Ahuod3n – A redesigned low-cost foldable wooden stool

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ABSTRACT

This project delves into the experimental and statistical analysis of material selection factors such as availability, cost efficiency, and durability, tensile strength, and sagginess of materials that could be potentially used to build the seating area of a foldable wooden stool. In the course of the experimental process, paper, plastic, and leaves were used as the experimental groups for the analysis. A further test was carried out to test if weaving patterns of the materials affected tensile strength. The mechanical properties of the experimental groups were statistically analyzed to decide on the material's usability. Conclusively, plastic straws had the highest tensile strength and least sag per unit mass, making it the most suitable material amongst the three to withstand the higher load placed on the seating area. In attempts to reduce the sagginess of the plastic straw, two weaving patterns, rustic plait, and, three-strand braid, of equal length underwent a repeated sagginess test. The rustic plait weaving pattern resulted in the least sag per 700g loaded on it. With these results the seating area of the stool was fabricated from rustic-plaited plastic straws.

The empathic motive behind this project is to redesign simple household furniture from repurposed materials for less privileged homes in the rural areas of Sub-Saharan Africa.

KEYWORDS: material selection; strain sensor; furniture; ultimate tensile strength; stool

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1. INTRODUCTION

In this project, experiments were performed to explore cost-effective materials in the designing of the seating surface of a stool. Conventional materials were considered, such as paper, naturally occurring substances, and plastics for fabrication to minimize cost.

According to Garside, the global production of paper stood at 411 million metric tons, as of 2016, rating paper as one of the most used materials in the world [1]. Paper is defined as a material manufactured in thin sheets from the pulp of wood or other fibrous substances, which can be used for writing, drawing, or printing on and as well as wrapping material [2]. Paper was selected because it is easy to come by due to its mass production. The thickness of a paper can be measured with a pair of vernier calipers. The strength and durability of paper are based on the type of material used to make it and the length of it, respectively. For this experiment, A4 sheets were selected for use, since they are ubiquitous.

Next, leaves from the Brahma Edulis tree were chosen for this project because they are ubiquitous .The Brahma tree is like a palm tree with its leaves in the shape of a fan. The tree grows to a height between 4.5 -13 meters tall. This plant was the best choice at our disposal because of its proven strength and durability, which were some of the features in our design.

Finally, plastics were chosen to curb the problem of plastic waste pollution. Plastic straws cannot be easily recycled, and hence they are littered everywhere and typically end up in the ocean. According to Ocean Conservancy's Tides system, straws made up a considerable portion of the trash in the sea, in early 2018. Five hundred million straws are used daily in the USA. This number is enough to circle round the earth 2.5 times [3]. Based on this problem, this experiment considered it as one of the materials, with the aim of recycling plastic straws to reduce plastic waste pollution.

The mechanical properties of the three materials were compared to find the best. A one-way ANOVA, along with a linear regression model, was carried out in selecting the material with the highest tensile stress and least sagginess, respectively. Theoretically, a material with a high tensile strength would perform better in a sagginess test. The best material was further passed through a sagginess test comparing two different weaving patterns for the one that gives the least sag. In concluding which model results in the least sag for the strongest of the three materials, a student's T-test was employed. This material selection process is visualized in Fig 1.

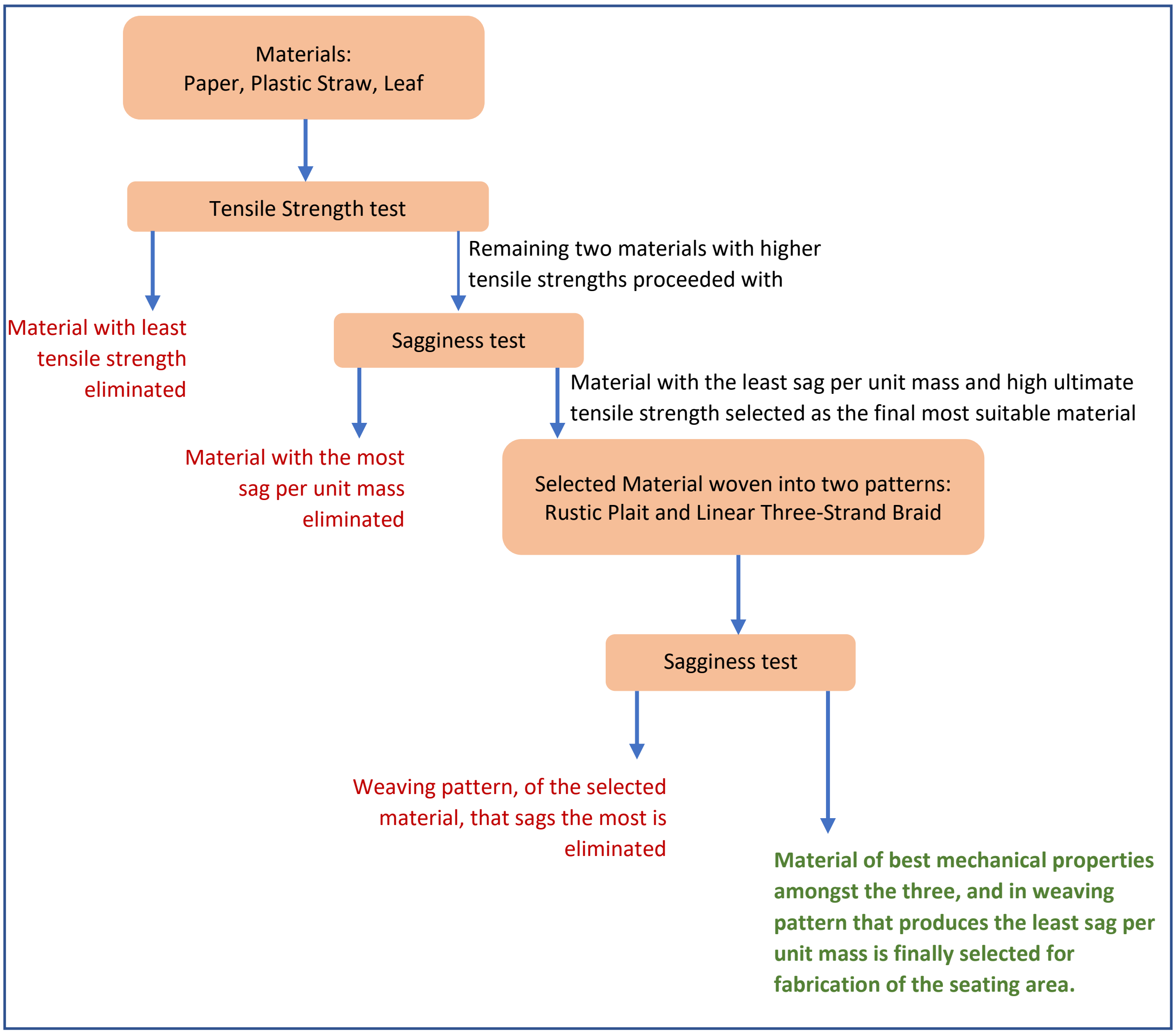

Fig. 1 Material selection process for the seating area of the stool

2. METHODS

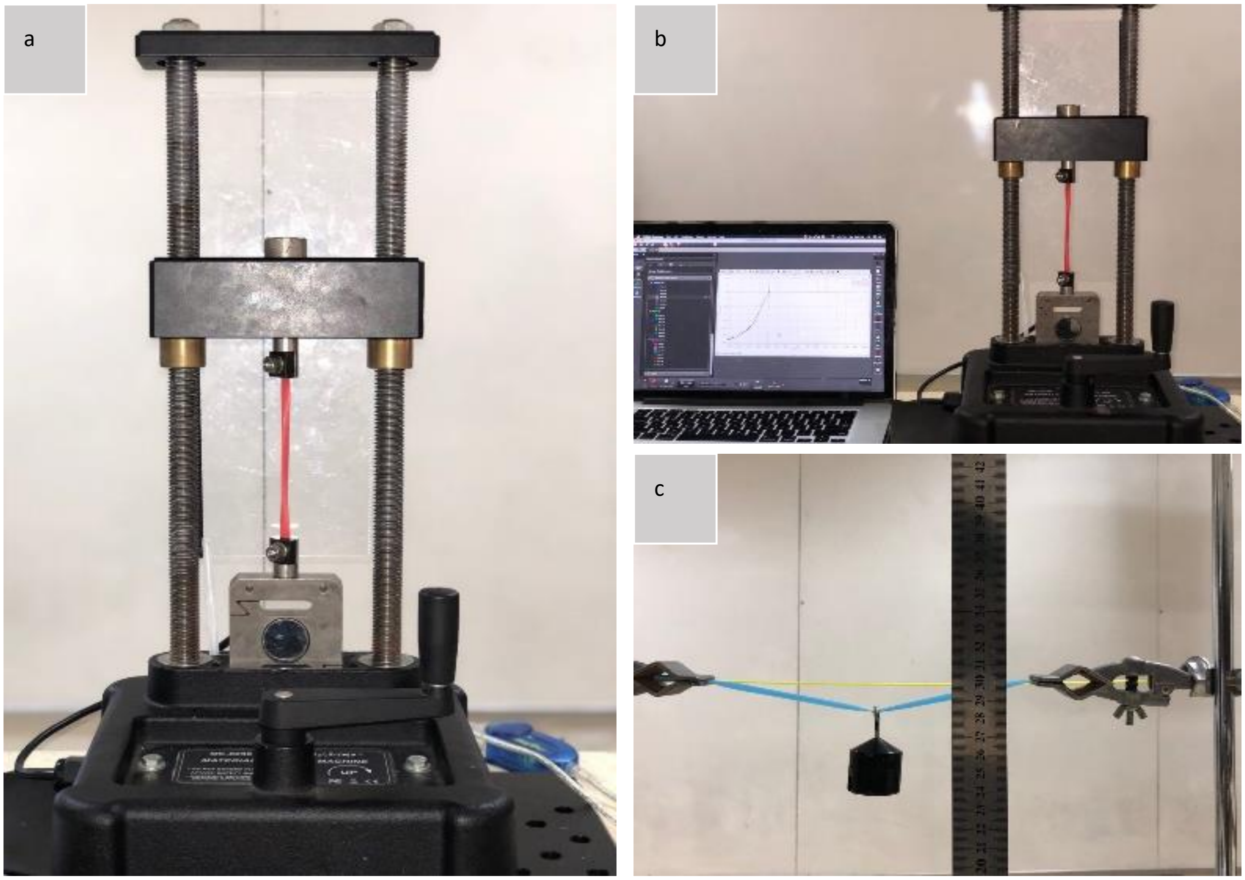

Fig. 2. (**a**)Extensometer with straw clasped and being extended. (**b**)Extensometer with PASCO Capstone Software to record force and position data as materials are being extended and (**c**) Sagginess Test experimental setup.

A. Ultimate Tensile Stress Test of Strips (Test A)

Five strips of straw, paper, and the Brahea Edulis leaf of similar length, width, and thickness (11cm x 1cm x 0.1cm) were used for this test. The test was conducted using an extensometer and the PASCO Capstone Software. The software generated force versus extension graphs (Fig 2a & 2b) for each material. Based on the length (measured using a ruler) and area (measured using a micrometer screw gauge) of each strip, tensile stress versus strain graphs was produced. Consequently, the Ultimate Tensile Stress (UTS) for each material was obtained from the peaks of the graphs generated.

The stress was calculated using the relation:

$$\sigma = \frac{F}{A}$$

where:

σ is tensile stress

F is force applied

A is the cross-sectional area

The strain was calculated using the relation:

$$\varepsilon = \frac{\delta}{L}$$

where:

ε is the tensile strain
δ is extension
L is original length

B. Sagginess Test of Strips (Test B)

Five strips of straw, paper, and the Brachia Edulis leaf of similar length and width (25cm x 1cm x 0.1cm) were used for this test. The test was conducted by clamping the ends of each strip using two retort stands, hanging a range of masses (200g, 400g, 500g, 700g) in the middle of each strip and measuring the extension from the horizontal baseline (Fig 2c). These measurements were used to plot a mass against extension graph for each material.

C. Sagginess Test of weaving patterns (Test C)

Based on the results from Test A and Test B, the material with the highest tensile strength and lowest sagging was chosen. Two weaving patterns (4 Strand Rustic Plait & Linear 3 Strand Braid) were created from that material, and a sagginess test from Test B was performed on five (5) strips of each weaving pattern.

3. RESULTS AND DISCUSSION

Table 1 summarizes the mean mechanical properties obtained from test A and test B for the three material strips used.

Material	Mean Ultimate tensile stress / *Pa*	Mean sag per unit mass / *m kg*$^{-1}$
Double layered paper strip	2.94×10^8	N/A
Brahea Edulis leaf strip	4.01×10^8	0.04
Straw	9.72×10^8	0.03

Table 1. Summary of Mechanical Properties

A. Ultimate Tensile Stress Test of Strips (Test A)

Ultimate tensile stress point is the breaking point of the material when undergoing a forced extension. This property is indicated for each of the materials of straw, leaf, and paper in the stress versus strain graph (Fig. 3a) as the point where there is no change in extension, thus no increase in strain for an increase in stress (increase in force) – the sharp turning point of each line for each of the materials. Conclusively, the results of the ultimate test showed the straw strip had the highest ultimate tensile stress of 9.72×10^8 Pa ($p<0.05$), followed by that of the leaf at 4.01×10^8 Pa ($p<0.05$) and the lowest being that of paper at 2.94×10^8 Pa ($p<0.05$) (fig. 3b). Straw is the most suitable material to be used for the seating area of the stool as per this test, due to it having the highest ultimate tensile stress (thus can withstand a more significant extensive force before breaking).

B. Sagginess Test of Strips (Test B)

From the results of the sagginess test, the different materials exhibited different extensions per each mass hung on it. A graph of mass hung versus the extension (Fig. 3c) showed straw had the least extension per unit mass placed on it, at 0.03m/kg ($p<0.05$), whereas that of leaf was 0.04m/kg ($p<0.05$). This estimate was obtained by calculating the gradients of each best fit line for each of the materials and comparing their values. The use of paper in this test was discontinued as paper tore when 400g was hung on it - it outrightly dissatisfied the experiment objectives, which is to arrive at the strongest of the three materials. Straw is the most suitable material to be used for the seating area of the stool because it possessed the lowest extension of sag per unit mass.

C. Sagginess Test of weaving patterns (Test C)

The determining factor for this test was the weaving pattern of the chosen material. Thus the load applied on the strip was kept constant at 700g. The analysis showed that the rustic plait weaving pattern of straw had the least extension per unit mass as compared to the linear three-strand braid of straw. For the 700g hung in the middle of the rustic plait weaving pattern of straw, there was a mean extension of 0.0526m ($p<0.05$), giving the rustic plait an extension per unit mass of 0.0751 m/kg. Whereas the linear three-strand had a mean extension of 0.075m ($p<0.05$), when the 700g mass was hung on it, giving it an extension per unit mass of 0.107 m/kg. Consequently, the rustic plait weaving pattern of straw is the most suitable as compared to the linear three-strand braid weaving pattern for the seating area of the redesigned stool as it sags the least per unit mass placed on it.

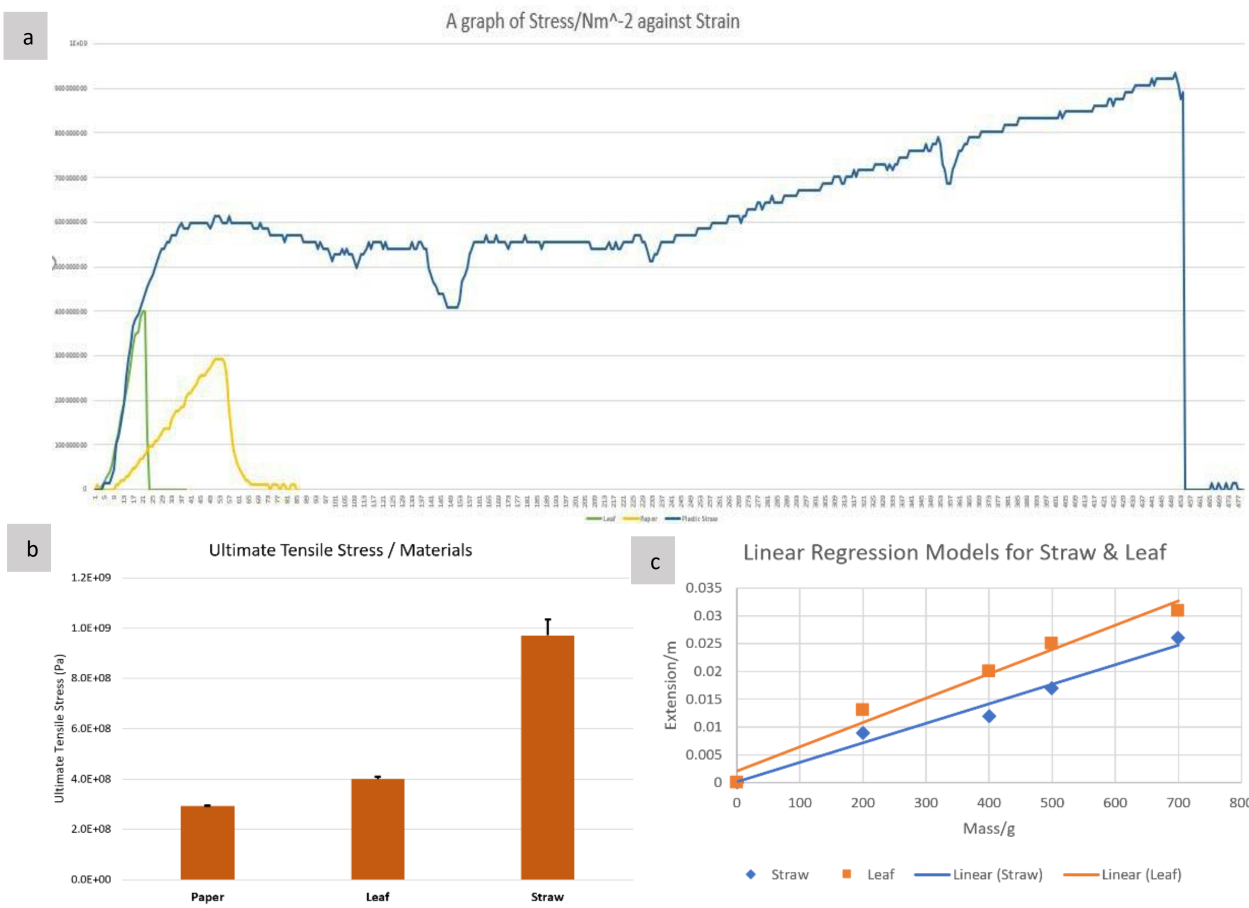

Fig. 3 (**a**) Tensile stress against strain graph. The blue curve representing straw, green representing Brahea Edulis leaf strip and yellow representing double-layered paper strip. (**b**) Bar graph of mean ultimate tensile stress of each material. Error bars represent standard deviation. (**c**) Graph of mass against extension with lines of best fit plotted for each material. The orange line represents the Brahea Edulis leaf strip, and the blue line represents the plastic straw.

D. Statistical Analysis

The data obtained from the three materials being tested (plastic straws, Brahea Edulis leaves and double-layered paper strips) and the two weaving patterns (rustic plait and linear three-strand braid) were used to calculate the mean ultimate tensile stress' and the mean extensions needed to draw conclusions in test A, B and C. The sample size used in Test A was 5 of each of three materials, giving a total sample size of 15 strips. Each of the five strips of straw was randomly selected from 50 identical straws. Each of the five strips of double-layered paper was randomly chosen from 150 sheets of standardized A4 paper, then cut and folded once into a double layer of equal length and width dimensions to the strips of the other materials. Each of the five strips of leaves was cut from 5 randomly selected leaf blades out of 10 leaf blades. Eighteen straws were randomly chosen from 500 straws and used for each of the 16 woven strips for the rustic plait weaving pattern laid on the stool. Giving the total number of randomly selected straws for the rustic plait at 288. 15 straws were randomly chosen from 500 straws and used for each of the 16 woven strips for the linear three-strand braid weaving pattern laid on the stool. Giving the total number of randomly selected straws for the linear three-strand braid at 240.

The scientific hypothesis of one material having the highest ultimate tensile stress as a strip, least sag per unit mass as a strip and the least sag per unit mass dependent on the weaving pattern, were converted into statistical hypotheses and summarized in table 2.

Property	**Null hypothesis (H_0)**	**Alternative hypothesis (H_a)**
UTS	$UTS_P = UTS_L = UTS_S$	$UTS_P \neq UTS_L \neq UTS_S$
SES	$SES_S = UTS_L$	$SES_S \neq UTS_L$
SEW	$SEW_R = SEW_L$	$SEW_R \neq SEW_L$

Table 2. Statistical Hypotheses

Where UTS is the mean ultimate tensile stress of strip, SES is the sagginess extension of strip, and SEW is the sagginess extension of the weaving pattern.

In table 2, UTS_P, UTS_L and UTS_S, represent the mean ultimate tensile stress of paper, leaf, and straw respectively. SES_S and SES_L mean the sagginess extension of a strip of straw and leaf respectively. In comparing the mean sagginess extension for the weaving patterns, SEW_R and SEW_L represent the mean sagginess extension for the Rustic Plait weaving pattern and the Linear Three-strand braid weaving pattern respectively.

For Test A, a Shapiro-Wilk test was performed on each material's ultimate tensile stress data to check for normality. The results for the normality test on the data points for each material are summarized in table 3.

Materials	**Shapiro-Wilk p-value**	**Normal**
Double layered paper strips	0.2011	Yes
Brahea Edulis leaf strips	0.4685	Yes
Straws	0.6995	Yes

Table 3 Shapiro-Wilk Normality Test Results

Upon concluding the data for each material is normal as data for each material had a p-value greater than 0.05, the statistical difference between the ultimate tensile stress materials was checked by performing a one-way ANOVA test and a Tukey posthoc analysis to identify the differences if any. This tested the null hypothesis for UTS detailed in table 2, and the results are summarized in Table 4.

Material comparisons	ANOVA test p-value	Tukey test p-values	Statistical difference
Paper-Leaf	2.48×10^{-2}	0.0014404	Yes
Straw-Leaf	2.48×10^{-2}	< 0.0000001	Yes
Straw-Paper	2.48×10^{-2}	< 0.0000001	Yes

Table 4 ANOVA and Tukey P-value Results

These test results conclude there is the statistical difference between the ultimate tensile stress results of the three materials, as each Tukey test comparison resulted in a p-value of less than 0.05, using a 95% confidence interval.

For test B, a linear regression test was carried out on each material's mass against extension plot, and correlation was checked for. The results from the linear regression test are presented in table 5.

Residual standard error:	50.6 on 2 degrees of freedom
Multiple R-squared:	0.9825
Adjusted R-squared:	0.9649
F-statistic:	56.03 on 2 and 2 DF
p-value:	0.01753

Table 5 Linear Regression Test Results

The linear regression model generated resulted in an adjusted R-squared value of 0.9649 and a p-value of 0.01753. These indicate the curves are an extremely good fit to the data points obtained and 96.49% of the variance in the extension can be calculated from the variance in masses hung (independent variable). The p-value of less than 0.05 indicates a correlation between mass and extension for that of paper and for that of straw. With these two models generated with an adequately good fit, there is a visible difference in their gradient. It can be concluded then that their gradients are statistically different, and straw extends the least per unit mass, as it has the lowest extension per unit mass gradient.

For test C, a Welch Two Sample T-test for rustic plait and linear three-strand braid was carried out with a 95% confidence interval to compare their mean sagginess when 700g was hung on each strand. The Welch Two Sample T-test allowed for analysis to cater for the possibility of the two patterns having unequal variances, although they were made from the same material. The null hypothesis for this test was that of SEW aforementioned in table 2. The results of this test are shown in table 6.

Rustic Plait (Tyrolean) vs. Linear 3 strand braid	
t = -16.885**, df =** 5.3462**, p-value =** 7.635×10^{-6}	
alternative hypothesis: true difference in means is not equal to 0	
95 percent confidence interval:	
-0.02574489	-0.01905511
sample estimates:	
Mean sag of Rustic /m	**Mean sag of 3-strand /m**
0.0526	0.075

Table 6 Welch Two Sample T-test

This test concluded with statistical difference between the mean sag for rustic plait and the mean sag for the linear three-strand braid, as a p-value of 7.635×10^{-6} was obtained, which is less than 0.05.All statistical analysis tests were carried out using R-Studio.

4. CONCLUSION

There was statistical significance obtained in the ultimate tensile stress tests as well as the sagginess tests, indicating the mean ultimate tensile stress' of the three materials, as well as the mean sagginess of the three materials, are not equal, rejecting their null hypotheses. Thus, enabling the selection of a suitable material for the designing of the seating area of the stool. A material with the highest tensile strength, as well as the least sag per unit mass placed on it, is the preferred material to be used for the seating area of the stool to be able to withstand a higher load placed on the stool than the others. With these preferences, plastic straws concluded in being the most suitable material to be used for the seating area of the stool.

Still with an aim to achieve the least sag per unit mass placed on the stool, the rustic plait weaving pattern of the plastic straw was used, as from tests conducted had sagged the least per 700g placed on it as compared to the linear three-strand braid.

Based on this material and weaving pattern selection the foldable wooden stool was built as shown in Fig. 4 and Fig. 5 with its seating area being plastic straws woven in rustic plait patterns.

Fig. 4 Detailed zoom on plastic straw rustic plait weaving pattern.

Fig. 5 Resulting foldable wooden stool with seating area made out of plastic straw woven in a rustic plait.

The durability of the seating area is the primary factor in the experiment; hence, the plastic deformation that the straw goes through is not convincing enough. Nevertheless, a potential solution for increasing the durability of the seating area is to bind the straw strips with an adhesive. The prototype above is still under iterative research and redesigning process, as things stand, Ahuod3n is suitable for the average child between the ages of 3-10 years old due to the low elastic limit of straw strips.

5. ACKNOWLEDGMENTS

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6. REFERENCES

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