Investigating the Strength of Plastics created via Polymer Cross-Linking

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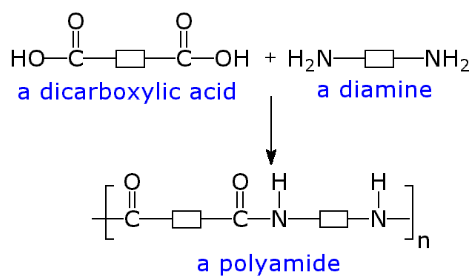
Research Question:

What is the effect of changing the concentration of the boric acid used in a reaction with polyvinyl acetate (school glue) on the internal strength of the cross-linked polymer created via their reaction, as measured through the use of a hanging scale?

Introduction:

My exploration into the world of plastic and polymer creation first began when I started playing with my Lego sets as a child and teenager. At that point, I did not understand how the company was able to create such small yet durable plastics, and with my knowledge at the time, I could not understand the chemical reactions going into its creation. Fast-forward to last month, and my teacher had just taught us about condensation polymers, and the organic reaction formula for creating them :



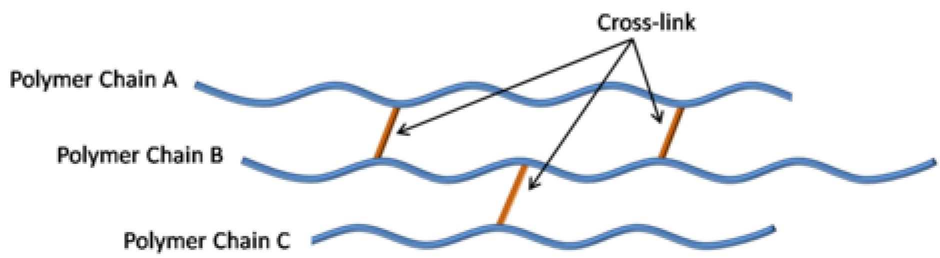
A diagram showing how two generic compounds (a dicarboxylic acid and a diamine) can react together to create a polyamide. This theory can also be used to create various other polymers

This was how I was first introduced to polymers, and learned about how to create them. This initial concept led me to further research about another type of polymers, cross linked polymers, which was supposedly the main method of creating inorganic plastics. More information regarding the creation of cross-linked polymers will be listed below. Now that I had learned how to create a polymer, I worked towards creating much stronger plastics at relatively cheap costs. This led me to the notion of changing the concentration of one of the reactants, boric acid, and recording the changes to the internal strength of the polymer. With these ideas in mind, I hypothesised the methodology behind this experiment, in order to determine the most effective way to create strong cross-linked polymers.

Background:

Cross Linking Polymers

Cross-linking is considered to be the formation of covalent bonds that hold together segments of several polymer chains. When done effectively, the product contains a random three-dimensional network of interconnected polymer chains.

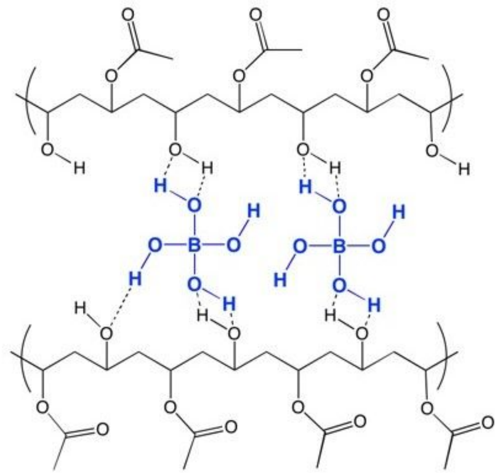


A diagram showcasing how cross-links are created between long polymer chains to connect them to each other, thus creating one long chain

The general trend shows that as a substance produces more cross-links between the polymer chains, it is seen as having more rigidity, hardness, and melting point. Due to this property, almost all forms of hard plastic s are creating using cross-linking. One example of a cross-linked plastic is *melamine*, which is used in plastic crocker and epoxy resin glues.

Borax Reaction with Polyvinyl Acetate

One of the reactions analyzed was the reaction between borax and polyvinyl acetate. Polyvinyl acetate is most abundant in school glue, and is known for having the property of bonding very readily with various materials, and then 'permanently' connecting to them when solidified (hence why it is used as a glue). When borax is added to polyvinyl acetate, however, the consistency changes. The borax molecules act as 'bridges' between the long chains of polymers, increasing the length of the polymers and forming closed polymer circuits within the entire mixture.When this compound is then dehydrated, it solidifies into a much stronger inorganic compound compared to when glue first hardens. This change in physical properties is also, in turn, due to the presence of boron in the compound; by introducing this new chemical which forms tightly knit bonds with every other element, the overall integrity of the compound increases.



A diagram showing how Borax reacts with polyvinyl acetate to from long polymer chains, which when in a hydrated state, can become silly putty, while becoming a hard plastic when anhydrous

Hypothesis:

According to the above mentioned data regarding cross links between borax and long polymer chains, I hypothesize that there will be a logarithmically increasing relationship between the concentration of boric acid used, and the internal strength of the cross-linked polymer product from the reaction. This is because in higher concentrations of boric acid, there exists more borax ions, which can cause more “bridges” or connections between long chains of polymers to be made. By establishing more connections between the chains of polymers, the overall physical qualities of the product increases as more energy would be required to break all of the bonds. It would be logarithmically increasing due to the fact that the concentration of the boric acid will increase exponentially, however the internal strength of the products will increase linearly. When combining a linear progression in one axis with an exponential progression in another, a logarithmic progression is established.

Variables:

Independent	*Concentration of Boric Acid* - the concentration of the boric acid was measured by adding a set amount of the borax ($Na_2[B_4O_5(OH)_4] \cdot 8H_2O$) to varying volumes of water. It was calculated in mol dm^{-1} with an uncertainty of 0.005%. To represent boric acid concentration: the volumes chosen were in an exponentially increasing form, going as follows; 0.01953125dm^3 (4%), 0.0390625dm^3 (8%), 0.0778125dm^3 (16%), 0.15625dm^3 (32%), and 0.3125dm^3 (64%).
Dependent	*Internal Strength of the Polymers* - the amount of weight that the cross-linked polymer could take before breaking in half, measured in kilograms using a hanging scale with an uncertainty of 0.1kg. To measure this variable: the created polymers were attached individually via a piece of string to the hanging scale. The plastic was then held on one end by a person, while the hanging scale was pulled until the plastic broke.

Controlled	Method of Control	Possible effect on results
Mass of Borax	Using an electronic balance, 2.5g of borax was measured and transferred to a 500cm^3 beaker	Changing the mass of borax used changes the number of moles, which directly changes the concentration of the solution.
Shape of Container	Similarly shaped boats were made using aluminum foil to ensure that all the samples resemble the same object	Changes to the shape of the product would in turn change the structural integrity of it and may create imbalances in terms of internal strength
Volume of Glue - 10cm^3	Using a 25cm^3 measuring cylinder, 10cm^3 of glue was measured out and placed in a 20cm^3 measuring cup	Changes to the volume of glue will result in a different consistency and concentration of polyvinyl acetate ions, which can change the lengths of the polymers and thus affect the internal strength

Volume of Water used with Glue - $10cm^3$	Using a $25cm^3$ measuring cylinder, $10cm^3$ of water was measured out and placed in a $20cm^3$ measuring cup	Changes to the volume of water will result in a different consistency and concentration of polyvinyl acetate ions, which can change the lengths of the polymers and thus affect the internal strength
Volume of Borax Solution - $5cm^3$	Using a $25cm^3$ measuring cylinder, $5cm^3$ of the borax solution was measured out and placed in a $500cm^3$ beaker	Changes in the volume of borax solution will affect the length of the reaction and how many cross-links are created, therefore affecting the internal strength
Volume of Glue Solution - $20cm^3$	Using the $20cm^3$ measuring cup as whole, all $20cm^3$ of the glue solution was poured in a $500cm^3$ beaker	Changes in the volume of glue solution will affect the number of polyvinyl acetate ions in the reaction, changing the lengths of the polymers and therefore affecting the internal strength
Temperature and Pressure during Reaction - STP (Standard Temperature and Pressure)	The experiment was conducted in the exact same room and area on various different days to ensure that all reactions undergo in the same conditions	If the experiment was conducted in varying conditions, the changes in temperature and pressure would affect how the reactions occurs, which can affect the number of cross-links and therefore affect the internal strength

Uncontrolled	**Method of Control**	**Possible effect on result**
Temperature after Reaction	By maintaining the relatively same low temperature, the process is maintained	High temperatures would cause additional reactions, which could completely change the product
Layering of Aqueous Polymer	By pouring in the same angle and same way, similar layering will occur	Layering of the polymer changes the physical structure, therefore affecting the internal strength

Apparatus:

- Magnetic Stirrer
- Hot Plate
- Stirring rod
- Weighing boat
- Electronic balance ± 0.01g
- 25cm^3 measuring cylinder ± 1cm^3
- 5 x 2.5g borax formula
- Water
- 2 x 500cm^3 beaker ± 12.5cm^3
- 20cm^3 measuring cup ± 2.5cm^3
- 5 x 2cm (height) by 4cm (length) by 2cm (width) aluminum foil boats
- Hanging scale ± 0.25kg
- String
- 100cm^3 measuring cylinder ± 1cm^3

Risk Assessment:

Hazard	**Control Measure**
Safety: Borax is toxic to the body when ingested, and causes severe irritation of the eyes	Wear eye protection, and cover hands using gloves when dealing with the higher concentrations
Safety: Glassware was being used throughout the lab, which could break and cut someone	Exercise caution when handling glassware, and be aware of your surroundings
Safety: Glue can get stuck in the drains, and cause clogging of the pipes	Dispose of the glue in a piece of tissue and then throw into the garbage can
Safety: When heating up the solution, nauseating fumes were released	Conduct the experiment underneath a fume hood to ensure no fumes escape
Environmental: Borax is toxic for the plants and can poison water samples in higher concentrations	The chemical should be appropriately diluted using water, and then poured down the drain
Environmental: Polyvinyl Acetate (glue) is toxic for all forms of life, and can cause skin irritations as well	The chemical should be wrapped in tissue and disposed of into a garbage can
Ethical	No ethical issues to note as there were no uses of living organisms.

Preemptive Calculations:

$$Na_2[B_4O_5(OH)_4] \cdot 8H_2O = 201.22\ g/mol \pm 0.1\ g/mol$$

One of the first things I needed to determine was the grams of borax I would use for all my samples. To determine this, I picked an arbitrarily small amount of moles to offset the relatively large molar mass of the borax compound, such that the grams of borax remains small.

$$n = \frac{m}{MM}$$

$$0.0125\ mol = \frac{m}{201.22\ g/mol}$$

$$m = 2.5g$$

Next I had to calculate each individual volume for the concentration of boric acid I was going to make. Since I already knew what the five concentrations were, all I had to do was work backwards from there, using the number of moles of borax to determine the respective volumes.

4% concentration : $v = \frac{n}{c}$

$$v = \frac{0.0125\ mol}{0.04\ mol/dm^3}$$

$$v = 0.3125dm^3$$

8% concentration : $v = \frac{n}{c}$

$$v = \frac{0.0125\ mol}{0.08\ mol/dm^3}$$

$$v = 0.15625dm^3$$

16% concentration : $v = \frac{n}{c}$

$$v = \frac{0.0125\ mol}{0.16\ mol/dm^3}$$

$$v = 0.078125dm^3$$

32% concentration : $v = \frac{n}{c}$

$$v = \frac{0.0125\ mol}{0.32\ mol/dm^3}$$

$$v = 0.0390625dm^3$$

64% concentration : $v = \frac{n}{c}$

$$v = \frac{0.0125\ mol}{0.64\ mol/dm^3}$$

$$v = 0.01953125dm^3$$

Procedure:

Creating the Polyvinyl Acetate Solution

1. Pour $10cm^3$ of Elmer's glue into the $20cm^3$ measuring cup
2. Pour $10cm^3$ of water into the same measuring cup
3. Using a stirring rod, mix the water with the glue until there the mixture is consistent throughout
4. Repeat steps 1-3 fourteen more times for each sample created

Creating the 0.0125mol Boric Acid Solution

1. Place 2.5 grams of the borax formula into the 500cm^3 beaker
2. Pour 0.01953125dm^3 of water into the beaker to create the 64% solution
3. Using the magnetic stirrer, mix the borax formula with the water until most of the formula has dissolved (please note that not all of it will dissolve)
4. Repeat steps 1-3 for 0.0390625dm^3 (32%), 0.078125dm^3 (16%), 0.15625dm^3 (8%), and 0.3125dm^3 (4%) of water

Creating the Cross Linked Polymer

1. Pour 5cm^3 of the 0.0125mol boric acid solution into a second 500cm^3 beaker
2. Pour the entire amount of the polyvinyl acetate solution into the same beaker
3. Using a stirring rod, stir the mixture until it thickens
4. Pour the thick solution into an aluminum foil boat
5. Using a hot plate, heat up the solution on a low heat setting for 45 minutes
6. Set aside the solution and let it cool for one week
7. Remove the solidified polymer from the aluminum foil
8. Repeat steps 1-7 for 2 more samples for the same concentration of boric acid
9. Repeat steps 1-8 for the other concentrations of boric acid

Testing the Strength of the Polymer

1. Tie the polymer created to one end of a piece of string
2. Tie the other end of the string to a hanging scale
3. Have one person hold the polymer back, while the other person pulls the hanging scale until the polymer breaks
4. Record the weight value for which the polymer broke
5. Repeat steps 1-4 for the remaining fourteen samples of polymers, recording it by concentration and trial

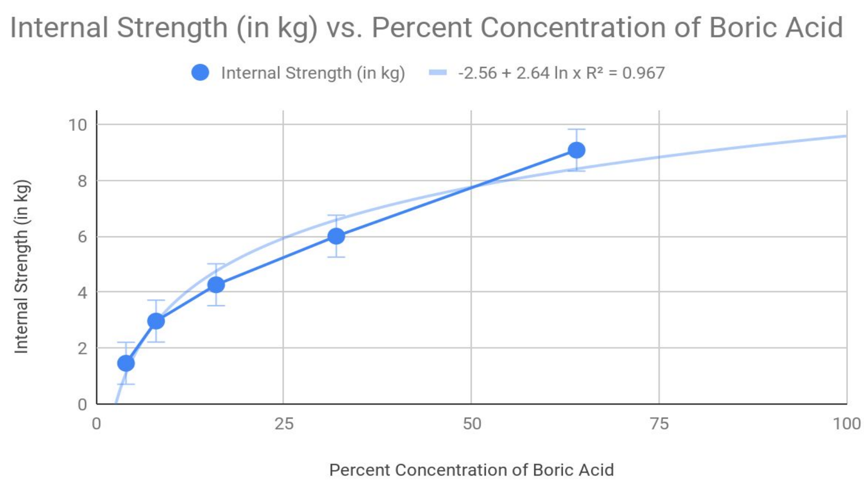
Results:

Concentration	Trial	Strength (in kg) ± 0.25kg	Average Strength (in kg) ± 0.75kg
4%	1	1.45	1.46
	2	1.62	
	3	1.31	
8%	4	2.55	2.97
	5	3.42	
	6	2.95	
16%	7	4.23	4.27
	8	3.99	
	9	4.68	
32%	10	6.17	6.01
	11	6.08	
	12	5.79	
64%	13	8.61	9.09
	14	10.21	
	15	8.45	

An image of my plastics created after a week of cooling, taken 2018-12-19

One of the interesting things to note when creating the cross-linked polymers is that as the concentration increased, the products became more opaque. This would be due to the additional cross-linking between the long polymer chains, making them appear more visible. As the polymer chains become more visible, the overall opacity of the product increases. Therefore the samples with the 64% concentration of boric acid were seen to have the highest levels of opacity.

Data Processing with Graphing:



Graph showing the relationship between the internal strength and concentration

Conclusion:

The positive correlation between the percent concentration of boric acid and the internal strength (in kg) of the cross-linked polymers shows that as the concentration of boric acid increased, it led to an increase in the internal strength of the polymer, making them much harder to break and able to withstand much more strain. Therefore, increasing boric acid concentration results in stronger cross-linked polymers.

The error bars shown in the graph include the absolute uncertainty of the measured variable. This correlates with the raw data, showing concurrence with the accuracy of the experiente conducted.

These results signify an accurate match with the hypothesis stated above; that there would be a logarithmically increasing relationship between the concentration of boric acid used, and the internal strength of the cross-linked polymer product from the reaction. This hypothesis was demonstrated by the overall shape of the linear graph. When looking at the R^2 value of a logarithmic line of best fit, there is an accuracy of 0.967, indicating an approximate 96.7% match from my raw data to the computer-generated logarithmic line of best fit.

This pattern in the data collected was assumed to be caused by the increased number of cross-links between the long polyvinyl acetate polymer chains. The general trend for polymers is that the longer the chain, the stronger the polymer. Through the cross-links created by the borax ions filling in the gaps between the polyvinyl acetate polymer chains, the overall length of the chain increases greatly, therefore increasing the internal strength of the polymers. As higher concentration are used, there exists more borax ions to cross-link with the polyvinyl acetate ions, further proving my hypothesis of internal strength increasing logarithmically in relation to boric acid concentration

Evaluation:

Limitation	Improvement
The borax powder was not properly sealed away and had an open lid, making it open to contamination via the air. This would reduce the cross-linking effects of the borax, which would drastically change the physical properties of the polymer. These changes would result in a lower value for the amount of weight which the polymers could have handled.	One thing to be done is to properly seal the the borax container with a lid so that no air contamination could occur Another thing would be to store the open borax in a much cooler place as fewer reactions are to occur in colder temperatures, and therefore the air contamination will not have any effect on the borax
The actual test for the internal strength of the polymer was on the basis of another person holding the polymer while I pulled the hanging scale. The person would tend to move towards or away from the direction I am	One thing would be to set the polymer as a ‘bridge’ across two objects, and pull the hanging scale downwards until the ‘bridge’ breaks.

pulling. This would result in varying values for the internal strength of the polymer, ranging from above to below the actual value, depending on the way which the person moved.	Another way would be to attach a proper force probe to the polymer and measure the force required to break the polymer.
The polymer ended up layering in various different ways while being settled into the aluminum foil boats. This would change the overall structure of the polymer, which in turn would change the internal strength of the polymer based on the number of layers which were formed.	One way to ensure no layering is to use a palette knife or a piece of paper and smooth out the solution in the boat. Another way would be to create one large template for the various concentrations, and cut out each trial to test the polymer
Elmer's school glue is not a pure source of polyvinyl acetate. Since there are other chemicals found inside the glue, these chemicals could potentially have other side reactions with the borax, causing various other things to occur. This could potentially affect the internal strength of the polymer as the polymer could be bonded to many other chemicals.	One way would be to buy proper polyvinyl acetate from a store to use with the borax. Another way would be to replace the polyvinyl acetate with polyvinyl alcohol as they both end up having the same reaction when mixed with borax.

Although the air contamination could have an effect on the borax, since the borax is already a hydrated solid, not much will occur when combined with the air as there are not many elements which could have proper reactions with the borax particles.

In order to extend this investigation into the internal strength of polymers created through the use of cross-linking, it would be crucial to experiment and record the changing melting and boiling points of the plastic. If the melting point for the plastic increases greatly, this would mean that there is also another relation between the concentration of boric acid and the overall strength of the polymer. Another interesting thing to experiment would be the introduction of halogenated borax particles rather than regular borax particles. This would be an interesting way to see how the strength of the plastics are affected by the boron cross-link bridges with the aid of various halogens.

Citations:

“5 - Condensation Polymers - IGCSE Chemistry.” *Google Sites*, sites.google.com/site/internationalgcsechemistry/year-11-topics/topic-5---synthetic-polymers-double-award/5---condensation-polymers.

“GCSE Bitesize: Structure and Properties of Polymers - Higher.” BBC, BBC, www.bbc.co.uk/schools/gcsebitesize/science/ocr_gateway_pre_2011/carbon_chem/6_designer_polymers4.shtml.