

Background

Origami Applications

- Origami folding mechanics are being used in fields such as aerospace, robotics, and medicine (Meloni et al., 2021).
- Origami mechanics require paper that can withstand repeated folding while being easy to fold.
- To determine the effectiveness of certain additives in achieving these characteristics.

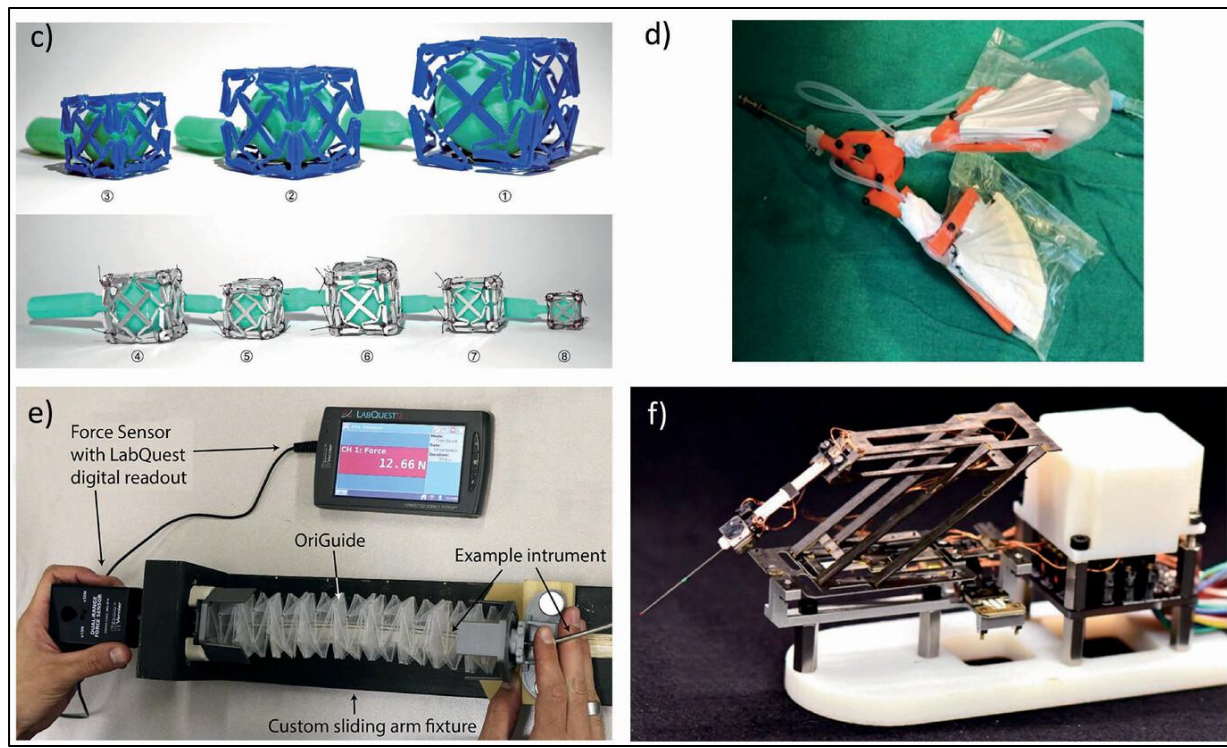


Figure 1. Origami-based biomedical devices (Meloni et al., 2021).

Paper Additives

- In 2022, total paper production weighed in at more than 414 million metric tonnes (Statistica Research Department, 2024).
- Chemical additives utilized in the paper making process result in a mill effluent that is detrimental to nearby aquatic environments.
- Bio-polymeric additives were selected to be characterized in the context of origami applications.
- Effective at increasing paper strength measurements in addition to being environmentally safe and sustainable (Basu et al., 2021).

Constraints

Origami Folding Parameters

Origami applications require paper that:

- Has a low thickness
- Can withstand repeated folding → folding endurance
- Takes a low force to crease → folding resistance
- Stays folded after a crease → folding elasticity

Paper Fiber

Abaca paper typically has a high folding endurance and low thickness, in part due to its high average fiber length (Liu et al., 2013).

Abaca is known to increase in strength with increased lengths of pulp beating. The pulp was beat for trials of 30, 90, and 180 minutes.

Bio-polymeric Additives

- Nanofibrillated Cellulose (5%, 10%)
- Carboxymethyl Cellulose (0.2%, 0.8%)
- Guar Gum (0.3%, 0.8%)
- Chitosan (0.5%, 1.5%)

Objectives

- I - Test Professionally Made Paper
- II - Bio-polymeric Additives and Pulp
- III - Develop Paper Sheets
- IV - Dual Polymer Combinations
- V - Test Paper Samples
- VI - Data Analysis

Discussion

- NFC 10% and Guar 0.8% seem to be the most effective at enhancing folding endurance.
- Hand papermaking did not result in exceptionally consistent thicknesses; however, most paper landed between 0.06 and 0.08 mm.
- For paper specimens with 1 or 2 double folds, the strip almost never broke along the intended fold line. This shows that 1-2 creases does not decrease the integrity of the paper past its randomly weaknesses. 5 or more double folds had a noticeable effect on the paper's tensile index.
- While this is an improvement, it still falls short of current standard chemical additives.

Future Research

Folding Resistance and Folding Elasticity

- The next parameters to determine effectiveness of paper in origami applications is folding resistance and folding elasticity.
- An apparatus similar to the one use in Rao et al. will be used to determine the force exerted on a fold by a roller and plot it against its fold radius.
- This will produce a stress vs. strain graph to determine the relationship between applied force and folding radius.

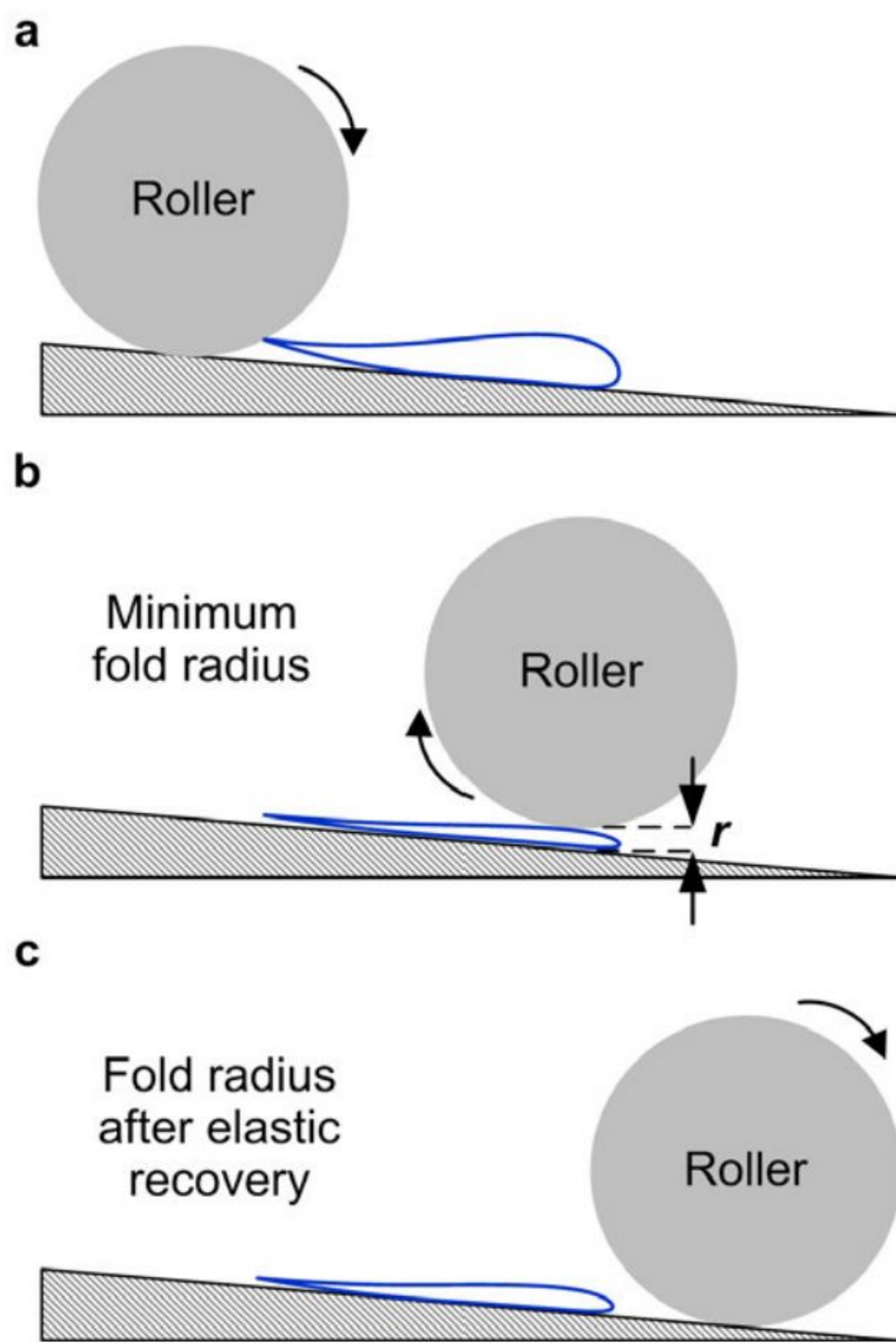


Figure 11. Schematic of the rolling experiment used to determine the relationship between applied force and folding radius (Rao et al., 2013).

Beating Times

- Continue to test sheets for pulp that was beaten for 30 or 90 minutes.

Dual Polymer Combinations

- Dual polymer systems have been found to further increase the effectiveness of bio-polymeric additives due to their cationic and anionic nature.
- Continue to develop sheets and test combinations of the previously used additives.

References

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Analysis of bio-polymeric wet-end paper additives in the context of origami folding applications

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Experiment



Figure 2. Valley Lab Beater with pulp (Image courtesy of the researcher).



Figure 3. Deckle box filled with pulp (Image courtesy of the researcher).



Figure 4. Developed paper sheets on deckles (right) and laid out on a felt (left) (Image courtesy of the researcher).

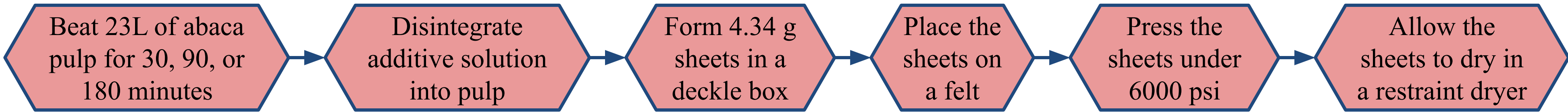


Figure 5. Papermaking process at the Minnesota Center for Book Arts (Figure courtesy of the researcher).

Folding Endurance Test

- Measure tensile index after apply a number of double folds.
- Paper sheets were cut into 2.5 cm x 18.0 cm strips, according to TAPPI 494.
- 0-50 double folds were applied to the specimen using a bone folder.
- The specimens were tested for their tensile index.
- Plotting the tensile index against the number of double folds visualized the rate at which the tensile strength decreases.



Figure 6. Paper in tensile tester (Image courtesy of the researcher).

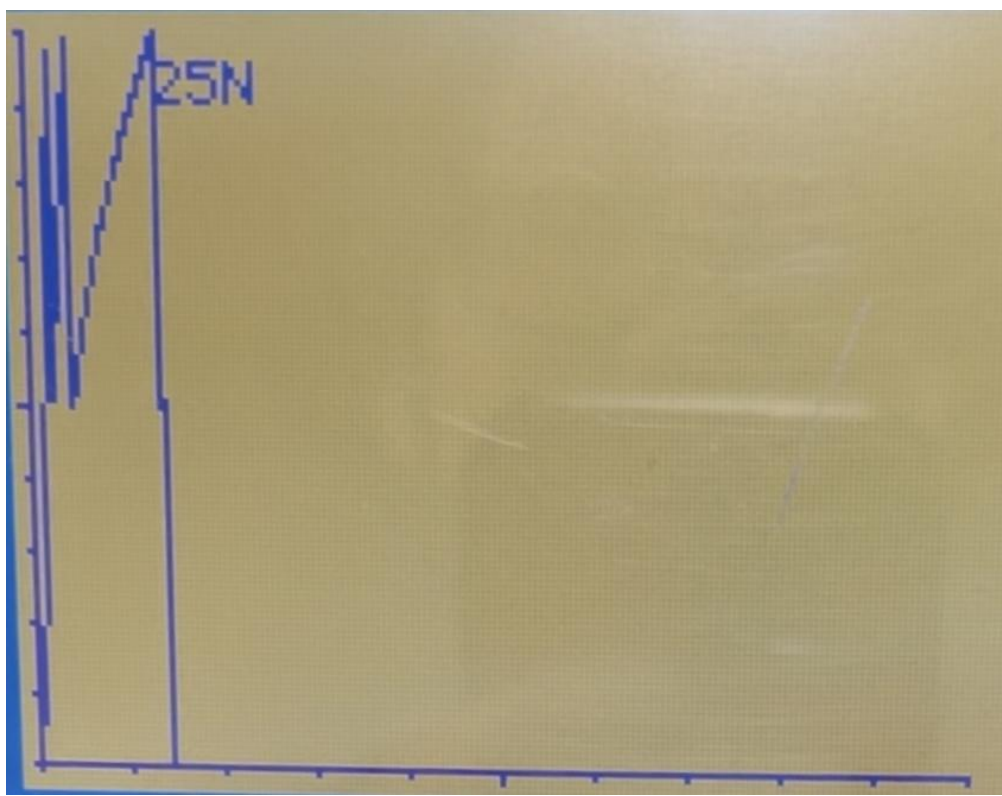


Figure 7. Stress vs. strain graph of a tensile test (Image courtesy of the researcher).

Results

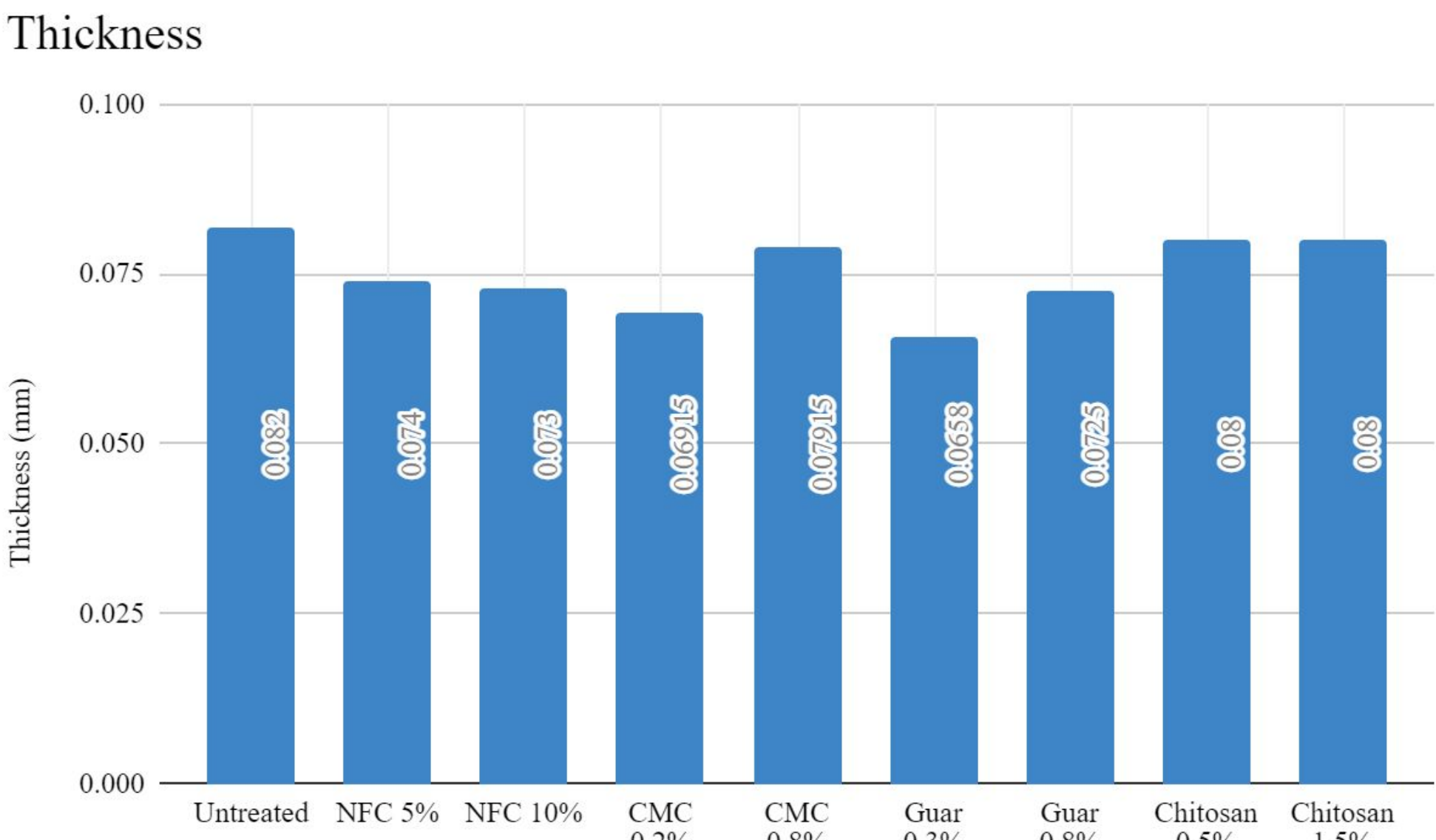
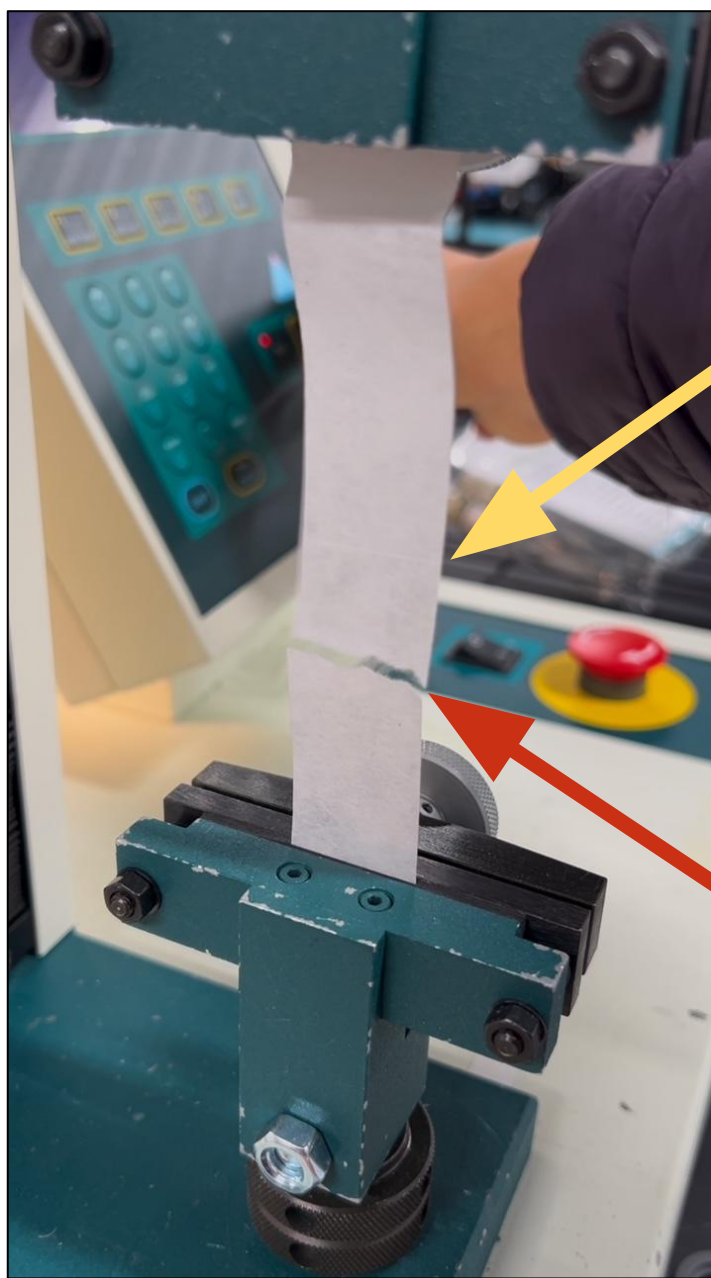


Figure 8. Bar graph visualizing the thicknesses of paper sheets for each additive including the untreated trial. Thickness is measured in millimeters (Figure courtesy of the researcher using Google Sheets).

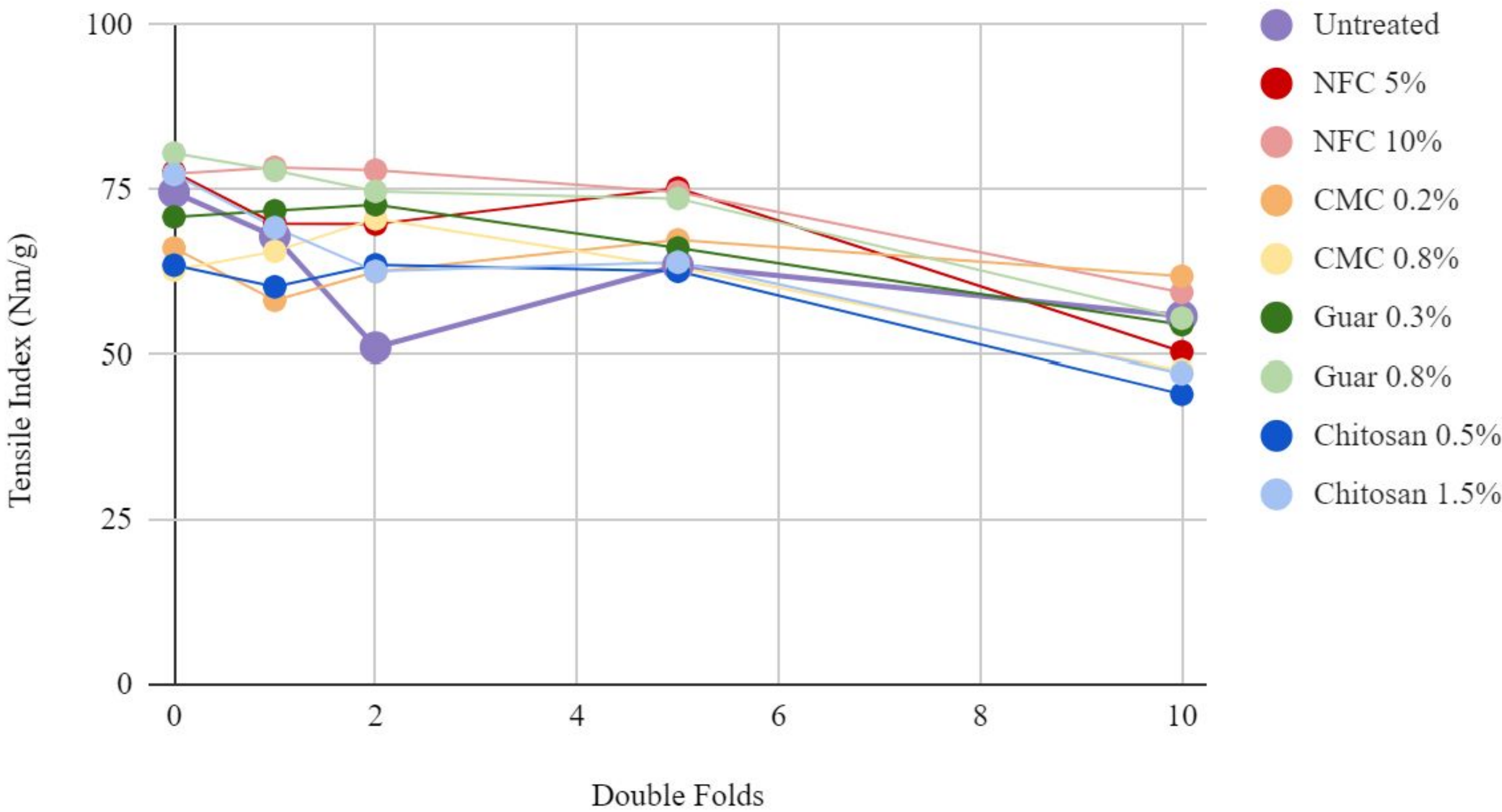


Double Fold Line

Fracture Line

Figure 9. Paper specimen in the Tinius Olsen H5k-S Tensile Tester after fracture. The specimen did not fracture along the intended fold line. Arrows indicate the double fold line (yellow) and the fracture line (red) (Image courtesy of the researcher).

Folding Endurance of Paper Beat for 180 minutes



Discussion

- NFC 5%, NFC 10%, Guar 0.3%, Guar 0.8%, and Chitosan 1.5% sheets appear to outperform the untreated trial (control).
- NFC 10% and Guar 0.8% performed the best, with a 19.21% and 16.93% increase respectively.

Figure 10. Line graph comparing the tensile index and folding endurance of paper sheets with different additives. The tensile index paper specimens were plotted against the number of double folds applied to them for each additive. The tensile index for the untreated trial (control) is indicated by larger points (Figure courtesy of the researcher using Google Sheets).