ABSTRACT: Offshore oil- and gas-field development is shifting from shallow water to deepwater on a large scale. Deepwater shallow bentonite slurry drilling fluid has a single composition and a simple structure. Therefore, the bentonite slurry drilling fluid has been neglected for the shallow wellbore strengthening ability. Based on the shallow geological characteristics and bentonite hydration mechanism, considering the economy and application effect, the optimization of bentonite slurry drilling fluid from four aspects of viscosity enhancement, adsorption, trapping, and physical plugging to carry out deepwater shallow wellbore strengthening research has been undertaken. For an indoor simulation of bentonite slurry and its drilling slurry-making process using a 2−10% mass concentration of bentonite slurry drilling fluid, laser particle size analysis found an interesting phenomenon different from the traditional understanding: for every 5% increase in particle size accumulation in the range of 0.1−100 μm, the bentonite slurry particle size increases linearly. Based on this interesting phenomenon, the basic performance of drilling fluids with different concentrations of bentonite slurry was evaluated. Experiments were conducted to introduce cationic emulsified asphalt as a deformation filler and to explore a new inexpensive drilling and wellbore strengthening material, AEH-P. The effectiveness of deepwater shallow strengthening was evaluated for AEH-P and cationic emulsified asphalt from both mechanistic and experimental aspects. It is obvious that the wellbore strengthening effect is the result of both particle settling and particle size matching. By exploring the relationship among bentonite slurry hydration dispersion, the charged nature, particle concentration, and the wellbore strengthening effect, a set of low-cost deepwater shallow bentonite slurry drilling fluids with a good wellbore strengthening effect are constructed. The research results provide a method to strengthen the wellbore for the subsequent fast and efficient drilling of deepwater shallow wells, further improving the drilling efficiency.

1. INTRODUCTION

With continuous development, offshore oil and gas exploration and development technology has gradually expanded to deepwater and ultradeepwater wells. Compared with land or shallow water, the deepwater drilling environment is more complex and faces more technical problems.1,2 In the process of deepwater drilling, the shallow wellbore strengthening problem has not been well solved due to the need to consider both practicality and economy.3−6

The deepwater shallow geological environment is more complex, with low temperatures, shallow faults, hydrates, and abnormal pressures creating many difficulties and uncertainties for shallow drilling fluids.7,8 Taking the Ledong area of the Yingqiong Basin in the South China Sea as an example, the correspondence between drilling fluid and strata during deepwater drilling is shown in Figure 1. The shallow deepwater strata are generally distributed in the Ledong Formation, mainly between 800 and 1500 m at the beginning of the subsea mudline, and the drilling fluid is seawater or bentonite slurry drilling fluid.9,10 The deepwater shallow geological features of the China Yingqiong Basin are mainly the following: (1) Physical characteristics of the shallow lithology: in general, the upper part is dominated by large sets of mudstone with thin layers of siltstone and muddy siltstone in a muddy background. The lower part is dominated by muddy siltstone with medium-thick bedded mudstone and thin bedded siltstone. The clay minerals are about 16−21% and quartz is about 40−44%, where the clay minerals are mainly a Yimeng mixed layer. (2) Shallow fracture and pore throat characteristics: micropores and ultramicror-fractures dominate, most pores are between 1 and 30 μm, rock pores are not uniform, most areas do not have chemical gaps,
and a locally concentrated distribution. (3) The temperature and pressure characteristics of the shallow layer: the formation pressure equivalent is between 1.05 and 1.36 g/cm², the safety density window is less than 0.3 g/cm³, and the temperature spans 0 to 60 °C. The impact of shallow hydrate formation on drilling operations needs to be considered during the drilling process. (Hydrate control is not the focus of this paper, so it is not analyzed here.) Bentonite slurry drilling fluids, which are mainly used in the current deepwater shallow drilling process, have not yet considered the effect of wellbore strengthening, which may cause wellbore instability, collapse, and leakage.

At present, shallow wellbore problems seriously affect the deepwater drilling safety and drilling efficiency, and different scholars have put forward different views on bentonite slurry-enhanced wellbore. Chao et al. studied the improving effects of vegetable gum, sodium polyacrylate, and grafted starch on the stability and filtration loss properties of bentonite retaining wall mud and prepared polymer-modified bentonite slurry with stable viscosity, low filtration loss, and little applied admixture, which can be used to solve technical problems such as the shrinkage and collapse of holes in the construction of water-sensitive geology. Guo et al. prepared terpolymer water-bentonite drilling fluids using mechanical stirring and ultrasonic superimposition, which are commonly used in industry. The mud cake formed by the terpolymer water-bentonite drilling fluid had a smooth and dense surface. The analysis of clay particle size in the terpolymer water-bentonite drilling fluid confirmed that ultrasonic oscillation could reduce the average particle size and broaden the particle size distribution, while an ultrafine clay particle fraction appeared. Saboori et al. introduced copper oxide/polyacrylamide nanocomposites to improve the rheology, filtration, and thermal conductivity of bentonite drilling fluids, and the experimental results showed a significant increase in the viscosity of bentonite slurry drilling fluids. The improved bentonite drilling fluid has a significantly lower filtration loss and mud cake thickness, and the mud cake obtained with the nanocomposite additive is smoother and less porous, with a significant increase in thermal conductivity. In summary, bentonite slurry drilling fluids are mainly used to enhance the wellbore through viscosity enhancement, adsorption, trapping, and physical plugging, but there are basically no field application cases due to the high cost of additives in the aforementioned bentonite slurry drilling fluids.

In this paper, we address the problem of the shallow wellbore strengthening of the bentonite slurry drilling fluid in the drilling process of offshore wells, considering both economics and practicality, and perform shallow well wall strengthening from four aspects: viscosity enhancement, adsorption, trapping, and physical plugging. We introduced AEH-P (aqueous enhanced high-strength material particles), a new inexpensive drilling method with wellbore strengthening material, and cationic emulsified asphalt as additives to bentonite slurry drilling fluids. We also designed experiments on deepwater shallow wellbore strengthening to evaluate the effect of wellbore strengthening in order to achieve the desired wellbore strengthening effect to reduce the cost of deepwater drilling and increase the revenue from deepwater oil and gas extraction.

2. EXPERIMENTAL PREPARATION AND METHODS

2.1. Experimental Preparation. 2.1.1. Experimental Instruments. We used an X’Pert PRO MDX X-ray diffractometer, PANalytical B.V.; a multilinked medium-pressure filtration loss meter, Qingdao Haitongda Special Instrument Co.; an LS-609 laser particle size analyzer, Omicron Instruments, Zhumai, China; a six-speed viscometer, Qingdao Chuangmeng Instrument Co.; an SU8010 high-resolution field emission scanning electron microscope, Hitachi; and a nanoparticle size potentiometer zeta Litesizer 500, Anton Paar, Inc. 2.1.2. Experimental Samples. We used sodium bentonite, Weifang, Shandong Province, China; aqueous enhanced high-strength material particles (AEH-P), Synthesis in Key Laboratory of Oil and Gas Drilling Engineering, Yangtze University; and cationic emulsified asphalt, Jingzhou, Hubei Province China.

2.1.3. Experimental Filter Paper. The filter paper with 2.5, 8, and 20–25 μm pores was selected to simulate 1–30 μm pores and ultramicrofracture. Whatman filter paper (2.5 μm, 8 μm, 20–25 μm), Waterman, U.K., was also used.
2.2. Experimental Methods. 2.2.1. X-ray Diffraction (XRD). 2.2.1.1. Bentonite XRD Clay Analysis Experiments. A portion of the bentonite was placed on a sample table, and the bentonite was analyzed using an X-ray diffractometer to obtain the content of different clay minerals in the bentonite.

2.2.2. API Filtration Loss. We carried out bentonite slurry drilling fluid API (American Petroleum Institute) filtration loss experiments. The API filtration loss tester is shown in Figure 2.

![API filter loss tester](image)

2.2.3. Scanning Electron Microscopy (SEM). 2.2.3.1. Mud Cake SEM Experiments on Bentonite Slurry Drilling Fluids. After the mud cake was fast freeze-dried, some of the mud cake samples were removed and sprayed with ion-sputtered gold. The microstructures of different mud cakes were observed by SEM to determine the wellbore strengthening properties of bentonite slurry drilling fluids.

2.2.4. Rheological Properties. 2.2.4.1. Experiments on the Rheological Properties of Bentonite Slurry Drilling Fluids. The bentonite slurry drilling fluid to be measured is placed in the drilling fluid cup, and the corresponding viscosity indications are measured at speeds of 600, 300, 200, 100, 6, and 3 rpm, respectively. The apparent viscosity (AV), plastic viscosity (PV), and dynamic shear (YP) of the bentonite slurry drilling fluid are obtained from the measured viscosity indications to determine the rheological properties of the bentonite slurry drilling fluid.

2.2.5. Particle Size Distribution. 2.2.5.1. Experiments on Particle Size Distribution of Bentonite Slurry Drilling Fluid Base Slurry. Bentonite powder is configured into different concentrations of 2, 4, 6, 8, and 10% of bentonite slurry drilling fluid base slurry. Bentonite slurry drilling fluid base slurry with different concentrations was measured wet with a laser particle size meter for the particle size distribution.

2.2.6. Zeta Potential. We performed experiments on the effect of deformation filling materials on the hydration and dispersion of bentonite slurry. Add the deformation filling material to the bentonite slurry drilling fluid and disperse it well. Take a small amount of well-dispersed bentonite slurry drilling fluid in a zeta potential meter to measure the zeta potential value of bentonite slurry drilling fluid. The stability of the particle colloidal dispersion in bentonite slurry drilling fluids was analyzed by zeta potential values of bentonite slurry drilling fluids.

2.3. Wellbore Strengthening Method with Drilling. The deepwater shallow wellbore strengthening mechanism is shown in Figure 3, and a shallow wellbore with numerous pores, ultramicrofractures, and shallow geological instability drilling fluid technology is the main vehicle for implementing technical improvements.
measures to stabilize the wellbore. Deepwater shallow wellbore strengthening is mainly reinforced with drilling, combined with the hydration mechanism of the bentonite composition, and deepwater shallow bentonite slurry drilling fluid system development should follow the following principles.

1. Define the pores and ultramicrofractures to be sealed, retard pressure transfer and filtrate intrusion, and improve the stability of the deepwater shallow formation wall to reduce its filtration loss.

2. The bentonite slurry drilling fluid has more solid particles, and when the drilling fluid forms a mud cake, a large number of solid-phase particles participate in wall building and form the mud cake by bridging the large particles and filling the small particles gradually. The influence of different particle size classes of solid particles on the water loss and wall-building properties of pores as well as ultramicrofractures is important.

3. Strengthen the inhibition of bentonite slurry drilling fluid on the deepwater shallow well wall and the ability to cement and cure the wellbore to retard further softening of the formation and also to improve the deepwater shallow drilling speed and shorten the formation soaking time.

Based on experiments and related modeling conducted by Cook and Contreras, it was shown that mud cake is important in preventive borehole reinforcement and largely responds to wellbore strengthening. Bentonite slurry drilling fluid will form a mud cake in the pores and ultramicrofractures around the wellbore and will isolate the pores from the ultramicrofractures. The ability of the mud cake to isolate the pores and microfractures from the well wall pressure is a key factor in this phenomenon. Therefore, combined with the geological analysis of deepwater shallow drilling, deepwater shallow bentonite enhanced wellbore experimental research is carried out as follows.

1. Using different pore size filter paper to simulate formation pores and ultramicrofractures, the API filtration loss experiment allows us to use the bentonite slurry drilling fluid to assess the filtration loss and the filter cake quality under different pore size filter papers.

2. To carry out shallow formation wellbore strengthening under different materials, different materials are added to the bentonite slurry drilling fluid to strengthen the wall-building performance and reduce the filtration loss in order to select the optimal solution for strengthening the wellbore under different pores.

3. Using mud cake and filtration loss as the main evaluation tools, the amount of filtration loss after the API experiment and the quality of the final mud cake formed to strengthen the wellbore were observed to reflect its wellbore strengthening effect.

### 2.4. Development of AEH-P, a Deepwater, Shallow, Wide-Grain Composite Drilling Method with Wellbore Strengthening Material

Deepwater shallow wellbore strengthening in the field with drilling well wall strengthening materials commonly use rigid bridging particles for wellbore strengthening. Rigid bridging particles are mainly calcium carbonate particles, or quartz sand. Such particles are mainly in the pores or ultramicrofractures to play a bridging and filling role, basically with no deformation, a single rigid material sealing is also single, and rigid bridging to match the particle size requirements are high. Therefore, this paper selects rigid bridging particles consisting of calcium carbonate with silica, elastic filling particles consisting of graphite, and a kind of inert microfine short-cut fiber material in a certain ratio to compound a new composite blocking particle, AEH-P (Figure 4). Using the physical plugging mechanism for deepwater shallow wellbore strengthening, AEH-P has a variety of drilling fluids with drilling wall strengthening material characteristics and low price, with good practicality and economy.

From the point of view of the mechanism of mud cake formation, whether a high-quality mud cake can be formed on the wellbore is a fundamental reflection of whether the drilling fluid is a good wall builder, and it is also a favorable supplement to strengthen the plugging property of drilling fluid. Solid particles in the drilling fluid are an important part of the formation of a high-quality mud cake, so on the basis of the original performance, the appropriate amount of AEH-P is added to the bentonite slurry drilling fluid system in order to form a high-quality mud cake and improve the system sealing.

Figure 4. New composite blocking particle AEH-P.
and wall protection to ensure the stability of the deepwater shallow wellbore.

3. RESULTS AND DISCUSSION

3.1. Properties of Bentonite Slurry Drilling Fluid

3.1.1. Content of Bentonite Components. The XRD clay analysis of the bentonite is shown in Figure 5.

![Figure 5. XRD clay analysis figure](http://pubs.acs.org/journal/acsodf)

From Figure 5, we can see that the bentonite is mainly composed of montmorillonite and illite, of which the pure montmorillonite content accounts for 35% and the illite/montmorillonite mixture accounts for 61.4%, which provides good-slurry making and wall-making properties for the bentonite.

3.1.2. Basic Properties of Bentonite Slurry. The basic performance evaluation of bentonite slurry drilling fluids with different concentrations is shown in Table 1.

| Bentonite Slurry Concentration | Ø600/Ø300 | Ø200/Ø100 | Ø6/Ø3 | AV (mPa·s) | PV (mPa·s) | YP (Pa) |
|-------------------------------|------------|-----------|-------|------------|------------|--------|
| 2% bentonite slurry           | 3/2        | 2/1       | 0/0   | 1.5        | 1          | 0.5    |
| 4% bentonite slurry           | 8/5        | 3/2       | 0/0   | 4          | 3          | 1      |
| 6% bentonite slurry           | 15/10      | 7/5       | 2/2   | 7.5        | 5          | 2.5    |
| 8% bentonite slurry           | 20/12      | 9/7       | 2/2   | 10         | 8          | 2      |
| 10% bentonite slurry          | 41/28      | 22/16     | 11/9  | 20.5       | 13         | 7.5    |

Table 1. Table of Evaluation Results of Bentonite Slurry Performance

3.1.3. Filtration Loss of Bentonite Slurry. API filtration loss experiments were conducted for different concentrations of bentonite slurry drilling fluids through 2.5, 8, and 20–25 μm size filter papers, respectively. The filtration losses of drilling fluids with different concentrations of bentonite slurry for different pore filter papers are shown in Figure 6.

As can be seen in Figure 6, the filtration loss of bentonite slurry drilling fluid decreases continuously as the bentonite slurry drilling fluid concentration increases. When the bentonite slurry drilling fluid concentration increases from 8 to 10%, the decrease in the filtration loss of the bentonite slurry drilling fluid is small.

3.1.4. Mud Cake Thickness of Bentonite Slurry. Different concentrations of bentonite slurry drilling fluids were passed through 2.5, 8, and 20–25 μm size filter papers, and the mud cake thicknesses of different concentrations of bentonite slurry drilling fluids are shown in Figure 7.

It can be seen from Figure 7 that the thickness of the mud cake increases sequentially with the increase of the bentonite slurry concentration, and the thickness of the mud cake under the large pores is larger than that under the small pores. The bentonite concentration is 8% when the mud cake thickness does not change with the change in pore space, indicating that the concentration of the 8% bentonite slurry drilling fluid particle size distribution is more uniform and the 8% bentonite slurry performance is more stable, so the reverse discharge of the fluid will be close to 7 to 8% viscosity of the bentonite slurry drilling fluid.

3.1.5. Particle Size Distribution of Bentonite Slurry. We determined the laser particle size analysis of a drilling fluid with different concentrations of bentonite slurry, which is shown in Figure 8.

The particle size distribution of a bentonite slurry drilling fluid of different concentrations shows that the particle size accumulation of the bentonite slurry drilling fluid is more uniform from 50 to 80%.

3.2. AEH-P to Bentonite Slurry Sealing Ability

3.2.1. Bentonite Slurry + 5% AEH-P with Different Meshes. Experiments were selected to add 3000, 2000, 1000, 800, 500, 300, 200, and 100 mesh AEH-P to the drilling fluid of 8% bentonite slurry. The addition of AEH-P has basically no effect on the rheological properties of the bentonite slurry drilling fluid, which has good follow-through. The AEH-P scanning electron microscope is shown in Figure 9. We used the drilling fluid of bentonite slurry with AEH-P added through 2.5, 8, and 20–25 μm Whatman filter paper for an API medium-pressure filtration loss experiment to observe the amount of filtration loss, mud cake thickness, and mud cake denseness for comparative evaluation.

The mud cake thickness is shown in Figure 11. AEH-P enhances the mud cake denseness and reduces the mud cake thickness. The filtration loss of bentonite slurry drilling fluid is shown in Figure 10. The instantaneous sealing performance of pores is greatly improved by adding AEH-P with small particle sizes. AEH-P with 200 particle size has the best sealing performance for pores of 2.5 μm, AEH-P with 500 particle size has the best sealing performance for pores of 8 μm, and AEH-P with 500 particle size has the best sealing performance for pores of 20–25 μm.

3.2.2. Bentonite Slurry + Different Concentrations of AEH-P. The bentonite hydration swelling is shown in Figure 12, where
the volume of bentonite powder swelling in water is about 6 times larger and the percentage of solid particles added to AEH-P as a percentage of the overall bentonite slurry drilling fluid solid particles is very small. The electron micrograph of bentonite powder is shown in Figure 13, from which it can be seen that the bentonite powder is fine and scale-like under SEM, indicating that the bentonite powder contains a large amount of clay minerals, mainly montmorillonite. In order to better reduce the filtration loss to improve the wall-building properties to achieve the effect of wellbore strengthening, we increasing the percentage of effective solid particles to be achieved. We increase the concentration of 200-purpose AEH-P on 2.5 μm pores and increase the concentration of 500-purpose AEH-P on 8 μm pores and 20−25 μm pores. The experiments are as follows:

① 8% bentonite slurry drilling fluid + 8% AEH-P (200 mesh) through 2.5 μm pores;

② 8% bentonite slurry drilling fluid + 10% AEH-P (200 mesh) through 2.5 μm pores;

③ 8% bentonite slurry drilling fluid + 8% AEH-P (500 mesh) through 8 μm pores;

④ 8% bentonite slurry drilling fluid + 10% AEH-P (500 mesh) through 8 μm pores;

⑤ 8% bentonite slurry drilling fluid + 8% AEH-P (500 mesh) through 20−25 μm pores; and

⑥ 8% bentonite slurry drilling fluid + 10% AEH-P (500 mesh) through 20−25 μm pores.

The experimental results of the filtration loss after increasing the AEH-P concentration are shown in Figure 14. When increasing the concentration of 200 mesh AEH-P from 5 to 8% under passing 2.5 μm pores, the filtration loss was reduced by 12.67% and the filtration loss was 13.8 mL, while when increasing the concentration to 8 to 10%, the filtration loss was basically unchanged. When increasing the concentration of 500 mesh AEH-P from 5 to 8% under passing 8 μm pores, the filtration loss decreased by 8.75% to 14.6 mL, while when AEH-P increased from 8% to 10%, the filtration loss increased. The mud cake thickness of AEH-P on different pores is shown in Figure 15 and increased when AEH-P increased from 8 to 10%.

3.2.3. Hydration and Dispersion Properties of Bentonite Slurry. Bentonite slurry drilling fluid is mainly composed of bentonite, and bentonite can constitute bentonite slurry drilling fluid due to the hydration mechanism of the bentonite composition, the essence of which is the hydration and expansion of montmorillonite contained in bentonite.
bentonite slurry drilling fluid can be seen from the hydration of the montmorillonite formation process, with two main factors affecting the performance of montmorillonite gel: the degree of stripping and the degree of dispersion of montmorillonite in water.

3.2.3.1. Degree of Stripping. Bentonite powder in the montmorillonite crystal layer above and below contains oxygen atoms. In the crystal layer between the intermolecular force connections, the connection force is weak, and water molecules easily enter the crystal layer, causing lattice expansion and bentonite hydration expansion. More importantly, due to the role of lattice substitution, montmorillonite with many negative charges can adsorb cations of equal power. The interlayer cation substitution and homocrystalline homomorphic substitution of different valence cations in montmorillonite are shown in Figure 16. When cationic emulsified asphalt is added to the bentonite slurry drilling fluid, the structure, layer spacing, zeta potential, and morphology of montmorillonite change when quaternary ammonium cations in cationic emulsified asphalt replace the interlayer cations of montmorillonite, aluminum in octahedra and silicon in tetrahedra, providing a suitable environment for the hydration and dispersion of bentonite powder. Therefore, montmorillonite is a swelling clay mineral, which greatly

Figure 10. Filtration loss of AEH-P with different mesh sizes on different sizes of filter paper: (a) filtration loss of AEH-P with different mesh sizes on 2.5 μm size filter paper, (b) filtration loss of AEH-P with different mesh sizes on 8 μm size filter paper, and (c) filtration loss of AEH-P with different mesh sizes on 20–25 μm size filter paper.

Figure 11. Mud cake thickness at 8% concentration bentonite slurry drilling fluid base slurry + AEH-P.

Figure 12. Bentonite hydration and swelling diagram: (left) hydrated for 24 h and (right) not hydrated.

Figure 13. SEM of bentonite powder: (left) under 1000X and (right) under 3000X.

Figure 14. Filtration loss of AEH-P with different concentrations and different mesh sizes.
increases its colloidal activity and provides good slurry-making properties for bentonite.

3.2.3.2. Dispersion Degree. The expansion of bentonite in water is mainly the result of the physicochemical interaction between the clay mineral montmorillonite and the pore fluid. The interlayer interaction of montmorillonite with a 2:1 type of mineral structure is weak, and water molecules can easily enter and form a thick bound water film, which is complex and mainly caused by the repulsive force and van der Waals suction generated by the diffusion double-layer phenomenon. When bentonite and water form a system, a diffuse double layer is formed around its surface. The relationship model between bound water and the diffusion bilayer structure is plotted in Figure 17. Bentonite can interact with water and adsorb bound water. In order of formation are strong adsorption bound water, loose and weak adsorption bound water, and free water. The distribution of various types of bound water on the surface of bentonite is different under different types of water.

In section 3.1.5, laser particle size analysis has been performed for different concentrations of bentonite slurry, and the particle sizes with accumulation percentages for five different concentrations, 2, 4, 6, 8, and 10%, are shown in Figure 18. The particle size growth is linear when the accumulation range is from 50 to 80%. The particle size and particle accumulation size of bentonite slurry with 2, 4, and 6% concentrations differed significantly from those of bentonite slurry with 10% concentration, while the particle size and particle accumulation size of bentonite slurry with 8% concentration were almost indistinguishable from those of bentonite slurry with 10% concentration. The original particle size of bentonite powder is about 200−300 μm, which shows that different concentrations of bentonite powder with respect to the degree of stripping and the degree of dispersion in water are not the same and will appear after the hydration and dispersion of bentonite powder. The particle size will be in the 0.1−100 μm range of a uniform distribution, the particle size accumulation is every 5%, and the particle size increases with the linear growth of this interesting phenomenon.

Different concentrations of the bentonite slurry drilling fluid resting time are shown in Figure 19, and it can be seen that just after the hydration of the bentonite slurry drilling fluid the dispersion effect is very good. However, after 2 h a 6% concentration of bentonite slurry drilling fluid obviously leads to a delamination phenomenon. Only when the concentration of
bentonite slurry is more than 6% does the bentonite slurry drilling fluid have good stability, so in the deepwater shallow drilling process, there is need to combine the site formation clay mineral content and clay mineral slurry properties to adjust the concentration of the bentonite slurry drilling fluid to meet the drilling needs.

In the field of deepwater shallow drilling there is a more interesting phenomenon, regardless of the deepwater shallow geology. As long as the clay minerals containing the montmorillonite type can be hydrated and swollen, drilling into the slurry after the return bentonite slurry drilling fluid the concentration is always about 7 to 8%. Does 7 to 8% bentonite slurry drilling fluid to meet the drilling process, there is need to combine the site formation clay into the slurry after the return bentonite slurry drilling fluid the concentration is always about 7 to 8%. Does 7 to 8% bentonite slurry drilling fluid have dynamic stability in deepwater shallow drilling?

3.2.4. Particle Settling and Particle Size Blocking Matching. AEH-P with a particle size of 200 has the best blocking properties for 2.5 μm pores, and AEH-P with a particle size of 500 has the best blocking properties for 8 μm pores and 20–25 μm pores, which is obviously not in line with the principle of matching particle size blocking in the general state. AEH-P solid particles will obviously sink, and here we introduce Bai,31 McNown,32 and Yao33 and ideas from others to derive the Stokes equation (eq 1) for bentonite slurry drilling fluid solid particles.

\[
V = \frac{(d - \rho)}{0.018} d^2 \times 1.03 \sqrt{\frac{g}{\mu}} \times \sqrt{1 + \frac{(1 - \phi) \cdot G_0}{146K}} - 1
\]

\[
\frac{(1)}{\mu} \times \frac{(d - \rho)}{0.018} d^2 \times 1.03 \sqrt{\frac{g}{\mu}} \times \sqrt{1 + \frac{(1 - \phi) \cdot G_0}{146K}} - 1
\]

\(d\) is the diameter or particle size of the particle, \(m\); \(\delta\) and \(\rho\) correspond to the density of the particles and media, \(g/\text{cm}^3\); \(m\) is the mass of particles, \(kg\); \(G_0\) is the mass of spherical particles in the medium, \(g\); \(\mu\) is the medium viscosity, \(\text{Pa} \cdot \text{s}\); and \(K\) is a factor of 1.

In bentonite slurry drilling fluids with AEH-P added, the density of AEH-P is 2.75 \(g/\text{cm}^3\), the density of 8% bentonite slurry drilling fluid is 1.05 \(g/\text{cm}^3\), the spherical coefficient \(\chi\) is about 0.9, the viscosity of bentonite slurry drilling fluid is 9 mPa·s, the average diameter of 200 mesh AEH-P is about 75 μm, and the diameter of 500 mesh AEH-P is about 30 μm. The settling velocities of AEH-P particles with different mesh sizes in the bentonite slurry drilling fluid are shown in Table 2.

Figure 19. Different concentrations of bentonite slurry drilling fluid resting (left without resting, right resting 2 h).

Table 2. AEH-P Settling Velocity Table

| AEH-P mesh | sinking speed (mm/s) |
|------------|---------------------|
| 200 mesh   | 0.0191              |
| 500 mesh   | 0.0004              |

The particle size has a great influence on the sinking speed. Two hundred mesh AEH-P sinks 47.75 times faster than 500 mesh AEH-P in general. Therefore, the 200-particle sample does not fit well in the particle size class, but the particle settling rate affects the plugging performance of the bentonite slurry drilling fluid. The schematic diagram of particle-to-pore sealing is shown in Figure 20.

Figure 20. Schematic diagram of pore blocking by particles.

The sinking of solid particles in AEH-P first seals the 2.5 μm pores, and then the other particle sizes of solid particles in the bentonite slurry fill the gaps. The clear filtrate from 2.5 μm pores indicates that the mud cake formed after the AEH-P particles have sealed the pores is better at trapping solid particles of other particle sizes. Although the settling speed of 8 μm and 20–25 μm pores with 200 mesh AEH-P is fast and can be sealed instantaneously, the filtrate of 8 μm and 20–25 μm pores is very turbid when the solid particles of other particle sizes in the bentonite slurry are sealed again, indicating that the mud cake formed after the instantaneous sealing with 200 mesh AEH-P is less effective in capturing solid particles of other particle sizes. The mud cake formed by 500 mesh AEH-P after pore blocking is better at trapping solid particles of other particle sizes, so AEH-P with 200 mesh particle size has the best performance for 2.5 μm pore blocking, and AEH-P with 500 mesh particle size has the best performance for 8 μm pore and 20–25 μm pore blocking.

3.2.5. Relationship between Particle Concentration and Infiltration Capacity. In the experiments with 8% bentonite slurry + different concentrations of AEH-P, the filtration loss of bentonite slurry drilling fluid increased instead when the AEH-P concentration increased from 8 to 10% through different pore sizes (2.5, 8, and 20–25 μm), and the mud cake thickness also increased. It shows that the particle concentration in physical plugging has a large effect on the filtration loss. The effect of particle settling and particle size sealing matching on well wall reinforcement was discussed previously and here the experiment changed only the AEH-P concentration in the bentonite slurry drilling fluid, so the formation of high-quality mud cake is also the key to influencing the amount of filtration loss. The structure of the bentonite slurry drilling fluid mud cake is shown in Figure 21, which is divided into outer and inner mud cakes. The outer mud cake is classified into a float layer, compressible layer, dense layer, and ultradense layers from the drilling fluid contact surface to the rock surface of the wellbore depending on the degree of denseness.
The mud cake with different concentrations of AEH-P added to the bentonite slurry drilling fluid to filter out the mud cake is shown in Figure 22, where the false floating and compressible layers of the mud cake are flushed to reveal the real solid mud cake. It is obvious from Figure 22 that the real mud cake with an 8% concentration of AEH-P is significantly denser than that with 10%. This is due to the formation of a stable inner mud cake of the bentonite slurry drilling fluid, which allows only the bentonite slurry drilling fluid filtrate to intrude into the formation, laying the foundation for further evolution of the outer mud cake on the wellbore.

When the concentration of AEH-P is too large, the large AEH-P in the bentonite slurry drilling fluid will take priority over the small bentonite particles to enter the ultradense layer of the mud cake. The solid particles in the bentonite slurry drilling fluid continue to accumulate to form the outer mud cake, and the permeability gradually decreases and is compacted so that the high concentration of AEH-P in the bentonite slurry drilling fluid produces an accumulation of mud cake that is not dense enough. The permeability of the mud cake is higher, resulting in increased filtration loss, which is not conducive to the strengthening of the wellbore in shallow deepwater.

### 3.3. Emulsified Asphalt Compounded with Bentonite Slurry

AEH-P will produce a better effect on wellbore strengthening, reducing the amount of filtration loss to a certain extent but still not meeting the field requirements. Because AEH-P strengthens the wellbore mainly by a physical plugging mechanism, it is uniformly dispersed in the bentonite slurry drilling fluid and comes up through particle size matching and particle sinking. Based on this, combined with the good hydration mechanism of the bentonite slurry in water, cationic emulsified asphalt was introduced to compound with 8% bentonite slurry in order to achieve a better well wall strengthening effect.

The 8% bentonite slurry drilling fluid was added to 0.5, 1, and 1.5% cationic emulsified asphalt to pass through 2.5, 8, and 20–25 μm Whatman filter paper for the API medium-pressure filtration loss test to observe the amount of filtration loss, mud cake thickness, and mud cake denseness for comparison and preference.

As shown in Table 3, there was a significant increase in viscosity with the addition of 0.5% emulsified asphalt to the bentonite slurry drilling fluid. The mud cake thickness of the bentonite slurry drilling fluid is shown in Figure 24, and both decreased to a great extent compared to the mud cake with the addition of AEH-P, while the viscosity decreased instead when the addition of emulsified asphalt continued to increase. Different concentrations of emulsified asphalt in different pores under the filtration loss is shown in Figure 23. We found that 20–25 μm pores with a 0.5% emulsified asphalt sealing effect and 2.5 and 8 μm pores with a 1.5% emulsified asphalt sealing effect are the best whereas 1% emulsified asphalt is the worst for plugging pores of any size.

### 3.3.1. Influence of Deformation Filling Materials on the Hydration and Dispersion of Bentonite Slurry

The 8% bentonite slurry drilling fluid was added to 0.5, 1, and 1.5% cationic emulsified asphalt. The previous section of the bentonite slurry drilling fluid with different amounts of cationic emulsified asphalt showed that its viscosity has an impact. We added 0.5% cationic emulsified asphalt, bentonite slurry drilling fluid with an apparent viscosity of 14 mPa·s, and 1 and 1.5% of

---

**Table 3. Bentonite Slurry (8%) + Emulsified Asphalt Performance Evaluation Results**

| emulsified asphalt addition | Ø600/Ø300 | Ø200/Ø100 | Ø6/Ø3 | AV(mPa·s) | PV(mPa·s) | YP(Pa) |
|-----------------------------|-----------|-----------|-------|-----------|----------|--------|
| 8% bentonite + 0.5% asphalt  | 28/19     | 15/11     | 4/3   | 14        | 9        | 5      |
| 8% bentonite + 1% asphalt    | 21/12     | 9/5       | 1/1   | 10.5      | 9        | 1.5    |
| 8% bentonite + 1.5% asphalt  | 22/13     | 9/6       | 3/2   | 11        | 8        | 4      |

---

Figure 21. Physical model diagram of the mud cake structure.

Figure 22. AIP filtration loss mud cake: (left) 8% AEH-P and (right) 10% AEH-P.
cationic emulsified asphalt to the bentonite slurry drilling fluid. The apparent viscosity of the bentonite slurry drilling fluid decreased to 10.5 and 11 mPa·s instead. The zeta potential analysis data for bentonite slurry drilling fluids with 0.5, 1, and 1.5% cationic emulsified asphalt added are shown in Table 4.

The zeta potential of montmorillonite interlayer cations in bentonite slurry drilling fluid has a significant effect on the zeta potential of montmorillonite, so bentonite will be added to the drilling fluid with different concentrations of cationic emulsified asphalt. The absolute value of the zeta potential of a 0.5% concentration of cationic emulsified asphalt bentonite slurry is significantly higher than the blank group, and the absolute values of the zeta potentials of 1 and 1.5% concentrations of cationic emulsified asphalt bentonite slurry are smaller than for the blank group.

In the bentonite slurry drilling fluid of montmorillonite, the aluminum-oxygen octahedron Al$^{3+}$ is replaced by quaternary ammonium cations, so the absolute value of the zeta potential of the blank group is less than 0.5% concentration of cationic emulsified asphalt bentonite slurry, but a large number of quaternary ammonium cations will again inhibit the hydration and dispersion of bentonite slurry. That is, the concentration of metal cations has a significant effect on the surface potential of montmorillonite, and the effect varies according to the concentration of cations. Therefore, matching zeta potential values are favorable for the formation of gel systems. The larger the absolute value of the zeta potential, the better the dispersion of montmorillonite particles.

### 3.4. Compounding of AEH-P with Emulsified Asphalt

Based on the hydration mechanism of physical blocking and the bentonite slurry, the following experiments were selected for the compounding of AEH-P with emulsified asphalt. ○8% bentonite slurry drilling fluid + 0.5% emulsified asphalt + 8% AEH-P (200 mesh) through 2.5 μm filter paper; ◯8% bentonite drilling fluid + 1.5% emulsified asphalt + 8% AEH-P (500 mesh) through 8 μm filter paper; and □8% bentonite + 1.5% emulsified asphalt + 8% AEH-P (500 mesh) through 20−25 μm filter paper.

The amount of filtration loss of the compounded bentonite slurry drilling fluid is shown in Figure 25. The addition of AEH-P with emulsified asphalt has a very significant reduction in filtration loss, which is below 8 mL for all types of pores, and the instantaneous filtration loss is greatly enhanced compared with the addition of emulsified asphalt only. The mud cake characteristics are shown in Figures 26 and 27, where it can be seen that the mud cake formed by the compounded bentonite slurry drilling fluid is thinner and denser.

| cationic emulsified asphalt concentration | mean zeta potential (mV) |
|------------------------------------------|--------------------------|
| bentonite slurry drilling fluid           | −18.6                    |
| bentonite slurry drilling fluid + 0.5% cationic emulsified asphalt | −22.3                    |
| bentonite slurry drilling fluid + 1% cationic emulsified asphalt | −11.3                    |
| bentonite slurry drilling fluid + 1.5% cationic emulsified asphalt | −9.5                     |

Since the zeta potential of montmorillonite interlayer cations in bentonite slurry drilling fluid has a significant effect on the zeta potential of montmorillonite, bentonite will be added to the drilling fluid with different concentrations of cationic emulsified asphalt. The absolute value of the zeta potential of a 0.5% concentration of cationic emulsified asphalt bentonite slurry is significantly higher than the blank group, and the absolute values of the zeta potentials of 1 and 1.5% concentrations of cationic emulsified asphalt bentonite slurry are smaller than for the blank group.

In the bentonite slurry drilling fluid of montmorillonite, the aluminum-oxygen octahedron Al$^{3+}$ is replaced by quaternary ammonium cations, so the absolute value of the zeta potential of the blank group is less than 0.5% concentration of cationic emulsified asphalt bentonite slurry, but a large number of quaternary ammonium cations will again inhibit the hydration and dispersion of bentonite slurry. That is, the concentration of metal cations has a significant effect on the surface potential of montmorillonite, and the effect varies according to the concentration of cations. Therefore, matching zeta potential values are favorable for the formation of gel systems. The larger the absolute value of the zeta potential, the better the dispersion of montmorillonite particles.

### 3.4. Compounding of AEH-P with Emulsified Asphalt

Based on the hydration mechanism of physical blocking and the bentonite slurry, the following experiments were selected for the compounding of AEH-P with emulsified asphalt. ○8% bentonite slurry drilling fluid + 0.5% emulsified asphalt + 8% AEH-P (200 mesh) through 2.5 μm filter paper; ◯8% bentonite drilling fluid + 1.5% emulsified asphalt + 8% AEH-P (500 mesh) through 8 μm filter paper; and □8% bentonite + 1.5% emulsified asphalt + 8% AEH-P (500 mesh) through 20−25 μm filter paper.

The amount of filtration loss of the compounded bentonite slurry drilling fluid is shown in Figure 25. The addition of AEH-P with emulsified asphalt has a very significant reduction in filtration loss, which is below 8 mL for all types of pores, and the instantaneous filtration loss is greatly enhanced compared with the addition of emulsified asphalt only. The mud cake characteristics are shown in Figures 26 and 27, where it can be seen that the mud cake formed by the compounded bentonite slurry drilling fluid is thinner and denser.

| Table 4. Table of Zeta Analysis of Bentonite Slurry Drilling Fluid |
|---------------------------------------------------------------|
| cationic emulsified asphalt concentration | mean zeta potential (mV) |
|------------------------------------------|--------------------------|
| bentonite slurry drilling fluid           | −18.6                    |
| bentonite slurry drilling fluid + 0.5% cationic emulsified asphalt | −22.3                    |
| bentonite slurry drilling fluid + 1% cationic emulsified asphalt | −11.3                    |
| bentonite slurry drilling fluid + 1.5% cationic emulsified asphalt | −9.5                     |

Since the zeta potential of montmorillonite interlayer cations in bentonite slurry drilling fluid has a significant effect on the zeta potential of montmorillonite, bentonite will be added to the drilling fluid with different concentrations of cationic emulsified asphalt. The absolute value of the zeta potential of a 0.5% concentration of cationic emulsified asphalt bentonite slurry is significantly higher than the blank group, and the absolute values of the zeta potentials of 1 and 1.5% concentrations of cationic emulsified asphalt bentonite slurry are smaller than for the blank group.

In the bentonite slurry drilling fluid of montmorillonite, the aluminum-oxygen octahedron Al$^{3+}$ is replaced by quaternary ammonium cations, so the absolute value of the zeta potential of the blank group is less than 0.5% concentration of cationic emulsified asphalt bentonite slurry, but a large number of quaternary ammonium cations will again inhibit the hydration and dispersion of bentonite slurry. That is, the concentration of metal cations has a significant effect on the surface potential of montmorillonite, and the effect varies according to the concentration of cations. Therefore, matching zeta potential values are favorable for the formation of gel systems. The larger the absolute value of the zeta potential, the better the dispersion of montmorillonite particles.
Through experimental evaluation, a set of deepwater shallow bentonite slurry drilling fluid systems with good practicality are formed for different formation pores, as shown in Table 6.

### 3.4.1. Filtration Loss Performance of Bentonite Slurry and Control Methods.

At certain temperatures and pressures, the bentonite slurry drilling fluid will filter out into the formation. The filtration loss of bentonite slurry drilling fluid is bound to form a mud cake on its percolation surface. Bentonite slurry drilling fluid with low filtration loss can generally form a thin and tough mud cake with dense structure, scouring resistance, and a low friction coefficient on the percolation surface. According to the equation for the static filtration loss of drilling fluid,

$$q_{FL} = \frac{2k \Delta p (\varphi_{SC}/\varphi_{SM} - 1)}{\mu} t^{1/2}$$

$q_{FL}$ is the percolation rate velocity of the drilling fluid filtrate, cm$^3$/s; $k$ is the permeability of the mud cake, μm$^2$; $\Delta p$ is the pressure difference between the two sides of the mud cake; atm; $\mu$ is the viscosity of the filtrate, mPa·s; $(\varphi_{SC}/\varphi_{SM} - 1)$ is the solid-phase content factor; and $t$ is Time, s.

From the equation of static filtration loss (eq 2), it can be seen that the filtration loss of bentonite slurry drilling fluid is proportional to the filtration loss area, square root of the permeability time, mud cake permeability, solid-phase content factor, and pressure difference between the two sides of the mud cake and inversely proportional to the square root of the viscosity of the filtrate.

In the process of deepwater shallow drilling, since a certain flow rate of bentonite slurry drilling fluid can be equal to the deposition rate of solid particles on the mud cake after a certain time of flow, which means that the mud cake thickness tends to be constant, it can be assumed that both $k$ and $L$ are constants. Under this condition, the equation for the dynamic filtration loss of drilling fluid is derived as follows:

$$q_{FL} = \frac{kA \Delta p f}{\mu L}$$

$q_{FL}$ is the percolation rate velocity of the drilling fluid filtrate, cm$^3$/s; $k$ is the permeability of the mud cake, μm$^2$; $A$ is the infiltration area, cm$^2$; $\Delta p$ is the pressure difference between the two sides of the mud cake, atm; $f$ is the time, s; $\mu$ is the viscosity of the filtrate, mPa·s; and $L$ is the thickness of the mud cake, cm.

From eqs 2 and 3, it can be seen that the factors affecting the static filtration loss also have an effect on the dynamic filtration loss but to a different extent.

$$K = \frac{Q \mu L}{A \Delta p}$$

$K$ is the permeability of the mud cake, mD; $Q$ is the flow through the mud cake at a differential pressure $\Delta p$, cm$^3$/s; $L$ is the thickness of the mud cake, cm; $\mu$ is the viscosity of the filtrate, mPa·s; $A$ is the infiltration area, cm$^2$; and $\Delta p$ is the
pressure difference between the two sides of the mud cake, atm. The static permeability $K$ of the selected bentonite slurry drilling fluid mud cake is shown in Table 7.

Table 7. Table of Permeability of the Bentonite Slurry Drilling Fluid Mud Cake on 2.5 $\mu$m Pores

| bentonite slurry drilling fluid type          | penetration rate (mD) |
|---------------------------------------------|-----------------------|
| 8% bentonite slurry drilling fluid          | 0.0041                |
| 8% bentonite slurry drilling fluid + 5% AEH-P (200 mesh) | 0.0032                |
| 8% bentonite slurry drilling fluid + 0.5% cationic emulsified asphalt | 0.0010                |
| 8% bentonite slurry drilling fluid + AEH-P + cationic emulsified asphalt | 0.0009                |

According to Table 7, adding different materials to the bentonite slurry drilling fluid can effectively reduce its mud cake permeability so that the clay particles remain small and have a reasonable size distribution, which can produce a thin, tough, and dense structure of the mud cake, reducing the permeability of the filter cake. From eqs 2 and 3, it can be seen that bentonite slurry drilling fluid can reduce the amount of filtration loss by increasing the viscosity and decreasing the permeability, thus achieving a good wellbore strengthening effect.

3.4.2. Seepage Plugging Ability of Simulated Formation. The shallow rocks in deep water are weak and loose. The rapid plugging ability of drilling fluid directly determines the amount and depth of filtrate invasion. The change in the seepage ability in the perimeter wave and range of the well can reflect the rapid plugging ability of drilling fluid. The rock cuttings of the formation and epoxy resin are used to form the core of the simulated formation in the laboratory. The simulated core is used to determine the influence of bentonite slurry and its optimization system on the formation seepage capacity. The experimental results are shown in Table 8.

Table 8. Core Plugging Ability of Drilling Fluid with Respect to Simulated Formation

| drilling fluid number | permeability (mD) | bearing capacity (MPa) | intrusion depth (mm) |
|-----------------------|-------------------|------------------------|----------------------|
| 8% bentonite slurry   | 1                 | 9.64                   | 0.8                  |
| + 8% AEH-P(200 mesh) | 2                 | 8.67                   | 2.2                  | 38.5 |
| 8% bentonite slurry   | 3                 | 8.23                   | 2.7                  | 32.4 |
| + 8% AEH-P(500 mesh) | 4                 | 7.46                   | 2.9                  | 26.5 |
| 8% bentonite slurry   | 5                 | 9.21                   | 3.1                  | 24.2 |
| + 1.5% emulsified asphalt | 6               | 9.98                   | 4.6                  | 16.1 |
| 8% bentonite slurry   | 5                 | 6.79                   | 5.1                  | 11.2 |
| + 1.5% emulsified asphalt |               |                        |                      |
| + 8% AEH-P(300 mesh) |                   |                        |                      |

The permeability of the simulated core used in the experiment is concentrated in 6–10 mD, which has good consistency and ensures the effectiveness of the experimental results. The experimental results show that adding AEH-P and emulsified asphalt to the simulated core can significantly improve the plugging ability of bentonite slurry drilling fluid while drilling. The plugging effect of AEH-P materials is less than that of emulsified asphalt materials, which is related to the nature of the materials. The liquid filling plugging materials can better fill the pores, but the pressure-bearing granular materials will have a better pressure-bearing effect under the premise of higher wellbore pressure and a longer perimeter length. Therefore, the combination of particles and emulsified asphalt can better improve the pressure-bearing capacity. At the same time, the invasion depth after the combination is greatly reduced, which will reduce the impact of changes in physical and chemical properties caused by filtrate invasion on the stability of the shaft wall while ensuring that a certain degree of invasion can improve the stability around the shaft wall. The combination reflects the obvious plugging advantages.

4. CONCLUSIONS

(1) The good slurry-making properties of bentonite come from the content of clay minerals, mainly montmorillonite. The wall-building properties of the bentonite slurry drilling fluid and the filtration loss reduction effect increase with increasing concentration. When the bentonite slurry drilling fluid concentration increases to 8%, the bentonite slurry drilling fluid concentration increases, but the wall-building properties and the filtration loss reduction effect do not increase significantly.

(2) For different deepwater shallow pores, the experimental and theoretical analysis shows that AEH-P with a particle size of 200 mesh has the best wall-building and filtration loss reduction effect for pores of 2.5 $\mu$m. The AEH-P with a particle size of 500 mesh has the best wall-building properties and filtration loss reduction for pores of 8 $\mu$m and 20–25 $\mu$m.

(3) Experiments have shown that charged particles in cationic emulsified asphalt at suitable concentrations affect the diffusion double electron layer of montmorillonite, thus affecting the hydration dispersion of bentonite slurry drilling fluid. Cationic emulsified asphalt increases the negative electrical properties and thickens the water layer on the surface of the clay particles, which increases the agglomeration stability of the clay particles. The 0.5% concentration of emulsified asphalt has the best wall-building effect on 20–25 $\mu$m pores and filtration loss reduction. The 1.5% concentration of emulsified asphalt has the best wall-building properties and filtration loss reduction for 2.5 and 8 $\mu$m pores.

(4) Shallow-well wall strengthening was carried out through the experiment of compounding AEH-P with emulsified asphalt and bentonite slurry with respect to viscosity enhancement, adsorption, trapping, and physical plugging at the same time. A set of deepwater shallow bentonite slurry drilling fluid systems with good practicality are formed: water + bentonite + AEH-P + emulsified asphalt.

■ AUTHOR INFORMATION

Corresponding Authors

Peng Xu — College of Petroleum Engineering, Yangtze University, Wuhan 430100, China; Key Laboratory of Drilling and Production Engineering for Oil and Gas, Wuhan 430100, China; Cooperative Innovation Center of Unconventional Oil and Gas, Wuhan 430100, China; orcid.org/0000-0002-7747-2423; Email: cdxupeng@yangtzeu.edu.cn

Mingbiao Xu — College of Petroleum Engineering, Yangtze University, Wuhan 430100, China; Cooperative Innovation
Authors

Yu Zhang – College of Petroleum Engineering, Yangtze University, Wuhan 430100, China; Key Laboratory of Drilling and Production Engineering for Oil and Gas, Wuhan 430100, China

Lei Pu – College of Petroleum Engineering, Yangtze University, Wuhan 430100, China

Xinying Wang – College of Petroleum Engineering, Yangtze University, Wuhan 430100, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c03986

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support from the Open Fund (grant nos. UOG2022-02, UOGBX2022-02, and UOGBX2022-01) of the Cooperative Innovation Center of Unconventional Oil and Gas, Yangtze University (Ministry of Education & Hubei Province) and the National Natural Science Foundation of China (grant no. 51804044).

REFERENCES

(1) Aftab, A.; Ismail, A.R.; Ibupoto, Z.H.; Akeiber, H.; Malghani, M.G.K. Nanoparticles based drilling muds a solution to drill elevated temperature wells: A review. Renewable Sustainable Energy Rev. 2017, 76, 1301–1313.

(2) Aftab, A.; Ismail, A.R.; Khokhar, S.; Ibupoto, Z.H. Novel zinc oxide nanoparticles deposited acrylamide composite used for enhancing the performance of water-based drilling fluids at elevated temperature conditions. J. Pet. Sci. Eng. 2016, 146, 1142–1157.

(3) Lin, Y. Analysis and Application on Shallow Hazard Prediction Technology in Deepwater Drilling. Master’s Thesis, China University of Petroleum: Beijing, 2017.

(4) Tan, Q.; Deng, J.; Sun, J.; Liu, W.; Yu, B. Leak-off mechanism and pressure prediction for shallow sediments in deepwater drilling. J. Ocean Univ. China 2018, 17, 65–71.

(5) Xu, Y.; Guan, Z.; Jin, Y.; Liu, Y.; Sun, Y.; Zhang, B.; Sheng, Y. Risk assessment method of subsea wellhead instability in consideration of uncertain factors in deepwater drilling. Arabian J. Sci. Eng. 2018, 43, 2659–2672.

(6) Zhao, X.; Qiu, Z.; Wang, M.; Xu, J.; Huang, W. Experimental investigation of the effect of drilling fluid on wellbore stability in shallow unconsolidated formations in deep water. J. Pet. Sci. Eng. 2019, 175, 595–603.

(7) Bhandari, J.; Abbassi, R.; Garaniya, V.; Khan, F. Risk analysis of deepwater drilling operations using bayesian network. J. Loss Prev. Process Ind. 2015, 38, 11–23.

(8) Chen, X.; Gao, D.; Yang, J.; Luo, M.; Feng, Y.; Li, X. A comprehensive wellbore stability model considering poroelastic and thermal effects for inclined wellbores in deepwater drilling. J. Energy Resour. Technol. 2018, 140, 092903.

(9) Jin, S.; Zhang, C.; Meng, W.; Yu, Y.; Xu, F.; Dong, Z. Gas hydrate risk and preventative measures for drilling and completion operations in LS 17–2 deep water gas field. China Offshore Oil Gas. 2015, 27, 93–101.

(10) Zhang, L.; Zhang, C.; Huang, H.; Qi, D.; Zhang, Y.; Ren, S.; Wu, Z.; Fang, M. Gas hydrate risks and prevention for deep water drilling and completion: A case study of well QDN-X in Qiongdongnan Basin, South China Sea. Pet. Explor. Dev. 2014, 41, 824–832.

(11) Xu, Yuqiang; Guan, Zhichuan; Xu, Chuanbin; Zhang, Hongning; Zhang, Huizeng. Risk evaluation methods of gas hydrate formation in the wellbore of deepwater drilling. Acta. Pet. Sin. 2015, 36, 633–640.

(12) Zhang, Y. Research on Wellbore Pressure and Kill Engineering Calculation of Deepwater Wells. Master’s Thesis, Southwest Petroleum University: Chengdu, 2016.

(13) Tian, Z.; Tian, B.; Chen, Z.; Deng, J.; Hao, X. Research and application of deepwater wellbore stabilization in Baiyun Depression. Oil. Drill. Prod. Technol. 2015, 37, 96–98.

(14) Sun, C.; Feng, Z.; Chen, Q. Preparation and Property of Polymer Modified Bentonite Mud. Chin. J. Colloid Polym. 2018, 36, 78–80.

(15) Guo, W. Y.; Peng, B. Highly effective utilization of vinyl copolymer as filtrate reducer of water-bentonite drilling fluid under ultrasonic oscillations. J. Appl. Polym. Sci. 2022, 139, 51831.

(16) Saboori, R.; Sabbaghi, S.; Kalantariab, A. Improvement of rheological, filtration and thermal conductivity of bentonite drilling fluid using copper oxide/polyacrylamide nanocomposite. Powder Technol. 2019, 353, 257–266.

(17) Chu, Q.; Lin, L. Synthesis and properties of an improved agent with restricted viscosity and shearing strength in water-based drilling fluid. J. Pet. Sci. Eng. 2019, 173, 1254–1263.

(18) Kania, D.; Yunus, R.; Omar, R.; Abdul Rashid, S.; Mohamed Jan, B.; Aulia, A. Adsorption of non-ionic surfactants on organoclays in drilling fluid investigated by molecular descriptors and monte carlo random walk simulations. Appl. Surf. Sci. 2021, 538, 148154.

(19) Xu, C.; Zhang, J.; Kang, Y.; You, L.; Yan, X.; Cui, K.; Lin, C.; Key, S. Investigation on the transport and capture behaviours of lost circulation material in fracture with rough surface. International Petroleum Technology Conference, 2019.

(20) Mirabbasi, S. M.; Ameri, M. J.; Alsaba, M.; Karami, M.; Zargarbashi, A. The evolution of lost circulation prevention and mitigation based on wellbore strengthening theory: a review on experimental issues. J. Petrol. Sci. Eng. 2022, 211, 110149.

(21) Cook, J. The role of filtercake in wellbore strengthening. IADC/SPE Drilling Conference and Exhibition, 2016.

(22) Contreras, O. Wellbore strengthening in sandstones by means of nanoparticle-based drilling fluids. SPE Deepwater Drilling and Completions Conference, 2014.

(23) Liu, J.; Qiu, Z.; Luo, Y.; Wang, W.; Wang, Q.; Huang, D.; Zhang, X. Experimental study on leak prevention technology for oil-based drilling fluids with drilling. Drill. Fluid Completion Fluid. 2015, 32, 10–14.

(24) Hua, C. Drilling fluid technology for mud loss control and borehole wall stabilization in the slant section of horizontal wells in Sulige gas field. Drill. Fluid Completion Fluid 2018, 35, 66–70.

(25) Shang, Y. Study on Synthesis and Clay Stabilizer Properties of Quaternary Ammonium Salts. Master’s Thesis, Ocean University of China: Qingdao, 2009.

(26) Aftab, A.; Ali, M.; Arif, M.; Panhwar, S.; Saady, N. M. C.; Al-Khdheewai, E. A.; Mahmoud, O.; Ismail, A. R.; Keshavarz, A.; Iglauser, S. Influence of tailor-made TiO₂/API bentonite nanocomposite on drilling mud performance: Towards enhanced drilling operations. Appl. Clay. Sci. 2020, 199, 105862.

(27) Aftab, A.; Ali, M.; Shahid, M. F.; Mohanty, U. S.; Jha, N. K.; Akhondzadeh, H.; Azhar, M. R.; Ismail, A. R.; Keshavarz, A.; Iglauser, S.; Environmental friendliness and high performance of multifunctional tween 80/ZnO-nanoparticles-added water-based drilling fluid: an experimental approach. ACS Sustainable Chem. Eng. 2020, 8, 11224–11231.

(28) Yan, H.; Zhang, Z. Effect and mechanism of cation species on the gel properties of montmorillonite. Colloids Surf., A 2021, 611, 125824.

(29) Chen, J.; Anandarajah, A.; Inyang, H. Pore fluid properties and compressibility of kaolinite. J. Geotech. Geoenviron. 2000, 126, 798–809.

(30) Wang, P. Study for Quantitative Analysis of Water Absorbed on Clays and Their Hydration Mechanism. Ph.D. Thesis, Southwest Petroleum University: Chengdu, 2001.

(31) Bai, Y. Performance Control Principle of Deep Water-Based Drilling Fluids with High Temperature and High Density. Ph.D. Thesis, Southwest Petroleum University: Chengdu, 2014.
(32) McNown, J. S.; Malaika, J. Effects of particle shape on settling velocity at low reynolds numbers. *Trans., Am. Geophys. Union.* 1950, 31, 74−82.

(33) Yao, S. Interference Settlement Velocity of Homogeneous Spheroids. *Nonferrous Met., Miner. Process. Sect.* 1982, 6, 30−34.

(34) Liao, R.; Tang, Y.; Gu, J. Experimental study on the formation law of mudcake at the second interface of cementing in oil and gas horizontal wells. *Xinjiang Oil Gas.* 2018, 14, 47−53.

(35) Li, P. Study on Changing with Hydrophilic Channel of Wellbore Rock and Mud Cake Drilling Fluid. Ph.D. Thesis, Southwest Petroleum University: Chengdu, 2017.

(36) Duan, Y.; Yang, H. Review of Mud Cake Formation Mechanism and Evaluation Method of Drilling Fluid. *Sci. Technol. Eng.* 2021, 27, 11443−11454.

(37) Xu, W.; Luo, R. Evaluation of interaction between emulsified asphalt and mineral powder using rheology. *Constr. Build. Mater.* 2022, 318, 125990.

(38) Bageri, B. S.; Adebayo, A. R.; Al Jaberi, J.; Patil, S. Effect of perlite particles on the filtration properties of high-density Barite weighted water-based drilling fluid. *Powder Technol.* 2020, 360, 1157−1166.

(39) Liu, Z.; Song, G.; Li, B.; Liu, X. Drilling Fluid Filtration Law and Its Regression Equation. *Drill. Fluid Completion Fluid.* 1995, 5, 19−23.

(40) Chang, A.; Sun, H.; Zhang, Y.; Zheng, C.; Min, F. Spatial fractional darcy’s law to quantify fluid flow in natural reservoirs. *Phys. A (Amsterdam, Neth.).* 2019, 519, 119−126.