering is also widely used to determine the degree of rock weathering and to characterize rock masses (Kahraman et al., 2008; Kahraman and Kesimal, 2014).

The Vp in rocks is influenced by mineral compounds and fabrics of a rock, pore spaces and pore water, density, weathering and alteration, confining pressure and temperature, bedding characteristics, crack or joint attributes (filler material, roughness, water, attitude, etc.), and anisotropy (Sharma and Singh, 2008). The ASTM C20-00 (2015) technique is used in the Vp tests carried out in this study. Table 2 describes the values of Vp, and the findings of this study revealed that with the increase in values of Vp, Brazilian strength, Böhme abrasion measure, ISI, UCS, durability, and tensile strength also increased. This evidence reflects that there is a direct relationship between these parameters and Vp values.

The recorded average Vp values of dry and wet NG specimens are 4.96 and 5.89 km/s, respectively, which fall in the very high velocity range (Table 2) of Anon's classification (1979). The V_p values for dry conditions increased with depth, from 4.32 km/s at zero depth to 5.76 km/s at 30 m depth. The values of Vp enhanced in samples after saturation range between 5.23 at zero depth and 6.34 km/s at 30 m depth. The depicted results of greater values of Vp in the analyzed saturated and dry NG samples are well matched and consistent with the rock's high density and low porosity, making them suitable for any subsequent construction application.

4.4 Impacts of depth variations on geomechanical properties of Najran Black granite

Rock's composition, form, and size, as well as the aging of the material and storage circumstances (Siegesmund and Dürrast, 2014), influence the factor of stability or strength of rock fabric. Important characteristics for identifying the lithologies and for the stability of the rocks or stones are strength. The obtained findings can be applied right away as long as there is an adequate structural safety margin. However, instead of the separate qualities of rock constituting minerals, including strengths of compression, mechanical, Brazilian, and tensile, they are frequently assessed based on the durability of rock and its elements.

4.4.1 Uniaxial compressive strength (UCS) ASTM D2938-95 (2002)

When loading per unit area at a site where failure of framework occurs due to splitting or shear and loading, this is known as UCS. This is a critical parameter for comparing rock strength levels in rock testing. The UCS is critical for determining the utility and cladding of rocks as design and construction materials. Rocks with great strength can be utilized for flooring and keystones, whereas low-strength materials are recommended for ornamental purposes (Kuscu et al., 2003). The average recorded UCS values of NG samples

TABLE 3 Comparison of the physical and mechanical properties of the studied area with those reported in previous studies conducted in various locations worldwide.

Rock properties	Empirical relation	Coefficient of determination (R^2)	Researchers
P wave (m/s)	$V_P = 2.76\rho - 0.98$		Birch (1961)
	$V_P = 2.33 + 0.08\ \rho^{3.63}$		Christensen and Salisbury (1975)
	$V_P = 3.66\rho - 4.46$	–	Gaviglio (1989)
	$V_P = 2.61\rho - 1.0 \pm 0.4$	–	Henkel et al. (1990)
	$V_P = 5.00\rho - 8.65$	0.55	Starzec (1999)
	$V_P = 4.32\rho - 7.51$	0.81	Yasar and Erdogan (2004)
Density (gr/cm^3)	$\rho = 0.213V_P + 1.256$	0.82	Kahraman and Yeken (2008)
	$\rho = 0.0011V_P - 0.0847$	0.97	Khandelwal and Singh (2009)
	$\rho = 0.19 + 1.61$	0.58	Yagiz (2011b)
	$\rho = 0.0027V_P+12.02$	0.83	Diamantis et al. (2009)
	$\rho = 0.0002V_P + 1.7752$	0.87	Kurtulus et al. (2011)
	$\rho = 0.00028V_P + 1.59$	0.93	Sarkar et al. (2011)
	$\rho = 0.202V_P + 1.794$	0.86	Khandelwal (2013)
Porosity (%)	$VP = 6.32n - 0.016$	0.76	Al-Harthi et al. (1999)
	$V_P = 6.52–0.36\ n$	0.66	Turgrul and Zarif (1999)
	$V_P = 4.08n^{-0.42}$	0.79	Sousa et al. (2005)
	$n = -4.733V_P + 29.377$	0.88	Kahraman et al. (2008)
	$n = -0.0002V_P+1.70$	0.84	Diamantis et al. (2009)
	$n = -0.0031V_P+16.736$	0.87	Kurtulus et al. (2011)
	$n = -5.19V_P + 27.1$	0.86	Yagiz (2011b)
Water absorption (%)	$W_a = -2.248V_P + 13.76$	0.90	Kahraman et al. (2008)
	$W_a = -2.23V_P + 11.6$	0.85	Yagiz (2011a), Yagiz (2011b)
Slake durability index (%)	$Id = 0.0069V_P + 78.577$	0.78	Sharma & Singh (2008)
	$Id4 = 1.131VP + 93.26$	0.73	Yagiz (2011a)
	$Id2 = 0.71VP + 95.7$	0.69	Yagiz (2011a), Yagiz (2011b)
	$Id = 0.0014VP + 92.970$	0.90	Sarkar et al. (2011)
	$Id = 0.001VP + 94.84$	0.93	Khandelwal (2013)
Uniaxial compressive (kg/cm2)	$UCS = 35.0VP - 31.5$	–	Freyburg (1972)
	$UCS = 2.45V\ 1.92$	–	Militzer and Stoll (1973)
	$UCS = 1277e - 117 = Vp$	–	McNally (1987)
	$UCS = 36.0VP - 31.2$	–	Goktan (1988)
	$UCS = 35.54VP - 55$	0.64	Tugrul and Zarif (1999)

(Continued on the following page)

TABLE 3 (*Continued*) Comparison of the physical and mechanical properties of the studied area with those reported in previous studies conducted in various locations worldwide.

Rock properties	Empirical relation	Coefficient of determination (R^2)	Researchers
	UCS = 2.45V 1.92	–	Militzer and Stoll (1973)
	UCS = 9.95V 1.21	0.69	Kahraman (2001)
	UCS = 31.5VP − 63.7	0.80	Yasar and Erdogan (2004)
	UCS = 22.032V 1.247	0.72	Sousa et al. (2005)
	UCS = 64.2VP − 117.99	0.90	Sharma &Singh (2008)
	UCS = 56.71VP − 192.93	0.67	Çobanoğlu and Çelik (2008)
	UCS = 133.3VP − 227.19	0.96	Khandelwal and Singh (2009)
	UCS = 36VP − 45.37	0.93	Sharma and Singh (2010)
	UCS = 0.14VP − 899.33	0.83	Diamantis et al. (2009)
	UCS = 64.2VP − 117.99	0.90	Sharma and Singh (2008)
	UCS = 56.71VP − 192.93	0.67	Çobanoğlu and Çelik (2008)
Schmidt rebound hardness	*HS = 0.0319VP − 92.442*	0.77	Kurtulus et al. (2011)
	HS = 0.006VP + 9.52	0.80	Kurtulus et al. (2013)
Point load strength index (MPa)	*IS(50) = 0.0018VP − 1.9906*	0.95	Kurtulus et al. (2011)
	IS(50) = 0.0042VP − 14.602	0.90	Kurtulus et al. (2011)
	IS(50) 0.0022VP − 3.096	0.73	Aligholi et al. (2017)
Tensile strength (MPa)	*TS = 0.701e0.00052VP*	0.89	Vasconcelos et al. (2008)
	TS = 0.008VP + 3.84	0.78	Kurtulus et al. (2011)
Fe2O3	Fe_2O_3 *= 0.0667 Depth + 6.1694*	*0.9025*	Current study
PV	*PV = 0.0464 Depth + 4.1753*	*0.9107*	
TS	*TS = 147 Depth+ 10.538*	*= 0.9447*	
SW	*SW = −0.0175 Depth + 1.0124*	*= 0.9647*	
Bhm	*Bhm = −0.149 Depth + 10.155*	*= 0.9839*	
USC	*USC = 1.7931 Depth + 128.52*	*= 0.9447*	

[a]For legend of symbols see Table 2.

at 30 m depth are 159 MPa, as depicted in Table 2. The recorded highest value of UCS at 30 m depth in samples of NG is 187 MPa at a depth of 30 m, whereas the lowest UCS value was 132 MPa at zero depth with an average value of 160 MPa. These results indicate that the UCS increased with the increase in depth. According to ISO14689-1, all the study samples bear compressive strengths, which are categorized as very strong (2003).

4.4.2 Abrasion resistance (Böhme abrasion test)

Wear resistance is a key factor in determining the suitability of a stone for use on a surface. The abrasion test of ASTM (C241/C241M) yields an index number, which means that when the substance touches the stone on the surface, such as bare feet or shoes; the tempo of footsteps and walking; house entrances, receptions, sales or showrooms, and public spaces, it experiences greater levels of radiation. In this paper, the recorded average values of abrasion resistance of NG samples are 7.62 $cm^3/50\ cm^2$. Results demonstrate that the values of abrasion resistance decreased with the increase in depth, and hence the abrasion resistance decreased with depth. The highest value (9.93 $cm^3/50\ cm^{2)}$ was recorded at zero depth, whereas the lowest measured value was at 30 m depth (5.43 $cm^3/50\ cm^2$).

4.4.3 Brazilian strength (σ_t) ASTM D3967-95a

The length-to-diameter ratio of the core specimens was 1:2 (6 cm in diameter to 3 cm in length). For testing, the sample was kept between testing machines at a small distance of 0.5 times the core diameter between each end (ASTM D3967-95a). With the maximum recorded load, the specimen was subjected to a higher charge until failure. Values of Brazilian strength in the range of 16.65–20.46 MPa, averaging 18.48 MPa, were recorded for NG samples along depths varying from zero to 30 m. Results depict that the Brazilian strength increased as the depth increased (Table 2).

4.4.4 The impact strength index (ISI)

It is a widely employed tool applied in both laboratory and field experiments for strength properties (Sharma et al., 2011). The impact intensity index is the quantity of rock that remains in the starting size range after the test. The average NG sample values along the depth are 79 percent (Table 2). According to Bilgin et al. (1988), the investigated materials can be categorized as "very hard".

4.4.5 Tensile strength test (σt) (ASTM D638-14)

The results of the tensile strength test showed that the tensile strength decreased with the increase in depth, from a depth of zero to 30 m. The recorded maximum value of the tensile strength test at 30 m depth was 15.33 MPa, whereas the observed minimum value at zero depth was recorded as 10.82 MPa. The recorded tensile strength values for NG samples along the depth range (zero to 30 m) were 13.04 MPa as average values. The difference in values of tensile strength recorded at different depths of NG is because of the prevalence of fractures in the material close to the surface (Table 2).

4.5 Impact of depth variations on strength parameters of Najran Black granite

Great certainty is observed when depth increases the wet and dry P-wave velocity conditions of the Najran granite samples. Based on the recorded values of water absorption in the rocks, a decrease in water absorption occurs when the depth increases (Figure 4A). The maximum UCS values of granite rocks were recorded (Figure 4B), which indicates that as the depth increases, the UCS also increases. The values recorded of Brazilian strength and Böhme abrasion strength (MPa) of the rocks of Najran increase with depth (Figures 4C, D), which reflects that an increase in depth increases the Brazilian and Böhme abrasion strengths. The values of tensile strength and ISI of the samples (Figure 4E) depict that as the depth enhances, the tensile strength and the ISI also enhance. Figure 6C shows the effect of the Fe_2O_3 content and the depth, i.e., when the depth is enhanced, the Fe_2O_3 content also increases (Figures 5A–C).

In fact, there is a strong association between the Fe_2O_3 content and UCS, water absorption, and all physical and mechanical aspects. The values obtained from laboratory tests show a decrease in water absorption, with an increase in the Fe_2O_3 content. Water absorption is one of the most important properties of the rocks affected by their mineral composition and the sum of void spaces (Bell, 1987). A rock density allows for the identification of Fe_2O_3 material. However, the analysis shows that although the granites in current study have similar density values, density alone cannot be a valid index for estimating the quantity of Fe_2O_3 in the material. The mineralogical composition is an influencing rock strength factor according to the inherent characteristics of each mineral and their susceptibility to weathering (Sousa, 2014).

The highest stress withstood by a material in a stretching state was quantified by the test of tensile strength. With the increase in depth, the withstanding of the increasing pressure was observed in all samples of Najran Black granite, from 159 MPa to the highest UCS value of 187 MPa (Figure 6). Indeed, there is a close link and relationship found between the depth and UCS, water absorption, Vp content, and weathering. Laboratory analyses depict that with an augmentation in depth, a decrease in Ab occurs, as it is the imperative characteristic of rocks by porosity and mineral make-up (Bell, 1987). Among the strength factors of the rock, the most influential property is the mineralogical make-up or composition due to the inherent attributes of each mineral and its weathering-prone state (Sousa, 2014). This is further underscored by the regression analysis that delineates strong coefficients of correlation with index tests resulting in greater than 90% R^2 values. Based on the findings observed, regression analysis is a predictive tool that can be employed to estimate and correlate the mechanical attributes with the depth (Table 3).

5 Conclusion

"This study documents 84 samples of granite collected from the same rock unit in the Najran area". Mineralogical, chemical, physio-mechanical, and geotechnical tests were performed on these granite samples to find out the variation in strengths because of these factors. The depth of the collected samples varied from 0 to 30 m. Based on the current analysis, the following conclusions are drawn:

(1) When the depth of the sample increases from 0 to 30 m, the SDI, Brazilian strength, UCS, and tensile strength increase from 98.65%, 16.65, 132, and 10.82 MPa to 99.76%., 20.46, 187, and 15.33 MPa, respectively. Therefore, these mechanical parameters of the granite of Najran increase as the specimen depth increases. Moreover, the p-wave increases with the increase in depth, indicating low porosity, voids, and high density, which was also buttressed by the low water absorption that decreases with depth as well.
(2) The analyses of XRF revealed that with the depth, a higher content of iron was observed, along with a lesser value of water absorption. The values of both the UCS and the tensile strength augment as the iron content increases, whereas they reduce as the water absorption decreases.
(3) An interrelationship and close association prevailed between petrographic properties and mineral composition with the rock strength metrics. This means that various minerals can have opposing impacts on rock strength metrics.
(4) The relationship or link between depth and mechanical attributes was constructed by the empirical models, which were subsequently validated by inference to the rock strength with reference to the depth.
(5) Granite rock resists mechanical weathering at deeper depths, resulting in a decrease in porosity. Further influencing the

mechanical characteristics of the granite rock are depth-related variations in chemical composition, iron concentration, and porosity.

(6) It is recommended to perform similar studies on other granites in Saudi Arabia and establish a comprehension model using numerical simulation for better understanding of the granites of the entire region.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

AA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. YA: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. TD: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. OA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. JH: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing–original draft, Writing–review and editing. JI: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. AR: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. HA-A: Visualization, Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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