1 Introduction

1.1 Motivations and objectives

To ensure that "the rice bowl of energy must be in our own hands," China is ramping up storage and production efforts. In 2021, Sinopec's daily natural gas output reached 100 million cubic meters for the first time, with newly proven oil reserves of 167 million tons and proven natural gas reserves of 268.1 billion cubic meters. PetroChina's oil and gas production equivalent also reached 213 million tons, with newly proven oil and gas reserves hitting a record high. However, deep, offshore, low-permeability, and unconventional oil and gas reservoirs, along with increasingly complex development and production methods, often expose the cement sheath to high temperature, high pressure, and high construction loads (Wu et al. 2023).

Cement sheath as an important component of the wellbore barrier, needs to maintain good zonal isolation throughout the service life of oil and gas wells. During the process from cementing and completion to the formal operation of oil and gas wells, the cement sheath will undergo casing pressure test, fracturing, oil test, and other conditions, any of which will change the temperature and pressure in the wellbore and the stress distribution of the cement sheath. If the mechanical properties of the cement sheath cannot meet the requirements of the wellbore working conditions, it will cause cement sheath zonal isolation failure and sustained casing pressure (SCP). In severe cases, it will also lead to shut-in of oil and gas wells. After investigating 14 high-pressure natural gas wells in an oilfield in western China, it was found that in the initial stage of production after acid-fracturing and oil test, all high-pressure gas wells showed SCP to varying degrees (**Figure 1.1**) and normal production could only be maintained through wellhead pressure relief and well workover, which greatly increased the operating cost (Su et al. 2021). 9 out of 13 natural gas horizontal wells in southwest China also suffered zonal isolation failure during fracturing, failing of wellbore fracturing operation according to design (Tang 2018). 79.52 % of the 166 wells put into production in a shale gas reservoir have SCP of different degrees (Fan 2018). One of the main reasons for the above phenomenon is the failure of zonal isolation of the cement sheath under the changing load in the wellbore (He et al. 2022).

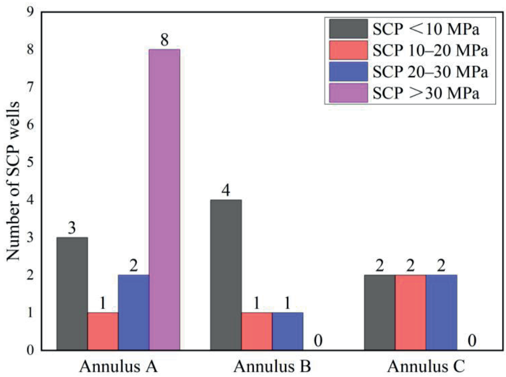


Figure 1.1 Sustained casing pressure of 14 high-pressure gas wells in an oil field in western China.

Clarifying the failure modes, causes, and influencing factors of zonal isolation of the cement sheath under complex load conditions can help optimize its mechanical properties and enhance zonal isolation performance. In this regard, a hollow-cylinder cement specimen was designed to characterize the mechanical properties of the wellbore cement sheath. A wellbore simulation device and zonal isolation test method were developed and established to replicate the stress environment experienced by the cement sheath in the wellbore. The potential factors contributing to the zonal isolation failure of cement sheaths were analyzed through physical simulation experiments. In response to these factors, mechanical integrity calculation and interface sealing evaluation models for the cement sheath were established. By comprehensively considering various failure modes of the cement sheath - such as tensile failure, strength failure, plastic deformation, interface crack propagation, and zigzag crack propagation - a zonal isolation evaluation and mechanical performance design method for the cement sheath was developed. Using this method, the failure mechanisms of zonal isolation in the cement sheath were analyzed, and the zonal isolation performance in two case wells was evaluated and optimized. The research results provide valuable guidance for predicting and preventing zonal isolation failure of cement sheaths under wellbore conditions.

1.2 Research status

1.2.1 Mechanical properties of oil (gas) wells' cement

The good mechanical properties of oil and gas well cement are fundamental for ensuring zonal isolation. In the 1990s, the primary mechanical requirement for cement was compressive strength. This was because higher cement strength during logging could reduce acoustic impedance and improve cementing quality. However, some researchers have found that uniaxial compressive strength alone is insufficient to accurately evaluate and characterize the deformation and failure behavior of the cement sheath in the wellbore. It is also necessary to consider deformation parameters, such as Young's modulus and Poisson's ratio, as well as other strength indices, including tensile and shear strength. (Thiercelin et al.).

Bosma et al. (1999) established a mathematical model based on continuum mechanics to evaluate the sealing capacity of cement sheaths. It was found that the change in the stress state in the cement sheath will lead to sealing failure. At the same time, in-situ stress will lead to the shear failure of the cement sheath. In addition, tensile failure is also one of the main failure causes of cement sheath. Finally, it is proposed that compressive strength cannot be used as an only index to evaluate the cement sheath sealing, and it is also necessary to put forward requirements for mechanical properties such as Young's modulus, Poisson's ratio, tensile strength, shear strength, and bond strength.

Le Roy-Delage et al. (2000) found that maintaining compressive strength and incorporating flexible materials to enhance elasticity are beneficial for ensuring the long-term isolation of foamed cement. In the same year, Bybee (2000) also found that the good deformation ability of the foamed cement is beneficial in improving its isolation ability.

Heinold et al. (2002) investigated changes in the tensile and bending strength of cement while studying the effects of additives on its mechanical properties. They found that adding an appropriate amount of modified materials could effectively enhance these strengths, whereas excessive addition would negatively affect the cement's mechanical properties. The authors suggested that improving tensile and bending strength helps prevent failure of the wellbore cement sheath, but also noted that evaluating the cement sheath's mechanical properties using only these two strengths is limited. They emphasized the need for further modeling research under wellbore stress conditions to better predict whether the cement sheath can meet wellbore sealing requirements. Ravi et al.(2002a, 2002b) similarly argued that enhancing the deformation capacity of the cement is beneficial for reducing the failure risk of the cement sheath.

Heinold et al. (2003) conducted research on the tensile strength of the cement. In his study, the tensile strength was measured using both the Brazilian splitting method and the uniaxial tensile test method (**Figure 1.2**). The results showed that the tensile strength obtained by the Brazilian splitting method was higher than that measured by the uniaxial tensile method. It is speculated that the Brazilian splitting method can avoid stress concentration and prevent premature failure of the sample during testing. Additionally, the study found that the sample diameter affects the results of the Brazilian splitting test. Therefore, Heinold suggests that further research and testing are needed to develop a standardized method for testing tensile strength.

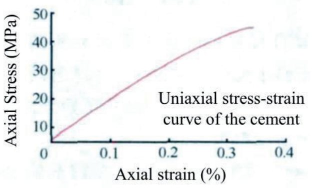
a) Brazil splitting method to test the tensile strength of the cement

b) Uniaxial tensile to test the tensile strength of the cement

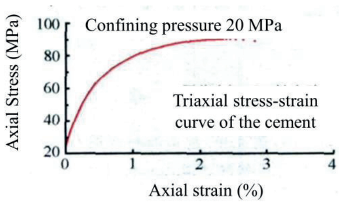
Figure 1.2 Test method of tensile strength of cement stone (Heinold et al. 2003).

Li et al. (2004a, 2004b) investigated methods to reduce the brittleness of cement. A rectangular cement sample was placed on a fulcrum, and a force was applied at the center to measure its bending displacement. The deformation per unit of bending strength was calculated by dividing the bending displacement by the bending strength, which served as the evaluation parameter. The plasticity of the cement was analyzed, and it was found that the modified material could improve its deformation capacity.

Analysis of early research on the mechanical properties of the oil (gas) wells' cement indicates a consensus that enhancing the strength and deformation capacity benefits wellbore isolation. Consequently, scholars have conducted extensive theoretical and experimental studies. At this time, most studies have obtained Young's modulus and Poisson's ratio of the cement through bending tests and compressive tests. However, some scholars have found that the above test methods fail to simulate the influence of pressure on the mechanical properties of the cement. There is a problem that the test conditions are different from the service conditions of the wellbore cement sheath, which makes the test results difficult to reflect the real situation of the wellbore cement sheath. In this regard, Li et al. (2007a, 2007b) proposed the research method of using the triaxial rock mechanics test system to test the mechanical deformation behavior of the cylinder cement specimen under confining pressure. It has been found that, unlike the brittle failure characteristics of the cement under uniaxial compression, cylinder cement specimens exhibit certain plastic behavior under confining pressure, with their mechanical deformation characteristics described as brittle-plasticity (**Figure 1.3**). In the same year, Garnier et al. (2007) also investigated the mechanical properties of cement under triaxial compression and suggested that, in addition to compressive strength, Young's modulus can be used to characterize its deformation capacity. Furthermore, the corresponding failure criteria can be applied to describe the failure behavior of cement under various confining pressures.



a) Uniaxial stress-strain curve of the cement



b) Triaxial stress-strain curve of the cement

Figure 1.3 Uniaxial and triaxial stress-strain curves of cement stone (Li et al. 2007b).

In addition, other research was conducted to (Li and Guo 2008, Li et al. 2008) further analyze the stress-strain law of toughened cement by the triaxial compression test method. The triaxial test results show that compared with the original cement, the toughened cement showed a plastic enhancement trend under triaxial compression conditions, but the failure strength was decreased (**Figure 1.4**).

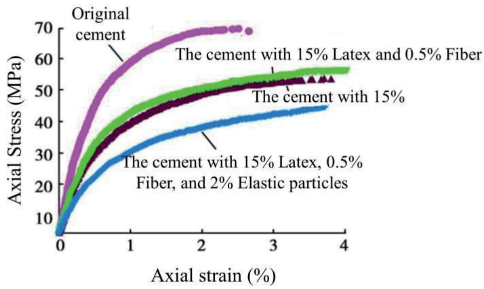


Figure 1.4 Stress-strain curves of toughened cement and original cement (Li et al. 2008).

In the same year, Iverson et al. (2008) also used a triaxial compression testing machine to test the mechanical properties of the cement, including Young's modulus, Poisson's ratio, failure strength, friction angle, and cohesion force. By comparing the deformation behavior of cement under confining pressure and without confining pressure, they found that confining pressure induces distinct elastic and plastic deformation stages in the material. This further demonstrates the significant influence of confining pressure on the mechanical properties of the cement.

Akram and Sharrock (2009) investigated the mechanical properties of cement under uniaxial and triaxial compression and analyzed its failure strength, Young's modulus, and Poisson's ratio. They found that the failure strength of the cement sheath increased with higher confining pressure. Compared to Young's modulus of the cement under uniaxial compression, Young's modulus after applying confining pressure is slightly higher, but overall, confining pressure has little effect on Young's modulus.

Fakharian and Eghbali (2012) investigated the mechanical properties of sand samples containing Portland cement using cyclic loading in a triaxial test. They found that under lower cyclic loading conditions, the stiffness of the samples decreased as the number of cycles increased, leading to the development of residual strain. Furthermore, the mechanical properties of the samples deteriorated under cyclic conditions, resulting in a significant difference between the mechanical properties observed in the first cycle and those measured in the final cycle.

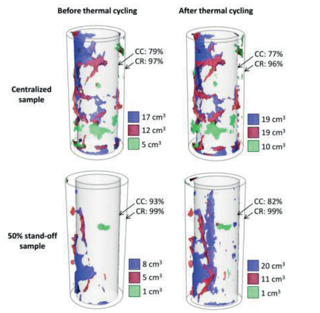
Lu et al. (2013) investigated the mechanical properties of the cement of various curing periods under triaxial compression to study the cement sheath integrity. They found that as the period increased, the failure strength, yield strength, yield strain, and Young's modulus of the cement also increased. In the same year, based on triaxial compression and cyclic loading tests, Liu (2013) described the nonlinear stress-strain behavior of the cement and developed a corresponding constitutive equation. By incorporating this equation into the wellbore mechanics model, a damage index for the cement sheath was proposed, enabling a quantitative description of the mechanical damage, deformation, and failure behavior of the cement sheath under loading conditions.

According to the above research on the mechanical properties of the cement, scholars have observed differences in its behavior under triaxial and uniaxial compression conditions. By referencing the triaxial compression test method from rock mechanics, the triaxial compression test of the cement has become a standard approach for evaluating the mechanical properties of the cement. In studies on cement modification, the advantages of modified cement in terms of deformation and strength are often demonstrated through triaxial compression tests (Li et al. 2014, Zhang et al. 2020, Zhang et al. 2018). Additionally, parameters such as Young's modulus, Poisson's ratio, and the failure characteristics of cement under different confining pressures are widely used in the calculation and analysis of cement sheath mechanical models (Guo et al. 2013, Zhang 2011, Gao et al. 2014).

In recent years, research into the mechanical properties of cement has advanced. In addition to simulating the effects of confining pressure on cement, it has become crucial to replicate the "ring" structure of the underground cement sheath and perform relevant tests. To address this, some researchers have developed wellbore simulation devices to analyze cement sheath failure by placing cement slurry between simulated casing and formation, forming a cement sheath, and applying temperature and pressure.

De Andrade et al. (2014) and Albawi et al. (2014) designed both centralization and eccentric casing-cement sheath-rock combinations, and simulated the effects of wellbore temperature cyclic on the bonding at the cement sheath interface. After testing, CT scans of the samples revealed that temperature changes caused debonding at the interfaces between the cement sheath, casing, and rock. Under eccentric conditions, the cement sheath debonds from the interface earlier. Additionally, compared to the casing centralization, the debonded area at the cement sheath interface was larger under eccentric conditions (**Figure 1.5**).

a) Casing-cement sheath-rock combination

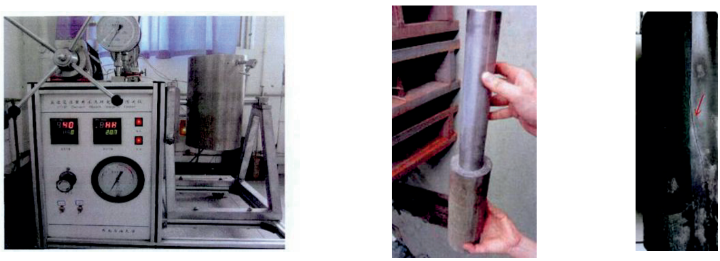


b) CT scan results of the combination after temperature cycling

Figure 1.5 Test samples and test results in De Andrade's study (De Andrade et al. 2014).

Yang et al. (2015) placed cement slurry between double-layer casings, with and without drilling fluid, and analyzed the formation of micro-annulus in the cement sheath by applying mechanical pressure to the outer wall of the casing. Based on CT scan results, they found that the drilling fluid affects the bonding at the cement sheath interface and leads to micro-annulus formation under load conditions. Additionally, the study compared changes in the micro-annulus for self-healing cement and conventional cement under the same load. The tests showed that self-healing cement exhibits better deformation capability, and the micro-annulus volume at the interface is smaller compared to conventional cement under high pressure.

Zhang et al. (2016) and Li et al. (2016) developed a mechanical damage simulation device for cement sheaths to replicate the wellbore environment. Using the von Mises stress criterion, they established a mechanical equivalence method that translates wellbore pressure to the device, thereby restoring the actual conditions of the wellbore cement sheath. Focusing on high-pressure gas wells in the Tarim Oilfield, they examined the stress environment of cement sheaths in both shallow and deep formations by designing integrity tests under high and low confining pressures. The tests investigated the failure behavior of the cement sheath by maintaining a constant confining pressure, gradually increasing the internal casing pressure to its maximum, and then gradually decreasing it. Results showed that under high confining pressure, the cement sheath maintained its integrity as internal casing pressure increased; however, when the internal casing pressure decreased, the cement sheath debonded from the interface, resulting in annular gas channeling. CT scanning has revealed that the cause of the above phenomenon is plastic deformation of the cement sheath during increased internal casing pressure, failing the interface bonding during decreased internal casing pressure. Under low confining pressure, annular gas channeling occurs in the cement sheath as internal casing pressure increases. Observation test results indicate that the cement sheath develops axial cracks, so the integrity failure under low confining pressure is due to tensile failure of the cement sheath (**Figure 1.6**). Based on these findings, researchers have conducted targeted modification studies to enhance the deformation capacity and failure strength of the cement sheath. It was found that the mechanical properties of the modified cement sheath meet the requirements under test conditions, and no mechanical failure occurs.



a) Mechanical damage simulation device of cement sheath b) Bonding failure c) Tensile failure

Figure 1.6 Cement sheath mechanical damage device and test results (Zhang 2016).

Tang (2017) investigated the influence of injection-production loads in gas storage wells on the cement sheath integrity using the aforementioned device, assessing whether the cement sheath would be damaged or fail through multiple cycles of loading and unloading. Initially, an integrity test was conducted under injection and production conditions in a gas storage well, revealing that the cement sheath could maintain its integrity after 40 cycles. Subsequently, integrity tests were performed under injection-production pressure differences of 5 MPa, 10 MPa, and 15 MPa, respectively. The results showed that the cement sheath failed after 376, 141, and 54 cycles, respectively, indicating that higher injection-production pressure differences accelerate fatigue failure of the cement sheath. Additionally, after modifying the cement sheath, its integrity under loading and unloading conditions was tested again. It was found that enhancing the toughness of the cement sheath can effectively improve its resistance to fatigue failure.

Zeng et al. (2019) developed a set of large-scale devices to evaluate cement sheath integrity under cyclic loading (**Figure 1.7**). The results showed that the cement sheath could maintain its integrity after multiple cycles when the internal casing pressure variation was low. However, at higher ranges of internal casing pressure variation, integrity failure occurred after pressure cycles. Additionally, as the internal casing pressure variation increased, the number of cycles required for cement sheath failure decreased. Researchers have analyzed the failure mechanisms of cement sheaths using numerical models and found that the cement sheath undergoes plastic deformation during internal casing pressure loading and develops residual strain during unloading. With an increasing number of cycles, the plastic deformation area within the cement sheath expands, leading to uncoordinated deformation at the casing-cement sheath interface. When the interface tensile stress exceeds the bonding strength of the cement sheath, micro-annulus forms at the interface, ultimately compromising the cement sheath integrity.

a) Cement sheath integrity evaluation b) The cement sheath sample after the test