Investigating the rate of sublimation of pykrete

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Abstract

This study investigates the relationship between the exposed surface area of pykrete and its rate of sublimation. Pykrete is a very strong material made out of ice mixed with wood pulp, about as strong as some concretes. An experimental approach is taken, in which two investigations are carried out. The first investigation ensures that there is a measurable mass loss of pykrete. Three pykrete rods are made and stored in a regular consumer freezer. The samples are taken out and weighed every day for about a week, then the masses are plotted against time. There is a clear trend of mass loss over time in this freezer. Lessons learnt from this investigation was used to develop a second one. This second investigation aims to find out if there is a relationship between the exposed surface area and the pykrete's rate of sublimation. 100g of pykrete was stored in four polypropylene containers, each with different cross-sectional areas, stored in a different freezer. Their weights were measured using an improvised pulley system and a force sensor every day for five days, and their weight loss plottod against time. This investigation measured an increase in weight over time for the samples in the two larger containers, and the samples in the smaller ones had almost no change in weight. The uncertainties were too large and this result is not definitive. This study's conclusions indicate that there is indeed a measurable sublimation of pykrete under certain conditions, that there could be a relationship between the exposed surface area of pykrete and its sublimation rate, and further investigations are required to establish this relationship more precisely.

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Contents

1 Introduction

1.1 Research question

The research question is to find out how the exposed surface area of pykrete affects its rate of sublimation.

1.2 Definitions

- *Pykrete* is an ice alloy made out of ice mixed with wood pulp.
- *Sublimation of pykrete* is the process in which it loses mass as the ice in it changes directly into gas.

1.3 Background

1.3.1 Pykrete

Pykrete is an extremely strong ice alloy made out of ice mixed with wood pulp, named after Geoffrey Pike (*Pykrete* 2013; Perutz, 1948). It has been dubbed "super-ice" for its strength, and can be as strong as some concretes (Siddiqui and Bastian, 2010), while at the same time being very eco-friendly due to its biodegradable mixture, which makes it seem to be a viable construction material of the future.

And so, this material has been investigated for this purpose. Pike did not invent the material but initiated the study of building ships out of ice in Britain in WWII. Project Habakkuk was the plan to study and build giant floating aircraft carriers, which were almost floating islands, out of this material. The bergships, as they were called, were to be a base for many of the fighters and bombers in the middle of the Atlantic and Pacific. However, due to advancements in aviation technology, these bergships were ultimately not needed in the war and never built (Collins, 2002; Perutz, 1948). Nevertheless, in areas which have year-round temperatures far below 0°C, pykrete might still be suitable for building structures. Such a place could be inside a refrigerated warehouse, in Antarctica, and even elsewhere in the solar system, such as on the surface of the Saturnian moon Enceladus (*Enceladus: Overview* n.d.).

1.3.2 Sublimation and its impact

A significant mass loss can be potentially disastrous for any structure built using pykrete. The strength of the pykrete comes from the water molecules forming a crystalline structure around the wood pulp, forming an "ice alloy" (Hendrick, 2005). With the loss of this ice to the environment, the structure will be weakened, collapsing eventually.

To illustrate the sublimation of ice, Figure 1 contains photos of some ice with cut up photocopier paper mixed in before freezing, both taken in the lab. The photo on the left shows the sample just after it was created, and the one on the right shows the same sample (behind that new pykrete rod) after a few months left in the home freezer (described in the Approach in Section 1.4).

(a) Pykrete just after creation (b) Pykrete after a few months

Figure 1: Sublimation of a trial pykrete sample

The ice is sublimating and leaving the paper behind. As pykrete is similar to this sample in that it is simply paper mixed into ice with both materials being immiscible, a similar fate could befall a pykrete structure.

By finding out the rate of mass loss of pykrete as a function of its surface area, the costs of maintaining a pykrete structure can then be estimated.

1.4 Approach

An experimental approach is taken. Pykrete samples stored in freezers are weighed over a few days, and graphs of mass or weight against time are plotted, and the gradient of the best fit line, the rate of mass loss, is obtained.

Section 2 is the report for the first investigation. It involves the "home freezer" and has two purposes: to verify that there is indeed a measurable loss of mass of the pykrete, and to act as a trial run for the second investigation. The home freezer is simply a regular consumer freezer that was present in the lab.

Section 3 is the report for the second investigation. It involves a "microbiology freezer" and attempts to answer the research question. The surface area of the pykrete is changed and the change in weight recorded. This investigation was developed from the lessons learnt and limitations of the first investigation, detailed later in Section 2.5. This freezer is a freezer used by the biology labs in my school to store microbiology samples at a temperature much lower than the minimum temperature of the home freezer.

2 First investigation – is the mass loss measurable?

As stated in the approach, this investigation attempts to verify that there is indeed a measurable loss of mass of the pykrete, and is a trial run for the second investigation with the microbiology freezer.

The most common ratio of wood pulp to water is 14% by mass (*Pykrete* 2013; Hendrick, 2005), because the strength of pykrete increases only marginally with ratio greater than that (Perutz, 1948). This is the concentration I will use, and the wood pulp will be blended newspapers.

2.1 Variables

- Time from the start of the experiment (independent variable)
- Mass of the containers with pykrete (dependent variable)

2.2 Apparatus and Materials

- Mass balance (±0.001g)
- Clock (±1 min)
- Calendar
- Pykrete pulp (makes one pykrete rod)
  - Distilled water
  - 1 sheet of tabloid-sized newspaper
  - 250 cm^3 beaker
  - 100 ml plastic measuring cylinder
  - Blender
  - A non-fragile rod such as a test tube holder
  - Plastic takeout food container

2.3 Method

2.3.1 Making the pykrete rods

1. Place the 250 cm^3 beaker on the mass balance, and tare it.

2. Fill the beaker with about 9.8 g of newspaper. Record this mass as "Mass paper".

3. Tare the balance again.

4. Add the corresponding proportion (14% paper by mass) of distilled water. Record this mass as "Actual mass water".

5. Pour the contents of the beaker into the blender.

6. Turn the blender on. The newspapers will move be pushed away from the blades and stick to the sides of the blender. Turn the blender off, then use the rod to push the damp newspaper back onto the blades. Repeat this step until the newspaper looks sufficiently blended. This could take about 10 minutes.

7. Pour the contents of the blender into the beaker.

8. Transfer the contents of the beaker to the measuring cylinder, compacting the mixture with the rod.

9. Place the measuring cylinder in the freezer.

10. Wait 24 hours for the pykrete to freeze.

11. Remove the measuring cylinder from the freezer.

12. Remove the pykrete rod from the cylinder. This could be accomplished by running tap water at room temperature over the base and sides of the cylinder, and tapping it on a table until the rod loosens sufficiently and slides out.

13. Place the rod in a plastic container and immediately place both in the freezer.

14. Repeat all these steps for the next rod sample.

2.3.2 Obtaining the pykrete and container masses

1. Tare the balance.

2. Remove a pykrete sample, in its container, from the freezer.

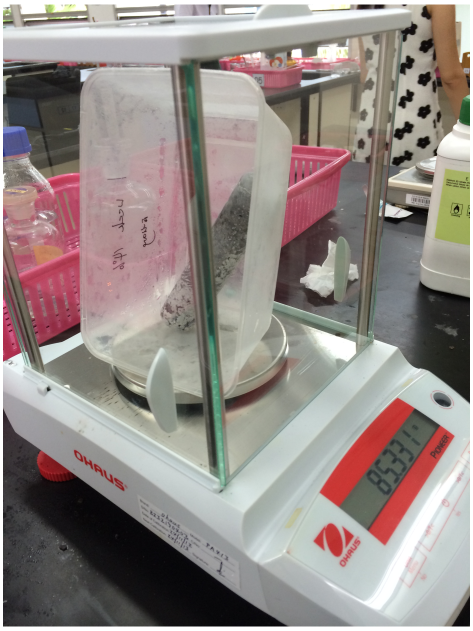


Figure 2: Weighing Rod 1

3. Quickly place the sample and its container on the balance as shown in Figure 2.

4. The reading on the balance will keep increasing at a decreasing rate. Wait until the reading stays constant for 5 s, then record the mass as m.

5. Record the time and date. The time and date of the first m reading will be time $t = 0$. Subsequent t readings will be calculated as t min after this point.

6. Repeat steps 1 to 5 for all the remaining containers.

7. Repeat steps 1 to 6 up to three times every day for at least 5 days.

8. Graph the change of mass m against time t for each container, and obtain the gradient of the line.

2.4 Results

2.4.1 Freezer

The temperature of the freezer was $(-17.6 \pm 0.1)\,^{\circ}\mathrm{C}$.

2.4.2 Notes on using the plastic measuring cylinder

The plastic measuring cylinder was not too weak and cracked after I made three trial samples (not used in this experiment), as seen in Figure 3a. Two pyrex measuring cylinders were tried too, but both broke after one ice sample each.

In the interest of preserving the nine remaining new plastic cylinders, the only ones the school had, an alternative had to be found. No other cylindrical containers could be successfully improvised, so the plastic cylinder had to be repaired.

Building upon the electrical resistance lab experiments done in physics class, current was passed through a nichrome wire, which was hot enough to melt the plastic where they touched, sealing up most of the cracks, as seen in Figure 3b. Sticky tape did the rest. This process was repeated for every rod created, as the crack reopened and grew.

(a) Cracked cylinder (b) Repaired cylinder

Figure 3: Repairing of the plastic measuring cylinder used

All three rods used in this experiment were created with this repaired measuring cylinder. A container was placed below the cylinder when placed in the freezer to catch all the water escaping from the crack, and it always remained empty.

2.4.3 Pykrete rods

Table 1: Masses of water and newspaper used to create the pykrete pulp

Rod no.	Mass paper/g (± 0.001)	Intended % paper by mass	Expected mass water/g	Actual mass water/g (± 0.001)	Total mass/g (± 0.002)	Actual % paper by mass
1	9.688	14	59.512	59.616	69.200	13.98
2	9.861	14	60.575	60.555	70.436	14.00
3	9.581	14	58.855	58.921	68.436	13.99

Table 1 contains the masses of water and newspaper for the pykrete pulp used to create each of the three rod samples.

2.4.4 Mass loss

When the samples and their boxes are removed from the freezer, the masses would increase at a decreasing rate. Condensation was also observed forming on the containers and on the samples. For consistency, the mass, accurate to the third decimal place, was only recorded once it stayed constant for 5 s. This duration was chosen because the mass seemed to increase indefinitely and also to prevent the pykrete from melting, but is otherwise arbitrary. The containers are also of the same size, to reduce the effect of condensation on the trend.

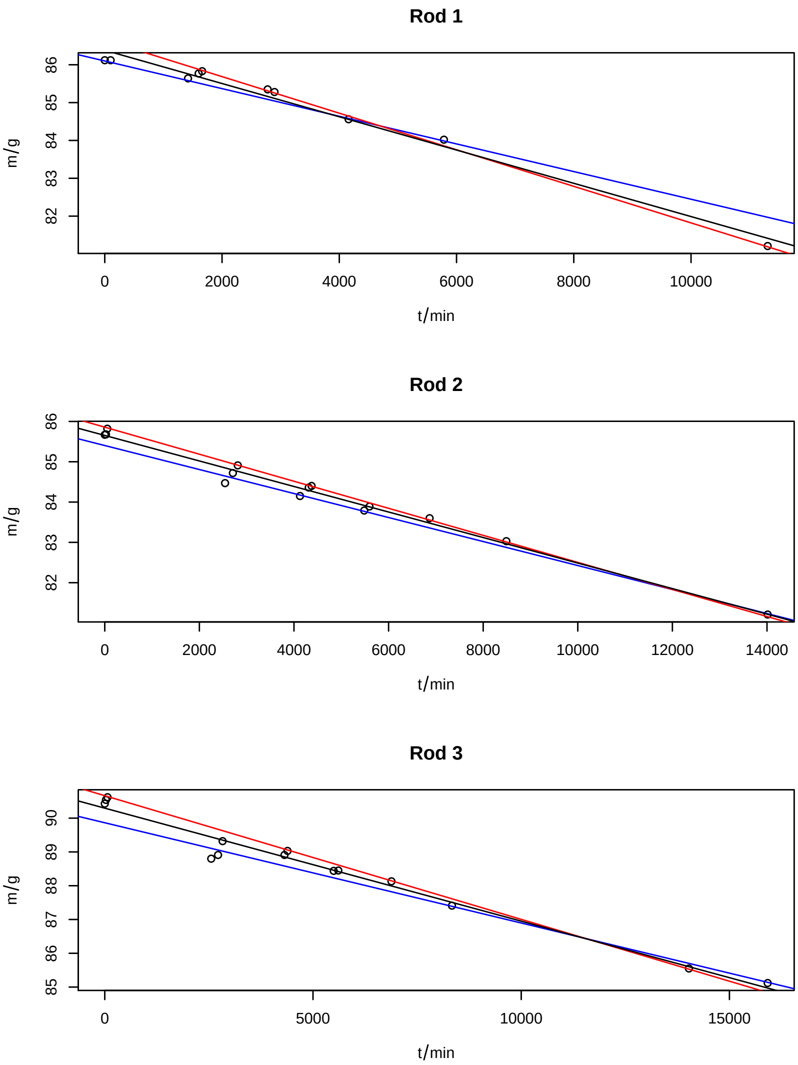


Figure 4: Plots of masses of the three rods m against time t

Figure 4 contains the graphs of mass against time for the three rod samples used.

Table 2: Rates of mass loss r and their absolute uncertainty Δr

Rod no.	$r/\mathrm{\mu g\,min^{-1}}$	$r_{\min}/\mathrm{\mu g\,min^{-1}}$	$r_{\max}/\mathrm{\mu g\,min^{-1}}$	$\Delta r/\mathrm{\mu g\,min^{-1}}$
1	439.48	365.30	483.20	74.18
2	316.65	297.74	335.51	18.91
3	334.51	296.72	366.07	37.80

Table 2 contains the final rates of mass loss for all three rod samples. The rates of mass loss r, is equal to the negative of the gradients of the lines of Figure 4 as $r = -\frac{\mathrm{d}}{\mathrm{d}t}m$. The uncertainty of r, Δr, is calculated by taking the largest absolute difference between r and each of $r_{\min}$ and $r_{\max}$, the gradients of the shallowest (blue) and steepest (red) possible lines respectively.

2.5 Conclusion

2.5.1 Trends

There is a reproducible downward trend between days. However, the mass would increase when I weigh the sample more than once a day, but return to the original day-to-day trend the next day.

2.5.2 Evaluation and improvements

As all the samples were kept in the same freezer, of a type normally found in homes, I hypothesized that the gain in mass was due to condensation forming on the ice samples when they were removed from the freezer to be weighed, and that a frost-free system was causing the loss in mass over days.

2.5.2.1 Frost-free system Frost-free systems are common in freezers, where the freezer periodically thaws to get rid of frost, which can accumulate over time from the water vapour in the air. When the freezer thaws, it removes that frozen condensation and some ice from the sample along with it, causing a steady loss in mass.

2.5.2.2 Condensation when removed from freezer As mentioned above in Section 2.4.3, when the samples and their boxes are removed from the freezer, the masses would increase at a decreasing rate. This could be explained by the condensation forming on it as it is out of the freezer and in room temperature air. Also, Singapore, where this experiment is conducted, has a very humid climate. This is a source of error as the actual mass of the pykrete rods and its containers cannot be obtained accurately.

2.5.3 Summary

As explained above, the loss in mass can be explained by other factors other than the natural sublimation of the pykrete. The next investigation will incorporate the lessons learnt from this one.

3 Second investigation – how does the exposed surface area affect the rate of mass loss?

In this second and final experiment, the surface areas of the pykrete samples will be changed, to find out how the surface area of the pykrete will affect its rate of mass loss.

A freezer borrowed from the biology lab will be used since it does not have a frost-free system. In addition to that, the masses of the ice samples will be measured in the freezer without opening the freezer door to prevent condensation from affecting the mass. This will be done using a pulley system and a force sensor outside the freezer.

3.1 Variables

- Exposed surface area of pykrete (independent variable)
- Weight of the containers and pykrete minus the frictional force between the string and the freezer door, and the friction of the pulley (dependent variable; recorded as F)
- Time between collection of data points (constant 24 hours)
- Humidity and temperature of freezer (constant; the freezer door will be closed throughout the experiment, and so an insignificant amount of air will enter and escape the freezer)
- Material of the containers (constant; polypropylene containers are used)

3.2 Apparatus and Materials

- Pykrete pulp
  - Distilled water
  - About 10 sheets of tabloid-sized newspaper
  - $250\,\mathrm{cm}^3$ beaker
  - Mass balance
  - Blender
  - A non-fragile rod such as a test tube holder

- Setup to measure the weight of the samples
  - Clock ($\pm 1\,\mathrm{min}$)
  - Calendar
  - Freezer
  - Temperature sensor
  - Retort stand with a retort stand clamp
  - Force sensor ($\pm 0.05\mathrm{N}$)
  - Data logger
  - Metal rod for the force sensor
  - Ruler and set square
  - 4 containers of different capacities with vertical sides but otherwise identical
  - 4 thin strings
  - Masking tape and marker to label the strings
  - 4 pulley systems (improvised)
    - Rubber bands
    - 2 carts including 2 axles with 2 wheels each
    - 4 retort stand clamps

3.3 Method

3.3.1 Assembling the weighing setup

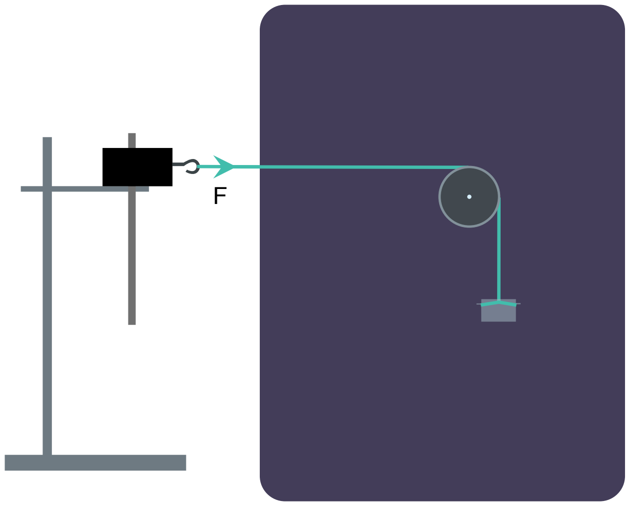
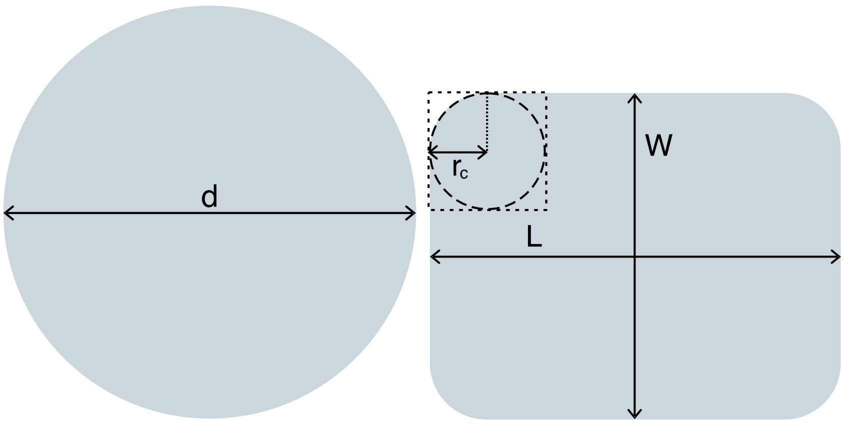


Figure 5: Finished pulley setup in the freezer

Figure 5 is an illustration of the setup, with the wheel and container inside the freezer.

1. Use the ruler to measure the length and width of each rectangular container, and the diameter of each circular container, as illustrated by Figure 6. Record these as L, W and d respectively.



(a) Small and Big Circle (b) Rectangle and Square

Figure 6: Illustration of what L, W, r_c and d represent

2. Use the set square to measure the corner radii of each of the rectangular containers, also illustrated by Figure 6. Record this as r_c.

3. Cut 4 lengths of string, each about 3m long, one for each container.

4. Tie one end of a string to a container, making sure the container and a 100g test weight in it can be safely suspended with the string. The test weight is roughly the mass of the final pykrete pulp, so it helps tell whether the setup will be able to support the pykrete and its container.

5. Label the string with masking tape, for identification when the freezer door is closed.

6. Repeat steps 4 to 5 for the other 3 containers.

7. Attach the pulleys to the freezer. For freezers like the one used in this experiment, which has drawers of metal with holes in the base, clamp each cart upside down to the drawer with two retort stand clamps. If necessary, tie rubber bands to secure the clamps. Figure 7 shows one cart that was used.

Figure 7: Pulley setup; a cart clamped one of the freezer's drawers

8. Hang the containers on the pulleys, or for my cart, on one wheel of each axle.

9. Thread the strings out of the freezer, closing the door behind it. The rubber seal between the freezer door and the freezer should provide enough friction to keep the string in its place.

10. Tie a loop at the end of the string hanging out of the freezer.

11. Tape the strings to the side of the freezer for orderliness. Figure 8 shows the finished setup in the freezer.

Figure 8: Finished setup

3.3.2 Making the pykrete

This is similar to the procedure to make the pykrete rods, except for the quantities of the materials involved and the containers the pulp is put into.

1. Place the 250 cm^3 beaker on the mass balance, and tare it.

2. Fill the beaker with two sheets of newspaper. Record this mass as "Mass paper".

3. Tare the balance again.

4. Add the corresponding proportion (14% paper by mass) of distilled water. Record this mass as "Actual mass water".

5. Pour the contents of the beaker into the blender.

6. Turn the blender on and off (the Pulse function). Use the rod to push the damp newspaper back onto the blades and repeat this step until the newspaper looks sufficiently blended. This could take about 10 minutes.

7. Place the beaker on the mass balance and tare it.

8. Fill the beaker with 100g of the pulp from the blender.

9. Transfer the contents of the beaker to a container in the freezer, compacting the mixture with the rod. Figure 8 shows a trial sample in a box similar to "Square" about 24 hours after this step was completed.

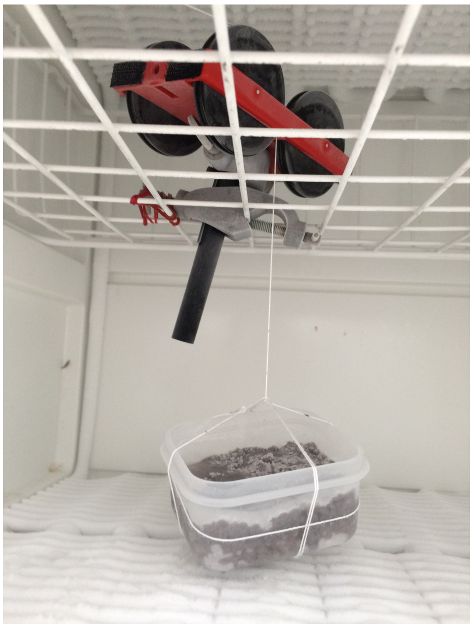


Figure 9: Finished pykrete in a trial Square box

10. Repeat steps 7 to 9 for the other three containers. The containers have different cross-sectional areas which will result in different exposed surface areas of the pykrete.

3.3.3 Obtaining the pykrete and container weights

1. Attach the force sensor to the metal rod, with the force sensor above the center of gravity of the metal rod.

2. Clamp the metal rod securely to the retort stand. This should be a stable stand.

3. Connect the force sensor to the data logger and set it to a range of ± 10N.

4. Hook one of the strings onto the force sensor as shown in Figure 10. This image was taken during some experimentation, and uses a marker instead of the metal rod, and the force sensor is not connected to a data logger.

Figure 10: Retort stand setup outside the freezer

5. Where the string enters the freezer, pull the rubber seal apart, forming a gap. This will remove any additional friction between the string and the rubber.

6. Tilt the retort stand away from the freezer as shown in Figure 11 and slowly let it return to its rest position.

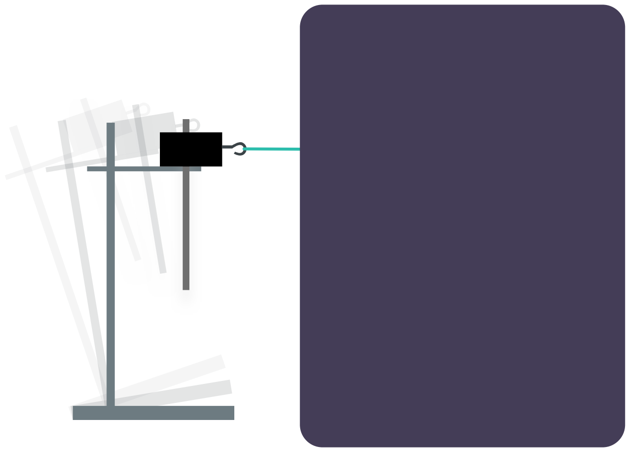


Figure 11: Tilting the retort stand

7. Record the force reading on the data logger as F, and the time and date. As with step 5 in Section 2.3.2, the time and date of the first F reading will be time $t = 0$. Subsequent t readings will be calculated as t min after this point.

8. Repeat steps 4 to 7 for the other 3 containers.

9. Repeat steps 1 to 8 five times, approximately 24 hours apart, for 5 data points.

10. Plot a graph of the change in F from F at $t = 0$ against time t for each container, and obtain the gradient of the best fit line.

11. Plot these gradients against the surface areas of their respective containers.

3.4 Results

The freezer was so cold that all the thermometers in the lab were unable to measure its temperature. It is safe to say that it is lower than $-20.0\,°C$, the minimum temperature they could measure.

3.4.1 Containers

The four containers used were made of polypropylene, all purchased at a Daiso convenience store. Table 3 is a summary table of the nicknames given and dimensions of their internal cavity, where L is the length, W is the width, r_c is the corner radius, and d is the diameter. Only circular containers have diameters measured; other rectangular containers are measured for the other three quantities. This is illustrated by Figure 6. Do note that the “Square” is actually a rectangle, it just looked like a square.

Table 3: Dimensions of containers

Container	L/cm (±0.10)	W/cm (±0.10)	r_c/cm (±0.10)	d/cm (±0.10)
Rectangle	12.00	8.00	1.30	
Square	7.90	6.90	1.40	
Big Circle				9.50
Small Circle				7.90

From those measured dimensions, the surface area A, exposed to the environment, of any liquid inside it is equal to the cross sectional area of the container, as it will take the shape of the cavity. However, as pykrete is a solid the surface exposed will not be perfectly flat and could contain imperfections, A is not a precise value.

The percentage uncertainty of A is obtained differently for the circular containers and the others. As A for circular containers is equal to $\pi\left(\frac{1}{2}d\right)^2$, the percentage uncertainty is simply $2\frac{\Delta d}{d} \times 100\%$, where Δd is the absolute uncertainty of d.

However, A for the rectangles is more complicated. Refer to Figure 6b. A is equal to the area $(L \times W) - 4$ times the area of unshaded area of the square with length $2r_c$, which is equal to $(L \times W) - (2r_c)^2 + (\pi \times r_c^2)$. Therefore the percentage uncertainty of A is calculated with this formula:

$$\frac{\left[\left(\frac{\Delta L}{L} + \frac{\Delta W}{W}\right) \times (L \times W)\right] + 2^2\left[\left(2 \times \frac{\Delta r_c}{r_c}\right) \times r_c^2\right] + \pi\left[\left(2 \times \frac{\Delta r_c}{r_c}\right) \times r_c^2\right]}{A} \times 100\%$$

With that, Table 4 shows the surface areas A for all four containers calculated from the data in Table 3.

Table 4: Surface areas A for each container and their percentage uncertainties

Container	A/cm^2	% uncertainty A
Rectangle	95	3.9
Square	53	3.5
Big Circle	71	2.1
Small Circle	49	2.5

3.4.2 Pykrete pulp

Table 5 contains the masses of water and newspaper used to create the pykrete pulp used. (100.00 ± 0.04) g of this pulp was put in all the containers, and frozen.

Table 5: Masses of water and newspaper used to create the pykrete pulp

Mass paper/g (±0.001)	Intended % paper by mass	Expected mass water/g	Actual mass water/g (±0.001)	Total mass/g (±0.002)	Actual % paper by mass
58.869	14	361.62	361.760	420.629	13.995

3.4.3 Weight loss

Table 6: Weights of the containers F at different times

Container	t/min (±1)	F/N (±0.05)	$-\Delta F$/N(±0.10)
Rectangle	0	0.24	0.00
	1324	0.33	-0.09
	2432	0.31	-0.07
	4291	0.33	-0.09
	5797	0.37	-0.13
Square	0	0.58	0.00
	1326	0.56	0.02
	2428	0.55	0.03
	4290	0.52	0.06
	5797	0.60	-0.02
Small Circle	0	0.32	0.00
	1326	0.32	0.00
	2422	0.30	0.02
	4288	0.32	0.00
	5796	0.32	0.00
Big Circle	0	0.34	0.00
	1325	0.58	-0.24
	2425	0.51	-0.17
	4290	0.53	-0.19
	5797	0.60	-0.26

The force F, measured by the force sensor, is equal to the weight of the pykrete sample and its container, minus the frictional force between the string and the freezer door and the friction of the pulley. Figures 11 and 5 above show how the F is measured. Table 6 shows the readings for F at different times, and the weight loss $-\Delta F$, the calculated difference between F at $\mathrm{t} = 0\,\mathrm{min}$ and F. The mass loss $-\Delta m$ can then be obtained, since $-\Delta F = -\Delta m \times g$.

The F values are much lower than the actual weight of the pykrete and the container. If $(100.00 \pm 0.04)\,\mathrm{g}$ was present in the container, the actual weight of just the pykrete itself will be $m \times g = 100.00\,\mathrm{g} \times 9.81\,\mathrm{N\,kg^{-1}} \approx 0.981\,\mathrm{N}$. This shows that there is a lot of friction present, which came from the string's contact with the fridge and the pulley.

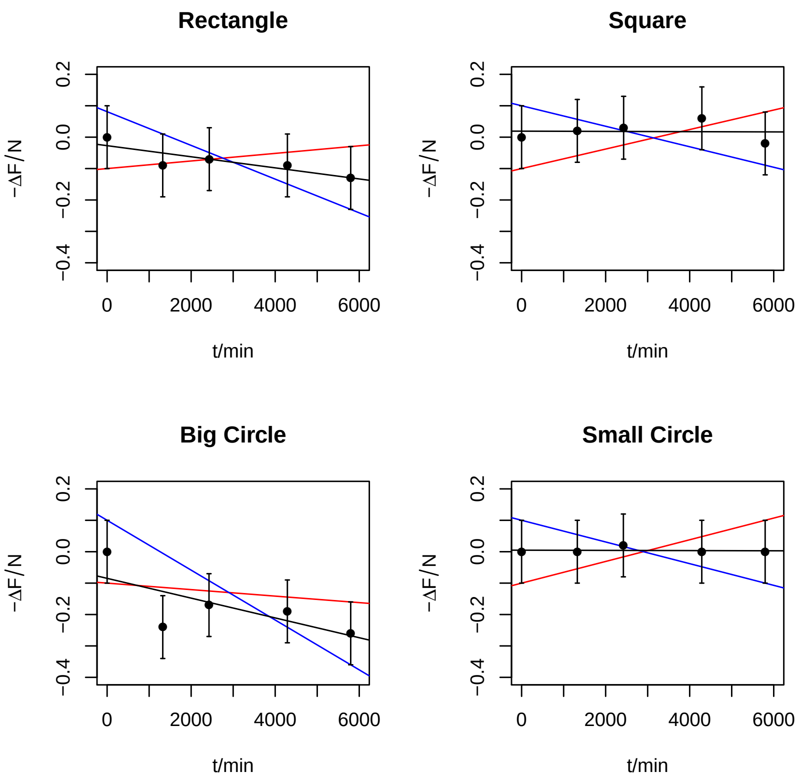


Figure 12: Weight loss $-\Delta F$ against time from start of experiment t[1]

[1]The uncertainty of the time is ± 1 and insignificant compared to the scale of the time axis.

Figure 12 shows the plots of mass loss against time for all the containers. The black line is the line of best fit, the blue line is the shallowest possible slope, and the red line is the steepest possible.

Table 7: Rates of weight loss r and their absolute uncertainty Δr

Container	$r/\mathrm{N\,min^{-1}}$	$r_{\min}/\mathrm{N\,min^{-1}}$	$r_{\max}/\mathrm{N\,min^{-1}}$	$\Delta r/\mathrm{N\,min^{-1}}$
Rectangle	-1.77×10^{-5}	-5.37×10^{-5}	1.21×10^{-5}	3.60×10^{-5}
Square	-3.90×10^{-7}	-3.26×10^{-5}	3.11×10^{-5}	3.23×10^{-5}
Big Circle	-3.15×10^{-5}	-7.94×10^{-5}	-1.04×10^{-5}	4.79×10^{-5}
Small Circle	-3.23×10^{-7}	-3.45×10^{-5}	3.45×10^{-5}	3.48×10^{-5}

Table 7 shows the rates of weight loss r, which is equal to the gradients of the lines of Figure 12 as $r = -\frac{\mathrm{d}}{\mathrm{d}t}F = \frac{\mathrm{d}}{\mathrm{d}t}(-\Delta F)$. The uncertainty Δr is calculated by taking the largest absolute difference between r and each of $r_{\min}$ and $r_{\max}$, the gradients of the shallowest (blue) and steepest (red) possible lines respectively.

3.5 Conclusion

3.5.1 Trends

Unfortunately, the results captured in this second investigation are unusable because of the extremely high uncertainties present. The best fit lines show that the weight will actually increase with time, although with the high uncertainties present, the weight could also decrease with time.

3.5.2 Evaluation and suggestions for improvement

3.5.2.1 Friction Most of the uncertainty of $-\Delta F$ is caused mainly by the friction between the string and both the fridge and the pulley. More pulleys could be used in places where the string makes contact with the freezer, which will reduce friction.

3.5.2.2 Time The upward trend observed in same Figure 12 could be more obvious had the experiment been done for a longer time. 20 days would produce a clearer picture and clarify if the trend was caused by the uncertainty of $-\Delta F$ or is actually due to a mass loss.

3.5.2.3 Other impurities in the pykrete The newspapers used as the wood pulp also contain impurities such as ink, which may contribute to error by changing the nature of the ice. Although this is relatively minor, it could cause some inconsistencies with the strength of the pykrete. A simple solution will be to use blank paper.

3.5.3 Potential for further investigation

Despite the lack of data, there seems to be a trend with regards to the surface area and the weight difference. The samples with a larger exposed surface area, namely Rectangle and Big Circle, have a downward trend, while the other two with a smaller area have a horizontal trend. This could possibly show that there is a relationship between the exposed surface area and the rate of mass loss, although there is insufficient data to conclusively prove it.

4 Overall conclusion

Although the second investigation had no usable data, the rate of mass loss data from the first investigation will only be relevant to structures that experience a short, daily thawing, which could still be useful in places like a freezer building, or on a planet where the rotation of the planet would bring the structure to face the sun. Either way, more data is needed for both cases.

4.1 Possible follow-up investigation

A potential future third investigation would be able to build on both of the investigations mentioned here. Apart from the points already stated in the conclusions of both investigations, these are a few more issues that need to be solved.

4.1.1 Temperature

The temperature of the freezer used would be recorded with a suitable apparatus such as a thermocouple, as according to the Maxwell-Boltzmann distribution, water particles will be more likely to escape the ice lattice at higher temperatures due to the higher average kinetic energy of the particles, and hence the temperature is important. The second investigation had the temperature recorded at below $-20\,°C$, the minimum temperature the lab's thermometers could measure, and I suspect that the actual value is lower.

4.1.2 Measuring mass

The approach of using pulleys, probably one of the best possible given the limited resources available, was unfortunately compromised by the friction and the relatively low precision of the force sensor.

A more precise approach, one considered but could not be done, is to place a weighing scale, properly calibrated, directly in the freezer, and the masses read with a lightbulb and camera mounted inside the freezer. That would avoid the friction problem entirely, but would require special weighing scales that can operate in temperatures below $-30\,°C$.

Another solution is to find or drill a hole in the top of the freezer that drops directly into the freezer cavity. Although the force sensor is still required, this will remove the need for a pulley system.

4.2 Implications

Nevertheless, if there is a positive relationship between mass loss and surface area exposed, corporations operating pykrete facilities may look into methods of shielding or coating the material somehow to slow the rate or stop it altogether. Structures made out of pykrete for long term use such as vaults may be impractical if the structure will collapse after a period of time, and in such cases traditional materials such as concrete may be a safer, cheaper solution. If there is a negative relationship, however, structures made out of this material could build themselves from a simple, cheap scaffold, although it may take a relatively long time. This would be especially beneficial to colonies on other planets where resources such as electricity and people are scarce.

This investigation is a starting point and narrows down the rate of mass loss and surface area to a value close to and around zero, a value that may be narrowed down further by additional experiments. This would prove that pykrete is a possible material for construction.

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