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ORIGINAL PAPER

The influence of quartz content on modulus of elasticity and Poisson's ratio in quartz sandstone

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Abstract

High content of quartz in various sizes can affect the physical and mechanical properties, in particular the modulus of elasticity and Poisson's ratio. Sandstones are composed of clay-sized to coarse sand-sized quartz minerals, which will affect rock plasticity. The existence of clay-sized sand will certainly have a different impact from the clay-sized material composed of clay minerals. This study aims to determine the influence of quartz mineral content in sandstone on the modulus of elasticity and Poisson's ratio. The analysis was carried out on undisturbed samples of quartz sandstone taken from the Warukin Formation. Uniaxial test was performed on the samples by referring to the ASTM standard. To identify the relationship between the quartz content and the modulus of elasticity as well as Poisson's ratio, simple regression method was implemented. The result shows that quartz content has a very strong correlation with modulus of elasticity in both axial and diametral conditions as well as with Poisson's ratio, indicated by the correlation degree of above 0.90. Each of 1% increase in quartz content is followed by 5% increase in modulus of elasticity in axial condition, 2.4% increase in modulus of elasticity in diametral condition, and 0.84% increase in Poisson's ratio. The elastic modulus increases as the quartz content increases due to the friction among the very heterogeneous quartz minerals (fine to coarse sand in size). When there is pressure, fine-sized quartz will experience deformation and will move to fill the voids so that the sandstone has a high strain.

Keywords Quartz sandstone · Modulus of elasticity · Strain · Poisson's ratio

Introduction

The higher the quartz content in a rock, the faster the change in water content will be due to adhesive property resulting from the voids between grains (Zhang et al. 2015). Conversely, if the content of clay mineral is higher, absorption in the rock will be lower because the water travels through the very fine grain pores. Rate of water absorption is highly dependent on the material porosity which depends on the rock minerals, grain size distribution, and cement (Mallo and Sani 2012). Composition of clay material significantly affects crack pattern in the rock mass (Fleureau et al. 2015). This micro-scale crack pattern will have an impact on the strain pattern and rock displacement. Composition and property of clay material can influence mechanical properties of rock (Gault 2015). Mineral composition and grain size distribution can have an impact on void ratio and are closely related to mechanical properties of rock (Rios et al. 2013).

The presence of clay material can increase cohesion but will decrease internal friction angle. To improve the mechanical properties of clay mineral, a combination of maintaining physical properties and exerting pressure on the material must be carried out (Akayuli et al. 2013). The content of clay mineral in sandstone, as part of component that weakens the sedimentary rock, needs to be analyzed quantitatively. A combination of water and clay mineral is an important part of calculating the degradation of mechanical properties of sedimentary rock (Nihei et al. 2000; Cherblanc et al. 2016).

More quartz content gives the rock an interlocking texture that forms euhedral crystalline authigenic quartz. In general, authigenic quartz significantly reduces the intergranular pore size and pore space, causing a significant reduction in porosity and permeability of sandstones (Chima et al. 2018). Modulus of elasticity and Poisson's ratio will be different for different bedding plane angles at the same confining stress (Gupta and Mishra 2020; Chang et al. 2020). Loading speed

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of uniaxial test has a strong linear correlation with strain and time. The increase in acceleration occurs near the sandstone experiencing failure which is defined as the limit of rock plasticity (Zeng et al. 2019; Chen et al. 2020). Deformation in sandstones is influenced by porosity, mineralogy, size, and shape of grain, lithification, stress conditions, and bedding structure (Fossen et al. 2007; Li et al. 2018). The evolution of Young's modulus and Poisson's ratio in sandstones consists of four stages: (i) stage I: material compaction; (ii) stage II: material degradation; (iii) stage III: material disintegration; and (iv) stage IV: failure (Yang et al. 2015).

Ratio of length to diameter (L/D) is closely related to the post-normal axial strain, where L/D of 1.5 has a higher strain compared to L/D of 2.4 or 3.5 (Munoz and Taheri 2017). The process of rock failure occurs due to the evaluation process of grain interactions starting from microscopic scale to failure. This process occurs because of the interaction, dilation, and distortion of rocks due to compression (Jiang et al. 2018). Crack development in sandstone occurs at four stages (Wang et al. 2016) that are:

1. Stage 1: Decrease in sandstone pores, where the grains rub against each other due to confining pressure which results in a gradual decrease in permeability.
2. Stage 2: Continuous decrease in void ratio and permeability until all the grains are mutually supported (linked). Compression continues to occur in the material up to the maximum limit identified as the limit of rock plasticity.
3. Stage 3: The occurrence of microcrack due to pressure and limit of rock plasticity that is exceeded.
4. Stage 4: A post-stage where when the microcrack is formed, the grains will adjust to new condition where the movement is controlled by the grain characteristics.

Axial strain will increase when the length of rock bridge is 5 to 9 mm and decrease when the length of rock bridge is greater than 9 mm. The values of axial strain form a parabolic pattern with a peak at the length of rock bridge 9 mm (Zhu and Yu 2020). Peak strength for sandstone decreases by 4.7–17.9% depending on the weak inclusions distribution. The decrease of sandstone peak strength depends on the angle of two weak inclusions (Zhao et al. 2021). Swelling ratio, lateral constrained swelling ratio, and swelling stress of rocks are very time dependent. The time of swelling can be categorized into the following: rapid, moderate, and slow phases (Zhang et al. 2020). Peak strength decreases by up to 15% when there is an increase in room temperature to 100 °C. The increase in temperature leads to microcrack in rocks (Woodman et al. 2021). Stress on sandstone is very dependent on the dimension of cubic block and porosity. Decrease in porosity and permeability causes rock stress to increase (Arasteh et al. 2020). Natural quartz shows a high internal friction, Q-1 = 5 × 10–4, but only slightly higher than shown by a poor grade of cultured quartz with moderate dislocation content (Heyliger et al. 2003). The difference is only 3% for Young's modulus of quartz sandstones tested by DMA (Dynamic Mechanical Analyzer) using the torsion pendulum force (Peng and Redfern 2013). Modulus of elasticity and Poisson's ratio in sandstones do not correlate with depth (Boutrid et al. 2019).

Previous researches have not touched a specific correlation regarding the correlation between mineral content and strain as well as Poisson's ratio, especially for quartz mineral content of sandstones which genetically has a low strain due to the low content of clay or fine material. Conversely, sandstones have the characteristic of a relatively high strain that is more or less the same as in claystone. With this condition, it is interesting to know the characteristic of sandstones and the correlation with modulus of elasticity and Poisson's ratio. This is the novelty of this study.

Materials and methodology

The samples of quartz sandstone were taken from sandstone unit of the Warukin Formation in Kusan Block, Tanah Bumbu, South Kalimantan (Figs. 1 and 2). The Warukin Formation has dominant rock units of sandstone and claystone with coal inserts. The claystone has clay mineral content of kaolinite and illite, 15% and 8% respectively, and clay-sized quartz mineral content ranging from 60 to 80% (Supandi et al. 2019). Claystone will experience degradation of its physical and mechanical properties when exposed due to changes in environmental condition (Supandi et al. 2018). The sandstone of the Warukin Formation consists of 90% quartz minerals in various sizes ranging from clay to coarse sand. Angle of rupture for the sandstone is approximately 53° with low rock hardness that is less than 1 MPa (Supandi et al. 2020). The provenance of quartz sandstone is from older formation as a result of recycled orogenic process (Supandi and Hartono 2020). Sampling was carried out on the surface of the newly exposed mine wall. The distribution of sample locations is from the bottom to the top of stratigraphy with a height difference of about 100 m vertically. Based on visual observation, no crack or microcrack was found in the sandstone samples. Rock description refers to ASTM D2488-00 standard, and sample handling refers to ASTM D5434-97. Sampling was carried out using cylinder for undisturbed sample with a diameter of 70 mm and a length of 50 cm. For each of sampling locations, 3 samples were taken to meet the need of laboratory tests. A total of 20 samples were tested in the laboratory. In handling and transporting samples from the sampling location to the laboratory, ASTM D4220-95 standard was followed.

Fig. 1 Sandstone outcrop at Warukin Formation in Kusan Block

To obtain the physical and mechanical properties, basic property tests and uniaxial compressive strength (UCS) test were performed. The modulus of elasticity was tested by using uniaxial test method for intact rock, referring to ASTM D3148-02. Basic property tests follow ASTM D2216-19 for water content and ASTM D7263-21 for density. The uniaxial test used digital compression unit with loading rate of 0.1 mm/s in room temperature of 36 °C. Petrographic analysis was carried out by using X-ray diffraction (XRD) and scanning electron microscope (SEM). Analysis of sandstone characteristic was also carried out, using thin section method and microscopic analysis.

The influences of quartz content on modulus of elasticity as well as on Poisson's ratio were obtained by performing simple regression analysis. Simple regression is a statistical method for estimating relationship pattern between one independent variable (or x, i.e., quartz content) and one dependent variable (or y, i.e., modulus of elasticity or Poisson's ratio). The initial step of the analysis begins by creating a scatterplot of independent variable and dependent variable to see how the relationship pattern is. Through the visualization, the relationship model is determined and then tested whether it fits with the data or not by F-test. In simple regression, F-test is equivalent to t-test on regression coefficient, and both tests are also equivalent to t-test on simple correlation (Darlington and Hayes 2017). From the regression analysis, the correlation coefficient (r) is also obtained.

Coefficient correlation (r) states the degree and direction of a relationship between variables. As a coefficient that states a direction of relationship, r can be negative when the relationship is inversely proportional, that is, when an increase in the value of one variable is accompanied by a

Fig. 2 Close-up of sandstone outcrop

Table 1 Interpretation of correlation coefficient according to Guilford (1956, in Van Aswegen and Engelbrecth 2009)

r	Interpretation
0.000 – 0.199	Slight, almost no relationship
0.200 – 0.399	Low correlation, definite but small relationship
0.400 – 0.699	Moderate correlation, substantial relationship
0.700 – 0.899	High correlation, very dependable relationship
0.900 – 1.000	Practically significant relationship

decrease in the value of the other variable, or a decrease in the value of one variable is accompanied by an increase in the value of the other variable. *r* that is positive indicates the relationship that is directly proportional, where an increase in the value of one variable is followed by an increase in the value of the other variable, or a decrease in the value of one variable is followed by a decrease in the value of the other variable. As a coefficient that states a degree of relationship, in general, $-1 \le r \le 1$ applies, where *r* of 1 indicates a perfect correlation. The interpretation of the degree is in Table 1, valid for both positive and negative *r* values.

Results

Total of sandstone samples used in the analysis is 20 samples. The sample determination is based on the description of sedimentary rock, referring to the Pettijohn classification in 1978. Detailed characteristics of the sandstone samples will be obtained based on tests of petrography, XRD, and SEM, as well as physical and mechanical properties. The analysis ignores weathering factor because quartz sandstones have strong property.

The result of petrographic analysis shows that there is abundant quartz in various sizes. The observation was at 10 × ocular magnification and 5 × objective magnification. Based on the observation, the following characteristics were found: brownish gray in color with massive structure, grain size texture of clay to coarse sand (ranging from less than 1/256 to 1 mm), medium sorting, rounded, and closed fabric (Fig. 3). The mineral composition based on the petrographic analysis is as follows:

1. Quartz (A1)
   White in plane-polarized light (PPL), white to gray in cross-polarized light (XPL), low relief without cleavage, anhedral, low pleochroism, with abundance of 73%
2. Clay mineral (J1)
   A mixture of illite and kaolinite, light brown in PPL, brown-gray in XPL, with abundance of 18%. BF and angle of extinction are difficult to observe because the mineral size is very small.
3. Organic carbon (D3)
   Dark brownish in PPL and XPL with abundance of 7%
4. Feldspar (B3)
   Light brown in PPL, white gray in XPL, subhedral-euhedral, carlsbad-albite twin, moderate pleochroism, one-way cleavage, with abundance of 2%.

The result of SEM analysis on sandstone samples is not much different from the result of petrographic analysis. The SEM test was carried out at 10,000 × magnification in order to obtain a very good picture of grain characteristics in the sandstones. The sandstones consist of quartz mineral in various sizes, from clay to coarse sand. Abundant voids were found, in accordance with the visual condition. Based on Fig. 4, it can

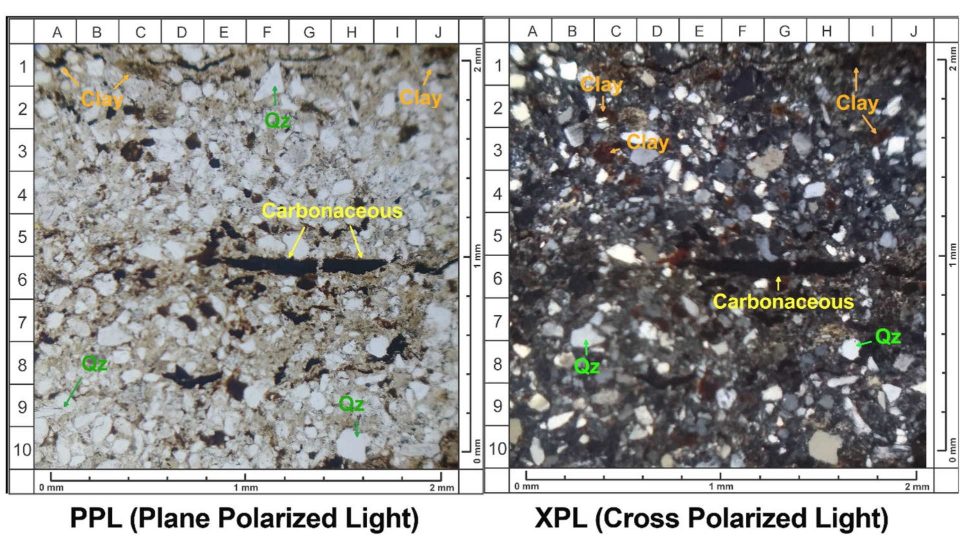

Fig. 3 Photomicrograph of thin section showing mineral composition of quartz with a small amount of clay and carbonaceous. Quartz mineral was found in various sizes ranging from clay to coarse sand

be seen that the granular structure of fine quartz mineral (clay) covers the large quartz mineral so that the quartz looks angular or irregular. The compactness of quartz material including quartz mineral appears to be brittle. This condition causes the fine-sized quartz material to move to fill the voids when the sandstone mass is under pressure, so it is predicted that the sandstone has a high strain.

The XRD test result shows that the sandstones are dominated by quartz mineral by almost 90% (Fig. 5). This result confirmed the results of petrography and SEM that quartz mineral is the main mineral in sandstones. The other minerals were found in very small amount. The quartz content of 20 sandstone samples ranges from 66 to 100% with an average of 90%.

According to the geological and geochemical analysis, the sandstones are quartz sandstones, and this is in accordance with the topic of this study. The study was conducted to identify the characteristics of quartz content against the physical and mechanical properties of rock, in particular the Poisson's ratio and modulus of elasticity. This can explain why the sandstones in Kusan Block have strain that is similar to claystone strain.

Physical property tests in laboratory were performed to obtain sandstone characteristics consisting of natural water content, specific gravity, density, void ratio, and saturation. The natural water content varies from 18.86 to 26.55% with an average of 22.24%. This value is relatively high and will certainly have an impact on the mechanical properties of rock. The specific gravity ranges from 2.31 to 2.70 with an average of 2.60. The average density of the sandstones is 1.97 g/cm^3 with a minimum density of 1.82 g/cm^3 and a maximum of 2.13 g/cm^3. The maximum void ratio is 0.82 and the minimum is 0.40 with an average of 0.62. The quartz sandstones are in saturated or near-saturated condition which is indicated by a maximum degree of saturation of 118.89% and a minimum of 82.81% with an average saturation of 94.61%. Generally, the physical property is still included in sandstone characteristics, and the mechanical property becomes one of the limiting factors of this research. The physical properties of quartz sandstones based on laboratory tests can be seen in Table 2.

Quartz content has a moderate relationship with the void ratio, which is indicated by a degree correlation value; it is 0.48. The correlation between the two variables has an inverse relationship where the increase in quartz content is followed by a decrease in the value of void ratio (Fig. 6). Each decrease from the 5% increase in quartz content was followed by a decrease in void ratio; it is 0.1. The variations in the size of sandstone grains ranging from fine to coarse cause the granules to interlock, so that the void ratio gets smaller. When the quartz content decreases, there is the potential for other minerals to enter the rock mass, so that the void ratio increases. The value of this void ratio is correlated with permeability and porosity, but in this study, the data obtained were not detailed enough.

The term clay material is more based on the grain size of material and it is not on the type of clay mineral. The clay materials are described as clay-sized materials

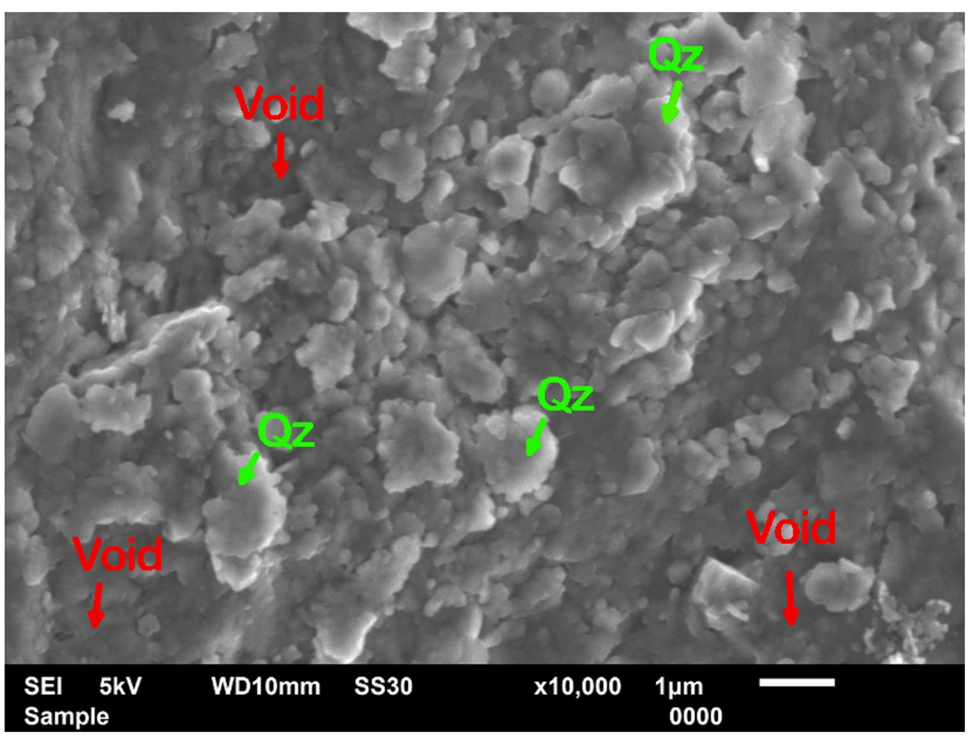

Fig. 4 Scanning electronic microscope (SEM) result from one of the sandstone samples

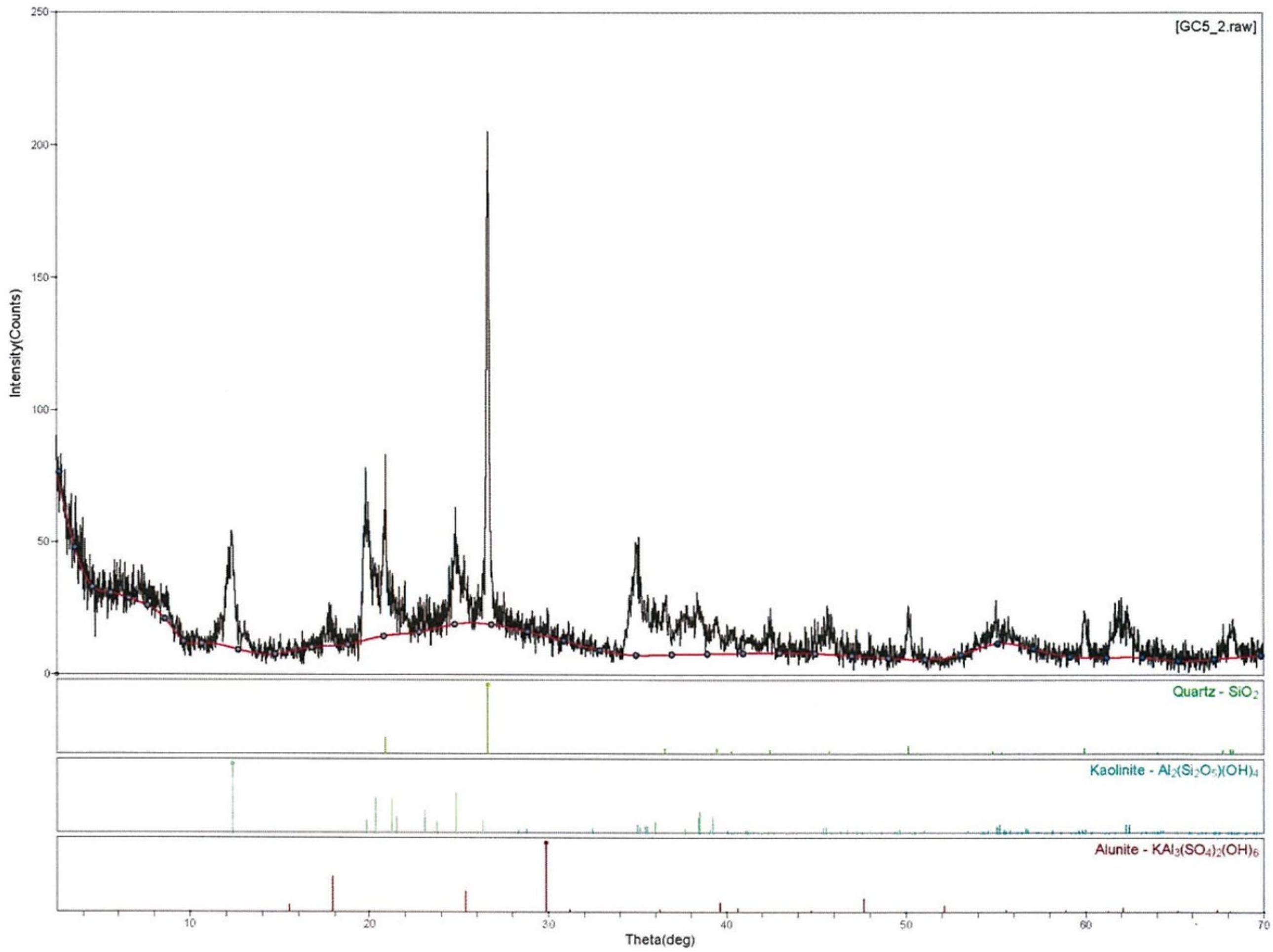

Fig. 5 X-ray diffraction (XRD) result from one of the sandstone samples

(< 1/256 mm); it is according to the Wentworth classification. The clay-sized quartz minerals come from a provenance of quartz minerals coming from older formations. As the result of tectonic processes and the occurrence of recycle orogens, it causes the quartz minerals to be transported, exposed and experiencing some deposition that resulted in quartz minerals up to the size of clay. It is enough to do research on the influence of fine materials on the mechanical properties of sandstone. So far, many studies have been carried out by looking at clay content on rock plasticity, but no one has investigated the effect of mechanical properties from the sandstone; it is due to the content of fine material in the form of quartz. Existing research is more about the content of clay as a clay mineral, and not as clay in terms of grain size. The content of quartz to the size of clay grains becomes very interesting to be discussed.

In this study, a complete method has been used to identify the mineral composition of rocks, so it can determine the type of mineral to the size of clay. The combination of XRD–scanning electron microscope (SEM) and thin section is one of the advantages in this research, so the data is very accurate. The results of the analysis from the three methods are mutually reinforcing, so that accurate analysis results are obtained. This research is very valid, because of the data used, and the method used is very valid and uses the appropriate standard.

The mechanical properties of sandstones were obtained from uniaxial test which results in the modulus of elasticity, Poisson's ratio, and other properties presented in Table 3. The modulus of elasticity was obtained under axial and diametral conditions. The strain is in units of millimeter (mm) and percentage, making it easier to be applied in field condition. The compressive strength has a very wide range, from 21.49 to 396.99 kPa, with an average of 119.28 kPa. The modulus of elasticity ranges from 529.10 to 3583 kPa with an average of 2289 kPa in axial condition. In diametral condition, the average modulus of elasticity is 3487 kPa with a minimum of 1920 kPa and a maximum of 4380 kPa. The Poisson's ratio ranges from 0.22 to 0.30 with an average of 0.27. The average axial strain is 5.63 mm with a maximum

Table 2 Physical properties of sandstones based on laboratory tests

No	Sample	Natural water content (%)	Specific gravity	Wet density (g/cm^3)	Dry density (g/cm^3)	Void ratio	Saturated density (g/cm^3)	Submerged density (g/cm^3)	Degree of saturation (%)
1	GC 1_1	23.68	2.617	1.887	1.526	0.715	1.943	0.943	86.62
2	GC 2_2	23.62	2.309	1.824	1.476	0.564	1.837	0.837	96.63
3	GC 3_1	25.42	2.687	1.847	1.473	0.825	1.925	0.925	82.81
4	GC 4_1	21.13	2.676	2.061	1.701	0.573	2.065	1.065	98.72
5	GC 5_1	26.55	2.636	1.844	1.457	0.809	1.904	0.904	86.50
6	GC 6_2	22.00	2.420	1.867	1.530	0.581	1.898	0.898	91.56
7	GC 7_1	21.65	2.679	2.009	1.652	0.622	2.035	1.035	93.27
8	GS 1_1	18.86	2.506	2.131	1.793	0.397	2.078	1.078	118.89
9	GS 2_1	21.10	2.670	2.001	1.653	0.616	2.034	1.034	91.50
10	GS 3_1	21.96	2.670	2.031	1.665	0.603	2.042	1.042	97.22
11	KC 1_1	22.13	2.600	1.971	1.614	0.611	1.993	0.993	94.17
12	KC 2_1	22.56	2.657	1.993	1.626	0.635	2.014	1.014	94.48
13	KC 3_1	22.94	2.657	1.922	1.563	0.700	1.975	0.975	87.07
14	KC 4_1	22.78	2.578	1.931	1.573	0.639	1.963	0.963	91.92
15	KC 5_3	20.59	2.542	1.981	1.643	0.547	1.996	0.996	95.63
16	KC 6_1	24.43	2.613	1.876	1.508	0.733	1.931	0.931	87.10
17	KC 7_1	22.21	2.650	2.010	1.644	0.612	2.024	1.024	96.25
18	KS 1_1	19.79	2.700	2.109	1.761	0.533	2.109	1.109	100.22
19	KS 2_1	22.27	2.506	1.998	1.634	0.534	1.982	0.982	104.60
20	KS 3_1	19.18	2.610	2.053	1.722	0.515	2.063	1.063	97.14

of 7.87 mm and a minimum of 4.08 mm. In the percentage of change from the initial condition, the axial strain ranges from 3.30 to 5.20% with an average of 4.41%.

Four properties that will be analyzed by using regression method in relation to quartz content are modulus of elasticity in axial condition, modulus of elasticity in diametral condition, Poisson's ratio, and percent change of axial strain. The data distributions can be seen in Fig. 6, where the values have been standardized to make it easier to be compared. Based on Fig. 7, the quartz sandstones have lower modulus of elasticity in axial condition than in diametral condition, seen from the values of elastic modulus in axial condition that tend to gather on the left of the values of elastic modulus in diametral condition. The distributions of elastic modulus

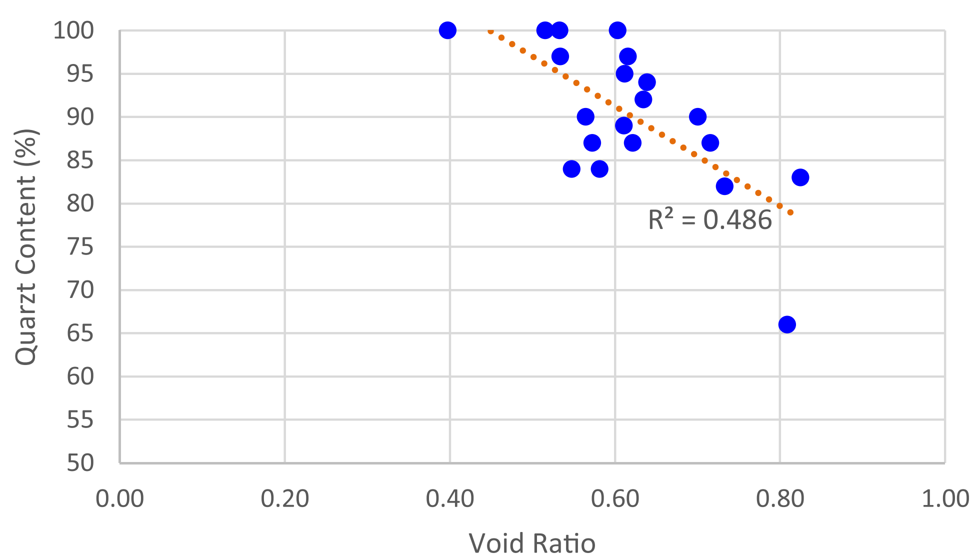

Fig. 6 Correlation quartz content with void ratio, decreasing void ration 0.1 while increasing quartz content 5%

Table 3 The result of uniaxial compressive strength (UCS) test on quartz sandstone

No	Sample	Quartz (%)	Compressive strength (kPa)	Modulus of elasticity (kPa)		Poisson's ratio	Axial strain (mm)	Change in axial strain (%)
				Axial	Diametral			
1	GC 1_1	87	60.01	1366	3330	0.263	4.750	3.98
2	GC 2_2	90	60.16	2352	3750	0.256	4.08	4.30
3	GC 3_1	83	22.66	1499	2819	0.245	4.88	4.25
4	GC 4_1	87	158.63	1971	3057	0.266	5.980	4.10
5	GC 5_1	66	21.49	529	1920	0.221	4.72	3.30
6	GC 6_2	84	40.40	1530	2879	0.253	5.13	4.24
7	GC 7_1	87	142.97	2021	3401	0.263	5.560	4.18
8	GS 1_1	100	396.993	3583	4297	0.297	7.820	5.20
9	GS 2_1	97	203.59	3073	3879	0.285	5.23	4.91
10	GS 3_1	100	98.52	3476	4202	0.288	6.48	5.09
11	KC 1_1	89	84.17	1783	3638	0.263	5.84	4.43
12	KC 2_1	92	31.67	2223	3751	0.278	5.38	4.37
13	KC 3_1	90	32.24	1677	3442	0.272	4.68	4.17
14	KC 4_1	94	119.45	2622	3671	0.268	5.620	4.49
15	KC 5_3	84	105.03	2187	2662	0.253	4.92	3.97
16	KC 6_1	82	60.791	1284	2540	0.259	5.080	4.05
17	KC 7_1	95	76.33	2618	3959	0.267	5.68	4.76
18	KS 1_1	100	224.11	3554	4246	0.300	7.160	4.93
19	KS 2_1	97	178.52	3099	3912	0.280	5.72	4.54
20	KS 3_1	100	267.79	3326	4380	0.297	7.87	4.97

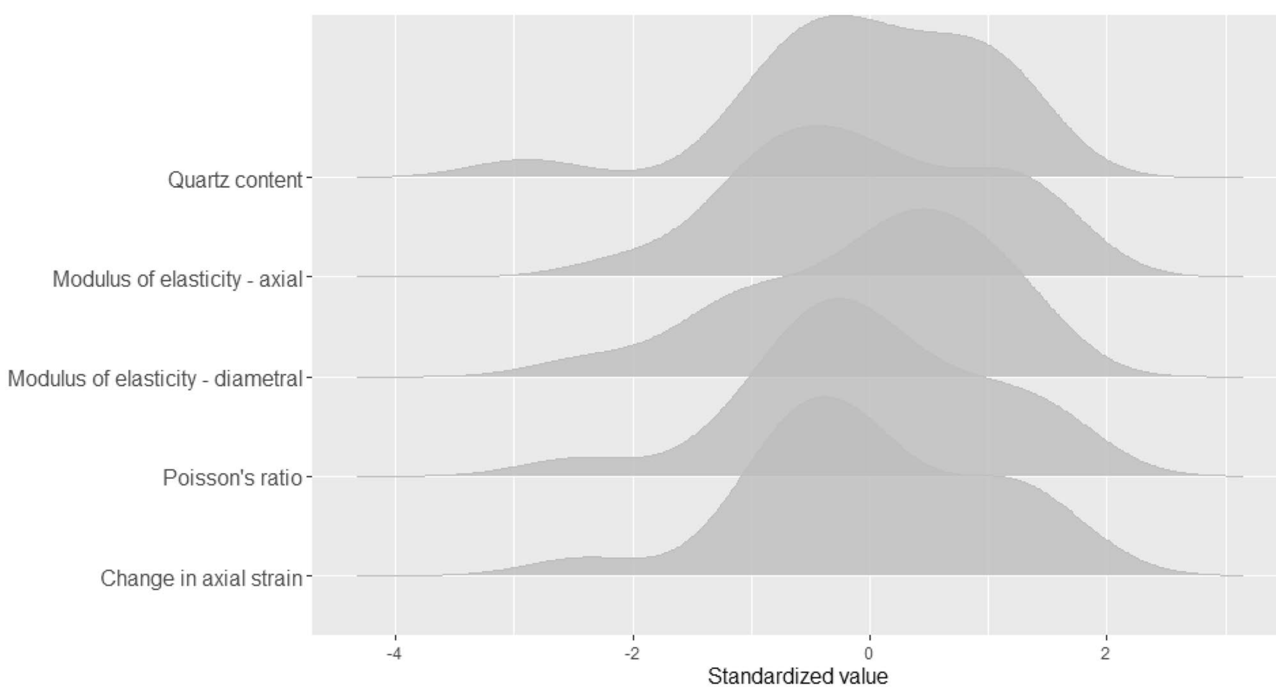

Fig. 7 Ridgeline plot of quartz content, modulus of elasticity in both axial and diametral conditions, Poisson's ratio, and change in axial strain showing the data distributions

in axial condition look similar to the distributions of Poisson's ratio and change in axial strain.

Figure 8 shows scatterplots of quartz content with the four properties as dependent variables (y). Based on the visualization, each of the plots shows a relationship pattern that the change in dependent variable as the quartz content changes begins relatively slowly and then accelerates, especially in the plot of quartz content with modulus of elasticity in axial condition. This pattern is similar to exponential model: $y = b_0 e^{b_1 x}$, where y is dependent variable (i.e., modulus of elasticity in axial condition, modulus of elasticity in diametral condition, Poisson's ratio, or percent change of axial strain), b_0 is a constant, b_1 is coefficient of regression which represents the relative change of y for a unit change of x, and x is independent variable (i.e., quartz sandstone). For each of dependent variables, the parameters of the model were estimated by nonlinear weighted least-squares method, which results in Table 4. All p-values in Table 4 are below significance level of 5%, so it can be concluded that the exponential relationships between quartz content and the dependent variables are significant. An increase of 1% in quartz content is followed by 5% increase in axial

Table 4 Results of regression analysis

Quartz content and modulus of elasticity in axial condition					
	Estimate	Standard error	t	p-value	r
b_0	22.2252	8.2290	2.7010	0.0146	0.9619
b_1	0.0505	0.0038	12.9870	1.40×10^{-10}	
Quartz content and modulus of elasticity in diametral condition					
	Estimate	Standard error	t	p-value	r
b_0	406.3000	63.2100	6.4270	4.75×10^{-6}	0.9643
b_1	0.0236	0.0017	14.1440	3.43×10^{-11}	
Quartz content and Poisson's ratio					
	Estimate	Standard error	t	p-value	r
b_0	0.1251	0.0081	15.3600	8.67×10^{-12}	0.9448
b_1	0.0084	0.0007	11.8900	$5.88\mathrm{e} \times 10^{-12}$	
Quartz content and change in axial strain					
	Estimate	Standard error	t	p-value	r
b_0	1.4141	0.1367	10.3400	5.29×10^{-9}	0.9464
b_1	0.0126	0.0010	11.9500	5.39×10^{-10}	

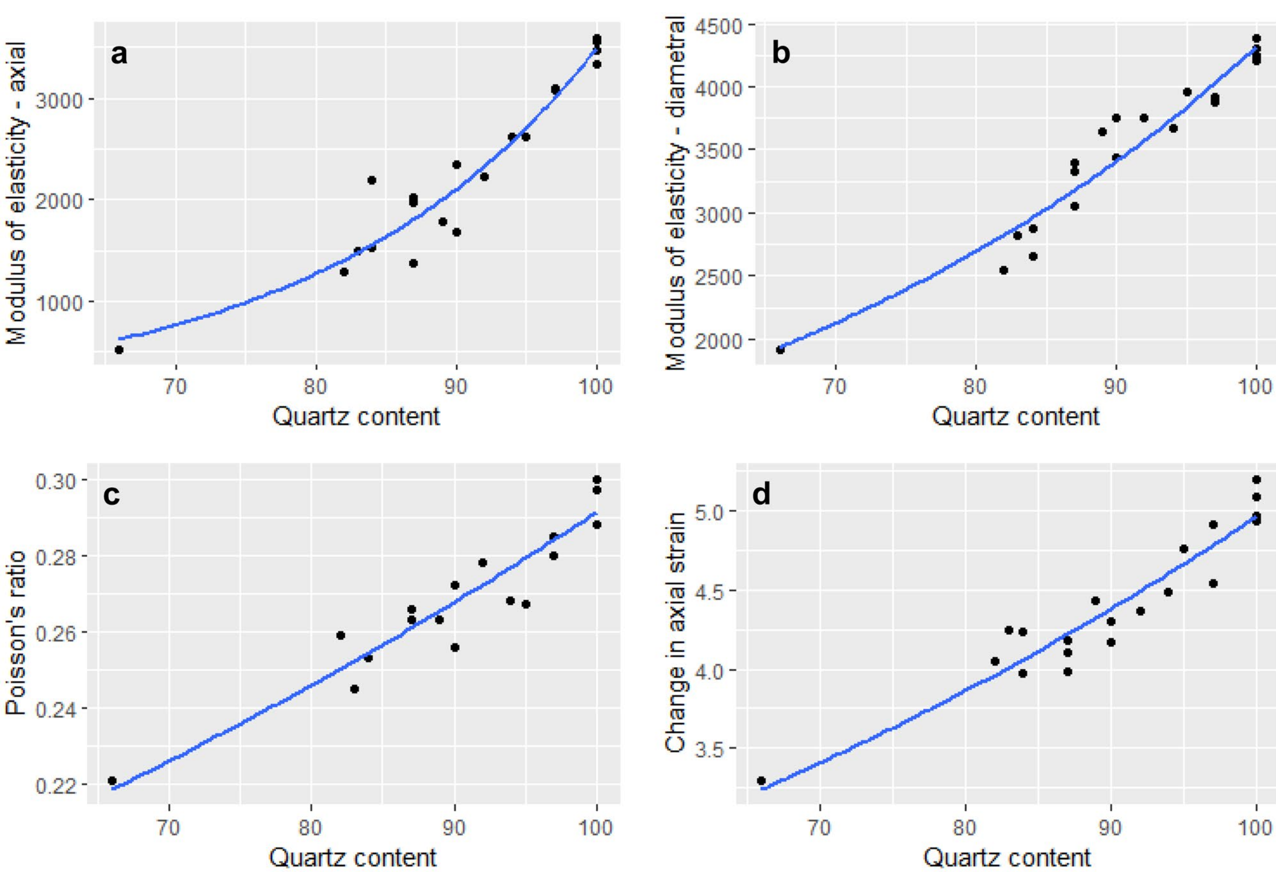

Fig. 8 Scatterplot of quartz content with modulus of elasticity in both **a** axial and **b** diametral conditions, **c** Poisson's ratio, and **d** change in axial strain showing the data distributions, along with the regression line

modulus of elasticity, 2.4% increase in diametral modulus of elasticity, 0.84% increase in Poisson's ratio, and 1.3% increase in axial strain change. When the quartz content is 0%, the modulus of elasticity is 22.22 kPa in axial condition and 406.30 kPa in diametral condition, the Poisson's ratio is 0.12, and the change in axial strain is 1.41%.

Based on the result of regression analysis, the coefficient of correlation is obtained. The correlation of quartz content as independent variable in the regression model with either modulus of elasticity in both axial and diametral condition, Poisson's ratio, or percent change of axial strain as dependent variable shows a very strong correlation indicated by the correlation degree of above 0.90. The positive correlation states that both quartz content and the dependent variable move in the same direction, where an increase in quartz content is followed by an increase in the dependent variable, and vice versa.

To strengthen the result of this analysis, the grain size distribution of quartz needs to be detailed to verify the sandstone strain. When the grain size varies widely from clay to coarse sand, the amount of strain will be clarified. The strain of sandstones is quite high due to the movement of interlocking materials.

Conclusions

The sandstones in Kusan Block are quartz sandstones where the quartz content ranges from clay to coarse sand in size with coarse sandstone fragments, fine to medium sandstone matrices, and silica cement. The average quartz composition is 90%. The natural water content is 22.24% while the specific gravity is 2.60. The density in natural condition is 1.97 g/cm^3 and the void ratio is 0.62. The quartz sandstones are saturated or near-saturated with a saturation degree of 94.61%.

The quartz content has a very strong correlation with modulus of elasticity in both axial and diametral conditions as well as with Poisson's ratio, indicated by the correlation degree of above 0.90. Each of 1% increase in quartz content is followed by an exponentially growth by 5% in axial modulus of elasticity, 2.4% in diametral modulus of elasticity, and 0.84% in Poisson's ratio. When there is no quartz content, the modulus of elasticity is 22.22 kPa in axial condition and 406.30 kPa in diametral condition, and the Poisson's ratio is 0.12.

The modulus of elasticity increases as the quartz content increases because of the friction among very heterogeneous quartz minerals (fine to coarse sand in size). Fine-sized quartz will experience deformation under pressure and move to fill the voids so that the sandstone has a high strain.

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Author contribution Supandi conceptualized the research design, designed the model and the computational framework, analyzed the data, and drafted the manuscript. Supandi worked starting from desk study, field investigation, carrying out simulations, analysis, and interpretation, as well as drafting this article. R Andy Erwin Wijaya worked on desk study for literature study, data analysis, and drafting this article.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Conflict of interest The authors declare no competing interests.

References

Akayuli C, Ofosu B, Nyako SO, Opuni KO (2013) The influence of observed clay content on shear strength and compressibility of residual sandy soils. Int J Eng Res Appl 3:2538–2542

Arasteh H, Saeedi G, Farsangi MAE, Esmaeili K (2020) A new model for calculation of the plastic compression index and porosity and permeability of gob materials in longwall mining. Geotech Geol Eng 38:6407–6420. https://doi.org/10.1007/s10706-020-01444-w

Boutrid A, Mamen B, Djouama MC, Chettibi M (2019) Depth effect on sandstone strength properties. Int Eng J 72:353–361. https://doi.org/10.1590/0370-44672018720107

Chang S, Xu JY, Bai EL, Zheng GH, Lv XC (2020) Static and dynamic mechanical properties and deterioration of bedding sandstone subjected to freeze–thaw cycles: considering bedding structure effect. Sci Rep 10:12790 https://doi.org/10.1038/s41598-020-69270-x

Chen F, Wang E, Zhang B, Zhang L, Meng F (2020) Prediction of fracture damage of sandstone using digital image correlation. Appl Sci 10:1280. https://doi.org/10.3390/app10041280

Cherblanc F, Berthonneau J, Bromblet P, Huon V (2016) Influence of water content on the mechanical behaviour of limestone: role of the clay minerals content. Rock Mech Rock Eng 49:2033–2042. https://doi.org/10.1007/s00603-015-0911-y

Chima P, Baiyegunhi C, Liu K, Gwavava O (2018) Diagenesis and rock properties of sandstones from the stormberg group, karoo supergroup in the eastern cape province of South Africa. Open Geosci 10:740–771. https://doi.org/10.1515/geo-2018-0059

Darlington RB, Hayes AF (2017) Regression analysis and linear models: concepts, applications, and implementation. The Guilford Press, Newyork

Fleureau JM, Wei X, Ighil-Ameur L, Hattab M, Bicalho KV (2015) Experimental study of the cracking mechanisms of clay during drying. In: Manzanal D, Sfriso AO (eds) From fundamentals to applications in geotechnics. IOS Press, Amsterdam, pp 2101–2108. https://doi.org/10.3233/978-1-61499-603-3-2101

Fossen H, Schultz RA, Shipton ZK, Mair K (2007) Deformation bands in sandstone: a review. J Geol Soc 164:1–15. https://doi.org/10.1144/0016-76492006-036

Gault AM (2015) The mineralogy and strength characteristics of selected glaciolacustrine clays in the Puget Sound region. University of Washington, Washington

Gupta N, Mishra B (2020) Experimental investigation of the influence of bedding planes and differential stress on microcrack propagation in shale using x-ray CT scan. Geotech Geol Eng 39:213–236. https://doi.org/10.1007/s10706-020-01487-z

Heyliger P, Ledbetter H, Kim S (2003) Elastic constants of natural quartz. J Acoust Soc Am 114:644–650. https://doi.org/10.1121/1.1593063

Jiang Y, Luan H, Wang Y, Wang G, Wang P (2018) Study on macro–meso failure mechanism of pre-fractured rock specimens under uniaxial compression. Geotech Geol Eng 36:3211–3222. https://doi.org/10.1007/s10706-018-0531-x

Li H, Li H, Wang K, Liu C (2018) Effect of rock composition microstructure and pore characteristics on its rock mechanics properties. Int J Min Sci Technol 28:303–308. https://doi.org/10.1016/j.ijmst.2017.12.008

Mallo SJ, Sani SD (2012) Influence of mineralogy and fabric on the engineering properties of the maingo granite porphyry, North Central Nigeria. Int J Mod Eng Res 2:4600–4608

Munoz H, Taheri A (2017) Specimen aspect ratio and progressive field strain development of sandstone under uniaxial compression by three-dimensional digital image correlation. J Rock Mech Geotech Eng 9:599–610. https://doi.org/10.1016/j.jrmge.2017.01.005

Nihei KT, Hilbert LB, Cook NGW, Nakagawa S, Myer LR (2000) Frictional effects on the volumetric strain of sandstone. Int J Rock Mech Min Sci 37:121–132. https://doi.org/10.1016/S1365-1609(99)00098-2

Peng Z, Redfern SAT (2013) Mechanical properties of quartz at the α-β phase transition: implications for tectonic and seismic anomalies. Geochem Geophys Geosystem 14:18–28. https://doi.org/10.1029/2012GC004482

Rios S, Fonseca AVD, Consoli NC, Floss M, Cristelo N (2013) Influence of grain size and mineralogy on the porosity/cement ratio. Geotech Lett 3:130–136. https://doi.org/10.1680/geolett.13.00003

Supandi, Hartono HG (2020) Geomechanic properties and provenance analysis of quartz sandstone from the Warukin Formation. GeoMate J 18:140–149. https://doi.org/10.21660/2020.66.50081

Supandi, Zakaria Z, Sukiyah E, Sudradjat A (2018) The correlation of exposure time and claystone properties at the Warukin Formation Indonesia. Int J GEOMATE 15:160–167. https://doi.org/10.21660/2018.52.68175

Supandi ZZ, Sukiyah E, Sudradjat A (2019) The influence of kaolinite-illite toward mechanical properties of claystone. Open Geosci 11:440–446. https://doi.org/10.1515/geo-2019-0035

Supandi, Zakaria Z, Sukiyah E, Sudradjat A (2020) New constants of fracture angle on quartz sandstone. Int J Adv Sci Eng Inf Technol 10: 1597–1603. https://doi.org/10.18517/ijaseit.10.4.8272

Van Aswegen AS, Engelbrecht AS (2009) The relationship between transformational leadership, integrity, and an ethical climate in organisations. SA Journal of Human Resource Management/SA Tydskrif vir Menslikehulpbronbestuur 7(1), Art. #175, 9 pages. https://doi.org/10.4102/sajhrm.v7i1.175

Wang HL, Xu WY, Jia CJ, Cai M, Meng QX (2016) Experimental research on permeability evolution with microcrack development in sandstone under different fluid pressures. J Geotech Geoenviron Eng 142:04016014. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001462

Woodman J, Ougier-Simonin A, Stavrou A, Vazaios I, Murphy W, Thomas ME, Reeves HJ (2021) Laboratory experiments and grain based discrete element numerical simulations investigating the thermo-mechanical behaviour of sandstone. Geotech Geol Eng 39:1–21. https://doi.org/10.1007/s10706-021-01794-z

Yang SQ, Ranjith PG, Huang YH, Yin PF, Jing HW, Gui YL, Yu QL (2015) Experimental investigation on mechanical damage characteristics of sandstone under triaxial cyclic loading. Geophys J Int 201:662–682. https://doi.org/10.1093/gji/ggv023

Zeng F, Folta BL, Labuz JF (2019) Strength testing of sandstone under multi-axial stress states. Geotech Geol Eng 37:4803–4814. https://doi.org/10.1007/s10706-019-00939-5

Zhang J, Apeagyei AK, Airey GD, Grenfell JRA (2015) Influence of aggregate mineralogical composition on water resistance of aggregate-bitumen adhesion. Int J Adhesion Adhesives 62:45–54. https://doi.org/10.1016/j.ijadhadh.2015.06.012

Zhang Z, Gao W, Huang J, Ouyang S, Zhang Z (2020) Swelling characteristics of red sandstone under cyclic wetting and drying. Geotech Geol Eng 38:4289–4306. https://doi.org/10.1007/s10706-020-01295-5

Zhao Z, Jing H, Shi X (2021) Experimental investigation and numerical modelling on strength and fracture behaviors of sandstone with weak distributed inclusions. Geotech Geol Eng 39:2521–2531. https://doi.org/10.1007/s10706-020-01643-5

Zhu J, Yu H (2020) Analysis of crack propagation characteristics of rock-like material with double closed cracks under uniaxial compression. Geotech Geol Eng 38:6499–6509. https://doi.org/10.1007/s10706-020-01451-x