

Investigation of the elastic properties of cement stone as a factor in ensuring well annular sealing integrity

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Abstract

Purpose. To establish the relationships between the elastic-strength and deformation properties of cement stone and its formation conditions, which determine the integrity and sealing capacity of the cement sheath in oil and gas wells.

Methods. The research methodology is based on a comprehensive, structured interpretation of experimental datasets characterizing the formation of cement stone produced from the base PCT I-100 Portland well cement. The relationships between the elastic and mechanical properties of the cement stone were evaluated using correlation analysis. Regression analysis incorporating the full set of available explanatory variables was used to develop mathematical models describing changes in cement stone properties under different formation conditions.

Findings. Young's modulus, strength, and deformation characteristics of cement stone depend substantially on curing age and temperature. A high curing temperature (75°C) accelerates the early development of elastic and strength properties and reduces creep deformation, but it does not yield the highest long-term strength. At 20°C, curing proceeds more slowly; however, at later stages, it results in greater stiffness and a more sustained increase in strength. Creep and residual deformation decrease with age, although their values are considerably higher at lower temperatures, thereby increasing the risk of defects in the wellbore casing system.

Originality. The importance of determining the elastic properties of cement stone, a key factor in the formation of leakage microchannels in wellbore casing systems, has been demonstrated. It was established that cement stone produced from the base PCT I-100 Portland well cement exhibits insufficient elastic properties at early curing stages, which may result in loss of contact with the casing string and surrounding rock under operational loading. Mathematical regression models were developed to assess the potential risk of leakage pathway formation during the early stages of cement stone curing by integrating the relationships between its mechanical properties and formation conditions.

Practical implications. The identified patterns in the deformation characteristics of cement stone can be useful for research institutions and industrial enterprises developing cement slurry formulations for well cementing.

Keywords: well; cementing; portland cement; cement stone; tightness

1. Introduction

The wellbore casing system comprises materials with different mechanical properties that respond differently to external factors. The cement stone filling the annular space of a well is generally considered the weakest element of the system. When it fails to perform its intended functions, the well can no longer fulfill its operational objectives. The integrity and sealing capacity of the cement sheath in the well annulus are critical to safe well operation [1], [2] and must effectively prevent fluid migration through the annular space [3]. One of the key approaches to ensuring the reliability of wellbore casing, particularly in deviated wells, is to maximize the casing string's concentricity within the wellbore, thereby promoting the formation of a uniform cement sheath [4]–[6]. Reliable well operation is possible only when the casing system remains stable, which requires forming a continuous cement

sheath with appropriate physical and mechanical properties, with strength and elasticity being particularly important [7].

However, owing to its insufficient elasticity, cement stone is susceptible to brittle failure under pressure and temperature fluctuations, mechanical loading, and chemical corrosion, which may result in the formation of microchannels. These defects compromise the integrity of the cement sheath and may consequently lead to sustained casing pressure [8]. After the cement slurry is pumped into the annulus and the cement stone forms, mechanical loads acting on the wellbore casing system may induce significant residual deformation of the cement stone, resulting in leakage pathways or damage to the cement sheath [9], [10].

Hardened cement stone does not always provide effective isolation of permeable formations, either due to placement problems or to loads that, over time, impair the integrity of

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the casing-cement stone interface [11]. It is known [12] that effective isolation of productive formations and reliable wellbore casing depend not only on the strength of the cement stone but also on its adhesion to the surrounding rock and casing pipes. Loss of cement sheath integrity due to material property incompatibility directly promotes fluid migration along or outside the wellbore casing system, as well as crossflow between formations. Behind-casing fluid migration and interformation crossflow may occur under various geological and technical conditions, even when modern cementing requirements are fully met [13]. Such technical failures result in economic losses and significant safety and environmental risks, including the potential contamination of aquifers.

The cement sheath is subjected to various loads during drilling and during casing integrity testing by pressure testing. According to [14], [15], pressure increases during drilling may exceed 40 MPa in oil wells. In comparison, the pressure applied during casing pressure testing may range from several tens of MPa in normally pressured formations to more than 80 MPa in high-pressure formations. At the early stage of cement stone formation, shrinkage and a decrease in pore pressure may occur, which are also considered among the causes of fluid migration in wells [16]. When cement hydration occurs at constant temperature and atmospheric pressure, the reduction in external volume is referred to as autogenous shrinkage [17]. If the hydration pressure differs from atmospheric pressure, the reduction in the external volume of the cement stone is referred to as macroscopic shrinkage. These findings are consistent with the research results reported in [18].

The effect of hydration conditions on the stress-strain behavior of cement stone after 144 h of hydration, followed by mechanical loading/unloading cycles, was investigated in [19]. The results showed that the stress-strain behavior of cement stone is affected more strongly by hydration pressure than by temperature. This indicates a high risk of macro- and microcrack formation at shallow well depths. During well construction and completion, the cement stone is subjected to various dynamic loads, among which the most destructive are impacts from the bottomhole assembly during drilling out of the cement plug and subsequent drilling of the next casing string, casing pressure testing, shaped-charge perforation for opening the secondary formation, and hydraulic fracturing. Increasingly intensive methods used to maintain the required production rate, together with increasingly complex drilling conditions, result in a growing number of operations that exert substantial dynamic effects on the wellbore casing system during the well construction cycle, as emphasized in [20].

According to industry standards and the guidelines of major oil and gas field operators, wellbore casing quality requirements primarily concern the properties of cement slurries and the compressive and flexural strength of cement stone. However, these standards do not provide recommendations on the required elastic and strength properties of cement stone under dynamic loading [21]. At present, particular attention is being paid to maintaining the integrity and sealing capacity of the wellbore casing system during secondary opening of productive formations [22].

Since, according to the forecasts reported in [23], explosive-based technologies are expected to remain the principal method for opening secondary formations among currently

known techniques over the coming decades, particular attention should be given to selecting cement slurry compositions resistant to the dynamic effects generated during such operations. The studies reported by these authors confirmed the formation of leakage pathways between the casing string and cement stone under dynamic loading due to insufficient elastic properties of the cement stone. The importance of the elastic modulus of cement stone as a key parameter governing its deformation behavior was emphasized in [24]. According to the research results presented in [25], the principal performance characteristics of cement stone should include its elastic modulus and shrinkage deformation parameters.

It is stated in [26] that cement slurries with enhanced elastic properties should be used to reduce the adverse dynamic effects on the cement sheath and improve the sealing integrity of the wellbore casing system. Normal-density cement stone without special additives is characterized by relatively low elastic properties, with a Young's modulus of 11-12 GPa and a Poisson's ratio of 0.15-0.17. The authors of [27] concluded that, given current trends in well construction, completion, and operational processes, developing cement system formulations with appropriate elastic properties is advisable to ensure effective resistance to dynamic loading and reduce the probability of fluid migration pathway formation. It is emphasized in [28] that cement stone should exhibit high fracture resistance under all types of stress states.

According to the data reported in [29], the formation of a 0.38- μ m microannulus results in a loss of bonding between the cement stone and the casing string; a 25- μ m microannulus is permeable to gas, whereas a 200- μ m microannulus is permeable to water and oil. It is stated in [30] that improving both the strength of the cement stone and its bonding strength with the casing string is important. In addition, [31] emphasizes the need to enhance the adhesion between cement stone and the metal surface, which is critical to preventing crevice corrosion.

Thus, the elastic modulus is an important characteristic that determines a material's ability to resist deformation under applied loading. However, unlike strength, which is generally determined under short-term loading, the elastic modulus is more sensitive to creep, residual deformation, and maximum deformation that develop over time under prolonged loading.

The authors of [32] present the results of compressive strength testing of cement stone specimens in accordance with API recommendations, together with measurements of Young's modulus and Poisson's ratio at different curing periods. They established that the compressive strength remains stable or decreases only slightly after two months of curing; Young's modulus decreases with time, by 81% over one year; and Poisson's ratio either increases or remains constant during prolonged curing. One-year testing of the mechanical properties indicates that the cement stone becomes increasingly susceptible to brittle failure due to insufficient elasticity.

The influence of specimen geometry on the accuracy of mechanical property measurements is also discussed in the literature. However, the authors of [33], after investigating the strength of cement stone specimens prepared from cement intended for well applications, established that within the range of specimen sizes and shapes recommended by the current regulatory documents of the oil and gas industry, these factors had no noticeable effect on the measured parameters.

Thus, despite the substantial body of existing research, several critical aspects of ensuring the integrity and sealing capacity of well cement sheaths remain unresolved. First, in most cases, the assessment of wellbore casing quality is limited to determining the compressive and flexural strength of cement stone. However, these parameters do not adequately reflect its actual behavior under variable conditions along the wellbore. Second, the role of the elastic modulus in reducing the risk of micro- and macrocrack formation, as well as the development of leakage pathways, remains insufficiently investigated. Third, despite the considerable amount of data on the effects of temperature and cement, their combined contribution to the development of residual deformations that may cause loss of contact with the surrounding rock and casing string has not yet been adequately established.

The present study focuses primarily on the experimental determination of the elastic properties of cement stone and their statistical analysis. Direct tests of interfacial bond strength between rock and steel, permeability of the contact zones, and microannulus formation were not performed within the scope of this study, as these represent subsequent stages of modeling. At the same time, the experimentally obtained and statistically validated values of the elastic constants of cement stone produced from the base well cement provide fundamental input data for analyzing the stress-strain state of the wellbore casing system. These data can be used to assess the behavior of the casing-cement stone-rock system under various operational loading conditions.

The study aims to determine the influence of cement stone formation conditions, produced from the base PCT I-100 Portland well cement, on its key mechanical properties that govern the quality and reliability of wellbore casing. This is achieved through the analysis of current scientific literature and practical data, structured interpretation of experimental results, correlation and regression analyses to evaluate relationships among the investigated parameters, and the development of regression models incorporating all available explanatory variables.

2. Materials and methods

Currently, oil and gas well cementing predominantly uses Portland cement-based slurries, including the base PCT I-100 well cement. Such binders are used both in their original form and for the preparation of modified cement mixtures and composite formulations. In all cases, the quality of wellbore casing depends on the properties of the cement stone, with each property playing a distinct but interrelated role in ensuring the reliability, durability, and stability of the cement sheath under various downhole conditions. It is important to consider that the properties of cement stone do not remain constant but change dynamically under the combined influence of thermobaric and mechanical factors.

To prevent brittle failure, cracking, and microannulus formation, an optimal balance between strength and deformability must be ensured, particularly between high stiffness and sufficient ductility of the cement stone. Therefore, the investigation of the mechanical and physical properties of cement stone is not only a relevant scientific task but also a practical necessity for improving the reliability of wellbore casing. In this context, experimental investigation of the elastic, strength, and deformation characteristics of cement stone is of particular importance, and the corresponding results are presented in Table 1 below.

Table 1. Results of the investigation of the elastic properties of cement stone

t	E	F_{pr}	$\varepsilon_c(t)$	ε_{res}	ε_{max}
Temperature equals 20°C					
1	3.94	8.2	1027	887	5030
	4.75	7.9	1143	905	4529
	3.66	7.78	1078	911	4998
	4.01	8.33	996	892	4476
3	8.95	19.65	425	175	1341
	9.45	18.97	427	162	1357
	8.08	17.03	365	159	1289
	9.33	18.31	344	173	1257
7	16.51	33.46	162	129	716
	15.95	35.0	143	133	803
	15.05	35.68	156	119	774
	14.32	34.24	136	125	768
Temperature equals 40°C					
1	6.11	14.22	704	423	2197
	5.84	13.63	712	397	2258
	5.65	14.57	697	385	2269
	6.09	14.04	689	417	2242
3	10.21	20.31	192	77	1088
	9.69	19.37	181	80	1142
	9.97	20.03	177	69	1104
	9.82	19.34	169	71	1182
7	11.67	22.48	130	50	948
	10.80	23.12	122	44	933
	10.54	24.02	136	43	897
	11.83	22.23	128	48	902
Temperature equals 75°C					
1	11.45	37.07	52	41	878
	11.6	37.69	49	39	917
	10.97	36.88	46	43	902
	11.01	37.42	53	34	859
3	12.71	39.58	45	35	834
	13.04	40.24	43	29	811
	12.59	40.55	39	31	788
	12.07	39.79	40	34	821
7	13.65	41.84	33	12	766
	14.22	42.05	30	17	751
	14.3	42.88	31	14	790
	13.85	42.49	29	15	744

The following symbols are used throughout the tables: Young's modulus, E (GPa); age of the cement stone specimen, t (days); prism strength, F_{pr} (MPa); creep deformation, $\varepsilon_c(t)$ (um); residual deformation, ε_{res} (um); and maximum deformation, ε_{max} (um).

The objects of the study were cement stone specimens prepared from a slurry based on PCT I-100 Portland well cement manufactured in Ukraine in accordance with the standard [34]. The cement slurry had a density of 1850 kg/m³ at a water-to-cement ratio of 0.5 and a flowability of 230 mm, which complies with the requirements of the specified standard. The cement stone specimens were prepared as standard prisms with dimensions of 40 × 40 × 160 mm and cured in water baths at 20, 40, and 75°C for 1, 3, and 7 days. Four cement stone specimens were used for each curing regime, and their elastic properties were investigated in two consecutive stages.

First, experimental studies were conducted to determine the elastic properties of the specimens as a function of curing time and temperature, with the results presented in Table 1. Subsequently, the relationships between the elastic and me-

chanical characteristics of the cement stone were evaluated using correlation analysis. Young's modulus and prism strength were determined in accordance with the methodology and requirements of [35]. In contrast, the methodology for determining creep, maximum deformation, and residual deformation was based on the general approaches specified in standards [36] and [37], which govern the determination of time-dependent deformation of materials under constant loading. The experiments were conducted using modern equipment available at the Educational and Research Laboratory of Well Cementing Slurries at Ivano-Frankivsk National Technical University of Oil and Gas.

The prism strength and Young's modulus of the cement stone specimens were determined using a hydraulic testing machine equipped with an automated data acquisition system by subjecting the specimens to uniaxial compression. The cement stone specimens were placed in the test setup equipped with fixtures for mounting longitudinal deformation indicators in accordance with the requirements of [38].

For determining prism strength and Young's modulus, each specimen was loaded stepwise to a load level equal to $(40 \pm 5)\%$ of the failure load. Each loading step corresponded to 10% of the failure load, while the loading rate within each step was maintained at (0.6 ± 0.2) MPa/s. At each loading step, the load was maintained for 5 min, and instrument readings were recorded at the beginning and end of the holding period. Upon reaching a load level of $(40 \pm 5)\%$ of the failure load, further loading of the specimen was performed continuously at a constant rate of (0.6 ± 0.4) MPa/s. The maximum force attained during the test was taken as the failure load.

The prism strength (F_{pr}) was calculated as follows:

$$F_{pr} = \frac{P}{S}, \quad (1)$$

where:

P – failure load measured using the hydraulic testing machine, N;

S – cross-sectional area of the specimen, m^2 .

Young's modulus (E) was calculated for each specimen at a load level equal to 30% of the failure load using the following equation:

$$E = \frac{\sigma_1}{\varepsilon_{1el}}, \quad (2)$$

where:

σ_1 – increase in stress from the reference zero level to the external load corresponding to $(30 \pm 5)\%$ of the failure load (P), N/m^2 .

An increase in stress was determined as follows:

$$\sigma_1 = \frac{P_1}{S}, \quad (3)$$

where:

P_1 – corresponding increase in external load to a level of $(30 \pm 5)\%$ of the failure load (P), N.

The parameter ε_{1el} is the increase in the instantaneous elastic relative longitudinal strain of the specimen at load level P_1 , measured at the beginning of each loading step. It was determined as follows:

$$\varepsilon_{1el} = \varepsilon_1 - \sum \varepsilon_{1cl}, \quad (4)$$

where:

ε_1 – increase in total relative longitudinal strain of the specimen corresponding to the load level P_1 , measured at the end of the corresponding loading step;

$\sum \varepsilon_{1cl}$ – increase in relative longitudinal strain caused by short-term creep during the load-holding periods at the loading steps up to the load level P_1 .

The relative strain was determined using the following equation:

$$\varepsilon_1 = \frac{\Delta l_1}{l_1}, \quad (5)$$

where:

Δl_1 – absolute increase in the longitudinal deformation of the specimen caused by the corresponding increase in stress;

l_1 – fixed gauge length used for measuring the longitudinal deformation of the specimen.

Before loading the cement stone specimens, their compressive strength and Young's modulus were determined to establish the appropriate load level, which is typically selected within the range of 0.2-0.4 of the ultimate strength; in the present study, a value of 0.3 was adopted. A compressive load was applied rapidly to the specimen, within 30 s, but without dynamic impact, and the instantaneous elastic strain, ε_0 , was recorded at that moment. Thereafter, the load was maintained strictly constant throughout the experiment, while the strain increase over time (ε_t) was recorded. Since the major portion of creep deformation in cement stone develops during the first few days, measurements were taken every 12 h for three days for all specimens. An identical unloaded specimen was used simultaneously to account for shrinkage deformation ($\varepsilon_y(t)$) during the experiment. The tests were conducted under laboratory conditions at natural air humidity.

Creep deformation $\varepsilon_c(t)$ was determined as follows:

$$\varepsilon_c(t) = \varepsilon_t(t) - \varepsilon_0 - \varepsilon_y(t), \quad (6)$$

where:

$\varepsilon_t(t)$ – total deformation of the cement stone specimen at time (t);

ε_0 – instantaneous elastic deformation;

$\varepsilon_y(t)$ – shrinkage deformation at time (t).

The maximum deformation ($\varepsilon_{\max}$) was evaluated as the total deformation recorded at the peak load immediately before the onset of failure:

$$\varepsilon_{\max} = \frac{\Delta l_{\max}}{l_0}, \quad (7)$$

where:

$\Delta l_{\max}$ – change in specimen length at the maximum load;

l_0 – initial specimen length.

To determine the residual deformation (ε_{res}), the specimen was loaded to 60% of its ultimate uniaxial compressive strength. The load was then gradually reduced to zero, after which the final specimen length (l_k) was recorded:

$$\varepsilon_{res} = \frac{l_0 - l_k}{l_0}. \quad (8)$$

For Equation (8), I used $l_0 - l_k$ because, under compression, the final specimen length is smaller than the initial length, and this form yields a positive residual deformation, consistent with the positive values reported in Table 1.

When justifying the selected load level, this value is generally chosen within the range of 30-60% of the ultimate uniaxial compressive strength, with 70% considered the maximum permissible level, since this range corresponds to the active development of residual deformation. At load levels exceeding 70%, nonlinear failure occurs, with deformation increasing rapidly due to the formation of macrodefects in the cement stone structure.

For structured interpretation of the experimental data, identification of relationships among the investigated parameters, and development of predictive models, correlation and regression analyses were performed. At the first stage, Pearson's correlation coefficient (r) was used to assess linear relationships between the variables. The statistical significance of the relationships was evaluated using p -values, with $p < 0.05$ considered statistically significant. Further interpretation focused on the presence and direction of statistically significant linear relationships between the parameters [38], [39].

At the second stage, three types of regression models were developed:

1. A full ordinary least squares (OLS) model incorporating all available predictors [40].
2. A simplified Backward Elimination (BE) model developed by stepwise removal of variables while retaining statistically significant predictors [41], [42].
3. A Lasso model employing L_1 regularization to reduce the effects of multicollinearity among the predictors [40], [43].

In all developed models, Young's modulus was considered the dependent variable, whereas specimen age (x_1), prism strength (x_2), creep deformation (x_3), residual deformation (x_4), and maximum deformation (x_5) were used as explanatory variables. The use of models with different structures enabled the evaluation of the effects of the investigated factors on Young's modulus. It accounted for correlations among the predictors in the regression analysis results.

Model accuracy was evaluated using RMSE and MAE [44], [45]. In addition, statistical diagnostics of the residuals were performed, including tests for normality (Shapiro-Wilk), autocorrelation (Durbin-Watson), and heteroscedasticity (Breusch-Pagan) [46], [47]. This made it possible to assess whether the developed models satisfied the principal assumptions of linear regression.

The calculations were performed in Python 3.11 using the pandas, NumPy, scikit-learn, statsmodels, and Matplotlib libraries. Microsoft Excel spreadsheets were additionally used to verify the consistency of the input data and to check selected intermediate calculations. Correlation and regression analyses were performed separately for each temperature regime to assess the dependence of Young's modulus on the investigated set of predictors.

The combination of methods applied ensures the reliability of the results and enables reproducibility of the experimental procedures.

3. Results and discussion

Following the experimental studies, the obtained data were subjected to structured interpretation and comprehensive analysis to evaluate the influence of cement stone formation conditions on its elastic and deformation characteristics. Based on correlation and regression analyses, the nature and degree of interrelationships among the investigated parameters were determined, and mathematical models were

developed to predict their variation as a function of the conditions of cement stone formation. The obtained results made it possible to assess the role of elastic properties in ensuring the sealing integrity of the well annulus.

3.1. Results of the analysis at a cement stone formation temperature of $T = 20^\circ\text{C}$

3.1.1. Correlation analysis

A correlation matrix was used to evaluate the relationships between Young's modulus and the explanatory variables. Pearson correlation coefficients and the corresponding p -values were used for the analysis.

Based on the experimental data, a correlation matrix was constructed for a curing temperature of 20°C (Table 2).

Table 2. Full correlation matrix (r ; p) at $T = 20^\circ\text{C}$

Parameter	t	F_{pr}	$\varepsilon_c(t)$	ε_{res}	ε_{max}
E	0.986 ($4.76 \cdot 10^{-9}$)	0.989 ($1.37 \cdot 10^{-9}$)	-0.922 ($1.98 \cdot 10^{-5}$)	-0.839 ($6.50 \cdot 10^{-4}$)	-0.879 ($1.68 \cdot 10^{-4}$)
t	—	0.995 ($1.61 \cdot 10^{-11}$)	-0.893 ($9.05 \cdot 10^{-5}$)	-0.786 ($2.46 \cdot 10^{-3}$)	-0.829 ($8.48 \cdot 10^{-4}$)
F_{pr}	—	—	-0.918 ($2.61 \cdot 10^{-5}$)	-0.824 ($9.93 \cdot 10^{-4}$)	-0.862 ($3.09 \cdot 10^{-4}$)
ε	—	—	—	0.974 ($9.65 \cdot 10^{-8}$)	0.983 ($1.19 \cdot 10^{-8}$)
ε_{res}	—	—	—	—	0.993 ($1.29 \cdot 10^{-10}$)

A strong positive correlation was established between Young's modulus and specimen age ($r = 0.986$), as well as between Young's modulus and prism strength ($r = 0.989$).

The deformation characteristics showed strong negative correlations with Young's modulus, with r values ranging from -0.839 to -0.922. This is consistent with a decrease in deformation parameters as the cement stone's stiffness increases.

Strong positive correlations were also observed among the deformation parameters, indicating substantial multicollinearity among the predictors.

3.1.2. Regression analysis

Based on the regression analysis of the experimental data obtained at a curing temperature of 20°C , equations were derived for the full OLS model, the simplified BE model, and the Lasso model. The equations of the developed models are as follows.

Full model (OLS):

$$E = 3.165 + 1.599 \cdot x_1 + 0.039 \cdot x_2 + 0.005 \cdot x_3 - 0.0004 \cdot x_4 - 0.001247 \cdot x_5. \quad (9)$$

Simplified model (BE):

$$E = 5.004 + 1.549 \cdot x_1 - 0.001 \cdot x_5. \quad (10)$$

Lasso model ($\alpha = 0.0167$):

$$E = 3.0228 + 1.1421 \cdot x_1 + 0.1365 \cdot x_2 + 0.0040 \cdot x_3 + 0.0011 \cdot x_4 - 0.0014 \cdot x_5. \quad (11)$$

Comparison of the developed regression models shows that the full OLS model provides the closest approximation to the experimental data; however, it is more sensitive to multicollinearity among the deformation parameters. The instability of individual coefficients indicates strong correlations among creep, residual deformation, and maximum deformation, which complicates the interpretation of their independent effects.

The simplified model obtained using Backward Elimination contains only statistically significant predictors. After excluding mutually correlated variables, specimen age and maximum deformation remain in the model. Reducing the number of parameters makes the equation more compact and facilitates its practical application.

Lasso regression accounts for correlations among the predictors through L_1 regularization, which reduces the contribution of secondary variables and stabilizes the coefficient estimates. This makes the model suitable for analyzing experimental data characterized by a high degree of multicollinearity.

The accuracy of the regression models was evaluated using R^2 , RMSE, and MAE, which were used to assess their ability to fit the experimental data (Table 3). Owing to the limited sample size, the evaluation was performed using the full experimental dataset without a separate external validation procedure. Therefore, the reported results reflect the models' ability to describe the dataset under investigation.

Table 3. Accuracy metrics of the regression models at $T = 20^\circ\text{C}$

Model	R^2	RMSE	MAE
Full (OLS)	0.9858	0.5590	0.4642
Simplified (BE)	0.9834	0.6045	0.4903
Lasso	0.9856	0.5645	0.4730

The full OLS model provides the best fit to the experimental data, as confirmed by the highest R^2 , the lowest RMSE and the lowest MAE. At the same time, the model is more sensitive to multicollinearity among the deformation parameters. The simplified Backward Elimination model shows only a slight decrease in accuracy; however, it has a more compact structure and offers better interpretability of the coefficients. The Lasso regression model obtained at $\alpha = 0.0167$ provides RMSE and MAE values close to those of the OLS model while being less sensitive to correlations among the predictors. This indicates that the regularized model can describe the experimental data without substantial loss of accuracy.

To compare the experimental and predicted values of Young's modulus, a Predicted vs Observed plot was constructed for the OLS, BE, and Lasso models (Fig. 1).

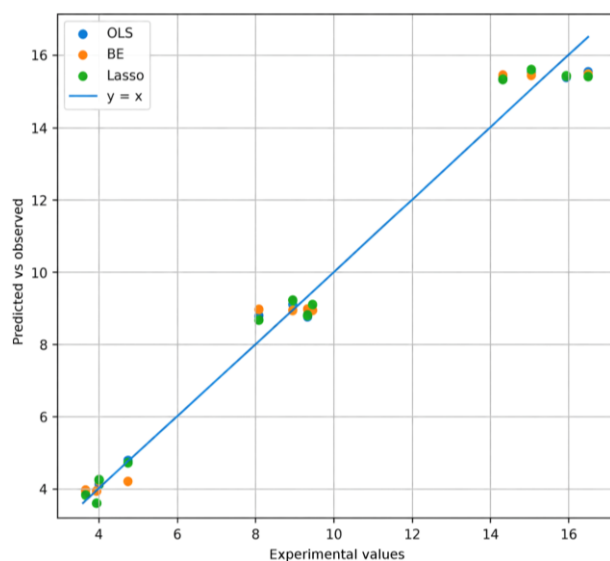


Figure 1. Comparison of the experimental and predicted values of Young's modulus for the OLS, BE, and Lasso models at $T = 20^\circ\text{C}$

For all models, the data points are located close to the $y = x$ line, indicating good agreement between the predicted and experimental values. The smallest scatter is observed for the OLS model, consistent with its highest R^2 and the lowest RMSE and MAE.

The Lasso model is only slightly less accurate than the OLS model, but it is less sensitive to multicollinearity among the predictors. The results of the statistical diagnostics of the developed regression models are presented in Table 4.

Table 4. Results of statistical diagnostics of the regression models at $T = 20^\circ\text{C}$

Model	Shapiro-Wilk W	Shapiro-Wilk p	Durbin-Watson	Breusch-Pagan p
Full (OLS)	0.978	0.973	1.324	0.075
Simplified (BE)	0.966	0.860	1.164	0.040
Lasso	0.976	0.960	1.551	0.068

To evaluate the distribution pattern of the errors, a residual plot for the Lasso model was constructed (Fig. 2).

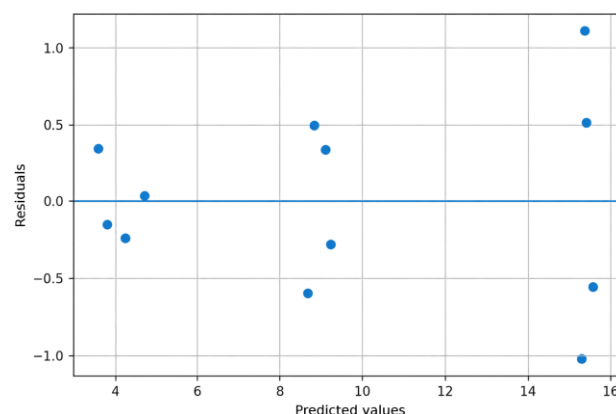


Figure 2. Residual plot of the Lasso model ($\alpha = 0.0167$) at $T = 20^\circ\text{C}$

The distribution of residuals around the zero level does not exhibit any pronounced systematic pattern. No substantial increase in residual variance with changes in the predicted values is observed either.

For all models, the Shapiro-Wilk test p -values exceed the significance level of 0.05, which is consistent with the assumption of normally distributed residuals. The Durbin-Watson statistics fall within a range indicating the absence of pronounced autocorrelation.

For the OLS and Lasso models, the Breusch-Pagan test did not indicate statistically significant heteroscedasticity ($p > 0.05$). For the BE model, $p = 0.040$, which may indicate moderate heterogeneity in the residual variance.

Overall, the diagnostic results did not reveal substantial violations of the principal assumptions of linear regression for the investigated models.

3.2. Results of the analysis at a cement stone formation temperature of $T = 40^\circ\text{C}$

3.2.1. Correlation analysis

The correlation matrix for a curing temperature of 40°C is presented in Table 5. For all correlation coefficients, $p < 0.01$. A strong positive correlation was established between Young's modulus and specimen age ($r = 0.877$). An even stronger correlation was observed between Young's modulus and prism strength ($r = 0.958$).

Table 5. Full correlation matrix (r ; p) at $T = 40^\circ\text{C}$

Parameter	t	F_{pr}	$\varepsilon_c(t)$	ε_{res}	$\varepsilon_{max.}$
E	0.877 ($1.79 \cdot 10^{-4}$)	0.958 ($9.35 \cdot 10^{-7}$)	-0.975 ($6.80 \cdot 10^{-8}$)	-0.969 ($2.19 \cdot 10^{-7}$)	-0.984 ($6.93 \cdot 10^{-9}$)
t	—	0.931 ($1.10 \cdot 10^{-5}$)	-0.806 ($1.56 \cdot 10^{-3}$)	-0.798 ($1.86 \cdot 10^{-3}$)	-0.843 ($5.74 \cdot 10^{-4}$)
F_{pr}	—	—	-0.949 ($2.42 \cdot 10^{-6}$)	-0.948 ($2.83 \cdot 10^{-6}$)	-0.969 ($2.11 \cdot 10^{-7}$)
ε	—	—	—	0.998 ($3.48 \cdot 10^{-13}$)	0.995 ($1.65 \cdot 10^{-11}$)
ε_{res}	—	—	—	—	0.993 ($1.48 \cdot 10^{-10}$)

The deformation characteristics showed strong negative correlations with Young's modulus: $r = -0.975$ for creep deformation, $r = -0.969$ for residual deformation, and $r = -0.984$ for maximum deformation. This is consistent with a decrease in the deformability of cement stone as its stiffness increases. Very strong positive correlations were observed among the deformation parameters ($r = 0.993$ - 0.998), indicating substantial multicollinearity among the predictors. The close relationships among these variables were taken into account when developing the regression models.

3.2.2. Regression analysis

Comparison of the developed regression models enables assessment of the effects of specimen age, strength characteristics, and deformation parameters on the Young's modulus of the cement stone. The full ordinary least squares (OLS) model includes five factors representing the mechanical and deformation characteristics:

$$E = 26.6983 + 0.4544 \cdot x_1 - 0.5619 \cdot x_2 + 0.0005 \cdot x_3 + 0.0019 \cdot x_4 - 0.0064 \cdot x_5. \quad (12)$$

The simultaneous inclusion of several mutually correlated deformation variables increases the model's sensitivity to multicollinearity and complicates the interpretation of individual regression coefficients.

The simplified model obtained using Backward Elimination contains only statistically significant predictors:

$$E = 25.9020 + 0.4765 \cdot x_1 - 0.5610 \cdot x_2 - 0.0056 \cdot x_5. \quad (13)$$

The model retains the minimum required set of parameters, among which specimen age and maximum deformation exert the greatest influence. The Lasso regression model with $\alpha = 0.0167$ is described by the following Equation:

$$E = 23.4789 + 0.3623 \cdot x_1 - 0.4174 \cdot x_2 - 0.00123 \cdot x_3 + 0.00409 \cdot x_4 - 0.00572 \cdot x_5. \quad (14)$$

The application of L_1 regularization reduces multicollinearity among predictors and yields more stable coefficient estimates. At the same time, the model accuracy metrics remain close to those obtained for the full OLS model.

The OLS model provides the closest approximation to the experimental data, whereas the BE and Lasso models yield comparable results with simpler model structures.

To evaluate the accuracy of the developed models, R^2 , RMSE, and MAE were calculated based on the approximation of the experimental data (Table 6). Owing to the limited sample size, the evaluation was performed on the full experimental dataset without cross-validation or external validation. Therefore, the reported results reflect the accuracy of the models' description of the investigated dataset.

Table 6. Accuracy metrics of the regression models at $T = 40^\circ\text{C}$

Model	R^2	RMSE	MAE
Full (OLS)	0.9903	0.2247	0.1908
Simplified (BE)	0.9900	0.2278	0.1905
Lasso	0.9895	0.2334	0.1944

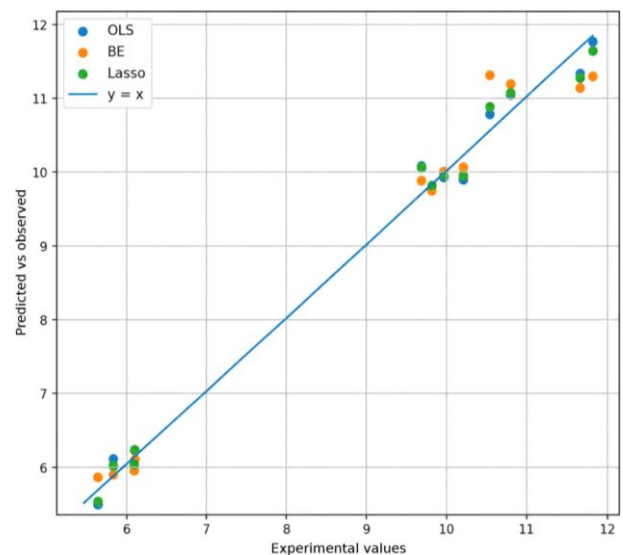
At 40°C , all models exhibit high coefficients of determination ($R^2 \approx 0.99$). The OLS model yields the lowest RMSE and the highest R^2 , whereas the BE model shows a comparable MAE. The simplified BE model achieves a similar level of accuracy with fewer predictors. The Lasso model shows only a slight increase in error compared with the OLS and BE models. The results of the statistical diagnostics of the developed regression models are presented in Table 7.

Table 7. Results of statistical diagnostics of the regression models at $T = 40^\circ\text{C}$

Model	Shapiro-Wilk W	Shapiro-Wilk p	Durbin-Watson	Breusch-Pagan p
Full (OLS)	0.960	0.790	2.502	0.911
Simplified (BE)	0.952	0.670	2.645	0.652
Lasso	0.973	0.940	2.439	0.448

For all models, the p -values of the Shapiro-Wilk test exceed the significance level of 0.05, which is consistent with the assumption of normally distributed residuals. The values of the Durbin-Watson statistic are close to 2, indicating that no pronounced autocorrelation of residuals is observed.

According to the results of the Breusch-Pagan test, no statistically significant heteroscedasticity was detected for any of the models ($p > 0.05$). The obtained results did not reveal any substantial violations of the principal assumptions of linear regression. To compare the experimental and predicted values of Young's modulus, a Predicted vs Observed plot was constructed for the OLS, BE, and Lasso models (Fig. 3).

**Figure 3. Comparison of the experimental and predicted values of Young's modulus for the OLS, BE, and Lasso models at $T = 40^\circ\text{C}$**

For all models, the data points are located close to the $y = x$ line, indicating good agreement between the predicted and experimental values. The smallest scatter of points is observed for the full OLS model, for which the highest R^2 value and the lowest RMSE and MAE values were also obtained.

To assess the distribution of residuals, a residual plot of the Lasso model was constructed (Fig. 4).

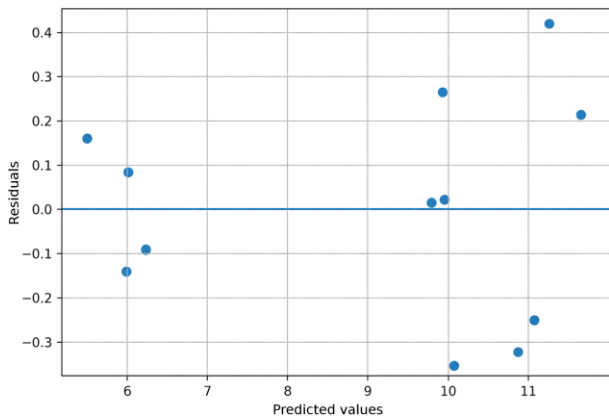


Figure 4. Residual plot of the Lasso model ($\alpha = 0.0167$) at $T = 40^\circ\text{C}$

The residuals are distributed around the zero level without a pronounced systematic pattern. No noticeable increase in residual variance with changes in the predicted values is observed.

3.3. Results of the analysis at a cement stone formation temperature of $T = 20^\circ\text{C}$

3.3.1. Correlation analysis

The correlation matrix for a curing temperature of 75°C is presented in Table 8. For most pairs of parameters, the p -values do not exceed 0.001.

Table 8. Full correlation matrix (r ; p) at $T = 75^\circ\text{C}$

Parameter	t	F_{pr}	$\varepsilon_c(t)$	ε_{res}	$\varepsilon_{max.}$
E	0.951 ($2.02 \cdot 10^{-6}$)	0.970 ($1.92 \cdot 10^{-7}$)	-0.912 ($3.63 \cdot 10^{-5}$)	-0.915 ($3.05 \cdot 10^{-5}$)	-0.880 ($1.63 \cdot 10^{-4}$)
t	—	0.955 ($1.39 \cdot 10^{-6}$)	-0.956 ($1.26 \cdot 10^{-6}$)	-0.969 ($2.16 \cdot 10^{-7}$)	-0.896 ($8.01 \cdot 10^{-5}$)
F_{pr}	—	—	-0.947 ($2.97 \cdot 10^{-6}$)	-0.932 ($1.03 \cdot 10^{-5}$)	-0.928 ($1.37 \cdot 10^{-5}$)
ε	—	—	—	0.892 ($9.75 \cdot 10^{-5}$)	0.882 ($1.45 \cdot 10^{-4}$)
ε_{res}	—	—	—	—	0.885 ($1.29 \cdot 10^{-4}$)

Strong positive correlations were established between Young's modulus and specimen age ($r = 0.951$), as well as between Young's modulus and prism strength ($r = 0.970$).

The deformation characteristics showed strong negative correlations with Young's modulus: $r = -0.912$ for creep deformation, $r = -0.915$ for residual deformation, and $r = -0.880$ for maximum deformation.

Strong positive correlations were observed among the deformation parameters ($r = 0.882$ - 0.969), indicating substantial multicollinearity among the predictors. The close relationships among these variables were taken into account when developing the regression models.

3.3.2. Regression analysis

Three regression models with different equation structures and sets of predictors were developed to describe Young's modulus.

$$E = -19.671 + 0.497 \cdot x_1 + 0.587 \cdot x_2 + 0.078 \cdot x_3 + 0.054 \cdot x_4 + 0.003 \cdot x_5. \quad (15)$$

The full ordinary least squares (OLS) model includes age, strength, and deformation characteristics. The use of mutually correlated deformation parameters complicates the interpretation of the individual model coefficients.

The simplified model obtained using Backward Elimination contains only statistically significant predictors, with prism strength remaining the principal factor.

$$E = -8.777 + 0.537 \cdot x_2. \quad (16)$$

Reducing the number of variables makes the model more compact and easier to use in practical calculations.

Lasso regression employs L_1 regularization to reduce the effect of multicollinearity among the predictors.

$$E = -13.013 + 0.329 \cdot x_1 + 0.503 \cdot x_2 + 0.044 \cdot x_3 + 0.026 \cdot x_4 + 0.002 \cdot x_5. \quad (17)$$

The use of Lasso regression is appropriate under conditions of strong correlations among the parameters and a limited experimental sample size.

At a curing temperature of 75°C , strong correlations are observed between the deformation and strength characteristics ($r = 0.882$ - 0.969). In the BE model, the deformation parameters are excluded as statistically redundant, whereas in the Lasso model, their contribution is reduced through regularization.

The accuracy of the developed models was evaluated using R^2 , RMSE, and MAE calculated from the approximation of the experimental data (Table 9). Owing to the limited sample size, the evaluation was performed on the full experimental dataset without cross-validation or external validation. Therefore, the reported results reflect the accuracy of the models' description of the investigated dataset.

Table 9. Accuracy metrics of the regression models at $T = 75^\circ\text{C}$

Model	R^2	RMSE	MAE
Full (OLS)	0.9682	0.2070	0.1644
Simplified (BE)	0.9403	0.2837	0.2408
Lasso	0.9643	0.2193	0.1801

At a curing temperature of 75°C , the highest model accuracy was obtained for the full OLS model. The simplified BE model shows a lower R^2 and higher RMSE and MAE, which are associated with the reduced number of predictors. The accuracy metrics of the Lasso model remain close to those obtained for the OLS model.

The results of the statistical diagnostics of the developed regression models are presented in Table 10.

Table 10. Results of statistical diagnostics of the regression models at $T = 75^\circ\text{C}$

Model	Shapiro-Wilk W	Shapiro-Wilk p	Durbin-Watson	Breusch-Pagan p
Full (OLS)	0.954	0.692	2.071	0.879
Simplified (BE)	0.966	0.865	1.502	0.996
Lasso	0.969	0.904	1.801	0.857

For all models, the p -values of the Shapiro-Wilk test exceed the significance level of 0.05, which is consistent with the assumption of normally distributed residuals. The values of the Durbin-Watson statistic are close to 2, indicating that no pronounced autocorrelation of residuals is observed. According to the Breusch-Pagan test, no statistically significant heteroscedasticity was detected for any of the models ($p > 0.05$).

No substantial violations of the principal assumptions of linear regression were identified for the developed models.

To compare the experimental and predicted values of Young's modulus, a Predicted vs Observed plot was constructed for the OLS, BE, and Lasso models (Fig. 5).

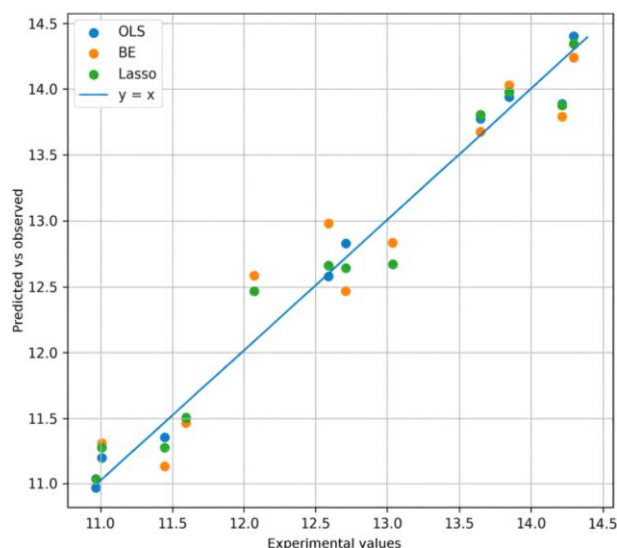


Figure 5. Comparison of the experimental and predicted values of Young's modulus for the OLS, BE, and Lasso models at $T = 75^{\circ}\text{C}$

For all models, the data points are located close to the $y = x$ line, indicating good agreement between the predicted and experimental values.

The smallest scatter of points is observed for the full OLS model. The BE model shows somewhat larger deviations from the experimental values, whereas the Lasso model's results remain close to those of the OLS model.

To assess the distribution of residuals, a residual plot was constructed for the Lasso regression model (Fig. 6). The residuals are distributed around the zero level without a pronounced systematic pattern. No noticeable relationship between residual magnitude and predicted values is observed.

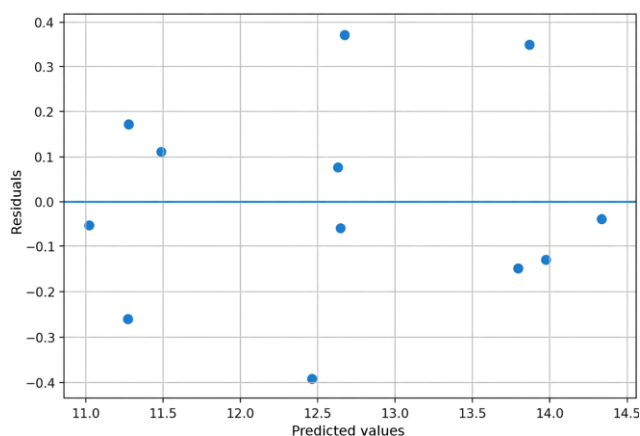


Figure 6. Residual plot of the Lasso model ($\alpha = 0.0167$) at $T = 75^{\circ}\text{C}$

4. Conclusions

Young's modulus of the cement stone increases with age at all curing temperatures. Higher temperatures promote rapid early-age strengthening, whereas lower temperatures

lead to the formation of a stiffer structure at later curing stages. The effect of temperature on strength is nonlinear: increasing temperature accelerates early strength development, whereas at elevated temperatures, maximum strength decreases over relatively prolonged curing periods. Creep deformation decreases with increasing specimen age; however, its magnitude depends strongly on the curing temperature. Residual deformation also decreases with age but does not disappear completely. Higher curing temperatures result in substantially lower residual deformation values.

Correlation analysis revealed statistically significant relationships among Young's modulus, strength characteristics, and deformation parameters. Strong mutual correlations were obtained among the deformation parameters, indicating substantial multicollinearity among the predictors. The full OLS model provides the highest accuracy in approximating the experimental data. The BE model has a simpler equation structure but lower accuracy metrics. The Lasso model provides accuracy metrics close to those of the OLS model.

According to the statistical diagnostics, no substantial deviations from the principal assumptions of linear regression were identified for the developed models. No statistically significant heteroscedasticity was detected in the OLS and Lasso models, whereas moderate heteroscedasticity was observed in the BE model. The Durbin-Watson statistics fall within a range indicating the absence of pronounced autocorrelation of the residuals.

The obtained regression relationships describe the variation in Young's modulus of the cement stone within the investigated ranges of curing temperature and curing time. Owing to the limited sample size, the model evaluation was performed without a separate external validation procedure.

Author contributions

Conceptualization: MS; Data curation: VT; Formal analysis: VT; Investigation: BM, IV(Jr.); Methodology: ID; Project administration: MS, OM; Supervision: OM, IV; Validation: IV; Visualization: BM, IV(Jr.); Writing – original draft: MS, VT, ID, BM; Writing – review & editing: OM, IV, ID, IV(Jr.). All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Дослідження пружних характеристик цементного каменю як чинника забезпечення герметичності затрубного простору свердловин

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Мета. Встановити залежності пружно-міцнісних і деформаційних властивостей цементного каменю від умов його формування, які визначають цілісність і герметичність цементної оболонки нафтогазових свердловин.

Методика. Методологія дослідження базується на комплексній структурованій інтерпретації масивів експериментальних даних щодо формування цементного каменю з базового портландцементу ПЦТ І-100. Оцінювання взаємозв'язків між пружними й механічними характеристиками каменю виконано за допомогою методів кореляційного аналізу. На основі регресійного аналізу із залученням усього комплексу доступних пояснювальних змінних побудовано математичні моделі, що описують зміну властивостей каменю під впливом умов його формування.

Результати. Встановлено, що модуль пружності, міцність і деформаційні характеристики цементного каменю істотно залежать від віку та температури тверднення. Висока температура (75°C) прискорює ранній розвиток пружних і міцнісних властивостей та зменшує повзучість, але не забезпечує максимальної довготривалої міцності. При 20°C тверднення відбувається повільніше, проте на пізніх стадіях формує більшу жорсткість і стійкіший приріст міцності. Повзучість і залишкові деформації зменшуються з віком, однак за нижчих температур вони значно більші, що підвищує ризик дефектів кріплення.

Наукова новизна. Доведено важливість визначення пружних властивостей цементного каменю як ключового чинника, що впливає на формування мікроканалів негерметичності у кріпленні свердловин. Встановлено, що цементний камінь на основі базового портландцементу ПЦТ І-100 має недостатні ранні пружні властивості, унаслідок чого під дією експлуатаційних навантажень, може порушуватись контакт між ним та обсадною колоною і гірською породою. Розроблено математичні (регресійні) моделі, які дозволяють прогнозувати ризики виникнення каналів негерметичності в цементному камені на ранніх стадіях його твердіння шляхом комплексної оцінки взаємозв'язків між його механічними характеристиками та умовами формування.

Практична значимість. Виявлені закономірності деформаційних характеристик цементного каменю будуть корисними для усунування і підприємств, що займаються розробленням рецептур тампонажних сумішей для цементування свердловин.

Ключові слова: *свердловина; кріплення; портландцемент; цементний камінь; герметичність*

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