1. Introduction

Biochar (BC) is a kind of pyrolytic carbon produced by biofuel or agricultural residues at relatively low oxygen content and temperature. Because of its potential to change the physical and chemical properties of soil and organisms, BC has been widely used in agriculture and the environment by a large number of scholars [1] as a new type of environment function material, which improved the polluted agricultural lands [2], fix the nutrition, reserve the bioavailability of water, immobilize environmental pollutants [3,4].

BC can penetrate surface water and even pollute the groundwater system through surface runoff, drainage or irrigation [5]. Although the proportion of micro-nanoparticles (MNPs) accounts for only a small part of the total BC production, it has high mobility and absorptibility. Especially when it adsorbs heavy metals, it will form micro-nano-biochar-heavy metal composite particles that can quickly move in the soil [6]. Once desorbed, heavy metals will migrate to farther places and cause large-scale pollution. So many scholars have analyzed and studied the phenomenon that 'colloid promotion' can accelerate the migration of pollutants (especially organic pollutants and heavy metals) in water or soil [7]. So far, among the main methods for removing and recovering heavy metals in water (chemical precipitation, redox, ion exchange, biological filtration, activated sludge method and adsorption), the adsorption method has the advantages of good purification effect, simple operation, and no secondary pollution. It is regarded as an effective and efficient treatment method and is widely used in the removal of heavy metals in urban wastewater and industrial wastewater. B is an excellent adsorbent. Therefore, a comprehensive understanding of various characteristics of MNPs, especially its advantages in transportation, can enable it to play its best role in restoring agricultural production and environmental protection [8–10].

The clay mineral is widely spread in the soil and easy to be obtained, being compatible to environment, and especially its absorption efficiency on heavy metal has become the study focus. The position and morphology of clay particles in the pores of the medium are the main factors affecting the retention of MNPs. Previous studies have tested the effect of clay mineral soil composition on retention and migration of biochar colloids in saturated porous media [11] and found that the clay minerals have the advantages of high surface areas, excellent chemical and mechanic stability, special crystal layer structure and better environmental compatibility, etc., enabling it to largely absorb the pollutants in the soil. In addition, the composition of the soil is very complex, and it is difficult to systematically study the effects of various components in the soil on the effect of biochar in a laboratory simulation environment. Studies have shown that the surface area of coated quartz sand is much larger than that of...
unmodified quartz sand, and modified quartz sand is more capable of adsorbing heavy metals such as Cd and Pb. Moreover, the adsorption of different minerals to heavy metal ions has obvious selectivity, and the adsorption isotherm of metal ions to surface charges conforms to the Langmuir model, which proves that there is chemical adsorption in addition to physical adsorption in clay minerals [12,13]. Although some studies have reported the migration behavior of biochar colloid in soil [14,15], the physicochemical property and biological characteristics of natural soil are very complex, and the actual transport behavior of biochar in the environment is different from that at obtained in a well-defined laboratory model. At present, many researches on BC migration are limited to the migration in porous media. The migration mechanism of BC colloid in soil, especially the clay mineral components of soil, has not been involved in the migration behavior of BC so far [16,17]. In addition, the migration and fate of micro-nano biochar (MMNBC) will also affect the migration of other substances in the soil. The function of BC on the migration of other pollutants is also closely related to the characteristics of the pollutants themselves. The impact of clay mineral colloids on the migration of MMNBC is urgently needed.

In this study, in order to better restore the real soil environment, kaolinite, montmorillonite and illite were used to modified quartz sand, and columns were used to simulate the transport process of modified micro-nano biochar in soil. Migration experiments were carried out under different IS and flow rates. Its purpose is: (1) to clarify the effects of IS and flow rate on MMNBC migration and retention in groundwater system; (2) to compare the effects of different heterogeneous media on MMNBC migration in soil; (3) to reveal what role clay minerals play in the migration of MMNBC.

2. Materials and methods

2.1 Materials

Divided the mature ramie plant into four parts (whole plant, bark, stem, leaf), then cut into 2–4 cm pieces, rinsed with tap water 3–4 times and DI water 3 times and put in 105°C Oven for drying. The dried ramie stalks were put into a pulverizer and smash them through a 1 mm sieve. Passed in N₂ (speed = 250 ml min⁻¹) to a tubular vacuum furnace as protection, respectively raised the temperature to 500°C at a rate of 10°C min⁻¹ and kept it for 120 min. After cooling down the room temperature, kept it in N₂ atmosphere for 120 min. Dry the cleaned ball and material (ratio 1:20), and then grinded BC (1.6 h, speed from 360 rpm to 280 rpm) to the micro-nano level (100–1000 nm) [18,19] by a ball mill (YXQ-4 L, Changsha Mickey Instrument Equipment Co., Ltd.). 1.00 g of the sample was added to a 250 mL beaker with a small amount of DI water (pH = 6.5) then Ultrasonic oscillation for 30 min to prevent the BC particles from agglomerating. Measured the particle size of BC in the laser particle size analyzer (TriStar II, Micromeritics Co., USA) and analyzed the particle size composition.

2.2 Heterogeneous medium

The preparation of quartz sand is very similar to the method of Gao [20]. First, sieved the quartz sand with a particle size of 20–40 mesh (Zhouzhi Qinfeng Quartz Sand Factory, China). Quartz sand was washed repeatedly with tap water until it was clear, and then soaked in HCl solution for 24 h. After repeated scrubbing, it was soaked in NaOH for 24 h and washed by DI. Quartz sand was placed in a 110°C oven for drying. And the clay minerals <2 μm are partially separated and settled by gravity.

Montmorillonite, illite, kaolinite (Tianjin Fuchen Chemical Reagent Company, Tianjin, China) modified medium [21]: Clay minerals were treated and purified with hydrogen peroxide, and gravity sedimentation to obtain particles with a particle size of <2 um, The suspension was flocculated with 50 mg l⁻¹ polyvinyl alcohol. The mixture was allowed to stand and centri-fuged for 5 min. Then it was mixed with quartz sand and dried for 24 h. The material was washed with deionized water, dried again at 80°C for 24 h, and then washed to remove the attached polyvinyl alcohol. Scanning electron microscope (SEM) (S-4800 Hitachi, Japan) was used to describe the surface morphology at 500, 1000, 2000, and 5000 magnifications, and the surface area was analyzed by scanning and energy spectroscopy. Dispersed the quartz sand (5 g) in an ultrasonic cleaner (KQ-500DE, Kunshan Ultrasonic Instrument Co., Ltd.) for 30 min before [22] determining the Zeta potential of quartz sand. Added quartz sand (5 g) under different experimental conditions to 25 ml reservoir bottle of background solution corresponding to the experimental conditions, dispersed in an ultrasonic cleaner (KQ-500DE, Kunshan Ultrasonic Instrument Co., Ltd.) for 30 min, and pipetted 1 ml of supernatant, then the Zeta potential was measured with a Zeta-Plus potentiometer (Zetasizer nano ZS90, Malvern Instruments, UK). Then, we abstained quartz sand (QS), kaolinite coated quartz sand (KCQS), illite coated quartz sand (ICQS) and montmorillonite coated quartz sand (MCQS) respectively.

2.3 Column experiment

Before conducting the column test, a 100 mg l⁻¹ concentration of MMNBC suspension was prepared. Dissolved MMNBC (500–750 nm) in a small amount of water and transferred it to a 2000 ml master flask. BC
was treated with ultrasound for 10 min using an ultrasound device. Finally, the initial pH of the solution was adjusted to 6.5 ± 0.2.

The migration experiments were conducted on sand columns with \( h = 15 \) cm and \( r = 3 \) cm. The sand columns were wet packed with DI water with stirring to minimize delamination and removal of the residual air in the column [23], in the process of filling the sand column, the QS was constantly stirred, which caused the sand to be squeezed and worn by each other and produces tiny quartz sand particles. Before the experiment, the sand column was rinsed with distilled water until the effluent was clear and free of impurities. During the process, adjusted the flow rate to the required flow rate for the experiment. When the flow rate was stable, switched to the transport solution to start the experiment. Varied the solution flow rate to 0.5 ml min\(^{-1}\), 1 ml min\(^{-1}\), 2 ml min\(^{-1}\), respectively. Flushed the columns with 10PVs of DI water and then by 3 PVs of MMNBC. Next, the column was leached with DI water to make the leachate concentration 0 [24]. From the beginning of the BCsolution, samples were taken every 5 min, 10 min, and 20 min. In the end, the concentration of micro-nano biochar (MMNBC) was measured by UV Spectrophotometer at 709 nm by the method of turbidity. In another series of experiments, IS was controlled (0.1 mol l\(^{-1}\), 0.01 mol l\(^{-1}\), 0.001 mol l\(^{-1}\)). First, a NaCl solution with the same IS of MMNBC was injected into the column to clarify the leakage solution. Next, the leakage solution was replaced with MMNBC (3PVs), and leached NaCl solution (at least 4PVs) to make the leachate concentration zero. In addition, samples were taken every 10 min starting with the MMNBC solution. In order to prevent the sedimentation of particles from affecting the measurement results, it is not suitable to place samples for a long time. Concentrations were determined by the same method [16].

### 2.4 Mathematical model

The mathematical model of solute transport is completed by the convection dispersion equation under the condition of one-dimensional saturated flow [25]. By using Hydrous-1D, MMNBC fitting migration process curve in heterogeneous medium can be accurately simulated [26,27]:

\[
\frac{\partial A_w}{\partial t} = D \frac{\partial^2 A_w}{\partial z^2} - \nu \frac{\partial A_w}{\partial z} - \rho \frac{\partial l}{\partial \theta}
\]  

(1)

Among them, \( A_w \) is the concentration(mg l\(^{-1}\))of solute in the water flow; \( D \) is the diffusion coefficient (cm\(^2\) min\(^{-1}\)); \( \nu \) is the Darcy velocity of water (cm min\(^{-1}\)); \( \rho \) is the bulk density of medium (g cm\(^{-3}\)); \( \theta \) is porosity, dimensionless.

In a stable solution system, the migration behavior of the colloid can be analyzed and evaluated by using the coefficient of coalescence rate of colloid K in the formula [28]:

\[
k = - \frac{Q}{\varepsilon L} \ln \left( \frac{A}{A_0} \right)
\]

(2)

\[
\rho \frac{\partial S}{\partial t} = k \left( 1 - \frac{l}{l_{\text{max}}} \right) A_w
\]

(3)

In the formula: \( k \) is coefficient of coalescence rate of colloid (min\(^{-1}\)); \( Q \) is the pore water velocity of the medium (m s\(^{-1}\)); \( \varepsilon \) is the porosity of the medium; \( L \) is the column height (m); \( A/A_0 \) is the peak value of the relative concentration of the breakthrough curve of colloid; \( l \) is the adsorption concentration of solute; \( l_{\text{max}} \) is the maximum deposition amount of particles (mg l\(^{-1}\) g\(^{-1}\)); Parameters \( k \) and Smax are obtained by using Hydrous \(^{-1}\)D.

### 3. Results and discussion

#### 3.1 Physicochemical properties of heterogeneous media

After ball milling, the particle size of the BC Kerry was around 500–700 nm, which belongs to nano particles. SEM scans and EDS spectra of QS in Figure 1 showed images of the coated-sand surfaces. In order to determine the amount of soil components coated on the surface of the QS medium, the coated QS column was washed with an electrolyte solution at 2 times the experimental flow rate until no covering was washed out. Afterwards, the coated QS was taken out, and the clay mineral-coated QS was washed repeatedly with 0.1 mol l\(^{-1}\) NaOH to make the clay mineral fall off the surface of the QS. The concentration of HA and the coverage of clay minerals was measured with an ultraviolet-visible spectrophotometer at a wavelength of 254 nm. Depicted that there were less wrinkles and attachments on the surface of the QS, and only 60% to 90% of the surface is coated. This result is consistent with previous report [29]. The EDS spectrum shows the surface of pure QS. These peaks clearly indicate that the soil components cover the QS surface. Pure QS is mainly composed of two elements, silicon and oxygen, which is similar to the situation of KCQS. Kaolinite is stacked as small pieces on the sand surface, which is also loaded with Al element (Figure 1(b)). MCQS (Figure 1(c)) exhibits multilayer, irregular, flaky when loaded onto the sand surface, and surface elements similar to those of the ICQS shown in Figure 1(d), whereas illite appears on the surface of the sand as a granular covering.

Negative charge of MMNBC gradually reduced with the exaltation of IS was signified in Table 1; QS and the other three media also had the same changing trend. Zeta potential was the main factor affecting the electrostatic repulsion between QS and colloidal
molecules, and studying it is of great significance for observing the migration phenomenon of MMNBC. According to the data, with the increase of electrostatic repulsion, the zeta potential decreased, thereby hindered the migration of MMNBC. The Zeta of the four media are all negative. There was a proportional relationship between the repulsive force and the absolute value of the charge. Under the same IS conditions, kaolinite had the largest repulsive force to MMNBC, meanwhile, MCQS had the lowest.

Analyzed the specific surface area and pore size distribution of the sample with an automatic gas absorber, and the adsorbed gas is nitrogen. The specific surface area of the heterogeneous medium is MCQS (0.632 m² g⁻¹) > ICQS (0.617 m² g⁻¹) > KCQS (0.446 m² g⁻¹) > pure QS (0.103 m² g⁻¹) based on the data displayed by Table 2, the specific surface area of the coated QS is basically an order of magnitude larger than the specific surface area of pure QS, this phenomenon is the same as before of research is similar [30].

### 3.2 Effect of flow velocity on MMNBC transport in heterogeneous media

The best transport effect of MMNBC is pure QS, followed by KCQS, then ICQS, and finally MCQS. This is because the break of the bond at the edge of the heterostructure or the protonation or deprotonation of the exposed hydroxyl groups [31] on the surface will generate variable charge sites on the surface that are

| Table 2: EDS data of different samples |
|-----------------|----------|----------|
| Element | Wt % | At % |
| C K | 05.23 | 09.38 |
| O K | 46.31 | 62.36 |
| SiK | 34.88 | 26.76 |
| PtM | 13.58 | 01.50 |
| O K | 38.84 | 57.68 |
| AlK | 09.13 | 08.04 |
| SiK | 38.58 | 32.64 |
| PtM | 13.45 | 01.64 |
| O K | 44.42 | 63.01 |
| MgK | 02.30 | 02.15 |
| AlK | 07.35 | 06.18 |
| SiK | 32.82 | 26.52 |
| PtM | 11.74 | 01.37 |
| CaK | 01.37 | 00.78 |
| O K | 46.41 | 65.42 |
| MgK | 00.45 | 00.42 |
| AlK | 07.30 | 06.10 |
| SiK | 31.46 | 25.26 |
| PtM | 11.89 | 01.37 |
| K K | 02.49 | 01.44 |

**Figure 1.** SEM scans and EDS spectra of pure quartz sand (a), kaolinite (b), montmorillonite (c), and illite (d) coated sand.
Table 1. The particle size and Zeta potential of MMNBC.

| Material                      | IS (μm)         | Zeta (mV) |
|-------------------------------|-----------------|-----------|
| MMNBC                        | 0.001 ± 36.58   | 515.62 ± 22 |
| MMNBC coated pure quartz sand | 0.001 ± 27.23   | /         |
| Pure quartz sand              | 0.001 ± 21.34   | /         |
| Kaolin coated pure quartz sand| 0.001 ± 9.49    | /         |
| Illite coated pure quartz sand| 0.001 ± 16.25   | /         |
| Illite coated pure quartz sand| 0.001 ± 10.24   | /         |
| Montmorillonite coated pure quartz sand | 0.001 ± 14.42 | /       |
| Montmorillonite coated pure quartz sand | 0.001 ± 8.19 | /        |
| Montmorillonite coated pure quartz sand | 0.001 ± 3.25 | /        |

Table 2. Basic properties of heterogeneous media.

| Material                          | Specific surface area (m²/g) | Percentage of Coverage (%) |
|-----------------------------------|------------------------------|-----------------------------|
| Pure quartz sand                  | 0.103                        | 0                           |
| Kaolin coated pure quartz sand    | 0.446                        | 52.14                       |
| Illite coated pure quartz sand    | 0.617                        | 64.22                       |
| Montmorillonite coated pure quartz sand | 0.632             | 83.67                       |

Figure 2. Breakthrough and fitted curves of MMNBC migration under the influence of different flow rates in heterogeneous media is in Figure 2. The minimal recovery rate of MMNBC in the migration process is 62.67%, 66.22% and 72.00% (Table 1), respectively, which increased with the flow rate. According to the R² (0.9478–0.9957) of fitted curve the fitted degree is high. The difference between Smax and K shown in Table 3 is not obviously different, so basically it can be considered that the flow velocity has a little effect on the migration of MMNBC. The results show that under the same experimental conditions, when the flow rate

proves that the composition of clay minerals can effectively prevent the migration of micro-nano particles in soil, which is similar to the research of Lu [32]. In terms of IS = 0.001 (Table 1) that the zeta potentials of the three clay minerals are all between ±10 and ±30, at which time the colloids begin to become unstable, and the attractive force exceeds the repulsive force, the dispersion is destroyed and coagulation or aggregation occurs, and the lower the Zeta potential (positive or negative), the more likely the colloid is to coagulate or aggregate [33]. This feature can also explain the different migration capabilities of three different clay minerals to MMNBC [10].

Figure 2. Breakthrough and fitted curves of MMNBC in a heterogeneous medium at a flow rate of 2.0 ml min⁻¹(a), 1.0 ml min⁻¹(b), 0.5 ml min⁻¹(c).
rising, the migration rate of MMNBC in the column will be higher. MMNBC has a higher migration rate in heterogeneous media at the same flow rate. Compared with the previous research (Wang, Zhang et al.), the migration rate of BC in micron scale is lower than that in micro-nano size. In addition, the solutions of the three groups of experiments all flow from the bottom to the top of the column mold, so basically the MMNBC deposited on the heterogeneous medium surface can be ignored due to the influence of gravity [34]. At the end of transportations, the concentration of MMNBC gradually decreases until \( C/C_0 = 0 \). The results proved that the increase of the flow rate shortens the contact time of MMNBC with heterogeneous media, the insufficient contact reduced the absorption of heterogeneous medium to the MMNBC and the increase of flow rate may also reduce the colloidal filtration efficiency and enhance the mobility of MMNBC in the heterogeneous medium (Maguire-Boyle, Garner et al.), which increases the migration rate of BC colloid in column. In addition, the change in solution flow rate increases the fluid shear force to balance the effects of various forces such as van der Waals force, charge repulsion and gravity in the water. Therefore, the MMNBC initially adsorbed on the medium is impacted and falls off, returns to the liquid phase, and transported with the solution (Chowdhury, Hong et al.). In fact, when the flow velocity of resolution slows down, the convection and diffusion between MMNBC and the medium will be more significant, thus increasing the contact impact efficiency between the two and inhibiting the migration of MMNBC in the medium [35].

### 3.3 Effect of ionic strength on MMNBC migration in heterogeneous media

When the IS of MMNBC was 0.001 mol L\(^{-1}\) and 0.01 mol L\(^{-1}\), the migration rate was as follows: \( \text{QS} > \text{KCQS} > \text{ICQS} > \text{MCQS} \) (Figure 3 (a, b)), which indicates that MMNBC has the strongest transport capacity in pure QS. In addition, the migration state of QS is similar to that of KCQS, while ICQS and MCQS are similar. And

| Media                                      | Flow rate (ml min\(^{-1}\)) | \( K \min^{-1} \) | \( \text{Smax (mg/g)} \) | Recovery rate (%) | \( R^2 \) |
|--------------------------------------------|----------------------------|-------------------|-------------------------|------------------|--------|
| Pure quartz sand                           | 2                          | 0.0057            | 4.8112                  | 88.963           | 0.9909 |
| Pure quartz sand                           | 1                          | 0.0071            | 5.0404                  | 84.8889          | 0.9736 |
| Pure quartz sand                           | 0.5                        | 0.0114            | 5.9761                  | 76.8889          | 0.986  |
| Kaolin coated pure quartz sand             | 2                          | 0.0076            | 5.4438                  | 85.3333          | 0.9887 |
| Kaolin coated pure quartz sand             | 1                          | 0.0107            | 5.8322                  | 80.4444          | 0.9909 |
| Kaolin coated pure quartz sand             | 0.5                        | 0.0128            | 6.4933                  | 73.8519          | 0.9613 |
| Illite coated pure quartz sand             | 2                          | 0.0109            | 5.9053                  | 79.4815          | 0.9734 |
| Illite coated pure quartz sand             | 1                          | 0.0124            | 6.0402                  | 77.4074          | 0.9711 |
| Illite coated pure quartz sand             | 0.5                        | 0.0165            | 13.7715                 | 65.9259          | 0.9957 |
| Montmorillonite coated pure quartz sand   | 2                          | 0.0129            | 9.0431                  | 72               | 0.9853 |
| Montmorillonite coated pure quartz sand   | 1                          | 0.0134            | 13.9847                 | 66.2222          | 0.9478 |
| Montmorillonite coated pure quartz sand   | 0.5                        | 0.0139            | 14.8806                 | 62.6667          | 0.9844 |

**Figure 3.** Breakthrough and fitted curves of MMNBC in heterogeneous media at an ionic strength of 0.001 mol L\(^{-1}\)(a), 0.01 mol L\(^{-1}\) (b), 0.1 mol L\(^{-1}\)(c).
when IS is 0.01 mol L⁻¹, the migration state is more obvious. The transport curves of MCQS and ICQS are more similar to each other, based on the EDS spectra of heterogeneous media (Figure 1), possibly because they have the same energy curves, except that the surface elements are also the same, so the migration effect is similar on MMNBC. Compared with pure QS and KCQS, the surface of MCQS and ICQS contains the required metal ions and is relatively rougher. When MMNBC flowed through the sand column, these characteristics made MMNBC more likely to be adsorbed on the surface of gravel. On the other hand, it can be seen from Table 4 that under the same IS, pure QS had the least charge, while montmorillonite had the most charge, which manifests that the MCQS had more positive charge to absorb more MMNBC. With reference to the coating rate, the coating amount of montmorillonite on the QS is the highest, which may also explain the greater effect on the migration of MMNBC. However, in addition to the effect of coating amount, kaolinite itself also has some effect on BC migration, and therefore has a minor effect on MMNBC [20]. As far as montmorillonite colloid is concerned, when it IS is 0.1 mol L⁻¹, its zeta potential is −3.25 ± 0.7. At this time, the colloid rapidly coagulates or agglomerates, and when it IS drops to 0.01 mol L⁻¹, its ξ potential rises to −8.19 ± 0.2, and the colloid tends to be stable. When it IS is changed to 0.001 mol L⁻¹, its ξ potential is −14.42 ± 1.3, and the colloid becomes more stable. In the process of increasing IS, the potential charge of clay minerals makes it to release more colloidal coagulation MMNBC, which hinders the transportation of MMNBC, until IS = 0.01 mol L⁻¹, there is almost no MMNBC outflow.

The migration experiments of four heterogeneous media particles on MMNBC are carried out in MMNBC solutions with IS of 0.001 mol L⁻¹, 0.01 mol L⁻¹ and 0.1 mol L⁻¹, respectively (Figure 3). The best fitting values and fitting parameters (Smax and K) are also listed in Table 4. Under various IS intensities, there were great differences in Smax and K of MMNBC in the four media, which indicates that the media itself and IS have a great influence on migration. The one-dimensional mass equation has a high degree of fit, with R² not less than 0.961. The recovery rates of MMNBC and IS showed a negative correlation, as shown in Table 4. When IS is 0.001 mol L⁻¹, the migration amount IS greater than 0.01 mol L⁻¹, which IS significantly different from that of IS = 0.1 mol L⁻¹ (the four media particles basically prevent all MMNBC flow). The data showed that MMNBC can migrate in the heterogeneous media, and only a small portion of MMNBC remains between the surface and the pore of the heterogeneous media. The experiment also showed that when the IS value of MMNBC in heterogeneous media was less than 0.1 mol L⁻¹, the adsorption capacity of BC decreased with the increase of IS [36,37]. The reason is that the surface complexes are formed between surface substances of heterogeneous media and MMNBC when the IS of MMNBC exceeds 0.01 mol L⁻¹ [38], thus increasing the interception of MMNBC by the media. The negative charges on the surface of MMNBC reacted with the positive charges on the surface of the medium (Table 1) in an electrostatic manner to aggregate particles and thus increased the effective adsorption sites of the medium. In addition, the Zeta potential can be enhanced by increasing IS to reduce the thickness of the diffusion layer of the double electric layer. Conversely, if the repulsion energy (Zeta potential) is reduced to a certain extent, the particles were attracted and formed loose flocculates, preventing them flow out of the sand column. In addition, the dense hydrated crust formed by Na⁺ also prevented MMNBC from entering the soil colloidal surface.

| IS  | Media                      | k(min⁻¹) | Smax Recovery rate (mg g⁻¹) |
|-----|----------------------------|----------|-----------------------------|
| 0.001 | Pure quartz sand          | 0.0083 | 20.5879 |
| 0.01 | Pure quartz sand          | 0.0185 | 38.367 |
| 0.1  | Pure quartz sand          | /       | 43.8519 |
| 0.001 | Kaolin coated pure quartz sand | 0.0131 | 27.7572 |
| 0.1  | Kaolin coated pure quartz sand | 0.0187 | 40.1052 |
| 0.001 | Illite coated pure quartz sand | 0.0171 | 37.6525 |
| 0.1  | Illite coated pure quartz sand | 0.0221 | 54.5147 |
| 0.001 | montmorillonite coated pure quartz sand | 0.0195 | 42.812 |
| 0.01 | montmorillonite coated pure quartz sand | 0.026 | 58.0734 |
| 0.1  | montmorillonite coated pure quartz sand | /       | 7.6296 |

4. Conclusion

In summary, the results of column experiments indicated that IS, solution velocity and clay mineral colloids influence the migration behavior of MMNBC. The transport of MMNBC in heterogeneous media increased with the decrease of IS. Because the coating added cations on the surface of QS, it can generate electrostatic reaction with the negative charge of MMNBC. Moreover, the stability of clay mineral colloids plays a crucial role in the flow rate of MMNBC, and MCQS will maximize the obstruction of the migration of MMNBC, because there are more
metal ions on the surface. This is also consistent with the law of electrostatic reaction. The higher the absolute value of the potential, the easier it is for the modified QS to have electrostatic interaction with MMNDBC and hindered its migration. However, the environmental conditions in the laboratory are relatively simple. Instead, the reality is much more complicated and the BC’s movement will be affected by other factors. Therefore, the co-transport of MMNDBC and pollutants in heterogeneous media needs further study.

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Disclosure of potential conflicts of interest

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