IB CHEMISTRY HL IA
Clay Soil Swelling

Research Question: What is the relationship between the factor by which the volume of sodium bentonite swells and the concentration of hydrochloric acid (HCl) /mol dm^{-3} when the acidic solution and sodium bentonite mixes?

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Contents

1 Introduction

From the engineers in my family, I have always been exposed to ideas surrounding the various unguessable factors that can result in the failure of a structure. For instance, while my father was discussing the various aspects important for consideration in the foundation of a structure, I was intrigued when he mentioned the different degrees that clay soils will swell under different acidic conditions, in which structures that are built upon clay soils must be engineered to withstand the expansion of the soil when the soil is contaminated from "natural processes" such as rain (Rama Vara Prasad, Hari Prasad Reddy, Ramana Murthy, & Sivapullaiah, 2018). While clay soil under an engineering context involves predicting and designing a structure according to the type of clay soil and the common levels of acidity to come into contact with the clay, I was brought to the research question of "What is the relationship between the factor by which the volume of sodium bentonite swells and the concentration of hydrochloric acid (HCl) in a separate solution /$\mathrm{mol\,dm^{-3}}$ when the HCl solution and sodium bentonite mix?"

2 Background Information

Clay soils, such as sodium bentonite, are composed of negatively charged "platelike layers" that are balanced by cations nested in between those layers (Chen, Grabowski, & Goel, 2022). Clay swelling when mixed with a solution mainly occurs as a result of the attraction of water molecules into the interlayer space of the clay, causing the interlayer space to grow (Chen et al., 2022).

The effect that the acidity of the solution plays on the degree to which the clay swells will vary depending on the composition of the clay. Sodium bentonite is expected to swell less when mixed with higher acidity solutions due to the interlayer cation replacement of Na^+ with the H^+ ions made available from the ionization of hydrochloric acid (HCl), in which because the ionic radius of H^+ (0.012 Å) is lower than that of Na^+ (1.02 Å), then the amount of clay swelling is reduced (Rama Vara Prasad et al., 2018). Despite these values, it is important to investigate the exact relationship of the clay's factor of swelling as a function of the mixed acid, in this case hydrochloric acid, as the ionic radii of Na^+ and H^+ do not make this relationship obvious and the cited literature regarding clay swelling focus on the pattern of the clay swelling as time progresses.

3 Proof of Concept

Before the experiment was performed, a proof of concept was done to determine whether there is a difference in swelling between different concentrations and what the range of concentrations should be in order to obtain a holistic result.

Initially, two test trials were done where 1.0 mL of 1.0 $\mathrm{mol\,dm^{-3}}$ HCl and 1.0 mL of water were each mixed into 1.0 mL of bentonite clay in 10 mL graduated cylinders. In both mixtures, the bentonite clay was not completely mixed with the solutions, with virtually all the acidic solution being absorbed by the clay as seen in Figure 1.

This heavy absorption of the clay was heavily problematic for the actual experiment, as not only does it result in partial swelling of the clay soil but also leads to difficulty in cleaning out the mixture especially in a 10 mL graduated cylinder. On the packaging of the bentonite clay, it recommends that the clay and solution should be mixed at a 1:10 ratio of volume.

Two additional test trials were done with 10 mL of 1.0 $\mathrm{mol\,dm^{-3}}$ HCl and 10 mL of water, each mixed into 1.0 mL of bentonite clay in 25 mL graduated cylinders. Mixing between bentonite clay and the solutions improved with a significant difference in swelling between the two mixtures (the acid swelled the clay by a factor of about 3, while the water swelled the clay by a factor of about 5.6). These two test trials are shown in Figure 2.

It was at this point when there was the realization that it is likely better to mix the clay into the solution rather than the other way around to ensure optimal absorption of the solution by the clay. However, what is to come next is determining the best maximum $[H^+]$ to see the optimal holistic result in the relationship between the factor of swelling and $[H^+]$. In this proof of concept, the method of mixing the solution into the clay was continued to ensure that there is consistency between the test trials.

One interesting qualitative observation at this point was that in the mixture of bentonite clay with water, there was a hole in the immersed bentonite clay, as seen in Figure 3.

It is unknown why this occurs, but it may be suggested that this could be as a result of mixing solution into the clay, therefore mixing clay into the solution may mitigate this issue.

Finally, 10 mL of 2.0 mol dm^{-3} was mixed with 1.0 mL of bentonite clay. The factor to which the bentonite had swollen by in this mixture (2.8 times) doesn't differ much compared to the mixture with 10 mL of 1.0 mol dm^{-3} HCl, therefore it was decided that 1.0 mol dm^{-3} will be the maximum concentration for this investigation.

Figure 1: Proof of Concept Trial of 1.0 mL 1.0 mol dm^{-3} HCl with 1.0 mL bentonite clay

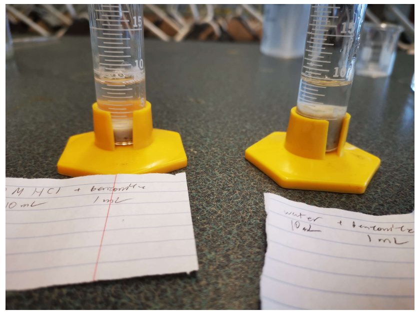

Figure 2: Proof of Concept Trial of 10 mL 1.0 mol dm^{-3} HCl (left) and 10 mL of water (right) with 1.0 mL bentonite clay

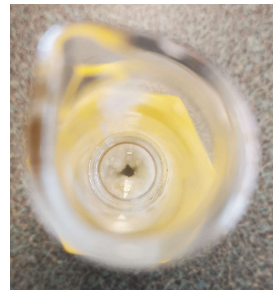

Figure 3: Hole in bentonite clay in test trial between 10 mL of water with 1.0 mL bentonite

4 Hypothesis

The hypothesis for this experiment is that the factor by which the volume of sodium bentonite swells will decrease as the concentration of H^+ ions of the mixed solution increases in a linear fashion given the prediction that a linear increase in [H^+] means a linear increase of the amount of H^+ ions that become available to replace Na^+ ions.

However, it is predicted that there will be a point where a decrease in swelling will begin to slow down when a deficiency of Na^+ ions in between the bentonite clay layers grows. It is hypothesized that this effect will be manifested as a horizontal asymptote on the plotted graph of the factor of swelling as a function of [H^+].

5 Variables

5.1 Independent Variable

The manipulated variable is the concentration of the hydrochloric acid solution mixed with the bentonite clay /mol dm^{-3}. In this lab, the manipulated variable will be changed by acid dilution.

5.2 Controlled Variable 1: Clay swelling duration

5.2.1 How to control it

For each trial, set a timer for 10 minutes and record the final volume when the timer ends.

5.2.2 Why it must be controlled

Inconsistent durations of time between trials will entail that the clays that were allowed more time to swell will swell more than it should relative to the other trials. Note that in the process, there will be a slight difference in duration allowed between the 5 trials that share the same [H^+]. This is not significant as due to the slow nature of clay swelling, a difference in duration by under a

5.1 Dependent Variable

The responding variable is the factor by which the clay has swollen by. The responding variable will be measured using a 25 mL graduated cylinder.

5.2 Controlled Variable 2: Volume of solution mixed with clay

5.2.1 How to control it

Consistently measure 10.00 mL of solution for each trial using a 10.00 mL pipette.

5.2.2 Why it must be controlled

Differing the volume of solution mixed with the clay between different trials will lead to major difference of the amount H^+ ions available to be exchanged with Na^+ ions in the clay. Because this ion exchange is essential to the behaviour of swelling in bentonite clay, the volume of the solution mixed with the clay must be controlled.

minute will not lead to major inconsistencies.

5.3 Controlled Variable 3: Volume of initial clay

5.3.1 How to control it

Consistently use a set volume of bentonite clay for each trial. Note that because bentonite is rather sticky and therefore is tough to clean out of a thin graduated cylinder, then it is best to standardize the volume of clay committed for the experiment by taking the volume of the dry bentonite with a graduated cylinder and transferring it to a weigh boat to determine what mass of clay is associative with the set volume of clay.

5.3.2 Why it must be controlled

Differing the volume of initial clay between trials will lead to major differences in sodium ions present in the clay. This will lead to inconsistencies of the swelling factor as there will be more/less sodium ions ready to be exchanged with hydrogen ions.

6 Equipment and Materials

- Lab Apron
- Lab Goggles
- Waste Beakers
- Distilled Water
- sodium bentonite clay
- 1.00 $\mathrm{mol\,dm^{-3}}$ hydrochloric acid (HCl) ($\pm$ 0.03 $\mathrm{mol\,dm^{-3}}$)
- 0.100 $\mathrm{mol\,dm^{-3}}$ hydrochloric acid (HCl) ($\pm$ 0.006 $\mathrm{mol\,dm^{-3}}$)
- (1) 10.00 mL Graduated Cylinder ($\pm$ 0.02 mL)
- (5) 25.0 mL Graduated Cylinders ($\pm$ 0.3 mL)
- (3) 100.0 mL Volumetric Flasks ($\pm$ 0.2 mL)
- 10.00 mL pipette ($\pm$ 0.04 mL)
- (5) Weigh Boats
- Pipette pump
- Scoopula
- (2) Stir rods
- Paper towel
- Digital Balance ($\pm$ 0.003 g)
- Timer

7 Safety, Environmental, and Ethical Considerations

- Lab apron and eye protection must be worn at all times during the experiment.
- No consumption of food or water during the experiment.
- Eyes that have made contact with the hydrochloric acid should be rinsed with water for several minutes, with contact lenses being removed if possible in the middle of the rinsing process.
- Thoroughly wash any skin with water and soap if it has been in contact with hydrochloric acid. Hands should also be thoroughly washed after completing the experiment.
- Move to an area of fresh air if hydrochloric acid is inhaled.
- If hydrochloric acid is swallowed, rinse mouth. Do not induce vomiting.
- When performing acid dilution, always add the acid into the water and not the other way around.
- Dispose of any waste containing acid to a waste beaker labelled with contents and approximate [H^+]. Dispose hydrochloric acid by neutralizing it with baking soda and flushing it with water 10 times the original waste volume.
- Take caution when attaching/detaching a pipette pump onto/from a pipette, ensuring that the distance between your two hands do not apply overwhelming torque onto the pipette.

8 Procedure

1. Put on lab apron and eye protection
2. Using the 10 mL pipette, transfer 50 mL of distilled water to the 100 mL volumetric flask
3. Top up the 100 mL volumetric flask with 1.0 mol dm^{-3} HCl to obtain a 100 mL solution of 0.5 mol dm^{-3} HCl
4. Repeat Steps 2 and 3 using 0.1 mol^{-3} HCl to obtain a 100 mL solution of 0.05 mol dm^{-3} HCl
5. Using the 10 mL pipette, transfer 10 mL of distilled water to the 100 mL volumetric flask
6. Top up the 100 mL volumetric flask with 1.0 mol dm^{-3} HCl to obtain a 100 mL solution of 0.01 mol dm^{-3} HCl
7. Using a scoopula, transfer bentonite clay into the 10 mL graduated cylinder until there is 1 mL of bentonite clay
8. Place a weigh boat onto the digital balance and tare the balance
9. Transfer all the bentonite clay in the 10 mL graduated cylinder into the weight boat and record the mass of the bentonite clay
10. Place another weight boat on the digital balance, tare the balance, then transfer enough bentonite clay using the scoopula such that the mass read by the balance matches the mass found in Step 9.
11. Repeat Step 10 for all 5 weigh boats.
12. Using the 10 mL pipette, transfer 10 mL of a solution to each 25 mL graduated cylinder
13. Flick the bottom of each weight boat such that all the clay reaches to one corner, then proceed to transfer the clay of each weigh boat to each 25 mL graduated cylinder as quickly as possible
14. Set a timer for 10 minutes
15. As the timer approaches its end, start flicking each graduated cylinder to force all the bentonite clay to be submerged at the bottom of the graduated cylinder
16. Once the timer ends, record the final volumes of bentonite clay in each 25 mL graduated cylinder
17. If the solution is acidic, first transfer remaining solution into the waste beaker, using an acid designated stir rod to remove the majority of the clay. Fill up the graduated cylinder with water, then transfer the water and any large chunks of clay into the waste beaker again
18. Repeatedly fill the graduated cylinder with water and scrub the interior with a stir rod wrapped by paper towel until no clay remains
19. Repeat Steps 10 to 18 for all solutions
20. Wash your hands thoroughly after the experiment and clean the laboratory workspace

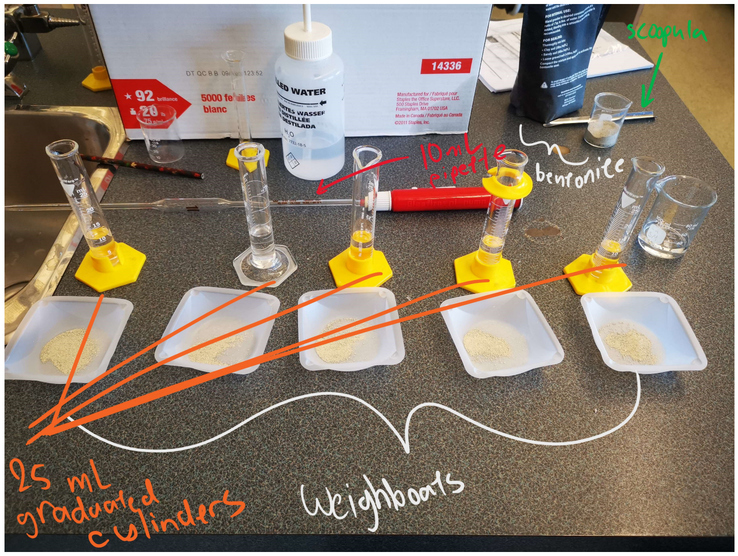

Figure 4: Lab setup prior to mixing between bentonite clay and the solution

9 Evidence

9.1 Qualitative Observations

- The sodium bentonite clay is a grey powder that appears in various sizes (fine to the size of a grain of sand). Fine parts of the clay easily stick to glassware and the weigh boats
- The hydrochloric acid is a clear colourless solution for all $[H^+]$ concentrations used in this experiment
- None of the trials lead to a hole in the submerged clay that was observed in the proof of concept mixture between water and bentonite clay
- When the clay is mixed with water
  - The submerged clay releases black solids resembling sesame seeds
  - The solution immediately changes into a murky white
  - The submerged clay turns into a dark grey in the form of fluffy particles significantly larger than the dry grains of clay
- When the clay is mixed with $0.01\,\mathrm{mol\,dm^{-3}}$ HCl
  - The clay turns into a dark grey, but not as dark as in the trials with water
  - Initially, solution mixed with the clay remains clear and colourless. However, the solution turns white and murky upon agitation
- When the clay is mixed with $0.05\,\mathrm{mol\,dm^{-3}}$ HCl or $0.1\,\mathrm{mol\,dm^{-3}}$ HCl
  - The solution overtime turns from clear and colourless to white and murky
  - Submerged clay is whiter than that of the $0.01\,\mathrm{mol\,dm^{-3}}$ trials
- When the clay is mixed with $0.5\,\mathrm{mol\,dm^{-3}}$ HCl or $1.0\,\mathrm{mol\,dm^{-3}}$ HCl
  - The solution immediately turns white and murky
  - There is bubbling at the meniscus of the solution
  - All the submerged clay is fine and does not stick to the glassware
- Especially for trials when $[\mathrm{HCl}] = 1.00\,\mathrm{mol\,dm^{-3}}$, the final volume of the submerged bentonite clay sometimes was below the minimum graduation on the 25 mL graduated cylinder. Therefore, the volume of the bentonite clay was difficult to determine in these trials.

9.2 Quantitative Data

The initial volume of the bentonite clay was $1.00\,\mathrm{mL} \pm 0.02\,\mathrm{mL}$, which was standardized to be $0.810\,\mathrm{g} \pm 0.003\,\mathrm{g}$.

Table 1: Raw data of final volume of bentonite clay for 5 trials of each hydrochloric acid concentration

Concentration of HCl in the solution $/\mathrm{mol\,dm^{-3}}$	Final Volume of submerged bentonite clay $/\mathrm{mL}$ $\pm 0.3\,\mathrm{mL}$				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0 (Distilled Water)	8.5	8.5	7.5	9.0	8.0
0.0100 ± 0.0007	8.0	8.5	9.0	9.5	7.5
0.050 ± 0.003	5.5	5.5	5.5	6.0	5.0
0.100 ± 0.006	5.0	5.0	5.0	5.0	5.0
0.50 ± 0.02	4.0	4.5	4.0	4.5	4.0
1.00 ± 0.03	3.0	3.0	2.8	2.8	2.0

9.3 Uncertainty Propagation

The $1.00\,\mathrm{mol\,dm^{-3}}$ HCl and $0.100\,\mathrm{mol\,dm^{-3}}$ HCl solutions were prepared by a lab technician using the following materials.

- $12.0\,\mathrm{mol\,dm^{-3}}$ HCl ($\pm 3\%$ according to (*Hydrochloric Acid, Concentrate 12M, ACS, 2.5L, DG APPLICABLE*, n.d.))
- $1000.0\,\mathrm{mL}$ Volumetric Flask ($\pm 0.6\,\mathrm{mL}$) for acid dilution
- $100.0\,\mathrm{mL}$ Graduated Cylinder ($\pm 0.3\,\mathrm{mL}$) for measuring volume of distilled water

The uncertainty for $1.00\,\mathrm{mol\,dm^{-3}}$ HCl and $0.100\,\mathrm{mol\,dm^{-3}}$ can then be calculated. A sample calculation for $1.00\,\mathrm{mol\,dm^{-3}}$ HCl is shown below.

$$C_2 = 1.00\,\mathrm{mol\,dm^{-3}}, \quad C_1 = 12.0\,\mathrm{M} \pm 3\%, \quad V_2 = 1000.0\,\mathrm{mL} \pm 0.6\,\mathrm{mL}$$

$$V_1 = \frac{C_2 V_2}{C_1} = \frac{1.00\,\mathrm{mol\,dm^{-3}} \cdot 1000.0\,\mathrm{mL}}{12.0\,\mathrm{mol\,dm^{-3}}} = 83.3\,\mathrm{mL}$$

From the uncertainty for the $100.0\,\mathrm{mL}$ graduated cylinder

$$V_1 = 83.3\,\mathrm{mL} \pm 0.3\,\mathrm{mL}$$

$$\Delta C_2 = C_2\left(\frac{\Delta C_1}{C_1} + \frac{\Delta V_2}{V_2} + \frac{\Delta V_1}{V_1}\right) = 1.00\,\mathrm{mol\,dm^{-3}}\left(3\% + \frac{0.6\,\mathrm{mL}}{1000.0\,\mathrm{mL}} + \frac{0.3\,\mathrm{mL}}{83.3\,\mathrm{mL}}\right) = 0.03\,\mathrm{mol\,dm^{-3}}$$

$$C_2 = 1.00\,\mathrm{mol\,dm^{-3}} \pm 0.03\,\mathrm{mol\,dm^{-3}}$$

The uncertainties for the rest of the diluted solutions are then determined in a similar fashion given the following considerations:

- The $0.50\,\mathrm{mol\,dm^{-3}}$ HCl solution was diluted from the $1.00\,\mathrm{mol\,dm^{-3}} \pm 0.03\,\mathrm{mol\,dm^{-3}}$ HCl solution
- The $0.050\,\mathrm{mol\,dm^{-3}}$ HCl solution and $0.0100\,\mathrm{mol\,dm^{-3}}$ HCl solution were diluted from the $0.100\,\mathrm{mol\,dm^{-3}} \pm 0.006\,\mathrm{mol\,dm^{-3}}$ HCl solution
- 3 $100.0\,\mathrm{mL} \pm 0.2\,\mathrm{mL}$ volumetric flasks were used for acid dilution
- A $10.00\,\mathrm{mL} \pm 0.04\,\mathrm{mL}$ pipette was used to measure volume of distilled water

10 Analysis

To find the factor of swelling, the final volume of submerged bentonite clay was divided by the initial volume of bentonite clay. Because the initial volume of bentonite clay was 1.00 mL, then the factor of swelling for each of the 5 trials would be the same. However, due to the presence of uncertainty in both the 25 mL graduated cylinder used for the final volume of submerged bentonite clay and the 10 mL graduated cylinder used to measure the initial 1.00 mL ± 0.02 mL of bentonite clay, a calculation is required for the factor of swelling's uncertainty.

The next step is to determine the upper and lower bounds of each trial's factor of swelling using this calculated uncertainty.

Now, the overall value of the factor of swelling can be determined using the average between the maximum and minimum values selected from the upper and lower bounds of each trial's factor of swelling along with half the difference between the same values.

Sample calculations for these are presented below using the first trial of the mixture between distilled water and bentonite clay.

Let F = Factor of swelling of the bentonite clay

V_f = The final volume of bentonite clay /mL

V_i = The initial volume of bentonite clay /mL

$$F = 8.5$$
$$V_f = 8.5\,\text{mL} \pm 0.3\,\text{mL}$$
$$V_i = 1.00\,\text{mL} \pm 0.02\,\text{mL}$$

$$F = \frac{V_f}{V_i}$$
$$\therefore \Delta F = F\left(\frac{\Delta V_f}{V_f} + \frac{\Delta V_i}{V_i}\right)$$
$$= (8.5)\left(\frac{0.3\,\text{mL}}{8.5\,\text{mL}} + \frac{0.02\,\text{mL}}{1.00\,\text{mL}}\right)$$
$$= 0.5$$
$$F = 8.5 \pm 0.5$$

$$F_{upper} = F + \Delta F = 8.5 + 0.5 = 9.0$$
$$F_{lower} = F - \Delta F = 8.5 - 0.5 = 8.0$$

$$F_{max} = 9.5, \quad F_{min} = 7.1$$
$$\overline{F} = \frac{F_{max} + F_{min}}{2}$$
$$= \frac{9.5 + 7.1}{2}$$
$$= 8$$
$$\Delta F = \frac{F_{max} - F_{min}}{2}$$
$$= \frac{9.5 - 7.1}{2}$$
$$= 1$$
$$F = \overline{F} \pm \Delta F$$
$$F = 8 \pm 1$$

Tables 2 to 5 present all the processed data for all trials.

Table 2: The uncertainty of the factor of swelling per trial for each concentration used in the experiment

Concentration of HCl in the solution /mol dm^{-3}	Uncertainty of the factor of swelling per trial				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0 (Distilled Water)	0.5	0.5	0.5	0.5	0.5
0.0100 ± 0.0007	0.5	0.5	0.5	0.5	0.5
0.050 ± 0.003	0.4	0.4	0.4	0.4	0.4
0.100 ± 0.006	0.4	0.4	0.4	0.4	0.4
0.50 ± 0.02	0.4	0.4	0.4	0.4	0.4
1.00 ± 0.03	0.4	0.4	0.4	0.4	0.3

Table 3: The upper bound of the factor of swelling per trial for each concentration used in the experiment

Concentration of HCl in the solution /mol dm^{-3}	Upper bound of the factor of swelling per trial				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0 (Distilled Water)	9.0	9.0	8.0	9.5	8.5
0.0100 ± 0.0007	8.5	9.0	9.5	10.0	8.0
0.050 ± 0.003	5.9	5.9	5.9	6.4	5.4
0.100 ± 0.006	5.4	5.4	5.4	5.4	5.4
0.50 ± 0.02	4.4	4.9	4.4	4.9	4.4
1.00 ± 0.03	3.4	3.4	3.2	3.2	2.3

Table 4: The lower bound of the factor of swelling per trial for each concentration used in the experiment

Concentration of HCl in the solution /mol dm^{-3}	Lower bound of the factor of swelling per trial				
	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
0 (Distilled Water)	8.0	8.0	7.1	8.5	7.5
0.0100 ± 0.0007	7.5	8.0	8.5	9.0	7.1
0.050 ± 0.003	5.1	5.1	5.1	5.6	4.6
0.100 ± 0.006	4.6	4.6	4.6	4.6	4.6
0.50 ± 0.02	3.6	4.1	3.6	4.1	3.6
1.00 ± 0.03	2.6	2.6	2.4	2.4	1.7

Table 5: The overall factor of swelling for each concentration of HCl

Concentration of HCl in the solution /mol dm^{-3}	Factor of swelling
0 (Distilled Water)	8 ± 1
0.0100 ± 0.0007	9 ± 1
0.050 ± 0.003	5.5 ± 0.9
0.100 ± 0.006	5.0 ± 0.4
0.50 ± 0.02	4.3 ± 0.6
1.00 ± 0.03	2.5 ± 0.9

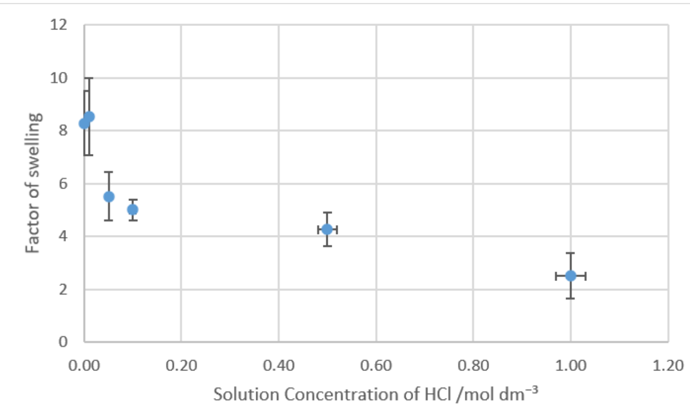

Figure 5: Factor of swelling of bentonite clay as a function of [HCl] /mol dm^{-3}

Plotting this processed data as factor of swelling of bentonite clay as a function of [HCl] results in the graph in Figure 5.

Recall that the original hypothesis stated that the dependent variable decreases as the independent variable increases, which is evident in the graphed data. However, the parts of the hypothesis that aren't so evident in the experimental data is that the relationship would initially be linear and then approach a horizontal asymptote.

Given that the gradient change is very immediate at approximately [HCl] = 0.050 mol dm^{-3} as well as the maintenance of a lower gradient for a significantly wider domain between [HCl] = 0.100 mol dm^{-3} to [HCl] = 1.00 mol dm^{-3}, the original section of the hypothesis regarding an initial linear relationship has been proven to be false.

However, the possibility of the presence of a horizontal asymptote is not removed. In hindsight of seeing the experimental relationship from the concentrations of HCl used in this experiment in that the final 3 data points maintain a relatively steady curve that sit above a factor of swelling of 2, it could be argued that since the minimum logical factor of swelling is 1, then the effects of an asymptote could have been observed had the domain of concentrations of HCl been significantly extended.

At a glance, the overall trend of the graph may either appear to be logarithmic, exponential, or of a reciprocal function. However, a logarithmic relationship does not have a horizontal asymptote, meaning that such a relationship would not apply to this experiment as the swelling factor must approach a plateau as Na^+ ions are depleted.

Figures 6 and 7 present the exponential and reciprocal best-fit trendline respectively. Visually speaking, the reciprocal trendline has a significantly better fit than the exponential trendline. This is numerically proven from the coefficients of determination (R^2) between the two relationships, where the R^2 value of the exponential best-fit trendline is 0.7165 whereas the R^2 value of the reciprocal best-fit trendline is 0.9512.

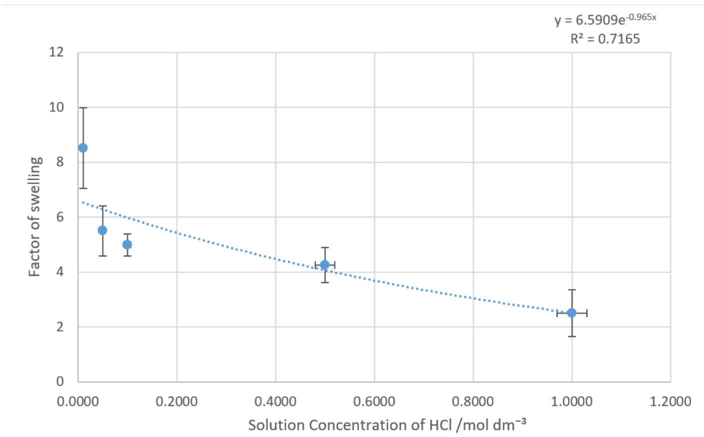

Figure 6: Factor of swelling of bentonite clay as a function of [HCl] with an exponential trendline

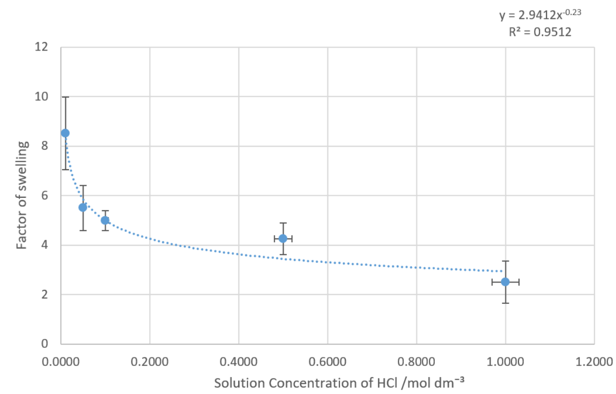

Figure 7: Factor of swelling of bentonite clay as a function of [HCl] with a reciprocal trendline

(Rama Vara Prasad et al., 2018) does not provide upfront any graphs for comparison under the context of this investigation. However, there is enough information within this source to analyze and convert into something insightful under this investigation's context. The final values of the swelling percentage in Figure 8 can be taken to determine to graph swelling percentage as a function of $[H_3O^+]$ according to these literature values.

Note that concentrations in the literature data are measured in normality (N), which is defined as "the number of gram or mole equivalents of solute present in one litre of a solution" (*Normality*, n.d.). Molarity can be determined from the formula $M = \frac{N}{n}$, where M is the molarity of the acid /mol dm^{-3}, N is the normality of the solution /N, and n is the number of protons in the acid (Gonzales, 2017).

Sample calculations for the conversions from normality to molarity are shown below.

$$
\begin{aligned}
N &= 4\,\mathrm{N}\ \mathrm{H_2SO_4}, \quad n = 2 \\
M &= \frac{N}{n} \\
&= \frac{4\,\mathrm{N}\ \mathrm{H_2SO_4}}{2} \\
&= 2\,\mathrm{mol\,dm^{-3}}\ \mathrm{H_2SO_4} \\
[\mathrm{H_3O^+}] &= 2\,\mathrm{mol\,dm^{-3}}
\end{aligned}
$$

$$
\begin{aligned}
N &= 4\,\mathrm{N}\ \mathrm{H_3PO_4}, \quad n = 3 \\
M &= \frac{N}{n} \\
&= \frac{4\,\mathrm{N}\ \mathrm{H_3PO_4}}{3} \\
&= 1.3\,\mathrm{mol\,dm^{-3}}\ \mathrm{H_3PO_4} \\
[\mathrm{H_3O^+}] &= \sqrt{K_a \times [\mathrm{H_3PO_4}]} \\
&= \sqrt{6.9 \times 10^{-3} \times 1.3\,\mathrm{mol\,dm^{-3}}} \\
&= 0.1\,\mathrm{mol\,dm^{-3}}
\end{aligned}
$$

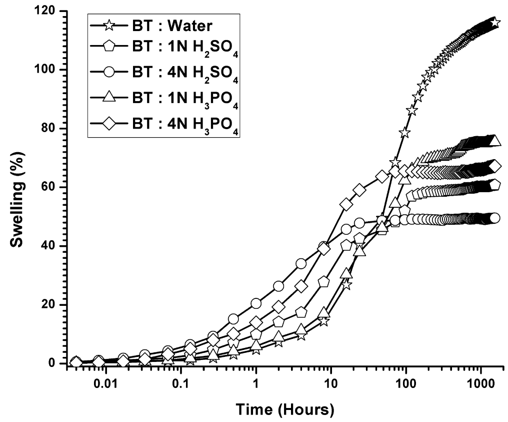

Figure 8: Literature data of Swelling percentage /% as a function of Time /h (Rama Vara Prasad et al., 2018)

Table 6: Literature values of final swelling percentage as a function of concentration of hydronium ions

Concentration of H_3O^+ /mol dm^{-3}	Swelling Percentage /%
2	50
0.5	60
0.1	68
0.05	76
0	116

Graphing the literature data produces the graph in Figure 9, which further confirms the hypothesis that factor of swelling is inversely proportional to $[H^+]$.

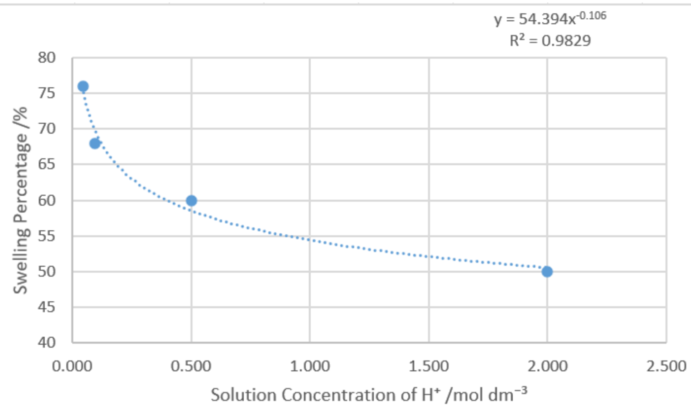

Figure 9: Swelling percentage /% as a function of concentration of H^+ ions in solution from literature data (Rama Vara Prasad et al., 2018)

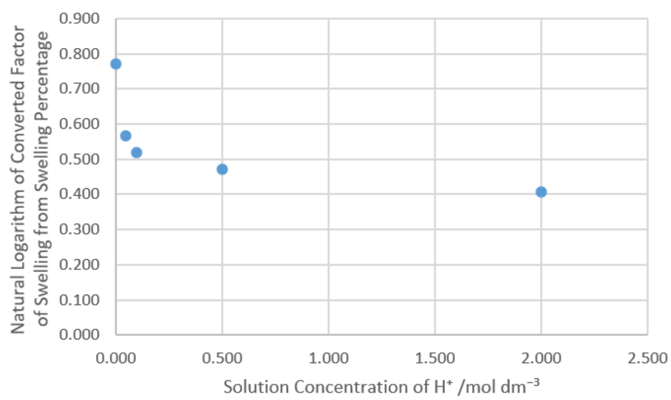

Figure 10: Natural logarithm of factor of swelling converted from swelling percentage as a function of concentration of H^+ ions in solution from literature data (Rama Vara Prasad et al., 2018)

To thoroughly compare this experiment's results against the literature data, it is best to find a way to linearize both relationships. If a reciprocal relationship is the best-fit for the relationship, then an idea from kinetics for linearization is to reciprocate the factor of swelling or swelling percentage. While doing this with the experimental data yield a result that is possibly linear as seen in Figure 11, doing this with the literature data yields a result that is not linear as seen in Figure 12. Taking the natural logarithm of the dependent variable was also a linearization technique from kinetics; however, this also fails to produce a linear relationship as seen in Figure 10.

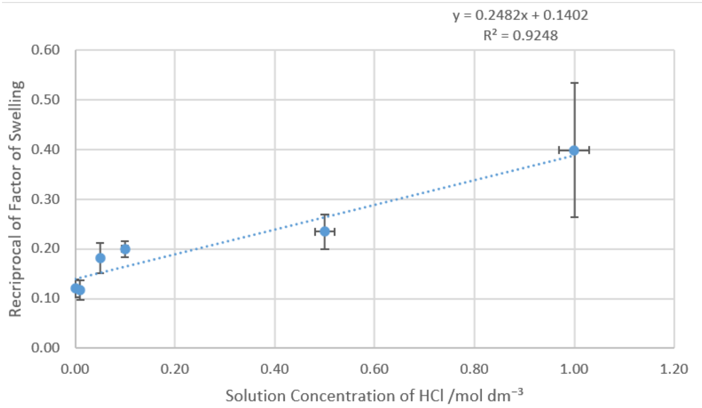

Figure 11: Reciprocal of factor of swelling as a function of [HCl] from experimental data

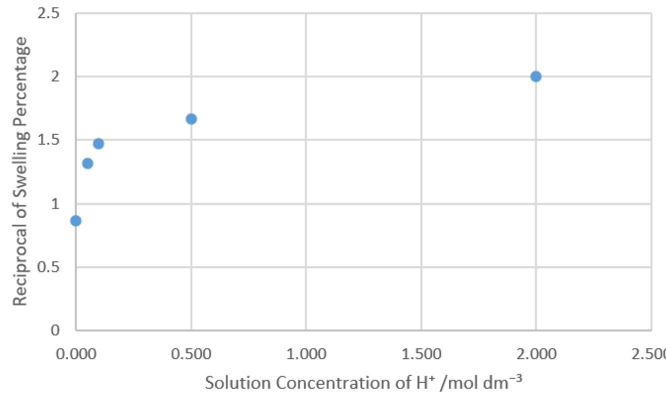

Figure 12: Reciprocal of swelling percentage as a function of $[H^+]$ from literature data (Rama Vara Prasad et al., 2018)

The method that produces the best visual linear results for both the experimental and literature data is by graphing the swelling factor or swelling percentage as a function of the pH of the acidic solution. Figure 13 shows this with the experimental data, and Figure 14 shows this with the literature data. *Note that this relationship is not truly linear in either of the two graphs and the presence of the linear trendline is to identify subtleties in the conclusion.*

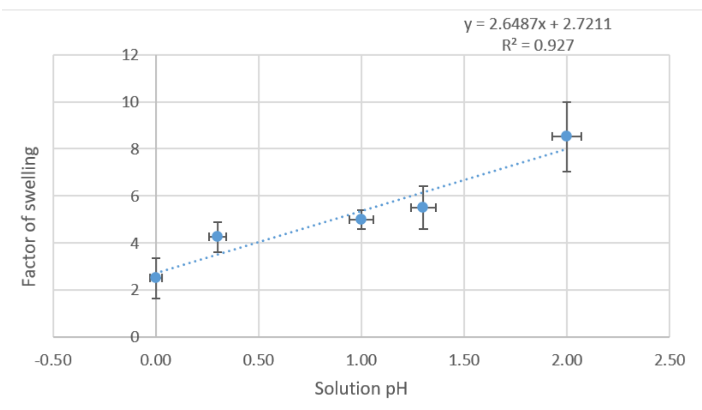

Figure 13: Factor of swelling as a function of solution pH from experimental data

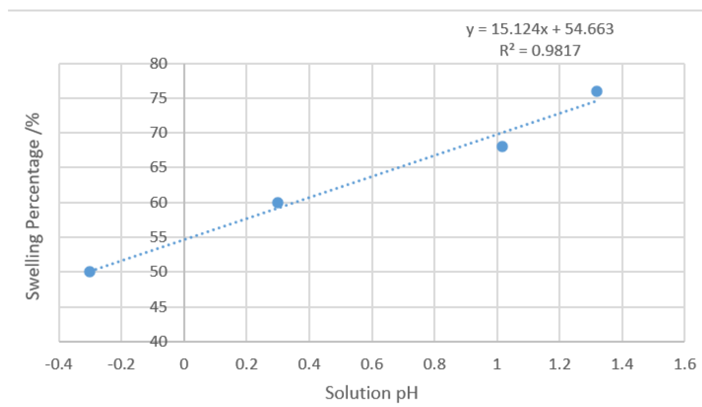

Figure 14: Swelling percentage /% as a function of solution pH from literature data (Rama Vara Prasad et al., 2018)

11 Conclusion

11.1 Summary

Contrary to the hypothesis, the experimentally determined relationship between the factor by which the sodium bentonite clay swells and a solution's concentration of HCl $/\mathrm{mol\,dm^{-3}}$ when the acidic solution and bentonite mix is inversely proportional ($F \propto \frac{1}{[\mathrm{HCl}]}$).

Upon closer comparison between the experimental data in Figure 11 and the literature data in Figure 12, one will notice that the two graphs do follow a similar trend until when $[\mathrm{HCl}] = 1.00\,\mathrm{mol\,dm^{-3}}$ in the experimental data where the trend is broken. This indicates that the experimental data point for when $[\mathrm{HCl}] = 1.00\,\mathrm{mol\,dm^{-3}}$ is not reliable, specifically that it is lower than reality.

Considering both $\mathrm{pH} = -\log[\mathrm{H}^+]$ and $F \propto \frac{1}{[\mathrm{HCl}]}$, the mathematical prediction would be that factor of swelling as a function of pH would be an exponential function. This confirms that Figure 13 is not linear, with the factor of swelling at $\mathrm{pH} = 0$ ($\mathrm{HCl} = 1.00\,\mathrm{mol\,dm^{-3}}$) previously proven to be an outlier. The linear appearance of the literature data in Figure 14 is likely due to its restricted domain, as substantial change in gradient of Figure 13 isn't observed until pH > 1.50, which the literature data does not exceed this pH value.

Ultimately, while this investigation disproved the hypothesis by demonstrating an inversely proportional relationship between the factor of swelling and the concentration of HCl in the mixed solution, the data did not lead to a precise and background-based mathematical relationship between the two variables.

11.2 Evaluation

Source of Error	Effect on data	Effect on result	How might this error be corrected in a future experiment
High ratio of solution to clay	Uncertainty of the 10 mL graduated cylinder is significant in comparison to the final volumes of the bentonite clay. Any volumes that were below the minimum graduation were not accurate.	Large final uncertainties in the factor of swelling Any concentrations of HCl that lead to the final volume to be lower than the minimum graduated cylinder graduation are deemed unreliable. In this investigation, it was when [HCl] = $1.00\,\mathrm{mol\,dm^{-3}}$ and caused the final factor of swelling for that concentration to be lower than reality.	Determining a ratio that offers enough use of bentonite clay to make the graduated cylinder's uncertainty insignificant that does not lead to overflow of clay or solution during swelling nor lead to irregular distribution of absorption throughout the clay
Loss of bentonite clay during transfer to graduated cylinder due to stickiness to glassware and weigh boats	Losing bentonite in the process of transferring it to the graduated cylinder would cause the amount of bentonite mixed within the solution to be less than 1.00 mL. This in turn would cause the final volume of swollen bentonite to be lower than reality, potentially in multiples relative to the original loss of dry bentonite. Because the amount of bentonite lost between each trial will vary, this source of error also contributes to variability in the final volume of submerged bentonite clay.	Lower factor of swelling than reality. Contributes to variability on the factor of swelling.	Scratch as much of the remaining bentonite on each weigh boat and perform another round of transferring bentonite to each graduated cylinder. Take each graduated cylinder and tilt it to a degree such that any bentonite stuck on the upper portion of the graduated cylinder is removed.
Significant portion of bentonite being in the form of large granules	The true volume of bentonite standardized to mass is lower than 1.0 mL. This would also mean that the volume of bentonite mixed with the solutions is lower than reality, causing the final volume of swollen bentonite to be lower than reality.	Lower factor of swelling than reality.	Incorporate into the process a section dedicated to pulverizing the bentonite. This can be done using a mortar and pestle.

Despite these sources of error, the methodology and process in this investigation allows for simple experimentation surrounding clay swelling. Overall, omitting the last experimental data point when [HCl] = $1.00\,\mathrm{mol\,dm^{-3}}$, the trend of the data points fit very similarly to the literature data. This is despite that fact that this experiment was performed using common laboratory equipment instead of scarce equipment dedicated for these types of investigations.

12 Extension

Another area of investigation regarding clay soil swelling is determining the relationship between factor of swelling and the surface area to volume ratio of the clay soil. The soil can be separated according to their size using sieves of various aperture sizes, which will indicate the diameter of the filtered clay.

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