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Improvement of aluminium powder application measure based on influence of gas hole on strength properties of oil well cement

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HIGHLIGHTS

- With increasing induced porosity the strength increases at first, subsequently decreases and then increases again.
- Pressure difference between gas holes, self stress and framework stress of cement stone influence the strength together.
- Making gas holes' diameter more uniform is beneficial for strength.
- We construct a model of formation process of gas hole structure.
- We improve the application measure of aluminium powder for forming the gas holes structure with uniform diameter.

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ABSTRACT

The research objectives were to investigate the influence of gas holes on strength properties of oil well cement, and to propose improvement of aluminium powder application measure. The results showed that with increasing induced porosity the strength increases at first, subsequently decreases and then increases again. Making gas holes' diameter more uniform was beneficial for strength. According to our model, avoiding each gas hole distribution area overlapping with others could form the gas hole structure with uniform diameter. This objective can be achieved by using different particle size of aluminium powder for different swelling volume of oil well cement stone.

1. Introduction

Cement has been used in underground sealing in oil and gas well [1]. One of the major requirements for oil well cement is to create a very low permeability barrier for fluids, especially on the boundary between cement-casing and cement-formation [2]. However, autogenous shrinkage and drying shrinkage may increase the risk of cracking the cement materials. In addition, cement is quite brittle and can be broken easily due to very small deformation when it is pressed, negatively increase the permeability. Therefore, volume shrinkages and intrinsic brittleness of cement are the main causes of sealing failure. Expansive additives have been widely used to compensate the shrinkage of cement-based materials to avoid cracking. The expansion can be realized by the hydration of expansive agents mixed in cement, such as sulfo-aluminate, free calcium oxide and uncombined magnesia [3], but these additives increase brittleness of cement [4]. In order to satisfy the requirements of sealing, the flexible and expanding cement material has been proposed [5–8].

Cement will expand through entrapping swelling gas holes artificially by adding aluminium powder during mixing [9,10]. Some indoor and field experiments showed that gas holes could reduce the Young's modulus and brittleness of the cement [11–13], therefore swelling gas holes are beneficial to compensating volume shrinkage and improving cement flexibility. While the expansion and flexibility cannot guarantee the sealing performance of cement stone in underground, compressive strength and interfacial bonding strength are also important. There must be enough compressive strength in cement to withstand the compressive loads that are exerted at the cement-casing interface [14], and the failure of zonal isolation generally occurs in the interface [15].

However, in cementing industry, less attention has been given to the effect of swelling gas holes on cement strength. In construction industry, in view of impermeability, durability and other characteristics, the study of influences of gas holes' parameters

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(geometric configuration, quantitative and qualitative) on the mechanical properties of aerated concretes have been carried out [16,17]. Whereas, because of high gas holes' pressure due to the restriction in well and the interface which should be paid more attention to ensure the zonal isolation, the strength properties of aerated concretes are not suitable for oil well cement.

In this paper, the effects of the gas holes on oil well cement compressive strength and cement-casing interfacial bonding strength are experimentally investigated. Results show that with increasing total gas holes volume compressive strength and interfacial bonding strength increase at first, subsequently decreases and then increases again. Through microscopic observation of cement thin section, the reason is analyzed. A physical model of gas hole distribution is built and the application technology of aluminium powder is improved.

2. Experimental

2.1. Materials

Class G oil well cement was used in our experiments. The typical chemical composition and physical properties of class G oil well cement is given in Table 1. Two kinds of different aluminium powder were choice, and the composition and physical properties are given in Table 2. At first, Al_1 was utilized. The dosage of Al_1 was kept at 0.01–0.06% by weight of cement (BWOC) and systematically studied as follows:

0.01%; 0.02%; 0.03%; 0.035%; 0.04%; 0.045%; 0.05%; 0.06%.

Moreover, in order to prevent gas holes from migration and accumulation, $CaCl_2$ was used to accelerate cement setting and hardening. Nine pastes were prepared as shown in Table 3.

Furthermore, six another pastes were prepared as shown in Table 4 to research the effect of aluminium powder physical properties on strength performance. Compared with the pastes in Table 3, the aluminium powder has larger particle size and smaller specific surface area.

2.2. Method

2.2.1. Manufacturing process

Cement slurry was mixed according to API Spec. 10B-3-2004. After being prepared, cement slurry was placed into compressive-strength moulds (5 cm × 5 cm × 5 cm) and interfacial bonding strength testing device which consisted mainly of steel sleeve, cap, and casing, etc. The interfacial bonding strength testing device is shown in Fig. 1. Considering the downhole condition, the device and moulds were put into high temperature high pressure curing chamber. The cement slurry were cured at 75 °C and 10 MPa for 72 h, and then the following experiments were carried out at 20 °C and 0.1 MPa.

2.2.2. Introduced porosity [18]

Suppose the density of gas is 0, and according to the conservation of mass before and after expansion, the formula (1) is got.

$$\eta = (1 - \rho_1/\rho_2) \times 100\% \quad (1)$$

where η is introduced porosity which is defined as the ratio of the total gas hole volume to the total apparent volume of the expanded material, and ρ_1 and ρ_2 are, respectively, the dry apparent densities of the expanded material and of the basic matrix.

2.2.3. Elastic modulus and Poisson ratio

The relationship between elastic parameters of solid and velocity of ultrasonic propagation in solid are given by:

$$V_P = \sqrt{\frac{E}{\rho}\frac{1-\nu}{(1+\nu)(1-2\nu)}} \quad (2)$$

$$\nu = \frac{V_P^2/2 - V_S^2}{V_P^2 - V_S^2} \quad (3)$$

where V_P is the longitudinal wave velocity, V_S is the shear wave speed, E is the elastic modulus, ν is the Poisson ratio, and ρ is the solid density.

Ultrasonic transducer (50 kHz) was used to test the V_P and V_S. The ν was calculated from formula (2), and then the E was obtained from formula (3).

2.2.4. Compressive strength and interfacial bonding strength

The expansion of cement stone only occurred in one direction due to the moulds constraints. The expansion direction remained vertical during the setting of the material. Compressive strength was measured in the direction perpendicular to expansion.

The testing procedures of interfacial bonding strength were as the following:

(1) Open the cap, install lock block and cushion block as shown in Fig. 2.
(2) Increase pressure on the lock block and record the maximum pressure P1 when cement and casing sliding occurs. P1 divided by the contact area of cement-sheath and casing was bonding strength.

2.2.5. X-ray diffraction

XRD analyses were conducted in the State Key Laboratory of Heavy Oil Research using a PANalytical X'Pert MPD X-ray diffractometer. The data acquisition was carried out within the range of well-known cement minerals 2–70° at a grade of 0.02° increments with Cu Kα radiation.

2.2.6. Microscopic structure of gas holes

According to the standard of SY/T 5913-2004, in the perpendicular expansion direction, the intermediate section of cement stone was made into thin sections of which the thickness was 0.03 mm. Polarizing microscope whose type was AXIO-SKOP40APOL, and manufacturer was the German ZEISS company was used to observe thin sections. Natural light microscopic images and orthogonal polarization microscopic images were acquired to analyze microscopic structure of gas holes.

3. Results and discussion

3.1. The relationship of η and Al_1 dosage

The relation curves between η and aluminium powder dosage is shown in Fig. 3; it can be seen that the introduced porosity increases linearly with the addition of aluminium powder.

3.2. Elastic deformation properties

The testing results of elastic modulus and Poisson ratio of different pastes are shown in Table 5. By increasing the dosage of aluminium powder the elastic modulus of expanded material decreases and the Poisson ratio increases. This phenomenon means that incremental porosity can improve the elastic deformation capacity of cement stone, which efficiently decrease the potential of brittle fracture.

3.3. Influence of gas holes on strength properties

Data obtained in previous studies [18] indicated that due to the porosity development, the compressive strengths of all the tested aerated concretes were decreasing with the aluminium powder dosage increasing. In our study, the compressive strengths and cement-casing interfacial bonding strength of oil well cement were tested, and the results are shown in Figs. 4 and 5. It can be observed that, with increasing induced porosity the compressive strength and interfacial bonding strength of expansive cement stone increases at first, subsequently decreases and then increases again, which is inconsistent with results obtained in previous study.

Because of sidewall and casing constraint, the expansive cement stone has self-stress which can balance part of external force. With the total gas hole volume increasing, the self-stress caused by

Table 1
Phase composition and physical properties of class G oil well cement.

C_3S (wt%)	C_2S (wt%)	C_3AC (wt%)	C_3AF (wt%)	Specific density (kg/L)	Specific surface area (m^2/kg)
53.7	30.46	2.8	8.0	3.17	332