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Novel functional materials with active adsorption and antimicrobial properties

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ABSTRACT

Certain materials can adsorb microbes but quickly become saturated, after which no further microbial adsorption can occur. Moreover, these adsorbed microbes will reproduce at a high rate and return to the environment. The application of adsorption and antibacterial materials represents a new development in air quality improvement. In this study, composite materials, which were prepared by adding an antibacterial material to an adsorbing material, performed the functions of both types of materials. The device based on the composite materials actively adsorbed and killed airborne microbes. This material will be helpful in the sterilization and improvement of the environment.

1. Introduction

In a poorly ventilated house that receives little sunlight, has an improper furniture arrangement, or is not cleaned well, the number of microbes in the form of microbial aerosols may increase greatly and cause pollution [1–3]. The occurrence of microbial aerosol pollution may weaken human immunity, leading to allergic asthma, respiratory infectious disease, or even death.

Antibacterial materials can kill nearly all airborne microbes but only when the microbes come into contact with the antibacterial material [4,5]. Adsorbing materials, e.g., red mud, have been applied for improving the air environment by trapping adsorbed microbes in their pores; however, these materials cannot kill the adsorbed microbes, which significantly limits their functionality [6,7]. A porous device based on red mud and an antibacterial material was fabricated. This device can adsorb and kill airborne microbes, effectively purifying indoor air.

2. Experimental details

Characterization of antibacterial red mud: The chemical composition of antibacterial red mud was characterized by X-ray diffraction (XRD). The XRD patterns were recorded using a Bruker D8 XRD instrument (Germany) with Ni-filtered Cu Kα radiation (λ=0.15418 nm) at an operation voltage of 40 kV with the current maintained at 40 mA for qualitative analysis.

Measurement of the adsorption rate: Un-acidified red mud, diatomite, zeolite, meerschaum, and montmorillonite were chosen as experiment samples. A total of 20 g of each material was placed into culture plates. The plates were hermetically packed with newspaper and autoclaved for half an hour at 121 °C. A portion of each sample (2 g) was directly placed on the substrates to test whether the powder samples had been completely sterilized. The other 18 g of each sample was placed on a piece of sterilized blank paper and three blank substrates were placed in the middle of the laboratory to adsorb airborne microbes. The three blank substrates were used to examine the quantity of deposited microbes. After 2 h, 2 g of each adsorbed sample was placed on the substrates. The colonies of all samples were obtained after the adsorbed samples and the blank substrates were incubated for 18 h at 37 °C and 60% humidity.

The adsorption rate was calculated based on the quantity of adsorbed microbes per square decimeter. The quantity of microbes that were actively adsorbed was calculated by subtracting the number of microbes on the blank substrate from the number of microbes on the surface of the adsorbed mineral powder. In addition, only those microbes that were adsorbed within the fringe of the powdered mineral were able to form colonies. The following formula was used:

$$AR = (CS/PC)^2 - (BC/DA) \quad (1)$$

where AR is the adsorption rate (cfu/dm^2), CS is the colony abundance of the surrounding powder (cfu), PC is the powder

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circumference (dm), BC is the colony abundance of the blank (cfu), and DA is the disk area (dm^2).

Preparation and testing of the device: A red mud sample and antibacterial zinc were mixed at a 10:1 proportion. The vesicant and dispersant were then added. The mixture was calcined for 3 h at 800 °C. After cooling to room temperature, the powdered mixture transformed into a porous functional device with a certain rigidity. The test of the removal of airborne microbes was as follows: (1) an unclosed one-cubic meter box was prepared, and the door of the box remained open for an hour to exchange the air with outside environment; (2) three blank substrates were placed into the box to adsorb the settling microbes for half an hour; (3) the functional device was placed in the box for 5 min, the device was removed and the quantity of microbes in the box was retested as in step 2; and (4) all of the blank substrates were placed into the culture incubator at 37 °C and 60% humidity for 18 h, and the number of cultured colonies was counted. The following formula for calculating the rate of microbe removal was used:

$$RR = [(BR - AR)/BR] \times (BV/AV) \quad (2)$$

where RR is the microbe removal rate (%), BR is the microbe quantity before removal (cfu/dm^2), AR is the microbe quantity after removal (cfu/dm^2), BV is the volume of the experimental box (dm^3), AV is the volume of adsorption device multiplied by one hundred (dm^3), and $BV/AV \leq 5$.

3. Results and discussion

Characterization of the antibacterial red mud: The presence of zinc sulfate in the antibacterial red mud is shown in Fig. 1. Micrographs of the antibacterial red mud obtained using scanning electron microscopy (SEM) indicated that the interspaces of the red mud were filled with large amounts of zinc sulfate.

Adsorption properties: The adsorption properties of the red mud, diatomite, zeolite, meerschaum, and montmorillonite were analyzed using different adsorption times. As shown in Fig. 2, the red mud gained demonstrated the highest level of adsorption at 400 cfu/dm^2 compared to the other samples. A photograph of the cultured microbes absorbed by the red mud is shown in Fig. 3.

The surface of cell wall is rich in hydroxyl, carbonyl, imidazolyl, and hydrosulfide groups [8–11]. These functional groups can react with red mud. Five widely accepted adsorption mechanisms regarding cell surfaces include complexation, ion exchange, static action, oxidation–reduction, and inorganic deposition [12–16]. It has been reported that the pH value can change the charge of cell and mineral surfaces. The changes can affect the physical force acting between cells and mineral surfaces and thus alter the adsorption effect of the mineral from a macroscopic perspective [17–20]. The experimental results were in accordance with these reports. The original red mud is an alkali material with a pH of 10.2 and has a strong ability to adsorb airborne microbes. However, the adsorption capacity was substantially lower when the red mud was transformed to an acidic material.

Property tests: The antibacterial effect of the device was tested using an oscillation method. The results showed that the antibacterial

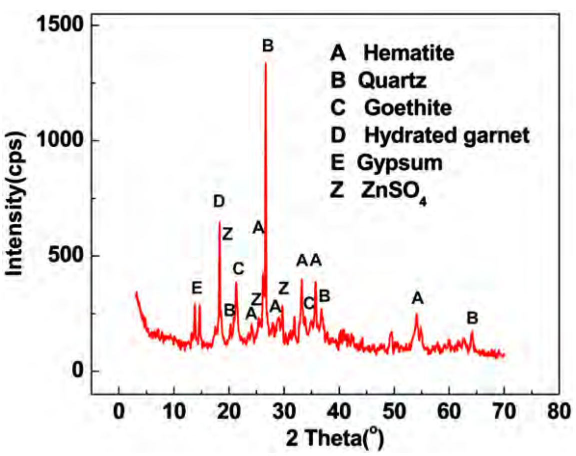

Fig. 1. XRD pattern of the antibacterial red mud.

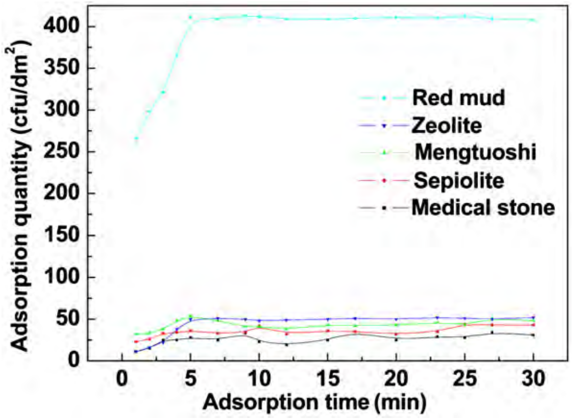

Fig. 2. A comparison of the adsorption capacities.

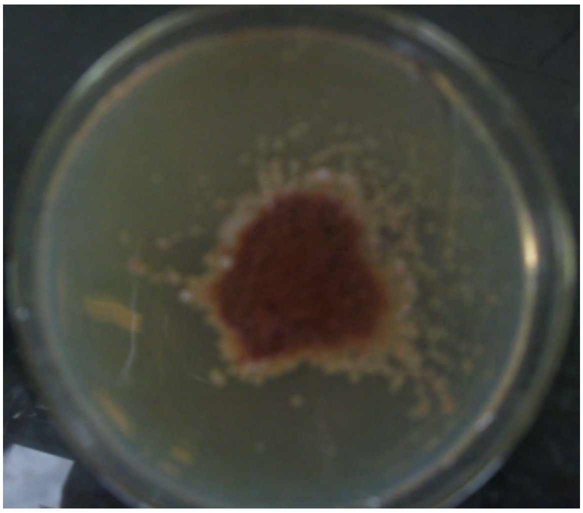

Fig. 3. Colonies of microbes adsorbed by the red mud.

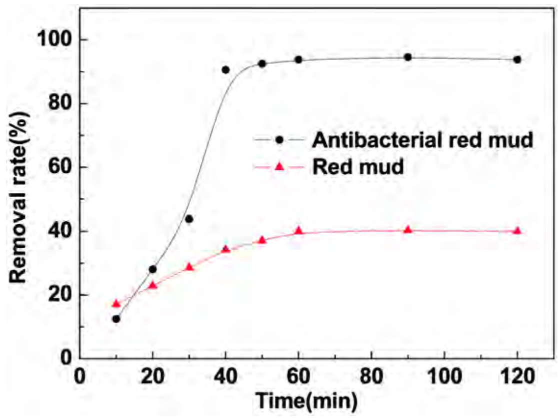

Fig. 4. Airborne microbe removal rates for the red mud and antibacterial red mud.

effect against *Staphylococcus aureus* and *Escherichia coli* was 99.0%; i.e., the device was capable of killing almost all of the *S. aureus* and *E. coli*. As shown in Fig. 4, the antibacterial red mud device killed greater than 90% of the microbes in 50 min, whereas only 38% were killed using red mud alone. The antibacterial red mud device could kill the continuously adsorbed microbes, whereas the red mud without the antimicrobial could not. The pores of the red mud will quickly become filled with adsorbed microbes, and these microbes will reproduce at a high rate. The produced microbes will slowly break away from the pores and return to the environment. In contrast, the antibacterial red mud can kill almost all of the adsorbed microbes and thus effectively reduce the quantity of microbes in the environment.

4. Conclusions

The results of this study indicated that red mud could actively adsorb microbes. The composite material of antibacterial red mud, fabricated by adding an antibacterial material to red mud, was used as the base for a porous device. This device was capable of adsorbing and killing airborne microbes, which demonstrated its potential use in air purification applications.

Acknowledgments

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