



Article

# Effect of Layer Charge Density on Hydration Properties of Montmorillonite: Molecular Dynamics Simulation and Experimental Study

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Received: 19 July 2019; Accepted: 14 August 2019; Published: 16 August 2019



**Abstract:** Four kinds of Ca-montmorillonite with different layer charge density were used to study the effect of charge density on their hydration properties by molecular dynamics simulation and experiments. The research results of Z-density distribution of water molecules,  $H_w$  (hydrogen in water molecules), and Ca in the interlayer of montmorillonite show that the hydration properties of montmorillonite are closely related to its layer charge density. If the charge density is low, the water molecules in the interlayers are mainly concentrated on the sides of the central axis about  $-1.3\text{ \AA}$  and  $1.5\text{ \AA}$ . As the charge density increases from  $0.38_{\text{semi-cell}}$  to  $0.69_{\text{semi-cell}}$ , the water molecules are distributed  $-2.5\text{ \AA}$  and  $2.4\text{ \AA}$  away from the siloxane surface (Si-O), the concentration of water molecules near the central axis decreases, and at the same time,  $\text{Ca}^{2+}$  appears to gradually shift from the vicinity of the central axis to the Si-O surface on both sides in the montmorillonite layer. The simulation results of the radial distribution function (RDF) of the  $\text{Ca}-H_w$ ,  $\text{Ca}-O_w$  (oxygen in water molecules), and  $\text{Ca}-O_t$  (the oxygen in the tetrahedron) show that the  $\text{Ca}^{2+}$  and  $O_w$  are more tightly packed together than that of  $H_w$ ; with the increase of the charge density, due to the fact that the negative charge sites on the Si-O surface increase, under the action of electrostatic attraction, some of the  $\text{Ca}^{2+}$  are pulled towards the Si-O surface, which is more obvious when the layer charge density of the montmorillonite is higher. The results of the RDF of the  $O_t-H_w$  show that with the increase of charge density, the number of hydrogen bonds formed by  $O_t$  and  $H_w$  in the interlayers increase, and under the action of hydrogen bonding force, the water molecules near the central axis are pulled towards the two sides of Si-O surface. As a result, the arrangement of water molecules is more compact, and the structure is obvious. Correspondingly, the self-diffusion coefficient shows that the higher the layer charge density, the lower the self-diffusion coefficient of water molecules in interlayers is and the worse the hydration performance of montmorillonite. The experimental results of the experiments fit well with the above simulation results.

**Keywords:** montmorillonite; layer charge density; hydration property; molecular dynamics simulation; experiment

## 1. Introduction

Montmorillonite has a two-dimensional nano-scale layered structure [1]. Its TOT crystal structure unit is aluminum-oxygen octahedron in the middle and silica-oxygen tetrahedron in the upper and lower layers [2,3]. The interlayer of its TOT unit (so-called interlayer domain) usually contains a certain amount of water molecules and some exchangeable cations, so it has higher cation exchange

capacity and higher water absorption and expansion capacity [4,5]. The hydration properties of montmorillonite have great influence on its application in various fields such as organic modification of montmorillonite, preparation of nanocomposite materials, drilling mud, pollution control, soil improvement, and others [6–10]; therefore, it is very important to study the hydration properties of montmorillonite.

Recently, with the development of science and technology, the methods of studying montmorillonite are not limited to experimental research. Computer molecular simulation can be used for theoretical research and experimental determination, which has been widely used in research of montmorillonite [11,12]. Compared with the traditional experimental research methods, the advantages of computer molecular simulation are obvious, which can not only simulate the molecular structure of the substance itself, but also simulate the dynamic change of the molecule when the substance reacts. It can visually describe the mechanism of reaction between substances at the molecular and atomic scales, and then verify the rationality of the experiment or predict the experimental results [13]. Skipper et al. first simulated the interlayer water structure of Na-montmorillonite and Mg-montmorillonite by using Monte Carlo (MC) and molecular dynamics methods (MD) in 1991, and proposed a complete MC simulation method for a clay-ion-water system in 1995, including the construction of the model, the selection of potential functions, and the processing of non-bonded interaction, which laid the foundation for the future molecular simulation study of montmorillonite [14,15]. Marry et al. studied the Na-montmorillonite and Cs-montmorillonite by MC and MD simulation methods, and compared their structural and kinetic characteristics with experimental data; their findings showed that the layer spacing calculated by molecular simulation, the diffusion coefficient of water molecules, and interlayer cations in a single layer hydrate were basically consistent with the experimentally measured data [16]. Therefore, MD simulation can be used as a new technology in the study of montmorillonite.

At present, molecular simulation technology has been successfully used to study the hydration characteristics of montmorillonite. Marry and Mignon studied the behavioral characteristics of different cations ( $\text{Li}^+$ ,  $\text{Na}^+$ , and  $\text{K}^+$ ) in the hydration process of montmorillonite by methods of MC and MD simulation, and found that as the water content between the smectite layers increased,  $\text{Li}^+$  and  $\text{Na}^+$  were easily separated from the montmorillonite interlayer, while  $\text{K}^+$  moved to the surface of the siloxane tetrahedron and was bound to the surface [17–19]. Rahromostaqim compared the hydration and expansion properties of illite-montmorillonite (I-MMT) and Na-montmorillonite using molecular dynamics simulation, and found that at low  $\text{CO}_2$  concentrations in Na-MMT, which has its layers' charge concentrated in its octahedral sheet, weak ion-surface interactions result in fully hydrated ions and, therefore, more extensive swelling than in I-MMT [20]. Most researchers believe that montmorillonite with stronger hydration ability layer cations (such as  $\text{Na}^+$ ,  $\text{Li}^+$ ) has higher expansion and hydrophilicity [21–24]. On the contrary, montmorillonite with weaker hydration cations ( $\text{K}^+$ ,  $\text{Cs}^+$ ) has lower swelling ability, poorer hydrophilicity, and its hydrophilicity is also affected by various factors (such as temperature, pressure, etc.) [5,25]. However, montmorillonite formed in different geological processes usually has different crystal chemical properties and layer charge characteristics, which will inevitably affect the hydration properties of montmorillonite, and therefore affect the physical and chemical performance of its derivatives [26]. As can be seen from the above, the previous studies in this field mainly focused on the influence of the interlayer cation types, temperature, and pressure conditions on hydration properties of montmorillonite [12,27,28]. Nevertheless, there are few studies about the effect of layer charge density on the hydration properties of montmorillonite.

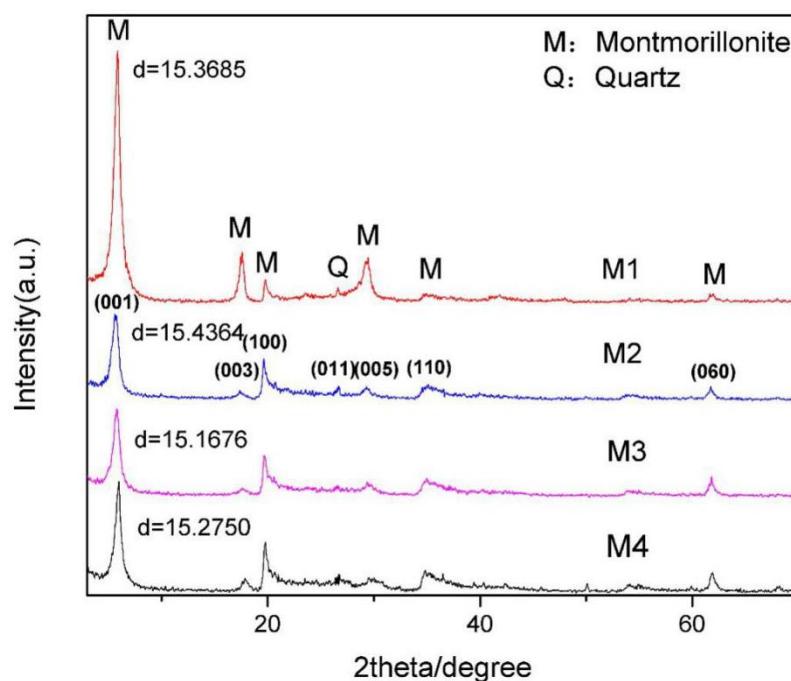
In this work, four kinds of montmorillonite formed in different geological processes in China were used as experimental materials, and according to the chemical analysis results of purified montmorillonites, the position of all kinds of ions in montmorillonite crystals was determined, and the crystal-chemical formula was calculated. On this basis, the crystal structure models of four kinds of montmorillonite were established. The effect of layer charge density on its hydration characteristics was studied both by the methods of MD simulation and experiment.

## 2. Experiment

### 2.1. Materials

Four kinds of Ca-bentonite ores from Wei Fang, Lai Xi, and Inner Mongolia (two types) in China were purified according to the principle of Stokes settlement in water. The four purified montmorillonites were denoted as M1, M2, M3, and M4, respectively. The particle size of purified montmorillonite was controlled below 2 microns.

The X-ray diffraction (XRD) spectrums of the four kinds of purified montmorillonite are shown in Figure 1, which shows that the four purified montmorillonites only contain few quartz impurities and can meet the requirements of crystal structure calculation. In addition, the chemical compositions of the four kinds of montmorillonite were analyzed by XRF. According to the chemical analysis results of montmorillonite (Table 1), the position of various ions in the lattice of montmorillonite and the corresponding crystal formulas were determined [29]. The calculation results are given in Table 2. The crystal chemical formulas of the four kinds of montmorillonite were as follows:  $(Ca_{0.16}Mg_{0.02}Na_{0.01}K_{0.01})_{0.38}(Si_{3.98}Al_{0.02})_4O_{10}(Al_{1.55}Mg_{0.35}Fe_{0.10})_2(OH)_2$ ,  $(Ca_{0.25}K_{0.01})_{0.51}(Si_{3.97}Al_{0.03})_4O_{10}(Al_{1.52}Mg_{0.43}Fe_{0.05})_2(OH)_2$ ,  $(Ca_{0.21}Mg_{0.04}Na_{0.05}K_{0.02})_{0.57}(Si_{3.94}Al_{0.06})_4O_{10}(Al_{1.49}Mg_{0.41}Fe_{0.08}Mn_{0.02})_2(OH)_2$ , and  $(Ca_{0.26}Mg_{0.05}Na_{0.04}K_{0.03})_{0.69}(Si_{3.94}Al_{0.06})_4O_{10}(Al_{1.38}Mg_{0.53}Fe_{0.07}Mn_{0.01}Ti_{0.02})_2(OH)_2$ , respectively. Therefore, the semi-unit layer charge density of the four kinds of montmorillonite were 0.38, 0.51, 0.57, and 0.69, respectively.



**Figure 1.** X-ray diffraction analysis of four kinds of purified montmorillonite.

**Table 1.** Chemical composition of four kinds of purified montmorillonite.

Chemical Composition	Sample/%			
	M1	M2	M3	M4
SiO <sub>2</sub>	61.22	60.64	60.59	59.79
Al <sub>2</sub> O <sub>3</sub>	21.53	20.95	21.07	19.37
Fe <sub>2</sub> O <sub>3</sub>	1.03	0.57	0.85	0.75
MnO	0.00	0.00	0.18	0.09
TiO <sub>2</sub>	0.00	0.00	0.00	0.27
MgO	4.45	5.30	5.37	6.85





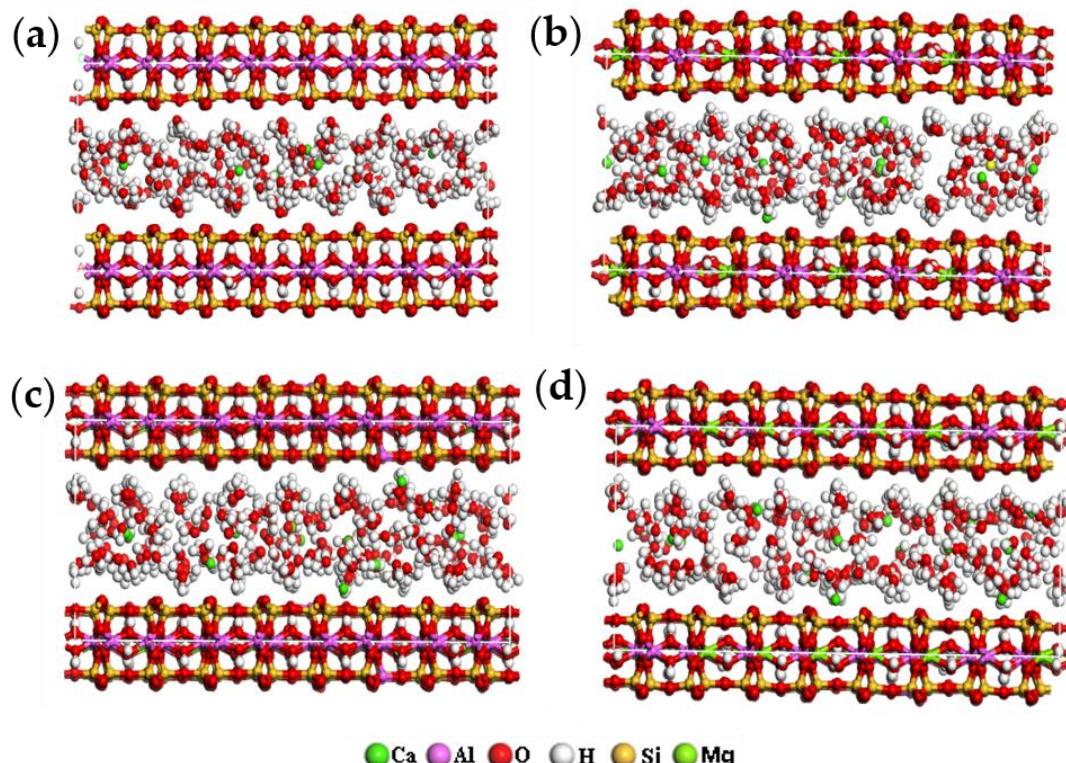
Thermogravimetric analysis (TG) was used to study the thermal stability of montmorillonite and further study the effect of layer charge density on the interlayer water precipitation temperature of montmorillonite. Derivative thermogravimetric analysis (DTG) is a function of the rate of change of weight and temperature or time, which can accurately reflect the initial reaction temperature of samples. The combination of the two techniques can be used to study the thermal stability of montmorillonite and further study the effect of charge density on the water precipitation temperature between layers of montmorillonite. The TG analysis was carried out using a TG/SDTA851e thermogravimetric/differential thermal synchronizer, manufactured by Mettler-Toledo (Zurich, Switzerland), with a working gas of N<sub>2</sub> and a heating rate of 5 °C/min. The starting temperature was 40 °C, and the end temperature was 300 °C; the sample was thoroughly dried at 100 °C for 12 h in advance.

### 3. Results and Discussion

#### 3.1. The Overall Distribution Characteristics of Water Molecules in the Interlayer of Montmorillonite

The final configuration model can directly reflect the distribution of water molecules in the interlayer of montmorillonite. The Z-density distribution curves reflect the density distribution of each component in the direction of vertical montmorillonite surface in the interlayer. The combination can further study the distribution and relative position of water molecules in the interlayer of montmorillonite.

According to the distribution characteristics of ions in the four types of montmorillonite in Table 1, combined with the detailed description in Section 2.2, the hydration models of the four kinds of montmorillonite with different charge density were finally optimized and shown in Figure 2.



**Figure 2.** The hydration models of montmorillonite (ball-and-stick model) (a) 0.375; (b) 0.500; (c) 0.563; (d) 0.688.

As can be seen from Figure 2, with the increase of the charge density in the montmorillonite, the water molecules in the interlayer gradually evolved from a random disordered arrangement into H<sub>w</sub> (H in the water molecules) turning to the siloxane surface of montmorillonite, while O<sub>w</sub> (O in the water

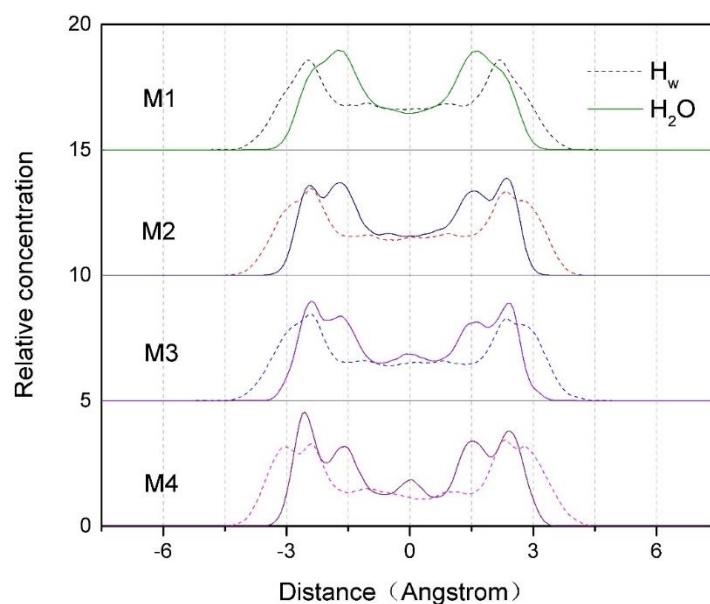
molecules) deviated from the siloxane surface. The above simulation results show that the charge density characteristics of montmorillonite has a significant influence on its hydration characteristics and interlayer ions distribution.

In this work, the molecular dynamics simulation software was used to study the influence mechanism of montmorillonite charge density on hydration performance by studying the Z-density distribution of water molecules,  $H_w$ , and  $Ca^{2+}$  in the interlayer, the mean square displacement curve (MSD) and diffusion coefficient of water molecules, and the radial distribution function (RDF) of  $Ca-H_w$ ,  $Ca-O_w$ ,  $Ca-O_t$ ,  $O_t-H_w$ , and  $O_t-Q_w$ .

### 3.2. Z-density Distribution

#### 3.2.1. Z-density Distribution of Water Molecules and $H_w$ in the Interlayer of Montmorillonite

Figure 3 shows the Z-density profiles of water molecules and  $H_w$  in the interlayer spaces of montmorillonites with different charge density. As can be seen from Figure 3, the two distribution peaks of water molecules in the interlayer domain are located about  $-1.3\text{ \AA}$  and  $1.5\text{ \AA}$  along the central axis, respectively, indicating that water molecules are mainly concentrated on both sides of the interlayer central axis of montmorillonite, while the two distribution peaks of  $H_w$  ( $H$  in water molecule) are located about  $-2.5\text{ \AA}$  and  $2.4\text{ \AA}$ , which is about  $0.9\text{ \AA}$  closer to the Si-O surface than that of water molecules. It indicates that due to the hydrogen bonds force formed by  $H_w$  and  $O_t$  ( $O$  in the tetrahedron), the water molecules are deflected, so the  $H_w$  are closer to the Si-O surface than that of the water molecules.



**Figure 3.** The Z-density profiles of water molecules and  $H_w$  within the interlayer spaces of montmorillonites with different charge density.

In addition, according to Figure 3, we can also find that the layer charge density of montmorillonite has a significant effect on the distribution of water molecules in interlayer. When the charge density is low (such as M1), the water molecules are mainly distributed near the central axis, which is shown as two sharp peaks in the Figure 3. With the increase of charge density (such as M2 and M3), the main peaks on both sides of the central axis begin to split, and at the same time, the peaks get weaker. When the charge density increases to 0.688 (such as M4), two new peaks begin to form near about  $-2.5\text{ \AA}$  and  $2.4\text{ \AA}$ , and so does the  $H_w$ . The reason is that with the increase of the charge density, more and more hydrogen atoms in the water molecules turn to the Si-O surface, the number of hydrogen bonds formed by  $H_w$  and  $O_t$  (Table 4 and Figure 10) increases, and as a result, more and more water molecules

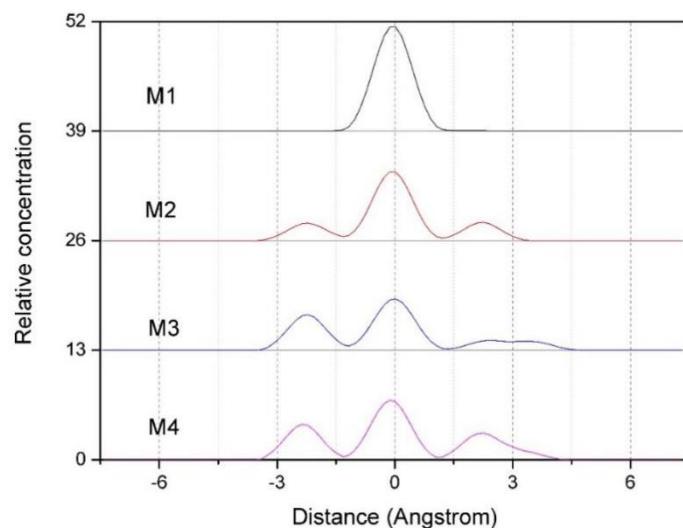
are closely bound to the Si-O surface. However, as the montmorillonite charge density increases, a new small peak of water molecules appears near the axis; the reason is that the water molecules distributed in the middle of the interlayer domain are subjected to an equal hydrogen bonding force from both of the two Si-O surfaces; this phenomenon is more obvious when the layer charge density of montmorillonite is higher.

**Table 4.** The hydrogen bond number and adsorption energy of montmorillonites with different layer charge density.

Item	M1	M2	M3	M4
$n$	208	221	235	243
Adsorption Energy (kcal/mol)	-1478.047	-1670.016	-1736.206	-1857.187

### 3.2.2. Z-density Distribution of $\text{Ca}^{2+}$ in the Interlayer of Montmorillonite

Figure 4 shows the Z-density profiles of  $\text{Ca}^{2+}$  in the interlayer of montmorillonites with different charge density. As can be seen from Figure 4, the charge density has a significant influence on the distribution of  $\text{Ca}^{2+}$ . With the increases in layer charge density, the  $\text{Ca}^{2+}$  appears to be gradually shift from the vicinity of the central axis to the Si-O surface on both sides in the montmorillonite layer, and this phenomenon is more obvious when the layer charge of montmorillonite is higher (such as M3, M4). The reason is that the  $\text{Ca}^{2+}$  between the layers of montmorillonite are subjected to electrostatic attraction of negative charges on the layers, causing the  $\text{Ca}^{2+}$  to diffuse to the Si-O surface. Since the montmorillonite with higher charge density has a large number of negative potential points, the  $\text{Ca}^{2+}$  in the interlayer are subjected to stronger electrostatic force; therefore, the diffusion of  $\text{Ca}^{2+}$  to the Si-O surface is more obvious. In general, the Z-density distribution of  $\text{Ca}^{2+}$  is similar to that of water molecules and  $\text{H}_\text{w}$  in water molecules.



**Figure 4.** The Z-density profiles of  $\text{Ca}^{2+}$  in the interlayer of montmorillonite with different charge density.

### 3.3. Mean Square Displacement (MSD) Curves and the Diffusion Coefficient of Water Molecules

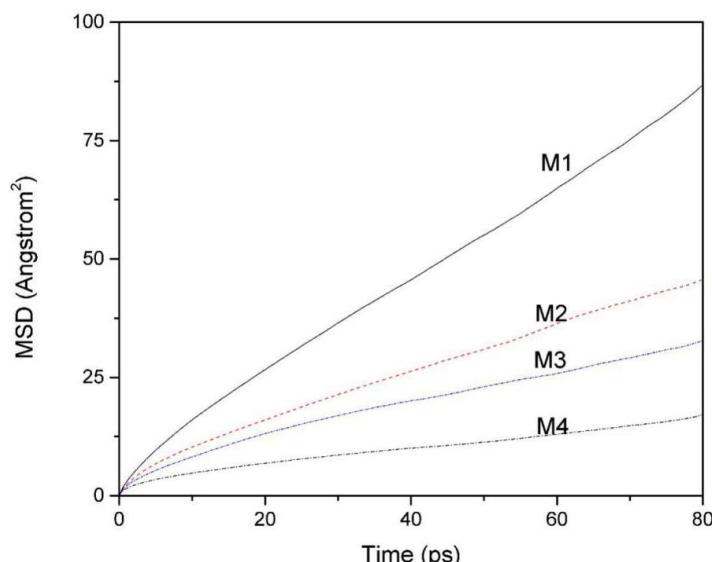
The MSD is the mean square of the change of particle position with respect to its initial position at different times, which can reflect the change of particle offset with time. The diffusion coefficient reflects the mobility of the particles, indicating the magnitude of the change of particle position with time, and its magnitude can be derived from the mean square displacement.

Figure 5 is the MSD of water molecules of montmorillonites containing 256 water molecules with different layer charge density. The self-diffusion coefficient of water molecules in the montmorillonite

interlayer can be derived from the MSD curves of water molecules. The magnitude of the diffusion coefficient is proportional to the slope of the MSD curves, i.e.: [33]

$$D = \frac{1}{6N_\alpha} \lim_{t \rightarrow \infty} \frac{d}{dt} \sum_{i=1}^{N_\alpha} \{[r_i(t) - r_i(0)]^2\} \quad (1)$$

where  $[r_i(t) - r_i(0)]^2$  is the mean square displacement of the molecule and  $N_\alpha$  is the total number of  $\alpha$  particles. The equation shows that the self-diffusion coefficient  $D$  is 1/6 of the slope of the MSD curve.



**Figure 5.** The mean square displacement (MSD) curves of water molecules of montmorillonites with different layer charge density.

It can be seen from Figure 5 that the MSD curves of the water molecules in the four kinds of montmorillonite are obviously different. Comparatively speaking, the mobility of water molecules in M1 is the highest and the mobility of water molecules in M4 is the lowest. According to formula (1), the calculated diffusion coefficient of water molecules (M1 to M4) is  $1.67 \times 10^{-10}$  m<sup>2</sup>/s,  $0.87 \times 10^{-10}$  m<sup>2</sup>/s,  $0.58 \times 10^{-10}$  m<sup>2</sup>/s, and  $0.28 \times 10^{-10}$  m<sup>2</sup>/s, respectively. Obviously, the diffusion coefficient of water molecules between layers decreases with the increase of charge density. The reason is that as the charge density of the layer increases, the number of hydrogen bonds formed between H<sub>w</sub> and O<sub>t</sub> increases, and more and more water molecules are bound to the Si-O surface, thus reducing its self-diffusion coefficient.

### 3.4. The Radial Distribution Function (RDF) of Ca-H<sub>w</sub>, Ca-O<sub>w</sub>, Ca-O<sub>t</sub>, O<sub>t</sub>-H<sub>w</sub>, and O<sub>t</sub>-Q<sub>w</sub>

The RDF reflects the probability density between two types of atoms and can reflect the aggregation characteristics of ions in the system. The RDF of  $\beta$  particles is evaluated as follows [33]:

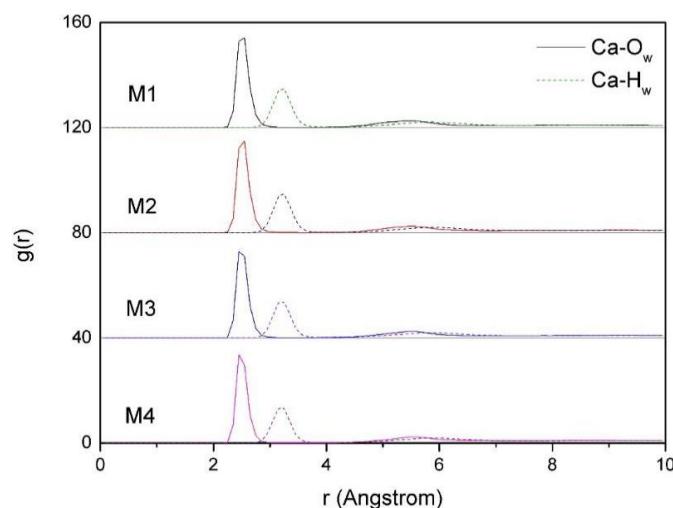
$$g_{\alpha\beta}(r) = n_\beta / 4\pi\rho_\beta r^2 dr \quad (2)$$

where  $g_{\alpha\beta}(r)$  is the radial distribution of  $\beta$ ,  $n_\beta$  is the number of  $\beta$  with a radius of  $r \rightarrow r + dr$ ,  $\rho_\beta$  is the number density of  $\beta$ , and  $r$  is the distance between  $\alpha$  and  $\beta$ .

#### 3.4.1. The RDF of Ca-H<sub>w</sub> and Ca-O<sub>w</sub>

The RDF of Ca-H<sub>w</sub> and Ca-O<sub>w</sub> of montmorillonites with different charge density are shown in Figure 6. By studying the RDF of Ca-H<sub>w</sub> and Ca-O<sub>w</sub> in the interlayer of montmorillonites with different charge density, we can study the action of Ca<sup>2+</sup> and water molecules between the layers of

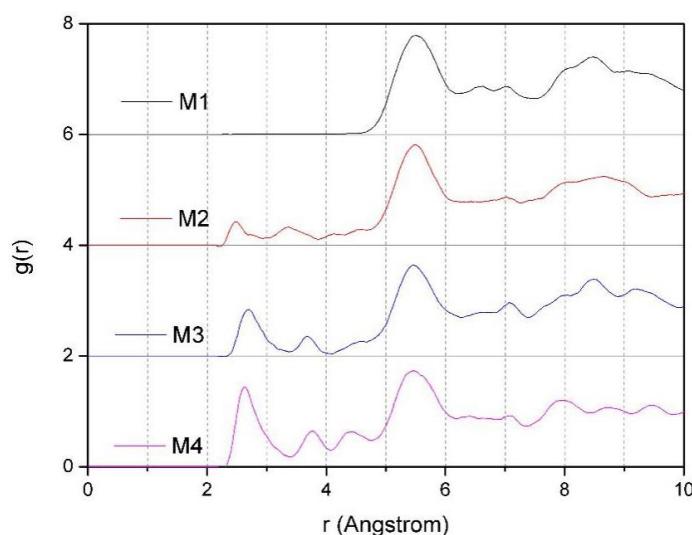
montmorillonite; therefore, the mechanism of the influence of  $\text{Ca}^{2+}$  on the distribution characteristics of water molecules can be further studied. It can be seen from Figure 6 that calcium ions are closely related to oxygen atoms in water molecules, the  $\text{Ca}^{2+}$  and the oxygen atoms in the water molecules are more tightly packed together than that of hydrogens so  $\text{Ca}^{2+}$  is more likely to have oxygen around than hydrogen in water molecules, and hydrated  $\text{Ca}^{2+}$  are formed near the Si-O surface. Comparatively speaking, it can be seen that there is little difference in the RDF of  $\text{Ca-H}_w$  and  $\text{Ca-O}_w$  characteristics with the increases of layer charge density.



**Figure 6.** The radial distribution function (RDF) of  $\text{Ca-O}_w$  and  $\text{Ca-H}_w$  of montmorillonites with different layer charge density.

### 3.4.2. The RDF of $\text{Ca-O}_t$

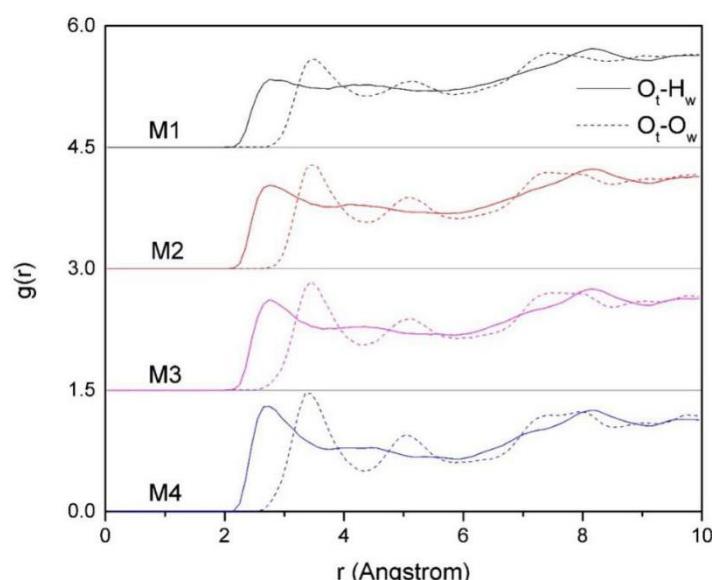
Figure 7 is the RDF of  $\text{Ca-O}_t$  of montmorillonites with different layer charge density. From Figure 7, we can find that with the increase in the charge density of montmorillonite, due to the fact that the negative charge sites on the Si-O surface increases, under the action of electrostatic attraction, some of the  $\text{Ca}^{2+}$  are pulled towards the Si-O surface; therefore, some new peaks appear around 2.6–4.5 Å, which is more obvious when the layer charge density of the montmorillonite is higher; this further indicates that calcium ions are close to the negative charge sites on the Si-O surface. The simulation results are consistent with Figure 2.



**Figure 7.** The RDF of  $\text{Ca-O}_t$  of montmorillonites with different layer charge density.

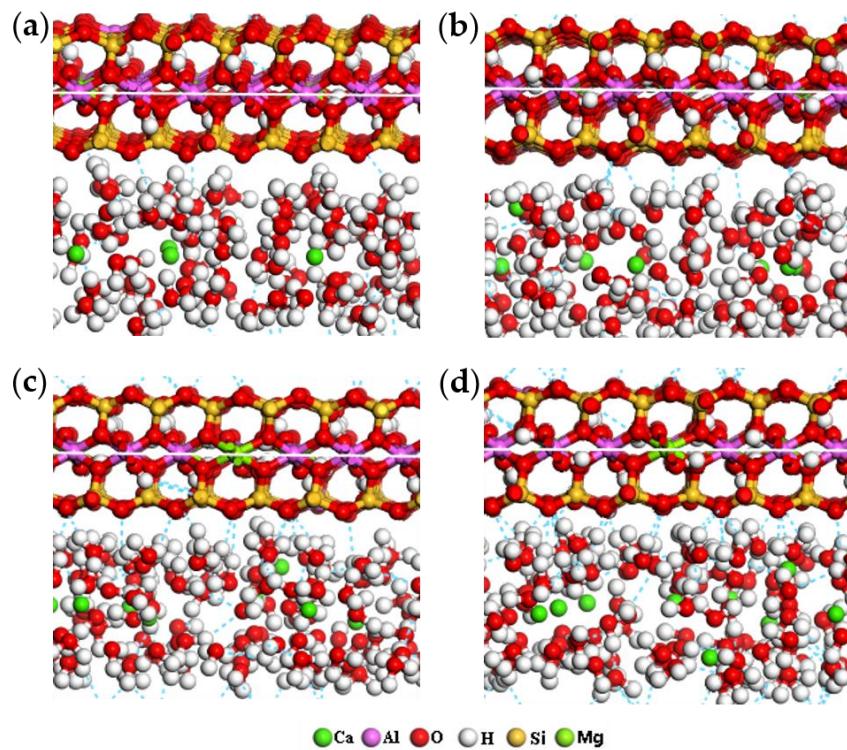
### 3.4.3. The RDF of $O_t\text{-}H_w$ and $O_t\text{-}O_w$

The RDF of  $O_t\text{-}H_w$  and  $O_t\text{-}O_w$  of montmorillonites with different charge density are shown in Figure 8. It can be seen that the maximum peak value of  $g(O_t\text{-}H_w)$  is approximately 2.5 Å, and the maximum peak value of  $g(O_t\text{-}O_w)$  is approximately 3.4 Å, which indicates that  $H_w$  is closer to the siloxane surface than  $O_w$  in water molecular. The reason is that the water molecules are polar molecules, the side of  $H_w$  is positively charged, and the side of  $O_w$  is negatively charged. On the other hand, the siloxane surface of montmorillonite is negatively charged, and due to the effect of the polar force, the  $H_w$  is close to the siloxane surface and forms hydrogen bonds with the  $O_t$ . As a result,  $H_w$  is closer to the siloxane surface than  $O_w$ . In addition, from Figure 8, we can also find that the effect of layer charge density of montmorillonite on the distribution of  $H_w$  and  $O_w$  in the layer is obvious. With the increases of charge density, the peaks of  $O_t\text{-}H_w$  and  $O_t\text{-}O_w$  get higher and steeper, which clearly indicates that the arrangement of  $H_w$ ,  $O_w$ , and  $O_t$  is tight, and the arrangement of water molecules in the montmorillonite inter-layer is more compact.



**Figure 8.** The RDF of  $O_t\text{-}O_w$  and  $O_t\text{-}H_w$  of montmorillonites with different layer charge density.

In order to further analyze the interaction between Si-O surface and water molecules in interlayer domain, we calculated the number of hydrogen bonds and the adsorption energy of Si-O surface to water molecules (Figure 9 and Table 4). It can be seen that the number of hydrogen bonds and the adsorption energy to water molecules also increase with the increase in the charge density of montmorillonite. It indicates that the water molecules in the montmorillonite with higher charge density are subjected to stronger polar force, and more and more  $H_w$  is diverted towards the Si-O surface, forming more hydrogen bonding with the  $O_t$ . Due to the influence of the polar force and hydrogen bonding force, Si-O surface of montmorillonite with higher charge density has higher adsorption energy to water molecules, which further indicates that the higher the layer charge density of the montmorillonite, the more difficult it is to hydrate.



**Figure 9.** Schematic diagram of hydrogen bond of montmorillonites with different layer charge density (dashed line is hydrogen bond). (a) 0.375; (b) 0.500; (c) 0.563; (d) 0.688.

### 3.5. Experimental Study

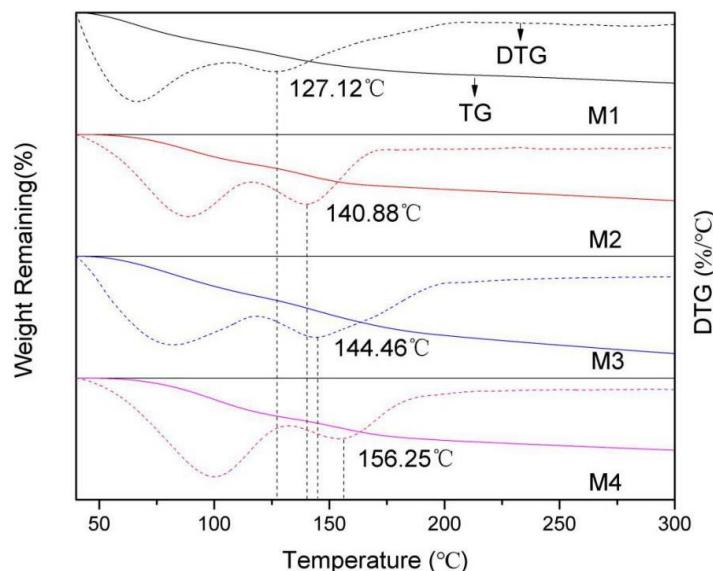
The effect of layer charge density on water moleculars diffusivity of montmorillonite at the molecular and atomic levels has been studied by MD techniques. In order to macroscopically study the effect of charge density on hydration performance of montmorillonite, some experimental studies on the hydration performance of montmorillonite were conducted. TG and DTG were used to study the thermal stability and the difference in water precipitation temperature among montmorillonites. The swelling capacity and the gelling value were used to evaluate the swelling and dispersibility of montmorillonite.

#### 3.5.1. Thermogravimetric (TG) and Derivative Thermogravimetric Analysis (DTG)

The TG and DTG of montmorillonites with different layer charge densities are shown in Figure 9. The derivative thermogravimetric curve of montmorillonite shows two peaks. The first peak appears between 40–100 °C and this is the release temperature of the adsorbed water in the montmorillonite; the second peak appears between 100–200 °C and this is the precipitation temperature of the interlayer water in the montmorillonite. The reason for the different precipitation temperature of water molecules is that the interlayer water is hydrogen-bonded by Si-O surface, and the energy required for precipitation is higher than that of the adsorbed water. However, with the increase of temperature, the movement of interlayer water molecules is more severe, and the above-mentioned hydrogen bonding force formed by O<sub>t</sub> and H<sub>w</sub> is difficult to limit the movement of water molecules, thereby causing the interlayer water to precipitate.

From Figure 10, we can also find that the maximum precipitation temperature of interlayer water molecules from M1 to M4 are 127.12 °C, 140.88 °C, 144.46 °C, and 156.25 °C, respectively, which indicates that as the charge density increases, the precipitation temperature of interlayer water of montmorillonite gradually increases. This is because the higher the layer charge density, the greater the number of hydrogen bonds formed by the H<sub>w</sub> and the O<sub>t</sub> (Table 3), the stronger the hydrogen

bonding force on the interlayer water, the higher the energy required for the precipitation of water molecules, and the higher the temperature required for the precipitation of interlayer water.

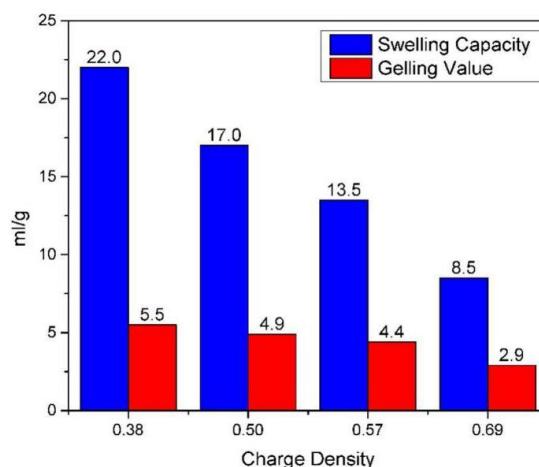


**Figure 10.** The TG and DTG curves of montmorillonites with different layer charge densities.

### 3.5.2. Swelling Capacity and Gelling Value of Montmorillonite

The hydration performance of montmorillonite includes swelling capacity and gelling value. The swelling capacity refers to the volume of montmorillonite after expansion in dilute hydrochloric acid solution. The gelling value is a comprehensive expression including the dispersibility, hydrophilicity, and swelling ability of the montmorillonite. Both of them can be used to characterize the hydration expansion properties of montmorillonite.

The swelling capacity and gelling values of the four kinds of montmorillonite were determined according to the literature [34,35] (Figure 11). As we can see from Figure 10, there are significant differences in the hydration properties of montmorillonites with different charge densities. The lower the layer charge density, the higher the swelling capacity and gelling values. The swelling capacity and gelling values of the montmorillonite with a charge density of 0.38 are 22 mL/g and 5.5 mL/g. The swelling capacity and gelling values of the montmorillonite with a charge density of 0.69 are 8.5 mL/g and 2.9 mL/g, which indicates that as the charge density of montmorillonite increases, the hydration expansion and dispersion performance of montmorillonite decrease, which is consistent with the results of the previous molecular simulation.



**Figure 11.** The swelling capacity and gelling value of montmorillonite with different layer charge density.





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