

Background

Origami Applications

- Origami folding mechanics are being used in fields such as aerospace, robotics, and medicine, such as biomedical implants and robots (Fig 1) (Meloni et al., 2021).
- Origami mechanics require paper that can withstand repeated folding while being easy to fold.
- The purpose of this study is to determine the effectiveness of certain additives in achieving these characteristics.

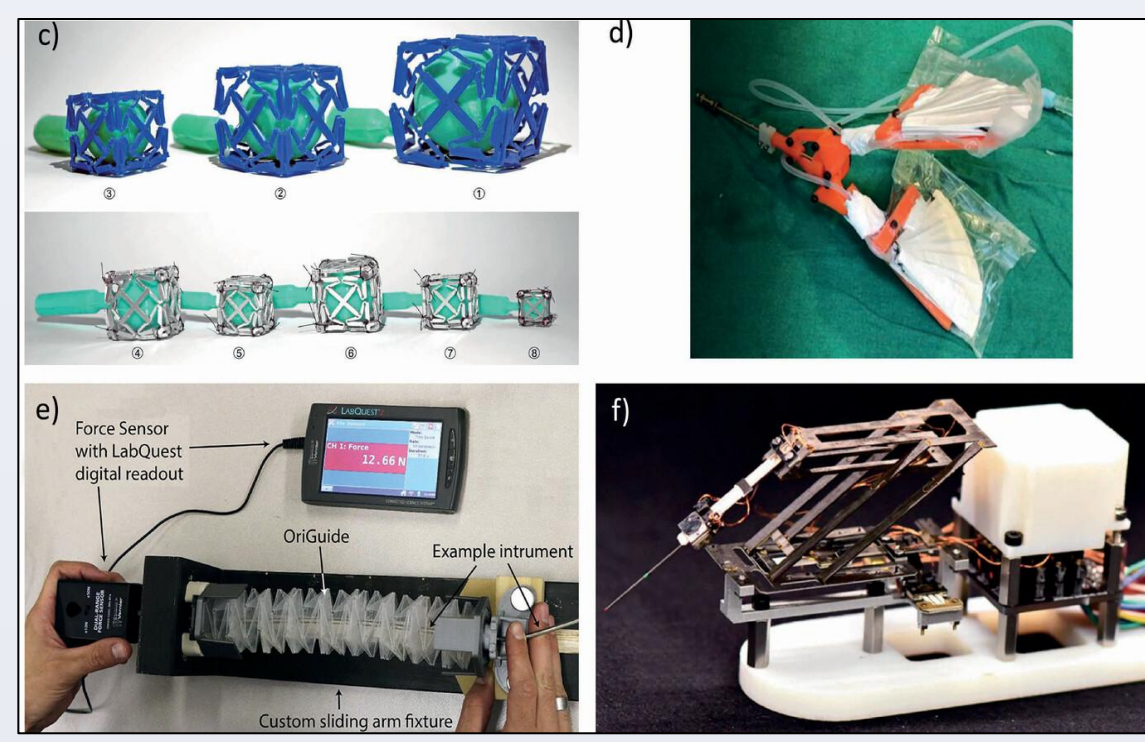


Figure 1. Origami-based biomedical devices, including an orthopedic implant (c), a surgical retractor (d), a support system for RAS procedures (e), and a robot for microsurgery (f) (Meloni et al., 2021).

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
- Stays folded after a crease → folding elasticity
- Takes a low force to crease → folding resistance

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 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%)

Paper Development

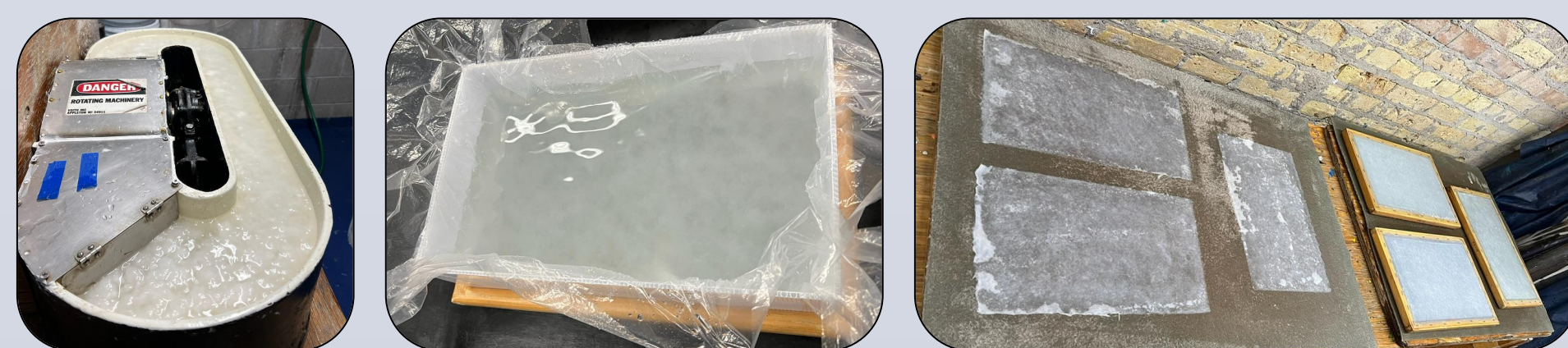


Figure 2. The Valley Lab Beater beating pulp for sheet making.

Figure 3. Deckle box filled with pulp before draining the water to develop an consistent paper sheet.

Figure 4. Developed paper sheets on deckles (right) and laid out on a felt to dry and be pressed (left).

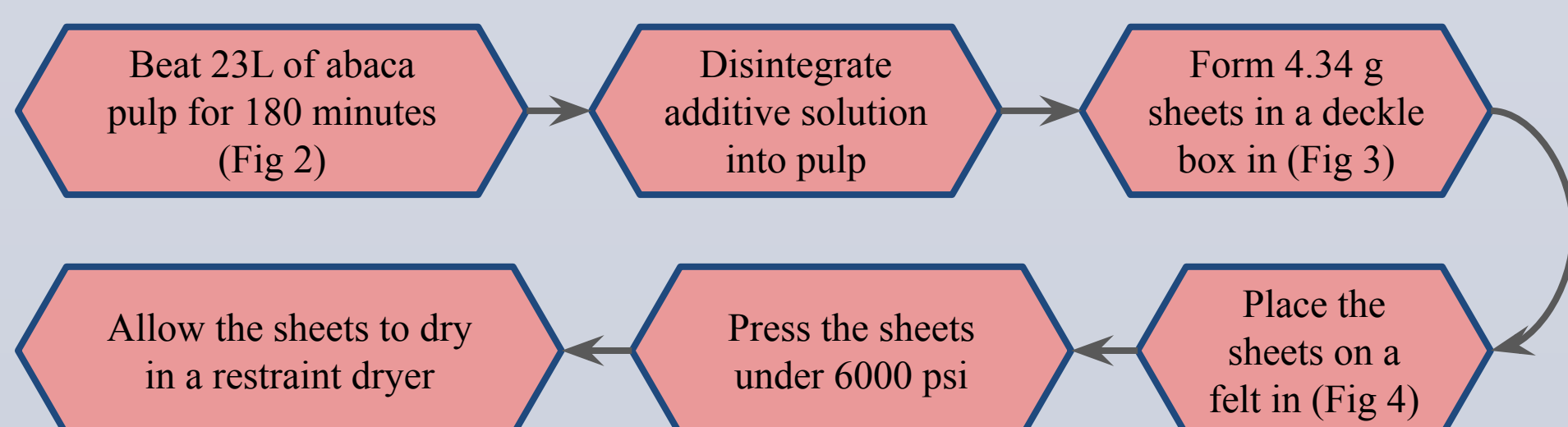


Figure 5. The step-by-step papermaking process used at the Minnesota Center for Book Arts.

Results

Folding Endurance

Folding Endurance Test

- Measured tensile index after applying a certain 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 using a tensile tester (Fig 6).
- Plotting the tensile index against the number of double folds visualized the rate at which the tensile strength decreases.



Figure 6. Rectangular paper sample being tested for tensile force in the Tinius Olsen HSK-S Tensile Tester.

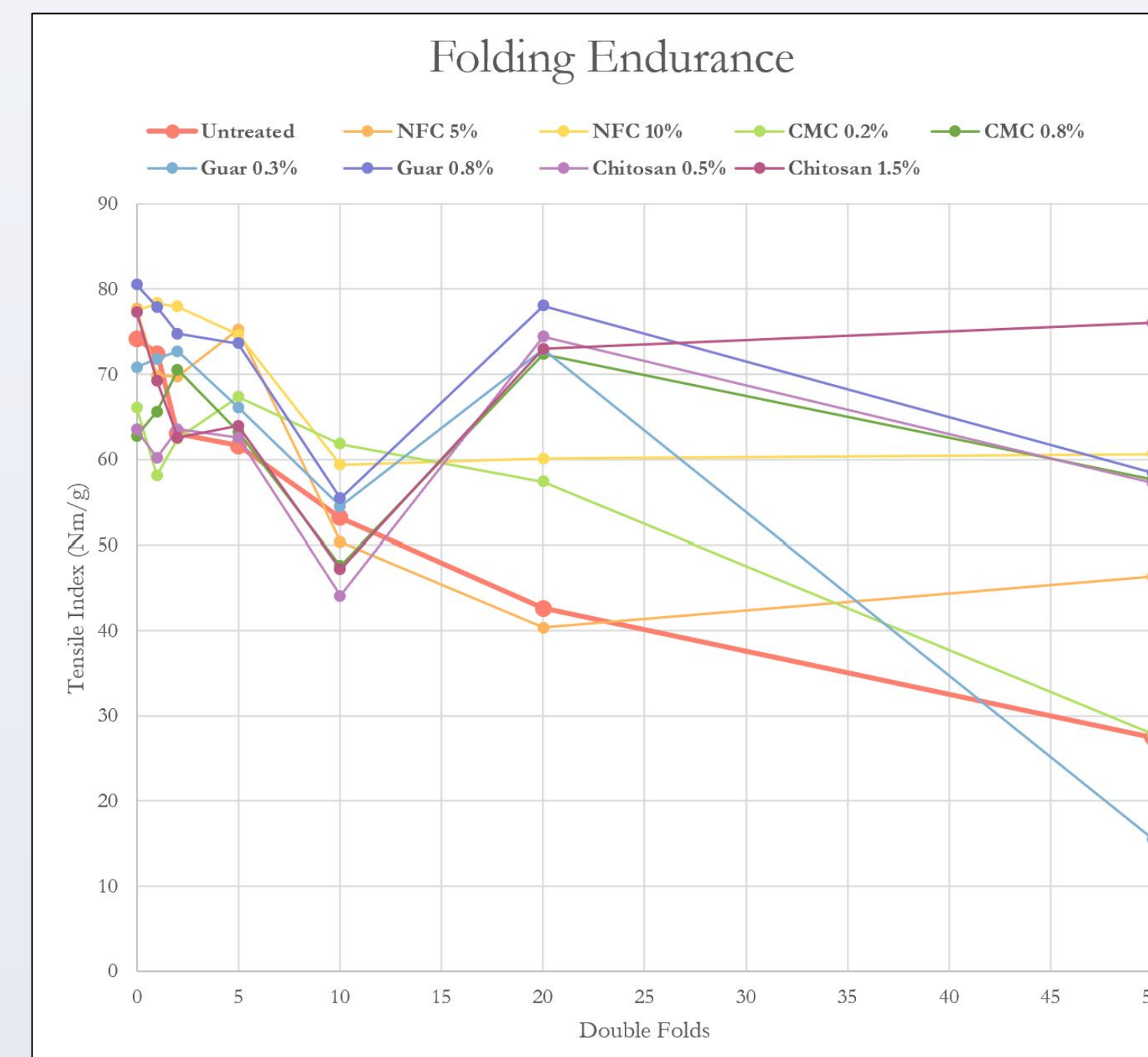


Figure 7. Line graph comparing the tensile index and folding endurance of paper sheets with different additives. The tensile index of paper specimens was plotted against the number of double folds applied to them for each additive.

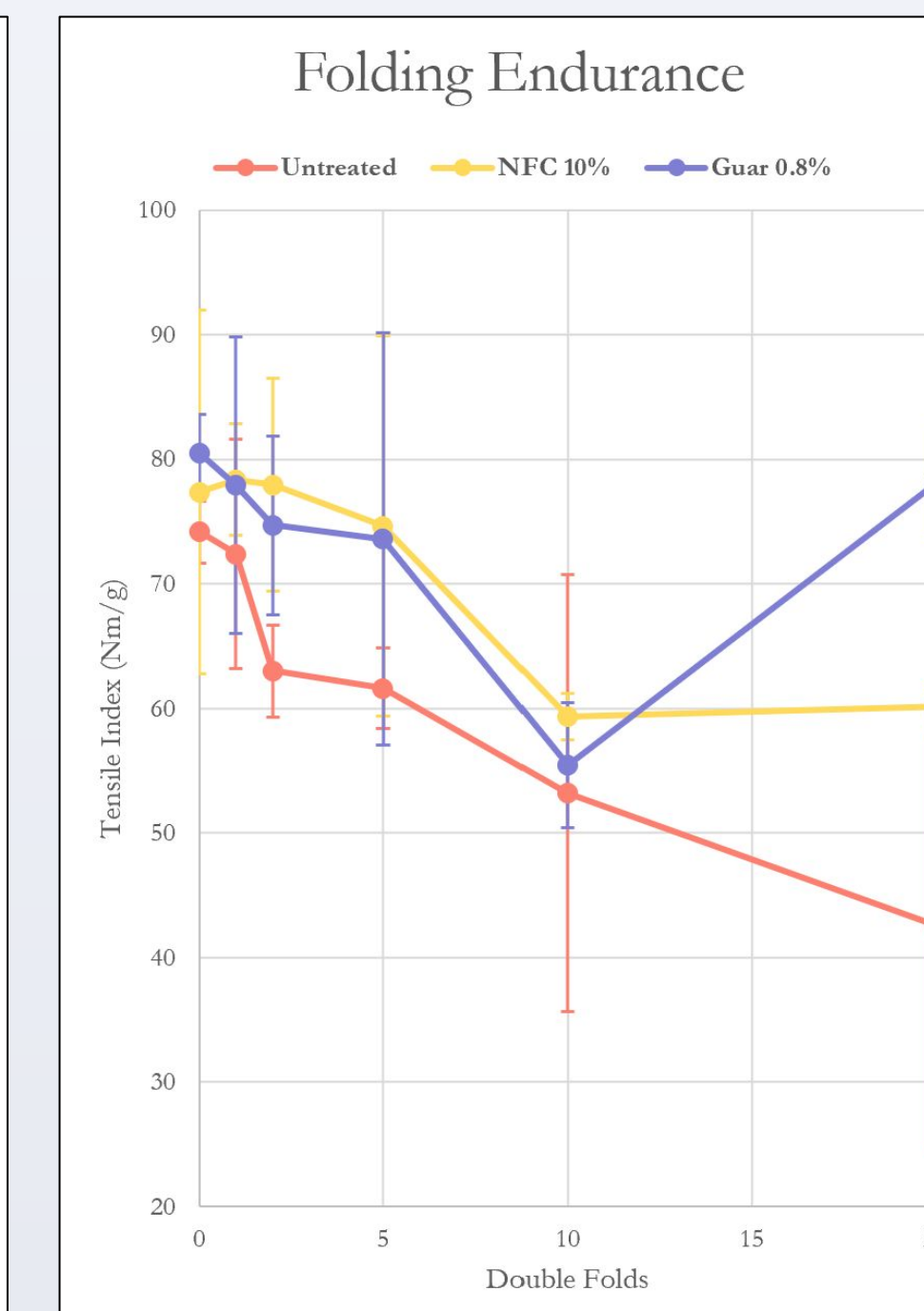


Figure 8. Line graph comparing the tensile index and standard deviation of the folding endurance of the Untreated, NFC 10% and Guar Gum 0.8% trials for 0-20 double folds. Error bars indicate one standard deviation.

Folding Elasticity

Folding Elasticity Test

- An apparatus similar to the one used in Rao et al. (Fig 9) was used to fold a strip of paper with a consistent force.
- Paper strips with 5 specific widths were rolled on an inclined plane with a steel roller, and the force per unit length was determined.
- The paper was cut 1 cm from the fold and the distance between edges was measured as the elastic radius
- Plotting the elastic radius against the force per unit length produced a stress vs. strain graph to determine the relationship between applied force and folding radius.

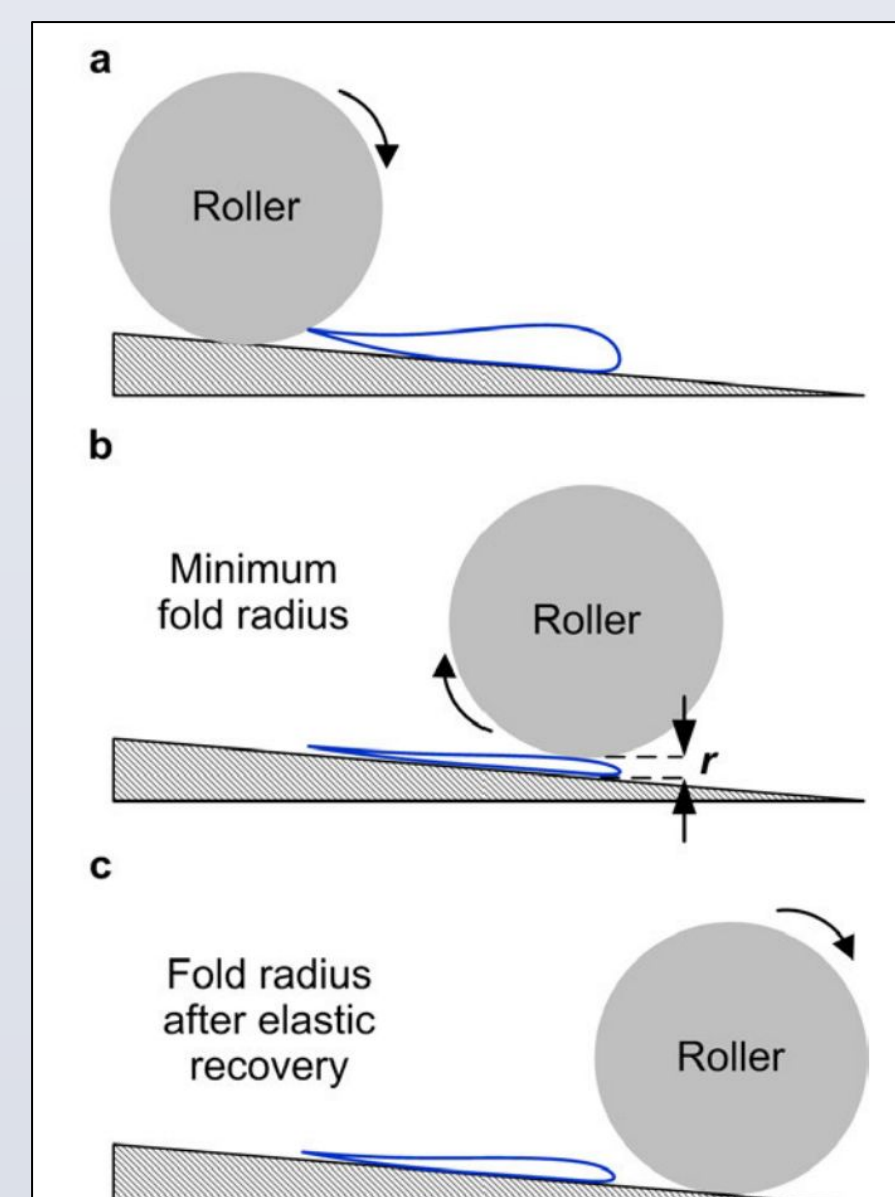


Figure 9. Schematic of the rolling experiment used to determine the relationship between applied force and folding radius (Rao et al., 2013).

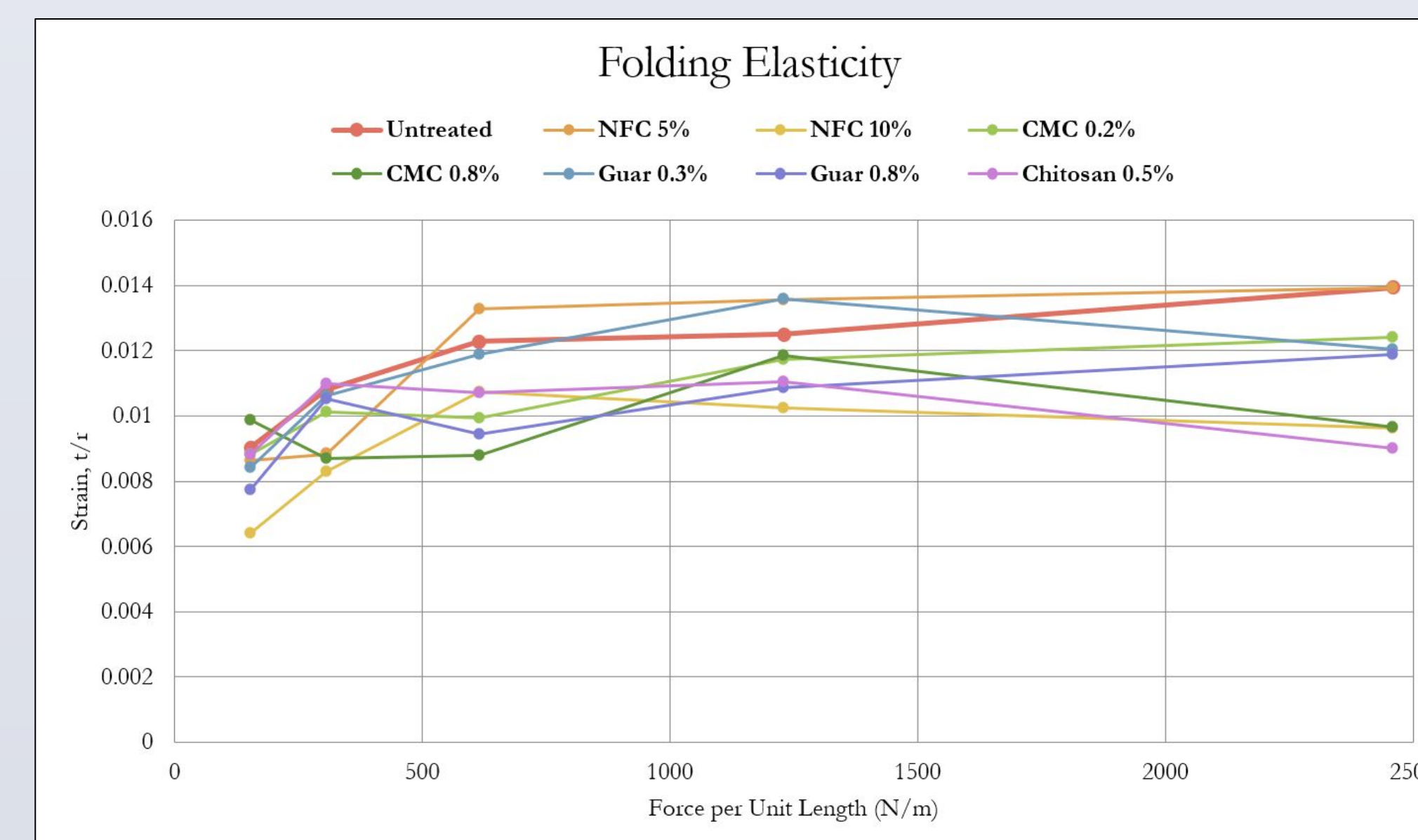


Figure 10. Line graph comparing the stress vs. strain graphs of papers with different additives. The strain (thickness/elastic radius) of the specimens were plotted against the force per unit length determined by the sample width.

Thickness & GSM

Figure 11. Bar graph visualizing the thicknesses of paper sheets for each additive. Thickness is measured in millimeters.

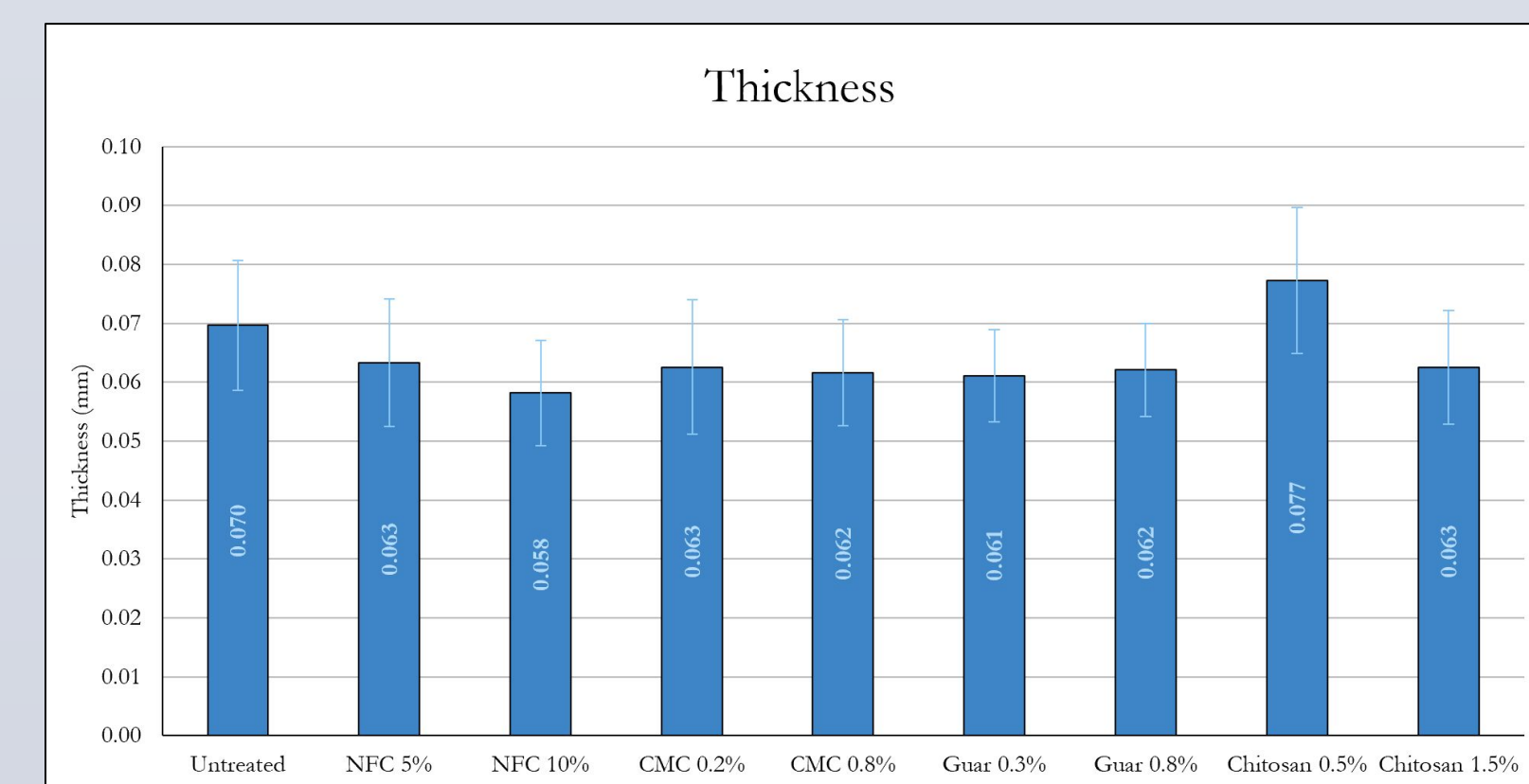
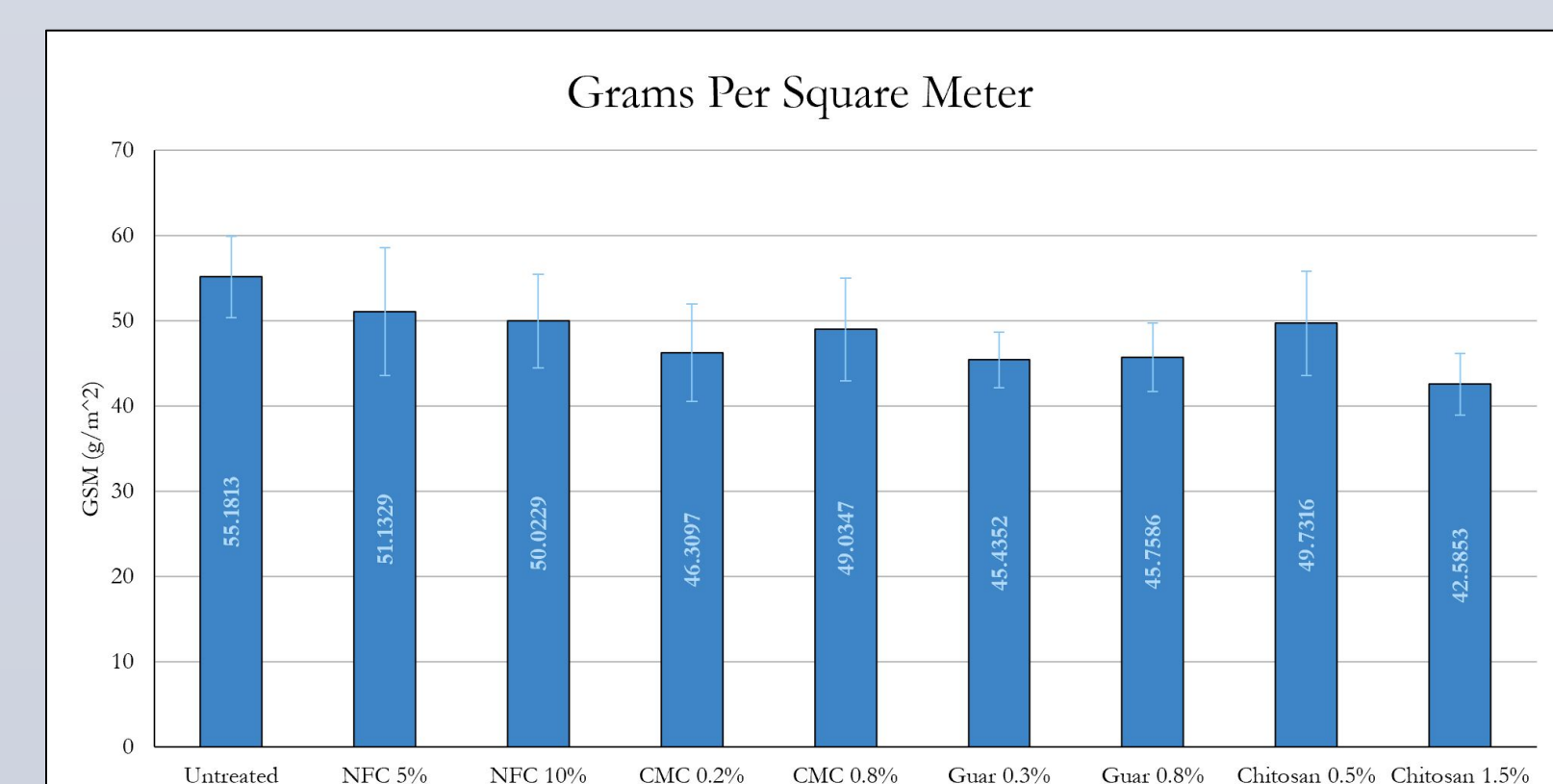


Figure 12. Bar graph visualizing the grams per square meter (GSM) of paper sheets for each additive. GSM is analogous to weight and is measured in Nm/g.



Cross Strength & Wet Strength

Figure 13. Bar graph visualizing the ratio of cross tensile strength against dry tensile strength. The tensile strength was measured for a strip of paper cut in the direction perpendicular to the standard tensile strength tests.

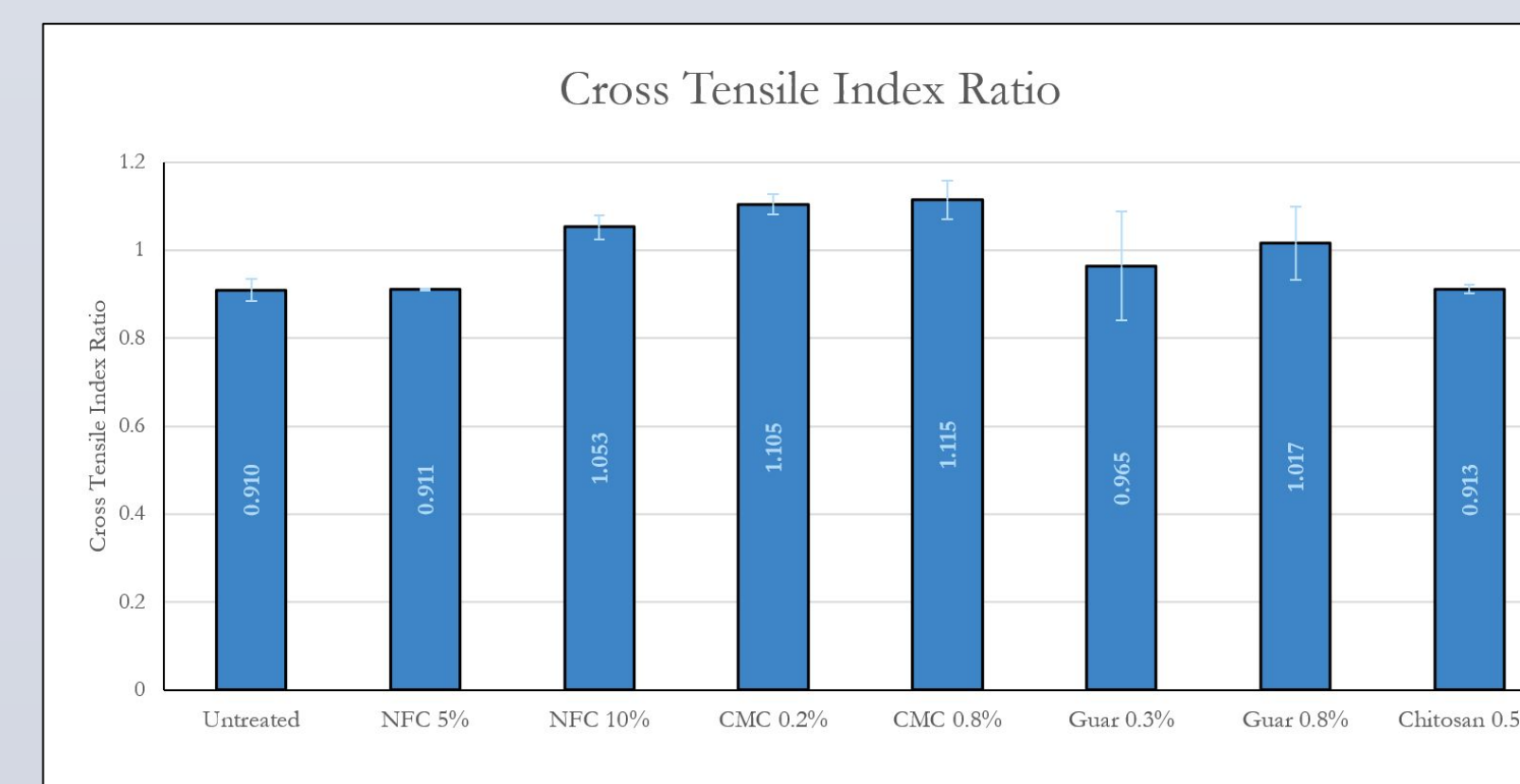
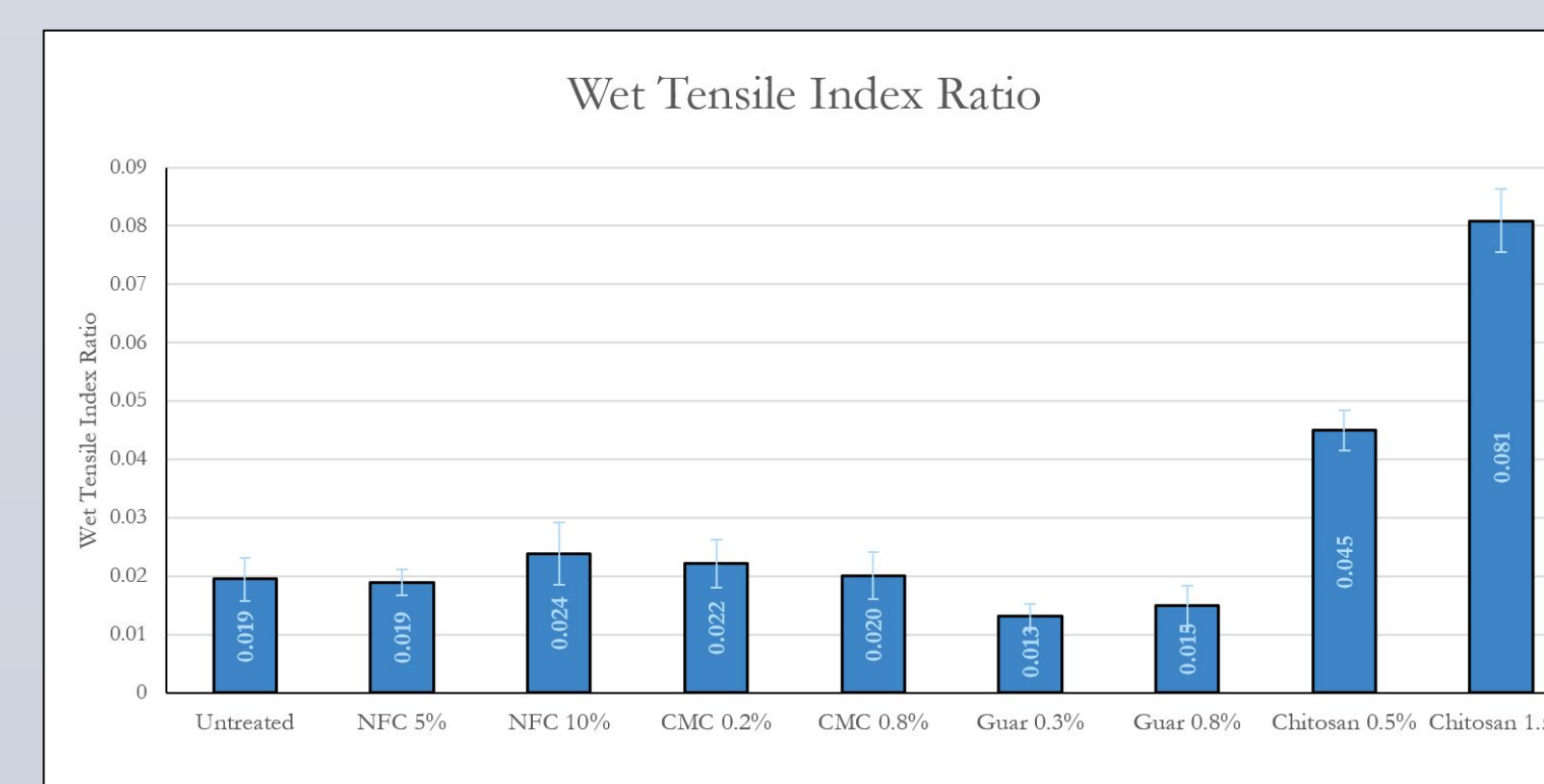


Figure 14. Bar graph visualizing the ratio of wet tensile strength against dry tensile strength. The tensile strength was measured for a strip of paper soaked in water for 5 minutes.



Implications

Folding Endurance

- Plotting tensile index against double folds showed that NFC and Guar samples outperformed the untreated trial (Fig 7).
- NFC 10% and Guar 0.8% were most effective at enhancing folding endurance, with 13.79% and 11.69% increases respectively, (Fig 8).
- Trials with 20-50 double folds diverged from the downward trend. Tensile index at 20 folds was similar to unfolded paper.
- Potential phenomenon of tensile strength increasing with folding could be useful in folding paper applications.
- Paper specimens with 1 or 2 double folds rarely broke along the fold line. 1-2 creases do not decrease the integrity of the paper past random weaknesses (Fig. 15).

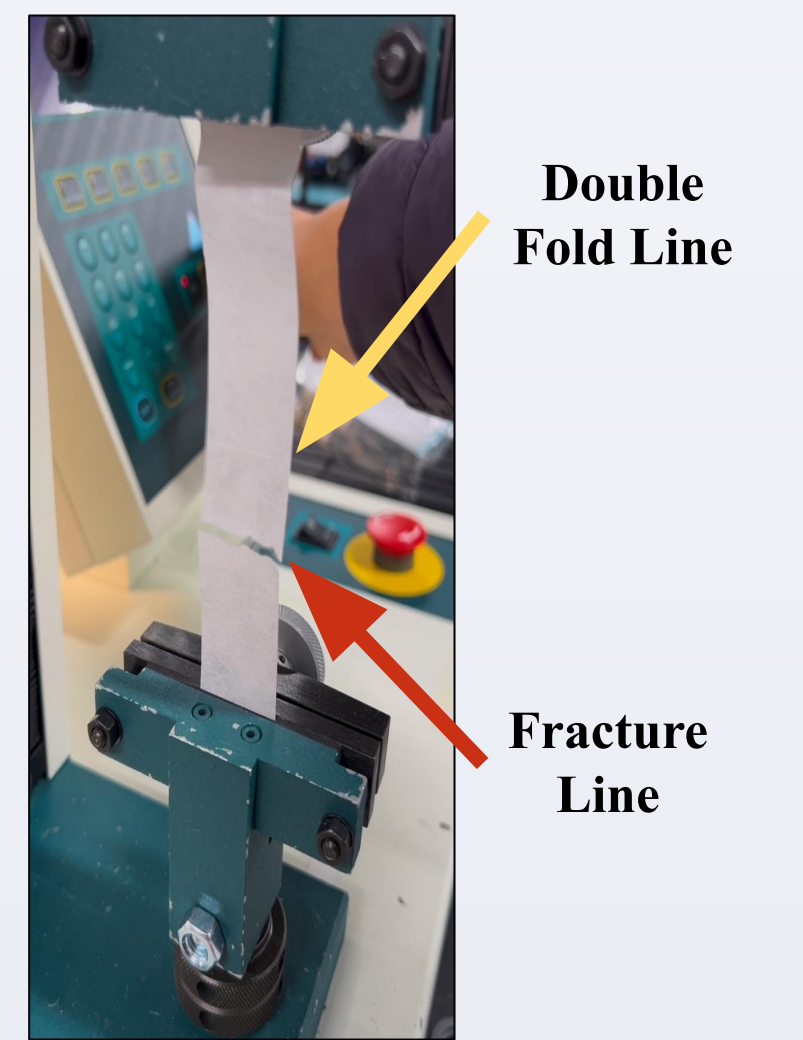


Figure 15. Paper specimen in the tensile strength tester after fracture. The specimen did not fracture along the intended fold line. Arrows indicate the double fold line (yellow) and the fracture line (red).

Folding Elasticity

- Graphing strain against force per unit length showed NFC 10%, CMC trials, Guar 0.8%, and Chitosan 0.5% retained folds less effectively than in the untreated trials (Fig. 10).
- Guar 0.8% performed marginally better than NFC 10%.

Thickness and GSM

- Thickness was consistent; most thicknesses from 0.06-0.07 mm (Fig. 11).
- There is no significant difference in GSM between additives (Fig. 12).
- Thickness appears to correlate with GSM.

Cross and Wet Tensile Strength

- The ratio of cross tensile index and standard tensile index for NFC 10%, CMC trials, and Guar 0.8% was greater than the untreated ratio and greater than or equal to a 1:1 ratio (Fig. 13).
- Traditionally papermaking has no significant weakness in cross strength.
- The ratio of wet tensile index and standard tensile index is roughly 0.02 for NFC, CMC, and Guar, and 0.04-0.08 for Chitosan samples (Fig. 14).
- Wet strength for all trials was less than the standard for wet-strength paper.

Future Research

Folding Endurance at High Double Fold Counts

- Folding endurance exhibited unusual behavior at 20-50 double folds.
- Tests at 20-50 double folds should be repeated with greater sample sizes to check the significance of the results.

Folding Resistance

- Folding elasticity is not necessarily representative of folding resistance.
- Folding resistance can be more accurately measured by performing the rolling test and measuring the folding radius at the time of the fold.

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 with combinations of previous additives.

References

- Basu, S., Malik, S., Joshi, G., Gupta, P. K., & Rana, V. (2021). Utilization of bio-polymeric additives for a sustainable production strategy in pulp and paper manufacturing: A comprehensive review. *Carbohydrate Polymer Technologies and Applications*, 2, 100050. <https://doi.org/10.1016/j.carpta.2021.100050>
- Liu, K., Takagi, H., & Yang, Z. (2013). Dependence of tensile properties of abaca fiber fragments and its unidirectional composites on the fragment height in the fiber stem. *Composites Part A: Applied Science and Manufacturing*, 45, 14-22. <https://doi.org/10.1016/j.compositesa.2012.09.006>
- Meloni, M., Cai, J., Zhang, Q., Sang-Hoon Lee, D., Li, M., Ma, R., Parashkevov, T. E., & Feng, J. (2021). Engineering origami: A comprehensive review of recent applications, design methods, and tools. *Advanced Science*, 8(13), 2000636. <https://doi.org/10.1002/adv.202000636>
- Minnesota Center for Book Arts. (2022, July 19). *Papermaking Lab - Minnesota Center for Book Arts*. Minnesota Center for Book Arts. <https://www.mnbookarts.org/papermaking-lab/>
- Rao, A., Tawfik, S., Shlian, M., & Hart, A. J. (2013). Fold mechanics of natural and synthetic origami papers. *Volume 6B: 37th Mechanisms and Robotics Conference*. <https://doi.org/10.1115/detc2013-13553>
- Statista Research Department. (2024, June 28). *Production volume of paper by type 2018*. Statista. <https://www.statista.com/statistics/270317/production-volume-of-paper-by-type/>