Effect of Hole on Oil Well Cement and Failure Mechanism: Application for Oil and Gas Wells

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Abstract: Cementing is an important operation in the drilling process. During the cementing process, mud cake, fracturing, perforation, and so on will cause holes in the cement sheath. Thereby, the size effect will reduce the cement strength, which will seriously affect the cementing quality. Several hole types were drilled to study the mechanical properties and damage mechanism of oil well cement. The stress distribution and failure process of cement containing a hole were studied using RFPA2D software. The experimental and simulation results demonstrate that an internal hole has an obvious effect on the cement performance. The hole will change the cement bearing capacity and affect the fracture direction. Three crack types exist: tensile, shear, and far-field. Both 2 and 5 mm vertical eccentric holes can reduce the cement tensile stress. Furthermore, the specimen tensile strength decreases with an increase in the diameter of holes. Horizontal eccentric holes with diameters of 2 and 5 mm will increase the cement tensile strength. Among these, the sample L2-2 exhibits a long crack path, high energy consumption, and a remarkable enhancement effect.

1. INTRODUCTION

Cementing is an important operation in the drilling process. The cement construction in the circular space between the borehole and casing is known as cementing (Figure 1a). During the cementing operation, cement is the main material for the cementing sheath, which provides the function of suspension and protective casing.1−4 Oil well cement is mostly Portland cement, with low tensile strength, poor impact resistance, and easy cracking under the action of force.5−8 Furthermore, its tensile strength is also an important parameter of the stability evaluation of oil well cement. Cement sheath holes easily appear in the cementing operation, imparting size effects and reducing the cement strength.3 In the cementing process, numerous factors cause holes to appear in the cement sheath. During the cement slurry curing process, unhydrated cement particles and a hole exist. The mud cake attached to the wall also causes holes in the cement. Large-scale operations, such as perforation and acid fracturing, will result in holes in the cement (Figure 1b). The perforating operation is an important factor affecting the cement sheath strength, and the hole left by the perforation will affect the cement sheath integrity. The stress concentration around the hole causes the actual carrying capacity of the cement sheath to be lower than the designed bearing capacity.10

In reality, brittle materials such as cement have nonlinear stress–strain characteristics and inherent defects. Therefore, there may be some differences between theoretical and practical results. Most indirect tests are based on the assumption that cement is an elastic material,11 but the brittleness of cement is obvious, and it is an inelastic material, so there will be some deviation between the theoretical analysis and the experimental results. The theory of elasticity is applicable to homogeneous materials, and whether it is applicable to cement materials needs further proof.

Ladva et al.12 pointed out that cement sheath failure is related to the mud cake produced by the cement volume shrinkage. Scholars have mainly studied the fracture toughness of test material,13,14 but few have explored the impact of the hole on the stress and failure characteristics of oil well cement. Wang et al.6 studied the effects of hydraulic fracturing on the cement sheath integrity and proposed that hydraulic fracturing would allow holes to be produced in the cement sheath and further damage its integrity. Certain scientific questions to be addressed include: How can cement with holes be destroyed under loading? What is the influence of the geometry and number of holes on the damage behavior and the destruction of cement sheath?

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of the oil well cement stone strength? Research on crack extension has always been a hot topic in the field of force, and research methods include numerical calculations, experimental observation, and theoretical analysis.\textsuperscript{15} Tang et al.\textsuperscript{16} studied the effects of a hole on the mechanical properties of oil well cement using finite-element and damage mechanics methods. A numerical model for the crack initiation and propagation in different hole types was proposed. Haeri et al.\textsuperscript{17} studied the concrete crack propagation process with different circular holes by means of experiments and numerical calculations. It was found that the cement sheath failure was mainly caused by the propagation of radial fractures on the central hole surface. Few studies have been reported on the effects of macro holes on the mechanical properties of cement and crack extension, both locally and globally. The internal hole of oil well cement can reduce its tensile stress, accelerate the cement sheath damage process, and even lead to cement sheath failure.

To investigate the mechanical properties and cracking process of specimens containing combined flaws with various holes, we conducted uniaxial compression tests in the laboratory. Moreover, RFPA\textsuperscript{2D} software was adopted to explore the corresponding mechanical mechanism further and to verify the rationality of the experimental results. This research mainly verifies the difference between theory and experiment and tries to establish the best procedure of simulation experiment. Exploration of the influence of voids on the tensile strength and fracture mechanism of the oil well

| Model name | Hole coordinate X(mm) | Hole coordinate Y(mm) | Model name | Hole coordinate X(mm) | Hole coordinate Y(mm) |
|------------|------------------------|------------------------|------------|------------------------|------------------------|
| V2-1       | 0                      | 0                      | V5-1       | 0                      | 0                      |
| V2-2       | 0                      | 5                      | V5-2       | 0                      | 5                      |
| V2-3       | 0                      | 10                     | V5-3       | 0                      | 10                     |
| V2-4       | 0                      | 15                     | V5-4       | 0                      | 15                     |
| L2-1       | -5                     | 0                      | L5-1       | -5                     | 0                      |
| L2-2       | -10                    | 0                      | L5-2       | -10                    | 0                      |
| L2-3       | -15                    | 0                      | L5-3       | -15                    | 0                      |

\textsuperscript{“}Diameter of V2 and L2 representative holes is 2 mm, and that of V5 and L5 representative holes is 5 mm.

Figure 1. (a) Cementing diagram. (b) Perforation diagram.

Figure 2. (a) Loading figure. (b) Sample V5-2.
cement is essential in cementing engineering and will provide guidance for future work.

2. MATERIALS AND EXPERIMENTS

2.1. Preparation of Samples. Cement slurries were prepared and cured according to the standards of API Recommended Practice 10B-2.2013.18 The experimental formula is as follows to simulate the actual operation conditions: G-grade well cement + 2% fluid loss additive (G33S) + water (wt %), with a water/cement ratio of 0.44. The Portland cement used in this study was G-grade oil well cement from a special cement plant in Jiahua, Sichuan. The G33S was obtained from Henan Weihui Chemical.

The G33S and cement powders were mixed and then agitated by a cement paste mixer. The cement slurry was mixed using a variable speed mixer; then, it was poured into a die-resistant mold. The interior faces of the molds and contact surfaces of the plates were lightly coated with a release agent. The solidified cylindrical specimen size was \( \varphi \times 50 \) mm (inner diameter) \( \times 25 \) mm. The cement slurries were kept in standard curing molds at 60 °C with 100% relative humidity for 14 days, following which all specimens were removed from the mold. Thereafter, the cement was placed in a high-speed drilling machine for drilling, and the drilling depth was 25 mm, which could just penetrate the sample.

Each sample contained a hole, the geometrical position and dimensions of which are displayed in Table 1. The intact sample was recorded as 00. It should be noted that each test was conducted six times to reduce the experimental error caused by sample variability. An actual image of sample V5-2 is provided in Figure 2b.

2.2. Method. A type TYE-300 machine with a measuring range of 300 kN (Figure 2) (obtained from Wuxi Building Material Instrument, China) was used to test the tensile strength of the circular specimens at 14 days. The test adopted the displacement loading method for control. In the tests, the loading rate was set to 0.25 mm/min, and the stress–strain curve was monitored. A constant rate loading process was applied, and the loading rate was sufficiently slow to ensure that the sample was static. Loading was stopped immediately once the peak load was reached to ensure the specimen integrity for observing and describing the failure mode. It should be noted that each test was conducted six times to reduce the experimental error caused by sample variability.

A uniaxial splitting tensile test of the cement, both with holes and intact, was carried out using the TYE-300B pressure testing machine. The tests were executed according to the splitting tensile standard.19

3. RESULTS AND DISCUSSION

3.1. Stress Distribution. 3.1.1. Central Hole Stress Distribution. According to the Kirsch formula of plane strain in elastic mechanics, the stress component \( M \) of any point around the central hole is

\[
\delta_r = \frac{p + q}{2} \left( 1 - \frac{r^2}{a^2} \right) + \frac{p - q}{2} \left( 1 - \frac{4r_a^2}{r^4} + \frac{3y_a^4}{r^4} \right) \cos 2\theta
\]  

(1)

\[
\delta_\theta = \frac{p + q}{2} \left( 1 + \frac{r^2}{a^2} \right) - \frac{p - q}{2} \left( 1 + \frac{4r_a^2}{r^4} - \frac{3y_a^4}{r^4} \right) \cos 2\theta
\]  

(2)

where \( \delta_r \) is the radial stress at point \( M \), \( \delta_\theta \) is the tangential stress at \( M \), and \( \tau_\phi \) is the shear stress at \( M \). The distribution of \( p \) and \( q \) is the vertical stress and horizontal stress of the specimen.

3.1.2. Eccentric Hole Stress Distribution. The stress distribution of the vertical eccentric hole is as follows:

\[
p = \frac{w}{\pi a t} \left\{ 2 + \frac{2a}{a - e} + \frac{2a}{a + e} \right\}
\]

(3)

The stress distribution of the horizontal eccentric hole is as follows

\[
p = \frac{w}{\pi a t} \frac{2(3a_c^2 - e^2)(a^2 - e^2)}{(a^2 + e^2)^2}
\]

(4)

where \( a \) is the radius of the disk, \( e \) is the eccentricity of the round hole, \( t \) is the thickness of the disk, and \( w \) is the pressure on the disk. The stress distribution determined by theoretical elasticity is applicable only to homogeneous, isotropic, and elastic materials.

3.2. Stress–Strain. Figure 3 displays the stress–strain curves of specimens with different holes under uniaxial compression. During the initial loading stage of loading, the tensile stress and strain curves of the cement with holes and intact exhibited superior linear elasticity. In the initial stage, temporary compaction of the cement occurred. The stress and strain difference between the cement with holes and the intact cement represented the compaction stage. The relationship between the deformation and the load of the cement was linear. A highly transient, nonlinear relationship between the deformation and the load of the cement was apparent when approaching the maximum load. The cement tensile stress reached a peak, and the large amount of elasticity that accumulated during the pressurization process could suddenly be released. The elastic release could cause the crack to expand rapidly at the cement loading end. The sample was immediately fractured, and the rising phase of the tensile stress–strain curve was obtained.

The hole had a significant influence on the stress–strain curve of the cement. The tensile stress–strain curve of the cement was smoothed by vertical eccentricity samples such as V2-2, V5-1, and V5-4. Compared with the axial strain, the stress increase was smaller, which means that the lateral expansion was limited. It was demonstrated that the vertical eccentric hole could reduce the crack propagation and failure rates of the cement stone. The stress–strain curve slope of the cement with a horizontal eccentric hole was small during the initial stage. With an increase in displacement, the load increased almost linearly until it suddenly decreased to its peak value. The horizontal eccentric hole increased the tensile stress of cement while also improving the cement crack growth rate, which caused the cement to be rapidly destroyed.

3.3. Toughness of Cement. The area surrounded by the stress–strain curve can be used to evaluate the toughness of the cement. It can be seen from Figure 4 that the toughness of the cement with holes is different from that of the intact cement, which indicates that the existence of the hole will affect the toughness of the cement and change the fracture ability of the cement. The toughness of cement containing perpendicular eccentric holes is almost reduced, but the
3.4. Tensile Stress. A tensile strength test of cement was carried out according to GB/T23561-2009. The tensile strength of cement was tested by a split tensile method. The nominal tensile strength is defined as

\[ R_c = \frac{2F_c}{\pi DL} \]  

where \( R_c \) is the tensile strength (MPa), \( F_c \) is the maximum load during failure (N), \( D \) is the bottom diameter of the specimen (mm), and \( L \) is the height of the specimen (mm).

Figure 5 illustrates the strength and deformation characterizations of specimens with different holes. Both experimental and numerical tests show that the eccentricity of the inner hole has a certain effect on the tensile strength of the disk.\(^{22}\)

The experimental results are different from those of the theory in Table 2. The ratio between the intact and the perforated was six times, and whereas there was no consistent difference in the theoretical results. There may be two reasons. One is that the material will affect the test results, and the other is that the distance between the holes may increase or decrease the strength of the cement. The results demonstrate that the strength of the cement with a 2 mm vertical eccentric hole was significantly lower than that of the intact cement, and the position of the vertical eccentric hole being closer to the loading point decreased the cement strength. Comparing sample V2-1 with the intact cement 00, the strength decreased from 3.32 to 2.78 MPa, which is 16.26%. With the change in the position over the hole, the downward trend still rose. The vertical eccentricity holes (5 and 2 mm) had a similar reduction effect on the tensile stress of the cement. A larger hole diameter resulted in lower cement stress. When the hole toughness of sample V2-3 is improved. The toughness of horizontal eccentric pore cement is first increased and then decreased. The results show that the larger the hole, the greater the impact on the toughness of cement.

![Figure 3](image1.png)  
**Figure 3.** (a) Stress–strain curve of 2 mm hole cement. (b) Stress–strain curve of 5 mm hole cement.

![Figure 4](image2.png)  
**Figure 4.** Toughness of different samples.

![Figure 5](image3.png)  
**Figure 5.** Tensile stress of cement paste.

| external diameter (\(a/\text{mm}\)) | eccentricity (\(e/\text{mm}\)) | \(p_{\text{stat}}/W\) |
|------------------------------------|-------------------------------|-------------------|
| 25                                 | 5                             | 6.16 5.25         |
| 25                                 | 10                            | 6.76 3.55         |
| 25                                 | 15                            | 8.25 1.83         |

Table 2. Effect of an Eccentrically Placed Hole on the Maximum Tensile Stress in Theory
was closer to the loading point, the effect on the cement tensile strength was more obvious. The effect of the horizontal eccentric hole on the cement tensile strength was not obvious. The strength of specimen L2-1 from V2-1 was reduced from 2.78 to 2.18 MPa, namely, by 21.58%. This is similar to the conclusion in most literature that the center hole reduces tensile stress. However, the strength of sample L2-2 did not decrease compared with that of sample L2-3; instead, it increased from 2.18 to 3.97 MPa, and the tensile stress increased by 82.11%. The tensile stress of sample L2-2 was higher than that of the intact cement. Similarly, the tensile stress of L5-2 and L5-1 in sample L5-3 increased. With an increase in the hole diameter, the influence of the horizontal eccentric holes increased. This demonstrates that a larger hole results in a more obvious increase in the cement tensile stress. Much literature has concluded that voids reduce the tensile stress of the material, but the situation still needs to be analyzed according to the materials’ own characteristics. This is because the load is not distributed along a line. Instead, it passes through a tape, so the strength increases. This will have the effect of reducing the maximum theoretical tensile stress, so a higher load is required to fracture the specimen. Compared with sample L2-1, the tensile stress enhancement effect of specimen L2-2 was remarkable, and the tensile stress was even higher than that of intact cement. The main crack length of L2-2 was longer than that of L2-1 and L2-3. The crack length was longer, and the energy consumption was larger, and thus the load could be higher than that of the other cement with a 2 mm diameter horizontal eccentric hole. There are two reasons. First, at such a large eccentricity, the distribution of load in a frequency band will have a considerable effect on the stress. Second, when a finite hole is near the loading plate (a rapidly changing region of stress), the simple theoretical method is not applicable.

3.5. Analysis of Failure Mechanism. 3.5.1. Final Crack Direction Analysis. It can be observed from Figure 8 that the surface on the cement sample of the hole exhibited a certain degree of flake dissection during loading, which indicates that the brittleness characteristic of the cement is obvious. The main macroscopic fracture forms are axial splitting, crack propagation, and surface peeling and fracture.

(1) Intact specimen. A large number of scholars have made a detailed study of the split mode of the intact specimen. It is found that the stress concentration near the contact area leads to premature fracture near the contact area. The fracture mode of the intact specimen is approximately the same, and the specimen has cracks or even a local fracture near the contact. This is similar to our test results, and it can be seen that the upper and lower loading ends of specimen 00 are damaged to a certain extent.

(2) Central hole. Figure 6 shows the final failure mode of the specimen with a central hole. The stress distribution and fracture mode of central hole were studied in detail by Mellor. Mellor found that the testing results of rock and ice are different from those of theory, which reveals the influence of the materials on the same experimental results. It is found that the vertical cracks were primary cracks and all other fractures were secondary cracks, regardless of the size of the holes. However, vertical cracks were not seen in sample V5-1, and three secondary cracks appeared on the surface. This shows that the material still has a certain influence on the fracture form of the specimen.

(3) Vertical eccentric hole. The distance between the vertical hole and the center of the circle can affect the length of the crack. It can be seen from samples V2-1 to V2-4 and V5-1 to V5-4 in Figure 8 that as the hole moved closer to the loading point, the crack propagation path on the cement surface became tortuous, and small cracks appeared at the edge of the hole. From samples V2-2, V2-3, V5-2, V5-3, and V5-4, it can be seen that the main crack contained a certain radius. In the sample, the main crack at the V2-3 fracture was the most representative, and its crack exhibited certain radians. Certain small cracks were evident at the edge of the hole, namely, the shear crack. During the development of these tiny cracks, the two terminals will gradually converge, resulting in the collapse of the cement wall. The local stress concentration at the hole inside the cement is caused by the external load, which leads to a crack in the inner hole edge. Certain fine cracks existed in the holes with diameters of 2 and 5 mm, starting from the edge
and spreading to the loading location. A larger hole diameter resulted in the effect of cracks in the cement being more obvious. As the hole approached the loading point, the shear cracks became increasingly shorter, demonstrating that the shear crack generation and direction were affected by the holes.

4) Horizontal eccentricity hole. Figure 7 shows the fracture law of the specimen with an eccentric hole. By comparing the crack direction of the specimen with the horizontal eccentric hole in the literature, it can be seen from the experiment that the horizontal eccentric hole can guide the crack strike of cement. The horizontal eccentric hole was further from the center point, and its main crack produced a certain curve with the hole. The main crack arcs of L2-2, L5-1, and L5-2 were obvious. Although the hole diameter was relatively small, the main crack still tended to move with the hole; however, it did not pass through the hole. It is indicated that the hole had a guiding effect on the cement stone crack. Because the diameter of the hole on the cement stone was small, the influence was not obvious. When the hole was large, the main crack not only deviated from the hole but also passed through it. The cracks in samples V5-3 and L5-2 were composed of three types. Owing to the appearance of the pore, the shear crack produced in sample L5-2 passed through the hole and produced a far-field crack when it was far from the hole and loading direction. Three crack types formed the macroscopic fracture of the cement. The tensile crack of V2-2, L2-1, L2-2, and L5-1 was the main crack. Owing to the existence of the hole, the main crack exhibited different degrees of migration in

Figure 7. Fracture patterns of a specimen with an eccentric hole. (a) Diameter of hole is 2 mm. (b) Diameter of hole is 5 mm.

Figure 8. Final failure mode of the hole cement.

3.5.2. Failure Analysis. Three main types of failure modes exist, including main, shear, and far-field cracks. The shear crack is marked as b in Figure 8 and is formed on both sides of the surrounding loading direction. The far-field crack, marked as c in the figure, is a crack far from the hole and under loading stress. Both intact and porous cement stones contain tensile cracks.

Samples V5-1 and V5-4 exhibited two crack types, namely, tensile and shear cracks. The shear and tensile cracks of the hole edge near the loading point were developed to form the cement macroscopic fracture. The initiation and expansion of the crack were the beginning of the stress concentration at the hole stretching. The maximum tensile stress concentration near the top and the bottom of the hole decreased gradually, and cracks occurred in the hole and propagated outward. The cracks in samples V5-3 and L5-2 were composed of three types. Owing to the appearance of the pore, the shear crack produced in sample L5-2 passed through the hole and produced a far-field crack when it was far from the hole and loading direction. Three crack types formed the macroscopic fracture of the cement. The tensile crack of V2-2, L2-1, L2-2, and L5-1 was the main crack. Owing to the existence of the hole, the main crack exhibited different degrees of migration in
the orifice direction. The hole in the cement can guide the direction of the main crack to a certain extent. On the basis of observation of the fracture surfaces in the specimen, it is noted that the fracture surfaces were relatively

Table 3. Specific Numerical Parameters Used in the Simulation

| object  | coefficient of homogeneity degree | mean elastic modulus (MPa) | mean intensity (MPa) | Poisson’s ratio coefficient | average Poisson’s ratio |
|---------|----------------------------------|-----------------------------|---------------------|----------------------------|------------------------|
| value   | 1                                | 3000                        | 30                  | 10 homogeneous degrees     | 0.25                   |

Figure 9. (a) Tensile strengths of the experimental and numerical simulations. (b) Deviation between the numerical simulation results and the experimental results

Figure 10. (a) Comparison between simulation and experimental results of intact specimen. (b) Comparison between simulation and experimental results of specimens with vertical eccentric holes.
smooth, and there was a small amount of debris, which could be caused by the local stress concentration on the fracture surfaces.

3.6. Numerical Simulation. To study the effect of the hole on the cement splitting tensile stress and damage mechanism, in this study, we simulated the cement damage process using RFPA3D software, which is a real fracture process analysis system based on elastic mechanics as a stress analysis tool, elastic damage theory, and tensile Mohr–Coulomb failure. The material mechanical properties must be determined in advance for the simulation, and experimental error is minimized by means of constant parameter modification. The material properties were set according to the actual cement features, and the specific numerical parameters are shown in Table 3. Figure 9a shows the tensile strengths of the experimental and numerical simulations, and Figure 9b shows the deviation between the numerical simulation results and the experimental results. Among them, the largest deviation appears in V2-1, and the smallest error appears in V2-2. In general, the simulation error is within the allowable range.

3.6.1. Failure Mechanism of Vertical Eccentricity Hole. The vertical eccentric hole diameter was similar to the extension mechanism of 2 and 5 mm, and the influence of the 5 mm hole on the cement was more obvious. This study simulated a 5 mm hole to observe its stress distribution and explain its influence mechanism. Figure 10 presents the maximum principal stress diagram of the analogue diagram, the simulated fracture diagram, and the macroscopic fracture diagram of the sample. The deep black edge of the hole in the simulation diagram represents the stress concentration position. It can be seen that the hole location is closely related to the subsequent specimen failure process.

The results show that both primary and secondary cracks are in good agreement with the experimental results. It can be observed from Figure 10a that the stress concentration phenomenon occurred at the loading points on both ends of the intact cement, and the stress on the load line was in a more uniform state. When the vertical eccentric hole appeared, the stress concentration at both ends was more obvious. Moreover, the hole on the cement surface changed the internal stress state. The cement stress state was changed from the stress on the loading line to the stress concentration of the upper and lower parts of the hole. The red arrow (Figure 10b) indicates the stress concentration at both ends through the hole. It can be seen from the final macroscopic rupture graph that the splitting and pulling cracks all passed through the hole, whereas the shear crack was produced at the edge of the hole, which is consistent with our experimental phenomena. Owing to the short distance between the hole and the loading point, the stress-bearing ability became weaker. The cracks at the loading point were more obvious, and rupturing occurred within a short time.

3.6.2. Failure Mechanism of Horizontal Eccentric Hole. The horizontal eccentric hole diameter was similar to the 2 and 5 mm extension mechanism, and the influence of the 5 mm hole on the cement was more obvious. This study simulated a 5 mm hole to observe its stress distribution and explain its influence mechanism. It can be seen from Figure 11 that the stress concentration was generated around the hole, indicating that the presence of the hole affected the internal stress distribution, thereby changing the cement bearing capacity.
The macroscopic fracture in Figure 11 indicates three crack forms, namely, tensile cracks a, b, and c as well as far-field and shear cracks. The shear crack of simulated specimen LS-2 developed toward the cement hole, and this phenomenon is similar to that of the real ruptured graph. In Figure 11, the main crack phenomenon in simulated samples LS-1 and LS-2 indicates the hole migration. However, it differs from the real rupture diagram owing to the error between the software simulation and the physical material parameters. Compared with simulated sample L5-2 and the experimental images, both tensile and shear cracks appeared, which demonstrates that the influence of the hole on the cement surface was still obvious. Only one main crack existed in LS-3 of the simulated sample. This demonstrates that the hole location was far from the center point, the influence on the cement crack strike was not obvious, and the action force was weak. The main crack of LS-3 did not pass through the hole, which is consistent with the experimental results.

4. CONCLUSIONS

In this work, the effects of the hole on the tensile stress and fracture mechanism of the cement were studied by a splitting test. Moreover, the analysis results were explained with the simulation software RFPA²D. Certain conclusions can be drawn, as follows:

1. Holes in the cement have a significant effect on the strength and deformation characteristics of the oil well cement. The hole position influences the cement crack initiation and direction. The vertical eccentric hole reduces the cement tensile stress, and the hole being closer to the loading point results in lower tensile stress. The horizontal eccentricity hole does not always reduce the cement tensile stress: When it is further from the center point of the cement, the tension stress will be higher.

2. It is established that the three crack propagation modes of cement stone with holes are tensile, far-field, and shear cracks.

3. On the basis of the simulation software RFPA²D, the simulation and experimental results are similar, which demonstrates that the simulated parameters are close to the actual cement material properties.

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Notes

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