Deformation and damage of cement sheath in gas storage wells under cyclic loading

Juan Li | Donghua Su | Shizhong Tang | Zaoyuan Li | Hua Wu | Sheng Huang | Jinfei Sun

Abstract
The mechanical damage and failure of cement sheaths in gas storage wells under cyclic loading have been studied extensively. However, because the test device cannot restore the wellbore condition, most studies have been theoretical or regular experimental. If the load-bearing mode and stress environment in a test device differ from those in a wellbore, then the damage and failure modes will deviate from what occurs in the actual wellbore. Therefore, it is necessary to explore a method that restores the wellbore condition and design a wellbore simulation device that reveals the deformation and damage of the cement sheath. In this study, the development laws of microannulus and microcracks in the cement sheath were studied by triaxial cyclic loading, low-field nuclear magnetic resonance imaging, and scanning electron microscopy. A device to evaluate cement sheath integrity was then developed. A stress equivalence method was proposed, based on the principle that the stresses at the first and second interfaces of the device are equal to those of the wellbore cement sheath. This method was used to design material, size, and experimental conditions to simulate the load-deformation law of a cement sheath in a gas storage well. The damage failure mechanism was investigated using the simulation results and computed tomography. Micropores and microcracks in the cement sheath increased continuously under cyclic loading. Damage accumulated, causing strength failure as the period of the cyclic loading increased. Plastic deformation of the cement sheath occurred under cyclic loading, but interfacial peeling did not. The reason is that the cement sheath is under compressive stress during loading and unloading, and the interface between the cement sheath and the outer wall is not damaged. This study provides a new method for studying the mechanical failure of a cement sheath under complex wellbore conditions.

Keywords
Cement sheath, cyclic loading, damage, deformation, gas storage well, mechanical failure
1 | INTRODUCTION

China has prioritized the development of natural gas resources to ease its reliance on petroleum. Natural gas is widely used in public transportation, daily life, and other fields. However, shortages can occur at the peak periods of gas usage during the winter. Therefore, natural gas surpluses are typically injected into closed underground gas storage systems during the off-season. Gas storage wells constructed from depleted oil or gas reservoirs are reliable and cost-effective. In general, gas injection and gas storage production are performed after drilling and cementing. Cementing the well involves setting casing pipes at a particular drilling depth into the formation and then filling the annular space outside the casing pipes with a cement slurry. The cement slurry supports and zonally isolates the casing pipes from the formation after it coagulates and hardens. Cementing is a critical step toward ensuring a long service life and the safe operation of gas storage wells.

The cement used in the engineering of oil and gas wells differs from the cement used in civil engineering. The high-temperature and high-pressure conditions of oil and gas wells require a cement with robust mechanical properties, such as high compressive strength and low elastic modulus. Moreover, the integrity of the cement sheath directly affects the service life of the oil and gas well. A mechanical failure of the cement sheath affects the safety of the ground personnel, increases the cost of a workover, and can lead to well abandonment. Pressure changes in a well are typically small during the production of oil and gas wells, and the load on the cement sheath from the casing and formation is relatively stable. However, in gas storage wells, the cement sheath experiences load variation from intermittent gas injection and production. When gas is injected, the pressure in the casing increases and exerts more pressure on the cement sheath (Figure 1A). When gas is produced, the casing pressure gradually decreases (Figure 1B). Although the maximum load in the wellbore is lower than the cement sheath strength, the constant changes in the load cause fatigue damage to the cement sheath and affect its integrity, leading to the failure of the annular seal. Therefore, it is necessary to investigate the mechanical properties of the cement sheath.

The majority of research on the mechanical performance of cement sheaths has focused on conventional cement stone properties: compressive strength, tensile strength, and triaxial compressive strength. However, cement sheaths are subjected to pressures from the casing and formation in the wellbore; these pressures cause radial and tangential stresses inside the sheath, resulting in a complex stress state and failure.

The stress state and failure mode of the cement sheath have been studied theoretically. Thiercelin et al proposed analytical formulas to simulate the response of a cement sheath under loading based on linear elasticity assumptions. Li et al researched the stress distribution of casing-cement sheath formations under thermal stress. Khandka established a method to analyze cement sheath failure based on thermoelastic theory. Li et al proposed a model for evaluating cement sheaths that considers thermal and in situ stresses. Chu et al established an elastic-plastic analysis model based on the Mohr-Coulomb theory to study the microannulus between the casing, cement sheath, and formation under casing pressure. An analysis of the initiation and development of microannuli during the loading and unloading of the casing inner pressure revealed that the tensile stress on the interface was the primary cause of microannulus when it exceeded the bonding strength. Gholami et al established an analytical model that considered the poroelasticity of the formation to evaluate the cement sheath integrity in deep vertical wells. Liu et al developed an analytical method that considered the in situ stresses as the initial stresses to eliminate the influence of additional displacements and found that existing methods overestimated the compressive stress within the casing and cement. Bu et al proposed a method based on the convergence-constraint theory to evaluate integrity that considered the influence of the hardening process. Although cement sheath integrity has been extensively studied using models that consider various wellbore conditions, the conclusions of these studies require support from laboratory experiments. Therefore, scholars have also carried out research and
experiments to test the mechanical properties of the cement sheath using a wellbore simulation device.

Goodwin and Crook\textsuperscript{21} constructed a simulated wellbore with a 139.7 mm inner casing and 193.7 mm outer casing to investigate the relationship between the mechanical properties of a cement sheath and temperature or pressure. However, the experiment did not consider the influence of confining pressure. Andrade and Aldawi\textsuperscript{32,33} used a wellbore simulator and analyzed the experimental results with simulation software (ANSYS) to investigate cement sheath damage under thermal loading. They proposed that cyclic thermal stress could cause the annulus seals of the cement sheath interfaces to fail. However, the simulator did not consider the effect of pressure on the cement sheath. Texas A&M University designed a simulated wellbore device to analyze the mechanism of cement sheath failure by applying mechanical stress on the casing.\textsuperscript{34} Subsequent studies used an improved device to test the effect of varying the casing inner pressure on the cement sheath under a constant confining pressure. However, in this experiment, the cement sheath was damaged by applying axial compressive stress on the upper and lower ends of the casing using a hydraulic press, which differed from the load-bearing mode of a cement sheath in an actual wellbore. Deng Kuanhai et al\textsuperscript{35} developed an experimental apparatus to test cement sheath integrity under varying temperatures and pressures. However, the results provided insight into the effects of temperature and pressure on the mechanical properties of cement sheath interfaces, such as cementing force, friction force, and shearing strength. Moreover, the load-bearing mode of the cement sheath in this device was like that of the simulated wellbore constructed by Texas A&M University. Therefore, it also differed from that in an actual wellbore. Xi Yan et al\textsuperscript{36} simulated the behavior of microannulus in the first interface of the cement sheath under fracturing conditions. They proposed a new cement slurry system based on the experimental results. These studies show that most simulated wellbore devices differ from actual wellbores due to the limitations of size, materials, and temperature and pressure conditions.

Most studies to date have conducted theoretical or experimental studies. Few studies have combined theory and experiment to construct a simulated wellbore that incorporates size, material, and loading conditions using a stress equivalence method to replicate the effect of the wellbore stress on the cement sheath.\textsuperscript{1,37} Li et al\textsuperscript{1,37} first converted the casing inner pressure of a wellbore to a von Mises stress to construct a simulated wellbore that replicated the stress state of the actual wellbore and evaluate the mechanical properties of a cement sheath. However, this study could not quantify the deformation law of the casing-cement sheath formation because the material around the cement sheath was a rubber cylinder, which allowed more deformation of the cement sheath and decreased the reliability of the integrity results.

In this study, the damage mechanism of a cement stone under cyclic loading was studied using triaxial cyclic loading, a classic theory of fatigue damage mechanics, low-field nuclear magnetic resonance (NMR) imaging, and scanning electron microscopy (SEM). A device to evaluate cement sheath integrity was developed. The design of a simulated wellbore test device (size, materials, and loading conditions) was based on the stress equivalence method. The stresses on the first and second interfaces of the cement sheath in the device were equal to those in the wellbore. The failure mechanism of the cement sheath was verified by deformation testing of the casing-cement sheath-simulated formation under cyclic loading and computed tomography (CT). This study demonstrates the reliability of the device and the accuracy of the experimental results, thereby providing a new method for evaluating the sealing ability of a cement sheath in a gas storage well.

2 | MATERIALS AND METHODS

2.1 | Materials

The material used in this study was a class G Portland cement. The formula for the cement slurry was as follows: 100% G-class cement (Aksu Qingsong Cement Plant) + 30% weighting agent (GM-1) + 25% silica fume + 7.8% anti-gas channeling agents (FLOK-2) + 7.9% fluid loss additive (HX-11L) + 5.9% dispersion agent (HX-21L) + 7.3% industrial salt + 0.2% fiber (polyvinyl alcohol) + 0.2% defoaming additive (DF-A) + 44% water. The density of the cement slurry was 2.05 g/cm\textsuperscript{3}.

2.2 | Triaxial cyclic loading test

A triaxial pressure testing system (Equipment model: RTR-1000, GCTS, USA; maximum test temperature: 150°C; maximum confining pressure: 140 MPa) was used to test the stress strain of the cement stone, according to the Chinese standard GB/T 50266-2013.\textsuperscript{38} The temperature and confining pressure were 85°C and 30 MPa, respectively. Cement stone specimens of 25 mm in diameter and 50 mm in length were prepared at 85°C and 30 MPa, and the stress-strain curve of the cement stone was measured under cyclic loading.

Mechanical damage of the cement stone occurs during cyclic loading according to the classic theory of damage mechanics and causes irreversible deformation. The elastic modulus of a damaged cement stone can be calculated as follows\textsuperscript{39}:

\[
D_i = 1 - \frac{E_D}{E} \quad (0 \leq D_i < 1),
\]

where \(E\) is the initial elastic modulus and \(E_D\) is the elastic modulus of the damaged cement stone.
where $E$ is the initial elasticity modulus; $D_i$ is the damage variable of the cement sheath after the $i$ th cycle, and $E_{D_i}$ is the elasticity modulus of the cement sheath after the $i$ th cycle.

### 2.3 Nuclear magnetic resonance

Internal pores and cracks in the cement stone before and after triaxial cyclic loading tests were evaluated using an NMR imaging device (Equipment model: AniMR-150, Shanghai Niumag Electronic Technology).

### 2.4 Scanning electron microscope

Cement stone specimens were freeze-dried under vacuum conditions before and after the triaxial cyclic loading tests. The microstructure was observed by SEM (Equipment model: Quanta 450, FEI, USA; acceleration voltage: 200 V to 30 kV; magnification: 6×-100 000×; resolution: high vacuum mode: 3.0 nm at 30 kV), and then, the development of micropores and microcracks was analyzed.

### 2.5 Cement sheath integrity

A test device was developed to simulate the wellbore structure, temperature and pressure conditions, and load-bearing mode of the cement sheath. The casing pressure and external pressure of the simulated formation were adjusted to equal those of the wellbore cement sheath. These adjustments were based on the principle of stress at the first and second interfaces of the cement sheath in the device to simulate the effects of actual working conditions on the deformation, damage, and failure of the cement sheath.

The test device consists of three systems. (a) A simulated casing-cement sheath-formation system (Figure 2) is the core component of the test device. Its primary role is to simulate the casing-cement sheath-formation structure and reproduce the wellbore conditions. The simulated system is placed in the temperature-controlled chamber. A interface and a pipeline are integrated into the upper part of the chamber. The simulated casing-cement sheath-formation system is constructed with single layers. (b) A capture and test system is integrated into the casing-cement sheath-formation simulation system to measure and transmit temperature and pressure data (Figure 3). A computer-controlled pressure pump applies pressure to the simulated casing-cement sheath-formation system, and a thermocouple adjusts the experimental temperature. The capture and test system also measures radial displacements of the casing and formation, circumferential deformations, gas flows, and acoustic waves. The radial displacement of the casing is measured by a displacement meter (Figure 4A), which is installed at the casing interface at a level of 90°. Three displacement meters can measure the relative displacement of a casing when it expands or contracts under pressure. The circumferential deformation is measured by a deformation meter that encloses a chain shape outside the simulated formation (Figure 4B). The accuracy of the test results is 1 µm, which can accurately measure the deformation of casing-cement sheath-simulated formation under varying pressure conditions. The gas source was connected to the cement sheath. When the cement sheath integrity fails, the gas flows through the cement sheath body or interface. The gas flow meter (Figure 4C) detects the amount of gas in real time. Four sonic probes (Figure 4D) detect the cement sheath failure position. The sonic probes in this device are acoustic receiving devices, which are different from the acoustic logging devices used to detect the filling of the cement sheath and the cementing quality.\(^{40,41}\) (c) A control system that controlled the experimental conditions and summarized the test data. The three systems and the test device are shown in Figure 5.

Compared with existing devices, the device used in this study has several advanced functions. (a) The test device replicates the shape of the wellbore cement sheath, and the forces exerted by the device are close to those that occur in the wellbore.\(^{42}\) (b) Prefabricated samples are not required for the pressurized curing chamber because the pieces can be cured and evaluated directly in the test device.\(^{1,37}\) This approach avoids damaging the cement sheath during cooling and exposure to reduced pressure before the test. (c) In addition to qualitatively evaluating the cement sheath failure by
a gas flow meter, the device measures the deformation of the simulated casing-cement sheath-formation system under various pressure and temperature conditions.

The cement slurry was initially poured into the annulus between the casing and simulated formation, and the temperature and pressure were set to 85°C and 30 MPa, respectively. The stresses on the first and second interfaces of the cement sheath were adjusted after 72 hours to replicate working conditions by regulating the casing inner pressure and the simulated formation outer pressure, based on the stress equivalence method. After the experiment starts, keep the experiment temperature and the simulated formation pressure constant. The internal casing pressure was adjusted by a computer-controlled pressure pump, adopt gradual pressurization to make the internal casing pressure reach the set value, and then used the same rate to reduce the casing internal pressure to 0 MPa. If gas channeling was not detected, it was necessary to recycle the loading and unloading pressures until the cement sheath failed to seal and gas channeling occurred. During the experiment, the radial displacement of the upper, middle, and lower casing and the circumferential displacement of the simulated formation were detected in real time. The device collected the acoustic signal data and detected when damage to the cement sheath occurred. The isolation
ability of the cement sheath was tested using a gas flow meter. At the end of the experiment, the simulated casing-cement sheath-formation system was removed for nondestructive testing.

2.6 | Computed tomography

Direct observation of the failure mode is challenging because the cement sheath is between the casing and the simulated formation. CT scanning (Equipment model: Phoenix v|tome|x s, Yinghua NDT Shanghai, Nanoscale Industrial CT) was used to observe the internal structure of the cement sheath.

3 | MODEL ESTABLISHMENT AND EXPERIMENTAL PARAMETERS

A stress equivalence method was initially developed to simulate the in situ stress and generate the load-deformation law of the device cement sheath. The device parameters were designed according to this model so that the deformation and failure laws of a wellbore cement sheath could be obtained.

3.1 | Assumptions

According to the basic principle of elastic mechanics, a problem with the cement sheath mechanical model is the axisymmetric strain in the plane. Therefore, several assumptions were made to simplify the model. (a) The casing is centralized. (b) High-quality cementing is performed, and strong bonds exist at the casing, cement sheath, and formation interfaces. (c) The formation and casing are composed of homogeneous, continuous, and isotropic linear elastic materials. (d) The cement sheath is a homogeneous, continuous, and isotropic linear elastic material before it is damaged. (e) The cement sheath exhibits no sliding with the casing and formation before the generation of a microannulus. (f) The tensile stress direction is positive, while the compressive stress direction is negative. The structure of the casing-cement sheath formation is illustrated in Figure 6.

3.2 | Stress calculation for the wellbore cement sheath

The stress distribution of a wellbore cement sheath needs to be explored under working conditions that simulate the load-deformation law of the cement sheath. We adopted the following formulas of the thick-walled cylinder theory to solve a model based on stress and displacement.

\[
\begin{align*}
\sigma_r &= \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} - \frac{r_i^2 P_i - P_o}{r_o^2 - r_i^2} \left( r_i - r_o \right), \\
\sigma_\theta &= \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} + \frac{r_i^2 P_i - P_o}{r_o^2 - r_i^2} \left( r_i - r_o \right) r^2.
\end{align*}
\]

\[
u = \frac{1 - 2\nu}{E} \frac{r_i^2 P_i - r_o^2 P_o}{r_o^2 - r_i^2} r + \frac{1 + \nu}{E} \frac{r_i^2 P_i - P_o}{r_o^2 - r_i^2} r^2.
\]
where \( r_1 \) and \( r_o \) are the inner and outer radii, respectively, of the casing, cement sheath, or formation; \( r \) is the distance from the center \( (r_1 \leq r \leq r_o) \); \( P_i \) and \( P_o \) are the inner and outer surface pressures of the casing, cement sheath, or formation; \( \sigma_r \) and \( \sigma_\theta \) are the radial and tangential stresses; \( u \) is the displacement of the casing, cement sheath, or formation, and \( E \) and \( \nu \) are the Young's modulus and Poisson's ratio of the casing, cement sheath, or formation.

The interface stress expression of the cement sheath can be obtained from Equations (2) and (3) as

\[
\begin{align*}
\sigma_\theta &= -P_i \\
\sigma_r &= \frac{r_1^2 + r_o^2}{r_o^2 - r_1^2} P_i - \frac{2r_1^2 r_o^2}{r_o^2 - r_1^2} \sigma_\theta \\
\sigma_\theta &= -P_i \\
\sigma_r &= \frac{2r_1^2 r_o^2}{r_o^2 - r_1^2} P_i - \frac{r_1^2 + r_o^2}{r_o^2 - r_1^2} \sigma_\theta
\end{align*}
\]

Cement sheath first interface: \( \sigma_\theta = -P_i \), \( \sigma_r = \frac{r_1^2 + r_o^2}{r_o^2 - r_1^2} P_i - \frac{2r_1^2 r_o^2}{r_o^2 - r_1^2} \sigma_\theta \)

Cement sheath second interface: \( \sigma_\theta = -P_i \), \( \sigma_r = \frac{2r_1^2 r_o^2}{r_o^2 - r_1^2} P_i - \frac{r_1^2 + r_o^2}{r_o^2 - r_1^2} \sigma_\theta \)

where \( \sigma_\theta \) and \( \sigma_r \) are the radial stresses at the first and second interfaces of the cement sheath; \( \sigma_\theta \) and \( \sigma_r \) are the tangential stresses at the first and second interfaces of the cement sheath, and \( P_i \) and \( P_o \) are the pressures at the first and second interfaces of the cement sheath.

\[\cdots\]

3.3 Stress equivalence method

The experiment used the same cement slurry as the wellbore so that the experiment and wellbore cement sheath could be considered to have the same mechanical properties (eg., Young's modulus, Poisson's ratio, and strength) under the same temperature and pressure conditions. The strain of the cement sheath must be identical under the same Young's modulus and stress, according to Equation (5). Therefore, when the stresses at the first and second interfaces of the device cement sheath are the same as those in the wellbore, a simulation of the load-deformation law of the cement sheath is achieved.

\[ E = \frac{\sigma}{\epsilon}, \]

where \( \sigma \) and \( \epsilon \) are the stress and strain, respectively.

The size and materials of the casing and simulated formation in the device are different than those in the wellbore. Therefore, if the experiment were conducted by directly applying the actual casing inner pressure and formation pressure, then the stress of the device cement sheath would deviate from that of the wellbore. Instead, a reasonable stress equivalence method is used to calculate the pressure required to ensure that the device cement sheath bears the same stress as the cement sheath in the wellbore.

The size of the simulated casing-cement sheath-formation system, casing inner pressure, and simulated formation outer pressure were adjusted in the test device after the stress at the interface of the device cement sheath was the same as in the wellbore.

Equation (7) was established based on the principle of tangential stress equality between the wellbore cement sheath and the device cement sheath at the first and second interfaces.

\[
\begin{align*}
\sigma_\theta &= \frac{r_2^2_{\text{wellbore}} + r_3^2_{\text{wellbore}}}{r_3^2_{\text{wellbore}} - r_2^2_{\text{wellbore}}} P'_{\text{wellbore}} - \frac{2r_2^2_{\text{wellbore}}}{r_3^2_{\text{wellbore}} - r_2^2_{\text{wellbore}}} \sigma_\theta \\
\sigma_r &= \frac{2r_2^2 r_3^2}{r_3^2_{\text{wellbore}} - r_2^2_{\text{wellbore}}} P'_{\text{wellbore}} - \frac{r_2^2 + r_3^2}{r_3^2_{\text{wellbore}} - r_2^2_{\text{wellbore}}} \sigma_\theta
\end{align*}
\]

\[
\sigma_\theta = -P'_{\text{device}} \\
\sigma_r = \frac{2r_2^2 r_3^2}{r_3^2_{\text{device}} - r_2^2_{\text{device}}} P'_{\text{device}} - \frac{r_2^2 + r_3^2}{r_3^2_{\text{device}} - r_2^2_{\text{device}}} \sigma_\theta
\]

where \( r_2^\text{wellbore} \) and \( r_3^\text{wellbore} \) are the inner and outer radii of the cement sheath in the wellbore, respectively; \( r_2^\text{device} \) and \( r_3^\text{device} \) are the inner and outer radii of the cement sheath in the device, and \( P'_{\text{wellbore}}, P'_{\text{device}}, P''_{\text{wellbore}}, \) and \( P''_{\text{device}} \) are the pressures at the first (') and second (") interfaces of the cement sheath in the wellbore and the device.

In Equation (7), \( P'_{\text{wellbore}} = P'_{\text{device}}, \) and \( P''_{\text{wellbore}} = P''_{\text{device}} \) because the stresses at the cement sheath interfaces in the device are the same as those in the wellbore. Therefore, Equation (7) can be simplified to the following:

\[
\frac{r_2^\text{wellbore}}{r_2^\text{device}} = \frac{r_3^\text{device}}{r_3^\text{wellbore}}.
\]

As long as the ratio of the inner diameter to the outer diameter of the cement sheath in the test device is the same as that in the wellbore, the tangential stresses of the cement sheaths in the device and wellbore are equal.

Equation (9) was established based on the principle of radial stress equality between the wellbore cement sheath...
and the device cement sheath at the first and second interfaces.

\[
\begin{align*}
\sigma_r' &= -P'_{\text{wellbore}} = -P'_{\text{device}} \\
\sigma_r'' &= -P''_{\text{wellbore}} = -P''_{\text{device}},
\end{align*}
\]

(9)

where \(P'_{\text{wellbore}}\) and \(P''_{\text{wellbore}}\) are obtained from the model presented in Section 3.2.

The key to maintaining equality between the radial stresses on the cement sheaths in the wellbore and device is to keep the pressures at the first and second interfaces of the cement sheath equal.

The size of the cement sheath was selected using Equation (8). In this study, the device cement sheath was a 1/3 scale model of the wellbore cement sheath, and then, the casing and simulated formation dimensions were set. Table 1 presents the parameters of the wellbore and the experimental materials. When the wellbore formation boundary is sufficiently long, its effect on the wellbore stress distribution can be ignored. Therefore, the formation boundary used to calculate the stress distribution of the wellbore cement sheath is 10 times the wellbore radius.

A steel cylinder is used to simulate the shape of wellbore formation and its restraint on the cement sheath. Although there are differences in the physical properties of steel and a formation, as long as the ratio of the cement sheath interface and the interface pressure meet the requirements based on the stress equivalence method, the stress conditions and load-deformation law of the device cement sheath will be consistent with those of the wellbore cement sheath.

Finally, the stress calculation model of the wellbore cement sheath is transformed into the following form:

\[
\begin{align*}
P'_{\text{device}} &= \frac{(1+r'_{\text{device}})^2}{E_{\text{device}}^2(r'_{\text{device}}-r''_{\text{device}})} + \frac{(1+r''_{\text{device}})^2}{E_{\text{device}}^2(r''_{\text{device}}-r'_{\text{device}})} - \frac{2r'_{\text{device}}^2}{E_{\text{device}}^2(r'_{\text{device}}-r''_{\text{device}})} P'_{\text{wellbore}} - \frac{2r''_{\text{device}}^2}{E_{\text{device}}^2(r''_{\text{device}}-r'_{\text{device}})} P''_{\text{wellbore}} \\
P''_{\text{device}} &= \frac{(1+r''_{\text{device}})^2}{E_{\text{device}}^2(r''_{\text{device}}-r'_{\text{device}})} + \frac{(1+r'_{\text{device}})^2}{E_{\text{device}}^2(r'_{\text{device}}-r''_{\text{device}})} - \frac{2r''_{\text{device}}^2}{E_{\text{device}}^2(r''_{\text{device}}-r'_{\text{device}})} P'_{\text{wellbore}} - \frac{2r'_{\text{device}}^2}{E_{\text{device}}^2(r'_{\text{device}}-r''_{\text{device}})} P''_{\text{wellbore}},
\end{align*}
\]

where “device” and “wellbore” indicate the parameters in the test device and the wellbore, respectively; \(E^c, E',\) and \(E''\) are the Young’s modulus of the casing, cement sheath, and simulated formation; \(v^c, v',\) and \(v''\) are the Poisson’s ratios of the casing, cement sheath, and simulated formation; \(r_1, r_2, r_3,\) and \(r_4\) are the casing inner diameter, cement sheath inner diameter, and the inner and outer diameters of simulated formation.

By substituting the stresses and pressures of the first and second interfaces of the wellbore and the parameters in Table 1 into Equation (10), the casing inner pressure and simulated formation outer pressure during the experiment can be obtained.

### 3.4 | Experimental conditions

The formation pore pressure was 26 MPa, and the maximum casing pressure was 90 MPa during gas injection, according to the data from the gas storage well. The wellbore pressure was equivalent to the test device based on the stress equivalence method. When the casing pressure was 70 MPa, and the simulated formation outer pressure was 30 MPa, the interface stress of the device cement sheath is equal to that in the wellbore. The experimental conditions are listed in Table 2. In addition, the experimental temperature of 85°C is the same as the wellbore.

### 4 | EXPERIMENTAL RESULTS AND DISCUSSION

#### 4.1 | Triaxial cyclic loading

The stress-strain relationship of the cement stone is measured at 85°C and 30 MPa confining pressure to investigate

| Elastic modulus (GPa) | Poisson’s ratio | Well size (mm) | Simulated size (mm) |
|----------------------|----------------|----------------|---------------------|
| Casing               | 206.85         | 0.3            | 170.0 (ID)          | 54.5 (ID)          |
|                      |                |                | 190.5 (OD)          | 63.5 (OD)          |
| Cement               | 4.3517         | 0.29           | 223.5 (OD)          | 74.6 (OD)          |
|                      |                |                | 2235(OD)            | /                  |
| Formation            | 50             | 0.36           | 2235(OD)            | /                  |
| Simulated formation  | 206.85         | 0.3            | /                  | 86.6 (OD)          |

**TABLE 1** Experimental parameters
the mechanical properties of the cement stone under triaxial cyclic loading. The triaxial compressive strength of the cement stone is 57 MPa, with good elastoplasticity (Figure 7). The mechanical properties of the cement stone under triaxial cyclic loading conditions are tested by applying a 70% limit deviator stress.

A new plastic strain was generated in each loading and unloading cycle, although each loading curve was approximately straight (Figure 8). The cement stone exhibits the maximum deformation during the first loading cycle. At later cycles, the cement stone exhibits different degrees of irreversible deformation, which causes the hysteresis loops to move to the right. In this case, the cement sheath suffers fatigue damage during the cyclic loading process, causing the cement stone to fail.

Fatigue failure tends to produce brittle cracks that gradually expand and lead to ultimate fracture under lower than normal conditions of alternating or cyclic stress. In cement stone, fatigue failure refers to the extension of micropores and microcracks into macrocracks. In this study, the classical fatigue theory was used to analyze the damage to the cement stone under cyclic loading.

Table 3 presents the values of strain and the elasticity module of the cement stone under cyclic loading. The cement stone accumulates permanent deformation under cyclic loading, and the elastic modulus gradually decreases during each period. Furthermore, the decrease in the elastic modulus as the number of loading cycles increases indicates that the stiffness of the cement stone decreases and the elastoplasticity increases.

The elastic modulus of the cement stone in the unloading stage is the modulus of unloading, while the elastic modulus in the first loading period is the initial modulus. The damage variable of the cement stone is calculated using Equation (1).

The damage variable of the cement stone is the maximal in the first cycle because the irreversible deformation of the cement stone is the largest (Figure 9). As the number of loading cycles increases, the damage variable of the cement stone continues to increase, indicating that internal damage is accumulating continuously. When the internal damage forms macroscopic fractures, the cement sheath exhibits mechanical failure.

4.2 | Scanning electron microscope

The cement stone microstructure plays a decisive role in its performance. Microstructural analysis by SEM allows the damage cracking law of the cement stone under triaxial cyclic loading to be investigated in greater detail.

The cement stone before cyclic loading is shown in Figure 10. The microstructure analysis shows that the polyvinyl alcohol fiber is completely affixed to the cement matrix. No obvious transition layers exist on the contact face (Figure 10A), indicating that the fiber improves the mechanical properties of the cement stone. Figure 10B,C show that the cement stone contains micropores of different sizes, and no apparent cracks exist in the cement matrix.

Cracks are present in the cement stone that pass through the fibers after cyclic loading, indicating that these fibers do not prevent the cement stone from cracking (Figure 11A). When the cement stone is subjected to cyclic loading, the size of the micropores in the cement matrix decreases, and the cement stone becomes compacted. Macroscopically, this
causes an increase in the stiffness of the cement stone. An apparent stress concentration exists at the edge of the micropores, leading to microcracks (Figure 11B). If the microcracks continue to extend, the cement stone can fail.

### 4.3 Nuclear magnetic resonance

SEM detects local features. Therefore, NMR is used to investigate the effects of cyclic loading on the cement stone microstructure more comprehensively.

The density of the cement stone and the development of pores and cracks are related to the pore diameter. The ratio of pores represents the proportion of pores and cracks in cement stone. If the number of pores and cracks in a certain volume of cement stone increases, the porosity increases. The ratio of pores having diameters of 5-50 μm decreases, but the ratio of pores with diameters of 200-2000 μm increases (Figure 12). After the sixth cycle, the ratio of pores having diameters between 5 and 50 μm decreases, and the ratio of the pores with diameters of 200-2000 μm dramatically increases. These data suggest that micropores shrink during loading cycles, and microcracks gradually increase as the number of cycles increase, causing irreversible deformation and producing macrocracks.

### 4.4 Cement sheath integrity and computed tomography scanning

The experimental and analysis results presented above represent the effects of cyclic loading on the mechanical properties and the behavior of micropores and microcracks in the cement stone. However, the stress state of the cement sheath in the wellbore is not entirely simulated because the cement stone is a sheath in the wellbore annulus. Moreover, the inner and outer surfaces of the cement sheath are restricted by the casing and formation, which differs from the free deformation that occurs during the triaxial cyclic loading tests of the cement stone. Therefore, a test device and an experiment were designed to simulate the state and
shape of the cement sheath. The data in Section 2.4.3 were used to design the experiment.

Under constant simulated formation pressure (30 MPa), there is no gas channeling or acoustic signal output after four cycles of casing inner pressure loading and unloading (Figure 13).

In the fifth cycle, a sonic probe is activated when the casing pressure increases to 30 MPa. Concurrently, the gas flow meter identifies a weak gas channeling. When the casing inner pressure decreases to 0, the gas flow increases to 32 sccm, and after 15 minutes, the gas flow stabilizes at 4 sccm, indicating that the cement sheath had been damaged. Although the casing inner pressure causes the casing to expand, the cement sheath is tightly compacted and exhibits isolation ability, so only a small amount of gas penetrates the cement sheath. When the casing inner pressure decreases to 0, the casing contracts, and gas channeling occurs in the cement sheath. However, when the casing inner pressure increases to 11 MPa, the gas flow decreases to 0 because the damage in the cement sheath is re-compacted by the casing pressure and simulated formation outer pressure. The gas channeling pressure is lower than the force at the damage position, so the gas does not penetrate the cement sheath.

The internal failure of the cement sheath is observed using CT (Figure 14). The cement sheath interface is tightly cemented, but an axial crack appears in the cement sheath and

---

**FIGURE 11** SEM after testing

(A) Cracks through fiber
(B) Microcracks through micropores

**FIGURE 12** Relationship between the ratio of pores and pore diameter

(A) First cycle
(B) Sixth cycle

**FIGURE 13** Gas flow and casing pressure curves of cement sheath failure
leads to gas channeling. Furthermore, pores of different sizes are observed in the cement sheath. These pores are not uniformly distributed and are primarily located in the cement sheath body rather than at the interface.

The cement sheath section exhibits an irregular distribution of pores and cracks (Figure 15). The macrocrack is a fatigue crack caused by cyclic loading. Microcracks expand via micropores, consistent with the SEM images in Figure 11B. Moreover, micropores appear on the left side of the cement sheath; these are smaller than the pores that generate microcracks, indicating that the stress concentration is more evident in the larger pores. The nonpenetrating microcrack in the radial direction of the cement sheath indicates that the cement sheath undergoes a process from failure to damage under cyclic loading.

A CT scan characterizes the mode of cement sheath failure but cannot accurately obtain the deformation law prior to failure. Therefore, it is necessary to measure and analyze the displacement data of the casing and simulated formation. The effects of the casing inner pressure on the radial displacement of the casing and circumferential deformation of the simulated formation under cyclic loading are displayed in Figures 16 and 17, respectively. In Figure 16, the radial displacements of the upper, middle, and lower casing are measured by three displacement meters in the capture and test system.

The radial displacements of the centralized casing are uniform (Figure 16). Concurrently, a comparison between the casing radial displacement and casing inner pressure demonstrates that they have the same trend; however, as the number of loading cycles increases, the radial displacement value at the same pressure point in each cycle is different and exhibits an increasing trend. There are two reasons for this phenomenon. First, the cement sheath is compacted by the structure, causing the volume of the cement sheath to decrease; second, the cement sheath undergoes plastic deformation, resulting in size changes. However, these changes do not affect the interfacial cementation.

The circumferential displacement changes with the casing inner pressure, and accumulation of displacement occurs (Figure 17).

The relationships between the radial displacement of the casing and the number of cycles under casing inner pressures of 0 and 63 MPa are shown in Figures 18 and 19, respectively. Circumferential displacement is converted into radial displacement by the relationship between the circumference and radius.

The radial displacement of the simulated formation is negligible (approximately $10^{-4}$) when the casing pressure is 0 or 63 MPa. Therefore, the radial displacement of the casing can be regarded as the radial displacement of the simulated casing-cement sheath-formation system.

The effect of the casing inner pressure on the casing radial displacement is shown in Figure 10. Because the casing and simulated formation are steel and have a higher yield strength than the cement sheath, the phenomenon resembles elastic deformation. When the casing inner pressure decreases, the casing recovers, but the cement sheath undergoes plastic deformation, which accumulates as the number of loading cycles increases, leading to a difference in the relative displacement. Because the casing inner pressure and casing radial displacement curve approximate the change in the loading and unloading of the cement sheath, the variation law is similar to the stress-strain relationship of the cement stone under triaxial cyclic loading. Therefore, the elastic modulus decreases, and the stiffness increases under cyclic loading in the wellbore. Moreover, failure occurs by the development and connection of micropores and microcracks within the cement sheath in response to pressure changes in the wellbore.

4.5 Analysis of the cement sheath interface

The radial displacement of the casing inner wall is a regular curve under cyclic loading, and the deformation is similar to the residual strain (Figure 20), suggesting that the cement sheath exhibits plastic deformation. However, when combined with the CT data in Figures 14 and 15, no interfacial peeling occurs at the cement sheath interfaces. Therefore, we investigated the elastic-plastic model of the cement sheath.

The microannulus calculation model and hypothesis proposed by Chu Wei et al. were used. The Mohr-Coulomb criterion was used as the yield criterion of the cement sheath. In
the loading stage, the cement sheath is an elastoplastic material, and in the unloading stage, the cement sheath undergoes elastic unloading. When the interface of the cement sheath bears radial tensile stress that is greater than the interface cementation strength, the interface peels. Otherwise, the bonding is not destroyed. The device parameters and test conditions in the study were selected, and compressive stress was defined as positive stress and the formation direction as the
positive direction. The results of the calculations are shown in Table 4.

In the loading stage, the cement sheath bears compressive stress that is greater at the first interface than at the second interface; therefore, plastic deformation occurs at the first interface. The plastic deformation of the cement sheath occurs in the first cycle, and at later cycles, the magnitude of plastic deformation increases. In the unloading stage, the stress distributed at the first and second interfaces of the cement sheath remains compressive stress. Therefore, although the cement sheath undergoes plastic deformation, the bonding surface is intact, and no peeling occurs. At the same time, the radial displacement of the interface position of the cement sheath in each cycle shows that the cement sheath is always in a state of compression, which explains why the cement sheath does not exhibit interfacial peeling.
5  |  CONCLUSIONS

The following conclusions can be drawn from the results of this study.

1. Using triaxial cyclic loading data in combination with classical fatigue damage mechanics, SEM, and NMR, we established the following: under cyclic loading, internal damage of the cement stone occurred and accumulated continuously, and the number of micropores and microcracks increased. Meanwhile, microcracks developed at micropore tips and formed macrocracks, lead to the eventual failure of the cement stone.

2. We used the principle of equal stress at the first and second interfaces of the cement sheath to propose a stress equivalence method. The material, size, and experimental conditions of the test device were designed to replicate the load-deformation law of the wellbore cement sheath in the device, based on the proposed stress equivalence method.

3. The displacement changes in the cement sheath under cyclic loading were similar to the stress-strain law of the triaxial cyclic loading test. At the same time, microcracks and micropores in the internal structure of the cement sheath caused damage under cyclic loading and eventually led to axial cracking and isolation failure.

4. Plastic deformation occurred at the first interface of the cement sheath under cyclic loading, but interfacial peeling did not occur because the first and second interfaces of the cement sheath always bear compressive stress under loading and unloading.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provide by the Research Project of Dagang Oilfield (DGYT-2018-JS-244) and the National Natural Science Foundation of China (5157041530). The State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation of SWPU are acknowledged for their assistance in laboratory tests.

ORCID

Donghua Su  https://orcid.org/0000-0002-6026-8362
Zaoyuan Li  https://orcid.org/0000-0003-0056-9574

REFERENCES

1. Li Z, Sun J, Luo P, Lin L, Deng Z, Guo X. Research on the law of mechanical damage-induced deformation of cement sheaths of a gas storage well. J Nat Gas Sci Eng. 2017;43:48-57.

2. Wanyan Q, Ding G, Zhao Y, Li K, Deng J, Zheng Y. Key technologies for salt-cavern underground gas storage construction and evaluation and their application. Nat Gas Industry B. 2018;5(6):623-630.

3. Nelson EB, Guillot D. Well Cementing. Sugar Land, TX: Schlumberger; 2006.
4. William C. L., Thomas C, Norton J. L. In: Formulas and calculations for drilling, production, and workover, Fourth Edition: All the Formulas You Need to Solve Drilling and Production Problems. Waltham, MA: Gulf Professional Publishing; 2016.

5. Zhang J, Tan Y, Zhang T, Yu K, Wang X, Zhao Q. Natural gas market and underground gas storage development in China. J Energy Storage. 2020;29:101338.

6. Zhang C, Cai J, Xu H, Cheng X, Guo X. Mechanical properties and mechanism of wollastonite fibers reinforced oil well cement. Constr Build Mater. 2020;260:120461.

7. Chen Y, Liang T, Peng X, Yu H. Calculation and analysis of the first interface micro-gaps of the thermal production wells. Adv Mech Eng. 2017;9(2):168781401668858.

8. Xi Y, Li J, Liu G, Cha C, Fu Y. Numerical investigation for different casing deformation reasons in Weyuan-Changning shale gas field during multistage hydraulic fracturing. J Petrol Sci Eng. 2018;163:691-702.

9. Chen Y, Peng X, Yu H. Mechanical performance experiments on rock and cement, casing residual stress evaluation in the thermal recovery well based on thermal-structure coupling. Energ Exploit Explot. 2017;35(5):591-608.

10. Al Ramis H, Teodoriu C, Bello O, Al Marhoon Z. High definition optical method for evaluation of casing - cement microannulus (CCMA). J Petrol Sci Eng. 2020;195:107719.

11. Kuanhai D, Wanying L, Tianguo X, Dezhi Z, Ming L, Yuanhua L. Experimental study the collapse failure mechanism of cemented casing under non-uniform load. Eng Fail Anal. 2017;73:1-10.

12. Li C, Guan Z, Zhao X, et al. A new method to protect the cementing sealing integrity of carbon dioxide geological storage well: an experiment and mechanism study. Eng Fract Mech. 2020;236:107213.

13. Meng M, Miska S, Yu M, Ozbayoglu EM. Mechanical behavior of Berea sandstone under cyclic loading: an application to dynamic loading of a wellbore. Spe-202487-PA. 2020.

14. Shahvali A, Azin R, Zamani A. Cement design for underground gas storage well completion. J Nat Gas Sci Eng. 2014;18:149-154.

15. Liu J, Guo X, Li Z. Study of the test method of key mechanical parameters of set cement in the gas storage well. J Southwest Petrol Univ (Sci Technol Ed). 2013;35(06):115-120.

16. Dillenbeck RL, Go Boncan VC, Rogers MJ. Testing cement static tensile behavior under downhole conditions. SPE-97967. 2005.

17. James S, Boukhelifa L. Zonal isolation modeling and measurements—past myths and today’s realities. SPE Drill Complet. 2008;23(1):68-75.

18. Garnier A, Fraboulet B, Saint-Marc J, Bois AP. Characterization of cement systems to ensure cement sheath integrity. In: OTC 18754; 2007.

19. Meng M, Miska S, Yu M, Frash L, Ozbayoglu EM. Prediction of monotonic strength of sandstone for accurate control of cyclic compression tests. In: ARMA 2020; 2020.

20. Jafariesfad N, Geiker MR, Gong Y, Skalle P, Zhang Z, He J. Cement sheath modification using nanomaterials for long-term zonal isolation of oil wells: review. J Petrol Sci Eng. 2017;156:662-672.

21. Goodwin KJ, Crook RJ. Cement sheath stress failure. SPE-20435-PA. 1992(7)(04):291-296.

22. Allix O, Hild F. Introduction to continuum damage mechanics. In: Continuum Damage Mechanics of Materials and Structures. Oxford: Elsevier Science Ltd; 2002.

23. Thiercelin M, Baumgarte C, Guillot D. A soil mechanics approach to predict cement sheath behavior. In: SPE-47375-MS. Society of Petroleum Engineers; 1998.

24. Thiercelin MJ, Dargaud B, Baret JF, Rodriguez WJ. Cement design based on cement mechanical response. In: SPE-52890-PA; 1998.

25. Jing L, Cheng-yan L, Shao-chun Y, Yin-min Z, Shao-wei C. Theoretical solution of thermal stress for casing-cement-formation coupling system. J Chin Univ Petrol (Edition of Natural Science). 2009.33(2):63–69.

26. KhandaK RK. Leakage behind Casing. Trondheim: NTNU; 2007.

27. Li Y, Liu S, Wang Z, Yuan J, Qi F. Analysis of cement sheath coupling effects of temperature and pressure in non-uniform in-situ stress field. In: SPE-131878-MS; 2013.

28. Chu W, Shen J, Yang Y, Li Y, Gao D. Calculation of micro-anulus size in casing-cement sheath-formation system under continuous internal casing pressure change. Petrol Explor Dev. 2015;42(3):414-421.

29. Gholami R, Aadnoy B, Fakhrui N. A thermo-elastic approach to evaluate cement sheath integrity in deep vertical wells. J Petrol Sci Eng. 2016;147:536-546.

30. Liu W, Yu B, Deng J. Analytical method for evaluating stress field in casing-cement-formation system of oil/gas wells. Appl Math Mech. 2017;38(9):1273-1294.

31. Bu Y, Ma R, Guo S, Du J, Liu H, Cao X. A theoretical evaluation method for mechanical sealing integrity of cementing sheath. Appl Math Model. 2020;84:571-589.

32. De Andrade J, Torsaeter M, Todorovic J, Opedal N, Stroisz A, Vralstad T. Influence of casing centralization on cement sheath integrity during thermal cycling. In: IADC/SPE Drilling Conference and Exhibition. Fort Worth, TX: Society of Petroleum Engineers; 2014:10.

33. Albawi A, De Andrade J. Experimental set-up for testing cement sheath integrity in arctic wells. In: OTC-24587-MS; 2014.

34. Yuan Z, Teodoriu C, Schubert J. Low cycle cement fatigue experimental study and the effect on HPHT well integrity. J Petrol Sci Eng. 2013;105:84-90.

35. Kuanhai D, Yue Y, Yi H, Zhonghui L, Yuanhua L. Experimental study on the integrity of casing-cement sheath in shale gas wells under pressure and temperature cycle loading. J Petrol Sci Eng. 2020;195:107548.

36. Xi Y, Li J, Tao Q, Guo B, Liu G. Experimental and numerical investigations of accumulated plastic deformation in cement sheath during multistage fracturing in shale gas wells. J Petrol Sci Eng. 2020;187:106790.

37. Li Z, Zhang K, Guo X, Liu J, Cheng X, Du J. Study of the failure mechanisms of a cement sheath based on an equivalent physical experiment. J Nat Gas Sci Eng. 2016;31:331-339.

38. GB/T 50266-2013. Standard for test methods of engineering rock mass.

39. Lemaître J, Dufailly J. Damage measurements. Eng Fract Mech. 1987;28:643-661.

40. Raab T, Reinsch T, Cifuentes SRA, Henninges J. Real-time well integrity monitoring using fiber-optic distributed acoustic sensing. SPE J. 2019;24(05):1997-2009.

41. Kruszewski M, Montegrossi G, Ramírez Montes M, et al. A wellbore cement sheath damage prediction model with the integration of acoustic wellbore measurements. Geothermics. 2019;80:195-207.
42. Wang X, Shen H, Sun B, et al. Mechanism of gas migration through microstructure of cemented annulus in deep-water environment. J Nat Gas Sci Eng. 2020;78:103316.
43. Zeng Y, Liu R, Li X, Zhou S, Tao Q, Lu P. Cement sheath sealing integrity evaluation under cyclic loading using large-scale sealing evaluation equipment for complex subsurface settings. J Petrol Sci Eng. 2019;176:811-820.
44. Tabatabaee Moradi SS, Nikolaev NI. Assessment of the cement failure probability using statistical characterization of the strength data. J Petrol Sci Eng. 2018;164:182-188.
45. Honglin X, Zhang Z, Shi T, Xiong J. Influence of the WHCP on cement sheath stress and integrity in HTHP gas well. J Petrol Sci Eng. 2015;126:174-180.
46. Amenzade IA. Theory of Elasticity. Moscow: Mir Publishers; 1979.
47. Jingjing F, Peiyu Y. Properties and microstructure of oil-well cement stone attacked by vitriol. J Chin Ceram Soc. 2012.40(5):671–676.

How to cite this article: Li J, Su D, Tang S, et al. Deformation and damage of cement sheath in gas storage wells under cyclic loading. Energy Sci Eng. 2021;9:483–501. https://doi.org/10.1002/ese3.869

APPENDIX A

Performance of cement slurry/stone
The cement slurry and stone performances were evaluated per the Chinese standard GB/T 19139-2012.

Cement slurry formula
The formula for the cement was as follows: 100% G-class cement (Aksu Qingsong Cement Plant) + 30% weighting agent (GM-1) + 25% silica fume + 7.8% anti-gas channeling agents (FLOK-2) + 7.9% fluid loss additive (HXL-11L) + 5.9% dispersion agent (HXL-21L) + 7.3% industrial salt + 0.2% fiber (polyvinyl alcohol) + 0.2% defoaming additive (DF-A) + 44% water.

Component testing
Table A1 shows the primary chemical components of the G-class oil-well cement, of which the two most abundant are CaO and SiO₂.

Parameters of the cement slurry
Parameters such as density, fluidity, free liquid volume, sedimentation stability, and rheological properties of the cement slurry were measured. The results are shown in Table A2.

Thickening time
The thickening time of the cement slurry was measured at 85°C and 30 MPa using a pressurized, single-cell consistometer. The test results are shown in Figure A1.

Curing and compressive strength of the cement stone
A pressurized, single-cell curing chamber was used to cure the cement stones (50 mm × 50 mm × 50 mm). The curing pressure was 20.7 MPa; the temperature was 85°C, and the curing time was 3 days. The cement stones are shown in Figure A2. The compressive strength results are shown in Table A3.

Tensile strength of the cement stone
The Brazilian splitting method was used to measure the tensile strength of the cement stone (50 mm × 25 mm). The samples are shown in Figure A3, and the test results are shown in Table A4.

Triaxial compressive strength of the cement stone
The cement stone was cured at 85°C and 30 MPa, and triaxial compressive strength testing was performed on core samples obtained from the cured cement stone. The core samples are shown in Figure A4. The test results are shown in Figure A5 and Table A5.

| TABLE A1 | Primary chemical components of G-class oil-well cement |
|-----------|--------------------------------------------------------|
| Chemical components | CaO | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | Na₂O + K₂O | SO₃ |
| Mass fraction (%) | 64.02 | 22.35 | 3.40 | 4.83 | 1.39 | 0.46 | 2.46 |
**FIGURE A1**  Thickening time of cement slurry

**FIGURE A2**  Cement stones after curing

**FIGURE A3**  Cement stone samples

**FIGURE A4**  Cement stone core samples
**FIGURE A5** Triaxial compressive strength curves of cement stone core samples

**TABLE A2** Parameters of the cement slurry

| Density (g/cm³) | Fluidity (cm) | Free fluid | Sedimentation stability (Density contrast) (g/cm³) | Reading of shear stress (600/300/200/100/6/3) |
|----------------|---------------|------------|----------------------------------------------------|----------------------------------------------|
| 2.05           | 18            | 0          | 0                                                  | 251/147/110/59/10/7                         |

**TABLE A3** Compressive strength of the cement stone

| Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 |
|----------|----------|----------|----------|----------|----------|
| Compressive strength (MPa) | 27.6 | 31.8 | 28.4 | 29.7 | 27.9 | 30.1 |

**TABLE A4** Tensile strength of the cement stone

| Sample 1 | Sample 2 | Sample 3 |
|----------|----------|----------|
| Tensile strength (MPa) | 27.6 | 31.8 | 28.4 |

**TABLE A5** Triaxial compressive strength and Young’s modulus of cement core samples

| Sample 1 | Sample 2 | Sample 3 |
|----------|----------|----------|
| Triaxial compressive strength (MPa) | 57 | 58.4 | 51 |
| Young’s modulus (MPa) | 4351.7 | 4945.2 | 4700.2 |