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Effect of Submersion in Water on the Strength of Paper

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ABSTRACT

The purpose of this research is to determine how the strength of paper changes with time after being submerged in water and how it varies with the paper's water content. This is done using an experiment involving paper being submerged in water. Measurements are taken every 5 minutes after submersion. Water content is measured by calculating the percentage change in mass of the paper. The strength is measured by placing the paper on top of two books, half the paper on one book and half on the other, after which the books are pulled apart creating a gap between them. When the paper curves 1 cm down, the length between the books is measured. The greater this length, the stronger the paper. It was discovered that upon submersion, the paper absorbs water, raising its water content by about 37% and resulting in an approximately equal percentage fall in strength. As time passes, strength increases for the first 30 minutes, reaching the strength of dry paper after 18 minutes. It then falls. Furthermore, it was also discovered that a rise in water content from 0% to about 3% leads to a rise in strength, while any subsequent rise in water content leads to a fall in strength. The paper was strongest 30 minutes after submersion with a water content of 3.08%. In addition, once the paper reaches a water content of 0%, its strength is greater than it is before submersion, suggesting that water submersion causes permanent change to paper.

Keywords: ***Physics, Paper, Water, Strength***

Subject: Physics

INTRODUCTION

Let's say you are doing some work using a sheet of paper. You get thirsty. You grab some water to get a drink, but as you do so, you find out that you spilt some. You look at the paper in front of you, drenched. Your deadline is approaching soon, so what do you do? If you pick it up now, it will certainly tear. Will it even dry in time? Do you wait for it to dry, or do you start over?

Paper is a material composed of 90% to 99% cellulose fibres, which is the primary structural component of paper (Sahin & Arslan, 2008, p. 1). These fibres are bonded to each other through the use of interfiber bonds which greatly affect the physical properties of paper (Sahin & Arslan, 2008, p. 1).

A study was conducted by Cambridge University in 1992 with the purpose of exploring the mechanical properties of paper (Vitale, 1992). They found that upon being submerged in water, these interfiber bonds in the paper are disrupted, leading to a fall in all mechanical properties of the paper, including strength (Vitale, 1992). They also discovered that the interfiber bonds are regained after the paper dries, leading to the paper regaining the lost strength (Vitale, 1992).

However, even though the reasons behind the varying strength have been studied, the precise relationships between time, water content and the strength of paper are not yet well understood and researched. The way that the strength of paper varies with water content is very significant and so should be researched. This is because it will provide information on the water content at which paper is the strongest, hence allowing for the development of stronger paper through manipulation of its water content. It will also provide information on the extent to which the strength of the paper will be returned to its original value when water content returns to 0%. This will allow the average person to know if a wet piece of paper will ever return to its original form.

The way that the strength of wet paper varies with time is also very significant because it is very applicable to the average person. For example, if a person accidentally spills water or other liquid on an important piece of paper such as an important document, they will not be very concerned with how the chemical and physical properties of the paper have changed. Instead, they will be concerned with the extent to which the paper will regain its strength and the amount of time it will take before the paper can be safely handled again without the risk of tearing or other damage.

Therefore, the purpose of this study is to determine how the strength of paper varies with time after it is submerged in water. Furthermore, this study also aims to explore how water content affects the strength of paper. The water content of paper refers to the proportion of the mass of the paper that is water. This will be done by performing an experiment involving A4 sheets of paper submerged in water.

MATERIALS AND METHODS

Materials Used:

- Water
- 3 Sheets of Paper
- Two Books of level height
- Stopwatch
- Paper Towel
- Electronic Balance
- Ruler

The mass of one A4 sheet of paper is measured using the electronic balance. The length withstood by the paper, representing the strength of the paper, is also measured. The two books of level height are brought together such that they are touching each other. The paper is then placed on these books such that half of the paper lies on one book and the other half lies on the other book. The books are then pulled apart, making sure that the paper remains stationary. It is also ensured that both books have an equal area of the paper in contact with them. As the books are pulled further apart and a gap form between them, causing the paper to curve between them. When the bottom of this curve is 1 cm from the surface of the books, measured using the ruler, the distance between the books is measured, also using the ruler. This is the length withstood by the paper.

The same A4 sheet of paper is then submerged in water. Tap water is used as it is easily accessible and the purity of the water does not affect the strength of paper (Vitale, 1992). A paper towel is then used to gently blot the paper in order to remove the excess water on the surface of the paper that has not been absorbed.

To measure the water content of this wet sheet of paper, the mass of the paper is measured using the electronic balance. The water content is then calculated as the mass of water in the paper as a percentage of the total mass of the sheet of paper.
The length withstood by this sheet of paper is also measured using the above-mentioned process. The greater the length withstood, the easier it is for the paper to maintain its structure, hence meaning that the paper is stronger

This process is repeated every 5 minutes for 45 minutes. Time is measured using the stopwatch. This is then repeated two more times in order to get three trials of the experiment.

RESULTS AND DISCUSSION

The results of the experiment are shown in Tables 1 to 4 and in Figures 1 and 2. A data reading was taken every five minutes for 45 minutes after submerging the paper in water. This was repeated 3 times in order to get data for three trials. To ensure that the data collected is accurate, the average of the readings for the three trials was calculated for each data set.

The Water Content of Paper is the proportion of the mass of the paper that is water, expressed as a percentage. In order to calculate the water content of the paper, the mass of the paper is measured at each iteration of time and for each trial, as shown in Table 2. The dry mass of the paper for each trial is also measured and is shown in Table 1. The water content (w) for each trial at each time is calculated using the following formula:

$$w = \frac{m_f - m_d}{m_f} \times 100$$

In this formula, m_f is the final mass measured, shown in Table 2 and m_d is the mass of the dry paper, shown in Table 1. The length withstood by the paper was also measured and is shown in Table 4 for each iteration of time. The length withstood by the dry paper is shown in Table 1. The length withstood represents the strength of the paper where the greater the length withstood, the greater the strength. This is because if the paper is able to withstand a greater length before curving 1 cm, it means that it is better able to maintain its structure, hence it is stronger.

Table 4 and Figure 1 show the relationship between Time since being submerged in water and the Length Withstood by the paper. As shown in Table 1, a dry A4 sheet of paper can withstand an average length of 16.3 cm. However, immediately after being submerged in water, it can only withstand an average length of 10.3 cm. This shows that the strength of the paper has significantly decreased. However, the strength of the paper then starts to increase, increasing for the first 30 min. The rate at which strength increases is slower for the first 15 min, but is more rapid for the next 15 min. The paper is strongest at 30 min with a length withstood of 23.6 cm. After 30 min, the strength begins to decrease, decreasing rapidly from 30 min to 35 min. It then increases more slowly for the final 10 minutes.

Using the curve in Figure 1, it can be determined that the strength of the paper is regained approximately 18 min after being submerged in water. This is because 18 min is the time when the length withstood would be approximately 16.3 cm, which is the length withstood by the dry paper. Therefore, a piece of paper becomes safe to handle with a low risk of tearing after about 18 minutes of becoming wet. However, the strength of the paper will not remain at this value but will increase for the next 12 minutes and will then decrease, remaining greater than the strength of the dry paper.

Table 5 and Figure 2 show the relationship between Water Content and Length Withstood by the paper. According to Table 1 and Table 2, the average mass of the paper increased from 5.25 g to 8.34 g upon submersion, meaning that 3.09 g of water was absorbed by the paper, leading to the sheets of paper having an increased average water content of 37.1%. This increase in the water content led to a fall in the strength of the paper, shown by a fall in the length withstood from 16.3 cm to 10.3 cm, a 36.8% fall in strength. This percentage is very close to the increase in water content of the paper. This suggests that the percentage increase in the water content of paper is approximately equal to the percentage decrease in strength immediately following the increase in water content. This pattern is further reinforced through the use of the data from the individual trials. In Trial 1, a 37.0% increase in water content led to a 36.6% decrease in strength. In Trial 2, a 37.2% increase in water content led to a 36.6% decrease in strength. In Trial 3, a 37.1% increase in water content led to a 36.8% decrease in strength.

As the average water content is increased from 0.0633% to 3.08%, the strength of the paper increases from a length withstood of 18.7 cm to 23.6 cm. The rate of increase is slower as water content increases from 0.0633% to 2.23%, but is faster as water content increases from 2.23% to 3.08%. The paper is strongest at a water content of about 3.08%. The strength of the paper then decreases as the water content increases from 3.08% to 37.1%. The rate of this decrease is very rapid at first but gradually slows down as water content increases, as shown by the curve in Figure 2. Therefore, it means an increase in the water content of paper from 0% to about 3.08% leads to an increase in strength, but any further increase in the water content leads to a fall in strength.

As shown in Table 1, the average length withstood by the sheets of paper before being submerged in water is 16.3 cm. However, after the sheets of paper dry and reach an average water content of 0% about 45 min after being submerged, the length withstood is about 18.7 cm, which is 2.4 cm, or about 14.7% greater. This means that the exact strength and hence, physical properties of the paper are not returned to their original value even after the paper completely dries to a water content of 0%. This suggests that submerging a sheet of paper in water results in permanent changes to the paper that prevent its strength from completely returning to its original value upon drying. In fact, the strength actually increases, meaning that submerging a sheet of paper in water and drying it is a way of increasing the strength of an A4 sheet of paper.

CONCLUSIONS

In conclusion, after being submerged in water, the strength of the paper falls. It then rises for 30 min, then gradually falls. The paper is safe to handle without much risk of tearing after approximately 18 min. Upon submersion, the increase in water content of the paper (about 37%) is roughly equal to the immediate percentage decrease in strength. Furthermore, as water content increases from 0% to about 3%, the strength of the paper increases, but then decreases for any subsequent increase in water content. The paper is strongest at a water content of approximately 3.08%. Moreover, submersion results in a permanent change to the paper which results in its strength not returning to its original value even after the paper completely dries.

Tables and Figures:

Table Showing Mass and Length Withstood by Dry Paper				
	Trial 1	Trial 2	Trial 3	Average
Mass (g)	5.26	5.24	5.25	5.25
Length Withstood (cm)	16.1	16.4	16.3	16.3

Table 1. Table showing the mass of and length withstood by the paper for each trial prior to being submerged in water. The average length withstood and mass were calculated by adding the values for each trial and then dividing this sum by 3.

Table Showing Change in the Mass of Paper with Time after being Submerged in Water				
Time (min)	Mass (g)			
	Trial 1	Trial 2	Trial 3	Average
0	8.37	8.32	8.34	8.34
5	7.53	7.47	7.49	7.50
10	6.71	6.67	6.69	6.69
15	6.21	6.18	6.19	6.19
20	5.68	5.71	5.70	5.70
25	5.54	5.58	5.55	5.56
30	5.40	5.43	5.42	5.42
35	5.36	5.38	5.37	5.37
40	5.31	5.34	5.32	5.32
45	5.26	5.25	5.25	5.25

Table 2. Table showing the change in the mass of paper with time after being submerged in water. A reading is taken every 5 minutes for 45 minutes, starting from the time the paper is taken out of the water after being submerged. A separate sheet of paper is used for each trial. The mass is measured using an electronic balance to the nearest two decimal places.

Table Showing Change in the Water Content of Paper with Time after being Submerged in Water				
Time (min)	Water Content (%)			
	Trial 1	Trial 2	Trial 3	Average
0	37.2	37.0	37.1	37.1

5	30.2	29.9	29.9	30.0
10	21.6	21.4	21.5	21.5
15	15.3	15.2	15.2	15.2
20	7.39	8.23	7.89	7.84
25	5.05	6.09	5.41	5.52
30	2.59	3.50	3.14	3.08
35	1.87	2.60	2.23	2.23
40	0.942	1.87	1.32	1.38
45	0	0.190	0	0.0633

Table 3. Table showing the change in the water content of paper with time after being submerged in water. A reading is taken every 5 minutes for 45 minutes, starting from the time the paper is taken out of the water after being submerged. A separate sheet of paper is used for each trial. The water content is expressed as a percentage and represents the percentage mass of paper that is water. The water content (w) for each trial at each time is calculated using the following formula:

$$w = \frac{m_f - m_d}{m_f} \times 100$$

In this formula, m_f is the final mass measured, shown in Table 2 for each respective trial at each respective time. m_d is the mass of the dry paper, shown in Table 1 for each respective Trial. The resulting value is rounded to the nearest 3 significant figures.

Table Showing Change in the Length Withstood by Paper with Time after being Submerged in Water				
Time (min)	Length Withstood (cm)			
	Trial 1	Trial 2	Trial 3	Average
0	10.2	10.4	10.3	10.3
5	12.2	12.3	12.3	12.3
10	13.0	13.4	13.3	13.2
15	14.4	14.7	14.5	14.5
20	17.5	17.7	17.6	17.6
25	20.2	20.3	20.2	20.2
30	23.5	23.7	23.5	23.6
35	20.9	21.1	20.7	20.9
40	19.5	20.2	19.8	19.8
45	18.4	19.1	18.7	18.7

Table 4. Table showing the change in the length withstood by paper with time after being submerged in water. A reading is taken every 5 minutes for 45 minutes, starting from the time the paper is taken out of the water after being submerged. A separate sheet of paper is used for each trial. The length withstood is measured by placing the piece of paper between two surfaces and then gradually increasing the length of the gap between these two surfaces. The length withstood is the length at which the paper curves 1 cm. It, therefore, represents the strength of the paper where the greater the length withstood, the greater the strength. The data is collected to the nearest millimeter, or the nearest 1 decimal place in centimeters.

Table Showing Relationship between Water Content and Length Withstood by Paper	
Water Content (%)	Length Withstood (cm)
0.0633	18.7
1.38	19.8
2.23	20.9
3.08	23.6
5.52	20.2
7.84	17.6
15.2	14.5
21.5	13.2
30.0	12.3
37.1	10.3

Table 5. Table Showing Relationship between Water Content and Length Withstood by Paper. The data on water content is the average water content, obtained from Table 3. The data on length withstood is the average length withstood, obtained from Table 4. Time is used as a data bridge. The data is sorted in ascending order of Water Content.

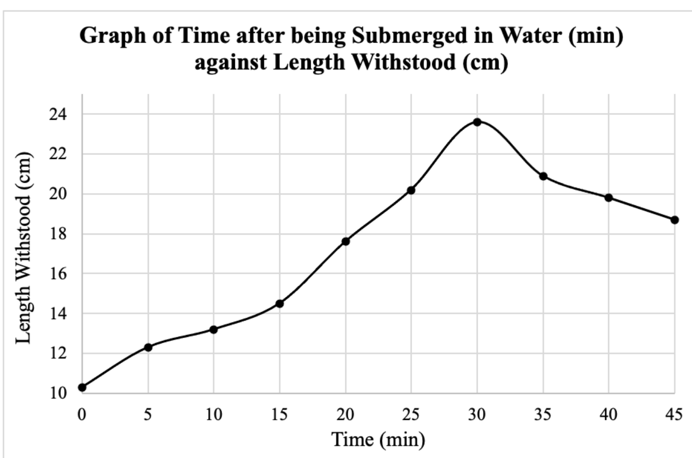

Figure 1. Graph of Time after being Submerged in Water (min) against Length Withstood (cm). The data for length withstood is the average length withstood for each iteration of time, obtained from Table 4.

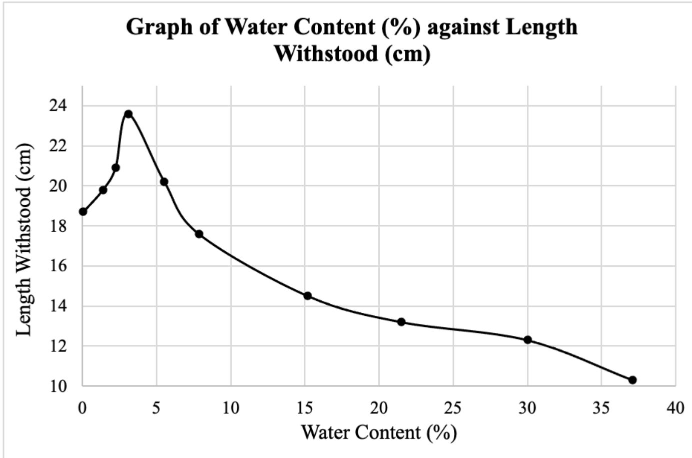

Figure 2. Graph of Water Content (%) against Length Withstood (cm). The data is obtained from Table 5.

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