Applied Transient Network Theory

Strain-Rate Dependant Behavior in a Transient Polymer Network Model

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INTRODUCTION

- The transient network theory describes how polymer networks with temporary crosslinks produce viscoelastic behavior under strain, and it is widely used in soft matter physics,, bioengineering and biomedical models of living tissue.
- *We hypothesize that a slime-based transient polymer network is stiffer at high strain rates and softer at low strain rates because cross links do not have enough time to detach and reorganize.*
- Specifically, we predict high strain rates will increase apparent stiffness and cause earlier fracture, while low strain strain rates will allow greater deformation and time-dependent flow.

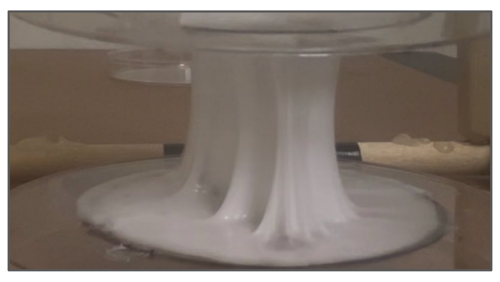


Figure 1: slime pulled at low a strain-rate (picture taken by finalists)

PROPERTIES OF SLIME

Slime forms a transient polymer network:
PVA chains are reversibly crosslinked by borate ions from borax, creating dynamic bonds that can detach and reform.
The reversible crosslinking is what gives slime viscoelastic behavior, meaning stiffness is dependent on the deformation timescale.
Viscoelastic behavior (Figure 2) is shown in the viscoelasticity curve.

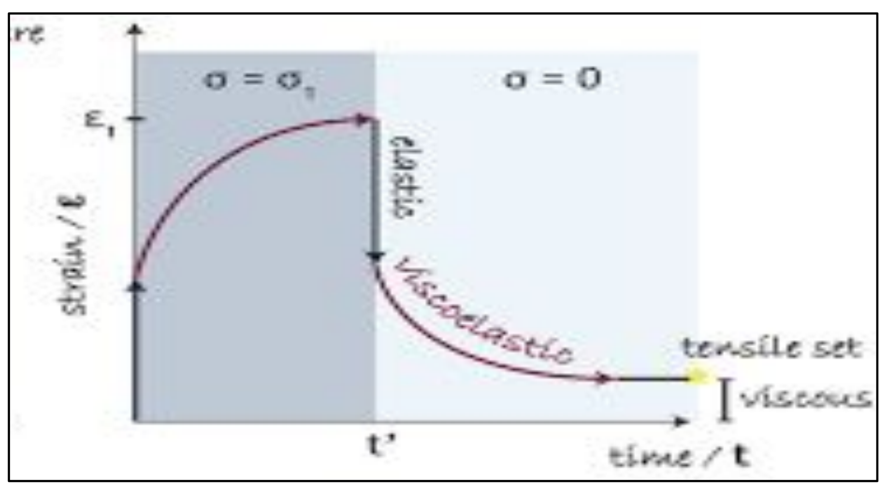


Figure 2: Stress relaxation curve demonstrating viscoelastic behavior under constant strain. Stress initially rises elastically and then decreases over time as molecular rearrangement and crosslink detachment occur, illustrating the transition from elastic-dominated to viscous-dominated response (figure from https://www.researchgate.net/figure/The-viscoelastic-stress-response-of-a-typical-elastomer-The-stress-strain-curve-left_fig3_363415599)

LOW VS. HIGH STRAIN RATES

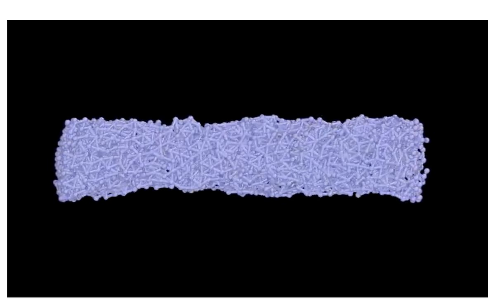


Figure 3: Slow (Low Strain-Rate) Loading Simulation. Created by the finalists
Simulation of a transient polymer network under slow deformation. Polymer chains reorient and reorganize during loading, producing necking and greater elongation. Reversible cross links detach and reattach, allowing stress redistribution and resulting in viscous-dominated behavior.

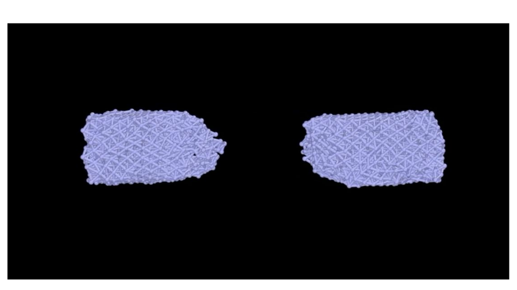


Figure 4. Rapid (High Strain-Rate)Loading Simulation. Created by the finalists
Simulation of a transient polymer network under fast deformation. Limited molecular rearrangement occurs, and the network stretches collectively, exhibiting elastic-dominated behavior. Crosslinks do not have sufficient time to detach and reorganize, resulting in increased apparent stiffness and more abrupt fracture.

METHODOLOGY

- First, we constructed a pulley system and a wooden frame with the string attached to a force sensor cart.
- The cart was tied to a step motor which winds the string to provide force.
- The pulley system allowed us to pull a petri dish with slime attached to it up in order to measure the force required to stretch the slime before it fractures.
- The motor consistently malfunctioned so we replaced it with a weight hanging off the table.
- The variables we tested were different strain rates, which varied based on the time in motor tests and weights in the gravity drops.
- We ran the motor at varying speeds to hinder the strain rate in order to observe the change in viscosity.
- The slime recipe and displacement of the cart remained constant in all experiments.

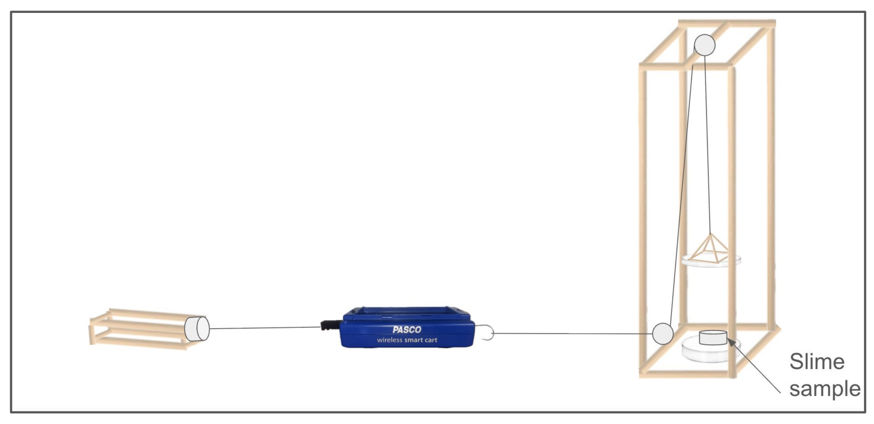


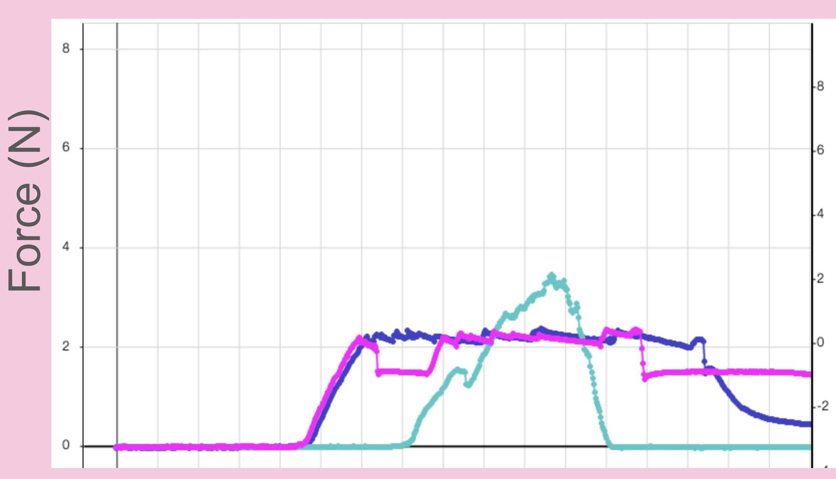
Figure 5: Experimental apparatus (Figure created by finalists)

RESULTS

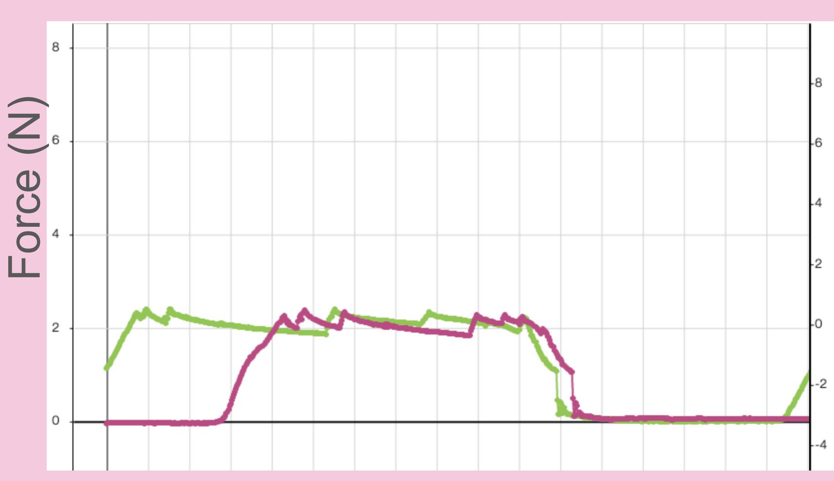
We had three experimental groups: 10 second motor trials (n=6), 20 second motor trials (n=6), and gravity drop trials (n=10)

Condition	Mean Force (N)	Standard Deviation (N)
10s motor	2.99 N	0.75
20s motor	2.40 N	0.01
Gravity Drop	6.67 N	1.03

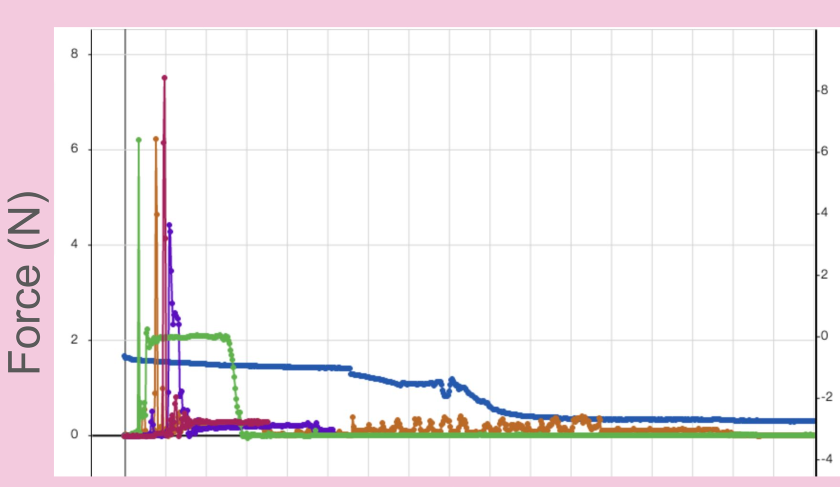
Table 1: In the gravity trials, we tested a range of forces to find the boundary between liquid-like and solid-like behavior. At 3.13 N, the slime behaved as a solid. As weight was reduced the slime continued to behave as a solid until 2.28 N where the slime transitioned to a liquid-like state. (Chart created by finalists)



Force(N) vs time(s) graphs for 10s motor trials. Graph created by finalists



Force(N) vs time(s) graphs for 20s motor trials. Graph created by finalists



Force(N) vs time(s) graphs for gravity trials Graph created by finalists

KEY REFENCES

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STATISTICAL ANALYSIS

We performed a Welch's Two-Sample t-test and calculated t=1.57 and p=0.215. Because our calculated p was greater than our threshold value of 0.05 there is no statistically significant difference between the forces from the two time intervals.

DISCUSSION

- The comparison of loading times (10 s versus 20s) was not statistically significant.
- Gravity trials identified a critical force threshold of 2.28N as the boundary between solid and liquid phases.
- The results validated prior work on transient network theory suggesting that network connections govern resistance to flow.
- These results determined that the slime was more viscous and required a larger amount of strain to break the slime.
- Sources of error could include slight variability in the slime composition, and the duration of time that slime was on the petri dish before we began collecting data.
- During data collection, a primary challenge was maintaining a consistent force. We initially used a motor-driven system, but it wasn't strong enough to consistently pull the slime without error. We revised the experiment and used a weight-based loading method to measure the transient network behavior and viscosity of the slime more consistently.
- Our results could have been impacted by the temperature of the room, as a change in temperature could affect polymer formation in the slime, making it more viscous.

CONCLUSIONS

- Our results align with transient polymer network theory described by Vernerey, Long & Brighenti (2017), which predicts that mechanical response depends on crosslink detachment and reattachment kinetics.
- The absence of a significant difference between 10s and 20s strain rates suggests both fall within a similar relaxation regime that allows network reorganization.
- However, at the threshold-like transition observed near 2.28 N in gravity trials supports models of force-dependent network breakdown and cohesive instability described by Lamont, Bouklas & Vernerey (2024).
- Impact (gravity-drop) trials demonstrated clear force dependance, indicating that larger differences in loading rate or stress may be required to observe significant stiffness variation.
- Fibrillation refers to the formation of thin filaments as the materials stretches, indicating progressive failure rates than a sudden fracture. Slower force applications demonstrated clear force dependence.
- The increased time-dependant stretching observed at lower strain rats further suggests that the network has sufficient time to reorganize and draw into laid-bearing filaments.

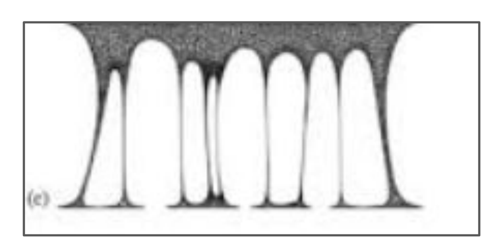

Figure 6: Fibrillation (figure from https://journals.aps.org/prfluids/abstract/10.1103/PhysRevFluids.6.013301)

APPLICATIONS

- The viscoelastic properties of slime are similar to those of medical adhesives and could guide their design.
- Our work has several practical applications in biomedical and engineering applications. Beyond force-tunable bandages, our research also has applications requiring medical adhesive systems, including wearable medical devices, such as a continuous glucose monitor that adheres to the skin to track blood sugar levels.
- Adhesion Stability Under Normal Movement: No statistically significant difference was observed between moderate strain rates (10 s vs 20 s). This suggests that a force-tunable bandage may maintain consistent adhesion under everyday (slow) movements without sudden failure.
- Resistance to Sudden Forces: Gravity-loading rials produced significantly higher peak forces and revealed a threshold behavior (2.28 N), indicating that transient polymer adhesives can resist higher sudden loads before flowing. This property is desirable for bandages that must withstand accidental tugs or impacts.
- Designing for Controlled Detachment: The solid-to-liquid transition indicates adhesives can be engineered to yield at a critical force, enabling removal with reduced skin damage and informing the design of safer, more comfortable adaptive medical adhesives.