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Influence of bacteria–coal electrostatic interaction on coal cleaning

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ABSTRACT

Bacteria have been studied in bioflotation and bioflocculation processes for impurity removal. Electrostatic forces are important for adsorption of bacteria onto mineral surfaces. In the present study, three strains of bacteria: *Bacillus subtilis*, *Paenibacillus polymyxa* and *Mycobacterium phlei*, are used to emphasize the importance of bacteria–coal electrostatic interaction on coal cleaning. They differ in their point of zero-charge (PZC). Flotation experiments were conducted using each bacterium individually to reduce coal impurities. Although promising results were observed for all studied bacteria, *B. subtilis* was the best. By correlating the PZC of coal particles as well as the bacteria, it was found that the superiority of *B. subtilis* is related to wider PZC difference between the coal and *B. subtilis*.

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1. Introduction

Bioflotation and bioflocculation have been evaluated for mineral beneficiation (Deo and Natarajan, 1999; Elmahdy et al., 2009, 2011). The application of bio-beneficiation for desulfurization of coal in particular attracts special attention (El Zeky and Attia, 1987; Raichur et al., 1996; Townsley et al., 1987; Hosseini et al., 2005). Several strains of bacteria have been used for desulfurization (sulfur removal) and de-ashing (mineral matter removal) of coal (Demirbas and Balat, 2004; Sripriya et al., 2003; Attia et al., 1993).

The adsorption and adhesion of bacteria onto mineral and coal surfaces are controlled by several factors. Previous studies have indicated that the ionic strength, bacterial species and mineralogy are among those factors (Van Loosdrecht et al., 1989; Scholl et al., 1990; Scholl and Harvey, 1992; Mills and DeJesus, 1994). In addition, the electrostatic force besides van der Waal forces, hydrophobic interaction and hydrogen bonding play a crucial role for bacteria–mineral adsorption.

In the current study, the importance of electrostatic forces in the bacteria–coal interaction was studied by using three strains of bacteria. The main difference between these bacteria is the difference in their point of zero charge (PZC). In addition the application of each strain of bacteria to reduce the impurity level (either sulfur content or mineral matter (ash)) was tested. The effect of PZC difference on adsorption of bacteria on raw coal (as a mixture of coal, sulfur and ash) was characterized using adsorption kinetics, adsorption isotherm and flotation tests.

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2. Experimental

2.1. Materials

2.1.1. Coal sample

A 10 kg representative sample of El-Maghara coal was kindly supplied by the Sinai Coal Company, Egypt. The sample was chemically analyzed by standard analytical methods (Edwards et al., 1958). The coal sample was crushed and wet ground, using ball mill, to −325 mesh (−45 μm ASTM).

2.1.2. Bacteria

Bacteria were isolated from El-Maghara mine water. They were spread on nutrient agar plates and incubated at 30 °C for 7 days. Representatives of the various types of bacterial colonies were selected and purified. Bacterial strains were cultured and maintained in a medium having the following composition (prepared in 1 L): 5 g sodium chloride, 10 g beef extract and 10 g peptone at pH 7.2, or 5 g potassium di-hydrogen orthophosphate, 0.6 g magnesium sulfate, 2.5 g sodium citrate, 5 g asparigine and 20 ml glycerin at pH 7. Cultures were grown on a rotary shaker (100 rpm) for 14–16 h at 30 °C. A stock of bacterial solution was prepared, counted, then stored at 0–5 °C. Bacterial cells were counted in a Petroff–Hausser counting chamber under microscope after appropriate dilutions.

2.2. Methods

2.2.1. Electro-kinetic measurements

Zeta-potential was measured after agitation of 0.1 g of coal, −325 mesh (−45 μm ASTM) size, in a 100 cm^3 of 1×10^{-2} M KCl solution. The surface charge, as a function of pH, of each bacterium

Table 1
Chemical analysis of Maghara coal sample.

Constituent	%
Fixed carbon	40.25
Volatile matter	49.11
Mineral matter (ash)	6.65
Organic sulfur	1.2
Pyritic sulfur	1.5
Total sulfur	3.31

and coal was determined using a “Zeta-meter system 3 + unit”. A dilute suspension of coal, at required ionic strength, was prepared and pH was adjusted using KOH or HCl. The suspension was conditioned for 5 min for pH stabilization before zeta-potential was measured. The reported values are the average of 5 readings.

For bacteria, the harvested bacterial sample was re-suspended in KCl solution of proper strength (1×10^{-2} M). The pH was adjusted and allowed to equilibrate for 30 min after which the zeta readings were taken.

2.2.2. Adsorption kinetics and isotherm

Adhesion studies were conducted by mixing coal and bacteria (3% pulp density coal suspension in a bacterial suspension of predetermined cell count) in either distilled water or electrolyte solution. The effect of time, cell concentration and pH on the adsorption was studied. The bacteria cells were counted as an average of five readings to determine the residual concentration of bacteria. The adsorbed amount was calculated as the difference between initial and residual concentrations.

2.2.3. Coal flotation tests

The flotation experiments were conducted with each strain of bacteria as a flotation reagent, i.e., depressant for sulfur and ash minerals in a Denver flotation cell (D-12) of 1.0 L capacity at 1000 rpm. Tap water was used in all tests. Preconditioning of flotation feed, by shaking for desired time, was carried out by addition of 50 g of the ground coal to 200 cm^3 aliquot of adapted culture solution at desired pH.

3. Results and discussion

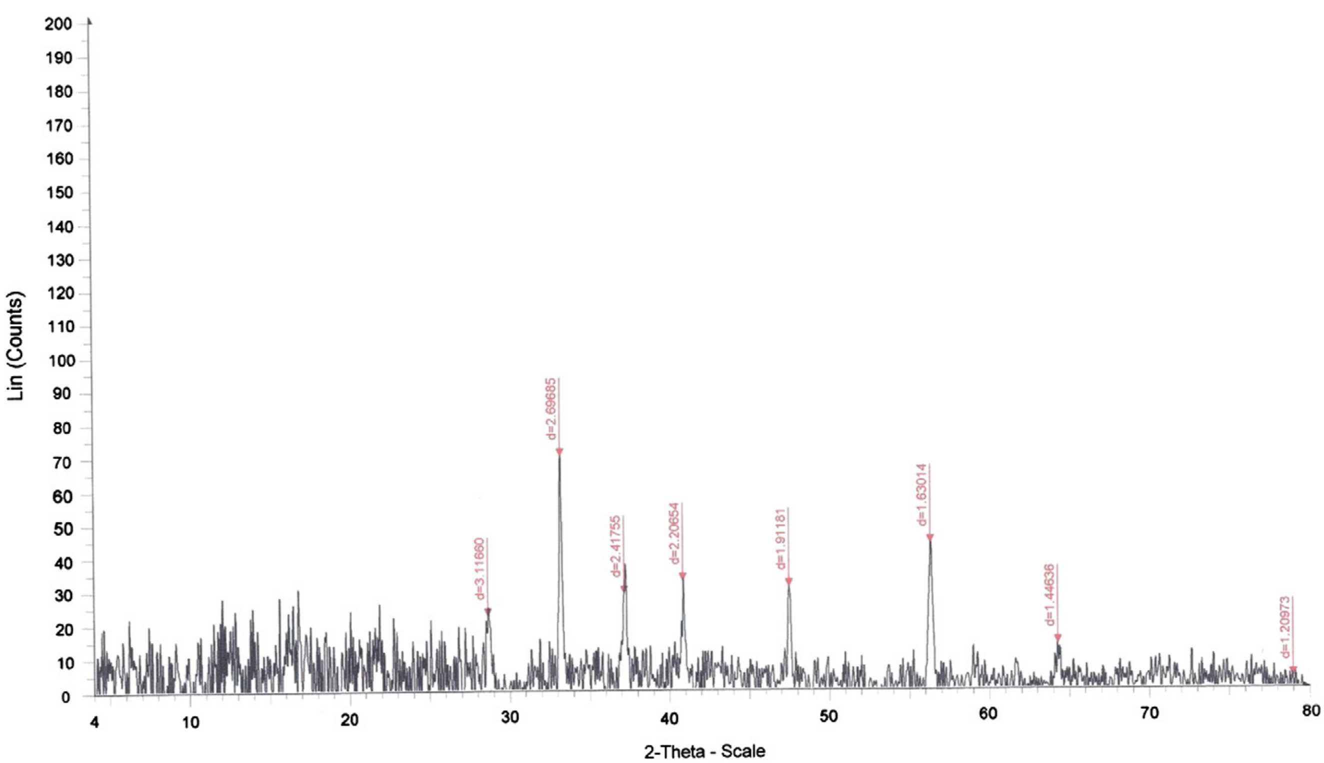
3.1. Sample characterization

El-Maghara coal sample was characterized by XRD and chemical analyses. Table 1 shows the main chemical components of the coal sample. It indicates that the coal sample is semi-bituminous coal due to its high volatile matter (49.1%) and fixed carbon (40.2%). In addition, the sample contains sulfur compounds as main harmful impurities where the total sulfur reaches 3.30%. On the other hand, the XRD pattern of the coal sample shows the presence of broad peaks of amorphous carbon between $2\theta = 8°$ and $2\theta = 28°$ besides the small peaks for quartz and hematite as the main associated mineral matters (ash), Fig. 1.

3.2. Electro-kinetic measurements

3.2.1. Coal and bacteria

Fig. 2 shows the zeta potential, as a function of pH, for *B. subtilis*, *P. polymyxa*, *M. phlei*, coal and coal–bacteria interactions. It is clear that the three strains of bacteria differ in their point of zero charge (PZC). In other words the PZC of coal particles, *B. subtilis*, *P. polymyxa* and *M. phlei* are located at pH 2.5, 4, 2.5 and 2.0, respectively. The zeta potential, for both coal and bacteria, becomes more negative with



d-spacing	3.116	2.696	2.417	2.206	1.911	1.630	1.446
Phase	Quartz, kaolinite	pyrite	pyrite	kaolinite	Pyrite, kaolinite	kaolinite	quartz

Fig. 1. X-ray diffraction of coal sample.

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