ISSN 2712-8008
Volume / Том 21 №2 2021
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.276+622.323
Article / Статья

Analysis of the Dependence between Acoustic and Physico-Mechanical Properties of Terrigenic Rocks

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Анализ зависимости между акустическими и физико-механическими свойствами горных пород терригенных отложений

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Received / Получена: 11.09.2020. Accepted / Принята: 01.02.2021. Published / Опубликована: 01.04.2021

Keywords:
Young's modulus, longitudinal wave, transverse wave, ultimate strength in volumetric compression, effective stress, acoustic properties.

During the entire development of the oil and gas field, it is necessary to carry out a complex of various studies aimed at identifying the parameters of the productive layer. One of such studies is the analysis of core material, as a result of which the following parameters of the rock are determined: porosity, permeability, Young's modulus and others. The listed characteristics must be taken into account when building a geological and hydrodynamic model of a field. In addition to these parameters, the strength properties of the rock should be determined, since they are necessary in the design of the wellbore. Such characteristics can be obtained by conducting research in specialized laboratories. This is not always possible due to various reasons. A number of studies confirm the fact of the relationship between the acoustic properties of a rock (the velocity of the longitudinal and transverse waves) and the strength characteristics. The acoustic properties of the rock must be taken into account when interpreting the acoustic logs of the wells, which allows to reveal the distribution of rocks along the wellbore. Based on the velocities of ultrasonic waves propagation, it is possible to calculate the dynamic modulus of elasticity, which allows to assess the tendency of the rock skeleton to compaction as a result of the effective stress action. Therefore, determination of the rock acoustic properties is necessary when planning the field development and its implementation.
The results of laboratory studies aimed at establishing the relationship between the strength and acoustic properties of rocks are presented. During the experiment, the dynamic Young's modulus was also determined and its relationship with the speed of ultrasonic waves propagation was revealed. As a result of laboratory studies, empirical dependences of the ultimate strength in volumetric compression (σ_c), dynamic modulus of elasticity (E) and the velocity of transmission of longitudinal (v_p) and transverse (v_s) waves were obtained. An assessment of the obtained values was given over the entire measurement range.

Ключевые слова:
модуль Юнга, продольная волна, поперечная волна, предел прочности при объемном сжатии, эффективное напряжение, акустические свойства.

Во время всей разработки нефтяного и газового месторождения необходимо проводить комплекс различных исследований, направленных на выявление параметров продуктивного горизонта. Одним из таких исследований является анализ кернового материала, в результате которого определяются следующие параметры горной породы: пористость, проницаемость, модуль Юнга и другие. Перечисленные характеристики необходимо учитывать при построении геологической и гидродинамической модели месторождения. Помимо этих параметров следует определять прочностные свойства горной породы, так как они необходимы при проектировании ствола скважины. Такие характеристики можно получить, проведя исследования в специализированных лабораториях. Это не всегда возможно вследствие различных причин. Ряд исследований подтверждает факт зависимости между акустическими свойствами горной породы (скорость прохождения продольной и поперечной волны) и прочностными характеристиками. Акустические свойства горной породы необходимо принимать во внимание при интерпретации акустического каротажа скважин, который позволяет выявить распределение пород вдоль ствола скважины. Исходя из скоростей распространения ультразвуковых волн, можно вычислить динамический модуль упругости, который позволит оценить склонность скелета горной породы к уплотнению в результате действия эффективного напряжения. Поэтому определение акустических свойств горной породы необходимо при планировании разработки месторождения и ее осуществлении.
Представлены результаты лабораторных исследований, направленных на установление зависимостей между прочностными и акустическими свойствами горной породы. В ходе эксперимента был также определен динамический модуль Юнга и выявлена его связь со скоростью распространения ультразвуковых волн. В результате лабораторных исследований получены эмпирические зависимости предела прочности при объемном сжатии (σ_c), динамическом модуле упругости (E) и скорости прохождения продольных (v_p) и поперечных волн (v_s). Дана оценка полученных значений на всем диапазоне измерений.

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Please cite this article in English as:
Petrakov D.G., Penkov G.M., Solomoychenko D.A. Analysis of the Dependence between Acoustic and Physico-Mechanical Properties of Terrigenic Rocks. *Perm Journal of Petroleum and Mining Engineering*, 2021, vol.21, no.2, pp.71-75. DOI: 10.15593/2712-8008/2021.2.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Петраков Д.Г., Пеньков Г.М., Соломойченко Д.А. Анализ зависимости между акустическими и физико-механическими свойствами горных пород терригенных отложений // Недропользование. – 2021. – Т.21, №2. – С.71–75. DOI: 10.15593/2712-8008/2021.2.4

Introduction

The analysis of core material is a part of the mandatory procedure in the design of the hydrocarbon field development. As a result of core studies, various parameters are obtained which are necessary for building, for example, geological and hydrodynamic models. Such indicators can be:

1) filtration and capacity properties;

2) physical and mechanical properties, etc.

The listed properties play one of the leading roles when choosing a development system or planning activities aimed at enhancing reservoir oil recovery. Various authors [1–37] studied physical and mechanical properties of rock in carbonate and terrigenous deposits, including their strength characteristics.

The acoustic properties (propagation speed of longitudinal and transverse wave) of rock, same as those mentioned above, can be determined under laboratory conditions, since these indicators are necessary for the processing of formation logs and seismic data. Depending on these properties, the type of rocks that make up a productive horizon is determined. Also, based on these parameters, it is possible to calculate the dynamic elasticity (Young's modulus, Poisson's ratio) of rock. Knowing the dynamic elasticity parameters, it is possible to estimate how much the rock matrix is liable to compaction due to effective stress. A large number of works [38–42] are devoted to the determination of dynamic indicators of rock elasticity, as well as to the identification of relationship with the static data. Since the propagation speed of longitudinal and transverse waves depends on the type of rock and mode of occurrence, there is a need to determine these values for each hydrocarbon field separately. The determination of acoustic properties allows not only to identify dynamic elasticity indicators, but also to clarify some of the strength properties of rock. The laboratory studies were carried out in order to establish the relationship between the ultimate strength under volumetric compression, dynamic Young's modulus and acoustic properties of rock.

Experiment Procedure

The experiment procedure can be divided into the following stages:

1. Preparation of samples for tests. The process of sample preparation includes: processing of end surfaces, measurment of the length, diameter and weight of the sample, sealing of the sample in a waterproof container, installation of sensors for measurment of longitudinal and transverse deformation, as well as for determination of acoustic properties of rock.

2. Performance of experiment:

a) the sample was put into the triaxial cell;

b) the cell was filled with working fluid. The temperature was set taking into account the formation conditions data (Table 1);

c) the overburden pressure and formation (pore) pressure was set step-by-step. The holding time at each stage was 5 minutes. At each stage, the side pressure increased by 3 MPa, and the pore pressure by 2 MPa;

d) the required values of formation and rock pressures (see Table 1) were established, the axial load was gradually increased until the sample destruction. Loading rate – 1 MPa/s.

The measurement of the propagation speed of ultrasonic waves was carried out before the start of the test (the sample was not loaded), after reaching the formation conditions. The measurement of the longitudinal and transverse deformation value was carried out throughout the entire loading stage.

3. Processing of results.

3.1. Determination of static indicators. The ultimate strength under volumetric compression σ at the given rock and pore pressure for each sample was calculated by the formulas [43, 44]:

$$\sigma = \sigma_д + \sigma_г - \sigma_п, \qquad (1)$$

$$\sigma_д = \frac{P}{F}, \qquad (2)$$

where P – differential load applied to the ends of the sample, N; F – cross-sectional area of the sample, m^2; $\sigma_д$ – differential stresses, Pa; $\sigma_г$ – rock pressure, Pa; $\sigma_п$ – pore pressure, Pa.

Young's modulus and Poisson's ratio. Young's modulus (E) was determined on the linear section of the $\sigma_д$ – $\varepsilon_{//}$ diagram as the ratio of the increment in differential stresses $\Delta\sigma_д$ (to the increment of relative longitudinal deformations $\Delta\varepsilon_{//}$ [45, 46]:

$$E = \frac{\Delta\sigma_д}{\Delta\varepsilon_{//}} = \frac{\sigma_д^2 - \sigma_д^1}{\Delta\varepsilon_{//}^2 - \Delta\varepsilon_{//}^1} = \frac{op}{of}. \qquad (3)$$

3.2. Determination of dynamic parameters. The initial data for determination of the dynamic parameters were the differential load measured during the test, the time of longitudinal and transverse waves travel through the sample, and the sample density.

In accordance with the terms of reference and the test program, the dynamic indicators were determined by the following formulas [47, 48]:

– Young's modulus: $$E_d = \frac{\rho V_s^2\left(3V_p^2 - 4V_s^2\right)}{V_p^2 - V_s^2}; \qquad (4)$$

where V_p, V_s, ρ – longitudinal wave speed, transverse wave speed and sample density, respectively;

– the speed of ultrasonic waves is determined by the formula [47, 49]:

$$V_i = \frac{L}{t_i}, \qquad (5)$$

where L– distance between the centers of transducers facility (sounding base), m; t_i– time of longitudinal (transverse) wave travel through the sample, s.

Research Results

Core samples of terrigenous sediments were taken from the X field to carry out the tests. 17 rock samples with the set formation conditions given in Table 1 were tested as part of the research.

Table 2 provides a geological description of these samples. After carrying out the experimental tests, the data were entered in the table (Table 3).

After determination of the dynamic characteristics of the samples, tests were carried out to determine the ultimate strength under volumetric compression. The results of the dependencies obtained following the laboratory studies are shown in Figure *a*, *b*.

In order to evaluate the accuracy of the identified dependencies, a check was carried out by determination of the values using these formulas and comparing with the values btained in the course of laboratory studies. The error in the calculated values is estimated by the distance from the diagonal line 1:1. The results of the check are presented in the figure: *c*, *d*.

Table 1

Parameters of formation conditions set for rock samples testing

Item No.	Sample code	Formation	Test temperature, °C	Pore pressure, MPa	Side pressure, MPa
1	2-BT-40	Lower Oligocene	140	21.3	83.1
2	3-BT-40	Lower Oligocene	140	21.3	83.1
3	6-BT-9	Upper Oligocene	136	35.1	85.0
4	7-BT-9	Upper Oligocene	136	35.1	84.9
5	8-BT-9	Upper Oligocene	136	35.1	82.9
6	11-BT-3	Lower Miocene	112	16.5	62.4
7	12-BT-116	Lower Miocene	108	22.6	66.4
8	13-BT-116	Lower Miocene	108	22.6	66.4
9	14-BT-4	Lower Miocene	108	22.6	62.6
10	15-BT-9	Upper Oligocene	136	35.1	82.6
11	18-DR-17	Lower Miocene	72	11.3	41.1
12	20-DR-29	Lower Miocene	78	12.0	33.6
13	21-DR-15	Lower Miocene	72	11.3	47.9
14	22-DR-15	Lower Miocene	72	11.3	47.9
15	24-DR-17	Lower Miocene	72	11.3	35.2
16	25-BT-9	Upper Oligocene	136	35.1	82.6
17	26-BT-9	Upper Oligocene	136	35.1	82.6

Table 2

Geological description of samples

Item No.	Sample code	Formation	Interval. Sampling depth	Description
1	2-BT-40	Lower Oligocene	Int. 3813.0-3822.0 m; depth 3820 m	Brownish and gray, polymictic, arkosic, fine-to-medium grained sandstone with admixed large grains, evenly parallel medium-bedded
2	3-BT-40	Lower Oligocene	Int. 3813.0-3822.0 m; depth 3813.4 m	Brownish and gray, polymictic, arkosic, coarse-to-medium grained, massive sandstone with low-carbonaceous sections
3	6-BT-9	Upper Oligocene	Int. 3798.0-3836.8 m; depth 3826.3 m	Gray, polymictic, arkose, fine-grained, sorted, aleurolite sandstone
4	7-BT-9	Upper Oligocene	Int. 3798.0-3836.8 m; depth 3821.2 m	Gray and dark gray, polymictic, highly argillaceous siltstone (interlayers up to the transition to argillite), with parallel plane, cross and swaley bedding
5	8-BT-9	Upper Oligocene	Int. 3720.6-3833.5 m; depth 3732.2 m	Dark gray, coarse-grained, fine-areneceous, argillaceous, unevenly carbonaceous, highly micaceous, finely parallel layered, dense siltstone
6	11-BT-3	Lower Miocene	Int. 2824.0-2841.8 m; depth 2827.0 m	Brown sandstone as a result of oil saturation, polymictic, arkosic, medium-to-coarse grained, with admixed gravel, medium-graded, massive
7	12-BT-116	Lower Miocene	Int. 3078.0-3092.5 m; depth 3079.5 m	Light gray, quartz-feldspathic, fine-grained, sorted, massive sandstone
8	13-BT-116	Lower Miocene	Int. 3078.0-3092.5 m; depth 3078.6 m	Light gray, quartz-feldspathic, fine-grained, sorted, massive sandstone
9	14-BT-4	Upper Oligocene	Int. 2841.0-2844.0 m; depth 2841.0 m	Brown sandstone as a result of oil saturation, polymictic, arkosic, medium-to-coarse grained, with admixed gravel, medium-graded, massive
10	15-BT-9	Upper Oligocene	Int. 3720.0-3733.5 m; depth 3721.5 m	Interlensing of gray sandstone and dark gray siltstone. Polymictic, fine-grained sandstone with argillaceous-carbonaceous cement, highly micaceous (biotite, muscovite), dense, of medium strength. Argillaceous, carbonaceous, highly micaceous, thin-layered siltstone
11	18-DR-17	Lower Miocene	Int. 2241.0-2249.0 m; depth 2244.5 m	Variegated, cherry-brown sandstone with greenish-gray lenticular segments, quartz-arkose, fine-to-medium grained, with uneven admixture of coarse sand and gravel grains
12	20-DR-29	Lower Miocene	Int. 2293.0-2302.0 m; depth 2296.6 m	Brown, quartz-arkose, uneven-grained sandstone with admixed gravel material (grain size 1-8 mm), turning into sand-gravel rock in some sections
13	21-DR-15	Lower Miocene	Int. 2170.0-2179.0 m; depth 2176.6 m	Brownish and gray sandstone as a result of oil saturation, arkosic, with nonuniform structure, gradually changing within the sample from coarse-to-medium grained to fine-to-medium grained
14	22-DR-15	Lower Miocene	Int. 2170.0-2179.0 m; depth 2175.5 m	Greenish and gray, moderately sorted, sandy-argillaceous siltstone with an unclear layering pattern, rich in mica (biotite, muscovite); dense
15	24-DR-14	Lower Miocene	Int. 1921.0-1929.0 m; depth 1921.5 m	Variegated, cherry-brown sandstone with greenish and gray sections, quartz-arkose, fine-to-medium grained, with significant admixture of coarse grains and gravel
16	25-BT-9	Upper Oligocene	Int. 3720.60-3733.50 m; depth 3723.5 m	Interlensing of gray sandstone and dark gray siltstone. Fine-grained polymictic sandstone with carbonaceous-argillaceous cement. Argillaceous, carbonaceous, highly micaceous, thin-layered siltstone
17	26-BT-9	Upper Oligocene	Int. 3720.60-3733.50 m; depth 3724.5 m	Gray, polymictic, coarse-grained, fine-sandy, well-sorted siltstone with carbonaceous-argillaceous cement, dense

Table 3

Results of determination of static parameters of rock samples
and dynamic parameters after creation of formation conditions

Item No.	Sample code	Formation	Static data		Dynamic data			
			Ultimate strength, MPa	Young's modulus, 10^4MPa	Density, kg/m^3	Longitudinal wave speed, m/s	Transversal wave speed, m/s	Young's modulus, 10^4MPa
1	2-BT-40	Lower Oligocene	124.1	1.54	2397	3359	2045	2.42
2	3-BT-40	Lower Oligocene	131.0	1.75	2346	3521	2142	2.60
3	6-BT-9	Upper Oligocene	115.8	1.64	2459	3587	2151	2.77
4	7-BT-9	Upper Oligocene	149.4	3.26	2497	4065	1921	2.50
5	8-BT-9	Upper Oligocene	209.7	1.84	2500	4679	2331	3.63
6	11-BT-3	Lower Miocene	107.6	1.50	2054	3450	1987	2.03
7	12-BT-116	Lower Miocene	111.4	1.95	2530	3635	1561	1.71
8	13-BT-116	Lower Miocene	121.3	2.04	2063	3800	1830	1.86
9	14-BT-4	Lower Miocene	161.5	2.12	2215	3359	1854	1.95
10	15-BT-9	Upper Oligocene	165.5	3.68	2440	3368	1964	2.34
11	18-DR-17	Lower Miocene	86.8	1.74	2190	2870	1470	1.25
12	20-DR-29	Lower Miocene	44.0	1.29	2091	2048	1165	0.72
13	21-DR-15	Lower Miocene	93.4	1.62	2207	3250	1530	1.40
14	22-DR-15	Lower Miocene	89.4	1.58	2340	3138	1450	1.34
15	24-DR-17	Lower Miocene	89.4	1.50	2341	2472	1434	1.20
16	25-BT-9	Upper Oligocene	152.0	3.45	2385	3678	1873	2.22
17	26-BT-9	Upper Oligocene	109.7	1.48	2315	3397	2074	2.40

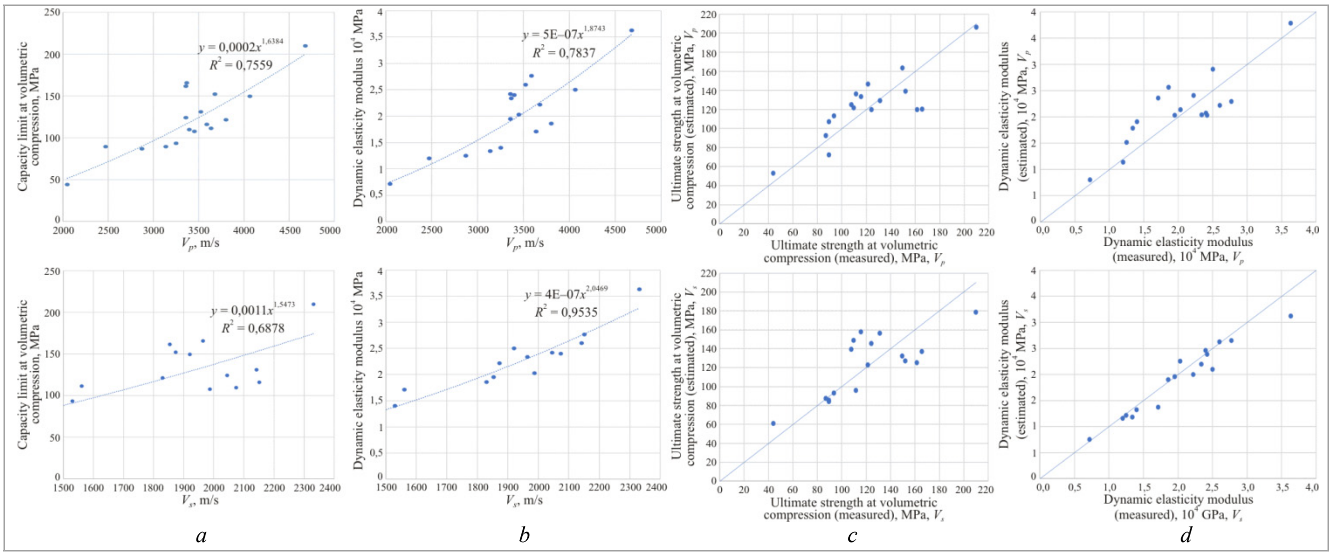

Fig. Dependence on the propagation speed of longitudinal V_P and transverse V_S waves: *a* – ultimate strength under volumetric compression; *b* – dynamic elasticity modules; *c* – measured and calculated values of σ_c; *d* – measured and calculated value of *E*

Conclusion

In the course of laboratory research, the following physical and mechanical parameters of rock were determined: ultimate strength under volumetric compression, static and dynamic elasticity modules, propagation speed of ultrasonic waves.

A relationship between the dynamic Young's modulus, the ultimate strength under volumetric compression, and the acoustic properties of rock was established. The obtained dependencies will make it possible to numerically evaluate strength and elasticity indicators when processing well logs or, for example, as a result of seismic data processing.

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