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Mechanical properties of sandstone using non-destructive method

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The understanding of physical and mechanical properties of rock is considered as critical in drilling, geo-engineering, and construction applications. As an example, the awareness of these rock parameters contributes to avoid or minimizing instability around the wellbore while drilling. The laboratory experiment of understanding of these parameters can be done in two-different ways: static, where the sample subjects to destruction after the test and dynamic, known as non-destruction method. The non-destructive method using ultrasonic waves under a series of different stress conditions, starting from 7 to 56 MPa with incrementation of 7MPa, has been used in this paper in order to characterize the mechanical properties of dry Zbylutów sandstone at 20 and 80°C. The velocity of primary (P) and secondary (S) waves within these ranges has been recorded in order to understand the behavior of the mechanical properties. The results showed that the Young's modulus, bulk modulus, shear modulus, and Lame's constant of Zbylutów sandstone have a positive correlation with good coefficient correlation with the increased stress, while the Poisson's ratio showed a negative correlation. Besides, the effect of temperature on the rock parameters is approved by the decrease of primary wave velocity in this two-different temperature range. Such results are necessary when preparing the appropriate mud weight for drilling process, which is related to wellbore instability.

***Key words*:** mechanical properties; non-destructive method; sandstone; stresses; temperature effect

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Introduction. All stages of drilling process such as drilling designing, well completion, and production (не является частью процесса бурения) require a better understanding of the mechanical properties of surrounding rock such as elastic modulus and rock compressive strength, in which contributes mainly to the instability of the wellbore as well as inducing fractures [2, 8]. For instance, it is well known that collapsing is due to misunderstanding of these parameters [3, 6]. Measuring of such parameters can be conducted in two different ways: static and dynamic measurement, in which the static measurement can be done in lab where the sample is loaded by stresses until failure occurs, or by in-situ tests, while the dynamic measurement, non-destruction method, is carried out in lab without destroying the samples, in which the sonic waves are used to perform such experiment [17]. Compressional (V_p) and shear waves (V_s) velocities are measured from logs or in lab and used to calculate the dynamic mechanical properties of rock [10, 11].

Numerous studies confirm the difference between the results from these two methods. The static measurement is the more realistic, direct, and very close to the actual engineering needs as it represents the occurred deformation under large amount of stresses, which refers as the underground high stresses condition, while the dynamic measurement is more continuous and easier [5, 9]. Therefore, dynamic moduli are quite different than static moduli but both techniques are required in order to well understand the mechanical parameters of the rock formation. As usual, the static moduli are smaller than the corresponding dynamic. Such difference is depending also on the rocks state. It is larger for weak rocks and decreases with increased confinement. However, Hao Xu et al. has established a relationship between dynamic and static measurement, which can be used in case the static measurement cannot be conducted in the laboratory or missing equipment [16].

While drilling, the in-situ stress distribution around the wellbore is being disturbed and changed, which contributes to the instability of the wellbore. So, understanding of the rock behavior under stress and temperature is a key point to addressing such challenge.

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Backgrounds and methods. Mechanical properties of rock are characterized by the elastic as well as inelastic properties. The elastic properties consist of Young's modulus, shear modulus, bulk modulus, and Poisson's ratio; while fracture gradient and formation strength represent the inelastic properties. The elastic properties concern with the resistance to volume and shape deformation and it follows the Hooke's law within small deformation. This deformation is depending on the driven acting force from the geological situation, its nature, and the following elastic moduli such as Young's modulus E, (2) and shear modulus μ, (3). The estimation of the dynamic mechanical properties of rock can be done by using the acoustic waves and considering the rock sample as isotropic and linear elastic [1]. Then, the V_p/V_s ratio and density, ρ, are used to calculate the mechanical properties of the rock sample [8]. The following formula express the relationship between the acoustic waves velocity, density and the mechanical properties of rock:

$$v = \frac{\frac{1}{2} - \left(\frac{V_s}{V_p}\right)^2}{1 - \left(\frac{V_s}{V_p}\right)^2}, \quad (1)$$

$$E = \rho \frac{V_p^2 (1+v)(1-2v)}{(1-v)}, \quad (2)$$

$$\mu = \rho V_s^2, \quad (3)$$

$$\lambda = \rho(V_p^2 - 2V_s^2), \quad (4)$$

$$\mathrm{AI} = \rho V_p. \quad (5)$$

where V_p is the velocity of P-wave, m/s; V_s is the velocity of S-wave, m/s; ρ is the bulk density, kg/m^3; v is the Poisson's ratio; E is the Young's modulus, Pa; μ is the shear modulus, Pa; λ is the Lame's constant, Pa; AI is the acoustic impedance, kg·m^{-2}·s^{-1}.

Twelve samples from Zbylutów, located in the southern part of Poland, have been used during the experiment. The moisture trapped in the samples was removed using an electrical oven at 70°C for more than 24 hours. Next the density of each sample was measured. The density of dry sample was calculated from the mass (in g) and bulk volume (in cm^3) of the sample. Both ends of the samples were polished and lapped parallel up to ± 0.20 mm in order to minimize the error and protect the sample from damage due to higher stress. Also, the cylindrical sides are made straight active with accuracy of ± 0.30 mm over the full length of each sample.

The AVS 1000 apparatus was used to conduct the dynamic measurement (Fig.1). It is composed of parametric pulsar, tektronix digitizing oscilloscope, and sonic platens containing P and S-wave transducers as well as receivers. The time-of-flight of P-wave and S-wave is recorded and their velocities are calculated accordingly as the ratio between the sample length and the travel time [12]. The ultrasonic measurement uses high frequency signals, approximately 1000 kHz for compressional and 500 kHz for shear waves. The system was calibrated using aluminum and copper samples with well-known velocities. The arrangement of AVS 1000 is shown by the following diagram.

Results and discussions. The density of Zbylutów sandstone is ranging from 2.34 to 2.48 g/cm^3 with a median value of 2.43 g/cm^3, whereas the porosity of samples is ranging from 2.80 to 4.95 % with a median value of 4.23 %. The results in this paper represented the median of the investigated properties. The median value has been chosen by the fact that it is not affected by the outlier values. The correlation between the mechanical properties and stress was expressed by the central tendency of the measured values within the ranges of the independent values.

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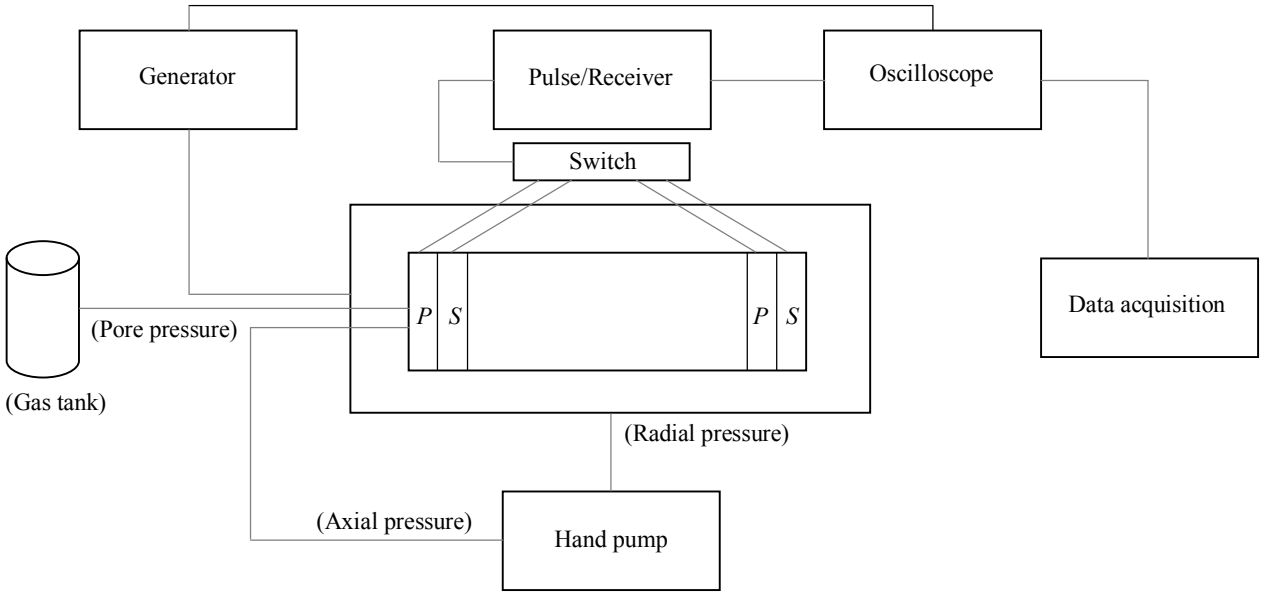


Fig.1. Scheme of AVS 1000 apparatus

The measurement of mechanical properties was conducted at two-different temperature and carried out in-situ level of stresses. The result (Fig.2) showed that the velocity of *P* and *S*-waves were proportionally increasing with stresses, but only *P*-waves velocity inversely proportional to temperature. The temperature caused weaknesses to the sample. On the contrary, the increased stress was closing the crack inside the sample [15]. Also, the acoustic impedance profile also showed the increase of compressional velocity of the rock against stresses (Fig.3, *f*).

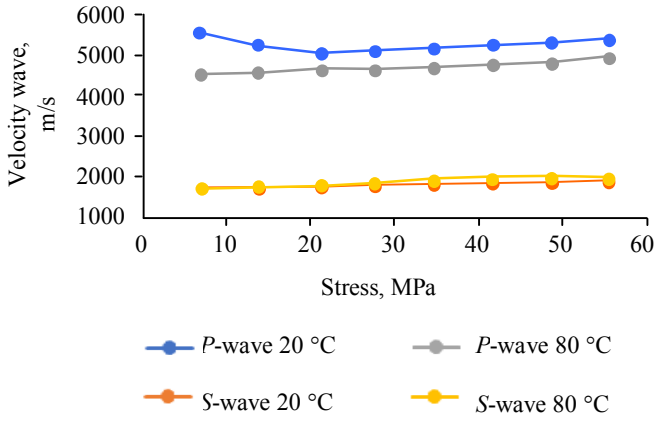


Fig.2. Velocity of P and S waves versus confining stress

As bulk modulus was measuring resistance to compression, then it has been identified that increasing in stress resulted increasing of rock's resistance to compression. As shear modulus represented the ratio of shearing (torsional) stress to shearing strain, then increasing in stress increased the shearing inside the rock. The behavior of Poisson's ratio showed that geometric change of shape under stress was decreasing as long as stress increasing.

Young's modulus, bulk modulus, shear modulus, and Lame modulus of sandstone increase with stresses and decrease with temperatures and the rate of change varies with stress and temperature. The cracks being closed can be used as an explanation of the increase [13, 4], while the pore volume change can be used as an explanation of the decrease. The pore volume is increasing (even small portion) when the temperature raises and the differential expansion of temperature applied to minerals, forming the rock, may generate new cracks especially at the boundary of grains [7, 14].

Conclusions. The dynamic measurement is conducted in this paper in order to understand the impacts of raised stress and temperature to the mechanical properties of the dry Zbylutów sandstone. Based on the results:

1. Young's modulus, bulk modulus, shear modulus, and Lame's constant of Zbylutów sandstone were proportional to increased confining stress and inversely proportional to increased temperature, while the Poisson's ratio is inversely proportional to increased stress and proportional to increased temperature.

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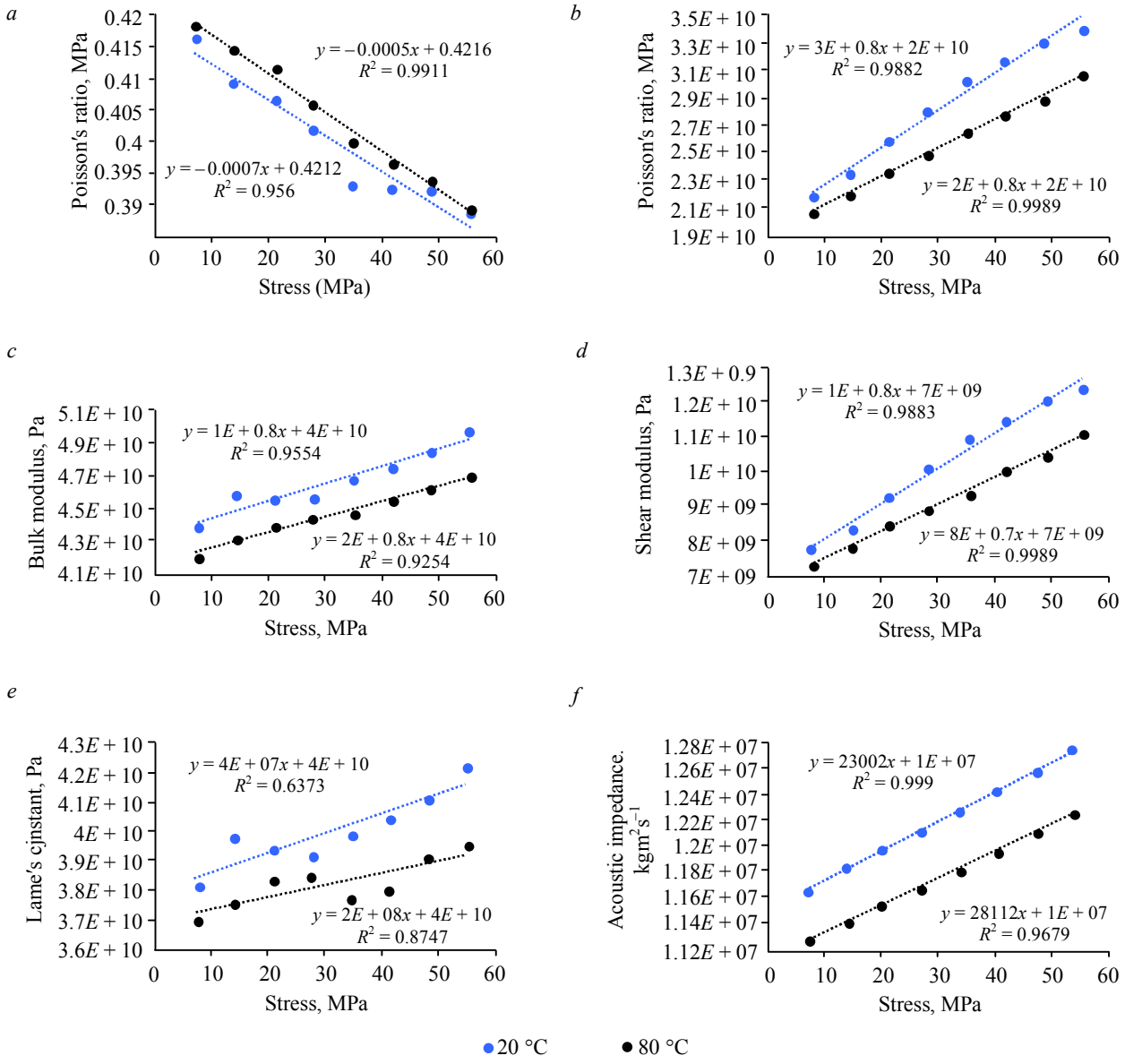


Fig.3. dynamic: *a* – Poisson's ratio; *b* – Young modulus; *c* – bulk modulus; *d* – shear modulus; *e* – Lame's constant; *f* – acoustic impedance versus confining stress at 20 °C and 80 °C

2. The acoustic impedance confirmed that raising of stresses resulted increasing of compressional velocities, while increasing of temperature decreased the compressional waves velocity through the rock samples.

3. The present result is necessary when formulating the mud weight windows program for drilling and allow the drilling operator to understand the behavior of the sandstone formation against stress and temperature.

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