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ORIGINAL PAPER

# Performance evaluation of laponite as a mud-making material for drilling fluids

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## Abstract

In this study, laponite was tested as a mud-making material for drilling fluids. Laponite is a synthetic smectite clay with a structure and composition closely resembling the natural clay mineral hectorite. Commercially available laponite was characterized by X-ray diffractometry, scanning electron microscopy and infrared spectrometry. Its dispersibility, salt resistance and high-temperature resistance were evaluated. The results showed that laponite possessed superior cation exchange capacity (140.4 mmol/100 g) with interlayer cations of $Na^+$ and $Li^+$. Laponite could easily be dispersed in water to yield increased viscosity with no influence from hydration time or temperature. On the other hand, laponite dispersions displayed an excellent heat resistance, with invariant apparent viscosity at high temperatures. For instance, the apparent viscosity of the 2 wt% laponite dispersion underwent changes between 22 and 24 mPa s after hot rolling at 180–240 °C for 16 h. Compared to existing mud-making materials, laponite exhibited better mud-making properties. Furthermore, laponite revealed good compatibility with other additives, and the water-based drilling fluids prepared with laponite as mud-making material showed an excellent stability at elevated temperatures and superior performance–cost ratios. Overall, these findings indicated that laponite had an excellent dispersibility at high temperatures and hence would have promising applications as high-temperature mud-making material for preparing water-based drilling fluids designed for ultra-high-temperature environments.

**Keywords** Laponite · Mud-making material · Dispersibility · High-temperature tolerance · Ultra-high-temperature water-based drilling fluids

## 1 Introduction

Bottom hole temperatures can exceed 200 °C during drilling deep oil/gas wells and hot dry rocks. This exposes the drilling fluids to high temperatures for long periods, creating new challenges for high-temperature resistance drilling fluids. Bentonite is the most important ingredient of water-based drilling fluids. It is used as a mud-making material to increase the viscosity and yield point of water-based drilling fluids with compact mud cake. However, bentonite particles suspended in water-based drilling fluids could form dispersions or coalescence at elevated temperatures, resulting in drastic changes in rheological properties of drilling fluids (Guven et al. 1988; Zhang 2010; İşçi and Turutoğlu 2011; Yao et al. 2014).

Hectorite is a trioctahedral smectite; a 2:1 layered silicate mineral with an octahedral MgO sheet sandwiched between two tetrahedral silica sheets, with a chemical formula of $Na_{0.3}(Mg, Li)_3Si_4O_{10}(OH)_2$. However, natural hectorite is a scarce clay often containing many complex impurities, making it challenging for research and development. On the other hand, laponite is a synthetic material with similar structure and composition to the natural hectorite. Laponite possesses high purity, good thickening and thixotropy, which makes it useful as a rheological modifier or a thixotropic agent in many liquids or dispersion product-based coatings, household/personal care, agriculture, medicine, paper and polymer film industries.

Current research dealing with laponite is mainly focused on preparation methods (Torii and Iwasaki 1987; Vicente et al. 2009, 2010), laponite organic modification (Malakul et al. 1998; Mustafa et al. 2016), laponite nanocomposite (Batista et al. 2011; Ghadiri et al. 2013; Boyaci and

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Orakdogen 2016), stabilizers of Pickering emulsions (Li et al. 2009; Teixeira et al. 2011), as well as state or performance of laponite dispersions, such as rheology (Pignon et al. 1997a, b; Joshi et al. 2008; Au et al. 2015; Au and Leong 2015), phase state (Mourchid et al. 1998; Au et al. 2015; Mohanty and Joshi 2016), colloidal properties (Mori et al. 2001;Willenbacher 1996) and viscoelastic structure (Pignon et al. 1997a, b; Mourchid et al. 1998). Nevertheless, research dealing with applications of laponite in water-based drilling fluids is rarely reported. Rare examples include use of laponite as a viscosifier (Qin et al. 2016) and a component in workover fluids (Mueller et al. 1989). Furthermore, systemic evaluation of the application of laponite as a mud-making material for drilling fluids has not so far been reported.

In this paper, laponite was tested as a mud-making material. First, the composition, physicochemical properties and structure of laponite were studied. Second, the performance of laponite dispersions was evaluated in terms of dispersibility, salt resistance and temperature resistance. Also, thickening mechanisms of laponite at high temperatures were examined. For comparison, three commercial clays were used as control groups. Finally, the performances of a water-based drilling fluid containing laponite used at ultra-high temperatures were discussed in terms of efficiency and cost.

# 2 Experimental

## 2.1 Materials

Laponite was obtained from Nanjing Baiyike New Material Technology Co., Ltd. Sodium bentonite (montmorillonite content of 69% as determined by quantitative XRD analyses) was obtained from Xiazijie Bentonite Co., Ltd. Attapulgite (palygorskite content of 70% as determined by quantitative XRD analyses) was kindly provided by Mingguang Attapulgite Processing Factory. Sepiolite (sepiolite content of 50% as determined by quantitative XRD analyses) was kindly provided by Xiangtan Yuanyuan Sepiolite New Material Co., Ltd., and sodium chloride was purchased from Beijing Reagent Co., Ltd. The high-temperature fluid loss additive (OCL-JA) was mainly composed of 2-methyl-2-acrylamidy-propyl sulfonic acid/acrylic acid/acrylamide graft copolymer and sulfonated humic acid derivatives.

## 2.2 Characterization of laponite

X-ray powder diffraction (XRD) analyses were performed with a Smart Lab X-ray diffractometer (Rigaku Corp., Japan) using Cu Kα radiation ($\lambda = 1.5406$ Å, 40 kV, 8°/min and 100 mA). Scanning electron microscope (SEM) images were taken with a focused ion beam–scanning electron microscope (LYRA3 XMU, TESCAN, CZ) under a vacuum of 800 Pa at an acceleration voltage of 25 kV. Fourier transform infrared (FTIR) spectra were recorded by a Nicolet iS10 infrared spectrometer (Thermo Fisher Scientific, USA) with a DTGS detector from 4000 to 400 $\text{cm}^{-1}$ at a resolution of 4 $\text{cm}^{-1}$.

## 2.3 Measurement of particle sizes

Particle size distributions of laponite dispersions were measured with a laser particle size analyzer (LA-950V2, HORIBA, Japan) at room temperature. The rate of circulation and agitation speed was set to 2890 L/min and 1735 rpm, respectively.

## 2.4 Measurement of zeta potentials

To characterize the hydration properties of laponite particles, the zeta potentials of laponite dispersions were measured with a potential meter (Zetasizer Nano ZS90, Malvern Instruments, UK) at room temperature. Before measurements, the laponite dispersions were diluted ten times with distilled water. Each sample was then measured in triplicate, and the average value of the zeta potential was used for analysis.

## 2.5 Rheological measurements

The rheological properties were characterized with a rotating viscometer (HTD13145, Qingdao Haitongda Special Instruments CO., LTD., China). The properties included apparent viscosity, plastic viscosity, yield point and gel strength. The apparent viscosity (AV), plastic viscosity (PV) and yield point (YP) were calculated from API recommended practice of standard procedure for field testing drilling fluids (Recommended Practice 2009).

To evaluate the temperature resistance, different clay dispersions were rolled for 16 h at desired temperatures using a hot rolling furnace (XGRL-4, Qingdao Haitongda Special Instruments CO., LTD., China). Note that temperatures of clay dispersions were same as the desired temperatures of rolling furnace. Next, the rheological properties were determined by a rotating viscometer after cooling to room temperature.

The filtration loss (FL) was measured by a filter press (SD6A, Qingdao Haitongda Special Instruments CO., LTD., China) under 689.5 kPa (100 psi) at room temperature for 30 min.

# 3 Results and discussion

## 3.1 Characterization of laponite

### 3.1.1 Chemical composition

The quantitative analysis of lithium cannot currently be measured with an X-ray fluorescence spectrometer.

**Table 1** Main chemical compositions of different clays

| Oxide | Content, wt% | | | |
|---|---|---|---|---|
| | Sodium bentonite | Attapulgite | Sepiolite | Laponite |
| $SiO_2$ | 64.06 | 57.56 | 58.07 | 47.73 |
| $Al_2O_3$ | 16.97 | 8.27 | 6.35 | – |
| $Fe_2O_3$ | 5.66 | 6.12 | 3.24 | – |
| MgO | 1.99 | 10.84 | 12.73 | 25.36 |
| CaO | 0.77 | 2.17 | 7.60 | – |
| $K_2O$ | 1.90 | 1.17 | 0.63 | – |
| $Na_2O$ | 1.42 | 0.03 | 0.07 | 2.42 |
| $TiO_2$ | 0.91 | 0.83 | 0.32 | – |
| $Li_2O$ | – | – | – | 1.36 |

– Means not determined

**Table 2** Physicochemical properties of different clays

| Sample | Gelling value, mL/15 g | Swelling capacity, mL/g | Cation exchange capacity, mmol/100 g |
|---|---|---|---|
| Laponite | 500 | 95 | 140.4 |
| Sodium bentonite | 499 | 57 | 81.6 |

**Table 3** Compared interlayer cation exchange capacity between different clays

| Sample | Interlayer cation capacity *E*, mmol/100 g | | | | |
|---|---|---|---|---|---|
| | $Li^+$ | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ |
| Laponite | 43.5 | 96.9 | 0 | – | – |
| Sodium bentonite | 0 | 72.6 | 0.56 | 5.11 | 3.36 |

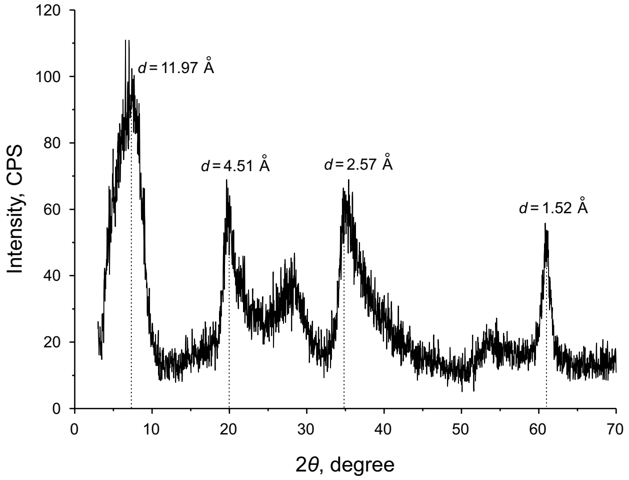

**Fig. 1** X-ray powder diffraction pattern of laponite

Consequently, the composition of laponite was determined by a PerkinElmer Optima 8300 ICP-OES (Thermo Fisher Scientific, US). For comparison, the compositions of other clay samples were also measured. Table 1 shows that laponite mainly consisted of silica and magnesium oxide.

### 3.1.2 Physicochemical properties

The physicochemical testing methods of Chinese standard GB/T 20973-2007 (Bentonite) were used to determine gelling value, swelling capacity and cation exchange capacity of laponite. The high cation exchange capacity of laponite indicated better hydration properties. Laponite exhibited good hydration and swelling properties, better than those of sodium bentonite (Table 2). Furthermore, the cation exchange capacity of laponite was superior to that of sodium bentonite, and interlayer cations of laponite were mainly composed of sodium and lithium counterions (Table 3).

### 3.1.3 XRD of laponite

As shown in Fig. 1, 001, 110, 200 and 060 reflections of laponite were observed at 7.37°, 19.64°, 34.75° and 61.08° ($2\theta$), with an interplanar spacing of 11.97, 4.51, 2.57 and 1.52 Å, respectively. These reflections corresponded to the common reflection of 2:1 layered silicate mineral. The 060 reflection, an important feature used for identifying smectites type, was located at 1.52 Å. This revealed that laponite belonged to 2:1 trioctahedral smectite. In addition, some reflections did not look sharp enough and there were no apparent reflections of impurities. Hence, it can be concluded that the tested laponite had poor crystallinity but very high purity.

### 3.1.4 SEM characterization

The SEM images of laponite are shown in Fig. 2. Laponite particles appeared very fine and relatively uniform, with a maximum particle diameter less than 25 μm (Fig. 2a). Furthermore, irregular plate-like particles with obvious lamellar structures were observed (Fig. 2b). In particular, many thin lamellar particles with diameters less than 5 μm were observed.

### 3.1.5 FTIR analysis

The FTIR spectrum of laponite is illustrated in Fig. 3. The broadband at 3443 $cm^{-1}$ was attributed to the stretching H–O–H vibrations of adsorbed water molecules. The sharp medium band at 1635 $cm^{-1}$ was assigned to H–O–H bending. The three main characteristic peaks of laponite detected

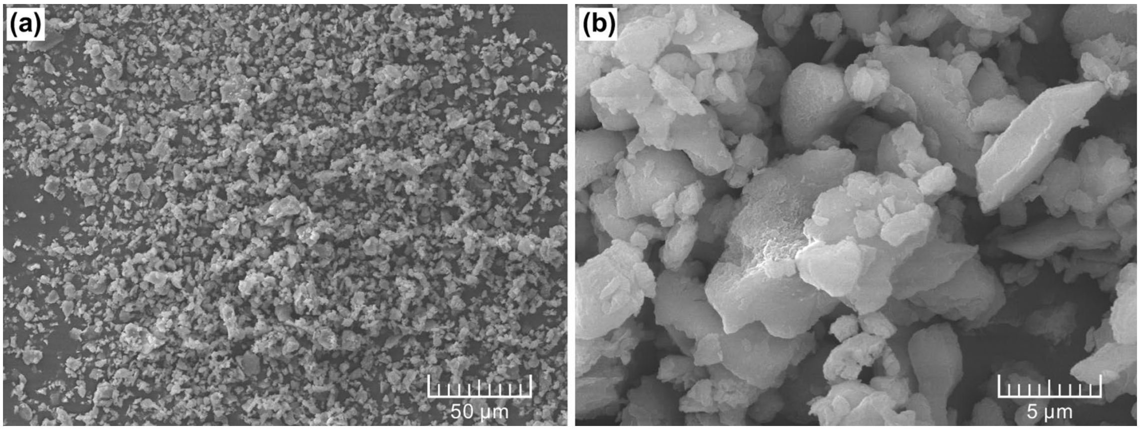

**Fig. 2** SEM images of laponite

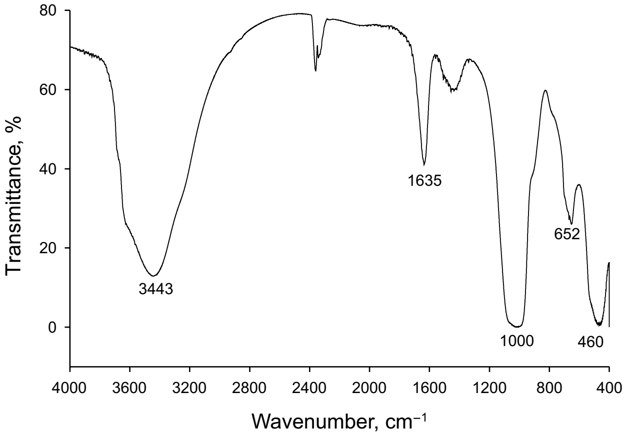

**Fig. 3** Infrared spectrum of laponite

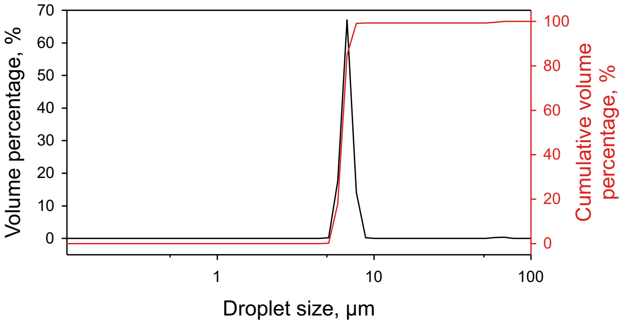

**Fig. 4** Particle size distribution of 0.2 wt% laponite dispersion

around 460, 652 and 1000 cm$^{-1}$ were attributed to Si–O–Mg deformation vibration, Mg–OH–Mg bending vibration (Madejová 2003) and Si–O stretching vibration (Madejová 2003), respectively. The presence of these bands confirmed the identity of laponite with absorbed water.

## 3.2 Particle size distribution of laponite dispersions

To determine particle size distributions of laponite dispersed in water, 0.2 wt% laponite dispersion was prepared and particle size distributions are shown in Fig. 4. The laponite dispersion showed a relatively wide particle size distribution ranging from 5 to 67 μm. Moreover, the particle size ranging from 5 to 9 μm dominated, accounting for 99.3% of cumulative volume percentage with an average particle size of 6.6 μm.

These data demonstrated that laponite dispersions were composed of monodisperse particles and small aggregations, consistent with reported literature (Nicolai and Cocard 2000; Balnois et al. 2003). The latter was mainly related to swelling capacity of smectite, which depended on the interlayer cation radius and the cationic hydration energy (Laird 1996; Anderson et al. 2010). Several interlayer cation radii were compared and found to increase in the following order: $Li^+ < Na^+ < K^+$. The interlayer cations of laponite were determined as $Na^+$ and $Li^+$ (Table 3). Due to small radius and high hydration energy of $Na^+$ and $Li^+$, more water molecules could easily be adsorbed on the surfaces of laponite particles. The electrostatic attractions of particle lamellae could be overcome by repulsive forces, causing swelling and exfoliating of laponite sheets.

## 3.3 Dispersive property of laponite

Different factors influencing dispersibility of laponite in water were studied, including hydration time, temperature and pH.

### 3.3.1 Effect of hydration time on dispersibility of laponite

Laponite was added to distilled water at different concentrations (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 wt%). Note that 0.5 wt% meant 0.5 g laponite was added to 100 g distilled water to form 0.5 g/100 g. The effects of hydration time on dispersibility of laponite were studied, and the results are displayed in Fig. 5. At laponite additions greater than 1.0 wt%, apparent viscosity (AV) values of laponite dispersions first grew and then kept steady as the hydration time extended (Fig. 5). The highest apparent viscosity was obtained at hydration periods ranging from 6 to 8 h. However, at a laponite dosage below 1.0 wt%, AV values of dispersions remained unchanged as the hydration time rose. This could mainly be attributed to the influence of laponite interlayer cation and osmotic swelling. As $Li^+$ has the smallest radius of interlayer cations followed by $Na^+$, smaller ionic radii would induce stronger interactions with water molecules, resulting in higher clay hydration degrees. Consequently, laponite particles underwent osmotic swelling and exfoliating, forming numerous unit layers. Next, these unit layers formed an oriented network by means of electrostatic repulsions arising from overlapped electric double layers. This led to increased apparent viscosity (Avery and Ramsay 1986; Mourchid et al. 1995; Levitz et al. 2000; Bhatia et al. 2003).

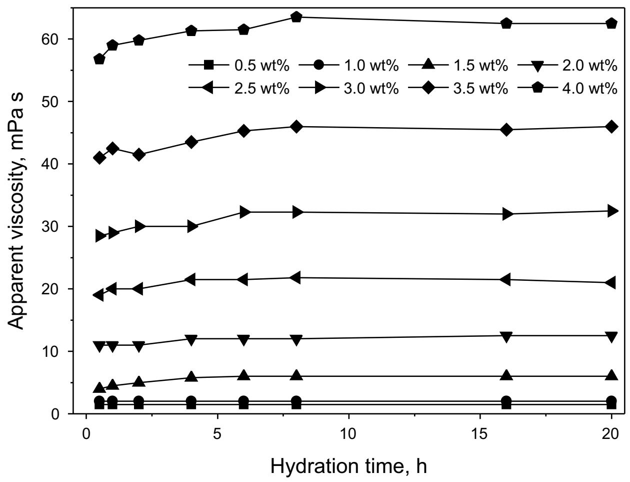

**Fig. 5** Effect of hydration time on apparent viscosity of laponite dispersions

### 3.3.2 Influence of hydration temperature and pH on dispersibility of laponite

During field drilling or laboratory testing, bentonite will normally be pre-hydrated with freshwater at normal temperature to prepare fully dispersed bentonite in water. Also, pH could influence dispersibility of clay particles in water-based drilling fluids, where the optimal pH of water-based drilling fluids normally lies around 8 to 10.

Therefore, laponite was added to distilled water at different concentrations to evaluate the effects of hydration temperature and pH of aqueous dispersions on dispersibility of laponite. The results obtained at hydration times of 8 h are displayed in Fig. 6. As the hydration temperature or pH increased, AV values of laponite dispersions fluctuated within a narrow range at the same content of laponite. These data suggested that the hydration temperature and pH of aqueous dispersions had almost no effect on the dispersibility of laponite.

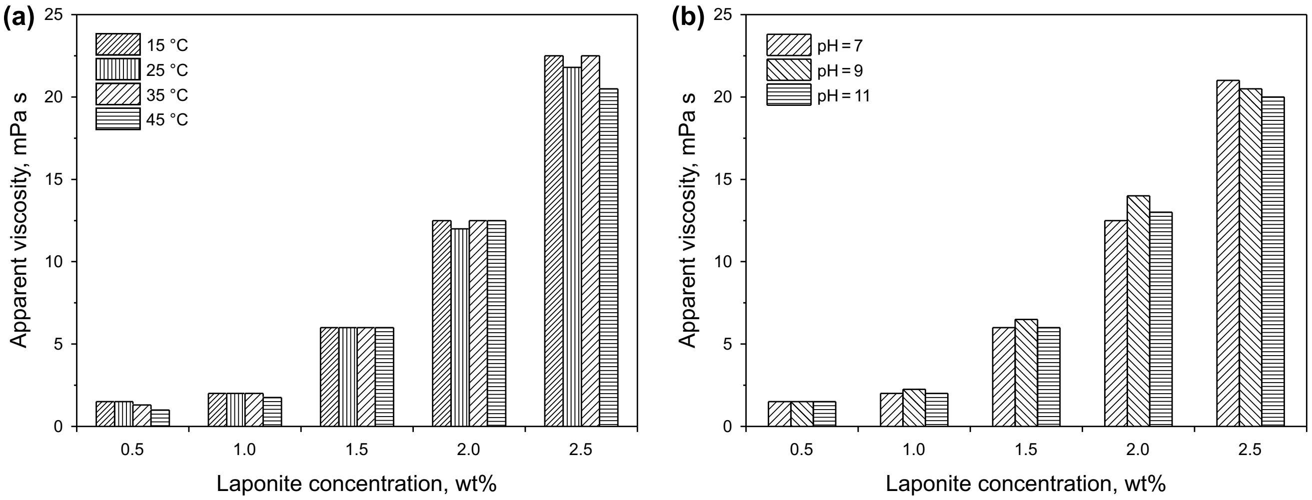

**Fig. 6** Effect of different factors on AV of laponite dispersions. **a** Hydration temperature; **b** pH

## 3.4 Laponite salt tolerance

During drilling, drilling fluids are often affected by specific factors, such as invasion of inorganic salts. Hence, sodium chloride (NaCl) was used to evaluate salt resistance of laponite. Different amounts of NaCl (2, 4, 6, 8 and 10 g) were added to 3 wt% clay dispersions (100 g), and the salt tolerance of different clay dispersions was evaluated under various conditions. As shown in Fig. 7, as the NaCl concentration increased, AV values of laponite dispersions decreased before aging or after 200 °C for 16 h. Also, the filtration loss of laponite dispersions showed first a declining tendency followed by a slow increase while AV values of other clay dispersions changed slightly. This could be explained that the electrical double layer of laponite particles was repressed and became thin in the presence of sodium chloride, resulting in aggregation of laponite particles and reduced strength of the "house of cards" structure (Olphen 1977; Cione et al. 2000; Shahin and Joshi 2012). On the other hand, a reduction in filtration loss of laponite dispersions may be related to the enlarged laponite particle sizes and the formed compact filter cake.

Compared to Fig. 7a and b, the obtained AV values of different clay dispersions containing the same concentration of NaCl after 200 °C hot rolling for 16 h were lower than those obtained before aging. For example, at 4 wt% NaCl concentration, the AV value of the laponite dispersion reduced from 10.5 to 5 mPa s after 200 °C aging. As shown in Fig. 7c, d, at a NaCl concentration higher than 3.2 wt%, the filtration loss of the laponite dispersion was lower than those of other clay dispersions.

In sum, laponite showed a poor salt resistance and its dispersibility in water was influenced by the ionic strength. However, the laponite had comparably better resistance to salt than other clays.

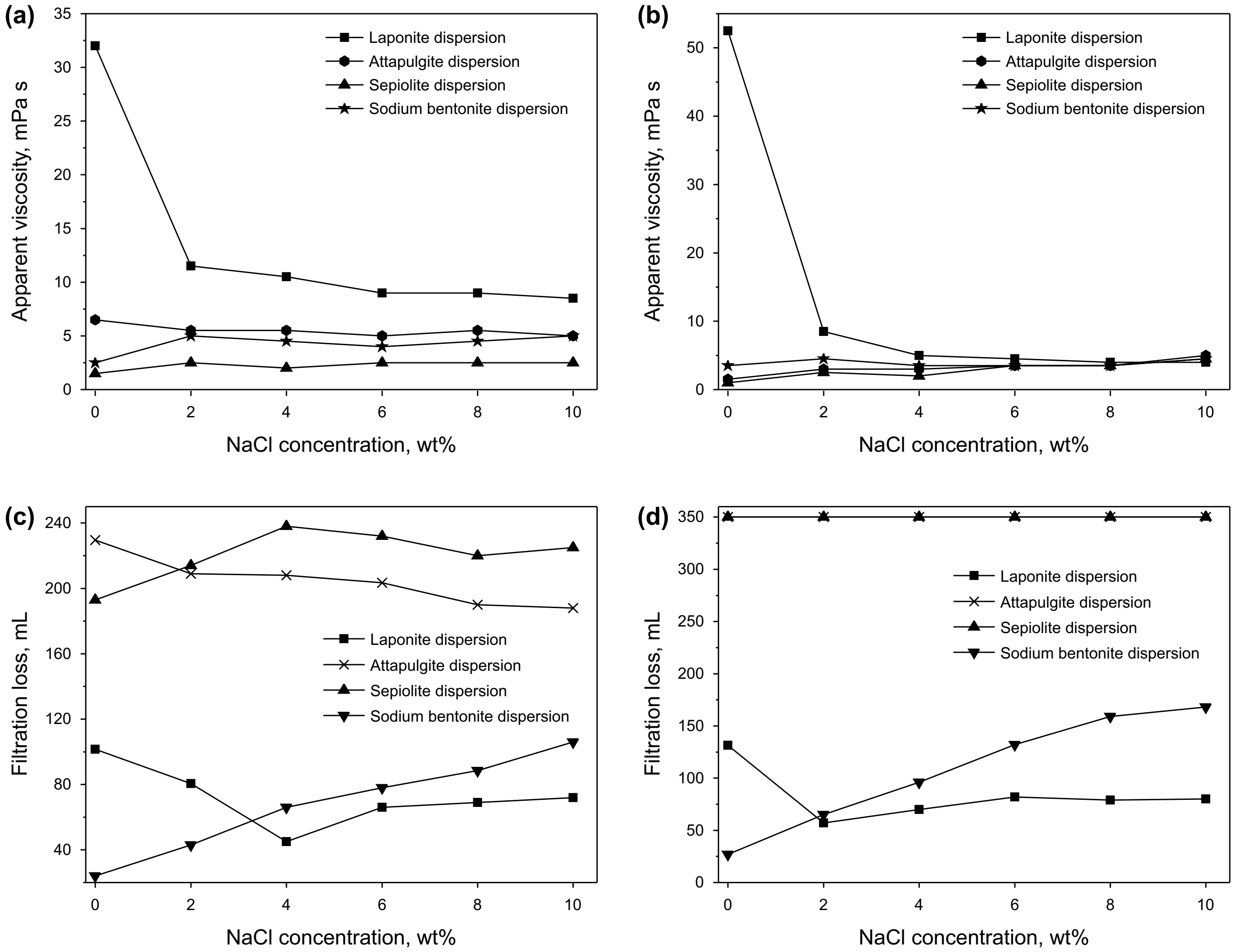

**Fig. 7** Comparison of salt resistance between clay dispersions under different conditions. **a**, **c** Before aging; **b**, **d** After aging at 200 °C for 16 h

### 3.5 Temperature resistance of laponite

As the drilling depth increases, the temperature in the borehole increases as well. Therefore, the effect of temperature on performances of both laponite and sodium bentonite dispersions was considered at aging temperatures varying from 80 to 240 °C. After aging at high temperatures for 16 h followed by cooling to room temperature, the AV values of clay dispersions were determined and the results are shown in Fig. 8. It can be seen that the AV values of laponite dispersions first increased then remained mostly unchanged as the aging temperature continued to rise (Fig. 8a). For instance, as the aging temperature increased from 200 to 240 °C, the AV values of the 2 wt% laponite dispersion fluctuated between 22 and 24 mPa s. This demonstrated that laponite had excellent thickening properties at high temperatures.

As observed in Fig. 8b, at a sodium bentonite addition below 3 wt%, the AV values of bentonite dispersions remained mostly unchanged as the aging temperature continued to rise. However, at the sodium bentonite addition above 3 wt%, the AV values of bentonite dispersions changed sharply with an increase in aging temperature and thickening or coalescence occurred at high temperatures. Therefore, the sodium bentonite content was often required to be below 40 kg/m$^3$ during preparation of high-temperature water-based drilling fluids.

To clarify the reason behind the thickening properties of laponite at high temperatures, the performance of the 2 wt% laponite dispersion was investigated in terms of yield point, average particle size and zeta potential (Fig. 9). As the aging temperature increased, the average particle size of the laponite dispersion gradually rose (Fig. 9a). On the other hand, the yield point of the laponite dispersion tended to increase at first and then kept mostly unchanged. These variations could be interpreted due to enhanced thermal motion of water molecules and reduced surface activity of laponite particles with temperature rising. In turn, this made the hydration shell thinner and electrostatic repulsion between particles decrease. And then aggregates of particles were formed, resulting in an increase in particle sizes. On the other hand, the thermal motion of laponite particles improved with increasing temperature, beneficial for overcoming its potential energy barrier (Tawari et al. 2001). Also, particles tended to form aggregates, which, in turn, were connected to form nematic ordering structures (Gabriel et al. 1996; Mourchid et al. 1998; Bakk et al. 2002; Lemaire et al. 2002), where the strength of nematic ordering structures grew with an increase in temperature. Macroscopically, the yield point or the structural viscosity of laponite dispersion increased.

Figure 9b reveals that as the aging temperature increased from 25 to 240 °C, the zeta potential of the 2 wt% laponite dispersion showed a downward trend, but the variability of the zeta potential was small and changed from −39.6 to −41.8 mV. The latter was related to accelerated hydroxyl dissociation of particle edge surfaces with temperature, resulting in increased pH and positive edge charges. In addition, hydration shells thinned and electrostatic repulsion between particles declined, causing reductions in the zeta potential.

Based on these results, an anti-high-temperature thickening mechanism of laponite could be proposed using Fig. 9. First, an increase in temperature resulted in more aggregates formed by laponite particles, which then were connected to form nematic ordering structures. This was macroscopically manifested as an increase in yield point and apparent viscosity of the laponite dispersion. Moreover, though more aggregates would be formed due to an increase in temperature,

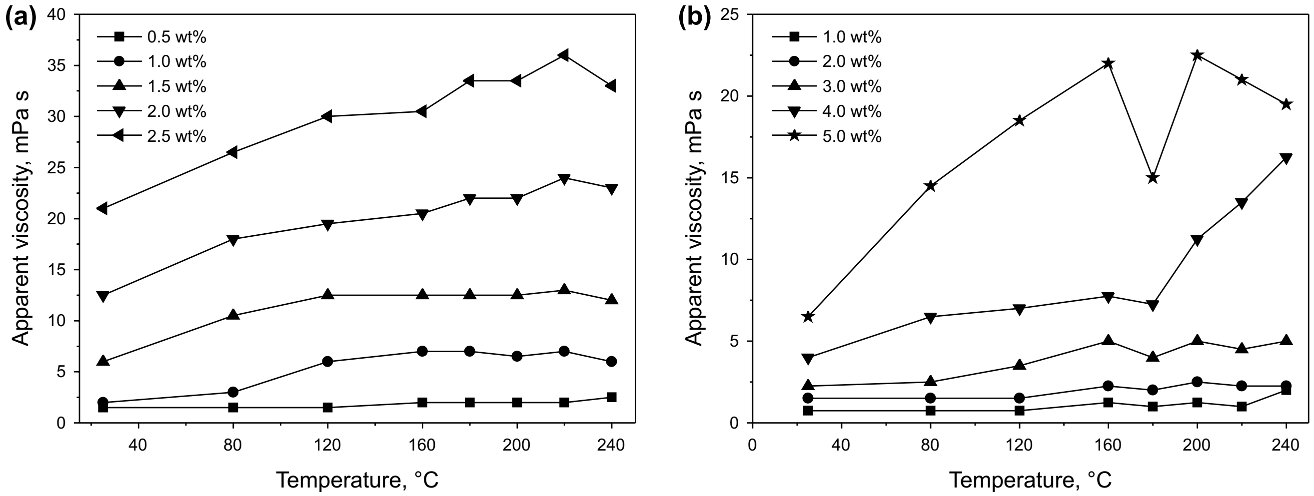

**Fig. 8** AV values of clay dispersions after aging at different temperatures. **a** Laponite; **b** Sodium bentonite

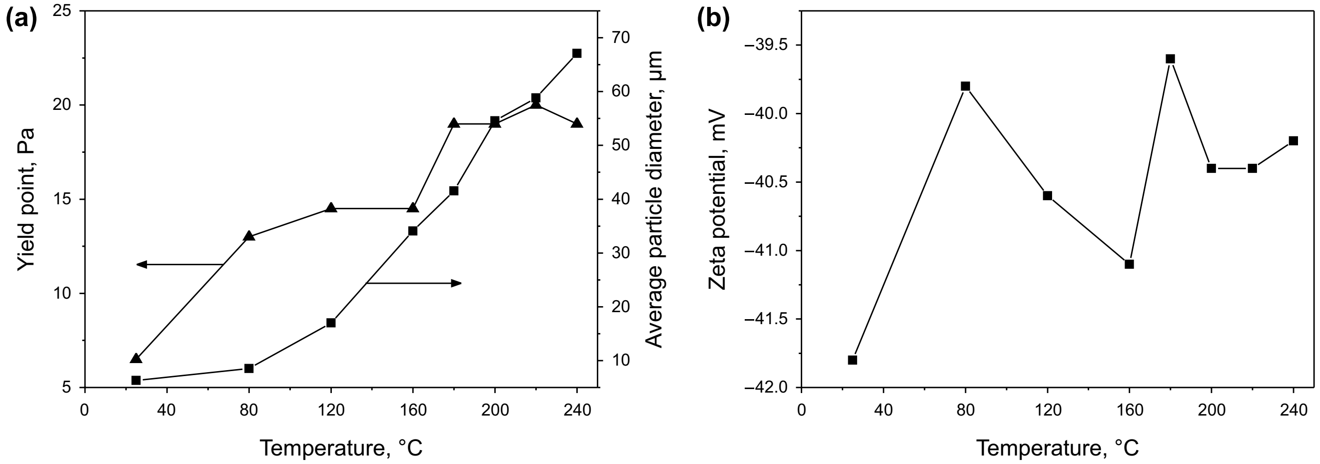

**Fig. 9** Effect of temperature on performances of 2 wt% laponite dispersion. **a** Yield point and average particle diameter; **b** Zeta potential

the laponite dispersion still showed good colloid stability at high temperatures.

## 3.6 Performance comparison of laponite as mud-making materials

According to International Standard ISO 13500-2008 (Specifications and tests of drilling fluid materials), the required dosage of bentonite for evaluating performances should be 6.4 wt%. However, when the laponite concentration was higher than 2.5 wt%, the laponite dispersion would form a gel. Hence 2.5 wt% laponite and 6.4 wt% clay dispersions were prepared to compare their performances before and after aging at 220 °C for 16 h. As shown in Table 4, the AV value of the 2.5 wt% laponite dispersion was slightly higher than that of the 6.4 wt% sodium bentonite dispersion before and after aging at 220 °C, but much higher than those of other clay dispersions. In addition, the ratio of yield point to plastic viscosity (known as YP/PV ratio) of the 2.5 wt% laponite dispersion was higher than that of other clay dispersions. This showed that laponite had better thickening properties at high temperatures. Nonetheless, the 2.5 wt% laponite dispersion also showed a high filtration loss, but filtrate reduction properties were better than both the 6.4 wt% attapulgite and sepiolite dispersions. The high filtration loss of attapulgite and sepiolite dispersions may be resulted from the lower purity of samples.

## 3.7 Performance of water-based drilling fluids with laponite at high temperatures

A water-based drilling fluid containing laponite as a mud-making material (1#) was prepared to investigate the compatibility of laponite with other drilling fluid additives. The performance of drilling fluids was determined, and the results are listed in Table 5. The water-based drilling fluid 1# had an excellent stability at high temperatures. After aging at 220 °C for 16 h, the AV values of drilling fluid 1# decreased and the YP/PV ratio increased. The reduction rate of AV values was estimated to be 21.9% before and after aging at 220 °C, and the added value of YP/PV ratio was 0.20 Pa/(mPa s). Nevertheless, the performances of drilling fluids 2#, 3# and 4# were much less than that of drilling fluid 1# in terms of AV, YP/PV ratio and gel strength. These results confirmed that laponite can be used as a mud-making material to prepare water-based drilling fluids for ultra-high-temperature environments. Furthermore, the water-based drilling fluids prepared with laponite showed an excellent stability at elevated temperatures and superior rheology without any addition of viscosifiers and thinners,

**Table 4** Performance comparison of different mud-making materials

| Mud-making material | AV, mPa s | | YP/PV ratio, Pa/(mPa s) | | Filtration loss, mL | |
|---|---|---|---|---|---|---|
| | Before | After | Before | After | Before | After |
| Sodium bentonite | 14.0 | 36.0 | 1.73 | 1.92 | 12.5 | 15.5 |
| Attapulgite | 30.0 | 5.0 | 2.24 | 1.44 | 160.0 | 234.0 |
| Sepiolite | 3.5 | 5.0 | 0.72 | 1.44 | 148.0 | 350.0 |
| Laponite | 21.0 | 36.0 | 2.40 | 10.56 | 129.5 | 213.0 |

**Table 5** Test results of water-based drilling fluids with different clays designed for high-temperature environments

| Drilling fluids | Test condition | AV, mPa s | YP/PV ratio Pa/(mPa s) | Gel strength, Pa |  | FL, mL | HTHP filtrate, mL |
|---|---|---|---|---|---|---|---|
|  |  |  |  | 10 s | 10 min |  |  |
| 1# | Before aging | 52.5 | 0.48 | 5.0 | 20.0 | 5.0 | – |
|  | After aging at 200 °C for 16 h | 30.5 | 0.67 | 2.5 | 4.0 | 5.6 | 38 (@200 °C) |
|  | After aging at 220 °C for 16 h | 41.0 | 0.68 | 3.5 | 5.0 | 5.2 | 39 (@220 °C) |
| 2# | Before aging | 15.0 | 0.07 | 0.5 | 1.0 | 4.8 | – |
|  | After aging at 200 °C for 16 h | 7.5 | 0.07 | 0 | 0.25 | 4.6 | 34 (@200 °C) |
|  | After aging at 220 °C for 16 h | 8.0 | 0 | 0 | 0.25 | 4.4 | 33 (@220 °C) |
| 3# | Before aging | 19.5 | 0.14 | 0.25 | 1.0 | 5.8 | – |
|  | After aging at 200 °C for 16 h | 6.0 | 0 | 0 | 0 | 5.5 | 28 (@200 °C) |
|  | After aging at 220 °C for 16 h | 6.0 | 0 | 0 | 0.5 | 5.5 | 28 (@220 °C) |
| 4# | Before aging | 19.0 | 0.11 | 0.5 | 1.0 | 5.6 | – |
|  | After aging at 200 °C for 16 h | 6.0 | 0 | 0.25 | 0.25 | 6.0 | 30 (@200 °C) |
|  | After aging at 220 °C for 16 h | 6.0 | 0 | 0.5 | 0.5 | 5.5 | 31 (@220 °C) |

1#: 2 wt% laponite + 3 wt% lignite resin (SPNH) + 3 wt% fluid loss additive (OCL-JA, for high-temperature environments) + 4 wt% asphalt powder + 2 wt% calcium carbonate powder; 2#: 2 wt sodium bentonite + 3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder; 3#: 2 wt% attapulgite + 3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder; 4#: 2 wt% sepiolite + 3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder

which were specially designed for modifying performance of drilling fluids at high temperatures.

### 3.8 Cost analysis of laponite

Currently, numerous Chinese companies produce laponite for use in coating, household and personal care. However, the cost is quite high with a price of about 70,000 RMB/ton. Even though laponite possesses excellent properties at high-temperature environments, laponite with such high cost will not be suitable for oil industries if only used as a mud-making material and substitute of sodium bentonite. Thus, an water-based drilling fluid designed for ultra-high-temperature environments was prepared using sodium bentonite and laponite as mud-making materials, and its performances were compared to other water-based drilling fluids containing viscosifier which was designed for ultra-high-temperature environments (Table 6). The viscosifier (HE 300 polymer) and fluid loss additive (Driscal® D polymer) designed for high-temperature environments were produced by Chevron Phillips Chemical Company at a cost of about 130,000 RMB/ton.

Table 6 revealed that the AV values of all formulations decreased after aging at 240 °C for 16 h. However, the other

**Table 6** Test results of water-based drilling fluids with different high-temperature viscosifiers designed for high-temperature environments

| Drilling fluids | Test condition | AV, mPa s | YP/PV ratio, Pa/(mPa s) | Gel strength, Pa |  | FL, mL | HTHP filtrate, mL |
|---|---|---|---|---|---|---|---|
|  |  |  |  | 10 s | 10 min |  |  |
| 5# | Before aging | 113 | 0.55 | 6 | 14 | 2.8 | – |
|  | After aging at 240 °C for 16 h | 29 | 0.51 | 3.5 | 22.5 | 3.8 | 22 (@200 °C) |
| 6# | Before aging | 80.5 | 0.47 | 4 | 6.5 | 4.8 | – |
|  | After aging at 240 °C 16 h | 29 | 0.43 | 3 | 14 | 3.8 | 25 (@200 °C) |
| 7# | Before aging | 63 | 0.48 | 6.5 | 21 | 3.4 | – |
|  | After aging at 240 °C for 16 h | 33.5 | 0.65 | 4 | 32 | 4.2 | 24 (@200 °C) |
| 8# | Before aging | 24.5 | 0.16 | 0.5 | 1.5 | 4 | – |
|  | After aging at 240 °C for 16 h | 16.5 | 0.48 | 1.5 | 12 | 4.8 | 27 (@200 °C) |

5#: 3 wt% sodium bentonite + 3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder +1 wt% viscosifier (HE 300); 6#: 3 wt% sodium bentonite + 3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder + 1 wt% fluid loss additive (Driscal® D polymer); 7: 3 wt% sodium bentonite + 1 wt% laponite + 3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder; 8#: 3 wt% sodium bentonite +3 wt% SPNH + 3 wt% OCL-JA + 4 wt% asphalt powder + 2 wt% calcium carbonate powder performances of drilling fluids 5#, 6# and 7# were slightly different. In practice, the AV values of drilling fluids 5# and 6# decreased dramatically with respective reduction rates of 74.3% and 64.0%, while that of the drilling fluid 7# containing laponite was 46.8%. These data confirmed the laponite was better than HE 300 and Driscal® D polymer in improving viscosifying properties of water-based drilling fluids at high temperatures. Moreover, when laponite and sodium bentonite were used together as the mud-making material to prepare water-based drilling fluids, laponite showed better performance–price ratios.

## 4 Conclusions

Commercially available laponite was characterized by XRD, SEM and FTIR, and the identity of laponite was confirmed. Its properties of dispersibility, salt tolerance and temperature resistance were also evaluated. The following conclusions could be drawn.

1. Laponite had excellent dispersibility in water, and hydration time, temperature and pH did not affect its dispersion.
2. Laponite exhibited excellent thickening properties at high temperature. For example, as the aging temperature increased from 200 to 240 °C, the AV values of the 2 wt% laponite dispersion fluctuated between 22 and 24 mPa s.
3. Laponite showed a poor resistance to salt, and it dispersibility in water was influenced by the ionic strength. However, the resistance of laponite to salt was comparably better than that of other clays.
4. Compared to existing mud-making materials, laponite showed better mud-making properties. Moreover, water-based drilling fluids containing laponite exhibited an excellent stability at elevated temperatures and superior rheology without the presence of viscosifiers and thinners which were high-temperature resistant.

Overall, these findings demonstrate that laponite has promising applications as a high-temperature mud-making material.

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