Thermodynamic, Kinetic and Equilibrium Studies of Pb (II) Ions Adsorption Using Ordinary Clay/Rice Husk Ash Based Geopolymers

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Abstract: One key global challenge is the existing disparity in water distribution resulting to millions of people lacking access to safe clean water. It is currently assessed that 1.1 billion individuals on the planet lacks access to improved quality water supplies. This is aggravated by the looming climate change and increased pollution threats posed by industrialization and population growth. Use of adsorbents for water treatment is preferable due to simplicity of the technique and cheap materials involved. Geopolymers can be easily synthesized hydrothermally using alumina and silica and possess amorphous surface for use as adsorbents. Clay minerals have been reported to contain alumina and silica and previous research show that rice husk ash as well contain substantial amounts of silica. Geopolymers can be easily synthesized hydrothermally using alumina and silica and possess amorphous surface that is useful for adsorption. Hence this work reports information on adsorption of Pb (II) using geopolymers GP-1, GP-2 and GP-3 synthesized with SiO\textsubscript{2}/Al\textsubscript{2}O\textsubscript{3} ratios of 4.16, 4.18 and 8.29 respectively. Adsorption of metal ions was found to increase from 70.54\pm 0.43 to 90.23\pm 0.04 with increase in Si/Al ratio from 4.16 to 8.29 in geopolymers. Equilibrium studies unveiled that experimental data for adsorption of Pb (II) ions best fitted in modified Langmuir Freundlich model. The adsorption capacities of 27.0, 79.58 and 209.9mg/g were obtained for GP-1, GP-2 and GP-3 respectively. Adsorption thermodynamics showed the process corresponded on spontaneous physiosorption activated by increase in temperature. Kinetic study on adsorption of Pb (II) ions onto clay based geopolymers was a Pseudo second order. This information may facilitate the development of optimized procedures for wastewater treatment, thus providing an alternative solution to environmental menace caused by heavy metal pollutants.

Key words: Thermodynamics, Kinetics, Equilibrium, Geopolymers, Adsorption.

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I. Introduction

The discharge of toxic heavy metals in water bodies is a serious pollution problem affecting water quality especially in wetlands and other water masses due to their toxicity and bio accumulative effect, creating a direct hazard to human health\cite{1}. There are known techniques for heavy metal wastewater treatments like; chemical precipitation, ion exchange, adsorption, membrane filtration among others\cite{2,3}. Chemical precipitation is not economical and produces large amounts of sludge, treatable with great difficulties. Ion exchange is expensive, especially when treating a large amount of wastewater containing heavy metals in low concentrations, so it cannot be used on a large scale while membrane filtration requires filter replacement that is expensive in terms of cost\cite{3}. The adsorption techniques present excellent approaches for treating industrial wastewaters containing metal ions, where solid adsorbents are employed for recovery of metal ions such as lead, copper, cadmium, nickel and zinc\cite{3}. In search for more adsorbents, geopolymers has proved effective in removal of metal ions from wastewater. Geopolymers are composed of silica and alumina similar to zeolite materials\cite{4}. Several researchers used metakaolin as ideal raw material for manufacture of geopolymers\cite{4,5} because of its high reactivity and purity compared to other clays\cite{6,7,8}. This work focuses on a new and green developing field that utilizes local Kenyan resources such as common clay that has not been used and rice husk waste for hydrothermal synthesis of geopolymers for wastewater management.
II. Experimental sections

2.1 Chemicals and reagents
Sodium hydroxide was used as a dissolution agent during geopolymer synthesis. Pb (NO₃)₂ and HNO₃ used in the adsorption experiments were of analytical grade and supplied by Sigma Aldrich. Preparation procedures and characterization of geopolymers are discussed in our earlier published work[11].

2.2 Synthetic effluent preparation
An accurate weight of 1.6 g Pb(NO₃)₂ was dissolved in 1 L of distilled water to make the stock solution. The stock solution was then diluted into the required concentrations using distilled water where necessary. Every time the stock and standard solution was prepared, it was shaken for about 1 hour using temperature controlled water bath electric shaker at 25°C and 120 rpm to ensure homogeneity.

2.3. Adsorption study
2.3.1 Effect of pH on adsorption process
Batch adsorption experiments were conducted by varying pH from 2 to 6 with initial Pb (II) concentrations of 100 mg/L, shaking speed of 120 rpm and room temperature of 25°C ± 1. The experiments were carried out in 100 mL plastic bottles and the total volume of the reaction mixture kept at 50 mL. The pH of solution was adjusted to desired values using the procedure adopted from Moreno-piraján and Giraldo[12]. The mixtures were shaken for a period of one hour in an electric shaker. The mixture was then filtered using whatman no 41 and residual metal ion concentration analysed using the procedure adopted from Ryan et al.[13].

2.3.2 Effect of contact time on adsorption process
The impact of residence time was investigated by varying time from 20 to 100 minutes. 0.10 g of geopolymer material was added in 50 mL of 100 mg/L metal ion solutions in each of a series of adsorption bottles. The bottles were placed in a thermostatic electric shaker at 120 rpm, maintained at 25°C ± 1. After 20 minutes of adsorption time was completed, the adsorbents were removed from the solution by filtration and the concentration of residual metal ion in each solution determined using AAS. Subsequently, the same procedure was repeated by adjusting time to, 40, 60, 80 and 100 minutes respectively.

2.3.3 Effect of temperature on adsorption process
The temperature range of 293 K to 328 K was used for Pb (II) ions adsorption to determine the equilibrium temperature. For each experimental run, 50 mL aqueous solution of the known concentration at optimum pH of 4.0 was put in a 100 mL stopped plastic bottles containing 0.10 g of the adsorbent. The bottles were placed in a thermostatic electric shaker at constant shaking speed of 120 rpm at specific temperature and withdrawn after shaking for one hour. Filtration was done and residual metal ions present analyzed.

2.3.4 Isotherm studies of adsorption process
Adsorption quantitative data of metal ions studied were treated using Freundlich; Langmuir, and modified Langmuir Freundlich. The models were used to determine adsorption capacities of the geopolymers synthesized using different clays and rice husk ash (RHA). A 100 mL stopped bottles were used where metal ion solutions with initial concentrations of 100 mg/L were placed. 0.10 g of each of the prepared adsorbents was added to each bottle and kept in an electric shaker at 25°C ± 1 for 1 hour in the laboratory to equilibrate[14]. AAS (AA 6300 Shimadzu) was used to determine both the initial metal ions concentration before adsorption (Cₒ) and the residual metal ion concentration (Cₑ) obtained after the adsorption process. The amount of adsorption at equilibrium, qₑ (mg/g), was calculated by equation 1.

\[
qₑ = \left[ \frac{Cₒ - Cₑ}{W} \right] V \quad \text{..................................................1}
\]

Where; Cₒ and Cₑ (mg/L) are concentrations of respective metal ions at initial and equilibrium conditions respectively. V is the volume of the solution (L) and W is the mass of dry adsorbent used (g) [15]. For the Freundlich isotherm, the plot of log qₑ against log Cₑ will give a straight line with a slope of 1/n and intercept of log Kₑ. For Langmuir isotherm, the plot of Cₑ/qₑ against Cₑ gives a straight line with a slope of 1/Qₑ max and intercepts 1/Qₑ max Kₑ. For modified Langmuir Freundlich isotherm Cₑ was plotted against qₑ and the model fitting was accomplished using the generalized reduced gradient algorithm available in Microsoft Excel solver.
2.3.5 Thermodynamic study of adsorption process

The sorption studies were carried out at different temperatures (293, 298, 308, 318 and 328 K). This was used to determine the effect of temperature on the thermodynamic parameters. The thermodynamic studies were performed using batch experiments. In each of the stoppered bottle contained 0.10 g of geopolymers and 50 mL of aqueous solutions. The experiments were carried out with initial concentration of 100 mg/L for all metal solutions at 25 °C ± 1 and pH 4 for Pb (II) ions. The residue was filtered after the 1-hour time of adsorption had been completed. The final concentration of metal ions left in the filtrate was analyzed using AAS. Adsorption standard free energy changes (ΔG°), the standard enthalpy change (ΔH°) and the standard entropy change (ΔS°) were obtained from experiments at various temperatures using equations 2 and 3[16].

$$\Delta G^\circ = -RT \ln K$$

$$\ln K = \Delta S^\circ / R - \Delta H^\circ / RT$$

where \( R (8.3145 \text{ J mol}^{-1} \text{ K}^{-1}) \) is the gas constant, \( K(\text{L g}^{-1}) \) is the Langmuir constant and \( T \) (K) is the absolute temperature[16].

2.3.6 Kinetics study

To perform the kinetics experiment, 0.10 g of the geopolymer adsorbents was placed in 100 mL stoppered bottles. 50 mL of 100 mg/L of the metal ions of monocomponent was added and the mixture put in a water bath electric shaker at residence time ranging from 20 to 80 minutes. The mixtures were kept at a constant shaking speed of 120 rpm at 25 °C ± 1 and then filtered and residual metal ions concentration contained in the filtrate measured using a spectrophotometer. This provides \( C_0 \), data, and equation (4) was used to calculate \( q_t \).

$$q_t = \frac{(C_0 - C_t)}{W}$$

where \( V \) is the volume of adsorbate solution in (L), and \( W \) is the mass of the adsorbent in (g). The data obtained was used to plot graphs of log (\( q_e \) - \( q_t \)) against t for Pseudo-first order and \( t/q_t \) against t for Pseudo-second order and determine kinetic parameters as per equations 5 and 6 respectively.

$$\log (q_e - q_t) = \log q_e - \frac{Kt}{2.303}$$

$$\frac{t}{q_t} = \frac{1}{K_2q_e^2} + \frac{1}{q_e}$$

Where \( q_e \) is amount adsorbed at equilibrium, \( q_t \) is amount adsorbed at a given time, t is residence time in minutes, \( K \) is Lagergren rate constant and \( K_2 \) is rate constant for Pseudo-second order.

III. Results and Discussion

3.1 Adsorption studies of geopolymers

3.1.1 Effect of pH

The adsorption of Pb (II) ions was found to be strongly dependent on the pH of the solution. Figure 1 demonstrates that the optimum pH for the adsorption of Pb (II) ions was about 4.0 on geopolymers which were rather acidic. Adsorption increased from over 50% at pH of 2 to higher mean percentages of 70.54 ± 0.43, 79.65 ± 0.27 and 90.23 ± 0.04 for GP-1, GP-2 and GP-3 respectively. GP-3 gave higher adsorption of Pb (II) than GP-1 and GP-2 and this could be associated with the high SiO2/ Al2O3 ratio in it[11] that led to increase in the silica content in the framework causing increased negatively charged groups of O-Si-O- in the geopolymers[17].

The low adsorption percentage of the metal ion at lower pH values could be explained by the competition between H+ and Pb (II) ions on the available exchange sites of the adsorbents[18]. At moderate pH values (4-5), linked H+ ions are released from the active sites leading to an increase of metal ions. However, the experiments on adsorption of Pb (II) ions could not be performed beyond pH of 6.0 due to the low solubility of

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Pb (II) hydroxide in water which forms as white precipitation at that pH\textsuperscript{19}. Similar trend of effect of pH on adsorption of Pb (II) ions was reported by Amer \textit{et al.} \textsuperscript{20} on adsorption of Pb (II), Zn (II) and Cd (II) ions onto polyphosphate-modified kaolinite clay.

**Figure 1:** Effect of pH on Pb (II) ions removal onto geopolymer materials (Pb (II) ions concentration = 100 mg/L, adsorbent dose = 0.1 g/50 mL, shaking speed = 120 rpm, temperature = 25 °C ± 1 and error bars indicate the average deviation from the mean).

3.1.2 Effect of residence time on adsorption process

The importance of contact time comes from the need for characterization of the feasible rapidness of binding and removal processes of the heavy metal ions by the new geopolymers and obtaining the optimum time for complete removal of the target metal ions\textsuperscript{21}. The result from figure 2 showed that adsorption efficiency increased with increase in contact time. This may be due to the fact that the number of active adsorption sites on the surface of adsorbent was more initially\textsuperscript{22}. The fast adsorbate adsorption at the initial stage was probably due to the initial concentration gradient between the adsorbate in solution and the number of vacant sites available on the adsorbent surface. Adsorption rate slowed down after 80 minutes and this could have been due to the electrostatic hindrance caused by already sorbed positively charged adsorbate species and the slow pore diffusion of the ions. The slow rate could also be due to lesser number of available active sites and slow rate of conveying adsorbates from the outer surface to the inner surface of the adsorbent \textsuperscript{22}. Similar results have been reported in literature\textsuperscript{23},\textsuperscript{24}.

**Figure 2:** Effect of contact time on Pb (II) ions removal onto geopolymer materials (Pb (II) ions concentration = 100 mg/L, adsorbent dose = 0.1 g/50 mL, shaking speed = 120 rpm, pH = 4.0 temperature = 25 °C and error bars indicate the average deviation from the mean).

3.1.3 Effect of temperatures on adsorption process

Temperature is a crucial parameter in adsorption reactions. Higher temperature increases adsorbate motion allowing the uptake of metal ions into the pores more easily, causing adsorption to increase. Figure 3 shows the effect of percentage removal of Pb (II) against temperature. The percentage removal increased from
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87.65 ± 0.30 to 90.15 ± 0.11 when temperature was varied from 293 to 328 K for adsorbents GP-1. The mean percentage removal increased from 89.77 ± 0.11 and 92.55 ± 0.08 to 91.5 ± 0.02 and 93.94 ± 0.05 when temperature was adjusted from 293 to 318 K and then dropped to 91.35 and 93.72% for adsorbents GP-2 and GP-3 respectively. According to Nassar and Magdy [25], increase in adsorption at equilibrium with increase in temperature is due to the acceleration of some originally slow adsorption steps or to the creation of some active sites on the adsorbent surface. Adsorption with ion exchange is an endothermic reaction, whereas adsorption with nonionic exchange is an exothermic reaction [26]. Therefore, increasing temperature increased the sorption rate suggesting that Pb (II) ions and Na ions underwent an ionic exchange to achieve heavy metal removal by the geopolymer. At temperature above 328 K, the thickness of the boundary layer decreased due to the increased tendency of the metal ions to escape from the geopolymer surface to the bulk of solution and this lead to decrease in adsorption as temperature increases [27]. Al-Zboon et al. [28] studied the effects of temperature on the adsorption of Pb (II) ions from aqueous solution by fly ash-based geopolymer, which showed a similar pattern.

![Figure 3: Effect of temperature on Pb (II) ions removal onto geopolymer materials (Contact time = 60 minutes, shaking speed of 120 rpm, pH = 4.0 and adsorbent dose = 0.1g/50mL).](image)

**3.1.4 Effect of the initial concentration**

Initial concentration of metal ions is an important factor for practical application [29]. Results of the study on the influence of initial Pb (II) ions concentration on the removal efficiency of the geopolymers are depicted in figure 4 and the results obtained indicated that the adsorption efficiency decreased with increase in initial Pb (II) ions concentration. Mean percentage removal decreased from 89.33 ± 1.12, 95.82 ± 0.05 and 88.15 ± 2.44 to 69.31 ± 0.04, 65.09 ± 0.03 and 67.04 ± 0.21 when concentration was varied from (20 – 500 mg/L) for GP-1, GP-2 and GP-3 respectively. In this study, adsorption decreased with increase of initial concentration and any increase of metal ion led to increase of the residual ion in solution. It is probable that along with increase of surface load (adsorbed substances) on the adsorbent, upper surface adsorption sites are saturated and the efficiency of removal decreased rapidly [30]. At lower concentrations, the number of moles of Pb (II) ions is small relative to the available adsorption sites on the adsorbent hence high rate of adsorption [31]. However, at higher concentrations, most of the adsorption sites are occupied by Pb (II) ions and the available sites of adsorption become fewer [32]. Rezaei [33] reported that with increase of metal ion concentration, adsorption decreases. This behaviour is connected with the competitive diffusion process of the metal ions through the micro- channel and pores in geopolymers [23]. This competition locks the inlet of channel on the surface and prevents the metal ions from passing deeply inside the geopolymer; hence adsorption occurs only on the surface [23]. A similar trend of decrease in adsorption of Pb (II) ions with increase in metal ion concentration was reported by Senthil Kumar and Gayathri [34].
isorbents | Freundlich | Langmuir | Langmuir-Freundlich |
<table>
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<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>$K_f$ (kg/mol)</td>
<td>$b$ (dm$^3$/g)</td>
<td>$Q_{max}$</td>
</tr>
<tr>
<td>GP-1</td>
<td>1.33</td>
<td>0.76</td>
<td>0.995</td>
</tr>
<tr>
<td>GP-2</td>
<td>1.33</td>
<td>0.75</td>
<td>0.983</td>
</tr>
<tr>
<td>GP-3</td>
<td>1.44</td>
<td>0.41</td>
<td>0.962</td>
</tr>
</tbody>
</table>

The equations of these models are: Langmuir: $q_e = Q_0K_fC_e / (1+K_fC_e)$; Freundlich: $q_e = K_fC_e^{1/n}$; Langmuir Freundlich: $q_e = Q_0(K_fC_e)^b / [1+(K_fC_e)^b]$.

These results show that the modified Langmuir Freundlich isotherm was best suited to describe metal ion dependent adsorption effects. Consequently, it implies that cooperative adsorption occurred between heterogeneous surface and homogenous surface of adsorbent. The indexes of heterogeneity, $b$ values were 0.72, 0.68 and 0.62 for GP-1, GP-2 and GP-3 respectively. According to Rushton et al. [35], approach of heterogeneity index to unity, indicates change of adsorbent surface to homogenous and whereas decrease approaching zero indicates change of surface to heterogeneous. The values obtained in this study shows increase in SiO$_2$/Al$_2$O$_3$ ratio as reported by Maingi et al. [36] on geopolymers GP-1, GP-2 and GP-3 favoured change of adsorption surface to heterogeneous. Increase in Si/Al ratio caused by use of different clays increased the isomorphous replacement of Si$^{4+}$ by Al$^{3+}$ hence producing more negative charges in the geopolymer lattice [36]. The negative charges are balanced by Na$^+$ which is exchangeable with heavy metal ions increasing adsorption capacities [37]. Adsorption capacities using Langmuir Freundlich isotherms are recorded in table 1. Günay et al. [38] also stated that three-parameter isotherm models resulted in better performance than two-parameter models.

### 3.3 Adsorption thermodynamic studies

The $\Delta H$ and $\Delta S$ values obtained are presented in table 2. The decrease in the value of $\Delta G$ with an increase in temperature shows that the reaction was more spontaneous, which indicates that adsorption was favoured by increase in temperature [39]. All $\Delta G$ values calculated were between 0 and -20 kJ/mole corresponding to spontaneous physisorption [40]. The positive values of $\Delta H$ obtained indicated the endothermic 

Figure 4: Effect of metal ion concentration on Pb (II) ions removal onto geopolymer materials (Contact time = 60 minutes, adsorbent dose = 0.1 g/50 mL, shaking speed = 120 rpm, pH = 4.0, temperature = 25°C and error bars indicate the average deviation from the mean).

<table>
<thead>
<tr>
<th>Adsorbents</th>
<th>$K_f$ (mg/g)</th>
<th>$R^2$</th>
<th>$Q_{max}$ (mg/g)</th>
<th>$K_{LF}$</th>
<th>$b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP-1</td>
<td>0.76</td>
<td>0.995</td>
<td>27.0</td>
<td>1.0x10$^4$</td>
<td>0.72</td>
<td>0.996</td>
</tr>
<tr>
<td>GP-2</td>
<td>0.75</td>
<td>0.983</td>
<td>79.58</td>
<td>1.5x10$^{-4}$</td>
<td>0.68</td>
<td>0.999</td>
</tr>
<tr>
<td>GP-3</td>
<td>0.41</td>
<td>0.962</td>
<td>209.9</td>
<td>5.85</td>
<td>0.62</td>
<td>0.982</td>
</tr>
</tbody>
</table>

Thermodynamic, Kinetic And Equilibrium Studies Of Pb (II) Ions Adsorption Using Geopolymers: Adsorption capacities obtained using Langmuir Freundlich isotherm models are as recorded in table 1. The adsorption data for Pb (II) ions on the adsorbents were fitted onto Langmuir, Freundlich, the Langmuir Freundlich mathematical models and their equilibrium constants are presented in table 1. The adsorption data for all the adsorbents best fitted into the modified Langmuir Freundlich isotherm. The variables estimation was done using the Microsoft excel solver with a non-negativity constraint restriction for $K_{LF}$ values. The $R^2$ values of the fitting were 0.996, 0.999 and 0.982 for GP-1, GP-2 and GP-3 respectively. The values of $R^2$ showed good fit for the experimental data. The results indicate that the L F isotherm is the best suited to describe metal ion dependent Pb (II) ions adsorption effects. Adsorption capacities obtained using L F isotherms are as recorded in table 1.

3.2 Adsorption isotherms

The adsorption data for Pb (II) ions on the adsorbents were fitted onto Langmuir, Freundlich, the Langmuir Freundlich mathematical models and their equilibrium constants are presented in table 1. The adsorption data for all the adsorbents best fitted into the modified Langmuir Freundlich isotherm. The variables estimation was done using the Microsoft excel solver with a non-negativity constraint restriction for $K_{LF}$ values. The $R^2$ values of the fitting were 0.996, 0.999 and 0.982 for GP-1, GP-2 and GP-3 respectively. The values of $R^2$ showed good fit for the experimental data. The results indicate that the L F isotherm is the best suited to describe metal ion dependent Pb (II) ions adsorption effects. Adsorption capacities obtained using L F isotherms are as recorded in table 1.
nature of adsorption and governs the possibility of physical adsorption\cite{41}. The low $\Delta H^\circ$ values also depict that the metal ion was physisorbed onto the adsorbent\cite{42,43}. The negative values of $\Delta G$ (Table 2) stipulated that the adsorption was highly favorable for Pb (II) ions. Additionally, the positive values of $\Delta S$ confirmed the increased randomness at the solid-solute interface during the adsorption process which shows the solution systems tends towards stability when the adsorption of Pb (II) ions on the surface of adsorbent occurred according to the second law of thermodynamics\cite{44}. More heat was required to bind the metal ions on the surface of adsorbent.

Table 2: Thermodynamic parameters for adsorption of Pb (II) ions onto geopolymers

<table>
<thead>
<tr>
<th>Geopolymer</th>
<th>$\Delta H$ (KJ/Mol)</th>
<th>$\Delta S$ (J/Mol/K)</th>
<th>293K</th>
<th>298K</th>
<th>308K</th>
<th>318K</th>
<th>328K</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP-1</td>
<td>2.49</td>
<td>15.51</td>
<td>-4.78</td>
<td>-4.93</td>
<td>-5.17</td>
<td>-5.62</td>
<td>-6.04</td>
</tr>
<tr>
<td>GP-2</td>
<td>2.08</td>
<td>14.99</td>
<td>-5.29</td>
<td>-5.46</td>
<td>-5.88</td>
<td>-6.28</td>
<td>-6.43</td>
</tr>
</tbody>
</table>

$\Delta H^\circ$ = Enthalpy change, $\Delta S$ = Change in entropy, $\Delta G$ = Change in Gibbs free energy

3.4 Kinetic studies

The slopes and intercepts of plots of log ($q_e$ - $q_t$) versus t were used to determine the first order rate constant $K_t$ and equilibrium adsorption density $q_e$. However, the experimental data deviated considerably from the calculated data as shown in table 3. A comparison of the results with the correlation coefficients is shown in table 3. The correlation coefficients for the Pseudo- first order obtained at the studied concentration were low compared to those of Pseudo- second order. In addition, the theoretical $q_e$ values found from the Pseudo-first order did not give reasonable values. This suggests that adsorption system of Pb (II) ions was not a first order reaction. The correlation coefficients for the second order kinetic obtained were greater than 0.95. The equilibrium adsorption capacities obtained with this model were more reasonable than those of the Pseudo-first order when comparing predicted results with experimental data. Moreover, the values of $R^2$ also indicated that this model produced better results. These indicate that the adsorption system studied belongs to the second order kinetic model that presupposes that Pb (II) ions adsorption on geopolymer adsorbents may have occurred through a chemical process involving the valence forces or exchanged electrons\cite{45}. Similar phenomena were also observed in adsorption of Cu (II) ions and Pb (II) ions on tea waste\cite{46}.

Table 3: Descriptive data on rate constants of Pb (II) adsorption on geopolymers as estimated from Pseudo-first and second order kinetic models

<table>
<thead>
<tr>
<th>Pseudo-first order</th>
<th>Pseudo-second order</th>
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<tbody>
<tr>
<td>GP</td>
<td>$q_e$(exp)</td>
</tr>
<tr>
<td>1</td>
<td>36.34</td>
</tr>
<tr>
<td>2</td>
<td>39.82</td>
</tr>
<tr>
<td>3</td>
<td>45.12</td>
</tr>
</tbody>
</table>

GP= Geopolymer adsorbents, SD = standard deviation, $q_e$ (exp) (mg/g) = $q_e$ obtained from adsorption experiment, $q_e$ (cal) (mg/g) = $q_e$ calculated from the Pseudo graphs, $K_t$ (min^{-1}) = rate constant for Pseudo –first order reaction, $K_s$(g/mg.min) = rate constant for Pseudo –second order reaction and $R^2$ = correlation coefficients, initial metal ion concentration = 100mg/L and residence time varied (20 - 100 minutes).

IV. Conclusions

Based on adsorption data obtained, GP-3 proved better in adsorption of Pb (II) ions than GP-1 and GP-2 as a result of its higher SiO$_2$/Al$_2$O$_3$. Geopolymers GP-3 recorded a high adsorption capacity of 209.9mg/g which makes it a potential good adsorbent. The experimental data was found to fit modified Langmuir Freundlich adsorption model better than the other models and hence was used for analyzing the efficiency of adsorption of the lead ions onto the geopolymers. The correlation coefficients for the second-order kinetic model obtained were greater than those of Pseudo- first order and therefore indicating that adsorption system studied belonged to the pseudo-second order. The positive values of $\Delta H$ obtained in this study indicate the endothermic nature of adsorption and governs the possibility of physical adsorption. Additionally, the positive value of $\Delta S$ confirmed the increased randomness at the solid-solute interface during the adsorption process which shows the solution systems tended towards stability when the adsorption of Pb (II) on the surface of adsorbent occurred according to the second law of thermodynamics. This study has shown that Kenyan common
clays which have few economic endeavors are good raw material for synthesis of geopolymers for adsorption application of Pb (II) ions.

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References


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