Evaluation of Paper Straws *versus* Plastic Straws: Development of a Methodology for Testing and Understanding Challenges for Paper Straws

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New alternatives to plastic straws are being considered due to consumer demands for sustainability and recent changes in government policies and regulations, such as bans on single-use plastic products. There are concerns regarding paper straw quality and stability over time when in contact with beverages. This study evaluated the performance and properties of commercially available paper straws and their counterpart plastic straws in various intended applications. The physical, mechanical, and compositional characteristics, as well as the liquid interaction properties of the straws, were determined. The paper straws were composed mainly of hardwood fibers that were hard sized with a hydrophobic sizing agent to achieve a contact angle of 102° to 125°. The results indicated that all the evaluated paper straws lost 70% to 90% of their compressive strength after being in contact with the liquid for less than 30 min. Furthermore, the paper straws absorbed liquid at approximately 30% of the straw weight after liquid exposure for 30 min. Increased liquid temperatures caused lower compressive strengths and higher liquid uptake in the paper straws. This report provides directions and methods for testing paper straws and defines current property limitations of paper straws relative to plastic straws.

Keywords: Paper straws; Plastic straws; Tensile strength; Compressive strength; Longevity

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INTRODUCTION

Straws provide a simple solution for drinking beverages more conveniently, which makes straws an excellent example of an item people take for granted. Currently, straws are massively consumed. The estimated disposable plastic straw consumption in the US is between 170 million to 490 million straws per day or 63 billion to 142 billion straws per year (Chokshi 2018).

Since the use of straws dates so far back, an accurate time and place of the first usage are impossible to determine. The earliest evidence of straw use was found in a Sumerian tomb dating back to 3000 B.C. The tomb seal showed two men drinking beer from a jar using a tube made of gold (Thompson 2011). In the 1800s, straws became popular and were made of ryegrass, a biodegradable material, which tended to change the flavor and disintegrate into the drink, leaving sediment at the bottom (Smith 2017). Paper, another biodegradable material, replaced ryegrass to solve these issues. Paper straws were the best option for several decades, but the straws still had one problem: they were not durable enough and lost their physical integrity and compressive strength. Thus, they easily collapsed once wet.

In the 1960s, the usage of plastic as a novel material changed the paper straw market to a point where no paper straws were produced after 1970 (Smith 2017). Plastics are remarkable materials with a wide variety of properties and are durable, inert, and moldable. The problem arose when plastic became a single-use, disposable material on a daily basis. The world produces more than 400 million tons of plastics every year, and 36% is destined for single-use materials, such as packaging, which in turn generates 300 million tons of waste (UNEP 2018). Of that amount, only 9% is recycled, 12% is incinerated, and the remaining 79% accumulates in landfills and dumps or is littered in the environment, with half of this amount coming from packaging waste (Geyer *et al*. 2017).

This amount of waste generates pollution and other environmental problems. Plastic pollution in oceans chokes and entangles sea life. It is also linked to diseases on coral reefs, as well as decreases in the reproduction and population growth of zooplankton (Ocean Conservancy 2017). Plastic products do not biodegrade, and instead, these materials break down into smaller pieces that can be consumed by organisms, putting them at risk (Shah *et al*. 2008; Eagle *et al*. 2016). Seabirds, marine turtles, and cetaceans are included among the 267 species most affected by plastic ingestion (Haetrakul *et al.* 2009; Simmonds 2012; Eagle *et al*. 2016).

Plastic litter in the ocean has been reported since the early 1970s, but it only started to draw attention from the scientific community in the last 25 years (Andrady 2011). Activism against single-use plastic, particularly plastic straws, started in 2015 after videos arose of a turtle with a plastic straw in its nose and because of media interest in the garbage patch in the Pacific Ocean (Minter 2018). Because of this, cities like Seattle, WA and Berkley, CA and big companies like Starbucks have announced the elimination of plastic straw use in the next few years (Brueck 2018; The Guardian 2018; Wootson 2018). In addition, Starbucks has announced a $10 million grant intended for the development of a global solution of a recyclable and compostable cup, claiming that the technology will be open to the public after its development (Starbucks Stories 2018).

It is important to point out that the bans need to take into account (and it is not always the case) people with disabilities, notably if the bendy (plastic) straws are banned, since many of the people depend on bendy straws to drink any beverage (Danovich 2018; Szymkowiak 2018). For this reason, a disposable plastic straw ban cannot merely be the solution to this problem. It is then necessary to have a viable alternative to plastic straws.

These market consumption changes and the increasing demand for more sustainable and environmentally friendly options to plastic have generated several alternative materials in the production of drinking straws (Smith 2017). Metal, glass, or silicon are some of the best alternatives for reusable straws. However, single-use straws made of paper are returning to the market. Even bendable straws made of paper are now available (Aardvark 2019). Several brands, mostly in China, the UK, and the US, have returned to products not seen in more than four decades (Smith 2017; BBC 2018; Sorensen and Reinke 2018).

Paper straws are once again the best option for a disposable straw to drink a beverage without the plastic waste that can last for over 500 years in the environment (UNEP 2018). Nevertheless, paper straws are still not durable enough and typically cost more than their plastic counterparts. They lose their mechanical integrity once they are in contact with a typical beverage, and some brands' straws can change the taste of the drink (Purtill 2018).

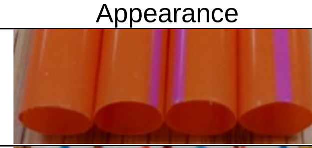
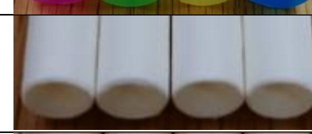
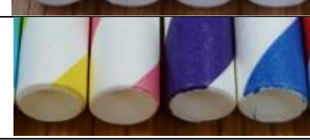
The aim of this study was to benchmark properties of paper straw already on the market with common, single-use plastic straws to identify which properties need improvement. The tensile and compressive properties as well as their interactions with liquids of commercial paper straws were compared with plastic versions.

EXPERIMENTAL

Materials

Four commercial brands of plastic straws and three commercial brands of paper straws were used for this research (names of the brands were excluded). All plastic and paper straws were acquired through Amazon.com, Inc. (Seattle, WA, USA). Common drinking (fountain) water, Coca-Cola (*i.e.*, Coke) (Atlanta, GA, USA), and Chick-fil-A (Atlanta, GA, USA) sweet tea were used as the beverages for the longevity tests. Table 1 describes each sample used.

Table 1. Straw Sample Descriptions

Material	Sample ID	Color/Characteristic	Appearance
Plastic	Plastic1	Orange	
	Plastic2	White/Bendable	
	Plastic3	Green	
	Plastic4	Multi-color	
Paper	Paper1	White	
	Paper2	Brown	
	Paper3	Multi-color	

Methods

The determination of the weight and dimensions of the straw samples was necessary to make a proper comparison between the paper and plastic straws. The weight, length, external diameter, and thickness were measured. In addition, the internal diameter, external area, basis weight, and density of the samples were calculated. A Mettler Toledo analytical balance (PB303-S; Columbus, OH, USA) was used for the weight measurements. All tests and measurements were made under standard conditions (23 °C and 50% relative humidity (RH)) using conditioned samples according to the TAPPI T402 sp-08 standard (2013). The fold endurance test was made with an MIT #1 Folding Endurance Tester (Tinius Olsen Testing Machine Co., Horsham, PA, USA) in accordance with the TAPPI T511 om-02 standard (2008).

The fiber length of the paper in the straws was measured with a fiber quality analyzer (FQA) (FQA-360; OpTest Equipment Inc., Hawkesbury, Ontario, Canada) according to the TAPPI T271 om-07 standard (2012). The sample disintegration was completed using a pulp disintegrator (TMI 73-18; Testing Machines, Inc., New Castle, DE, USA) using 0.5 g of paper straw sample in 1 L of water at 15000 rpm for 10 min.

The mechanical and longevity tests compared the plastic straws with the paper straws. The longevity test replicated a typical usage of these products under controlled conditions. The samples were placed in water at four different initial temperatures (0 °C, 21 °C, 48 °C, and 82 °C) and in a cold, carbonated beverage (0 °C). The liquid height was fixed at 2/3 of the paper straw's height. The longevity test exposed samples for different time lengths (0.5, 1.0, 2.0, 3.0, 4.0, and 6.0 h). For each time length, the entire sample was immediately weighed, and an axial and compression test was performed with the wet samples using the bottom part of the straw.

The paper straw tensile strength was measured based on the TAPPI T494 om-01 standard (2006) using a horizontal tensile tester (TMI 84-56; Testing Machines, Inc., New Castle, DE, USA) with an initial gap of 30 mm. The plastic straw tensile strength was measured based on ASTM D882-12 (2012) with a tensile testing machine (4443; Instron, Norwood, MA, USA) with an initial gap of 25 mm.

The compressive strength for both plastic and paper samples was measured based on ASTM D695-15 (2018) and ASTM D2412-11 (2018) using a tensile testing machine (4443; Instron, Norwood, MA, USA). The axial and radial configuration for compression was tested. A compression speed test of 10 mm/min was used for the axial configuration using samples with a length/diameter ratio of 2. A compression speed test of 1 mm/min was used for the radial configuration with a length/diameter ratio greater than 8.

A surface electro-optics (SEO) contact angle analyzer (Phoenix 300; Surface Electro-Optics Co., Ltd., Suwon City, Gyeonggi-do, Korea) was used to determine the contact angle and the surface tendency of the paper straws to absorb liquid. The angle was measured 10 s after the drop touched the surface. To control the formation speed of the drop, the software equipment defined the fast speed at 47 and the slow speed at 32. The drop that formed on the samples took 10 s for each trial before touching the surface. An industrial needle with a gauge of 27 was used for all tests.

Thirty paper straws of each brand were soaked in 1 L of water for 24 h to determine whether materials leached from the paper straws. The water was then analyzed with a portable turbidity meter (2020wi; LaMotte, Chestertown, MD, USA). Turbidity is the measurement of water cloudiness caused by particles suspended in the liquid (World Health Organization 2011), although each measurement method uses different units. For example, the nephelometric turbidity unit (NTU) is used by the Environmental Protection Agency (EPA) standard (Fondriest Environmental, Inc. 2014) and the formazin nephelometric unit (FNU) is used by the ISO standard (Hach 2019). However, these units can be considered equivalent, according to ASTM D6855-17 (2017).

RESULTS AND DISCUSSION

The length, external diameter, and internal diameter were measured for all straws tested. The thickness shown in Table 2 was calculated. The caliper was measured using a Vernier (Traceable Digital Calipers, Fischer Scientific, Hampton, NH, USA). The results shown in Table 3 were calculated based on these measurements. Despite the different dimensions of the plastic straw samples, the thickness of each sample was similar. The dimensions of the paper straw samples were similar as well, but the apparent density changed between the brands and had a relative difference of approximately 12%.

Table 2. Dimensions and Calculated Properties of Plastic and Paper Straws

Material	Sample ID	Length (mm)	External Diameter (mm)	Internal Diameter (mm)	Thickness (calculated) (mm)	Caliper (Vernier) (mm)
Plastic	Plastic1	250	7.57	7.04	0.27	0.21
	Plastic2	190	6.12	6.00	0.06	0.15
	Plastic3	198	6.29	6.16	0.07	0.18
	Plastic4	299	9.92	9.49	0.21	0.21
Paper	Paper1 (White)	192	6.13	5.33	0.40	0.52
	Paper2 (Brown)	195	6.14	5.22	0.46	0.50
	Paper3 (Color)	195	5.96	5.04	0.46	0.49

Table 3. Calculated Properties of Plastic and Paper Straws

Material	Sample ID	Area $\pi \times D \times L$ (mm^2)	Weight (g)	Basis Weight (g/m^2)	Density (kg/m^3)
Plastic	Plastic1	5946	1.068	179.7	855.6
	Plastic2	3660	0.469	128.3	855.0
	Plastic3	3911	0.556	142.2	812.5
	Plastic4	9320	1.381	148.2	705.8
Paper	Paper1 (White)	3690	1.100	298.1	569.2
	Paper2 (Brown)	3759	1.087	289.1	579.8
	Paper3 (Color)	3650	1.138	311.8	637.7

Fiber Quality Analyzer (FQA) Analysis

The FQA results are shown in Table 4. The fiber length and the coarseness indicated that all paper straws were made mainly of hardwood fibers. Hardwood fibers are approximately 1 mm in length with a coarseness of 0.08 mg/m (Smook 2002).

Contact Angle

The contact angle test reflects the relative hydrophobicity of the straws, as shown in Table 5. Generally, a contact angle with water larger than 90° forms with hydrophobic surfaces, and less than 90° for hydrophilic surfaces (Zhao and Jiang 2018). The contact angle for the plastic samples was between 80° and 98°. For all paper straws, the tested surface was considered hydrophobic because the angles were between 102° and 125°. The surface of the paper straws was more hydrophobic than that of the plastic straws; this is an indication of surface treatment made on the paper. The untreated paper will have a lower contact angle, and will absorb the liquid, additionally reducing the contact angle noticeably over time (Moutinho *et al.* 2007; Tyagi *et al.* 2019). On the other hand, the plastic straws are not expected to take up any significant amount of water, as the paper straws might, and the contact angle considered constant with time.

Table 4. Paper Straw Fiber Quality Analysis (FQA)

Sample ID	Paper1 (White)	Paper2 (Brown)	Paper3 (Color)
Fiber Length L_n (mm)	0.75 ± 0.05	0.72 ± 0.01	0.75 ± 0.00
Fiber Length L_w (mm)	1.12 ± 0.06	0.92 ± 0.01	0.99 ± 0.01
Fines (%) (Length Weighted)	14.43 ± 0.04	8.21 ± 0.53	7.50 ± 0.3
Curl Index (Length Weighted)	0.10 ± 0.01	0.11 ± 0.00	0.10 ± 0.00
Mean Width (µm)	20.3 ± 0.85	16.9 ± 0.00	17.2 ± 0.00
Kink Index (1/mm)	1.6 ± 0.01	1.83 ± 0.06	1.75 ± 0.06
Coarseness (mg/m)	0.08 ± 0.00	0.07 ± 0.00	0.07 ± 0.01

Note: L_n = Arithmetic average of fiber length and L_w = weighted average fiber length

Table 5. Contact Angle for Paper and Plastic Straws (10 s)

Sample ID	Contact Angle (°)	
	Inner Layer	Outer Layer
Plastic1	85.10	84.66
Plastic2	95.38	88.56
Plastic3	80.62	79.42
Plastic4	89.26	97.95
Paper1 (White)	112.83	132.29
Paper2 (Brown)	124.65	102.72
Paper3 (Color)	117.24	125.62

Dry Tensile Strength

The tensile strength was measured for the plastic and paper straws, Tables 6 and 7. Because of the inherent difference between these two materials, a fair comparison between the tensile properties was established using the specific strength and calculated by dividing the tensile strength by the density of the respective material. In this manner, the paper straws had a similar value between them, but the value changed considerably for the plastic straws. However, the paper straws had a higher specific strength with the exception of one of the plastic samples.

Fold Endurance

The fold endurance test determined the capacity of the straw to withstand repeated bending. The plastic straws offered a considerably higher resistance to this stress (Table 6). However, the paper straws were strong enough to resist typical usage and were unbroken after being bent multiple times (Table 7).

Table 6. Mechanical Measurements for the Plastic Straws. Tested under standard TAPPI conditions (23 °C and 50% relative humidity (RH))

Plastic	Plastic1	Plastic2 (Normal)	Plastic2 (Flexible Zone)	Plastic3	Plastic4
Load at Break (N)	192	94	99	164	212
Tensile Strength (MPa)	47.98	15.58	16.57	27.44	14.11
Specific Strength (KN × m/Kg)	56.08	18.22	19.38	33.78	19.99
Stretch (%)	1226.5	953.9	996.0	1279.0	1262.9
Young's Modulus (MPa)	850.93	242.20	71.67	457.55	256.11
Stiffness (kN/m)	709.11	201.83	59.73	381.30	320.13
Fold Endurance	> 5000	> 5000	> 5000	> 5000	> 5000

Table 7. Mechanical Measurements for the Paper Straws. Tested under standard TAPPI conditions (23 °C and 50% relative humidity (RH))

Paper	Paper1 (White)	Paper2 (Brown)	Paper3 (Color)
Load at Break (N)	99.97	113.10	132.90
Tensile Strength (kN/m)	10.00	11.31	13.29
Specific Strength (KN × m/Kg)	33.53	39.13	42.62
Stretch (%)	3.7	4.0	4.1
Stiffness (kN/m)	1219	1252	1285
Fold Endurance	2582	1985	1681

Figure 1 shows the plots of the strongest plastic and paper straws during the tensile test and displays the expected behavior of these types of polymeric materials.

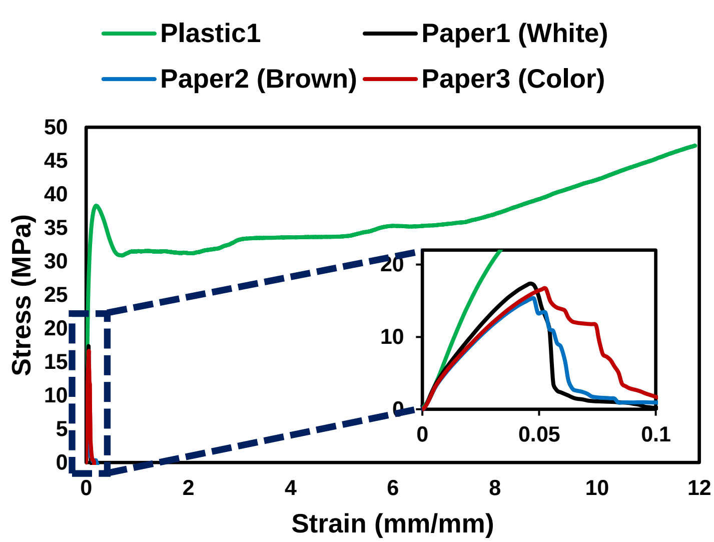


Fig. 1. Average tensile strength curves for paper and plastic straws; strongest plastic (plastic1) and paper1, paper2, and paper3. Enlargement of range to 0.1 mm/mm.

Overall, the plastic tended to be stronger than the paper. The force needed to break the paper samples was 60% of the force needed to break the plastic straw, and the plastic straws could stretch roughly ten times or more before failure. In addition, the paper straws failed at 3.6% to 4.1% of strain, and the paper was stiffer than the plastic.

Figure 1 shows a typical tensile curve for polymers (green trend), with a Hookean or elastic region with a linear response (Young's modulus) of strain and increasing stress. The tensile yield strength was the first point where the linear trend ceased, and the plastic deformation started. The ultimate stress was the reported tensile strength and is the maximum load the material can stand before it breaks, divided by the initial transversal area.

Axial Compression

Table 8 shows the compressive strength for the plastic and paper straws for the axial configuration. The Paper3 straws achieved the highest compressive strength of the paper straws, but when compared with plastic, the paper could only withstand half of the force of the strongest plastic straw.

Table 8. Dry Axial Compressive Strength for Plastic and Paper

Material	Sample ID	Compressive Strength (MPa)
Plastic	Plastic1	21.60
	Plastic2	11.97
	Plastic3	17.86
	Plastic4	15.85
Paper	Paper1 (White)	9.26
	Paper2 (Brown)	7.96
	Paper3 (Color)	9.99

Figure 2 shows the strongest of the plastic straws in contrast with the three brands of paper straws. The plastic cylindrical structure presented a narrower peak and the highest compression stress before it collapsed. In contrast, the paper showed a broader curve and reached the maximum load at a higher strain before it failed.

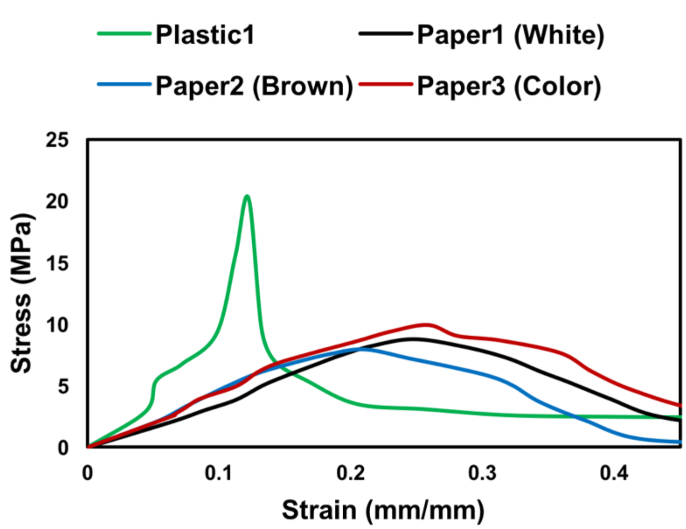


Fig. 2. Average compressive strength curves in the axial direction for plastic straws and the three brands of paper straws

Radial Compression

The results of the radial configuration compressive strength are shown in Table 9. The paper straws exhibited more strength and a higher modulus than the plastic straws. The plastic deformed more easily, with more obvious elastic (reversible deformation) behavior. People often enjoy this property, as they sometimes like to repeatedly bite the straw and have it come back to its original state. This reversible deformation is not as likely with paper straws.

Table 9. Dry Radial Compressive Strength for Plastic and Paper Straws

Material	Sample	Maximum Load (N)	Compressive Strength (kPa)	Young's Modulus (kPa)
Plastic	Plastic1	29.67	39.56	92.28
	Plastic2	13.93	19.35	51.19
	Plastic2 (Flexible Zone)	22.13	40.09	110.01
	Plastic3	12.09	21.89	97.52
	Plastic4	35.97	35.97	83.24
Paper	Paper1 (White)	8.75	124.75	517.25
	Paper2 (Brown)	6.00	83.00	438
	Paper3 (Color)	9.50	132.00	776.5

Paper2 (Brown) displayed the lowest strengths for both the axial and radial configurations. The axial configuration had a more considerable load tolerance than the radial configuration due to a geometrical configuration that allows an even distribution of the stress through the entire structure.

Figure 3 shows the radial compression curves of the plastic and paper straws. The transition between the elastic and plastic regions was not easy to distinguish in the plastic curve but was more easily shown in the paper curve. This means that the plastic acted as an elastic material without the plastic region for the strain tested. In addition, the paper could not recover the initial geometry of the material after the test, as did the plastic samples.

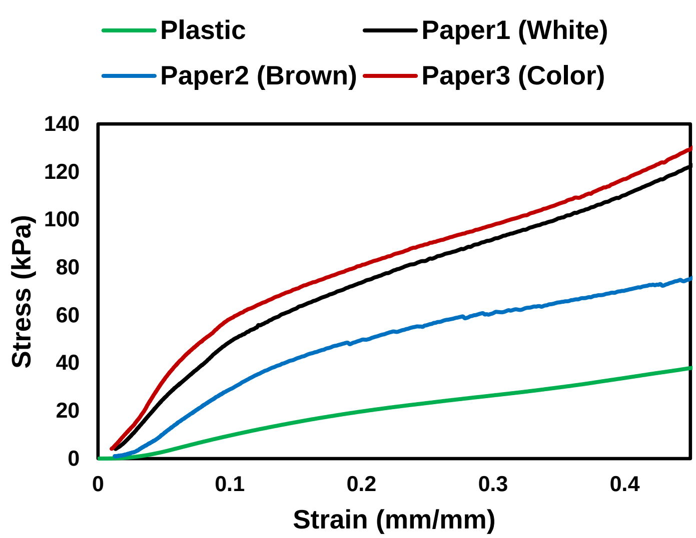


Fig. 3. Average compressive strength curves in the radial direction for plastic straws and the three brands of paper straws

Weight Gain for Different Liquids

The first part of the longevity test was to measure how much liquid the straws in the test conditions retained as a function of time. Figure 4 shows the weight gain of the straws due to water absorption versus time at room temperature. The weight gain increased at a high rate for the first 20 min, and then at a slower rate after that. Plastic straws showed negligible weight gain in all cases.

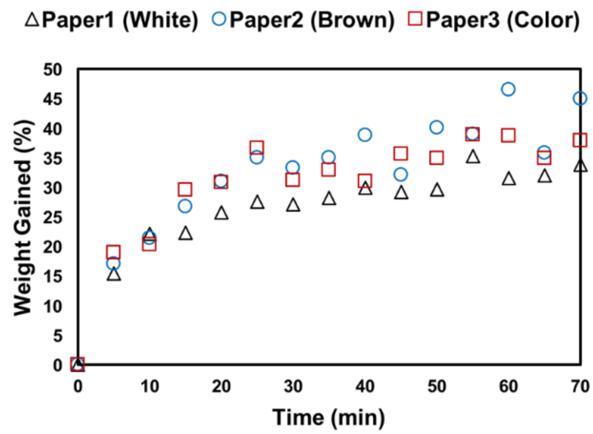


Fig. 4. Weight gain for paper straws in water at 21 °C in 5 min intervals

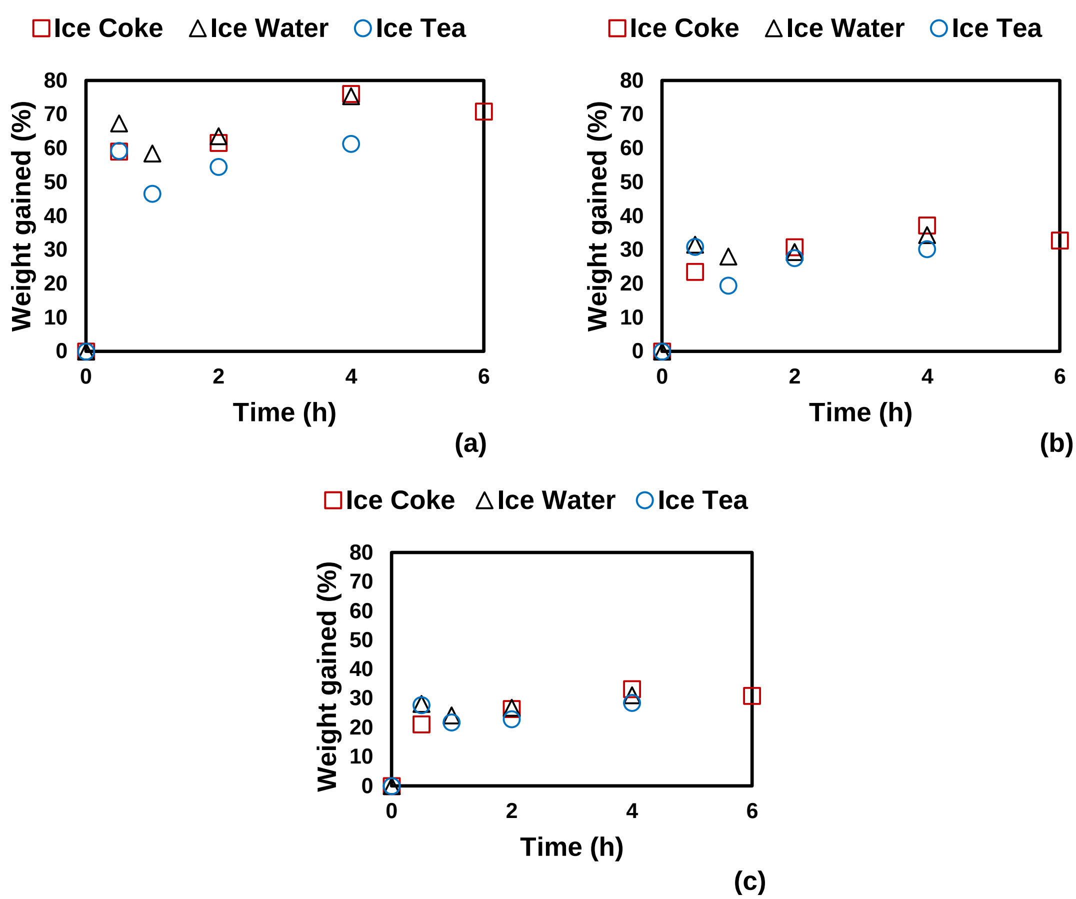


Fig. 5. Weight gained for (a) Paper1 (White), (b) Paper2 (Brown), and (c) Paper3 (Color) in three different beverages with an initial temperature of 0 °C

Figure 5 shows the weight gain as a percentage for Paper1 (White) (Fig. 5a), Paper2 (Brown) (Fig. 5b), and Paper3 (Color) (Fig. 5c) for some common beverages. This test was performed using the same initial temperature and liquid height in three different but common cold beverages: water, a carbonated beverage (Coke), and sweet tea. The most noticeable difference was between paper straw types rather than liquids. The Paper1 (White) straws gained up to 75% of their weight after four h of testing, while the other two brands only gained approximately 30% each. These results suggest that the brand of Paper1 (White) lacked the coating or protective material or had less internal sizing than did the other paper straws.

Weight Gain for Different Temperatures

Similarly, the three brands of paper straws were tested using water at three different temperatures (*i.e.*, 0 °C, 21 °C, and 48 °C). Paper1 (White) retained more liquid than the other paper straws. For Paper2 and Paper3 straws, the weight gain was higher for the higher liquid temperature, as expected. However, for Paper1 the opposite was true (Figure 6).

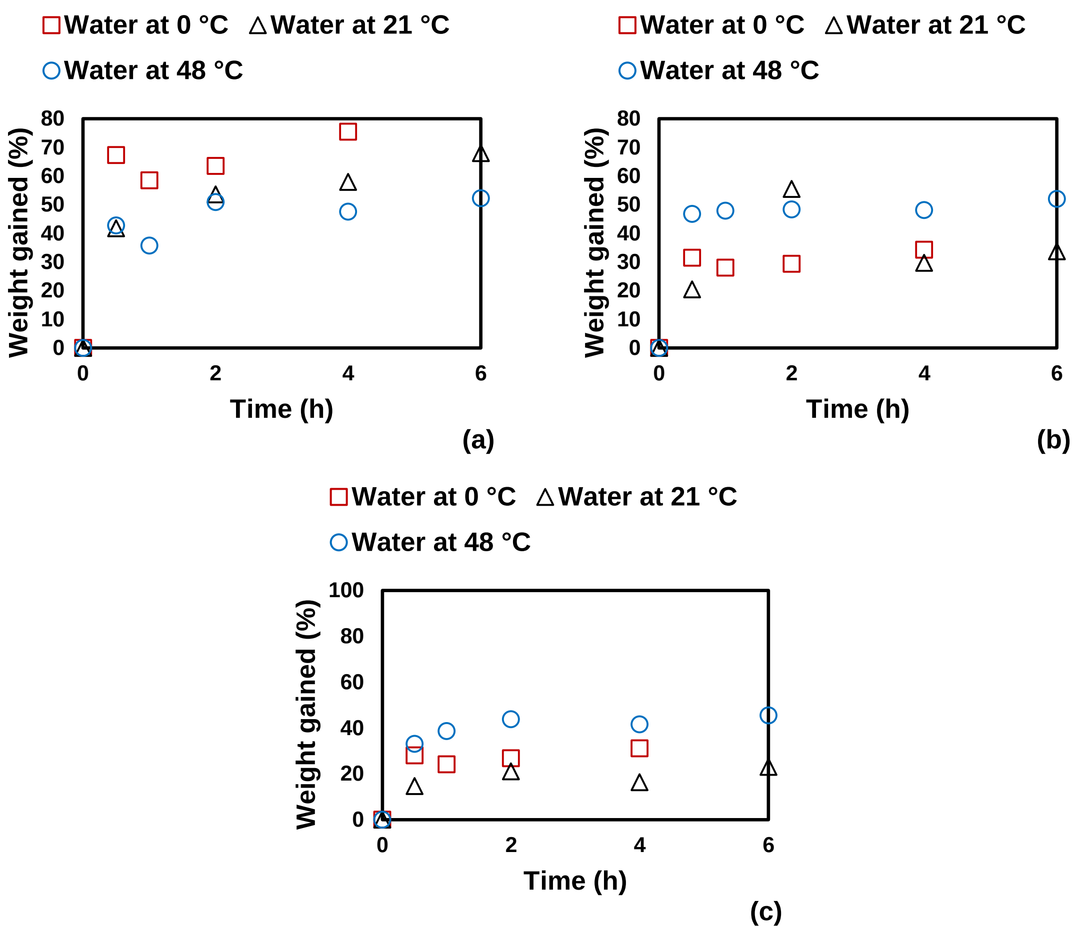
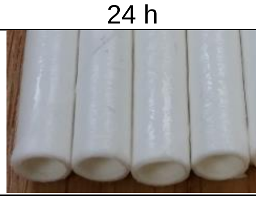
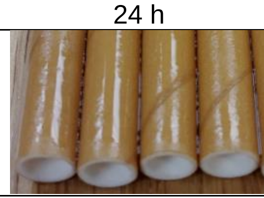


Fig. 6. Weight gained for (a) Paper1 (White), (b) Paper2 (Brown), and (c) Paper3 (Color) in water at three different initial temperatures

Effects of the Paper Straw and Liquid Interactions

A concern for using paper straws is how the appearance of the liquid and the straws are affected by the interaction between them. The appearance of the paper straws after 30 min and 6 h after being in contact with Coke is shown in Table 10. It is observed that the paper straws all showed a distinct darkening due to the absorption of the Coke.

Table 10. Paper Straw Appearance After Longevity Test

Paper1 (White)		Paper2 (Brown)		Paper3 (Color)	
Coke		Coke		Coke	
30 min	6 h	30 min	6 h	30 min	6 h
					
Water		Water		Water	
24 h		24 h		24 h	
					

To investigate whether the straws released any material/particles during the contact with the liquids, the turbidity of the water was measured after 6 and 24 h of the straws being in contact with the water. The appearance of the straws after 24 h in water is also shown in Table 10. The results indicated that the paper straws acquired the color of the liquid, but the straws did not visually change the appearance of the liquid and did not release any solids into the liquid, even under periods considerably larger than the average for these single-use disposable materials.

Material Transfer from Straw to Liquid Measured by Turbidity

The turbidity values obtained from the paper straws being in contact with water for 24 h are shown in Table 11. The liquid was completely clear to the human eye with an average value of 0.56 FNU (formazin nephelometric unit).

Table 11. Turbidity Measurement after 24 h of Direct Contact between Water and Paper Straws

Liquid	Turbidity (FNU)
Drinking Water	0
Water - Paper1 (White)	0.52 ± 0.11
Water - Paper2 (Brown)	0.63 ± 0.12
Water - Paper3 (Color)	0.53 ± 0.09

Compression of Paper Straws Exposed to Liquid

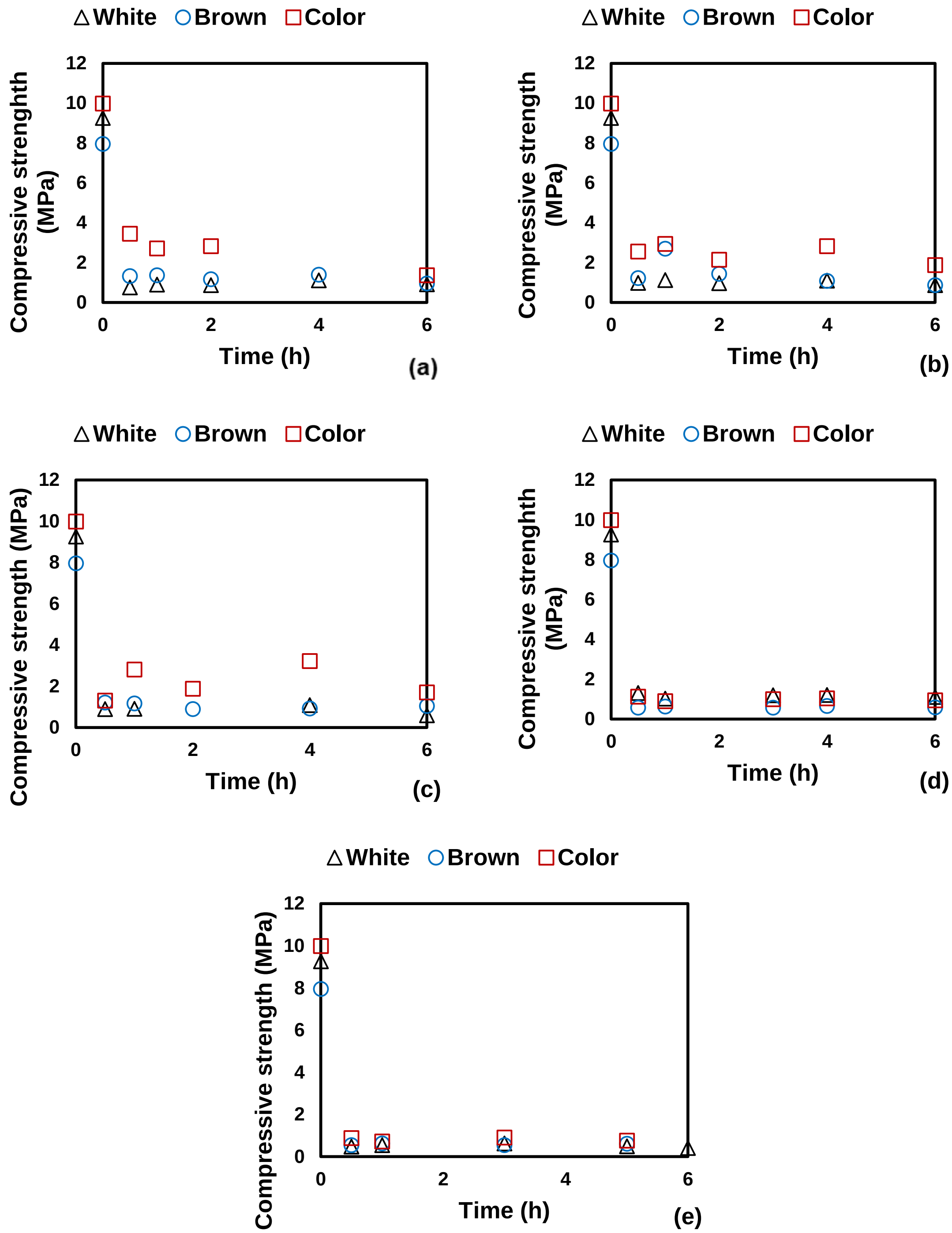


Fig. 7. Axial compressive strength *vs.* time for straws immersed in: (a) Coke at an initial temperature of 0 °C (temperature remained at 0 °C for 3 h, and after 6 h, the temperature reached 15 °C); (b) water at an initial temperature of 0 °C (temperature remained at 0 °C for 3 h, and after 6 h, the temperature reached 15 °C); (c) water at an initial temperature of 21 °C; (d) water at an initial temperature of 48 °C; and (e) water at an initial temperature of 82 °C

To be seen by the naked eye, the value must be at least 4 FNU (World Health Organization 2011), 55 FNU for a cloudy suspension, and 515 FNU for an opaque suspension (Fondriest Environmental, Inc. 2014). The values indicated that no relevant amount of solid migrated in the liquid. Considering that drinking water needs to have a value under 10 FNU to be acceptable, the paper straws did not noticeably contaminate the liquids after 24 h of direct contact (Minnesota Pollution Control Agency 2008; Muthuraman and Sasikala 2014).

Axial compression

In this section, the second part of the longevity test is discussed. The compressive tests of the paper straws in wet conditions as a function of time, with an initial liquid temperature and a fixed liquid height, was conducted. The axial and radial configurations were evaluated.

Figure 7a shows the compressive strength of the paper straws relative to the dry condition (point zero) as a function of time. The strength decreases by about 80% within the first 30 min and then retained that level throughout the rest of the test. The reduction of force was approximately 90% in some cases. The Paper3 (Color) straws remained as the brand with the highest compressive strength at every condition, in all liquids tested and at all temperatures. As shown in Figs. 7a and 7b, when the Coke and water were at the same initial temperature (0 °C), there was no relevant difference in compressive strength between the two beverages. As shown in Figs. 7b through 7e, initial temperature increases reduced the compressive strength of the paper straws even further. Several samples completely lost their structural integrity in the water at 82 °C, making the compression test not possible for these samples.

Radial compression

The longevity tests of the paper straw compressive strength in the axial direction of the straws are discussed in this section. The results for water at 0 °C and 21 °C, and Coke at 0 °C after two h in direct contact with the liquid are shown in Tables 12 to 14 for the paper straws.

Table 12. Radial Compression Strength for Paper1 (White) Straws out of the box* and after 2 h immersed in liquid

Liquid	Load (N)	Compressive Strength (kPa)	Young's Modulus (kPa)
Out of the box	8.75	124.75	517.25
Water at 21 °C	3.77	10.48	28.00
Ice Water	4.00	11.11	29.00
Ice Coke	3.80	10.55	27.00

*Out of the box refers to the results of Table 9, the compressive test of the straws before contact with any liquid

The Paper3 (Color) straws remained the strongest in terms of the load they could sustain. Similar to the axial configuration, the paper straws lost 80% to 90% of their compressive strength after exposure to the liquids for 30 min.

Table 13. Radial Compression Strength for Paper2 (Brown) Straws out of the box* and after 2 h immersed in liquid

Liquid	Load (N)	Compressive Strength (kPa)	Young's Modulus (kPa)
Out of the box	6.00	83.00	438
Water at 21 °C	5.50	15.29	41
Ice Water	4.81	13.38	33
Ice Coke	5.09	14.13	39

*Out of the box refers to the results of Table 9, the compressive test of the straws before contact with any liquid

Table 14. Radial Compression Strength for Paper3 (Color) Straws out of the box* and after 2 h immersed in liquid

Liquid	Load (N)	Compressive Strength (kPa)	Young's Modulus (kPa)
Out of the box	9.50	132.00	776.5
Water at 21 °C	12.00	33.33	92.0
Ice Water	9.49	26.36	64.0
Ice Coke	8.78	24.39	53.0

*Out of the box refers to the results of Table 9, the compressive test of the straws before contact with any liquid

The longevity test was also performed with water at different initial temperatures, as shown in Fig. 8.

The results show how the compressive strength was reduced by 80% to 85% after 30 min and remained in this range during the remainder of the test. Like the axial configuration, a higher temperature negatively affected the radial compressive strength and further reduced the results to close to 90% of the dry value.

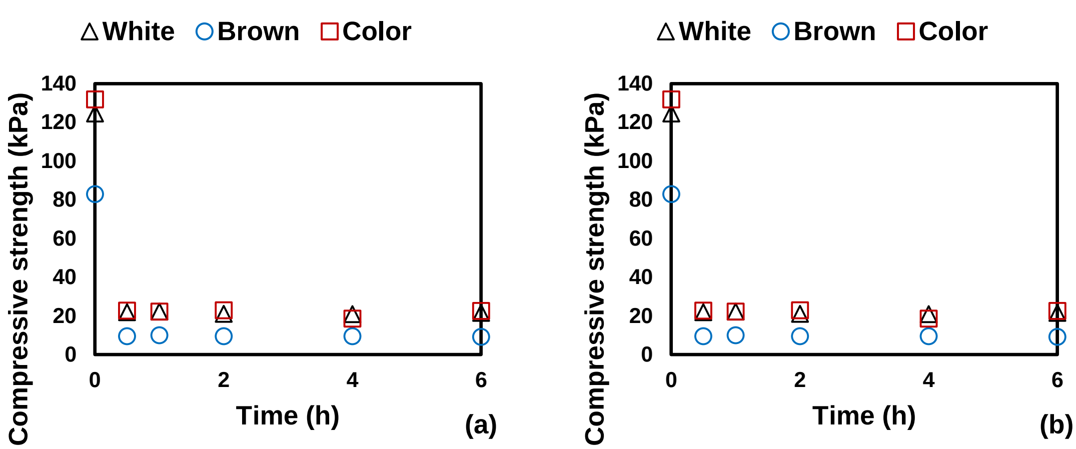


Fig. 8. Radial compressive strength *vs*. time for straws immersed in water at (a) an initial temperature of 48 °C and (b) an initial temperature of 82 °C

CONCLUSIONS

1. The paper straws were made mainly of hardwood fibers and had been treated to increase their hydrophobicity. Their surfaces formed initial contact angles with water in the range of 100° to 125°, indicative of hard sized paper surfaces.
2. The paper straws experienced weight gain almost immediately after exposure to liquids and gained weights of 30% to 50% within 60 min.
3. The plastic straws were generally stronger than the paper straws in the dry state and did not gain weight when immersed in fluids. Plastic straws did not display any decreases in mechanical properties upon immersion in liquids
4. Paper straws displayed higher compressive strength in the radial configuration under dry conditions than the plastic straws; however, the plastic straws returned to the original shape after release of the force, and the paper straws did not.
5. The type of fluid did not have a noticeable impact on the weight gain or wet strength of the paper straws.
6. An increase in the liquid temperature increased the weight gained for the paper straws and reduced the wet strength.
7. The paper straws did not release appreciable particle solids into the liquids as evidenced by liquid turbidity measurements before and after exposure to the paper straws.
8. None of the paper straws evaluated had considerable stability after 30 min in liquids, losing 80% to 90% of their strength within 30 min of exposure to liquid.
9. Tracking of the time-dependent weight gain and compressive strength of paper straws under immersion of liquids was an insightful way to evaluate paper straw product performance.

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