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Effects of the porous structure of cement sheaths on the deformation failure mechanism of wellbore cement sheaths

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Abstract
Two types of cement sheaths with different porosities were prepared by using cement materials and liquid silicon suspension. The distribution characteristics of the pore radius and space location of two types of cement sheaths were analyzed using CT scanning experiments and statistical principles to obtain their probability density distribution functions. Based on the distribution functions, the “single-layer” and “double-layer” porous models of two types of cement sheaths were constructed using a self-developed program incorporated with the FLAC 3D program. A series of numerical simulations were conducted to study the deformation and failure laws of wellbore cement sheaths under in situ stress and hydraulic pressure. The effects of the porosity and double-layer structure on the breakdown pressure, plastic failure zone, radial deformation, and stress distribution of the cement sheaths were analyzed. As a result, the effect mechanisms of the porosity and double-layer structure on the failure mode, failure path, and interaction between the cement sheath and metal casing were revealed. The failure modes and paths of single- and double-layer cement sheaths were obtained. This research provides a basis for understanding the characteristics of stress distribution, deformation, and failure mode of porous cement sheaths under hydraulic pressure.
Introduction

Hydraulic fracturing is a common stimulation method for exploiting unconventional low-permeability oil and gas resources such as coalbed methane, shale gas, and shale oil. The safety of metal casings in fractured wells is crucial for implementing hydraulic fracturing technology in the field. To ensure the safety and stability of a metal casing, cement mud should be injected between the metal casing and the wellbore to form a cement sheath. The cement sheath can effectively prevent corrosion, deformation, and failure of the metal casing. Failure of the cement sheath can cause a deformation of the metal casing and fracturing well collapse, resulting in hydraulic fracturing process failure and huge economic losses.

Studies have found that the cement type, stratum conditions, fracturing methods, and temperature environment significantly affect the safety of cement sheaths. Therefore, ensuring the integrity and safety of cement sheaths is crucial for safe exploitation of unconventional oil and gas resources.

As early as the 1970s, researchers found that stress effects can affect the integrity of cement sheaths. In the 1990s, a double-layer concentric casing simulation device was established to study the influence of stress on the tightness of a cement sheath under different temperatures and pressures. The results showed that radial cracks in the cement sheath caused by the casing pressure considerably influence cement ring failure. Further, some scholars established a mathematical model of the coupling effect of temperature and stress on a cement sheath under non-uniform in situ stress conditions. The effects of the change in casing temperature and pressure on the stress magnitude and distribution in the cement sheath under non-uniform in situ stress were studied. Subsequently, the Mohr-Coulomb failure criterion was used to evaluate the integrity of a cement sheath based on cement mechanical properties, casing pressure, and initial temperature. To explore the failure mechanism of cement sheaths, a set of integrity test experiment device for cement sheaths was developed, and comparative experimental research on cement sheath integrity was conducted under concentric and eccentric conditions. Existing research indicates that reducing the elastic modulus of a cement sheath can decrease stress and prevent its failure. Some scholars added rock asphalt particles modified by plasma technology into cement sheaths and tested their mechanical parameters. It was found that rock asphalt particles could effectively strengthen a viscoelastic cement sheath and increase the frictional force between cracks, thereby improving the impact resistance and deformation ability of the cement sheath.

In summary, these studies have played a positive role in deepening the understanding of the deformation and failure mechanisms of cement sheaths and improving their integrity and stability. However, cement is a heterogeneous material with numerous micropores, which can considerably influence the deformation and failure of cement sheaths under conditions of in situ stress and hydraulic fracturing. At present, most researches on the deformation and failure of cement sheaths do not consider the effects of pore structure, and mainly focuses on the mechanical characteristics of cement sheaths, failure crack geometry, and damage laws. Few studies have been conducted on the distribution characteristics of porous structures in cement sheaths and their influence on the stress distribution and deformation of cement sheaths, especially the effects on the failure mode and failure path of cement sheaths. The mechanisms by which the porous structure affects the deformation failure of cement sheaths are ill-understood. Therefore, exploring the effects of the porous structure on the stress distribution, deformation characteristics, failure mode, and failure path of cement sheaths, and revealing their deformation and failure mechanisms, is necessary. This can effectively prevent cement sheaths damage and improve their integrity, to reduce the huge economic loss caused by cement sheath failure in oil and gas exploitation.

To solve the abovementioned problems, two types of cement sheaths with different porosities were prepared: a net slurry cement sheath and a liquid silicon cement sheath. The distribution characteristics of the micropores of the two types of cement sheaths were analyzed using CT scanning experiments. Using a self-developed program incorporated with the FLAC 3D program, the porous models of the net slurry cement sheath and liquid silicon cement sheath were constructed to simulate their deformation and failure.
process under the combined action of in situ stress and hydraulic pressure. The reconstruction idea of porous models of cement sheaths is shown in Fig. 1. The effects of the porosity on the breakdown pressure, stress distribution, deformation, failure mode, and failure path of the cement sheaths were studied. The porous reconstruction models of “single-layer cement sheath” and “double-layer cement sheath” were employed to explore the effect of double-layer structure on failure and the interaction mechanism of the cement sheaths and metal casing.

![Figure 1. Reconstruction idea of porous models of cement sheaths.](image)

**Methodology**

**Cement sheath core preparation.**

In order to obtain the cement sheaths with different porosities, in this study, two types of cylindrical cores of cement sheaths were fabricated by using mixed materials: net slurry cement sheath cores and liquid silicon cement sheath cores. The sizes of the cylindrical cores were $\phi 25 \text{ mm} \times 50 \text{ mm}$. The composition of mixed materials included cement, quartz sand, water reducer, water, and liquid silicon suspension. The ratios of mixed materials are based on the engineering ratio on site, as shown in Table 1. The specific preparation process is as follows: First, the materials were weighed based on the material ratio. The weighed mixture was then placed in a blender and blended for 3 min to make it even. Finally, the mixture was poured into a cylindrical mold and formed after 72 h of high-temperature curing. The prepared cylindrical cores are shown in Fig. 2. The production process and curing time of all cylindrical cores were the same, which ensured the consistency of the porous structure distribution characteristics and mechanical properties of the same type of cement sheath core.

![Table 1. Mixed materials ratio.](image)
Mechanical properties of cement sheaths.

Uniaxial compression tests, Brazilian splitting tests, and triaxial compression tests were carried out to obtain the mechanical parameters of the net slurry cement sheath and liquid silicon cement sheath. The loading rate for the uniaxial compression test was 0.5 mm/min. Three groups of experiments were conducted for each cement sheath type. The experimental results were averaged to obtain the uniaxial compressive strength, elastic modulus, and Poisson ratio. The loading rate in the Brazilian splitting experiment was 0.1 mm/min. Three groups of experiments were also conducted for each type of cement sheath, and the experimental results were averaged to obtain the tensile strength. Triaxial compression tests were performed using a triaxial servo testing machine with confining pressures of 5, 15, and 25 MPa. The cohesion force and internal friction angle of the net slurry cement sheath and liquid silicon cement sheath were tested. The experimental results are listed in Table 2. Fig. 3 shows three types of experimental photographs, and Fig. 4 shows the stress-strain curves of uniaxial compression.

Table 2. Mechanical parameters of cement sheaths.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength /MPa</th>
<th>Compressive strength /MPa</th>
<th>Elasticity modulus /GPa</th>
<th>Poisson’s ratio</th>
<th>Cohesion force /MPa</th>
<th>Internal friction angle /°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net slurry cement sheath</td>
<td>2.0</td>
<td>53.78</td>
<td>4.59</td>
<td>0.16</td>
<td>5.6</td>
<td>30</td>
</tr>
<tr>
<td>Liquid silicon cement sheath</td>
<td>4.8</td>
<td>54.31</td>
<td>3.56</td>
<td>0.15</td>
<td>7.8</td>
<td>35</td>
</tr>
</tbody>
</table>

Figure 2. Cylindrical cores of cement sheaths.

Figure 3. Experimental photos.
Pore distribution characteristics of cement sheaths.

To analyze the distribution characteristics of the porous structure of the net slurry cement sheath and liquid silicon cement sheath, CT scanning experiments were performed by using an industrial CT scanning system. Consequently, CT scanning images of their porous structure were obtained. A total of 1950 CT images of each type of cement sheath were obtained using volume scanning with a scanning interval of 25.6 µm. The CT images were preprocessed to improve quality. First, a Gaussian filter and the median filter algorithm were used to process the noise points and ring artifacts of the CT images. Second, a threshold segmentation method was used to binarize the CT images. The binarized CT images of the porous structures are shown in Fig. 5.

Using the self-developed program, the porosities of all binarized CT images of the net slurry cement sheath and liquid silicon cement sheath were calculated, and the average value was obtained. Statistically, the average value represents the porosity of the cement sheath. The calculated results show that the porosity of the net slurry cement sheath is 1.25% and that of the liquid silicon cement sheath is 0.86%.

Spatial location distribution characteristics of pores.

In this study, the spatial location distribution characteristics of the pores of the clean slurry cement sheath and liquid silicon cement sheath were analyzed, and the distribution curves of the spatial location were obtained. The specific analysis process is as follows: Ten CT images were selected as representative layers.
from 1950 CT images of each type of cement sheath, numbered 140, 335, 525, 715, 905, 1095, 1285, 1475, 1665, and 1855, respectively. The CT images of all representative layers were evenly divided into 20 equal parts along the circumferential direction, and the number and probability density of pores in each part of each representative layer were calculated using a self-developed program. The probability density curves of the pores of every representative layer along the circumferential distribution were obtained, as shown in Fig. 6.

Figure 6. Spatial location distribution curves of pores.

It has been found that, for both the net slurry and liquid silicon cement sheaths, the probability density of the pore distribution along the circumferential direction of all representative layers is concentrated in the range of 4%–8%, which is approximately constant. This indicates that the pore spatial location is approximately uniformly distributed along the circumferential direction.

Distribution characteristics of pore radius.
By analyzing the binarized CT images of the porous structure, it can be observed that the pore radius distribution range of the net slurry cement sheath is 35.65–356.48 μm, and that of the liquid silicon cement sheath is 33.3–333.02 μm. According to the upper and lower limits of the distribution range of each cement sheath type, the distribution range of the pore radius was evenly divided into 10 equal parts. The number and probability density of pores in each part were calculated using a self-developed program. Fig. 7 shows the probability density distribution curves of the pore radii of all representative layers.

Figure 7. Probability density distribution curves of pore radius.
It can be seen from Fig. 7 that the pore radii of the net slurry cement sheath and liquid silicon cement sheath are all Gaussian distributed. The peak points of the distribution curves are 106.94 μm and 99.91 μm. It can be seen that the liquid silicon cement sheath has smaller pore radius than the net slurry cement sheath. This indicates that adding an appropriate amount of liquid silicon suspension in the mixed material can effectively reduce the pore size and porosity of the cement sheath and increase its compactness. The pore radius probability density distribution functions of the two types of cement sheaths can be uniformly expressed as shown in Eq. (1).

The pore radius probability density distribution function:

\[
f(r) = L_0 + \left( \frac{A}{B \sqrt{\pi}} \right) e^{-\left(\frac{r - r_0}{B}\right)^2}
\]  

(1)

Where \( L_0, r_0, A, \) and \( B \) are the statistical parameters. According to the experimental conditions in this study, the parameter values of the net slurry cement sheath are 0.0032, 102.73, 47.64, and 34.5, respectively, and those of the liquid silicon cement sheath are 0.0057, 99.51, 36.32, and 31.12, respectively.

**Pore formation in the reconstruction model.**

The pores are treated as spheres in the reconstructed model. Let the volume be \( V \), and the porosity be \( \rho_v \) of the reconstruction model of the cement sheath.

According to the probability density distribution function of the pore radius, number \( n(r_i) \) and total volume \( V(r_i) \) of pores corresponding to the radius \( r_i \) can be calculated. The formulas are shown in Eqs. (2) ~ (3):

\[
n(r_i) = \frac{V \rho_v}{\sum_j (f(r_j) \frac{4}{3} \pi r_j^3)} f(r_i),
\]

(2)

where \( n(r_i) \) and \( f(r_i) \) are the number and probability density of pores with radius \( r_i \).

\[
V(r_i) = n(r_i) \frac{4}{3} \pi r_i^3,
\]

(3)

where \( V(r_i) \) is the total volume of pores with radius \( r_i \).

A hexahedral mesh was used as the porous reconstruction model. According to Eq. (4), the number of meshes occupied by the pores with radius \( r_i \), \( N(r_i) \), can be calculated:

\[
N(r_i) = \frac{V(r_i)}{l^3},
\]

(4)

where \( l \) denotes the side length of the hexahedral mesh.

It can be seen from the above-mentioned analysis that the spatial locations of the pores satisfy a uniform distribution. The Monte Carlo method was used to generate three sets of uniformly distributed random number sequences using a self-developed program. These sets were used as the spatial coordinates of the pores in the reconstruction model. The pores in the reconstruction model were determined by combining the mesh number of the pores and their spatial coordinates.

**Porous reconstruction model of cement sheaths**

According to the field data, the geometric dimensions of the cement sheath and metal casing with a depth
of 1200 m are listed in Table 3.

**Table 3.** Geometric dimensions of the cement sheath and metal casing.

<table>
<thead>
<tr>
<th>Depth /m</th>
<th>Inside radius of casing /mm</th>
<th>Outside radius of casing /mm</th>
<th>Inside radius of inner layer cement sheath /mm</th>
<th>Outside radius of outer layer cement sheath /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1200</td>
<td>111.2</td>
<td>122.25</td>
<td>69.85</td>
<td>157.66</td>
</tr>
</tbody>
</table>

The pore size is very small compared to the cement sheath size, with a difference of five orders of magnitude. For accurately reproducing the micropores in the reconstruction model, the mesh of the reconstruction model should be finely divided. As a result, the number of meshes and the computational scale increases sharply. This complicates numerical calculations or even makes them impossible. To solve this problem, the geometric dimensions of the cement sheath and metal casing were reduced by 10 times in equal proportion in this study. The detailed geometric parameters are given in Fig. 8.

![Geometric parameters of the cement sheath and metal casing.](image)

**Figure 8.** Geometric parameters of the cement sheath and metal casing.

According to the above-mentioned geometric parameters of the cement sheath and pore formation method, a porous model of the cement sheath can be constructed using a self-developed FLAC 3D program. To analyze the interaction between the cement sheath and metal casing and their deformation and failure laws in the fracturing process, the porous reconstruction models of a “single-layer cement sheath” and “double-layer cement sheath” were established. Fig. 9 shows the porous reconstruction models of the net slurry cement sheath and liquid silicon cement sheath. The “single-layer” model of the net slurry cement sheath has about 3.33 million meshes, and the “double-layer” model has about 6.37 million meshes. The “single-layer” model of the liquid silicon cement sheath has about 4.3 million meshes, and the “double-layer” model has about 7.1 million meshes.
Boundary conditions of numerical simulation.

According to stress conditions, the cement sheath and metal casing generally do not exhibit axial deformation failure or bending instability. Therefore, vertical displacement constraints were imposed on the upper and lower surfaces of the cement sheath reconstruction model to limit its vertical deformation. A in situ stress of 28 MPa was applied to the surrounding surface of the reconstruction model. Hydraulic pressure was applied to the inner wall of the reconstruction model, which was gradually increased from 0 until the cement sheath failed.

Failure criterion and constitutive model

The Mohr–Coulomb criterion (Eq. (5)) was used to describe the cement sheath failure. The mechanical parameters are listed in Table 2.

\[ \tau_f = c + \sigma \tan \varphi, \]

where \( \tau_f \) denotes the shear strength, \( c \) is the cohesion force, \( \sigma \) is the normal stress on the fractured surface of a material, and \( \varphi \) is the internal friction angle.

An isotropic elastic constitutive model was used to characterize the material properties of the metal casing. The volume modulus and shear modulus were set to 167 GPa and 76.9 GPa, respectively.

The isotropic elastic constitutive equation is as follows (Eq. (6)):

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

where \( \varepsilon \) is the material strain, \( \sigma \) is the axial stress, and \( E \) is the elastic modulus of a material.

Results

Breakdown pressure of porous cement sheaths.

Fig. 10 shows the change curves of the breakdown pressure of the cement sheath. The results show that there is a significant difference in the breakdown pressure between the net slurry cement sheath and the liquid silicon cement sheath, as well as between the single-layer and double-layer cement sheaths. The breakdown pressures of the single-layer and double-layer models of the net slurry cement sheath are 44.2 MPa and 140 MPa, respectively, and those of the liquid silicon cement sheath are 46 MPa and 232 MPa,
respectively. The breakdown pressure of the liquid silicon cement sheath is obviously greater. The increase in the single-layer model is approximately 4%, and that in the double-layer model is approximately 66%. This indicates that the liquid silicon suspension can effectively improve the porous structure inside the cement sheath, reduce the porosity of the cement sheath, and enhance its fracturing resistance. However, the breakdown pressure of the double-layer cement sheath considerably higher than that of the single-layer sheath. This indicates that the double-layer structure significantly improves the fracturing resistance of the cement sheath. The breakdown pressure of the cement sheath is greatly increased under the mutual restraint of the double-layer cement sheath and metal casing. In summary, the liquid silicon suspension and the double-layer structure can effectively improve fracturing resistance and prevent cement sheath failure.

![Breakdown pressure comparison](image1.png)

**Figure 10.** Change curves of the breakdown pressure of the cement sheath.

**Plastic failure characteristics of porous cement sheaths.**

To analyze the evolution law of plastic failure zones of the cement sheath during fracturing, in this study, 25%, 50%, and 100% of the peak hydraulic pressure were selected as loading ratios. The plastic failure characteristics of these three loading ratios were analyzed. Fig. 11 and Fig. 12 show the distributions of the plastic zones with the three loading ratios of the single-layer and double-layer cement sheaths, respectively. Considering the characteristics of the plane strain, the cross sections of the cement sheath are shown.

![Plastic zone distributions](image2.png)

**Figure 11.** Distribution of plastic zones of the single-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.
Figure 12. Distribution of plastic zones of the double-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

For the single-layer cement sheath, Fig. 11 shows that at the initial stage of loading (25% of the peak hydraulic pressure), plastic failure zones appear in the inner wall and around the pores of the cement sheath. This observation is valid for both the net slurry and liquid silicon cement sheaths. This indicates that the cement sheath failure first starts from the inner wall and pores. Meanwhile, the plastic zone area of the net slurry cement sheath is larger than that of the liquid silicon cement sheath. The net slurry cement sheath easily undergoes plastic failure under the same hydraulic pressure. For the net slurry cement sheath, the plastic zones are primarily caused by shear failure. For the liquid silicon cement sheath, the plastic zones in the inner wall are still caused by shear failure, but those around the pores occur due to tensile failure owing to the decrease in porosity.

With an increase in hydraulic pressure, the plastic failure zones gradually extend to the outer wall of the cement sheath. This indicated that the failure path of the single-layer cement sheath is from the inner wall to the outer wall. When the hydraulic pressure reaches its peak point, the plastic failure zones cover most parts of the cement sheath, and the cement sheath fails completely. The plastic failure zones of the net slurry cement sheath are mainly caused by shear failure, whereas those of the liquid silicon cement sheath are induced by shear failure and tensile failure. It can be observed that the porous structure significantly affects the failure mode of the cement sheath. These pores are likely to cause shear failure in the cement sheath. A cement sheath with low porosity is subjected to tensile and shear failures, whereas a cement sheath with high porosity is mainly subjected to shear failure.

For the double-layer cement sheath, the interaction between the cement sheath and metal casing results in a significant change in the failure mode, as compared with the single-layer cement sheath (Fig. 12). At the beginning of loading, most of the plastic failure zones appear in the inner layer of the cement sheath, and a small part appears around the pores in the outer layer of the cement sheath. The plastic zones of the net slurry cement sheath are mostly caused by shear failure, whereas the plastic zones of the liquid silicon cement sheath are caused by both shear and tensile failures. The change in porosity results in a completely different failure mode around the pores. That is, the failure mode around the pores of the net slurry cement sheath is completely shear failure, whereas that of the liquid silicon cement sheath is completely tensile failure. When the hydraulic pressure reaches the peak point, the inner layer cement sheath completely fails, and most parts of the outer layer of the cement sheath enter plastic failure, whereas the metal casing remains intact. This indicates that the double-layer structure can effectively protect the metal casing and prevent the metal casing failure. Moreover, the double-layer structure of the cement sheath strengthens the effect of the
pores on the plastic failure zone of the cement sheath. Compared to the single-layer liquid silicon cement sheath, the plastic zones induced by the tensile failure of the double-layer liquid silicon cement sheath decrease, and the plastic zones induced by the shear failure increase. Fig. 13 gives the schematic diagram of failure paths of cement sheaths.

![Schematic diagram of failure paths of cement sheaths.](image)

**Figure 13.** Failure paths of cement sheaths.

**Radial plane deformation of porous cement sheaths.**

To analyze the deformation law of the cement sheath during fracturing, Fig. 14 and Fig. 15 give the radial plane displacement images of the cross sections of the single-layer and double-layer cement sheaths with the three loading ratios, respectively.

![Radial plane deformation images.](image)

**Figure 14.** Radial plane deformation of the single-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.
It can be observed from Fig. 14 that the porous structure significantly affects the radial deformation of the single-layer cement sheath. Owing to the effect of the pores, the radial displacement distribution of the single-layer cement sheath is not symmetrical. At the initial stage of loading, under the action of in situ stress and hydraulic pressure, the cement sheath produces outward displacement along the radial direction, causing the cement sheath as a whole to expand outward. However, the radial displacement of the cement sheath differs along the thickness, and that of the outer wall is greater than that of the inner wall. This indicates that the in situ stress plays a major role in the radial deformation of the cement sheath at the initial stage of loading. As the hydraulic pressure is increased, the radial displacement of the inner wall of the cement sheath increases rapidly. When the hydraulic pressure reaches its peak point, the radial displacement of the inner wall of the cement sheath exceeds that of the outer wall, and the maximum value appears in the inner wall of the cement sheath. Hydraulic pressure is the main factor controlling the radial deformation of the cement sheath, instead of in situ stress. This also verifies that the failure path of the single-layer cement sheath is from the inner wall to the outer wall. The maximum radial displacements of the net slurry and liquid silicon cement sheaths are 167 μm and 260 μm, respectively. The maximum value of the radial displacement of the liquid silicon cement sheath is obviously greater than that of the net slurry cement sheath. This indicates that the liquid silicon suspension can effectively improve the deformation ability of the cement sheath in addition to its fracturing resistance.

The deformation characteristics of the double-layer cement sheath considerably differ from those of the single-layer cement sheath. Because the casing has higher stiffness than the cement sheath, at the initial stage of loading, the minimum radial displacement occurs at the metal casing, and the maximum value appear in the inner and outer layers of the cement sheath. The displacement value of the inner layer of the cement sheath is not different from that of its outer layer. With a gradual increase in hydraulic pressure, the radial displacement of the inner layer of the cement sheath increases rapidly, whereas that of its outer layer increases slowly. When the hydraulic pressure reaches the peak point, the maximum radial displacement appears in the inner layer of the cement sheath, and the radial displacement gradually decreases along the radial direction of the cement sheath outward. Compared with the single-layer cement sheath, the radial displacement distribution of the double-layer cement sheath is more symmetrical and shows an annular distribution. It can be observed that the double-layer structure weakens the effect of pores on the deformation of the cement sheath. The maximum radial displacements of the net slurry and liquid silicon cement sheaths are 202 μm and 425 μm, respectively. The maximum value of the radial displacement of the liquid silicon cement sheath is larger than that of the net slurry cement sheath, which is consistent with
the conclusion about the single-layer cement sheath. However, the maximum radial displacement of the double-layer cement sheath is considerably larger than that of the single-layer cement sheath, indicating that the double-layer structure can also effectively improve the deformation ability of the cement sheath.

**Stress distribution characteristics of porous cement sheaths.**

To analyze the effects of pores and the single- and double-layer structure of cement sheaths on the stress distribution, Figure 16 and Figure 17 give the major principal stresses of the single-layer and double-layer cement sheaths with the three loading ratios, respectively.

**Figure 16.** Major principal stress of the single-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 17.** Major principal stress of the double-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

At the early stage of loading, the major principal stress of the single-layer cement sheath is completely in the state of compressive stress. Because the liquid silicon cement sheath has smaller pore size than the net slurry cement sheath, its stress concentration is more obvious, and the compressive stress value is higher. As the hydraulic pressure is increased, the major principal stress of the cement sheath gradually increases. When the hydraulic pressure reaches its peak load, the stress distribution in the cement sheath changes significantly. Both compressive and tensile stresses appear in the cement sheath. The compressive stress zones are significantly larger than the tensile stress zones in the net slurry cement sheath, whereas there is a slight difference between them in the liquid silicon cement sheath. In other words, the net slurry cement
sheath is still dominated by compressive stress, whereas the liquid silicon cement sheath by both compressive and tensile stresses. Therefore, the net slurry cement sheath mainly fails by compressive-shear failure, whereas the liquid silicon cement sheath—by shear and tensile failures. This indicates that the porous structure has a significant influence on the failure mode of the cement sheath from a stress point of view.

**Stress comparison between non-porous and porous cement sheaths.**

To further analyze the difference of stress distribution between non-porous sheath and porous cement sheath, the stress results of the porous cement sheath were compared with the stress results of a non-porous cement sheath obtained by other researchers. The comparative results are shown in Fig. 18.

**Figure 18.** Cross-section stress distribution of the single-layer cement sheaths.

By comparison, it is found that the major principal stress of the cross-section of the non-porous cement sheath is in the state of complete tensile stress. The stress value of the inner wall is higher than that of the outer wall of the cement sheath. This indicates that the failure mode of the nonporous cement sheath is mainly tensile failure, and the failure path is from the inside to the outside. However, the porous structure significantly changes the stress state of the single-layer cement sheath, which transforms from a single tensile stress to both tensile and shear stresses. Accordingly, the failure mode of the porous cement sheath changes from tensile failure to tensile and shear failures. The larger the porosity, the higher is the proportion of shear failure. This indicates that the pores are more likely to cause shear failure of the cement sheath. It should be noted that the porous structure does not change the failure path of the cement sheath. Regardless of the porosity, the failure path of the porous cement sheath is still from the inside to the outside.

The major principal stress distribution characteristic of the double-layer cement sheath is significantly different from that of the single-layer cement sheath. Compressive and tensile stresses appear in the cement sheath during the early stage of loading. Tensile stress mainly occurs in the metal casing, and compressive stress appears in the cement sheath. The compressive stress value of the inner layer of the cement sheath is greater than that of the outer layer of the cement sheath. This indicates that the double-layer cement sheath fails first from the inner layer of the cement sheath. This conclusion is consistent with that obtained from the analysis of the plastic failure zone. With an increase in hydraulic pressure, the compressive stress of the inner layer of the cement sheath gradually reaches the maximum value, whereas the compressive stress value of its outer layer is always smaller than that of its inner layer. When the hydraulic pressure reaches the peak point, the major principal stress of both the net slurry and liquid silicon cement sheaths completely enters the compressive-stress state. The major principal stress of the metal casing remains in the state of tensile stress. Compared with the single-layer cement sheath, the stress state of the double-layer net slurry cement sheath changes slightly, and the major principal stress is still compressive stress. However, the stress state of the double-layer liquid silicon cement sheath is very different, from the coexistence state of tensile stress and compressive stress to a single compressive-stress state. It can be observed that the double-
layer structure strengthens the influence of the porous structure on the stress distribution and failure mode of the cement sheath, which leads to a single shear failure in the cement sheath with low porosity.

Conclusions
In this study, porous reconstruction models of single- and double-layer cement sheaths were established. Based on the reconstruction models, the deformation failure laws of the cement sheath were studied under in situ stress and hydraulic pressure. The effects of pores and the single-double layer structure on the deformation failure of the cement sheath were analyzed from the aspects of breakdown pressure, plastic zone, deformation, and stress distribution. The results revealed the failure mechanisms of the porous cement sheath. The main conclusions are as follows:

1. The pore spatial locations of the net slurry cement sheath and liquid silicon cement sheath approximately satisfy a uniform distribution along the circumferential direction, and the pore radius follows a Gaussian distribution. The pore size and porosity of the liquid silicon cement sheath are smaller than those of the net slurry cement sheath. Liquid silicon suspension in a mixed material can effectively reduce the pore size and porosity of the cement sheath and increase its compactness.

2. The lower the porosity of the cement sheath, the higher the breakdown pressure. The breakdown pressure of the double-layer cement sheath is significantly higher than that of the single-layer cement sheath. The double-layer structure and liquid silicon suspension can effectively improve the fracture resistance of the cement sheath and prevent damage to the cement sheath.

3. The failure path of the cement sheath occurs from the inner wall and pore periphery to the outer wall, and the porous structure slightly influences this failure path. However, the porous structure significantly influences the failure mode of the cement sheath. The liquid silicon cement sheath with small porosity is subjected to tensile and shear failures, whereas the net slurry cement sheath with large porosity is mainly subjected to shear failure. Under the same hydraulic pressure, the cement sheath with a larger porosity is more likely to enter plastic failure. However, the double-layer cement sheath can effectively prevent failure of the metal casing. Moreover, the double-layer structure enhances the effect of pores in the plastic failure zone of the cement sheath with small porosity so that the shear plastic failure zone enlarges.

4. The porous structure significantly affects the radial deformation of the cement sheath. The smaller the porosity, the larger the radial displacement of the cement sheath. Owing to the influence of pores, the radial displacement distribution of the single-layer cement sheath is asymmetrical, and the radial displacement of the outer wall is smaller than that of the inner wall. The double-layer structure weakens the effect of pores on the deformation of the cement sheath such that the radial displacement of the double-layer cement sheath has a certain symmetry and shows a circular distribution. The radial displacement of the double-layer cement sheath is significantly larger than that of the single-layer cement sheath. Both the liquid silicon suspension and double-layer structure can effectively improve the deformation ability of the cement sheath.

5. The porous structure significantly influences the stress state of the cement sheath. The nonporous cement sheath is in a state of complete tensile stress, and the porous cement sheath is in a state of compressive and tensile stresses. The failure mode of the nonporous cement sheath is a single tensile failure, and that of the porous cement sheath is both tensile and shear failures. The larger the porosity, the larger is the compressive stress zone of the cement sheath, and the higher is the proportion of shear failure. The double-layer structure strengthens the influence of the porous structure on the stress distribution and failure mode of the cement sheath, increasing the shear failure zone of the cement sheath with low porosity.

This study provides a basis for in-depth understanding of the effect mechanisms of porosity on the breakdown pressure, deformation, stress distribution, and failure mode of cement sheaths. Notably, this study considers a cement sheath with one material ratio as the research object, and whether the conclusions are applicable to cement sheaths with other material ratios must be further verified. However, the
reconstruction method of the porous model of the cement sheath presented in this paper provides an effective way to study the failure mechanism of cement sheaths with other material ratios.

**Data availability**
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

**References**


44. Zeng B., Wang D., Song Y., Lian W. & Li J. Integrity Analysis of Cement Sheath in Annulus B of

**Figure legends**

**Figure 1.** Reconstruction idea of porous models of cement sheaths.

**Figure 2.** Cylindrical cores of cement sheaths.

**Figure 3.** Experimental photos.

**Figure 4.** Stress–strain curves of uniaxial compression.

**Figure 5.** Binarized CT images of the porous structure.

**Figure 6.** Spatial location distribution curves of pores.

**Figure 7.** Probability density distribution curves of pore radius.

**Figure 8.** Geometric parameters of the cement sheath and metal casing.

**Figure 9.** Porous reconstruction models of the cement sheaths.

**Figure 10.** Change curves of the breakdown pressure of the cement sheath.

**Figure 11.** Distribution of plastic zones of the single-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 12.** Distribution of plastic zones of the double-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 13.** Failure paths of cement sheaths.

**Figure 14.** Radial plane deformation of the single-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 15.** Radial plane deformation of the double-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 16.** Major principal stress of the single-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 17.** Major principal stress of the double-layer cement sheath: the rows, from top to bottom, represent the results of the net slurry cement sheath and liquid silicon cement sheath, respectively; the columns, from left to right, represent the results of three loading ratios: 25%, 50%, and 100% of the peak hydraulic pressure.

**Figure 18.** Cross-section stress distribution of the single-layer cement sheath.
Tables

Table 1. Mixed materials ratio.

<table>
<thead>
<tr>
<th>Water cement ratio</th>
<th>Cement /Kg</th>
<th>Quartz sand /Kg</th>
<th>Water reducer /ml</th>
<th>Water content of water reducer /ml</th>
<th>Water /ml</th>
<th>Liquid silicon suspension /ml</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.14</td>
<td>0.35</td>
<td>0.35</td>
<td>6.25</td>
<td>4.22</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 2. Mechanical parameters of cement sheaths.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength /MPa</th>
<th>Compressive strength /MPa</th>
<th>Elasticity modulus /GPa</th>
<th>Poisson’s ratio</th>
<th>Cohesion force /MPa</th>
<th>Internal friction angle /°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net slurry cement sheath</td>
<td>2.0</td>
<td>53.78</td>
<td>4.59</td>
<td>0.16</td>
<td>5.6</td>
<td>30</td>
</tr>
<tr>
<td>Liquid silicon cement sheath</td>
<td>4.8</td>
<td>54.31</td>
<td>3.56</td>
<td>0.15</td>
<td>7.8</td>
<td>35</td>
</tr>
</tbody>
</table>

Table 3. Geometric dimensions of the cement sheath and metal casing.

<table>
<thead>
<tr>
<th></th>
<th>Depth /m</th>
<th>Inside radius of casing /mm</th>
<th>Outside radius of casing /mm</th>
<th>Inside radius of inner layer cement sheath /mm</th>
<th>Outside radius of outer layer cement sheath /mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1200</td>
<td>111.2</td>
<td>122.25</td>
<td>69.85</td>
<td>157.66</td>
</tr>
</tbody>
</table>

Acknowledgments
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Author contributions
Y.Y. contributed the central idea, analyzed most of the data, wrote the initial draft of the paper, and provided the financial support. X. L. assisted with the models’ analysis and results. M.S. performed the experiment. All authors reviewed the manuscript.

Competing interests
The authors declare no competing interests.