Why Paper Straws Suck: Bamboo Straw Supremacy

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Abstract

The aim of this project is to compare the material properties of bamboo and paper straws (as alternatives to plastic straws). Flexural tests and water absorption tests were performed on both types of straws after they were submerged in water for varying amounts of time: for both types of straws, they were submerged in fresh water; for the bamboo straws, they were also tested after being submerged in salt water of a predetermined concentration. Additionally, an impact test was conducted on both straws when they are dry and only the bamboo straws after absorbing water for a predetermined amount of time. Paper straws absorbed an average of 2 grams of water over the three trials, while the non salinated bamboo straws absorbed an average of 1.67 grams of water and the salinated bamboo straws absorbed an average of 1.93 grams. For the flexural strength tests, bamboo straws had an approximately 15-18 times higher modulus of rupture - the maximum fiber stress at failure. Lastly, for the impact test, there was a clear trend that indicates that strength increases in this order: paper straws, bamboo straws, and wet bamboo straws. This study provides novel material testing methods and results for paper and bamboo straws which illustrates the superiority of bamboo straws over paper straws in many different areas of material property.

1 Introduction

Plastic straws are extremely ubiquitous in society. Because of its cheap but durable nature, single-use plastic straws can be found in many homes, restaurants, coffee shops, hotels, and more. In fact, Americans use 500 million plastic straws a day [1]. Although plastic straws are widespread, inexpensive, and convenient, they are not sustainable or environmentally friendly [2]. In reality, plastic straws frequently blow into oceans from landfills and are the 7th most collected item from beaches and an estimated 4.8-12.7 million metric tons enter the ocean in 2010 [3, 4]. Being primarily comprised of polypropylene (PP) - a unsustainable thermoplastic polymer[5] - plastic straws do not break down but break down into smaller micro-plastics which fish end up eating [6]. These micro-plastics also contain additives like anthropogenic contaminants which could end up bio-accumulating, causing harm not only to the ecology of specific environments but also to humans who eat afflicted seafood [7–9]. Beyond marine and freshwater ecosystems, micro-plastics can be found in terrestrial ecosystems which further broadens the scope of the lethal and sub-lethal impact micro-plastics have on organisms [10, 11].

Because it is clear that pollution from straws is a major issue, many organizations and companies have tried to remedy this. One of the sustainable development goals put in place by the United Nations, SDG 14.1, hopes to prevent marine pollution of all kinds, especially plastic pollution. Starbucks, a major multinational corporation, even replaced plastic straws with paper straws in 2020. Red Lobster, American Airlines and many other corporations followed suit.[12] Even the Chinese government realizes the significant issue with plastics, especially plastic straws, and have been implementing laws which is a complex process[13, 14].As the world transitions to more sustainable and environmentally friendly practices, an alternative to plastic straws is essential. Some potential alternatives include paper straws, which are the most popular, Poly-lactic acid biodegradable straws, Seaweed straws, etc. However, many of these alternatives have undesirable material, physical, and economic characteristics [15].

We want to assess bamboo's efficacy as an alternative to plastic straws because bamboo has many advantages: growing unusually fast, being widespread across the world, and having strong properties. This is due to its microfiber structures with lignin and hemicellulose (lignin-carbohydrate complex (LCC)) which gives it greater strength than concrete and steel by weight. Additionally, bamboo can show high tolerance against pressure and bending because of its low density and high mechanical characteristics. It is also important to note that bamboo's structure consists of fiber - which is mainly lignin, cellulose, and hemicellulose - which impacts its flexural strength. [16, 17]

In this study, we will analyze the material properties of bamboo straws, compared to paper straws, as a more effective alternative to plastic straws. More specifically, we hope to analyze the flexural strength and impact resistance of both bamboo and paper straws after varying water treatment times to simulate these straws in actual beverages. Additionally, we are going to do a material analysis of bamboo straws in a concentration of salt water after varying treatment times.

2 Methodology

2.1 Materials

Bamboo straws (Nimbus Bamboo) and paper straws (Jacent Stylish) were purchased on Amazon. Table 1 describes each of the straws used in this study. Plastic water bottles (500 ml) were also obtained as a container to submerge the straws in. Tap water and tap water with a 0.20 M salt concentration were used as the submerging liquid inside the plastic water bottle for each of the different tests.

Table 1: Material Descriptions of Both of the Straws Used In This Study

Material	Length (mm)	Outside Diameter (mm)	Inside Diameter (mm)	Weight (g)
Bamboo	199	8	4.9	4
Paper	196	7	4.8	2

2.2 Water Absorption Test

Bamboo straws and paper straws were first weighed to determine their mass (in grams) before being submerged in 500 ml of water in plastic water bottles for various lengths of time. After the straws were taken out of the water bottle, the straws were once again weighed to determine their mass. The difference between these two values was recorded, determining the mass of the absorbed water.

Four paper straws were submerged in non-salinated tap water for time periods of 30 min, 60 min, 90 min, and 120 min. After the water absorption test was performed on each of these straws, a flexural strength test was further performed on each straw (see subsection 2.3). This was repeated for four trials, totaling 16 paper straws.

Five bamboo straws were submerged in non-salinated tap water for time periods of 30 min, 60 min, 90 min, 120 min, and 360 min. After the water absorption test was performed on each of these straws, a flexural strength test was further performed on each straw. This was repeated for four trials, totaling 20 bamboo straws.

Five bamboo straws were submerged in salinated tap water for time periods of 30 min, 60 min, 90 min, 120 min, and 360 min. After the water absorption test was performed on each of these straws, a flexural strength test was further performed on each straw. This was repeated for four trials, totaling 20 bamboo straws.

A 0.2 M concentration of salt was assumed for the salinated tap water. This molarity is derived from adding 6 g of table salt to 500 ml of water. Assuming the table salt was primarily composed of NaCl, it is the case that

$$6 \text{ g NaCl} \times \frac{1 \text{ mol NaCl}}{58.44 \text{ g NaCl}} = 0.1 \text{ mol NaCl},$$

so the concentration of NaCl is

$$\frac{0.1 \text{ mol NaCl}}{500 \text{ ml}} = \frac{0.2 \text{ mol NaCl}}{1 \text{ L}} = 0.2 \text{ M NaCl}.$$

(It is worth noting that this is merely an approximation as the table salt is not pure NaCl, and the tap water is not distilled water.)

2.3 Three-Point Flexural Strength Test

The three-point flexural strength test was performed in order to measure the strengths of bamboo and paper straws after the various times of being submerged in water. Modulus

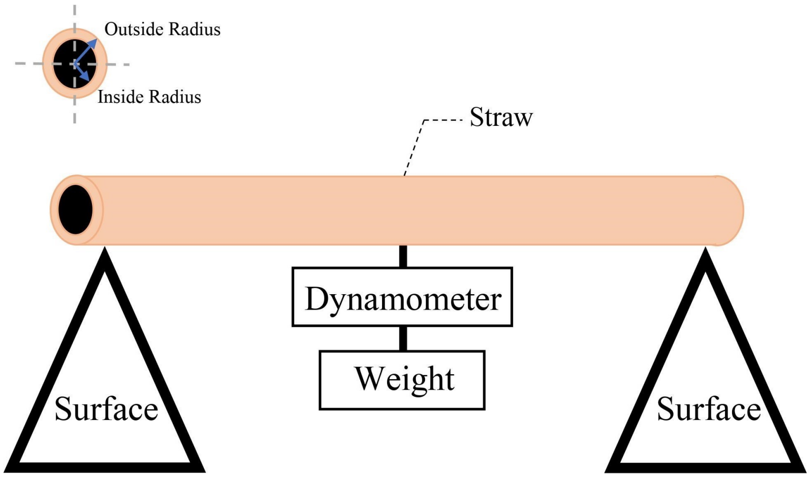

Figure 1: Diagram of The Testing Method For The Flexural Strength Test

of rupture is a measure of the maximum fiber stress at failure at rupture and is also know as flexural strength. The modulus of rupture was calculated using the following equation [18]:

$$\sigma = \frac{Mc}{I},$$

where σ is the stress, M is the applied moment at fracture, c is the distance from the neutral axis, and I is the second moment of inertia about the neutral axis.

The test was performed on each straw by holding it in place at its two ends on two surfaces. At the straw's center, a dynamometer was placed in a way such that weight could be hooked beneath it. This weight force would be increased until the straw would fracture, with the dynamometer used to measure how much weight was required for the fracturing of the straw (see Figure 1). Our experimentation allowed for at most 40 N of weight to be tested. Afterwards, flexural strength was attained.

2.4 Impact Test

The Izod impact test was conducted using a hammer attached to a pendulum (The hammer had a 0.635 kg head and 0.343 m handle) as shown in Figure 2.a and Figure 2.b.

For every test, the hammer's amplitude (the angle formed by the equilibrium position and the current position of the rod) started at 160°. After releasing the pendulum, the hammer would swing and impact the material at its equilibrium position. After the impact, the maximum amplitude of the pendulum would be measured. The lower the amplitude, the lower the impact force absorbed by the straw.

After collecting the amplitude of the different types of straws, the impact energy—the

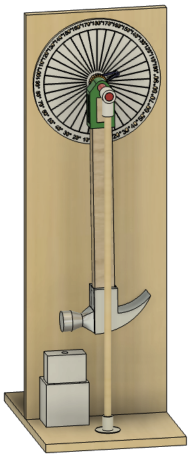

Figure 2.a: The CAD Model Of The Homemade Izod Impact Test Contraption

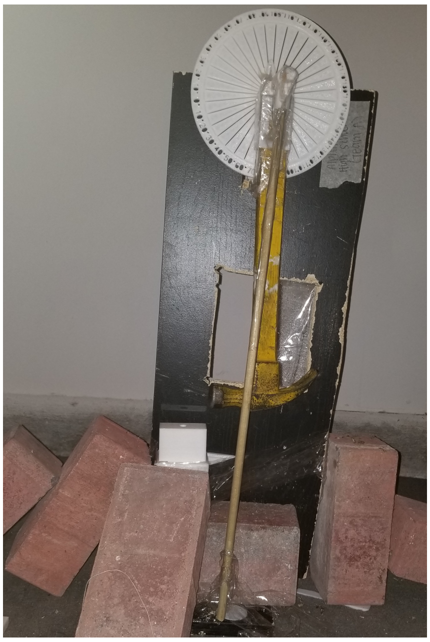

Figure 2.b: The Homemade Izod Impact Test Contraption (The Bricks Are For Stability)

energy absorbed by material—was observed—was calculated using the following equation:

$$\begin{aligned}\text{Impact Energy (J)} &= mgh_1 - mgh_2 \\ &= mg(h_1 - h_2),\end{aligned}$$

where m is mass of the bob in kilograms, g is the acceleration due to gravity, h_1 is the height of the bob from the ground at its starting position, and h_2 is the maximum height of the bob from the ground after the impact. This equation works on the basis of taking the maximum potential energy available to the pendulum and subtracting that by the energy of the pendulum after the impact. The difference of the two energies is equal to the impact energy.

In order to compare the results of the paper and bamboo straws, the impact toughness was calculated using the impact energy in joules divided by the wall thickness (outer diameter - inner diameter) of each respective straws in meters.

3 Results

3.1 Water Absorption Testing Results

Water absorption data for paper straws was collected in 3 trials which yielded the same results. This is shown in table 2 below. Absorption trends can be ascertained from Figure 3:

Table 2: Water Absorption For Paper Straws In Trial 1, Trial 2, and Trial 3

	Trial 1	**Trial 2**	**Trial 3**
Time (m)	Water Absorption (g)	Water Absorption (g)	Water Absorption (g)
30	1	1	1
60	2	2	2
90	2	2	2
120	3	3	3

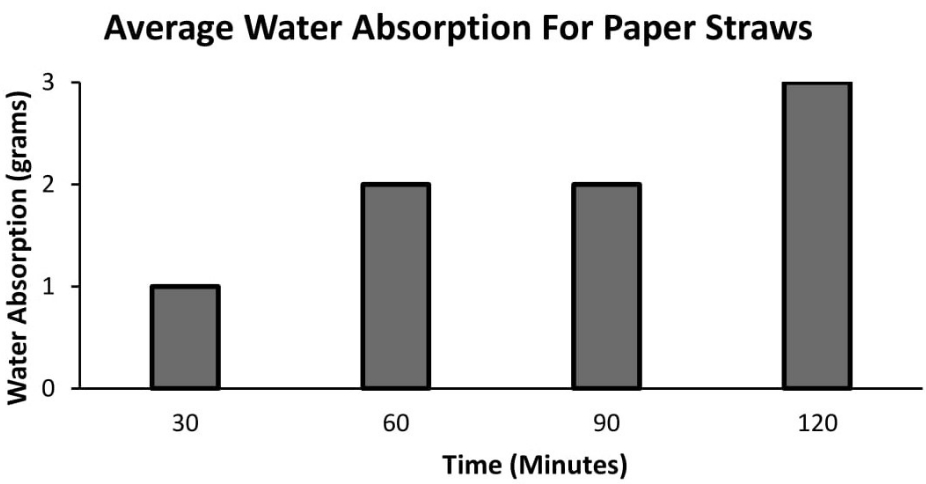

Figure 3: Bar Graph of The Average Water Absorption of Paper Straws

Water absorption data for bamboo straws was collected in 3 trials as well and yielded similar results. This is shown in table 3 below. Absorption trends can be ascertained from Figure 4:

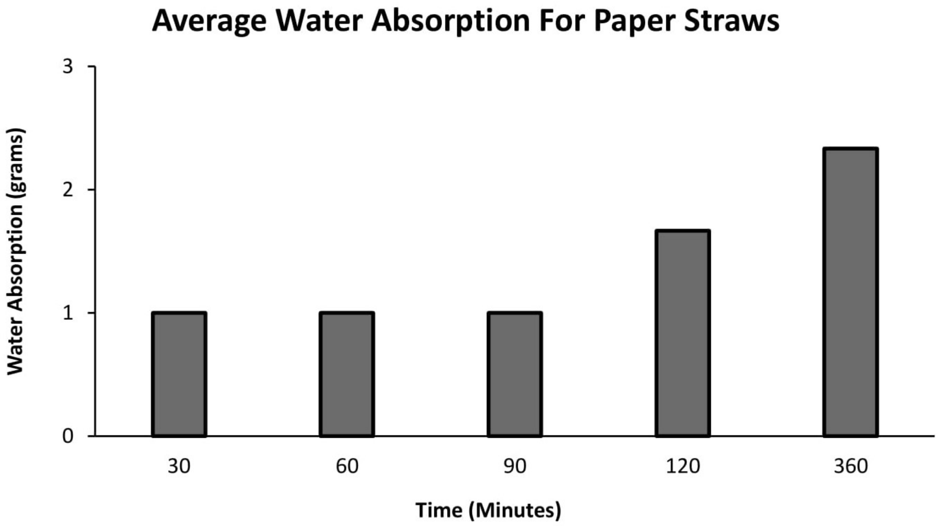

Figure 4: Bar Graph of The Average Water Absorption of Paper Straws

Table 3: Water absorption for bamboo straws in Trial 1, Trial 2, and Trial 3

	Trial 1	**Trial 2**	**Trial 3**
Time (m)	Water Absorption (g)	Water Absorption (g)	Water Absorption (g)
30	1	1	1
60	1	1	1
90	1	1	1
120	2	1	2
360	3	2	2

3.2 Flexural Strength Testing Results

We could only calculate the flexural strength (modulus of rupture) for paper straws because the force needed to completely fracture a bamboo straw was greater than 40 Newtons which exceeds the capabilities of our at home setups. Modulus of rupture is the maximum fiber stress at failure so it is a useful indication of the maximum load a object can withstand. For the bamboo flexural tests submerged in salinated and non-salinated tap water, the bamboo straws did not fracture at 40 newtons so data will be gathered from Amatosa et. al. in 2019 [19].

Table 4: Bending Fracture Force and Modulus of Rupture for Paper Straws For Trial 1

Time (minutes)	Bending Fracture Force (N)	Modulus of Rupture (MPA)
30	26.75	17.85
60	22.63	15.10
90	19.91	13.29
120	18.25	12.17

To calculate the modulus of rupture for paper straw, we used the modulus of rupture equation for cylindrical objects found in section 2.3. To solve for M we use this following equation:

$$M = \frac{PL}{4},$$

where P is the force in Newtons and L is the span in millimeters. For this example, we use the force, which changes in each duration of submergence, and the span, which is a constant, for trial 1 under 30 minutes of water submergence. This looks as follows:

$$M = \frac{(26.75 \text{ N})(70 \text{ mm})}{4} = 468.16 \text{ N mm}.$$

To solve for c, the following equation is used:

$$\mathrm{c} = \frac{h}{2},$$

where h is the height. Plugging in our values, we get:

$$\mathrm{c} = \frac{7 \text{ mm}}{2} = 3.5 \text{ mm}.$$

To solve for I, we use the following equation:

$$I_{\text{cylinder}} = \frac{\pi}{4}\left(r_o^4 - r_i^4\right),$$

where r_o is the outside radius and r_i is the inside radius which can be found in Table 1. Plugging in our values we get:

$$I_{\text{cylinder}} = \frac{\pi}{4}\left(3.5^4 - 2.4^4\right) = 91.8 \text{ mm}^4.$$

Plugging all of this into the modulus of rupture equation gets us:

$$\sigma = \frac{(468.16)(3.5)}{(91.80)} = 17.85 \text{ MPa}.$$

This process is repeated in excel for all the trials and durations of submergence. Figure 5 shows all of the modulus of rupture's for each trial.

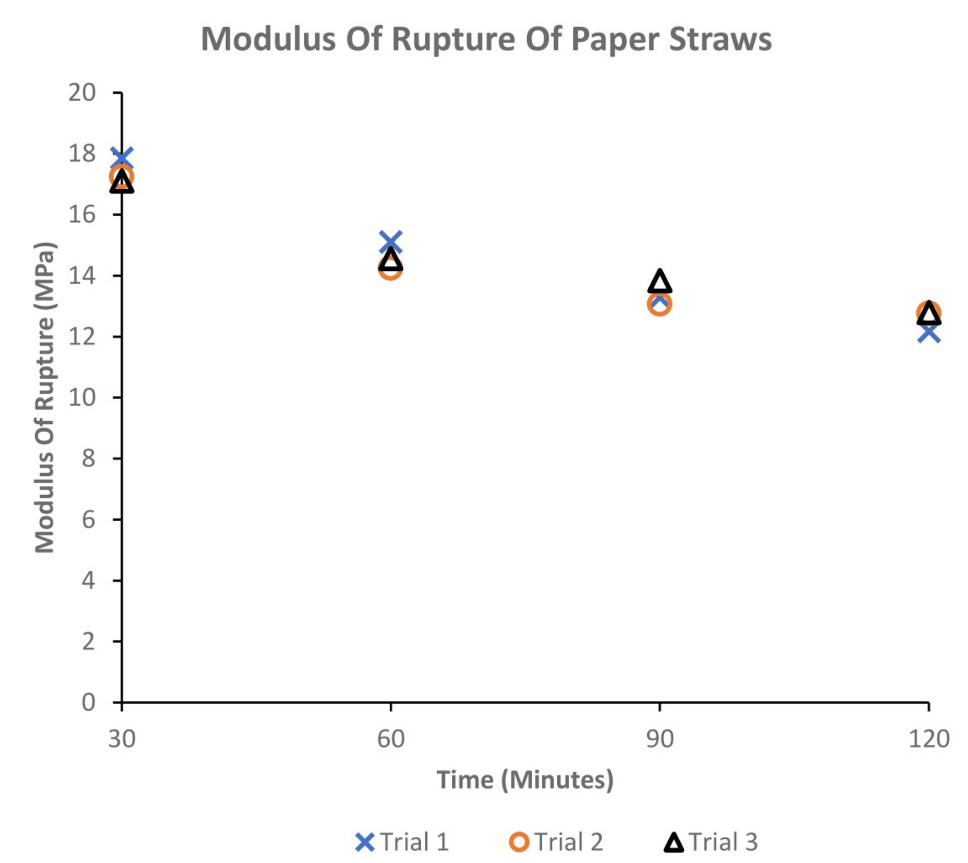

Figure 5: All of The Modulus of Rupture For Each Trial Plotted

As for the bamboo trials, because of our limited setup at home we could not fracture the bamboo so we will be referencing Amatosa et. al. in 2019 [19] where they conducted a material study on sea-water treated bamboo. Table 7 is their results:

Table 5: Modulus of Rupture for Bamboo (Dendrocoalamus asper) from Amatosa, 2019

Treatment	Modulus of Rupture (MPA)
Freshwater Treatment	188.05
Sea-Water Treament	218.35

Figure 6 illustrates the average modulus of rupture for the paper straws we measured and the modulus of rupture for bamboo straws from Amatosa, 2019 [19]. It is important to note that Amatosa et. al. did not submerge the bamboo in increments but it still provides a great visual comparison between each straw.

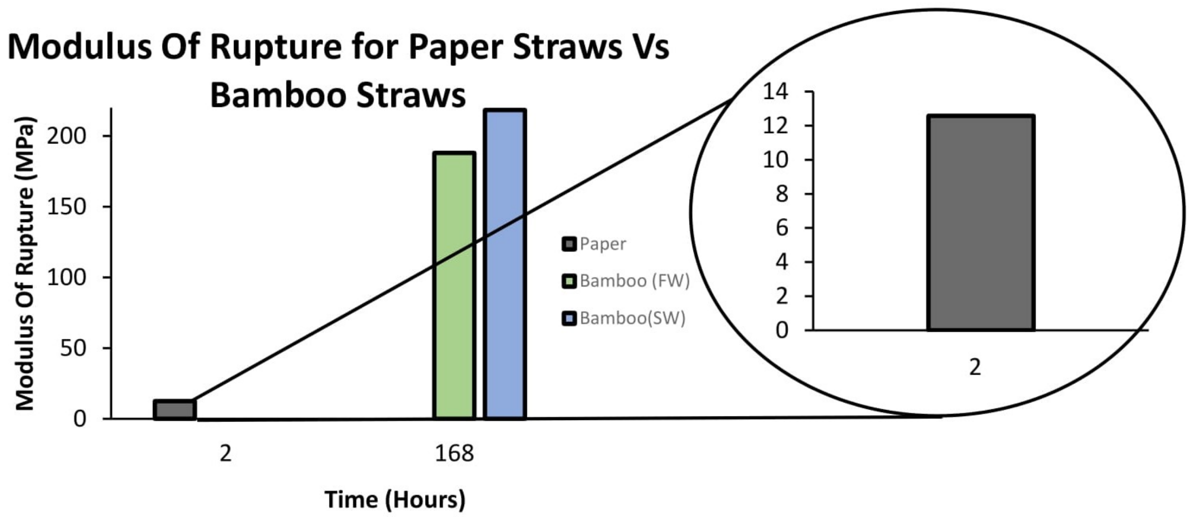

Figure 6: Bar Graph of The Average Modulus Of Rupture For Paper vs Modulus Of Rupture For Bamboo straws

3.3 Impact Testing Results

For the impact test, data were collected only for the dry paper straws, dry bamboo straws, and bamboo straws that have absorbed water for 6 hours (which be be called "wet" bamboo for the remainder of the Impact Testing Results section). This was mainly due to the limitations of the homemade Izod impact test contraption, which could only show changes in the impact energy in 10° increments. The results are shown in the tables below.

Table 6: Impact Energy and Impact Toughness for Dry Paper Straws

Trials	Impact Energy (J)	Impact Toughness (J/m)
1	0.63 ± 0.37	288.36 ± 168
2	0.374 ± 0.37	168.65 ± 168
3	0.63 ± 0.37	288.36 ± 168
4	0.37 ± 0.37	168.65 ± 168
5	0.63 ± 0.37	288.36 ± 168

Table 7: Impact Energy and Impact Toughness for Dry Bamboo Straws

Trials	Impact Energy (J)	Impact Toughness (J/m)
1	1.28 ± 0.37	411.94 ± 119
2	2.74 ± 0.37	883.42 ± 119
3	1.28 ± 0.37	411.94 ± 119
4	2.38 ± 0.37	767.37 ± 119
5	1.64 ± 0.37	527.99 ± 119

Table 8: Impact Energy and Impact Toughness for Bamboo Straws with Water

Trials	Impact Energy (J)	Impact Toughness (J/m)
1	0.63 ± 0.37	204.64 ± 119
2	3.86 ± 0.37	1244.59 ± 119
3	3.38 ± 0.37	1090.72 ± 119
4	3.38 ± 0.37	1090.72 ± 119

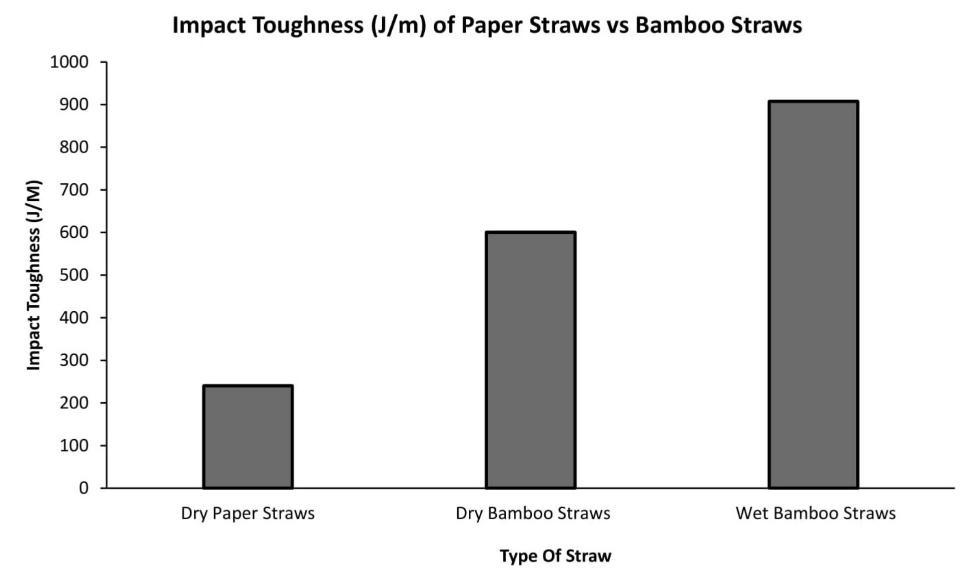

Figure 7: The Average Impact Toughness Of Dry Paper Straws, Dry Bamboo Straws, And Wet Bamboo Straws

Before calculating the impact toughness, the impact energy — the energy absorbed by the straws — needs to be calculated first. To calculate the impact energy, the total available energy (the potential energy at an amplitude of 160°) is subtracted by the energy not absorbed (the potential energy of the pendulum after the impact):

$$\begin{aligned}\text{Impact Energy} &= mgh_1 - mgh_2 \\ &= mg(h_1 - h_2).\end{aligned}$$

In other words, the impact energy can be obtained by subtracting the gravitational potential energies before and after the impact where m is mass (kg), g is acceleration due to gravity, and h is height of the head of the hammer from the floor.

Using the impact energy, the impact toughness can be calculated by dividing the impact energy by the thickness of the walls of the straws. For the paper straws, their wall thickness was 0.0022 m while the bamboo straws had a wall thickness of 0.0031 m.

When observing the data, a clear trend is shown. The order of the strength —from weakest to strongest — is in the following order: paper straws, dry bamboo straws, and wet bamboo straws. It is, however, important to note that there are outliers in the data set due to the inconsistencies of the impact caused to the wearing of the contraption.

4 Discussion

4.1 Water Absorption

Throughout all of the trials, the average water absorption for paper straws was 2 grams while the average water absorption for bamboo straws, submerged under non salinated tap water, was 1.67 grams. Under salinated tap water the average for bamboo was 1.93. Thus, on average, we found that paper straws absorb more water than bamboo straws on 30 minutes intervals of submergence. Additionally, on average, bamboo straws submerged under salinated water absorbed more water than bamboo straws submerged under non salinated water.

The results for paper straws are similar to the results of Gutierrez et. al. in 2019. In their study, they tested three different brands of paper straws under fresh water, iced Coke, iced tea, and more. At 30 minutes, they found that the three paper straws generally gained about 30% of their weight. After calculating percent weight gain, in our study the paper straws gained 50% of their weight. Similarly, in 60 minutes, Gutierrez et. al. found that the there straws generally gained 40% of their weight while we found that our paper straws gained 100% of their weight. The differences in results most likely stem from the different brands of the paper straws in each study, the non standardized temperature in our study, and the inexactness of our at home scales. Additionally, although we did not empirically measure it, we did observe the paper straws becoming more elongated in shape which matches the results from Huang et. al. in 2018 where they explained that water replaces the air to fill the holes in bamboo when the moisture content increases [20].

All in all, these results make sense because in everyday life, paper straws tend to weaken drastically under a short duration of time submerged in liquid. This proves the point that bamboo straws do not absorb water at fast as paper straws do so their longevity and usability trumps that of paper straws.

Our testing methods did have some flaws as mentioned before. Because we tested in different geographical locations, factors like humidity, specific temperature, and more were not exactly standardized to a great extent. Additionally, the scales we used to measure the weight, in grams, was limited in its capabilities since it could not measure more minute changes in weight. For future studies, more exact scales, and standard temperatures, pressure, altitude, and a wider variety of straws are potential improvements.

4.2 Bending

The results of the bending tests prove that for all paper straw trials, the longer the straws were soaked in water, the easier it was for them to bend under pressure. Throughout all of the trials, the average force needed to bend a paper straw after 30 minutes was 26.08 N. However, after 120 minutes, the paper straws were found to bend under an average of 18.85 N.

These results make sense because as paper straws are submerged for longer periods of time, they will absorb more liquid, ultimately making them weaker. This proves that over time, paper straws can become unusable as they absorb too much liquid to function properly.

Bamboo straws on the other hand, both submerged in salt water and those that absorbed just water, have been shown to withstand more force during the bending tests than paper straws and thus have a higher modulus of rupture. In all trials conducted, the bamboo straws failed to bend with 29.43 N of pressure or less. This comes to no surprise as it was expected that paper straws would bend under less pressure than bamboo straws. In fact, the modulus of rupture for bamboo straws 10 times higher than the modulus of rupture for paper straws even though they have been submerged for 166 hours more.

It is important to recognize that there were several flaws in our testing methods. Although each teammate utilized the same scale during the bending test, there may have been a human error made when finding the exact force needed to bend each straw.

4.3 Impact

The impact tests have returned a clear trend in the data. The dry paper straws have an average impact toughness of 240.47 J/m, dry bamboo straws have an average impact toughness of 600.53 J/m, and wet bamboo straws have an average impact toughness of 907.67 J/m.

It is important to recognize that paper and bamboo respond differently to impacts. Upon impact, paper will not fracture, but rather bend. However, bamboo, while having a greater impact toughness, will fracture and snap. This is mainly due to the more brittle nature of bamboo. Unfortunately, fractured bamboo straws result in sharp bamboo pieces that could potentially injure its users but it requires significant amount of energy to fracture it.

Our testing methods had flaws that were reflected in the data we've gathered. Due to only one member with access to machinery, a 3D printer, capable of making parts for the Izod impact test contraption, certain variables that impacted the results could be localized to the geographic location and/or the tools used. Furthermore, the contraption started wearing out after every test, which unfortunately resulted in the incremental increase in the inaccuracy of the data.

5 Conclusions

Plastic straws are clearly detrimental to the environment, so in this study we propose methods of testing the material proprieties of bamboo straws as an environmentally friendly alternative to plastic straws compared with paper straws. To do this we conducted three tests: a water absorption test, a flexural (bending) test, and an impact test.

In terms of water absorption, bamboo straws performed better than paper straws since they, on average, absorbed the least water. While bamboo straws, submerged under non salinated water, absorbed an average of 1.67 grams of water and bamboo straws, submerged under salinated water, absorbed an average of 1.93 grams of water, paper straws submerged under non-salinated water absorbed an average of 1.67 grams. This indicates bamboo straws are better than paper straws in terms of water absorption which bodes better for longevity in everyday life.

As for the flexural test, bamboo straws also performed better than paper straws. Although data was gathered from another journal article, we performed a three-point bending test to calculate the modulus of rupture. In the end, the modulus of rupture for bamboo was more than 10 times greater than the modulus of rupture for paper straws. Additionally, there a clear trend of the modulus of rupture decreasing the longer it is submerged under water. This indicates that bamboo straws are more durable in everyday life and will not rupture as easily as paper straws.

Lastly, an impact test was performed. To do this, a Izod impact test contraption was 3D printed. Although the impact toughness varied for each material, there was a clear trend that wet bamboo straws were the strongest followed by dry bamboo straws and paper straws. Once again, paper straws ranked last and will be the first to fracture if impacted in everyday life.

In the end, our study contains potential sources of error in each test but shows results that illustrate bamboo straws are overall better than paper straws. It is also clear that salt treatment of bamboo straws can increase its material proprieties. Although our study does not consider the economic, social, or political perspectives of the debate between bamboo straws and paper straws - this can be done in a future study, we show that in a material science perspective, bamboo straws trump paper straws.

6 Acknowledgements

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