ISSN 1062-7391, Journal of Mining Science, 2021, Vol. 57, No. 6, pp. 901–910. © Pleiades Publishing, Ltd., 2021.
Published in Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh, 2021, No. 6, pp. 27–37.

GEOMECHANICS

Correlations Between Mechanical and Index Properties of Sandstone from the Central Salt Range

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Received October 15, 2020
Revised March 13, 2021
Accepted November 11, 2021

Abstract—A study was conducted to uncover the possible correlations among mechanical and index properties of sandstones from formations of Salt Range area, Punjab, Pakistan. For this purpose, sandstone block samples were collected from seven formations of the Salt Range. The samples were prepared for rock testing according to the guidelines set by International Society of Rock Mechanics (ISRM). Defective samples were discarded and those meeting the ISRM specifications were tested for sonic velocities, dry density, porosity, uniaxial compressive strength, tensile strength and elastic constants. Results obtained were then statistically analyzed to find the predictive relationships. The analysis revealed that correlations exist between two groups of tested rocks. The predictive relationships were determined between porosity and static mechanical properties of rocks and between porosity and dynamic mechanical properties.

Keywords: Porosity, UCS, rock properties, correlation, Salt Range, sonic velocity.

DOI: 10.1134/S106273912106003X

INTRODUCTION

Rock characterization is crucial for engineering design of mines and underground structures and to solve several other geotechnical problems. The rock characterization is carried out by following complicated, often laborious, careful standardized laboratory procedures. From a wide range of rock properties, a few such as uniaxial compressive strength (UCS), Young's modulus, Poisson's ratio, tensile strength, and sonic wave velocities through rocks are frequently employed in the design computations of underground excavations, hydraulic structures, foundations, and several other geotechnical problems.

Dynamic testing of rocks is non-destructive and provides compression (P) wave and shear (S) wave velocity values which can be used to calculate dynamic elastic constants such as Poisson's ratio (v), Young's modulus (E), bulk modulus (K), and shear modulus (G). P- and S-wave velocity measurement techniques have been used for many years in mining and geotechnical engineering. These are also employed in the field for geophysical investigation and in the laboratories for the determination of dynamic rock properties. The important factors that influence the wave velocities through rocks are type of rock, mineralogical composition, density, porosity, anisotropy, pore-water, confining pressure, temperature, weathering, texture, structure, grain size, and grain shape. In general, the properties of rocks are influenced by both the internal factors e.g. degree of interlocking, grain size, texture, composition, pores, arrangement of minerals and pores, and external factors e.g. weathering. Several authors have tried to establish correlations between various the rock properties [1–5].

Although, it is a well-known fact that water deteriorates rocks and reduces their strength, however qualitative assessment of strength reduction between an oven-dried and a saturated sample is difficult to define. As an increase in porosity usually decreases density and elastic moduli and weakens the bonding between grains. Porosity has an effect on the mechanical properties of rocks [6–8]. Porosity alone has very little effect on the mechanical behavior but variation in size and distribution of pore spaces produce notably diverse mechanical properties.

This study aims to investigate the existence of relationships between mechanical (strength, Young's modulus and Poisson's ratio) and index (density, porosity, *P*- and *S*-wave velocity) properties for sandstone formation of the Salt Range.

1. LOCATION AND GEOLOGY

The Salt Range is located between the Jhelum River and the Indus River across the Northern Punjab Province of Pakistan (Fig. 1). The Salt Range is a hill system in the Punjab province of Pakistan, and is famous for its geology, mineral wealth, mining, and geological history. The area hosts many active mines producing rock salt, coal, limestone, gypsum, clays, and aggregate. In addition, the region also hosts many oil and gas production sites and fosters many geotechnical structures connecting major cities and strategic projects [9]. Given the increasing minerals and cement demands in the country, it is anticipated that there will be increased development of underground structures for mining, transportation, and civil engineering related works in this area. This will call for more elaborative determination of rock properties of the Salt Range. Let us consider in more detail the geological structure of rock formations in our area of interest.

Chinji (CH) formation is part of Siwalik group (Miocene). It consists of alternating beds of sandstone and argillaceous material. It has sediments of clastic origin of molasse type. The lithology typically consists of red clay with subordinate sandstone at the base that is overlain by thick sandstone with minor clay. Chinji formation consists of red clay with subordinate ash grey or brownish grey sandstone that is fine to medium grained, occasionally gritty, cross-bedded and soft. Scattered pebbles of quartzite and thin lenses of intra-formational conglomerate are present at different horizons throughout the formation.

Dhok Pathan (DP) formation is also a part of Siwalik group (Late Miocene-Early Pliocene). This formation is typically presented by monotonous cyclic alternations of sandstones and clay beds. The sandstone is commonly grey, light grey, gleaming white or reddish brown and occasionally brownish grey, greenish grey brown or buff colored, thick bedded, calcareous, moderately cemented, soft and cross-bedded.

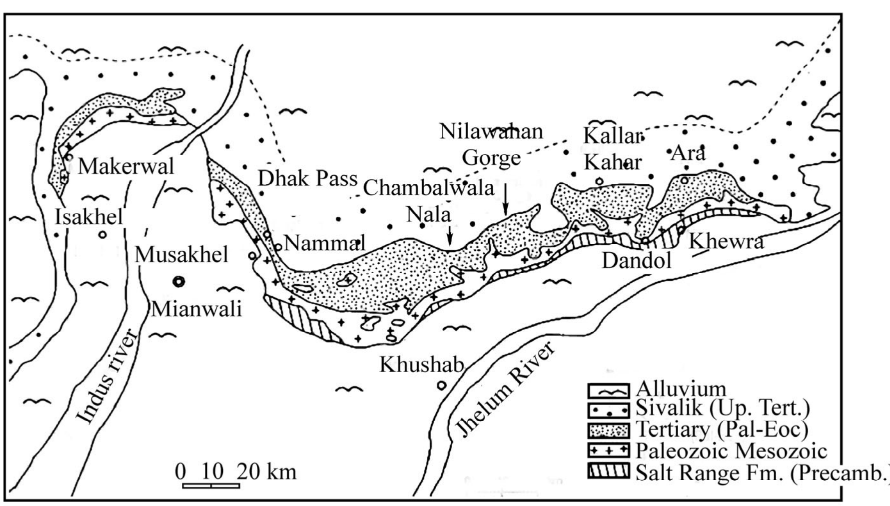

Fig. 1. Geological map of the Salt Range.

Kussak (KU) and Kussak Gluconated (KU-GL) formation (Cambrian) is composed of greenish-grey, glauconitic, micaceous sandstone, and greenish-grey siltstone, inter-bedded with light grey dolomite and some oolitic, arennaceous dolomite. Numerous layers of intra-formational conglomerate are present.

Baghanwala (BA) formation (Cambrian) is composed of red shale and clay, alternating with flaggy sandstone. The flaggy sandstone exhibits several colors including pink grey or blue green, especially in the lower half of the formation. Sedimentary structures such as ripple marks and mud cracks are common.

Chhidru (CU) formation (Upper Permian) at its base has shale of pale-yellowish grey to medium dark grey in color, overlying it are beds of calcareous sandstone with sandy limestone. The top most part of the Chhidru formation is a white sandstone bed with oscillation ripple marks. The sandstone is medium to fine grained with subordinate dark shale partings.

Warchha (WA) formation (Early Permian) consists of medium to coarse-grained sandstone, conglomeratic in places and has interbeds of shale. The sandstone is red, purple or shows lighter shades of pink and is cross-bedded.

2. MATERIALS AND RESEARCH METHODOLOGY

The block samples were collected from six different but representative sandstone formations from the Salt Range. The laboratory work included sample preparation conforming to ASTM standards followed by rock testing conforming to the ISRM standards. Sample preparation included diamond core drilling, core cutting and lapping. The AX and NX [10] sized cores were drilled from the block samples. Weathered and parted samples were discarded after visual examinations.

A total of 39 samples (n=39) were used to determine various rock properties. The physical and mechanical properties of the core samples were determined according to the ISRM suggested methods [11-14]. A two-hundred-ton capacity universal testing machine (UTM) was used for loading samples, ELE portable ultrasonic non-destructive index tester for determining *P*- and *S*-wave velocities and Helium porosimeter were used for determination of effective porosity of rocks.

The rock properties determined included dry density ρ, porosity η, uniaxial compressive strength (UCS), tensile strength T, static Young's modulus E_s, static Poisson's ratio υ_s, longitudinal wave velocity V_p, shear wave velocity V_s, dynamic Young's modulus E_d and dynamic Poisson's ratio υ_d. The results of testing are shown in Table 1.

3. CORRELATIONS BETWEEN POROSITY AND SANDSTONE PROPERTIES

The results obtained by the respective tests were statistically analyzed and the significant correlations between porosity, engineering and mechanical properties were selected for graphical representation. The coefficients of correlations and best-fit curves were calculated by the least squares curves fit method. The correlation equations, the graphs, the correlation coefficient values, and 95% prediction and confidence intervals are also given in the following pages.

The analysis of data revealed two rock groups within the tested rock types:

•Group A— Baghanwala (BA), Warchha (WA), Chhidru (CU) and Kussak Gluconated Sandstones (KU-GL);

•Group B—Dhok Pathan (DP), Chinji (CH) and Kussak (KU).

Table 1. Results of mechanical and index properties of sandstone

Sample ID	η, %	ρ, g/cm^3	V_p, km/s	V_s, km/s	E_d, GPa	υ_d	T, MPa	UCS, MPa	E_s, GPa	υ_s
BA-1	15.50	2.45	1.21	1.14	1.43	0.32	1.06	74.84	—	—
BA-2	15.43	2.52	1.31	1.23	1.76	0.33	2.84	26.32	2.50	0.47
BA-3	15.35	2.47	1.17	1.08	0.80	0.24	3.29	59.93	4.62	0.47
BA-4	15.30	2.46	1.34	1.26	1.65	0.31	2.45	21.71	—	—
BA-5	15.38	2.48	1.27	1.15	0.55	0.18	2.87	54.34	—	—
WA-1	18.80	2.64	2.82	2.29	1.49	0.05	3.68	92.29	33.90	0.42
WA-2	15.10	2.65	3.04	2.40	2.09	0.03	2.84	17.11	10.16	0.37
WA-3	15.50	2.63	2.79	2.38	0.47	0.08	2.56	78.42	—	—
WA-4	15.09	2.68	3.00	2.42	1.80	0.04	1.95	70.19	—	—
WA-5	15.20	2.36	3.37	2.52	2.97	0.01	2.77	76.09	7.74	0.35
KU-GL-1	15.98	2.39	1.77	2.52	7.61	0.15	0.05	45.52	3.70	0.19
KU-GL-2	18.36	2.36	1.71	2.39	7.01	0.15	0	47.27	—	—
KU-GL-3	16.04	2.17	1.76	2.34	6.98	0.17	0.10	52.32	—	—
KU-GL-4	16.09	2.20	1.57	1.46	1.41	0.25	0.15	40.91	7.16	0.42
KU-GL-5	15.99	2.17	1.49	1.36	0.88	0.21	2.04	43.09	—	—
KU-1	17.45	2.48	1.60	1.51	2.64	0.36	1.51	42.53	21.60	0.13
KU-2	14.67	2.55	0.68	0.59	0.20	0.11	0.91	43.02	26.75	0.17
KU-3	14.55	2.42	3.06	2.07	2.24	0.01	1.11	40.59	—	—
KU-4	14.59	2.43	2.86	2.00	2.02	0.01	0.96	38.07	—	—
CH-1	17.80	2.44	2.85	1.94	1.99	0.01	0.58	8.58	7.60	0.12
CH-2	15.70	2.64	2.12	1.52	1.22	0.01	0.12	9.71	7.70	0.22
CH-3	17.65	2.64	2.14	1.55	1.24	0.01	0.18	8.23	—	—
CH-4	17.62	2.65	2.05	1.48	1.13	0.01	0.14	9.11	—	—
DP-1	17.71	2.65	2.10	1.53	1.18	2.22	0.18	9.25	7.90	0.33
DP-2	17.83	1.46	3.28	3.93	14.49	2.15	0.05	6.67	—	—
DP-3	17.81	1.29	3.76	4.41	16.97	2.32	10.84	38.62	—	—
DP-4	17.69	1.46	3.13	3.75	13.11	2.14	8.81	36.40	—	—
CU-1	15.71	2.64	2.12	1.52	1.22	0.01	2.04	43.09	—	—
CU-2	18.57	2.64	2.14	1.55	1.24	0.01	1.48	42.19	7.74	0.35
CU-3	18.45	2.67	2.22	1.44	1.19	0.01	1.51	42.53	—	—
CU-4	18.48	2.65	2.05	1.48	1.13	0.01	0.91	43.02	—	—
CU-5	18.54	2.65	2.31	1.52	1.21	0.01	1.11	40.59	7.16	0.42

The porosity of groups A and B was correlated with different mechanical and engineering properties using regression analysis. The presence of the correlation between two variables was measured by the correlation coefficient r, and its value ranges from -1 to $+1$ for perfect negative and positive correlations respectively. The zero value of r shows no correlation at all between the tested variables. The relationship between porosity η and Poisson's ratio υ_s for the rocks of group A is negative, as shown in Fig. 2a. This relates to the work of [15, 16]. Figure 2b indicates that the Poisson's ratio increases with increase in pores for group B [17]. No correlations were found between porosity and other properties and moduli for group A. Group B rocks show negative relationship between porosity and static Young's modulus E_s (Fig. 2c). Similar relationship was found in [15].

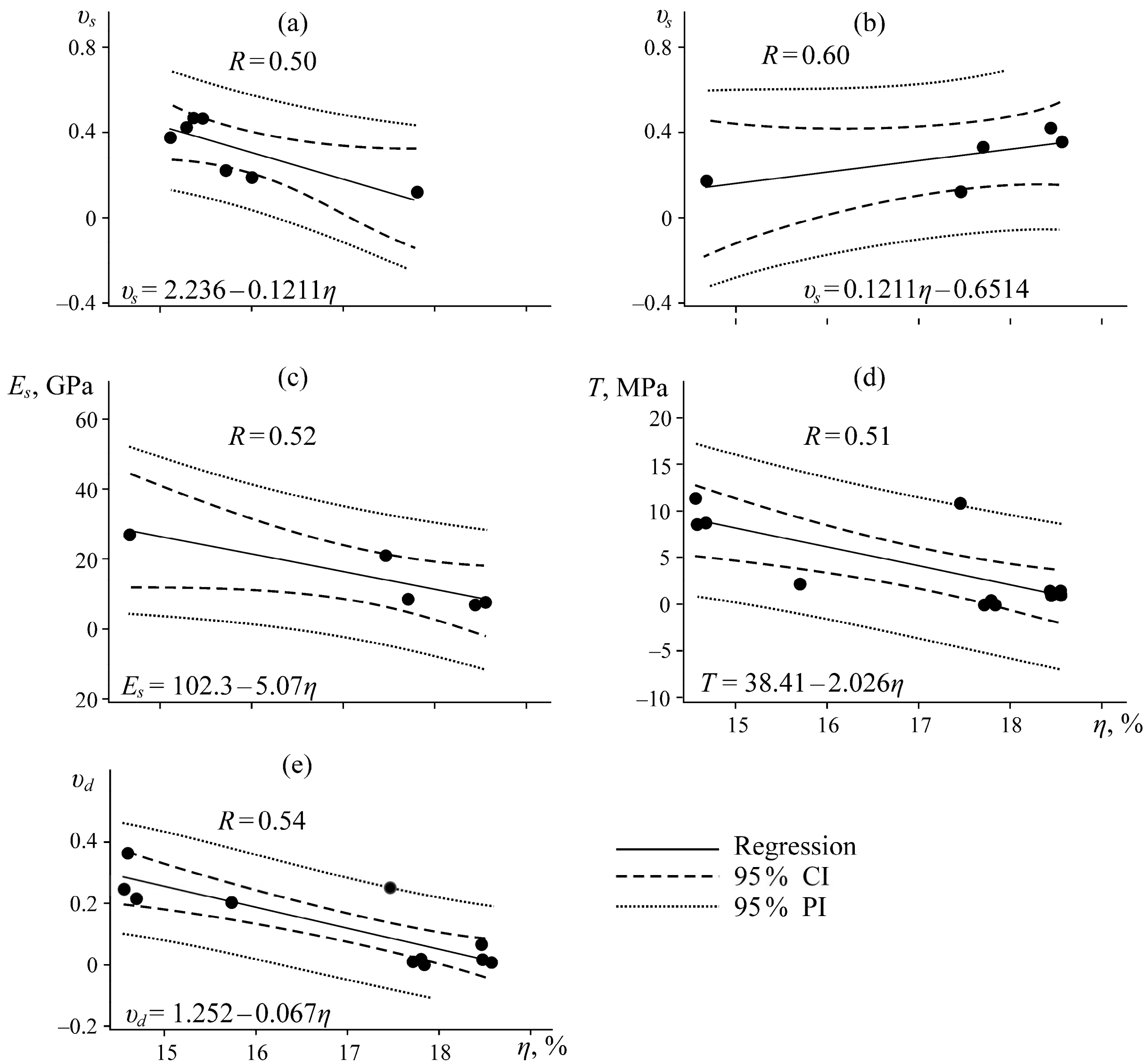

Fig. 2. Correlations between different properties of sandstone and porosity: static Poisson's ratios/porosity—group A (a); group B (b); static Young's modulus/porosity—group B (c); tensile strength/porosity—group B (d); dynamic Poisson's ratio/porosity—group B (e).

Porosity and tensile strength for group B rocks show negative correlation as shown in Fig. 2d. There is a negative relationship between dynamic Poisson's ratio and porosity for group B sandstones as indicated in Fig. 2e. Similar relationships were found in [15]. No relationship was found between porosity and dynamic properties for sandstones of group A.

4. CORRELATIONS BETWEEN STATIC AND DYNAMIC PROPERTIES OF SANDSTONE

Relationship subsisting between static and dynamic properties was found to be linear with different trends. Static Poisson's ratio increases with the increase in the tensile strength, for the sandstones of group A, but the same correlation is contradictory for sandstones of group B (Figs. 3a and 3b). The relationship between UCS and static Young's modulus for group A was found to be linear and positive, but for group B sandstones the same relation is negative, as seen in Figs. 3c and 3d. Same positive correlation was found in [18].

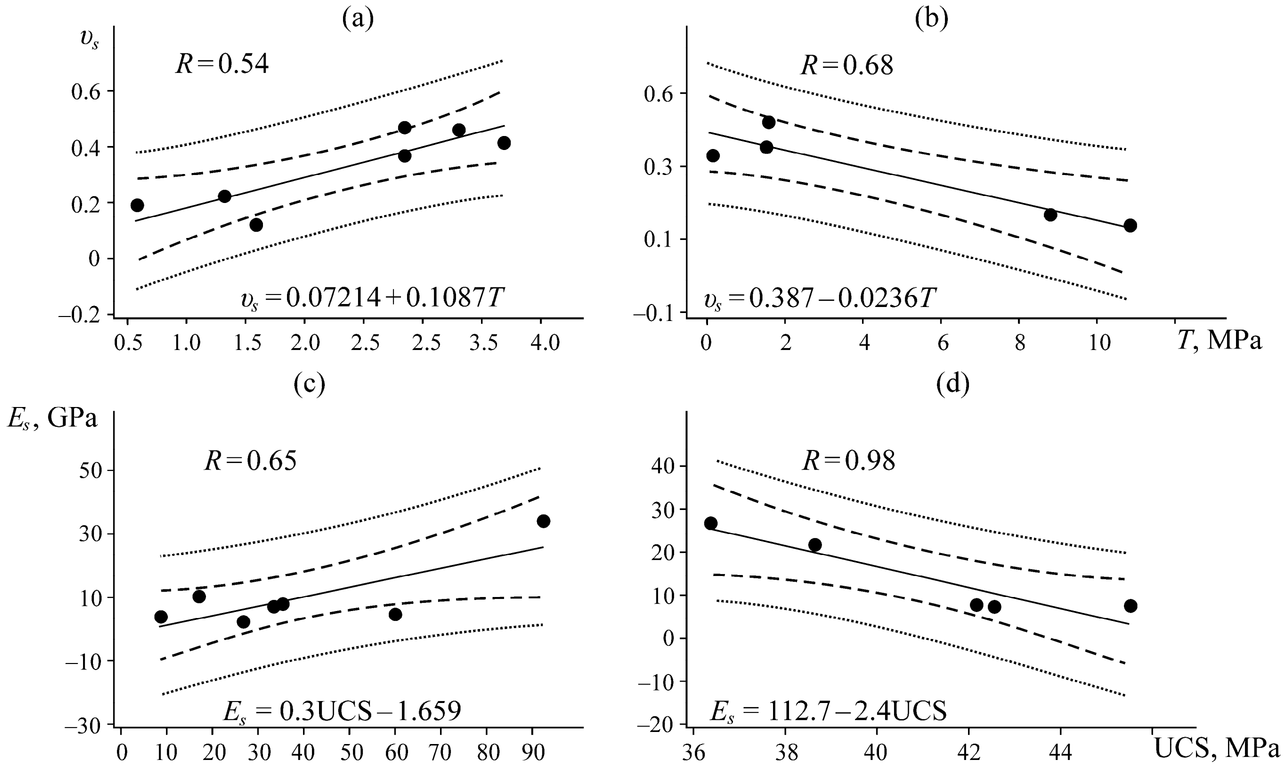

Fig. 3. Correlations between static and dynamic properties of sandstone: (a) static Poisson's ratio/tensile strength (group A); (b) static Poisson's ratio/tensile strength (group B); (c) static Young's modulus/UCS (group A); (d) static Young's modulus/UCS (group B).

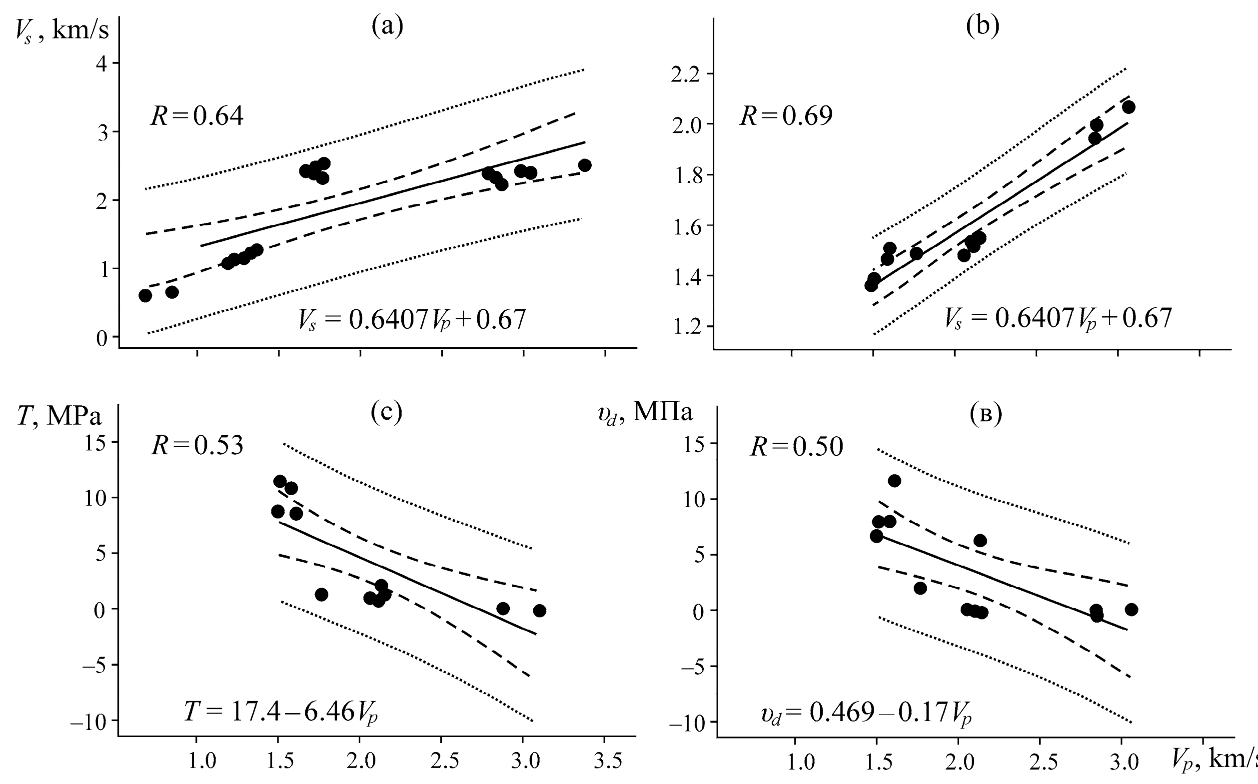

Fig. 4. Correlations between static and dynamic properties of sandstone: (a) *S*-wave velocity/*P*-wave velocity (group A); (b) *S*-wave velocity/*P*-wave velocity (group B); (c) tensile strength/*P*-wave velocity (group B); (d) dynamic Poisson's ratio/*P*-wave velocity (group B).

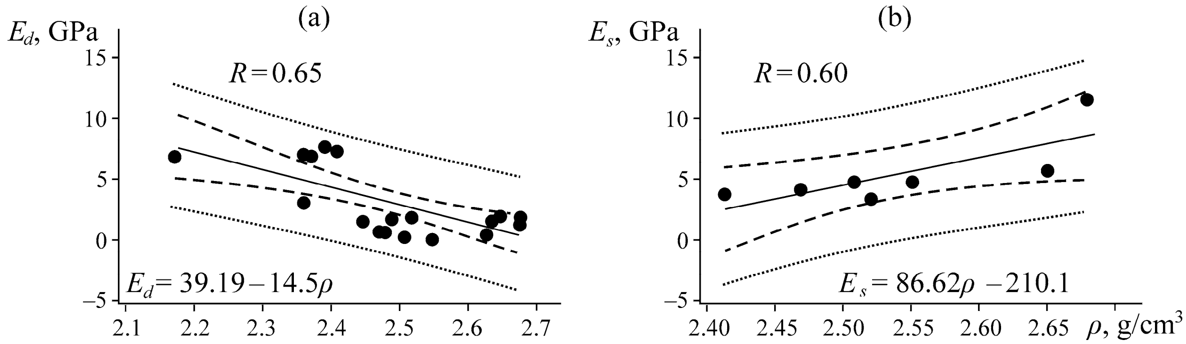

Fig. 5. Correlations between static and dynamic properties of sandstone (group A): (a) dynamic Young's modulus/density; (b) static Young's modulus/density.

The correlation between longitudinal wave velocity and shear wave velocity was found to be linear and positive for the two groups (Figs. 4a and 4b). The similar positive correlation was obtained in [18] and [2].

For sandstones of group B, longitudinal wave velocity was found to have a negative correlation with tensile strength and dynamic Poisson's ratio (Figs. 4c and 4d). A positive correlation between tensile strength and longitudinal wave velocity was reported in [2].

Density has negative correlation with dynamic Young's modulus and a positive correlation with static Young's modulus, for the sandstones of group A (Fig. 5). The relationships for static Young's modulus found in [18] and [3] were also positive.

The relations between dynamic Young's modulus and tensile strength, and dynamic Young's modulus and compressive strength for sandstones of group A were found to be negative but the relation between tensile and compressive strength was found to be a positive for the sandstones of group A, as shown in Fig. 6.

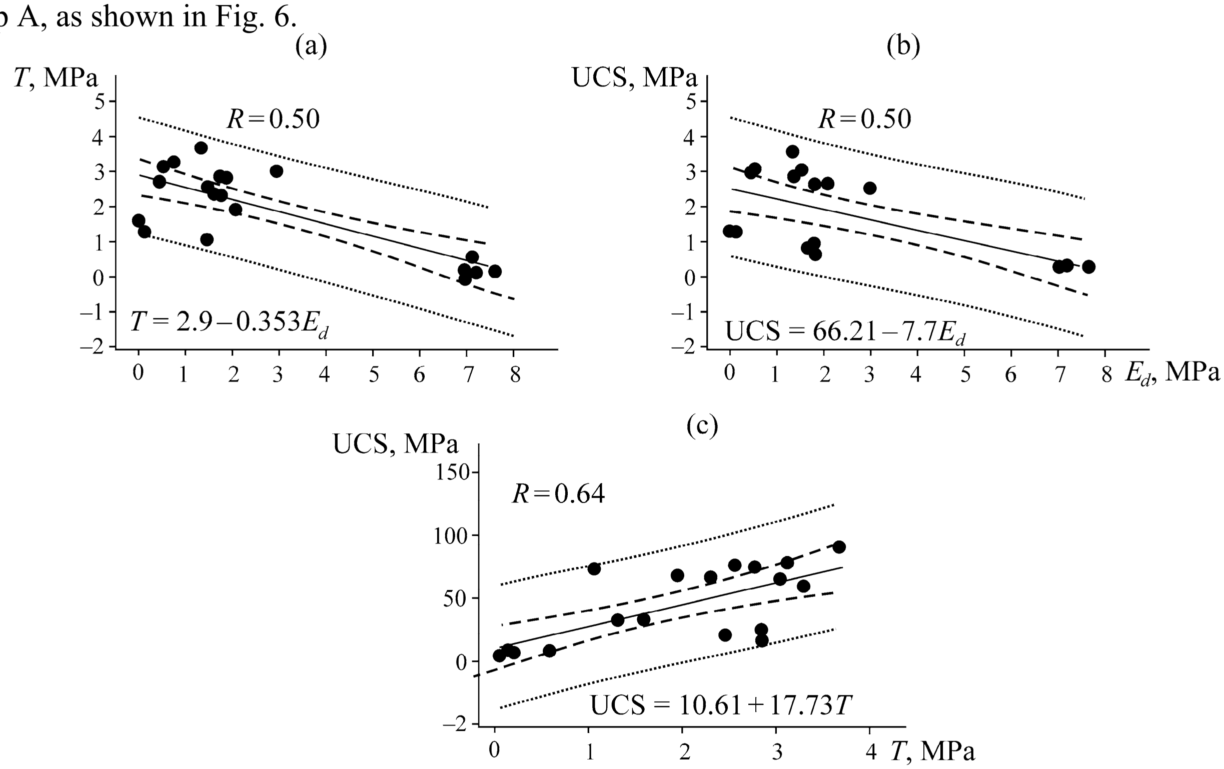

Fig. 6. Correlations between static and dynamic properties of sandstone (group A): (a) tensile strength/dynamic Young's modulus; (b) UCS/dynamic Young's modulus; (c) UCS/tensile strength.

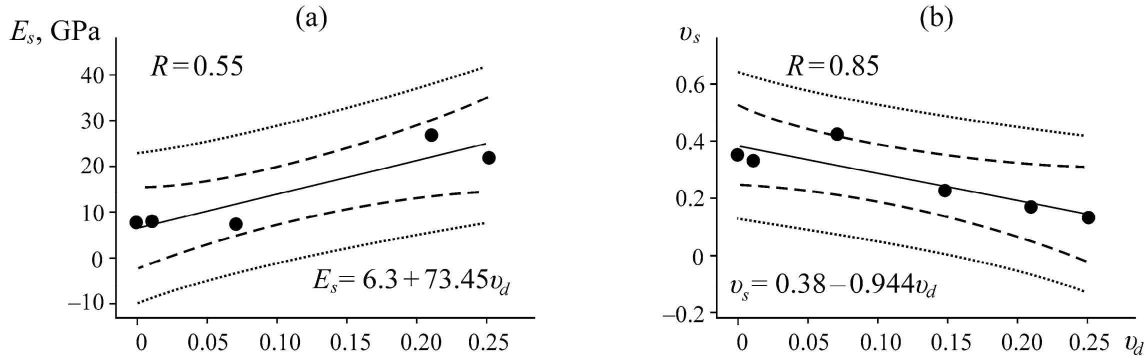

Fig. 7. Correlations between static and dynamic properties of sandstone (group B): (a) static Young's modulus/dynamic Poisson's ratio; (b) static Poisson's ratio/dynamic Poisson's ratio.

For the sandstones of group B, the relationship between dynamic Poisson's ratio and static Young's modulus is positive, and between dynamic Poisson's ratio and static Poisson's ratio was found to be negative (Fig. 7). Positive correlation was found between static Poisson's ratio and dynamic Poisson's ratio [2].

The relationship between static Poisson's ratio for the same group B and static Young's modulus was found to be negative as shown in Fig. 8a and relation between static Poisson's ratio and UCS is positive as shown in Fig. 8b. The positive relation between static Poisson's ratio and sandstone density is shown in Fig. 8c. The same negative correlation between compressive strength and Poisson's ratio was revealed; no correlation between Poisson's ratio and rock density and between Poisson's ratio and UCS was found in [5].

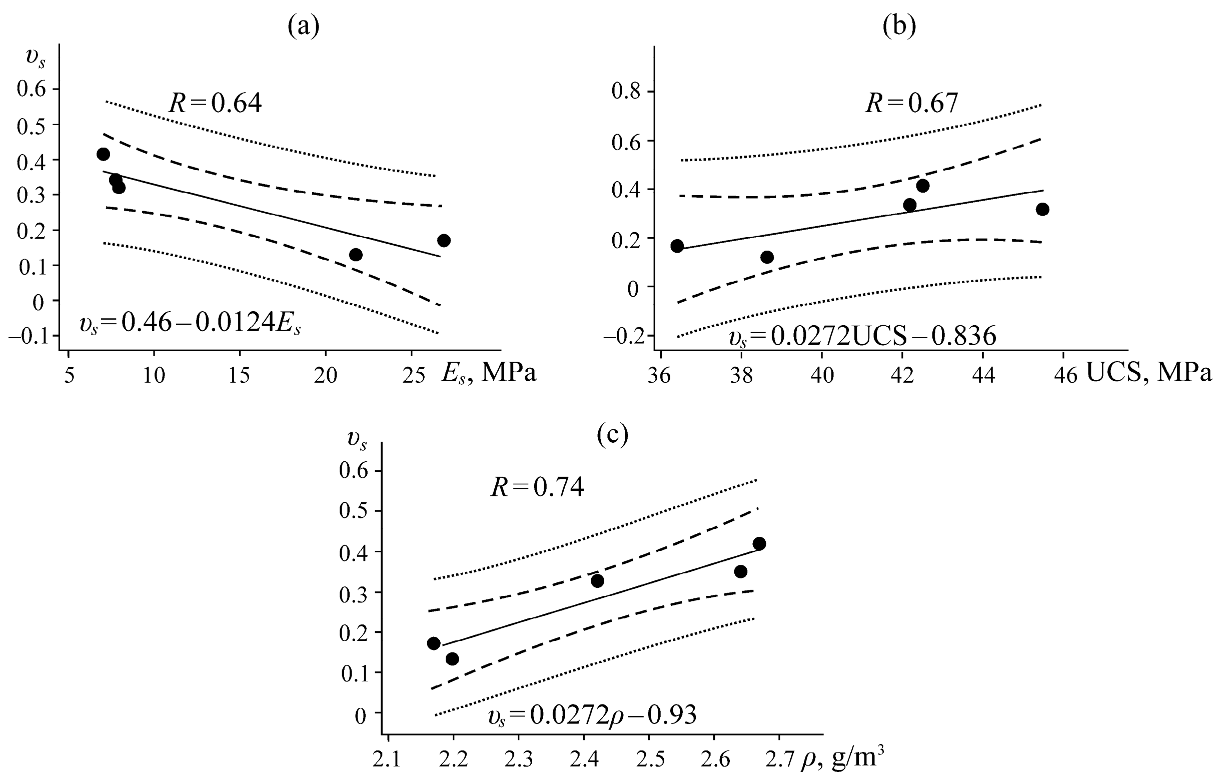

Fig. 8. Correlations between static and dynamic properties of sandstone (group B): (a) static Poisson's ratio/static Young's modulus; (b) static Poisson's ratio/UCS; (c) static Poisson's ratio/density.

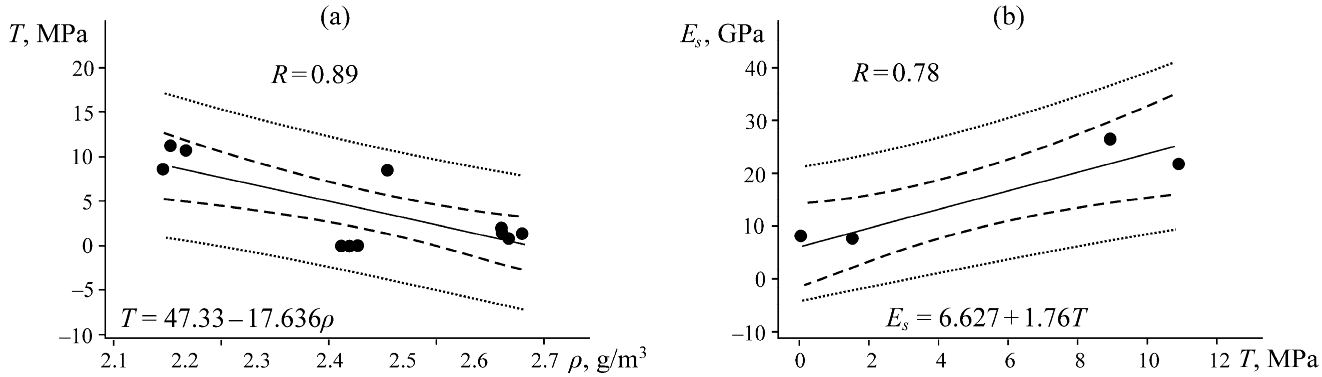

Fig. 9. Correlations between static and dynamic properties of sandstone (group B): (a) tensile strength/density; (b) static Young's modulus/tensile strength.

The relationship between tensile strength and density was negative, whereas relation between Young's modulus and tensile strength was found to be linear and positive for sandstones of group B (Fig. 9).

CONCLUSIONS

The results obtained during the tests were statistically analyzed by the regression method to identify the relationships between the properties. Sandstones from group A have a good correlation: between the static Young's modulus and compressive strength (0.65); between the dynamic Young's modulus and density (0.65); between the shear and longitudinal wave velocities (0.64) and between the values of compressive and tensile strength (0.64). Sandstones from group B have a good correlation in the following values: between static Young's modulus and compressive strength (0.98); between static and dynamic Poisson's ratio (0.85); between the static Young's modulus and compressive strength (0.78); between the velocities of shear and longitudinal waves (0.69); between the static Poisson's ratio and tensile strength (0.68) and UCS (0.67).

The results of this study showed that mechanical and index properties, the determination of which is time consuming and expensive, can be indirectly predicted through porosity, *P*- and *S*-wave velocity and density using the relationships established for a specific rock type. The reliability of this method can be confirmed by expanding this work to a larger number of rock samples from different locations.

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