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Physical and mechanical properties of sandstones from Southern Zanjan, north-western Iran

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Abstract. In this paper, three groups of quartz-rich sandstone were selected. These three groups include sandstones with low, medium and high quartz content. Three categories of tests including petrography tests, physical and engineering index property tests were performed on 26 samples of sandstones. Physical and engineering index property tests included porosity, density, *P*-wave velocity, and compressive and tensile strength tests. The purpose of the experiments/article was to find a relationship between different characteristics of the studied sandstone samples. Emphasis was placed on the effect of feldspar content and quartz content on the tensile and compressive strength of specimens. According to the results, significant relationships exist between the engineering index characteristics and the compressive and tensile strength of the samples as well as their elastic properties. The main finding of this research is that due to the presence of micro-mineral cracks in feldspar, increasing feldspar content reduces the compressive and tensile strength of the samples. Packing density, packing proximity, sub-angular and angular grains and quartz content are positively correlated with dry density and *P*-wave velocity and negatively correlated with porosity. Compressive and tensile strength and Young's modulus increase with increasing dry density, *P*-wave velocity, packing density, packing proximity, percent sub-angular and angular grains, and quartz content. Feldspar content has a positive correlation with porosity and a negative correlation with dry density and *P*-wave velocity.

Keywords: *porosity; dry density; laboratory tests; sandstone; quartz content; petrographic characteristics; engineering index properties; uniaxial compressive strength; P-wave velocity*

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INTRODUCTION

The tensile and compressive strengths of rock are of great importance in the design of underground structures. Today, according to numerous experiments, it is accepted that rock strength as well as physical properties of rocks are related to their petrographic and texture properties (Tandon, Gupta 2013; Amann *et al*. 2014; Ündül *et al*. 2015; Ündül 2016; Farrokhrouz, Asef 2017; Festa *et al*. 2018; Garia *et al*. 2019; Aladejare 2020; Hemmati *et al*. 2020, Lakirouhani *et al*. 2020). The texture of rock is defined as “degree of crystallization, grain size and granularity, fabric or geometrical relationship between the rock minerals and matrix” (Williams *et al.* 1982); therefore, texture properties are usually divided into grain size, grain shape, degree of grain orientation, packing density, mineral and matrix composition, degree of cementation, porosity, grain contact structures and micro-cracks (Ersoy, Waller 1995). These parameters are generally measured in the laboratory by conventional studies of thin sections (Bell 2016). Grain size is a significant microstructure parameter that affects the mechanical behaviour and physical properties of the rock. For instance, experimental results reported by Wong *et al.* (1996), Hugman and Friedman (1979), Fredrich *et al.* (1990), Hatzor and Palchik (1998), Palchik and Hatzor (2000), and Yusof and Zabidi (2016) indicate that rock strength parameters decrease with increasing grain size. Also, Skinner (1959), Olsson (1974), and Přikryl (2001) reported decreased uniaxial compressive strength with increasing grain size for tests on, respectively, anhydrite, dolomite, and granite rocks. However, Lakirouhani *et al.* (2020) observed that there is a significant positive correlation between grain size and uniaxial compressive strength, point load strength, Brazilian strength, and average Young’s modulus for dolomite rock samples. Alongside these studies, Sousa (2013) found a tendency for uniaxial compressive strength to increase proportionally to quartz grain size, while for granite rock there was no relationship between compressive strength and grain size. Mineral composition and quartz content are other important parameters which influence rock strength, but because of the inherent properties of each mineral, conflicting results have been reported in relation to quartz effect (Howarth and Rowland 1986).

First, Merriam *et al.* (1970) found a clear inverse relationship between the percentage of quartz and Brazilian tensile strength in granite rocks from California. The quartz content of the samples was about 30% and the dominant mineral was plagioclase. Fahy and Guccione (1979) and Shakoor and Bonelli (1991) showed a reverse relevance with a high correlation coefficient between quartz content and uniaxial compressive strength, i.e. an increase in quartz content decreases uniaxial compressive strength. Also, according to Shakoor and Bonelli (1991), quartz content has a reverse relationship with Brazilian tensile strength. By experimenting on nine Portuguese granites, Sousa (2013) observed that uniaxial compressive strength is not related to the quartz–feldspar ratio or quartz content. He found a tendency for strength to decrease with increasing quartz content. He attributed this to the increase in quartz–quartz contacts and decrease in the deformation capacity of the rock. Gunsallus and Kulhawy (1984) concluded that quartz content has a direct relationship with uniaxial compressive strength, and any increase in the percentage of quartz in all sedimentary rock samples resulted in an increase in uniaxial compressive strength. Tuğrul and Zarif (1999) determined the relationships between mineralogical composition and uniaxial compressive strength and Brazilian tensile strength in granite rocks by using simple regression analysis. Based on their study, feldspar content reduces strength while quartz content increases uniaxial compressive strength and Brazilian tensile strength. Zorlu *et al.* (2004) experimented on 5 groups of sandstone and found out that quartz content has a moderate correlation with uniaxial compressive strength, but the effect of textural properties on strength is more important than the effect of mineralogy. Meng and Pan (2007) reported that with increasing percentage of quartz, the strength, brittleness and bursting potential of clastic rock samples will increase; also, uniaxial compressive strength and failure duration are closely related to mineral composition. In addition, by petrographic and rock mechanics studies on Kozlu sandstone in the north of Turkey, Ulusay *et al.* (1994) concluded that quartz content had no significant effect on uniaxial compressive strength, elasticity modulus, or qualitative index (QI). In short, most researchers stated that the method of interlocking quartz grains is more important than the total percentage of quartz grains (Bell, Culshaw 1998; Heidari *et al.* 2013).

Although the relationship between petrographic characteristics and physical and mechanical properties of sandstones has been studied by several researchers, different results have been reported on the influence of quartz and feldspar content. The purpose of this paper is to investigate the textural and petrographic characteristics, engineering index properties, and mechanical properties of sandstone from northwestern Iran. The main emphasis in this study is to find the relationship between the microstructure of the studied sandstone samples and their strength parameters. A special innovation in this paper, which has not been discussed so far, is to investigate the effect of quartz and feldspar and to find relationship between the amount of feldspar and the strength parameters of the studied sandstone samples. For this purpose, three groups of quartz-rich sandstone were selected, namely sandstone with a low quartz content, a medium quartz content, and a high quartz content. Comprehensive tests, including petrographic, physical and mechanical tests, were performed on 26 samples of sandstones. Petrographic tests were performed to determine the mineral composition and microstructure of rock samples. The microstructure of the rock includes grain size and grain distribution, contact type, packing density and packing proximity. Experiments to determine the physical and engineering index properties of rocks included porosity, density, and *P*-wave velocity, and the third category of experiments included uniaxial compressive strength tests, Brazilian tensile strength and point load strength.

SAMPLING SITE, MATERIAL AND TEST PROCEDURES

The study area is located in Zanjan Province, north-western Iran, enclosed by longitudes 48°15' to 48°54' and latitudes 36°11' to 36°45'. In this area, early Paleozoic and mainly Cambrian clastic sediments such as sandstones belonging to the Zaigun, Lalun and top-quartzite formations appear in outcrops. Zaigun and Lalun formations are two geological formations of Iran in Alborz with early Cambrian age. An outcrop is the exposed rock, so it provides opportunities for sampling. All three formations have the same sedimentary and tectonic regime (Ghorbani 2019) and are rich in quartz, but the Zaigun formation has a lower quartz percentage, the Lalun formation has a moderate quartz content, and the top-quartzite formation has a high quartz content. Sampling locations are shown in Fig. 1.

Samples were taken from rock blocks with approximate dimensions of 30 cm × 40 cm × 40 cm to examine their mineralogical and petrological compositions. A microscopic thin section of the samples was prepared and then analyzed completely by a polarized microscope. Also, X-ray diffraction (XRD)

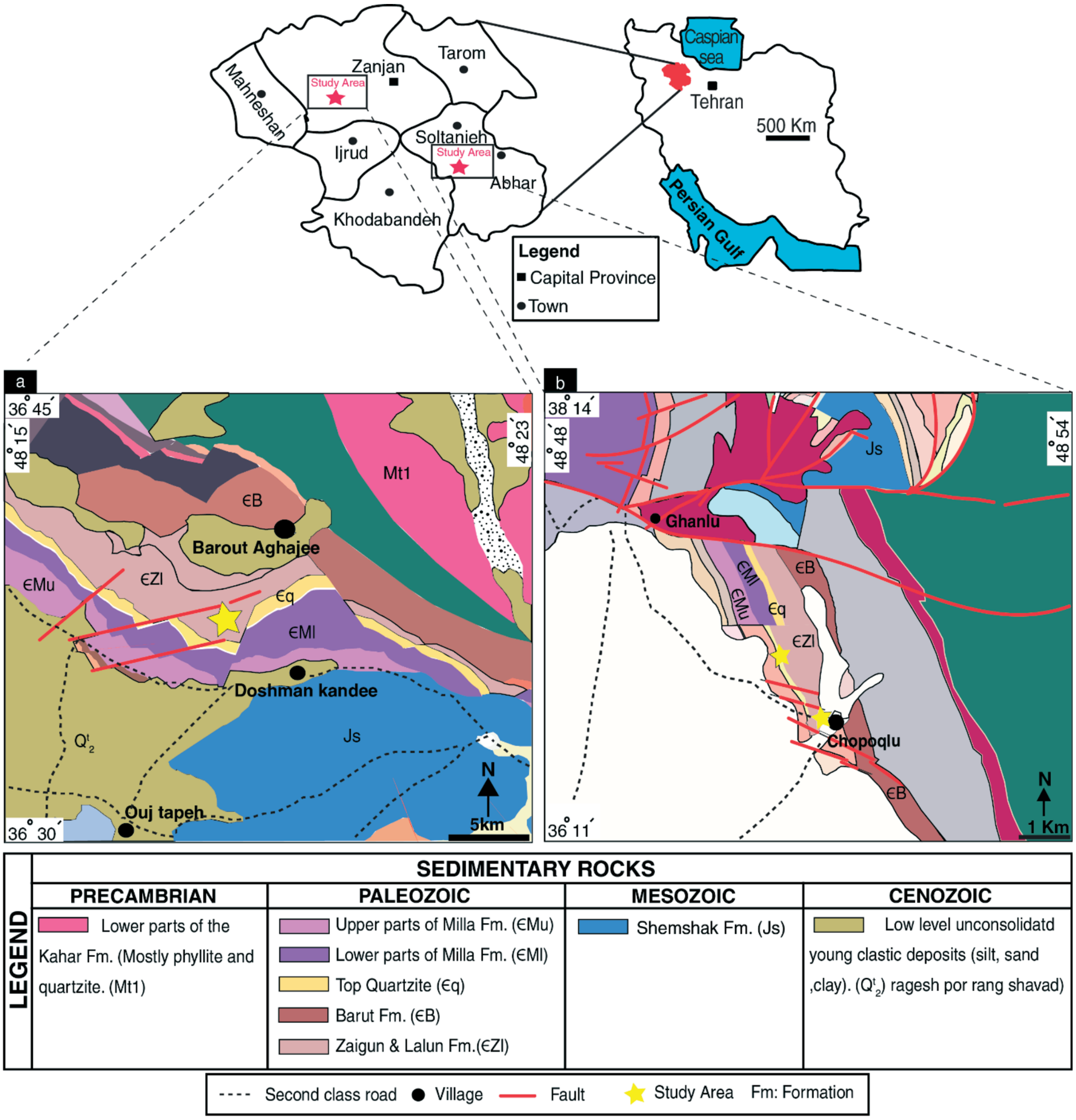

Fig. 1 a) Geological map and geographical location of study area 1. **b)** Geological map and geographical location of study area 2 (adapted with modifications from Babakkhani, Sadeghi 2004) tests were performed to determine the exact mineral composition of the samples. After petrographic observations, experimental tests for determining physical characteristics (porosity, density, *P*-wave velocity) and compressive and tensile strength of sandstones by the uniaxial compression test, Brazilian tensile strength test and point load strength test were conducted based on procedures proposed by Broch and Franklin (1972). Using the test results and for each sample, the average Young's modulus, secant modulus of elasticity and Poisson's ratio were determined according to the standard of the International Society for Rock Mechanics (Bieniawski, Bernede 1979). Also, porosity was measured by saturation methods (Brown 1981).

To perform the uniaxial compressive strength test, 26 cylindrical samples were cored from the blocks with no apparent signs of weathering and without evidence of macroscopic heterogeneity such as veins and joints. Ten samples were taken from the Zaigun formation, nine from the Lalun formation and seven from the top-quartzite formation. Each sample was 54 mm in diameter with a length-to-diameter ratio of 2.5. The cut end faces of cores were smoothed and made perpendicular to the core axes with a polishing and lapping machine in accordance with the requirements provided by Bieniawski and Bernede (1979).

RESULTS OF TESTS

Mineralogical composition

The study of microscopic thin sections showed the percentage of minerals and components of sandstone samples (Fig. 2). The results were obtained in three groups based on increasing mean quartz content (Table 1). Sandstone samples were mainly composed of quartz (59% to 95%) and feldspar (3% to 24%) and small amounts of rock fragments (1% to 7%), cement (0% to 9%) and matrix (0% to 7%). In most cases, quartz grains were very close together and interlocked together to form quartzite texture. Silica was the main cementing mineral. The pore spaces filled with silica minimized porosity. The amount of mica and heavy minerals was less than one percent.

XRD test results showed that quartz and feldspar were the main constituents of the samples, and muscovite, calcite and dolomite were minor minerals that confirm petrography observations. The presence of microcline in the samples, which had little strength to weathering indicated that the samples were fresh. Quartz in the samples was mostly single crystalline, which exhibits higher strengths compared to multi-crystalline quartz. Samples were categorized to arkose, sub-arkose and quartz arenite according to Folk's (1980) classification (Fig. 3).

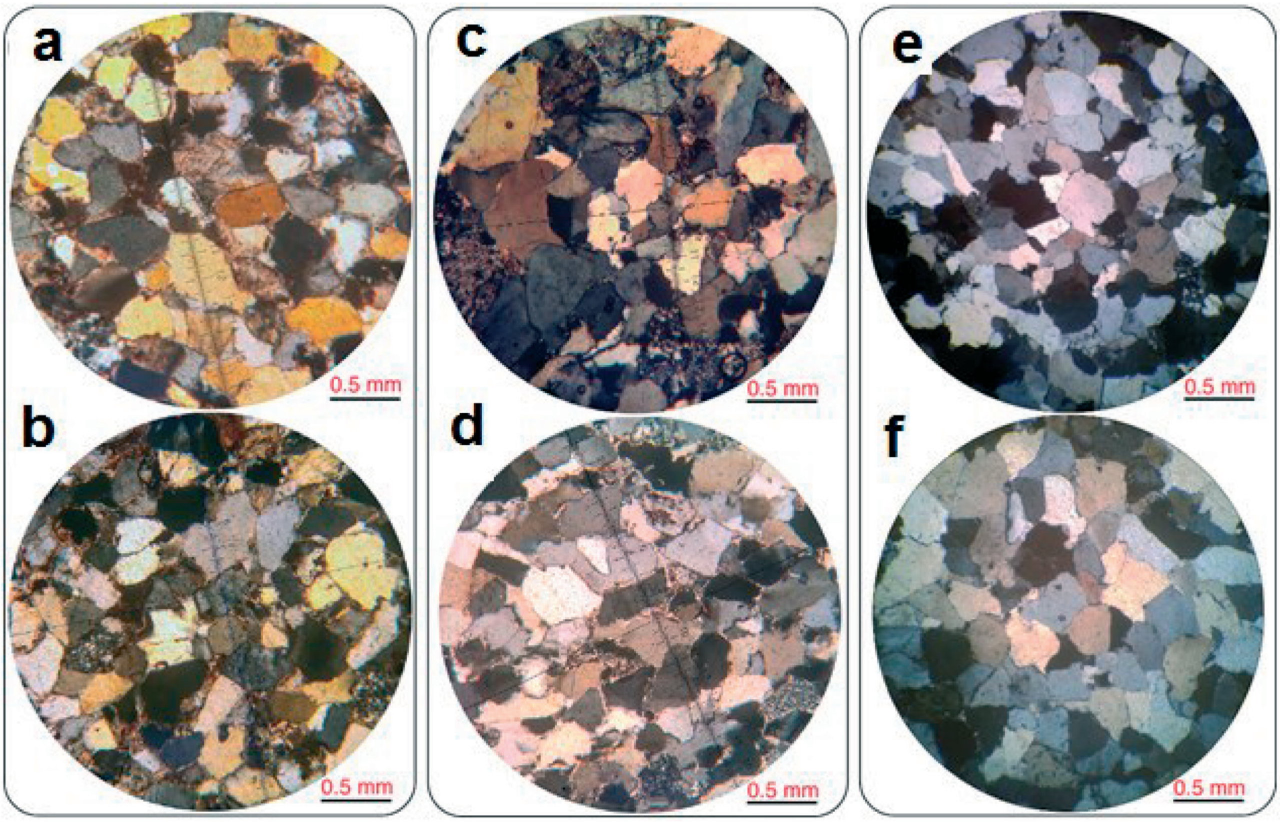

Fig. 2 Six samples of thin microscopic sections: **a, b** – samples with low quartz content, **c, d** –samples with medium quartz content, **e, f** – samples with high quartz content

Table 1 Results of lithology of the studied sandstone samples

	Sample name	Quartz	Feldspar	Rock fragment	Heavy mineral	Mica	Carbonate cement	Cement	Matrix	Void space	Opaque
Unit		%	%	%	%	%	%	%	%	%	%
Low quartz content	LQ1	64	24	5	0	1	0	0	3	0	3
	LQ2	70	18	4	0	0	0	1	4	0	3
	LQ3	61	21	4	0	0	2	3	4	0	5
	LQ4	63	18	4	0	1	0	4	4	0	6
	LQ5	61	24	5	1	0	0	3	3	0	3
	LQ6	62	18	5	1	1	0	2	4	2	5
	LQ7	60	23	5	0	0	0	2	5	1	4
	LQ8	73	18	3	0	0	0	1	3	0	2
	LQ9	65	21	6	0	0	0	2	4	0	2
	LQ10	62	21	6	0	0	0	2	5	2	2
	Average	64.10	20.60	4.70	0.20	0.30	0.20	2.00	3.90	0.50	3.50
	Standard deviation	4.23	2.50	0.95	0.42	0.48	0.63	1.15	0.74	0.85	1.43
	Maximum	73	24	6	1	1	2	4	5	2	6
	Minimum	60	18	3	0	0	0	0	3	0	2
Medium quartz content	MQ1	71	12	5	0	1	0	2	4	3	2
	MQ2	72	13	5	0	0	0	2	5	0	3
	MQ3	74	12	4	0	1	0	2	4	0	3
	MQ4	71	12	6	0	1	0	3	4	0	3
	MQ5	70	14	5	0	0	0	5	4	0	2
	MQ6	67	15	6	0	0	0	5	5	0	2
	MQ7	66	15	5	0	0	0	3	6	1	4
	MQ8	61	15	5	0	0	0	9	6	1	3
	MQ9	59	17	7	0	0	0	7	7	0	3
	Average	67.89	13.89	5.33	0.00	0.33	0.00	4.22	5.00	0.56	2.78
	Standard deviation	5.11	1.76	0.87	0.00	0.50	0.00	2.49	1.12	1.01	0.67
	Maximum	74	17	7	0	1	0	9	7	3	4
	Minimum	59	12	4	0	0	0	2	4	0	2
High quartz content	TQ1	76	12	4	0	0	0	3	4	0	1
	TQ2	75	12	4	0	0	0	3	5	0	1
	TQ3	90	4	2	0	0	0	2	0	1	1
	TQ4	92	4	1	0	0	0	2	0	0	1
	TQ5	90	5	1	0	0	0	1	2	0	1
	TQ6	95	3	1	0	0	0	1	0	0	0
	TQ7	93	4	1	0	0	0	1	1	0	0
	Average	87.29	6.29	2.00	0.00	0.00	0.00	1.86	1.71	0.14	0.71
	Standard deviation	8.24	3.95	1.41	0.00	0.00	0.00	0.90	2.06	0.38	0.49
	Maximum	95	12	4	0	0	0	3	5	1	1
	Minimum	75	3	1	0	0	0	1	0	0	0

Texture study results

The results of texture characteristics of the samples are presented in Table 2. The median grain size was in the range of 0.26 mm to 0.51 mm. According to Stow's (2005) classification, the samples are in the range of medium grain size sandstones. Samples are mostly well sorted (i.e. similar in size) and the shape of the grains in the samples was mainly rounded, sub-rounded and sub-angular. Texture studies by thin sections showed that there was usually linear contact and convex-concave contact between the grains. Such contacts indicate high compaction in the rock. The contacts were classified into grain-to-grain, grain-to-cement, grain-to-matrix, and grain-to-void space, but the most common contact type in the studied samples was grain-to-grain, with an average of 91.8%. The average percentage of cement, matrix, and voids in 26 samples was 2.73%, 3.69%, and 0.42%, respectively. Packing density is the fraction that is occupied by grains, and packing proximity is the space between the grains. According to the results, the averages of these two parameters were 92.0% and 86.8%, respectively. High values of packing density and packing proximity indicate a low content of cement and matrix, by which the grains are well-interlocking (Ulusay *et al*. 1994).

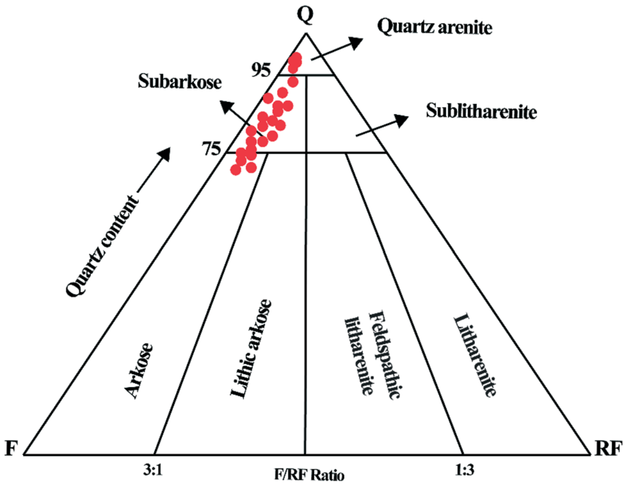

Fig. 3 Classification of samples using Folk's (1980) method

The results of engineering index properties, and tensile and compressive strength

The results of engineering index properties such as porosity (n), dry density (γ_d), and P-wave velocity (V_p), mechanical properties and strength of sandstone samples such as point load strength ($I_{s(50)}$), Brazilian tensile strength (σ_{t-Br}), uniaxial compressive strength (σ_c), Pisson's ratio (ν), average Young's modulus (E_{ave}), and secant modulus of elasticity (E_{sec}) are presented in Table 3. According to the results, the values of dry density of samples ranged between 2.60 g/cm^3 and 2.67 g/cm^3 – i.e. the sandstones had a high dry density (Anon 1979). Porosities varied between 0.77% and 2.06%, indicating that, based on Anon's (1979) Classification, the samples are mainly in the low porosity group. The P-wave velocities varied between 3.75 km/s and 5.24 km/s with the mean value of 4.55 km/s. The measured values of the Brazilian tensile strength of the samples were between 8.2 MPa and 25.5 MPa, and the mean value was 16.1 MPa. Uniaxial compressive strength varied from 114.8 MPa to 334.5 MPa with the mean of 223.2 MPa,

Table 2 Results of petrographic studies of sandstone samples

	Sample name	Median grain size	Grain shape						Type of contacts (1)				Type of contacts (2)				Packing density	Packing proximity
			Sub-round	Round	Very round	Sub-angular	Angular	Very angular	Point	Straight	Concave convex	Sutured	Grain to grain	Grain to cement	Grain to void	Grain to matrix		
	Unit	mm	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
Low quartz content	LQ1	0.27	52	20	5	20	3	0	2	50	43	5	96	2	0	2	95.3	90.9
	LQ2	0.27	45	25	10	18	2	0	3	70	25	2	95	1	0	4	75.7	70.0
	LQ3	0.28	22	45	5	25	3	0	3	65	30	2	96	1	0	3	96.4	90.9
	LQ4	0.29	30	42	4	19	5	0	3	70	27	0	95	2	0	3	81.0	76.9
	LQ5	0.30	35	40	5	17	3	0	3	72	25	0	94	3	0	3	83.6	76.9
	LQ6	0.30	30	42	5	20	3	0	2	72	26	0	93	2	2	3	89.2	84.6
	LQ7	0.33	47	30	5	16	2	0	3	53	42	2	92	2	1	5	91.7	85.0
	LQ8	0.35	40	36	6	14	4	0	2	48	48	2	97	1	0	2	93.0	87.5
	LQ9	0.40	50	33	6	10	1	0	2	43	50	5	96	2	0	2	92.4	87.5
	LQ10	0.50	52	30	8	9	1	0	1	53	42	4	94	2	2	2	88.8	83.3
Medium quartz content	MQ1	0.26	51	31	4	9	5	0	1	35	60	4	93	2	3	2	97.9	93.3
	MQ2	0.28	45	35	5	9	6	0	2	39	54	5	96	2	0	2	86.4	80.0
	MQ3	0.32	50	35	7	3	5	0	1	42	53	4	95	2	0	3	94.0	90.5
	MQ4	0.34	45	31	7	12	5	0	0	47	50	3	93	4	0	3	97.0	92.3
	MQ5	0.35	65	12	6	12	5	0	6	56	36	2	95	2	0	3	95.1	90.0
	MQ6	0.39	47	27	5	14	7	0	7	56	35	2	93	3	0	4	96.4	90.9
	MQ7	0.40	50	28	6	9	7	0	4	52	42	2	90	4	1	5	85.0	78.6
	MQ8	0.47	50	28	7	9	6	0	2	51	44	3	84	10	1	5	93.0	87.5
	MQ9	0.38	44	34	8	9	5	0	3	42	52	3	88	7	0	5	91.7	85.7
High quartz content	TQ1	0.29	35	8	0	50	7	0	3	55	41	1	95	3	0	2	96.4	91.7
	TQ2	0.35	29	10	5	49	7	0	2	58	39	1	95	2	0	3	96.6	90.9
	TQ3	0.42	10	0	0	80	10	0	0	80	20	0	98	2	0	0	97.0	91.7
	TQ4	0.51	15	0	0	72	10	3	0	85	15	0	98	2	0	0	90.5	83.3
	TQ5	0.45	20	0	0	70	7	3	0	75	25	0	97	1	0	2	93.4	90.0
	TQ6	0.45	10	0	0	75	15	0	0	80	20	0	99	1	0	0	96.7	90.5
	TQ7	0.39	14	0	0	70	15	1	0	75	25	0	98	1	0	1	97.0	95.8

and based on Anon's (1979) Classification, the samples are in the group of rocks with very strong to extremely strong bonds. The calculated values of the average Young's modulus and secant modulus of elasticity varied between 27.10 GPa and 53.30 GPa and between 19.90 GPa and 46.8 GPa, with the mean of 41.0 GPa and 32.9 GPa, respectively. Also, the measured value of point load strength varied between 3.34 MPa and 13.33 MPa with the mean of 9.83 MPa. According to classification of Broch and Franklin (1972), 46% of the samples had very high strengths and 54% of the samples showed extremely high strengths. The Poisson's ratio varied between 0.08 and 0.25 for the studied samples with a mean of 0.14. Based on the results of the present study, the mean ratio of uniaxial compressive strengths to Brazilian tensile strengths of low, medium, and high quartz content sandstones were 15.49, 13.92, and 13.47, respectively. Also, the variations in the mean ratio of uniaxial compressive strength to point load strength for the sandstones with a low, moder-

Table 3 Test results of engineering index properties and strengths of sandstone samples

	Sample name	Engineering index properties					Mechanical properties				Ratios		
		γ_d	n	$I_{s(50)}$	σ_{t-Br}	V_p	σ_c	E_{ave}	E_{sec}	ν	$\frac{\sigma_c}{\sigma_{t-Br}}$	$\frac{\sigma_c}{I_{s(50)}}$	$\frac{\sigma_{t-Br}}{I_{s(50)}}$
Unit		g/cm^3		MPa	MPa	km/s	MPa	GPa	GPa				
Low quartz content	LQ1	2.61	2.06	8.75	10.9	3.84	178.3	31.5	21.3	0.24	16.3	20.3	1.2
	LQ2	2.61	1.93	3.34	10.5	3.79	161.2	27.1	19.9	0.13	15.3	48.2	3.1
	LQ3	2.60	1.92	4.72	9.6	3.75	156.3	30.5	21.1	0.25	16.3	33.1	2.0
	LQ4	2.60	1.93	6.52	9.1	3.78	173.4	30.3	24.9	0.24	19.0	26.6	1.4
	LQ5	2.62	1.77	8.45	11	3.86	183.1	32.3	22.1	0.20	16.6	21.7	1.3
	LQ6	2.61	2.06	7.15	11.5	3.95	170.9	33.6	24.3	0.20	14.9	23.9	1.6
	LQ7	2.60	2.04	5.18	11	3.81	170.9	31.8	22.3	0.24	15.6	33.0	2.1
	LQ8	2.64	1.47	7.77	8.2	4.69	158.7	39.1	31.2	0.10	19.3	20.4	1.1
	LQ9	2.62	1.44	8.68	18	3.93	246.6	37.3	31.7	0.11	13.7	28.4	2.1
	LQ10	2.64	1.35	8.85	15.6	3.95	122.1	34.1	21.5	0.08	7.8	13.8	1.8
	Average	2.62	1.80	6.94	11.54	3.94	172.15	32.76	24.03	0.18	15.5	27.0	1.7
	Standard deviation	0.02	0.28	1.95	3.00	0.27	31.20	3.48	4.18	0.07	3.2	9.6	0.6
	Maximum	2.64	2.06	8.85	18	4.69	246.6	39.1	31.7	0.25	19.3	48.2	3.1
	Minimum	2.6	1.35	3.34	8.2	3.75	122.1	27.1	19.9	0.08	7.8	13.8	1.1
Medium quartz content	MQ1	2.63	0.98	10.54	18.6	5.05	280.8	49.8	40.8	0.11	15.1	26.6	1.8
	MQ2	2.64	0.98	11.79	19.3	4.52	322.3	47.3	35.4	0.21	16.7	27.3	1.6
	MQ3	2.65	1.26	12.23	16.0	4.56	210.0	43.6	32.3	0.12	13.1	17.2	1.3
	MQ4	2.65	0.77	12.34	17.2	5.08	261.3	50.0	34.2	0.10	15.2	21.2	1.4
	MQ5	2.66	1.35	12.78	13.2	4.96	219.8	38.3	32.7	0.10	16.7	17.2	1.0
	MQ6	2.64	1.00	13.33	17.0	5.02	283.3	38.3	38.3	0.08	16.7	21.2	1.3
	MQ7	2.61	1.34	12.70	19.6	4.60	222.2	40.6	37.9	0.10	11.3	17.5	1.5
	MQ8	2.63	1.40	12.58	20.8	4.85	151.4	41.8	34.2	0.08	7.3	12.0	1.6
	MQ9	2.61	1.08	9.92	19.9	4.88	261.3	50.8	37.8	0.16	13.1	26.3	2.0
	Average	2.64	1.13	12.02	17.96	4.84	245.82	44.50	35.96	0.12	13.9	20.7	1.5
	Standard deviation	0.02	0.22	1.11	2.36	0.22	50.49	5.08	2.88	0.04	3.1	5.3	0.3
	Maximum	2.66	1.4	13.33	20.8	5.08	322.3	50.8	40.8	0.21	16.7	27.3	2.0
	Minimum	2.61	0.77	9.92	13.2	4.52	151.4	38.3	32.3	0.08	7.3	12.0	1.0
High quartz content	TQ1	2.64	0.83	12.53	25.5	5.24	305.2	52.0	43.1	0.13	11.9	24.4	2.0
	TQ2	2.64	0.94	10.74	18.4	5.14	312.6	40.8	36.7	0.11	17.0	29.1	1.7
	TQ3	2.64	1.35	12.32	20.1	5.06	197.8	49.2	44.9	0.10	9.8	16.1	1.6
	TQ4	2.64	1.46	10.92	16.4	5.09	295.5	49.4	46.8	0.08	18.0	27.1	1.5
	TQ5	2.67	1.60	10.54	17.7	4.91	114.8	46.9	28.2	0.08	6.5	10.9	1.7
	TQ6	2.65	1.23	11.32	18.0	5.12	334.5	53.3	45.2	0.11	18.6	29.5	1.6
	TQ7	2.65	1.37	9.54	25.1	4.88	310.1	46.7	45.7	0.08	12.3	32.5	2.6
	Average	2.65	1.25	11.13	20.17	5.06	267.21	48.33	41.51	0.10	13.5	24.2	1.8
	Standard deviation	0.01	0.28	1.04	3.67	0.13	80.33	4.11	6.75	0.02	4.6	7.9	0.4
	Maximum	2.67	1.6	12.53	25.5	5.24	334.5	53.3	46.8	0.13	18.6	32.5	2.6
	Minimum	2.64	0.83	9.54	16.4	4.88	114.8	40.8	28.2	0.08	6.5	10.9	1.5

ate, and high mean percentage of quartz were 26.95%, 20.74%, and 24.22%, respectively. These values are in the range proposed by Norbury (1986) for sandstones, which should lie between 8% and 30%. The ratio of Brazilian tensile strength to point load strength in the studied samples with a low, moderate, and high percentage of quartz was 1.77, 1.51, and 1.83, respectively, and the mean value for all samples was 1.70.

CORRELATION BETWEEN ENGINEERING INDEX PROPERTIES AND STRENGTH OF THE STUDIED SANDSTONES

This section presents simple empirical linear relationships between parameters that have the highest correlation coefficient with each other. First, correlation coefficients were obtained using simple linear regression between engineering index characteristics and strength parameters of 26 studied sandstone samples. The Pearson's correlation coefficient (r) was obtained from the following equation:

$$r=\frac{n\sum(x_i y_i)-\left(\sum x_i\right)\left(\sum y_i\right)}{\sqrt{n\sum x_i^2-\left(\sum x_i\right)^2}\sqrt{n\sum y_i^2-\left(\sum y_i\right)^2}}, \qquad (1)$$

where n is the datasets number, x_i and y_i are pairs of parameters between which correlation and relationship are considered. Using simple linear regression, correlation and relationship between engineering index characteristics and strength parameters of 26 sandstone samples were obtained and the correlation coefficients (r) are presented in Table 4.

Significant negative correlations were established between porosity and uniaxial compressive strength (r = –0.69), point load strength (r = –0.77), Brazilian tensile strength (r = –0.72), average Young's modulus (r = –0.77), and secant modulus of elasticity (r = –0.71). However, correlation between porosity and Poisson's ratio (r = 0.59) was positive. Also, significant negative correlations were found between porosity and P-wave velocity (r = –0.80) and dry density (r = –0.59). Most other researchers have reported an inverse relationship between porosity and compressive and tensile strengths (Bell 1978).

Then, using simple linear regression, useful empirical relationships between engineering index properties and rock strength can be obtained. The first proposed relation is the relationship between P-wave velocity (km/s) and porosity (Fig. 4):

$$V_p = -1.115n + 6.133 \ (r = -0.80). \qquad (2)$$

Also, P-wave velocity (km/s) and density (g/cm^3) have the following relationship (Fig. 5):

$$V_p = 19.908n - 47.823\gamma_d \ \ (r = 0.72). \qquad (3)$$

The relationship between point load strength (MPa) and rock porosity is expressed as follows (Fig. 6):

$$I_{s(50)} = -5.352n + 17.425 \ \ (r = -0.77). \qquad (4)$$

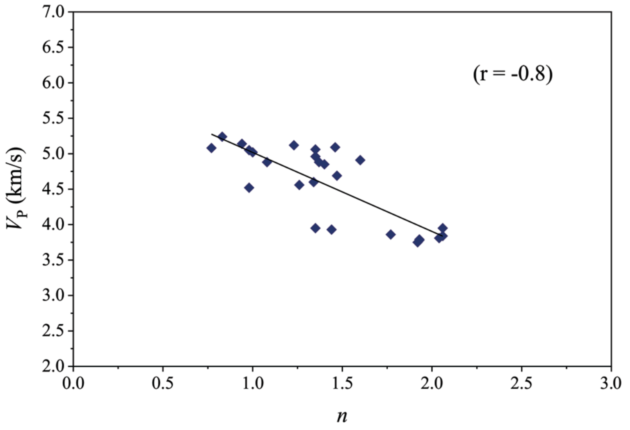

Fig. 4 P-wave velocity versus porosity

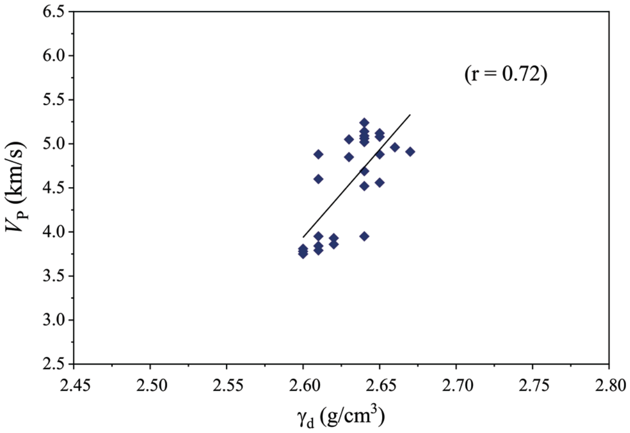

Fig. 5 P-wave velocity versus dry density

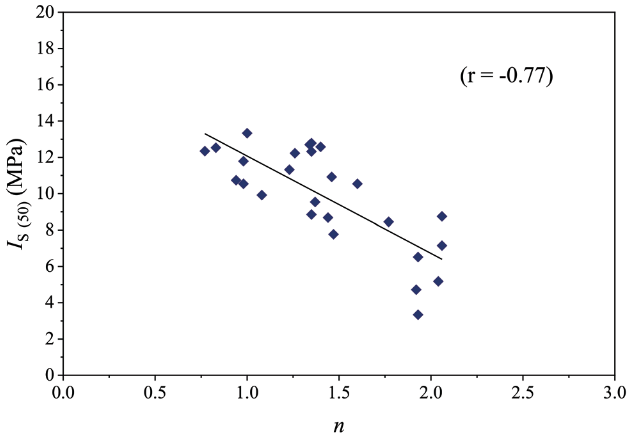

Fig. 6 Point load strength versus rock porosity

A significant positive correlation was observed between dry density and point load strength (r = 0.66), Brazilian tensile strength (r = 0.46), average Young's modulus (r = 0.62), and secant modulus of elasticity (r = 0.50), and weak correlation was found between dry density and uniaxial compressive strength (r = 0.3). D'Andrea *et al.* (1965), Bell (1978), Shakoor and Bonelli (1991), and Bell and Lindsay (1999) also observed that sandstones with higher densities have higher compressive and tensile strengths. Correlation between dry density and Poisson's ratio (r = –0.72) was negative. Shakoor and Bonelli (1991) also observed that Poisson's ratio decreased with increasing density, but Judd and Huber (1961), D'Andrea *et al.* (1965) and Bell (1978) found a positive correlation between density and Poisson's ratio. Also, a significant positive correlation was found between dry density and P-wave velocity (r = 0.72).

A significant positive correlation was obtained between P-wave velocity and uniaxial compressive strength (r = 0.61), point load strength (r = 0.80), Brazilian tensile strength (r = 0.69), average Young's modulus (r = 0.87), and secant modulus of elasticity (r = 0.87). As shown in Fig. 7, the average Young's modulus (GPa) had the following linear relationship with P-wave velocity (km/s):

$$E_{ave} = 12.581V_p - 16.233 \quad (r = 0.87). \tag{5}$$

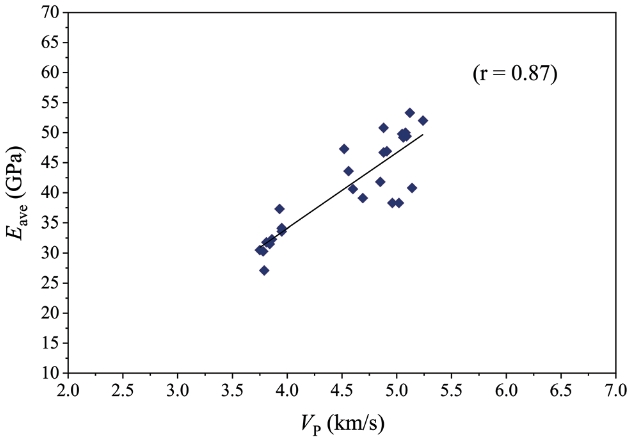

Fig. 7 Average Young's modulus versus P-wave velocity

Therefore, P-wave velocity is an indicator of rock strength. Correlation between P-wave velocity and Poisson's ratio was found to be negative (r = –0.70), and relationship between Poisson's ratio and P-wave velocity (km/s) was as follows (Fig. 8):

$$\nu = -0.075V_p + 0.477 \quad (r = -0.70). \tag{6}$$

A negative correlation was found between Poisson's ratio and point load strength, Brazilian tensile strength, average Young's modulus, secant modulus of elasticity, P-wave velocity and dry density. Shakoor and Bonelli (1991) and Bell (1978) also reported an inverse relationship between Poisson's ratio and both compressive strength and Young's modulus. The negative relationship between Poisson's ratio and uniaxial compressive strength was poor (r = –0.23). Bell (1978) and Bell and Lindsay (1999) also found no significant relationship between Poisson's ratio and uniaxial compressive strength. Also, significant positive correlations were obtained between Poisson's ratio and porosity (r = 0.59).

The average Young's modulus and secant modulus of elasticity had strong positive correlations with uniaxial compressive strength, point load strength and Brazilian tensile strength. Similar results have been reported by Deere and Miller (1966), Bell (1978), Shakoor and Bonelli (1991), and Bell and Lindsay (1999). Based on linear regression analysis (Fig. 9), the relationship between uniaxial compressive strength (MPa) and secant modulus of elasticity (MPa) is as follows:

$$\sigma_c = 0.0059E_{\mathrm{sec}} + 27.77 \quad (r = 0.77). \tag{7}$$

Brazilian tensile strength (MPa) versus average Young's modulus (MPa) (Fig. 10):

$$\sigma_{t\text{–}Br} = 0.0005E_{ave} - 2.75 \quad (r = 0.77). \tag{8}$$

Uniaxial compressive strength had a good correlation with Brazilian tensile strength (r = 0.60) and point load strength (r = 0.50). Also, there was a strong correlation between point load strength and Brazilian tensile strength (r = 0.69). In Figures 5 to 11, significant relationships between some parameters can be observed.

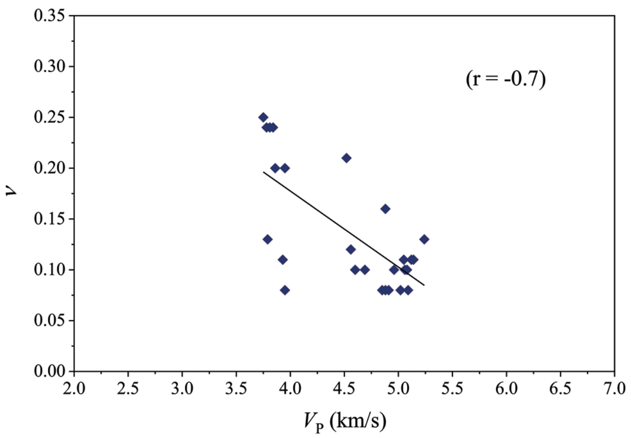

Fig. 8 Poisson's ratio versus P-wave velocity

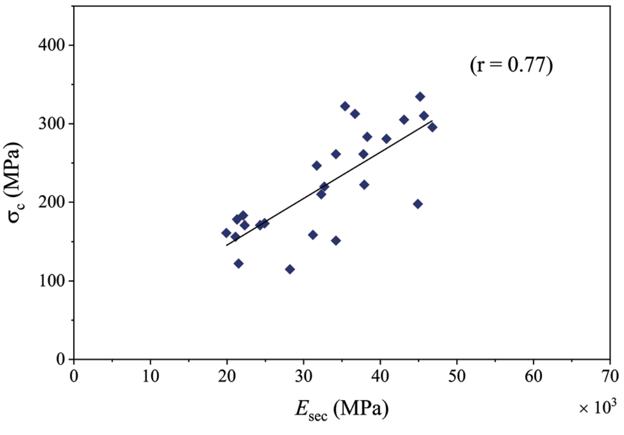

Fig. 9 Uniaxial compressive strength versus secant modulus of elasticity

Table 4 Linear correlation coefficients between the physical index properties and mechanical parameters of the studied sandstones

	σ_c	$I_{s(50)}$	$\sigma_{t\text{–}Br}$	E_{ave}	$E_{\sec}$	ν	V_p	γ_d	n
n	–0.69	–0.77	–0.72	–0.77	–0.71	0.59	–0.80	–0.59	1
γ_d	0.30	0.66	0.46	0.62	0.50	–0.72	0.72	1	–0.59
V_p	0.61	0.80	0.69	0.87	0.87	–0.70	1	0.72	–0.80
ν	–0.23	–0.59	–0.56	–0.48	–0.59	1	–0.70	–0.72	0.59
$E_{\sec}$	0.77	0.71	0.77	0.86	1	–0.48	0.87	0.50	–0.71
E_{ave}	0.64	0.71	0.77	1	0.86	–0.48	0.87	0.62	–0.77
$\sigma_{t\text{–}Br}$	0.60	0.69	1	0.77	0.77	–0.56	0.69	0.46	–0.72
$I_{s(50)}$	0.50	1	0.69	0.71	0.71	–0.59	0.80	0.66	–0.77
σ_c	1	0.50	0.60	0.64	0.77	–0.23	0.61	0.30	–0.69

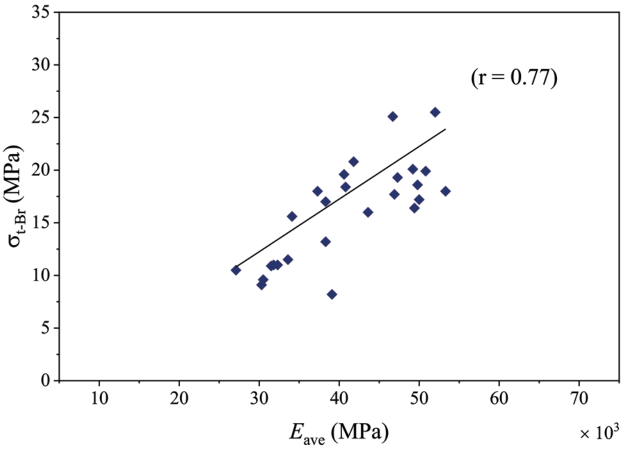

Fig. 10 Brazilian tensile strength versus average Young's modulus

CORRELATION BETWEEN PETROGRAPHIC CHARACTERISTICS, ENGINEERING INDEX PROPERTIES AND STRENGTH

In this section, we present the relationships between petrographic characteristics and engineering and strength characteristics of the tested sandstone samples. These results confirm the results obtained by previous researchers or, in some cases, are contrary to the results obtained by others, which are discussed below.

In this study, the correlation of 19 petrographic characteristics with engineering index and mechanical properties was analyzed, and the results are provided in Table 5. Because the very angular grain shape content, sutured grain contact content and grain-to-void contact content were very small in the studied sandstones, they were not involved in correlations.

According to Table 5, the petrographic parameters can be divided into three groups; the parameters of the first and second group have a significant relationship with engineering index properties and strength, but the third group includes grain contact types that have a weak correlation with engineering index properties and strength. The first group includes packing density, packing proximity, percentage of sub-angular and angular grains and quartz content, which are positively correlated with dry density and *P*-wave velocity and negatively correlated with porosity. Since compressive and tensile strength and Young's modulus increase with increasing dry density and *P*-wave velocity and with decreasing porosity, compressive and tensile strength and Young's modulus also increase with increasing packing density, packing proximity, percentage of sub-angular and angular grains and quartz content. Linear regression analysis suggests the following empirical relationship between secant modulus of elasticity (GPa) and angular grain shape (%):

$$E_{\sec} = 1.947Ang. + 21.71 \quad (r = 0.8), \tag{9}$$

where *Ang.* is the angular grain shape content (%). Also, the relationship between Poisson's ratio and packing density, packing proximity, percentage of sub-angular and angular grains and quartz percentage is similar to the relationship between Poisson's ratio and dry density and *P*-wave velocity and opposite to the relationship between Poisson's ratio and porosity. That is, there is a negative correlation between Poisson's ratio and packing density, packing proximity, percentage of sub-angular and angular grains and quartz percentage.

In contrast to the results obtained in this study on a positive correlation of packing density and packing proximity with dry density, Bell and Culshaw (1998) stated that these two parameters had no effect on dry density, but Bell (1978) for Fell Sandstone, Ulusay *et al*. (1994) for Kozlu Sandstone, and Bell and Culshaw (1998) for Sherwood Sandstone in England reported that as packing density and packing proximity increase, strength increases. Also, Ulusay *et al*. (1994), similar to the result obtained in this article, found a significant positive relationship and a significant negative relationship of the percentage of angular grains with compressive strength and Poisson's ratio, respectively.

Also, as the percentage of quartz increases, strength increases, because, according to Table 5, as the percentage of quartz increases, porosity decreases and grain-to-grain contact increases and more space is filled with quartz, wherefore strength increases. The result regarding the effect of quartz mineralization is consistent with the result obtained by Gunsallus and Kulhawy (1984), Bell and Lindsay (1999), Tuğrul and Zarif (1999), and Zorlu *et al*. (2004).

The relationship between grain size and engineering index properties and strength of the selected samples is similar to that of the first group. However, firstly, they have smaller correlation coefficients and, secondly, there is no significant relationship between sample grain size and uniaxial compressive strength. The reason for this could be a relatively small range of particle size changes in the samples. Bell (1978) and Ulusay *et al*. (1994) also did not find an important relationship between grain size and strength for Fell Sandstone and Kozlu Sandstone, respectively. Then, grain size has a positive moderate correlation with quartz content ($r = 0.41$), a similar result has been reported by Bell and Lindsay (1999) for sandstones of Newspaper Member of the Natal group near Durban. Newspaper Member is the most notable member of Natal group formation in Durban. In this group, most of the materials are fine- to medium-grained arkosic sandstones.

The correlation between grain size and porosity is poor ($r = -0.20$). Bell (1978) also reported a poor relationship between mean grain size and porosity.

The second group of petrographic parameters, including feldspar content and the percentage of rounded grain shape, have a positive correlation with porosity and a negative correlation with dry density and *P*-wave velocity. For this reason, as the percentage of rounded grains and the percentage of feldspar minerals increases, the uniaxial compressive strength, point load strength, Brazilian tensile strength, average Young's modulus and secant modulus of elasticity of the selected sandstone samples decreases and Poisson's ratio increases. Ulusay *et al*. (1994) also found an inverse relationship between the percentage of rounded grains and strength and a positive correlation between the percentage of rounded grains and Poisson's ratio. According to the linear regression analysis performed on the obtained data, the relationship between dry density (g/cm^3) and feldspar content (%) is as follows:

$$\gamma_d = -0.002F + 2.66 \quad (r = -0.7), \tag{10}$$

where *F* is feldspar content (%). Also, the relationship between *P*-wave velocity (km/s) and feldspar content (%) is as follows:

$$V_p = -0.07F + 5.52 \quad (r = -0.78). \tag{11}$$

Average Young's modulus (GPa) versus feldspar content (%):

Table 5 Linear correlation coefficients between texture characteristics and physical and mechanical properties of the samples

Petrographic characteristics	Engineering index properties					Mechanical properties			
	n	γ_d	V_p	σ_c	$I_{s(50)}$	σ_{t-Br}	E_{ave}	$E_{\sec}$	ν
Grain size	–0.20	0.43	0.38	–0.01	0.38	0.37	0.35	0.39	–0.67
Grain packing									
Packing density	–0.46	0.47	0.59	0.35	0.49	0.42	0.53	0.49	–0.29
Packing proximity	–0.42	0.50	0.56	0.32	0.45	0.43	0.51	0.47	–0.30
Grain shape									
Sub-rounded	–0.10	–0.15	–0.21	–0.19	0.09	–0.17	–0.31	–0.36	0.05
Rounded	0.26	–0.61	–0.63	–0.37	–0.41	–0.53	–0.54	–0.61	0.55
Very rounded	0.10	–0.39	–0.45	–0.36	–0.28	–0.41	–0.53	–0.58	0.15
Sub-angular	–0.06	0.42	0.45	0.28	0.15	0.37	0.46	0.52	–0.30
Angular	–0.37	0.50	0.68	0.60	0.49	0.59	0.67	0.81	–0.43
Type of grain contact (1)									
Point	0.07	–0.31	–0.17	–0.05	–0.01	–0.26	–0.46	–0.24	0.21
Straight	0.40	0.09	0.00	–0.09	–0.19	–0.09	–0.05	0.09	–0.06
Concave-convex	–0.43	–0.04	0.06	0.11	0.21	0.14	0.13	–0.04	0.03
Type of grain contact (2)									
Grain-to-grain	0.17	–0.07	–0.19	0.00	–0.39	–0.02	0.12	–0.04	0.20
Grain-to-cement	–0.21	0.18	0.27	0.07	0.46	0.05	–0.05	0.13	–0.26
Grain-to-matrix	0.13	–0.49	–0.28	–0.31	–0.16	–0.19	–0.42	–0.43	0.24
Mineral composition									
Quartz content	–0.28	0.68	0.61	0.42	0.35	0.44	0.64	0.67	–0.52
Feldspar content	0.47	–0.70	–0.78	–0.50	–0.55	–0.61	–0.79	–0.80	0.60
Rock fragment content	–0.11	–0.43	–0.32	–0.11	–0.02	–0.14	–0.33	–0.39	0.27
Cement	–0.20	–0.17	0.16	–0.04	0.24	0.15	0.02	0.06	–0.03
Matrix	–0.13	–0.40	–0.22	–0.15	–0.03	–0.04	–0.29	–0.36	0.21

$$E_{ave} = -0.98F + 55.14 \quad (r = -0.79). \tag{12}$$

Secant modulus of elasticity (GPa) versus feldspar content (%):

$$E_{\text{sec}} = -1.09F + 48.61 \quad (r = -0.8). \tag{13}$$

The correlation coefficients obtained in Table 5 show that feldspar reduces rock strength properties as well as the tensile and compressive strength of sandstone samples. Feldspar is an easily cleavable mineral. The presence of micro-mineral cracks and weak structures within feldspar reduces its strength (Onodera, Kumara 1980). There is a weak correlation between cement percentage and strength. Shakoor and Bonelli (1991) also did not find robust correlations between theses parameters in the sandstones they examined. The rock fragments content has a negative moderate correlation with dry density, and other petrographic parameters have weak correlation coefficients with rock strength. Rock fragments or lithic fragments are from a wide variety of lithotypes and commonly have source-specific textures.

CONCLUSIONS

In this work, comprehensive experiments were performed on 26 selected sandstone samples from north-western Iran. These tests included petrographic and mineralogical tests, tests to determine physical characteristics and engineering index properties, as well as tests to determine compressive and tensile strength. The aim of this study was to find a relationship between the different characteristics of sandstone rock samples with emphasis on finding the effect of quartz and feldspar mineral percentage on the strength of the samples. According to the results obtained:

- Considering the percentage of minerals content of the studied sandstones and the diagram proposed by Folk (1980) for naming sandstones, the selected samples are of arkose, sub-arkose and quartz arenite.
- Porosity is inversely related to dry density and *P*-wave velocity. Therefore, with increasing the porosity, the strength and modulus of deformation of the rock decrease and Poisson's ratio increases. With increasing density and *P*-wave velocity, strength and Young's modulus increase and Poisson's ratio decreases. However, the correlation coefficients of *P*-wave velocity are higher than those of other parameters, so it can be concluded that *P*-wave velocity is an indicator of the strength of the rock.
- Poisson's ratio is inversely related to dry density and *P*-wave velocity, as well as to the compressive and tensile strength of the samples and their Young's modulus, but directly related to porosity.
- The secant modulus of elasticity and average Young's modulus have a positive and significant correlation with the tensile and compressive strength of the rock. These two modulus have a positive and strong correlation with each other ($r = 0.86$).
- Uniaxial compressive strength has a moderate and direct relationship with Brazilian tensile strength ($r = 0.6$) and point load strength ($r = 0.5$).
- Among petrographic parameters, the type of grain contact and the amount of cement, matrix and rock fragment are generally not related to strength and parameters of the engineering index. However, the amount of cement and rock fragment has a moderate and negative correlation with dry density, *P*-wave velocity and modulus of elasticity.
- Grain size has a moderate and positive correlation with *P*-wave velocity and dry density.
- Packing density, packing proximity, sub-angular and angular grain shape have a moderate positive correlation with dry density, *P*-wave velocity, average and secant Young's modulus, and compressive and tensile strength, but are inversely related to porosity and Poisson's ratio. The correlation coefficients between the angular grain shape content and other parameters have a higher value.
- The percentage of rounded grain shape has a moderate and negative correlation with dry density and *P*-wave velocity, Therefore, the rounded grains content is inversely related to strength and Young's modulus.
- The percentage of quartz has a significant effect on increasing strength. Conversely, due to the presence of micro-mineral cracks in feldspar, increasing feldspar content reduces the compressive and tensile strength of the samples. Increasing quartz content reduces Poisson's ratio, and increasing feldspar increases Poisson's ratio. The correlation coefficients of the percentage of feldspar mineral with strength and elastic parameters and engineering index properties are higher than other coefficients.

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