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Sulphate removal over barium-modified blast-furnace-slag geopolymer

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Abstract

Blast-furnace slag and metakaolin were geopolymerised, modified with barium or treated with a combination of these methods in order to obtain an efficient SO\textsubscript{4}\textsuperscript{2-} sorbent for mine water treatment. Of prepared materials, barium-modified blast-furnace slag geopolymer (Ba-BFS-GP) exhibited the highest SO\textsubscript{4}\textsuperscript{2-} maximum sorption capacity (up to 119 mg g\textsuperscript{-1}) and it compared also favourably to materials reported in the literature. Therefore, Ba-BFS-GP was selected for further studies and the factors affecting to the sorption efficiency were assessed. Several isotherms were applied to describe the experimental results of Ba-BFS-GP and the Sips model showed the best fit. Kinetic studies showed that the sorption process follows the pseudo-second-order kinetics. In the dynamic removal experiments with columns, total SO\textsubscript{4}\textsuperscript{2-} removal was observed initially when treating mine effluent. The novel modification method of geopolymer material proved to be technically suitable in achieving extremely low concentrations of SO\textsubscript{4}\textsuperscript{2-} (< 2 mg L\textsuperscript{-1}) in mine effluents.

Keywords: blast-furnace slag, metakaolin, geopolymer, adsorption, sulphate
1 Introduction

Sulphate (SO$_4^{2-}$) is a common anion in both natural water and industrial wastewater, such as acid mine drainage. Natural sources of SO$_4^{2-}$ include the chemical weathering of sulphur-containing minerals and the oxidation of sulphides and sulphur [1–3]. SO$_4^{2-}$ is non-toxic, and sulphur is a necessary mineral for several organisms. However, high concentrations of SO$_4^{2-}$ in aqueous environments can cause the mineralisation of water, corrosion of reinforced steel, scaling of equipment and damage to mammals as well as endangering human health [1–4]. Under anaerobic conditions, SO$_4^{2-}$ can be reduced to hydrogen sulphide (H$_2$S) by sulphate-reducing bacteria. H$_2$S is dangerous to environmental ecosystems due to its reactivity, toxicity and corrosivity [1, 4].

In Finland, the SO$_4^{2-}$ limit in drinking water is set at 250 mg L$^{-1}$. However, the recommended maximum concentration is even lower (150 mg L$^{-1}$) to ensure that water pipes are not damaged [5]. Environmental agencies in many countries have set the maximum SO$_4^{2-}$ concentration between 250 and 500 mg L$^{-1}$ for both mine drainage and industrial effluents [2, 6]. When there is no established limit for SO$_4^{2-}$, limits for total dissolved solids (TDS) are usually defined, which means that SO$_4^{2-}$ concentrations must comply with the TDS values [7]. In many countries, increasingly strict legislation has been introduced to control water pollution, so there is a need for effective SO$_4^{2-}$ removal technologies.

The processes for SO$_4^{2-}$ removal from wastewater include biological treatment with sulphate-reducing bacteria, membrane filtration (e.g. reverse osmosis), adsorption and/or ion exchange and chemical precipitation as gypsum, barium sulphate or ettringite. However, these methods suffer from limitations. For example, precipitation produces a large amount of potentially toxic sludge. Low concentrations (approx. 1200 to 2000 mg L$^{-1}$) cannot be removed by lime precipitation because of the solubility of the CaSO$_4$ that is produced [2, 8, 9]. In addition, biological treatment and ion exchange are costly [2, 3, 10, 11]. An adsorption system has the potential to be used in a so-called hybrid-system with precipitation, in which the remaining sulphate concentrations after the precipitation process could be removed via adsorption.

Adsorption may be preferred for SO$_4^{2-}$ removal due to its simplicity, effectiveness and low cost [11, 12]. Suggested sorbents have included, for example, activated carbon [13], fly ash [14], limestone
[2, 15], minerals [3, 16–19], modified coir pith [6], modified rice straw [1], modified zeolites [20, 21], nano-alumina [22], soils [23–25] and waste materials [15].

Geopolymers are amorphous or partly crystalline inorganic polymers with a three-dimensional negatively charged framework structure, which is similar to zeolite [26–31]. They can be prepared at ambient or slightly elevated temperatures by the hydrothermal conversion of a solid aluminosilicate material, e.g. metakaolin [30, 32, 33], blast-furnace slag [34] or fly ash [29, 35–38] with an alkali hydroxide and/or silicate solution. In this study, blast-furnace slag (BFS) and metakaolin (MK) were used as a raw material for geopolymerisation. BFS is a residue product of smelting iron ore in a blast furnace and MK is a dehydroxylated form of the naturally occurring clay mineral kaolinite. BFS and MK are good raw material candidates for preparing geopolymers due to their abundance and easy availability [33, 34, 39, 40].

The series of geochemical reactions that comprise this process are not exactly known, but it has been suggested that they include mineral dissolution, aluminosilicate polycondensation and structural re-organisation [28, 29, 41–43]. Geopolymers possess permanent negative charges on Al on their structure that are balanced by exchangeable cations (e.g. Na⁺, K⁺, Li⁺, Ba²⁺) [43]. They have a high cation exchange capacity, which has been applied for the removal of metal(loids) [32, 33, 35, 38, 44, 45], dyes [29] and ammonium [46], but there are no studies on SO₄²⁻ removal to our knowledge. Because geopolymers have a low affinity for anions, a chemical modification is needed to apply a sorbent for anionic SO₄²⁻ removal. In literature, it has been reported that the chemical modification with inorganic salts such as NaCl, CaCl₂, BaCl₂ or FeCl₃ improves properties of zeolites and increase its efficiency in water treatment [47–49]. In the present study, a similar approach was applied for geopolymer modification. In the case of anion removal, the modification has been reported to for example create an oxi-hydroxide adsorption layer on the surface and change the surface charge (from negative to positive) [49, 50]. These changes allow to form stable complexes with anions in solution. In the present study, the BaCl₂ modification was expected to impregnate Ba in the framework structure of geopolymers and subsequently enable the surface precipitation or complexation of sulphate.

In this study, the effects of geopolymerisation, barium modification and a combined treatment on metakaolin (MK) and blast-furnace slag (BFS) were studied in order to develop an efficient SO₄²⁻.
sorbent for mine effluent. Comparative experiments were first performed for synthetic water (model solution). The influence of initial pH, initial SO$_4^{2-}$ concentration, sorbent dosage, contact time and temperature was studied. In addition, adsorption isotherms, kinetics and thermodynamic parameters were studied. Column studies were also performed for the most promising sorbent material: barium-modified BFS geopolymer (Ba-BFS-GP).

2 Experimental

2.1 Materials

BFS and MK were obtained from Finnish suppliers. Technical grade sodium hydroxide (VWR International) and sodium silicate (VWR International, SiO$_2$:Na$_2$O = 3.1–3.4) were used for the synthesis of geopolymers. NaCl and BaCl$_2$ were used in chemical modifications. A stock solution of SO$_4^{2-}$ was prepared by dissolving Na$_2$SO$_4$ (VWR 99.9%) in ultrapure water and further diluted to concentrations required for the experiments. The pH of the solution was adjusted through the addition of HCl and/or NaOH (FF-Chemicals).

A mine effluent (settled drainage water treated with ferric sulphate) sample was obtained from an underground gold mine and it was characterized earlier [44].

2.2 Geopolymerisation

An alkaline solution containing 10 M NaOH and sodium silicate (SiO$_2$:Na$_2$O = 3.1–3.4) in a weight ratio of 1:1 was prepared 24 h before use. BFS or MK was mixed with the alkaline solution in a weight ratio of 3:2 or 1.3:1, respectively. The mixtures were mixed for 15 minutes, vibrated for 2 minutes and allowed to consolidate for 3 days at room temperature. The resulting solid material was crushed to a particle size of 63–125 µm or 0.5–1 mm for batch (equilibrium) and dynamic (non-equilibrium) experiments, respectively. Materials were washed with ultrapure water, dried at 105 °C and stored in a desiccator.
2.3 Chemical modification

The materials (5 g) were mixed with 1 M NaCl solution (50 mL) for 24 h, filtered, rinsed with deionised water and dried at 105 °C to ensure that all the ion exchange sites were in the Na form. Barium modification was conducted by mixing the material (5 g) in a 1 M BaCl₂ solution (100 mL) for 16 h, filtering, rinsing with deionised water and drying at 105 °C. The materials were ground and stored in a desiccator before use.

2.4 Characterisation of the sorbent

The specific surface area, total pore volume and average pore size were determined from nitrogen adsorption–desorption isotherms at the temperature of liquid nitrogen (-196 °C) using a Micromeritics ASAP 2020 instrument. The X-ray diffraction (XRD) patterns of materials were obtained using a PanAnalytical Xpert Pro diffractometer, and chemical compositions were determined using a PanAnalytical Minipal 4 X-ray fluorescence (XRF) spectrometer. Fourier Transform Infrared Spectroscopy (FTIR) spectra of the sorbent were collected using a Perkin Elmer Spectrum One spectrometer.

2.5 Batch sorption experiments

In the batch sorption experiments the system was allowed to reach the sorption equilibrium. The screening of potential sorbents Ba-modified metakaolin (Ba-MK), Ba-modified metakaolin geopolymer (Ba-MK-GP), Ba-modified blast-furnace slag (Ba-BFS) and Ba-modified blast-furnace-slag geopolymer (Ba-BFS-GP) was performed at different initial pH values in mine effluent. Initial pH was adjusted by using HCl and/or NaOH. Ba-BFS-GP was selected for further experiments: the effects of initial SO₄²⁻ concentration, sorbent dosage, temperature and contact time were studied. The studied parameters are shown in Table 1. Samples were filtrated through 0.45 μm filter paper (Sartorius Stedim Biotech) or separated using a centrifuge. SO₄²⁻ concentration was determined in the filtrate solution via ion
chromatography (Metrohm 761 Compact IC) or a flow injection analysis system (Foss-Tecator Fiastar 5000).

All experiments were run as duplicates, except experiments with mine effluent. The sorption experiments were performed in acid-washed vessels to minimize contamination.

Table 1. Parameters for testing the effects of initial pH, initial SO\(_4^{2-}\) concentration, sorbent dosage, contact time and temperature on SO\(_4^{2-}\) removal efficiency.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial pH of solution</th>
<th>Initial SO(_4^{2-}) concentration [mg L(^{-1})]</th>
<th>Sorbent dosage [g L(^{-1})]</th>
<th>Contact time</th>
<th>Temperature [°C]</th>
<th>Sorbent</th>
<th>Water matrix</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect of initial pH</td>
<td>4, 6, 8, 10</td>
<td>850–870</td>
<td>5</td>
<td>24 h</td>
<td>22</td>
<td>Ba-MK, Ba-BFS, Ba-MK-GP, Ba-BFS-GP</td>
<td>Mine effluent*</td>
</tr>
<tr>
<td>Effect of initial SO(_4^{2-}) concentration</td>
<td>7–8</td>
<td>50–1000</td>
<td>5</td>
<td>24 h</td>
<td>22</td>
<td>Ba-BFS-GP</td>
<td>Synthetic</td>
</tr>
<tr>
<td>Effect of sorbent dosage</td>
<td>7–8</td>
<td>1200</td>
<td>0.5–15</td>
<td>24 h</td>
<td>10, 22, 40</td>
<td>Ba-BFS-GP</td>
<td>Synthetic</td>
</tr>
<tr>
<td></td>
<td>7–8</td>
<td>865</td>
<td>0.5–25</td>
<td>24 h</td>
<td>22</td>
<td>Ba-BFS-GP</td>
<td>Mine effluent*</td>
</tr>
<tr>
<td>Effect of contact time</td>
<td>7–8</td>
<td>1100</td>
<td>5</td>
<td>1 min – 24 h</td>
<td>22</td>
<td>Ba-BFS-GP</td>
<td>Synthetic</td>
</tr>
<tr>
<td></td>
<td>7–8</td>
<td>853</td>
<td>5</td>
<td>1 min – 24 h</td>
<td>22</td>
<td>Ba-BFS-GP</td>
<td>Mine effluent*</td>
</tr>
</tbody>
</table>

*There was a minor variation (850–870 mg L\(^{-1}\)) between the concentrations of different water samples.

2.6 Dynamic sorption experiments

In the dynamic experiments, the sorption was performed in the non-equilibrium state. The experiments were performed using a plastic column (diameter 44.0 mm, height 98.8 mm, volume 0.15 L), which was loaded with 30.45 g of Ba-BFS-GP with a particle size of 0.5–1 mm. The sorbent bed height was 2.0 cm with a bed volume of 30.41 cm\(^3\). Mine effluent with 820 mg L\(^{-1}\) SO\(_4^{2-}\) was pumped through the column by a peristaltic pump. The flow of effluent was adjusted to 0.24 or 0.85 L h\(^{-1}\), corresponding to 7.60 and 2.15 min empty bed contact time, respectively. Samples were taken from the outlet of the column at different time intervals.
2.7 Barium leaching test

To evaluate the stability of impregnated barium in Ba-BFS-GP, 0.125 g of material was added to 25 mL mine effluent and shaken 24 h. Barium leaching experiments were also performed with distilled water by weighing 0.005 or 0.125 g of Ba-BFS-GP to 10 mL or 25 mL of distilled water, respectively. Samples were filtered through 0.45 μm filter paper, and the barium concentration was analysed using inductively coupled plasma emission spectrometers (Thermo Electron IRIS Intrepid II XDL Duo or PerkinElmer Optima 5300 DV ICP-OES instrument) according to the SFS-EN ISO 11885 standard.

2.8 Adsorption isotherms

Bi-Langmuir [51], Sips [52], Redlich–Peterson (R–P) [53] and Toth [54] isotherms are presented in Equations 1–4, respectively. Isotherm parameters were obtained using nonlinear regression with the Microsoft Excel solver tool (GRG nonlinear).

\[ q_e = \frac{q_{m1} b_{L1} c_e}{1 + b_{L1} c_e} + \frac{q_{m2} b_{L2} c_e}{1 + b_{L2} c_e}, \]  

(1)

where \( q_{m1} \) and \( q_{m2} \) are the maximum adsorption capacities (mg g\(^{-1}\)) of two different adsorption sites. Similarly, \( b_{L1} \) and \( b_{L2} \) represent the energies (mg g\(^{-1}\)) of adsorption at these sites.

\[ q_e = \frac{q_m (b_s c_e)^n_s}{1 + (b_s c_e)^n_s}, \]  

(2)

where \( b_s \) (L mg\(^{-1}\)) is a constant related to the adsorption energy and \( n_s \) is a dimensionless constant characterising the heterogeneity of the system.

\[ q_e = \frac{K_R c_e}{1 + a_R c_e^p}, \]  

(3)
where $K_R$ (dm$^3$ g$^{-1}$) and $a_R$ (dm$^3$ mg$^{-1}$) are R–P isotherm constants and $\beta$ is an exponent, the value of which lies between 0 and 1.

$$q_e = \frac{q_{Th} K_{Th} C_e}{1 + (K_{Th} C_e)^{Th}},$$

(4)

where $q_m$ (mg g$^{-1}$) is the monolayer adsorptive uptake, $K_{Th}$ (L mg$^{-1}$) is the Toth isotherm constant and $Th$ is the dimensionless Toth isotherm exponent, which characterises the heterogeneity of the system.

The residual root mean square error (RMSE) and chi-square test ($\chi^2$) were used to assess the error:

$$\text{RMSE} = \sqrt{\frac{1}{n-p} \sum_{i=1}^{n} (q_{e\text{exp}} - q_{e\text{calc}})^2},$$

(5)

$$\chi^2 = \frac{\sum_{n=1}^{n} (q_{e\text{exp}} - q_{e\text{calc}})^2}{q_{e\text{calc}}},$$

(6)

where $n$ is the number of experimental data, $p$ is the number of parameters whilst $q_{e\text{exp}}$ and $q_{e\text{calc}}$ are experimental and calculated values of adsorption capacity in equilibrium.

### 2.9 Kinetic modelling

The kinetics of the adsorption processes were studied using the pseudo-first-order [55], the pseudo-second-order [56] and the Elovich [57] kinetic models:

$$\log (q_e - q_t) = \log q_e - \frac{k_f}{2.303} t,$$

(7)

$$\frac{t}{q_t} = \frac{1}{k_s q_e} + \frac{1}{q_e} t,$$

(8)
\[ q = \frac{1}{\beta} \ln \left( u_0 \beta + \frac{1}{\beta} \ln t \right), \]  

where \( q_e \) and \( q_t \) are the amounts of \( \text{SO}_4^{2-} \) sorbed (mg g\(^{-1}\)) at equilibrium and at time \( t \) (min), respectively. \( k_f \) (min\(^{-1}\)), \( k_s \) (g mg\(^{-1}\) min\(^{-1}\)) and \( u_0 \) (mg g\(^{-1}\) min\(^{-1}\)) are the pseudo-first-order, pseudo-second-order and Elovich rate constants, respectively. The Elovich parameter \( \beta \) (g mg\(^{-1}\)) is related to the extent of surface coverage and activation energy for chemisorption.

The diffusion mechanism was analysed using the intraparticle diffusion model [58]:

\[ q_t = k_{id} t^{1/2} + C, \]  

where \( k_{id} \) (mg g\(^{-1}\)min\(^{-1/2}\)) is the intraparticle diffusion on the rate determining step and \( C \) is the intercept related to the thickness of the boundary layer.

### 2.10 Sorption thermodynamics

The change in free energy (\( \Delta G \)), enthalpy (\( \Delta H \)) and entropy (\( \Delta S \)) were determined to describe the sorption of \( \text{SO}_4^{2-} \):

\[ \Delta G = -RT \ln (K_c), \]  

\[ K_c = \frac{q}{c_e}, \]  

\[ \ln K = \frac{\Delta S}{R} - \frac{\Delta H}{RT}, \]  

where, \( R \) is the universal gas constant (8.314 J mol\(^{-1}\) K\(^{-1}\)), \( T \) is the temperature (K), and \( K_c \) is the equilibrium constant.


3 Results and discussion

3.1 Sorbent characterisation

Specific surface area, average pore size and volumes (Table 2) of MK increase as a result of geopolymerisation. However, with BFS, the surface area and pore volumes increase whereas pore size decreases during geopolymerisation. Barium modification has no significant effect on surface area, pore sizes and volumes of geopolymerised BFS.

Table 2. Specific surface areas, pore sizes and volumes of sorbents.

<table>
<thead>
<tr>
<th>Sorbent</th>
<th>Specific surface area [m² g⁻¹]</th>
<th>Average pore size [nm]</th>
<th>V_{macro+meso} [cm³ g⁻¹]</th>
<th>V_{micro} [cm³ g⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MK</td>
<td>11.5</td>
<td>18.2</td>
<td>0.047</td>
<td>0.005</td>
</tr>
<tr>
<td>MK-GP</td>
<td>22.4</td>
<td>31.0</td>
<td>0.165</td>
<td>0.008</td>
</tr>
<tr>
<td>BFS</td>
<td>2.79</td>
<td>12.7</td>
<td>0.008</td>
<td>0.001</td>
</tr>
<tr>
<td>BFS-GP</td>
<td>64.5</td>
<td>5.93</td>
<td>0.070</td>
<td>0.025</td>
</tr>
<tr>
<td>BFS-GP-Ba</td>
<td>63.1</td>
<td>6.32</td>
<td>0.070</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Macropore: d₀ > 50 nm, Mesopore: 2 nm ≤ d₀ ≤ 50 nm, Micropore: d₀ ≤ 2 nm.

Table 3 shows the chemical composition of BFS, BFS-GP and Ba-BFS-GP. The main components of BFS are calcium, silicon, magnesium, aluminium and sulphur. In addition, sorbents included some other impurities. Aluminium and silicon contents decrease while Na content increases after geopolymerisation. In addition, the loss on ignition (L.O.I.) increases due to the increased water content. The decrease of CaO as BFS is converted into BFS-GP is possibly due to the dissolution of gehlenite and other phases [27]. In Ba-BFS-GP, Na ions are completely replaced by Ba, as signified by corresponding concentrations.

Table 3. Main chemical constituents as determined by XRF.

<table>
<thead>
<tr>
<th>Composition</th>
<th>BFS [w/w%]</th>
<th>BFS-GP [w/w%]</th>
<th>Ba-BFS-GP [w/w%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>38.5</td>
<td>29.9</td>
<td>26.3</td>
</tr>
<tr>
<td>SiO₂</td>
<td>27.2</td>
<td>25.8</td>
<td>26.8</td>
</tr>
<tr>
<td>MgO</td>
<td>9.4</td>
<td>6.4</td>
<td>7.1</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>8.4</td>
<td>5.9</td>
<td>6.7</td>
</tr>
<tr>
<td>SO₃</td>
<td>3.8</td>
<td>2.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>
The XRD patterns (Fig. 1) of BFS, BFS-GP, and Ba-BFS-GP indicate initially a completely X-ray amorphous structure, formation of hydrotalcite (Mg₆Al₂CO₃(OH)₁₆·4(H₂O)) and haturite (Ca₃SiO₅) after geopolymerisation and further formation of witherite (BaCO₃) after Ba-modification.

**Figure 1.** XRD patterns of blast-furnace slag (BFS), blast-furnace-slag geopolymer (BFS-GP) and barium-modified blast-furnace-slag geopolymer (Ba-BFS-GP) samples. HT = hydrotalcite, HAT = haturite, W = witherite.

FTIR spectra for BFS, BFS-GP and Ba-BFS-GP are shown in Fig. 2. The peak in the spectra of Ba-BFS-GP at 856 cm⁻¹ is related to the witherite (BaCO₃) vibration. The bands in the spectra of BFS, Ba-BFS and Ba-BFS-GP appearing at 960, 942, 894 cm⁻¹, respectively, belong to Si-O stretching vibrations [59]. The bands at 1471 and 1391 cm⁻¹ are associated with carbonate vibration in the structure of Ba-BFS-GP and Ba-BFS [26]. Carbon dioxide shows a strong band in the area of 2350 cm⁻¹, and thus the band in Ba-BFS-GP could be related to adsorbed carbon dioxide [60, 61].

**Figure 2.** The FTIR spectra of blast-furnace slag (BFS), barium-modified blast-furnace-slag (Ba-BFS) and barium-modified blast-furnace-slag geopolymer (Ba-BFS-GP).

### 3.2 Effect of initial pH and screening of sorbents

The effect of initial pH on the removal of SO₄²⁻ from mine effluent over BFS-GP, Ba-BFS-GP, Ba-MK and Ba-MK-GP is shown in Fig. 3. Sorption efficiency decreases slightly as the initial pH increases from 4 to 10. This may be due to the competition for the sorption sites by OH⁻ ions at high pH [22, 62]. Ba-BFS-

<table>
<thead>
<tr>
<th></th>
<th>Na₂O</th>
<th></th>
<th>Ba</th>
<th></th>
<th>Other*</th>
<th></th>
<th>L.O.I.</th>
<th></th>
<th>Sum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.3</td>
<td></td>
<td>8.0</td>
<td></td>
<td>0.0</td>
<td></td>
<td>2.9</td>
<td></td>
<td>90.9</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td></td>
<td>0.0</td>
<td></td>
<td>2.4</td>
<td></td>
<td>12.9</td>
<td></td>
<td>93.9</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td></td>
<td>17.3</td>
<td></td>
<td>0.0</td>
<td></td>
<td>0.0</td>
<td></td>
<td>99.4</td>
</tr>
</tbody>
</table>

*Including Ti, Fe₂O₃, K₂O, Mn.
GP is the most effective sorbent material and it was selected for further study. Sorption efficiency is c.a. 50% at pH range 4–10.

**Figure 3.** Total SO$_4^{2-}$ removal percent (left, solid lines) and total adsorbed amount (right, dashed lines) versus initial pH on the sorption of SO$_4^{2-}$ from mine effluent. Sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C, adsorbate: mine effluent ($C_0$, SO$_4^{2-}$: ~850–870 mg L$^{-1}$).

### 3.3 Effect of initial SO$_4^{2-}$ concentration

The effect of initial SO$_4^{2-}$ concentration was investigated with model solutions in the range of 100–1800 mg L$^{-1}$. The results are presented in Fig. 4. The SO$_4^{2-}$ sorption capacity of Ba-BFS-GP increases as the SO$_4^{2-}$ concentration is increased and reaches a maximum value (90 mg g$^{-1}$) at about 1200 mg L$^{-1}$.

The initial sharp rise of sorption capacity in Fig. 4 indicates that sorption sites are readily available and the surface becomes saturated as the curve levels off [22, 62].

**Figure 4.** Effect of the initial concentration on the sorption of SO$_4^{2-}$ on Ba-BFS-GP from model solution. Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C.

### 3.4 Effect of sorbent dosage and temperature

The effect of Ba-BFS-GP dosage on the removal of SO$_4^{2-}$ from model solution and mine effluent are shown in Fig. 5. In both cases the percentage of SO$_4^{2-}$ removal increases with the increasing sorbent dosage and reaches a saturation level at high doses. This phenomenon could be explained by the increase in surface area and the available sorption sites with an increase in the sorbent dosage [63–65]. The sorbent reached maximum removal of SO$_4^{2-}$ at dose 10 g L$^{-1}$ of sorbent, probably due to the of mass transfer resistance of SO$_4^{2-}$ from bulk liquid to the surface of the solid, which becomes important at high sorbent loading. In addition, at 40 °C the percentage of SO$_4^{2-}$ removal was decreased slightly with the higher dosage (> 10 g L$^{-1}$). The higher sorbent dosage results in interference or repulsive forces between binding sites and formation of particle aggregates,
decreasing the interaction of SO\(_4^{2-}\) with the sorbent and reducing the total surface area of the sorbent [10, 22, 63–66]. Maximum removal efficiencies with model solution and sorbent dosage 10 g L\(^{-1}\) were 68% (51.98 mg g\(^{-1}\)), 60% (59.67 mg g\(^{-1}\)) and 55% (51.98 mg g\(^{-1}\)) at 10, 23 and 40 °C, respectively. In the case of mine effluent, maximum sorption efficiency was 100% (85.69 mg g\(^{-1}\)) at 23 °C. The better removal efficiency of SO\(_4^{2-}\) in mine effluent compared to model solution could be explained by different initial concentrations and partially by the presence of sodium: sodium hinders SO\(_4^{2-}\) removal via the formation of aqueous sodium sulphate complex. The effect of sodium was calculated by MineQL software [67] to account for approximately 10% of the lower removal efficiency.

The sorption capacity (\(q, \text{mg g}^{-1}\)) increases as temperature is increased (Fig. 5). This indicates that the sorption is an endothermic process in nature. An increase in temperature from 10 °C to 23 °C has a larger effect on sorption capacity than a further increase from 23 °C to 40 °C.

**Figure 5.** Effect of Ba-BFS-GP dosage on SO\(_4^{2-}\) removal. a) Model solution: \(C_0(\text{SO}_4^{2-}): \sim 1200 \text{ mg L}^{-1}\), contact time: 3 h. b) Mine effluent: \(C_0(\text{SO}_4^{2-}): 865 \text{ mg L}^{-1}\), contact time: 24 h. In both cases initial pH was 7–8.

### 3.5 Adsorption isotherms

Bi-Langmuir, Sips, R–P and Toth isotherm models were applied for the experimental results of Ba-BFS-GP (Fig. 6 and Table 4). Comparison of the results for the errors (RMSE, \(X^2\)) and correlation coefficients (\(R^2\)) indicated that the SO\(_4^{2-}\) sorption onto Ba-BFS-GP from model solution can be best represented by the Sips isotherm. Maximum experimental (\(q_{m,\text{exp}}\)) and theoretical (\(q_{m,\text{calc}}\)) sorption capacities are quite similar. In the case of mine effluent, all studied isotherm models gave practically similar correlation coefficient values (\(R^2: 0.920–0.930\)) and errors.

**Figure 6.** Bi-Langmuir, Sips, Redlich-Peterson and Toth isotherms of SO\(_4^{2-}\) sorption on Ba-BFS-GP. a) Model solution: \(C_0(\text{SO}_4^{2-}): 100–1800 \text{ mg L}^{-1}\), sorbent dose: 5 g L\(^{-1}\). b) Mine effluent: \(C_0(\text{SO}_4^{2-}): 865 \text{ mg L}^{-1}\), sorbent dose: 1.3–15 g L\(^{-1}\). Initial pH was 7–8, contact time 24 h and temperature 22–23 °C.
Table 4. Isotherm parameters and errors for the sorption of SO$_4^{2-}$ removal on Ba-BFS-GP.

<table>
<thead>
<tr>
<th>Isotherm</th>
<th>Constant (unit)</th>
<th>Model solution$^a$</th>
<th>Mine effluent$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
<td>$q_m$ (mg g$^{-1}$)</td>
<td>91.1</td>
<td>119.0</td>
</tr>
<tr>
<td>Bi-Langmuir</td>
<td>$q_{m1}$ (mg g$^{-1}$)</td>
<td>42.109</td>
<td>55.290</td>
</tr>
<tr>
<td></td>
<td>$b_{11}$ (L mg$^{-1}$)</td>
<td>0.463</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>$q_{m2}$ (mg g$^{-1}$)</td>
<td>42.109</td>
<td>55.290</td>
</tr>
<tr>
<td></td>
<td>$b_{12}$ (L mg$^{-1}$)</td>
<td>0.463</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.926</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>8.737</td>
<td>10.452</td>
</tr>
<tr>
<td></td>
<td>$X^2$</td>
<td>3.810</td>
<td>7.501</td>
</tr>
<tr>
<td>Sips</td>
<td>$q_{sm}$ (mg g$^{-1}$)</td>
<td>83.691</td>
<td>110.580</td>
</tr>
<tr>
<td></td>
<td>$b_s$ (L mg$^{-1}$)</td>
<td>0.482</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>$n_s$</td>
<td>2.102</td>
<td>1.000</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.951</td>
<td>0.920</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>6.174</td>
<td>9.541</td>
</tr>
<tr>
<td></td>
<td>$X^2$</td>
<td>1.822</td>
<td>7.501</td>
</tr>
<tr>
<td>Redlich-Peterson (R–P)</td>
<td>$K_R$ (dm$^3$ g$^{-1}$)</td>
<td>48.978</td>
<td>57.107</td>
</tr>
<tr>
<td></td>
<td>$a_R$ (dm$^3$ mg$^{-1}$)</td>
<td>0.734</td>
<td>0.650</td>
</tr>
<tr>
<td></td>
<td>$\beta$</td>
<td>0.964</td>
<td>0.963</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.931</td>
<td>0.929</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>7.318</td>
<td>8.945</td>
</tr>
<tr>
<td></td>
<td>$X^2$</td>
<td>3.990</td>
<td>7.714</td>
</tr>
<tr>
<td>Toth</td>
<td>$q_{th}$ (mg g$^{-1}$)</td>
<td>64.937</td>
<td>85.863</td>
</tr>
<tr>
<td></td>
<td>$K_{th}$ (mg dm$^3$)</td>
<td>1.391</td>
<td>1.593</td>
</tr>
<tr>
<td></td>
<td>$T_h$</td>
<td>1.042</td>
<td>1.043</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.932</td>
<td>0.930</td>
</tr>
<tr>
<td></td>
<td>RMSE</td>
<td>7.257</td>
<td>8.870</td>
</tr>
<tr>
<td></td>
<td>$X^2$</td>
<td>3.943</td>
<td>7.071</td>
</tr>
</tbody>
</table>

$^a$ Model solution: Initial pH: 7–8, C$_0$(SO$_4^{2-}$): 100–1800 mg L$^{-1}$, m(Ba-BFS-GP): 5 g L$^{-1}$.

$^b$ Mine effluent: Initial pH: 7–8, C$_0$(SO$_4^{2-}$): 865 mg L$^{-1}$, m(Ba-BFS-GP): 1.3–15 g L$^{-1}$.

Contact time: 24 h and temperature 22–23 °C.

The sorbents produced were compared with other materials (Table 5). The Ba-BFS-GP shows a higher or comparable sorption capacity to other similar anion sorbents.
Table 5. Comparison of adsorption capacity $q_m$ (mg g$^{-1}$) of various sorbents for the removal of SO$_4^{2-}$ from aqueous phase.

<table>
<thead>
<tr>
<th>Sorbent</th>
<th>Capacity $q$ (mg g$^{-1}$)</th>
<th>pH</th>
<th>Concentration (mg L$^{-1}$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coir pith carbon</td>
<td>0.06*</td>
<td>4.0</td>
<td>20–80</td>
<td>[68]</td>
</tr>
<tr>
<td>Iron sand</td>
<td>1.15*</td>
<td>-</td>
<td>20–2000</td>
<td>[15]</td>
</tr>
<tr>
<td>(12 mmol g$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feldspar</td>
<td>0.275*</td>
<td>5.5</td>
<td>1–5</td>
<td>[5]</td>
</tr>
<tr>
<td>(29 mmol g$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surfactant-modified palygorskite</td>
<td>3.24*</td>
<td>4.0</td>
<td>20–130</td>
<td>[4]</td>
</tr>
<tr>
<td>ZnCl$_2$ activated coir pith carbon</td>
<td>4.9*</td>
<td>4.0</td>
<td>20–80</td>
<td>[68]</td>
</tr>
<tr>
<td>Surfactant-modified clinoptilolite</td>
<td>~7.0*</td>
<td>-</td>
<td>96–500</td>
<td>[20]</td>
</tr>
<tr>
<td>γ-Al$_2$O$_3$</td>
<td>7.7*</td>
<td>5.7</td>
<td>20–40</td>
<td>[69]</td>
</tr>
<tr>
<td>Surfactant modified coir pith</td>
<td>8.76*</td>
<td>2</td>
<td>10–50</td>
<td>[7]</td>
</tr>
<tr>
<td>Raw rice straw</td>
<td>11.68*</td>
<td>6.4</td>
<td>50–500</td>
<td>[1]</td>
</tr>
<tr>
<td>(221 mmol g$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>23.7*</td>
<td>9.6–9.8</td>
<td>588–1100</td>
<td>[2]</td>
</tr>
<tr>
<td>Filter sand</td>
<td>25.07*</td>
<td>-</td>
<td>20–2000</td>
<td>[15]</td>
</tr>
<tr>
<td>(261 mmol g$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkali-treated fly ash</td>
<td>43.0*</td>
<td>-</td>
<td>200</td>
<td>[36]</td>
</tr>
<tr>
<td>Ba-modified zeolite</td>
<td>64.10*</td>
<td>6.0</td>
<td>&lt;1000</td>
<td>[21]</td>
</tr>
<tr>
<td>(1.33 meq g$^{-1}$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epichlorohydrin and trimethylamine modified rice straw</td>
<td>74.76*</td>
<td>6.4</td>
<td>50–500</td>
<td>[1]</td>
</tr>
<tr>
<td>Ba-modified blast-furnace-slag geopolymer</td>
<td>119.00*</td>
<td>7–8</td>
<td>865</td>
<td>This study</td>
</tr>
<tr>
<td>Chitin-based shrimp shells</td>
<td>156.0*</td>
<td>4.5</td>
<td>2350</td>
<td>[70]</td>
</tr>
</tbody>
</table>

*Langmuir maximum sorption capacity, $q_{m,calc}$.  
^aExperimental maximum sorption capacity

3.6 Effect of contact time

The effect of contact time on the removal of SO$_4^{2-}$ by Ba-BFS-GP at room temperature is presented in Fig. 7. It can be seen from the curves that the sorption is rapid in the first 10 min while sorption equilibrium is attained at approximately 3 h. The rate of SO$_4^{2-}$ removal was higher at the beginning of the sorption experiment due to a larger number of available adsorption sites [71]. Maximum SO$_4^{2-}$ sorption capacities of Ba-BFS-GP were 159.1 mg g$^{-1}$ (74.5% removal) and 99.0 mg g$^{-1}$ (58.0% removal) in model SO$_4^{2-}$ solution and mine effluent, respectively.
Figure 7. Effect of contact time on the removal efficiency of $SO_4^{2-}$ onto Ba-BFS-GP. $\circ$: Model $SO_4^{2-}$ solution ($C_0$, $SO_4^{2-}$: 1100 mg L$^{-1}$), □: Mine effluent ($C_0$, $SO_4^{2-}$: 853 mg L$^{-1}$). Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, temperature: 22–23 °C.

3.7 Kinetic modelling

The pseudo-first-order, pseudo-second-order and Elovich kinetic models were used to evaluate the experimental data. The results are shown in Fig. 8, and the corresponding kinetic parameters are listed in Table 6. The best fit was observed with the pseudo-second-order kinetic model. Theoretical $q_{e,cal}$ values of the pseudo-second-order kinetic model agree well with the experimental uptake values.

Figure 8. a) Pseudo-first-order kinetic, b) pseudo-second-order kinetic and c) Elovich model plots of $SO_4^{2-}$ sorption on Ba-BFS-GP. $\circ$: Model $SO_4^{2-}$ solution ($C_0$, $SO_4^{2-}$: 1100 mg L$^{-1}$), □: Mine effluent ($C_0$, $SO_4^{2-}$: 853 mg L$^{-1}$). Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C.
### Table 6. Pseudo-first-order, pseudo-second-order and Elovich model parameters for Ba-BFS-GP in \( \text{SO}_4^{2-} \) removal.

<table>
<thead>
<tr>
<th></th>
<th>Pseudo-first-order model</th>
<th>Pseudo-second-order</th>
<th>Elovich model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_0 ) (mg L(^{-1}))</td>
<td>( q_{e,\text{exp}} ) (mg g(^{-1}))</td>
<td>( k_1 ) (min(^{-1}))</td>
</tr>
<tr>
<td>1100</td>
<td>159.08</td>
<td>40.51</td>
<td>0.0108</td>
</tr>
<tr>
<td>853</td>
<td>99.0</td>
<td>158.73</td>
<td>2.217E-03</td>
</tr>
</tbody>
</table>

|                  | \( C_0 \) (mg L\(^{-1}\)) | \( q_{e,\text{exp}} \) (mg g\(^{-1}\)) | \( q_{\text{calc}} \) (mg g\(^{-1}\)) | \( k_2 \) (g mg\(^{-1}\) min\(^{-1}\)) | \( R^2 \) |
| 1100             | 159.08                   | 158.73              | 2.217E-03     | 7.6E-04               | 0.9994       |
| 853              | 99.0                     | 100                 | 7.6E-04       | 0.9994               |

### 3.8 Weber and Morris intraparticle diffusion model

The Weber and Morris intraparticle diffusion model was applied to the kinetic data of Ba-BFS-GP against the \( \text{SO}_4^{2-} \) (Fig. 9). If a plot of \( q_t \) versus \( t^{1/2} \) presents a straight line from the origin, the rate-limiting step in the sorption mechanism is diffusion from the outer surface into the pores of the material. The data of \( \text{SO}_4^{2-} \) sorption on Ba-BFS-GP shows two plots, which do not pass through the origin. This indicates that intraparticle diffusion is not the rate-limiting step. The first stage can be attributed to the instantaneous or external surface sorption while the second stage is the low diffusion of adsorbate from the surface to the inner pore [62].

**Figure 9.** Weber and Morris intraparticle diffusion model plot of \( \text{SO}_4^{2-} \) sorption on Ba-BFS-GP. o: Model \( \text{SO}_4^{2-} \) solution (\( C_0, \text{SO}_4^{2-}: 1100 \) mg L\(^{-1}\)), □: Mine effluent (\( C_0, \text{SO}_4^{2-}: 853 \) mg L\(^{-1}\)). Initial pH: 7–8, sorbent dosage: 5 g L\(^{-1}\), contact time: 24 h, temperature: 22–23 °C.
3.9 Thermodynamic parameters

Standard enthalpy ($\Delta H$) and entropy ($\Delta S$) were obtained from the slope and intercept of the plot of $\ln K_c$ vs. $1/T$, as shown in Fig. 10 and listed in Table 7. The negative value of $\Delta G$ indicated that the sorption process is spontaneous in nature. Affinity of the Ba-BFS-GP for $SO_4^{2-}$ is represented by the positive value of $\Delta S$, which indicated that the sorption process increased the entropy at the solid/solution interface during the sorption process. The positive value of $\Delta H$ suggested that the interaction of $SO_4^{2-}$ and Ba-BFS-GP is endothermic in nature. The $\Delta H$ obtained from thermodynamic calculations ($\leq 40$ kJ mol$^{-1}$) suggests a physisorption process involving weak interactions. [10, 62, 66, 72–74]

Figure 10. Van't Hoff plot for adsorption of $SO_4^{2-}$ removal. Initial pH: 7–8, adsorbent dosage: 5 g L$^{-1}$, $C_0$($SO_4^{2-}$): 1200 mg L$^{-1}$.

Table 7. Thermodynamics parameters for the sorption of $SO_4^{2-}$ on Ba-BFS-GP at different temperatures.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>$\Delta G$ (kJ mol$^{-1}$)</th>
<th>$\Delta S$ (J mol$^{-1}$ K$^{-1}$)</th>
<th>$\Delta H$ (kJ mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-10.354</td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>-11.389</td>
<td>56.598</td>
<td>5.556</td>
</tr>
<tr>
<td>40</td>
<td>-12.059</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.10 Column studies

Column studies (Fig. 11) have been carried out for Ba-BFS-GP as a sorbent in order to study its sorption capacity in dynamic conditions. Flow rates of 0.24 and 0.85 L h$^{-1}$ were used for the breakthrough simulation. Initially, total $SO_4^{2-}$ removal was observed with a lower flow rate. However, the removal of $SO_4^{2-}$ starts to linearly decrease after 40 min (corresponding to 0.16 L of treated effluent) and drops below 50% after 140 min (corresponding to 0.56 L of treated effluent). Therefore, it could be estimated that 18.7 m$^3$ of mine effluent with a similar composition could be treated with 1 t of Ba-
BFS-GP with over 50% SO$_4^{2-}$ removal. After use, Ba-BFS-GP could be further utilised in selective radium adsorption from contaminated waters due to accumulation of BaSO$_4$ as indicated by Kunze et al. [75]

**Figure 11.** Breakthrough curves of SO$_4^{2-}$ by Ba-BFS-GP packed column for two different flow rates.

### 3.11 Barium leaching

The leaching of Ba from Ba-BFS-GP was studied in mine effluent and distilled water at initial pH values of 2 and 8. The results indicate that dissolved Ba$^{2+}$ concentrations from Ba-BFS-GP were 600 and 32 mg L$^{-1}$ at initial pH values 2 and 8 in distilled water. However, in the case of mine effluent ($C_0$(SO$_4^{2-}$): 850–870 mg L$^{-1}$), the dissolved Ba$^{2+}$ concentrations were 0.175 and 0.375 mg L$^{-1}$ at initial pH values 2 and 8, respectively. Clearly lower concentrations of dissolved Ba in mine effluent are due to the instantaneous precipitation of low solubility BaSO$_4$. The limit for Ba content in domestic water is 0.7 mg L$^{-1}$ [76], so it would be safe to utilise Ba-BFS-GP for treating industrial wastewater containing SO$_4^{2-}$.

### 3.12 Sorption mechanism

The sorption mechanism of geopolymers in the removal of cations from aqueous solutions has been suggested to be cation exchange [31, 44, 77]. However, geopolymers have low affinity towards sorption of anions due to negative zeta potential [46]. In the present work, geopolymers were converted into Ba-form by a cation-exchange process and further applied for SO$_4^{2-}$ removal. The probable removal mechanism of SO$_4^{2-}$ is based on the surface complexation or precipitation of extremely low solubility BaSO$_4$ ($K_{sp} = 1.08 \times 10^{-10}$ at 25°C, solubility 0.0031 g L$^{-1}$, 20°C) [50, 78]. Due to the low solubility, BaSO$_4$ is considered non-toxic. However, the removal of sulphate with the direct precipitation as BaSO$_4$ is not recommended due to generation of secondary waste in the form of sludge [14]. The presence of BaSO$_4$ was confirmed with XRD from a used sorbent material.
4 Conclusions

Ba-modified blast-furnace-slag and Ba-modified metakaolin with and without a geopolymerisation step were studied for \(\text{SO}_4^{2-}\) removal. Ba-modified geopolymerised materials exhibit higher \(\text{SO}_4^{2-}\) ion removal capacity than Ba-modified materials without a geopolymerisation step. This is explained by the cation exchange process (\(\text{Na}^+\) is replaced by \(\text{Ba}^{2+}\)) taking place in the geopolymer framework structure during Ba-modification. The best sorbent material for \(\text{SO}_4^{2-}\) removal was Ba-BFS-GP. The optimum pH required for maximum sorption was found to be 7–8. The maximum experimental sorption capacities were 91.1 and 119.0 mg g\(^{-1}\) for synthetic model solution and mine effluent, respectively. Sorption capacities found in this study were among the highest of reported in the literature. The Sips isotherm model described the sorption well. Sorption kinetics followed the pseudo-second-order kinetic model, and the Weber and Morris intraparticle diffusion model showed that the sorption mechanism included two different steps. The positive enthalpy value indicates that the adsorption process was endothermic in nature. The results from the present study indicate that Ba-BFS-GP could be a technically feasible \(\text{SO}_4^{2-}\) sorbent for wastewater treatment (e.g. in the mining industry) especially for applications in which very low \(\text{SO}_4^{2-}\) levels are desired.

Acknowledgments

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References


Graphical Abstract

Blast furnace slag (gehlenite) → Blast-furnace-slag geopolymer → Barium-modified blast-furnace-slag geopolymer

- Alkali treatment / geopolymerisation
- Ion-exchange

Sulphate removal capacity:
- Blast furnace slag (gehlenite): $q \approx 0 \text{ mg/g SO}_4^{2-}$
- Blast-furnace-slag geopolymer: $q \approx 0 \text{ mg/g SO}_4^{2-}$
- Barium-modified blast-furnace-slag geopolymer: $q \approx 119 \text{ mg/g SO}_4^{2-}$
Figure 2
Click here to download high resolution image
Figure 3

SO$_4^{2-}$ removal [%] vs. Initial pH

- Ba-BFS-GP
- Ba-BFS
- Ba-MK-GP
- Ba-MK
Figure 4
Click here to download high resolution image

The graph shows the removal of $SO_4^{2-}$ as a function of $C_0$ (concentration in [mg L$^{-1}$]). The $SO_4^{2-}$ removal is represented on the y-axis, while the concentration $C_0$ is on the x-axis. The data points indicate a decrease in $SO_4^{2-}$ removal with increasing concentration $C_0$. The graph also includes a dotted line which might represent a trend or additional information related to the removal efficiency.
Figure 8

(a) \[ y = -0.0047x + 1.6076 \]
\[ R^2 = 0.9776 \]

(b) \[ y = 0.01x + 0.1321 \]
\[ R^2 = 0.9994 \]

(c) \[ y = 6.1222x + 115.83 \]
\[ R^2 = 0.9214 \]

\[ y = 9.6473x + 30.348 \]
\[ R^2 = 0.8826 \]
Figure 1. XRD patterns of blast-furnace slag (BFS), blast-furnace-slag geopolymer (BFS-GP) and barium-modified blast-furnace-slag geopolymer (Ba-BFS-GP) samples. HT = hydrotalcite, HAT = haturite, W = witherite.

Figure 2. The FTIR spectra of blast-furnace slag (BFS), barium-modified blast-furnace-slag (Ba-BFS) and barium-modified blast-furnace-slag geopolymer (Ba-BFS-GP).

Figure 3. Total SO$_4^{2-}$ removal per cent (left, solid lines) and total adsorbed amount (right, dashed lines) versus initial pH on the sorption of SO$_4^{2-}$ from mine effluent. Sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C, adsorbate: mine effluent ($C_0$, SO$_4^{2-}$: ~850–870 mg L$^{-1}$).

Figure 4. Effect of the initial concentration on the sorption of SO$_4^{2-}$ on Ba-BFS-GP from model solution. Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C.

Figure 5. Effect of Ba-BFS-GP dosage on SO$_4^{2-}$ removal. a) Model solution: $C_0$(SO$_4^{2-}$): ~1200 mg L$^{-1}$, contact time: 3 h. b) Mine effluent: $C_0$(SO$_4^{2-}$): 865 mg L$^{-1}$, contact time: 24 h. In both cases initial pH was 7–8.

Figure 6. Bi-Langmuir, Sips, Redlich-Peterson and Toth isotherms of SO$_4^{2-}$ sorption on Ba-BFS-GP. a) Model solution: $C_0$(SO$_4^{2-}$): 100–1800 mg L$^{-1}$, sorbent dose: 5 g L$^{-1}$. b) Mine effluent: $C_0$(SO$_4^{2-}$): 865 mg L$^{-1}$, sorbent dose: 1.3–15 g L$^{-1}$. Initial pH was 7–8, contact time 24 h and temperature 22–23 °C.

Figure 7. Effect of contact time on the removal efficiency of SO$_4^{2-}$ onto Ba-BFS-GP. o: Model SO$_4^{2-}$ solution ($C_0$, SO$_4^{2-}$: 1100 mg L$^{-1}$), □: Mine effluent ($C_0$, SO$_4^{2-}$: 853 mg L$^{-1}$). Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, temperature: 22–23 °C.

Figure 8. a) Pseudo-first-order kinetic, b) pseudo-second-order kinetic and c) Elovich model plots of SO$_4^{2-}$ sorption on Ba-BFS-GP. o: Model SO$_4^{2-}$ solution ($C_0$, SO$_4^{2-}$: 1100 mg L$^{-1}$), □: Mine effluent ($C_0$, SO$_4^{2-}$: 853 mg L$^{-1}$). Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C.
**Figure 9.** Weber and Morris intraparticle diffusion model plot of $\text{SO}_4^{2-}$ sorption on Ba-BFS-GP. o: Model $\text{SO}_4^{2-}$ solution ($C_0$, $\text{SO}_4^{2-}$: 1100 mg L$^{-1}$), □: Mine effluent ($C_0$, $\text{SO}_4^{2-}$: 853 mg L$^{-1}$). Initial pH: 7–8, sorbent dosage: 5 g L$^{-1}$, contact time: 24 h, temperature: 22–23 °C.

**Figure 10.** Van’t Hoff plot for adsorption of $\text{SO}_4^{2-}$ removal. Initial pH: 7–8, adsorbent dosage 5 g L$^{-1}$, $C_0$($\text{SO}_4^{2-}$): 1200 mg L$^{-1}$.

**Figure 11.** Breakthrough curves of $\text{SO}_4^{2-}$ by Ba-BFS-GP packed column for two different flow rates.
Blast-furnace slag and metakaolin were geopolymerised, modified with barium or treated with a combination of these methods in order to obtain an efficient $\text{SO}_4^{2-}$ sorbent for mine water treatment. Of prepared materials, barium-modified blast-furnace slag geopolymer (Ba-BFS-GP) exhibited the highest $\text{SO}_4^{2-}$ maximum sorption capacity (up to 119 mg g$^{-1}$) and it compared also favourably to materials reported in the literature. Therefore, Ba-BFS-GP was selected for further studies and the factors affecting to the sorption efficiency were assessed. Several isotherms were applied to describe the experimental results of Ba-BFS-GP and the Sips model showed the best fit. Kinetic studies showed that the sorption process follows the pseudo-second-order kinetics. In the dynamic removal experiments with columns, total $\text{SO}_4^{2-}$ removal was observed initially when treating mine effluent. The novel modification method of geopolymer material proved to be technically suitable in achieving extremely low concentrations of $\text{SO}_4^{2-}$ ($\ll 2$ mg L$^{-1}$) in mine effluents.