THE EFFECTS OF SLIME COMPOSITION AND STRAIN RATE ON SLIME STRETCHINESS

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ABSTRACT

Slime, a non-Newtonian fluid, has stretchiness that varies with its composition and strain rate. A study on slime stretchiness can be improve slime creation in both research and the consumer product industry. Different mixtures of water, borax, and glue yield slime with differences in stretchiness, quantifiable in graphs of force versus distance. The breaking points of slime were found using a pull test on a texture analyzer. The fraction of samples that broke was graphed over strain rate and fit to a sigmoidal function to find the critical strain rate, or the rate at which 50% of the samples were predicted to break. Slime with a decreased amount of borax had a critical strain rate of 50.6 ± 20.0 mm/s, higher than slime with a regular amount of borax. Decreasing the amount of borax increases the slime stretchiness across different strain rates.

INTRODUCTION

Slime has slipped its way into popular culture as both a fun toy and an easy science experiment. Mattel first sold slime in the 1970's as a goopy substance that came in miniature trash cans [1]. Over four decades later, there is still a nation-wide market for slime, and slime-makers on Instagram and YouTube have been making hundreds of thousands of dollars from their creations [2].

Recipes for slime call for only a handful of ingredients. The slime made by Mattel comprises of guar gum and borax, while laboratory concoctions replace the guar gum with a synthetic solution of polyvinyl alcohol and water [3, 4]. The most common recipes for homemade slime use white glue, which contains polyvinyl acetate, instead of polyvinyl alcohol [5, 6]. Other ingredients such as food coloring, essential oils, and shaving cream can be added to vary color, scent, and texture [2]. While there are many variations of recipes for slime, there is a lack of research on slime created with polyvinyl acetate. This dearth in knowledge can cause harm, demonstrated when a young girl was hospitalized for third degree burns after incorrectly mixing borax in her slime [2]. A case study on how the different ingredients of slime affect its material properties would be useful for the consumer product industry, in which slime is on the rise.

Slime is well-liked because of its stretchiness, in which stretchiness is defined as the ability to expand while under tensile stress. Different mixtures of water, borax, and glue yield slime with different properties, including differences in stretchiness, which are quantifiable in graphs of force versus distance. Different recipes of slime can be stretched to breaking point using a texture analyzer with an attached TA-426 rig. The experiment shows which material properties influence the stretchiest slime, and how that stretchiness varies with different strain rates.

On a broader scale, because slime is a non-Newtonian fluid, the study of its material properties can have many more applications. Researchers have taken advantage of the viscoelastic properties of slime to create stretchable strain sensors and electrochromic devices [7, 8]. Finally, data from the stretching experiments on the texture analyzer will be useful in providing a framework for future stretch tests, which can be helpful for applications in the food industry.

BACKGROUND

VISCOSITY AND FLUID CLASSIFICATION

In fluid mechanics, fluids are typically classified by their viscosity. Viscosity is defined as the internal resistance of a fluid to flow [9]. Fluids with low viscosity, such as water or milk, are quicker to flow than fluids with high viscosity, such as molasses or honey. Fluids can be divided into four main categories: time-independent fluids, time-dependent fluids, viscoelastic fluids, and complex rheological fluids [5]. Most household fluids fall under the first three.

SHEAR-THICKENING AND SHEAR-THINNING FLUIDS

The first category of time-independent fluids are Newtonian fluids, whose viscosities depend only on temperature, and not applied shear stress. Most fluids studied in introduction fluid dynamics classes in mechanical engineering are Newtonian fluids.

The other class of time-independent fluids contains non-Newtonian fluids that can be further classified into shear-thinning and shear-thickening fluids. In these fluids, the application of shear stress causes viscosity to change, but the removal of the stress causes viscosity to return to its normal value [9]. A shear-thickening fluid becomes more viscous with increasing shear. This is shown when subjects sink even further while struggling with quicksand [10]. Shear-thickening fluids are also called dilatants because they dilate, or expand, when sheared [9]. By contrast, a shear-thinning fluid becomes less viscous with increasing shear.

The second category of fluids, time-dependent fluids, are similar to shear-thinning and shear-thickening fluids except that the viscosity depends not only on the rate of shearing but also on how long the shearing has been applied [9]. Thixotropic fluids are time-dependent shear-thinning fluids and negatively thixotropic fluids are time-dependent shear-thickening fluids [5].

VISCOELASTIC FLUIDS

The third category consists of viscoelastic non-Newtonian fluids. In a viscoelastic fluid, shear rate and viscosity depend both on the shear stress and on the extent of the deformation of the fluid [5]. Viscoelasticity is apparent in fluids with long polymer chains, as well as in emulsions in which one Newtonian fluid is dispersed in another [11]. Observed material properties of a viscoelastic fluid include the elasticity, self-siphoning, and Weissenberg effects. Figure 1 demonstrates the self-siphoning effect and the Weissenberg effect [5, 11].

Slime is a non-Newtonian fluid, though researchers disagree on which classification it falls under. Some sources claim it is a shear-thickening dilatant [4, 10, 12], while others take the more nuanced stance that it exhibits the properties of a viscoelastic fluid [5, 9, 13]. Both classifications indicate that slime will be more resistant to stretching, and therefore more likely to snap, at greater strain rates.

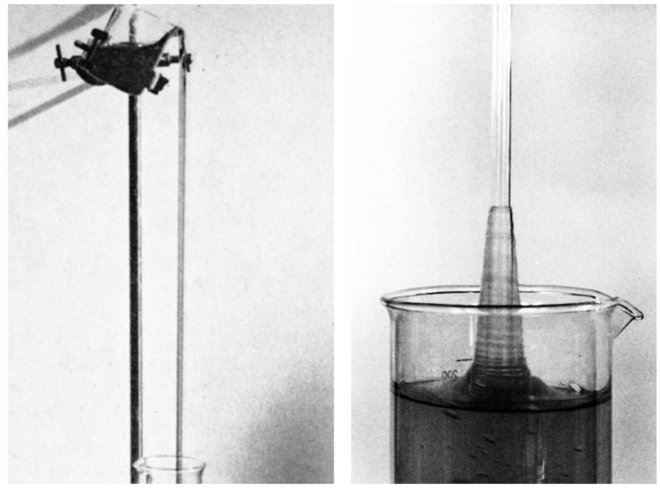

Figure 1: (Left) Demonstration of the self-siphoning effect: the fluid surface in the top beaker is well below the rim, yet the fluid continues to siphon itself out of the beaker [5]. (Right) Demonstration of the Weissenberg effect: the fluid steeps on top of the stirrer [11].

POLYMERIZATION AND CROSS-LINKING

The cross-linking of polymer chains is key to creating slime. Cross-linking involves the formation of bonds that link large molecules so that they are no longer free to slide past one another [10]. In slime, borax acts as the cross-linking agent, though it first has to be hydrolyzed in water. Borax, or ($Na_2B_4O_7 \cdot 10H_2O$), hydrolyzes in water solution to form a boric acid-borate buffer [3]. The buffer equilibrium is written as

$$B(OH)_3 + 2H_2O \rightleftharpoons B(OH)_4^- + H_3O^+ \qquad (1)$$

Prior research has explained the cross-linking of borax with polyvinyl alcohol [3, 9], which is similar to that of borax with polyvinyl acetate [5]. The first step of neutralizing borax with water is important because the borate ion, not boric acid, acts as the cross-linking agent [9]. The borate ion is tetrafunctional in interaction with the alcohol (OH) group, and thus creates three-dimensional gel networks from gums and polyvinyl alcohol [9].

Figure 2 shows a simplified representation of the cross-linking of borax with polyvinyl alcohol [3]. The cross-linking of borax with polyvinyl acetate, or white glue, is similar.

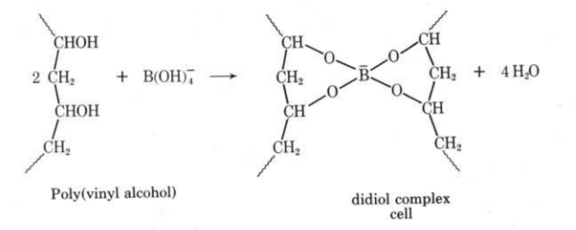

Figure 2: Simplified illustration of the cross-linking of borax with polyvinyl alcohol [3].

The simplification can be misleading because it implies that covalent bonds connect boron to oxygen to carbon atoms, which is not the case because the bonds must readily break and reform to account for the physical properties of the slime [3]. Research suggests that the system is in a state of dynamic equilibrium and the bonds are hydrogen bonds [3, 5, 9].

Changing the composition of borax should dramatically affect slime properties. An increased amount of borax in the slime mixtures will increase the cross-linking, and in turn reduce the stretchiness.

EXPERIMENTAL DESIGN

TEXTURE ANALYZER TEST

In order to test how slime stretchiness is affected by different ratios of ingredients, different samples of slime were prepared. The different slime samples were stretched on the TA.XT *plus* texture analyzer from Stable Micro Systems with the added probe of the TA-426, the extensibility rig. The actual rig consists of a base, a probe, and a ring, but only the probe was available. In the experimental setup the probe was inserted into the TA-95 chuck. A plastic container manually held down to the platform housed the slime.

The experiment consisted of three main stages, demonstrated in Figure 3. In the first stage, the descent, the probe started at a height of 60 mm, just above each slime sample. The probe then plunged into the slime at a rate of 10 mm/s and remained for 20 seconds in order for slime to accumulate on the probe. In the second stage, the slow ascent, the probe slowly lifted at a rate of 0.25 mm/s back to the 60 mm starting position. A faster rate caused some of the samples to slip off the probe before the test could be performed. In the third stage, the pull test, the probe switched speeds to one of the different strain rates tested for the experiment: 2.5 mm/s, 5 mm/s, 10 mm/s, 20 mm/s, 30 mm/s, and 40 mm/s.

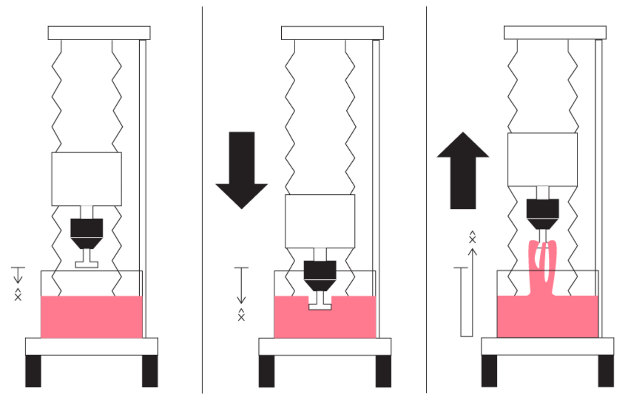

Figure 3: Diagram of the experimental setup showing the container of slime, the TA.XT *plus* texture analyzer, and the TA-426 extensibility probe in the TA-95 chuck. The figure shows the three main positions of the probe: starting position, descending position, and ascending position. The probe started at a height of 60 mm, just above each slime sample. The probe then plunged into the slime at a rate of 10 mm/s and remained for 20 seconds. It then slowly lifted at a rate of 0.25 mm/s in order for the slime to accumulate on the probe. Once it reached the starting height, the pull test began, with the probe extending at the different strain rates until the maximum height of 180 mm.

The texture analyzer pulled on the different mixtures of slime until either the mixture snapped or reached the maximum height of 180 mm. The maximum height (in millimeters) corresponds to the mixture's break length, used to determine stretchiness. Before running the experiments, the height and force were calibrated on the texture analyzer. Force calibration was conducted using a 2 kg mass.

SLIME PREPARATION

Four samples of slime were tested. The standard slime sample, the pink slime, was prepared using a common recipe for slime [5, 6]. The recipe calls for creating a glue and water mixture and a borax solution. To prepare the glue and water mixture, four ounces, or half a cup, of glue was mixed with four ounces of warm water. Food coloring was added to distinguish the sample. To prepare the borax solution, a teaspoon of borax was dissolved into four ounces of water. The variations of slime prepared involved adding shaving gel to create a fluffier slime like the popular slimes prepared on Instagram, and both increasing and decreasing the amount of borax. Table 1 shows the different ratios prepared.

Table 1: The different mixtures of slime, the first one being the standard batch. The * indicates that shaving gel replaced water in that sample and that the borax was added to 8 oz of water instead of 4 oz.

Slime Sample	Glue (oz)	Water (oz)	Borax (tsp) in 4 oz. Water	Weight (g)
Pink	4	4	1	238
Orange	4	4	2	269
White	4	4	¼	272
Aqua	4	4 *	1 *	204

RESULTS AND DISCUSSION

Raw data from Exponent, the texture analyzer software, from all the runs was exported into a master CSV and opened in MATLAB. Some sample graphs of force versus distance generated from the experiment can be seen in Figures 4 and 5. The narrow, very rapid increase in force magnitude represents the first stage of the experiment. The curving descent in force magnitude represents the second stage. Finally, the last stage, the stretch test, starts at the distance of 60 mm in the graph and represents the relevant data to be extracted.

The point at which the slime breaks, circled in Figure 4, is the point just before the magnitude of the force rapidly decreases to zero. As demonstrated in the graphs of the aqua slime and orange slime in Figure 4, this is not necessarily the point at which the force is the maximum. Instead, this point is found from the maximum change in force once the test starts. Data was imported into MATLAB in order to find the distance at which this maximum change occurs. A Boolean mask was applied to find all the data starting from a distance of 60 mm, which is when the tests started. The maximum of the force magnitude, in this case corresponding to minimum force, was found. The starting length of 60 mm was subtracted from this absolute value to find the break length, which is the maximum stretch length. If the sample did not break, this was noted.

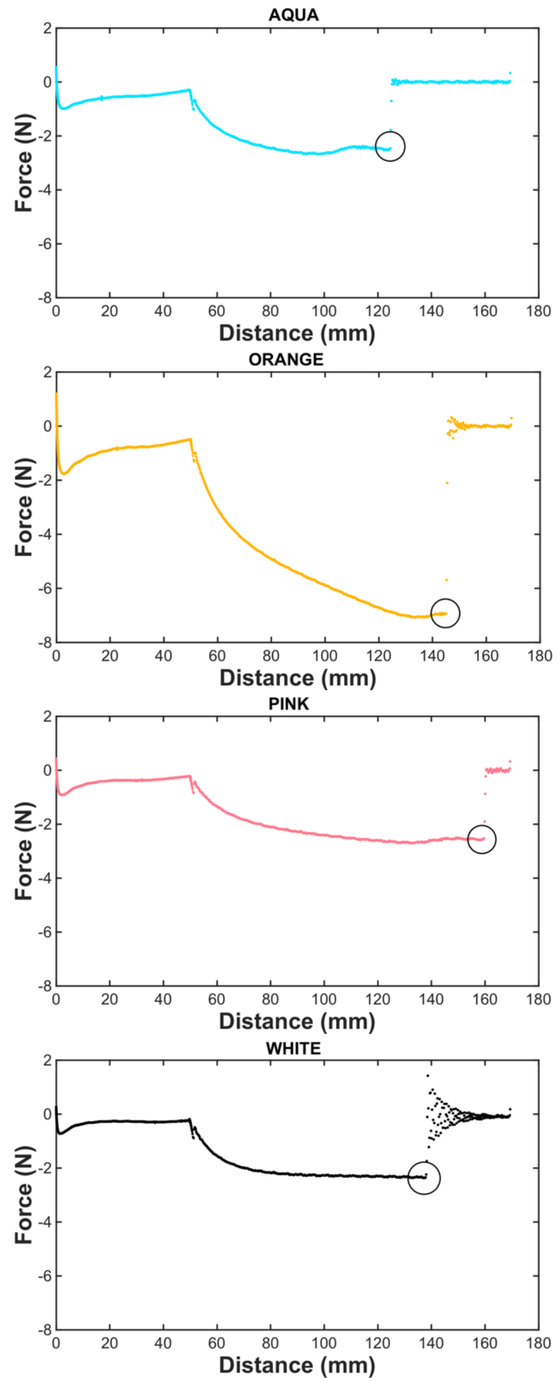

Figure 4: Graphs of trials for the aqua, orange, pink, and white slimes pulled at a strain rate of 40 mm/s. The break points of the slimes are circled on the graphs.

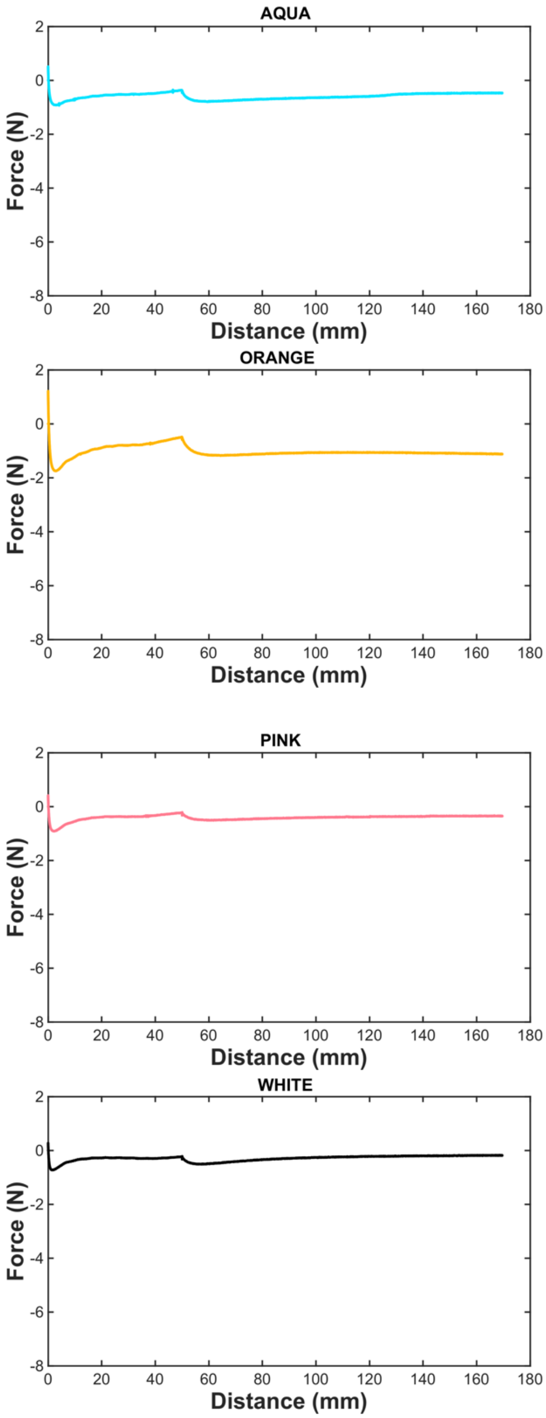

Figure 5: Graphs of trials for the aqua, orange, pink, and white slimes pulled at a strain rate of 2.5 mm/s. In all four runs, the slimes were stretched to the maximum height.

Each slime was pulled at the rate of 2.5 mm/s five times, and at 5 mm/s, 10 mm/s, 20 mm/s, 30 mm/s, and 40 mm/s four times, for a total of 25 trials per sample. The slimes did not break at the rate of 2.5 mm/s, but some started to break at the rate of 5 mm/s and all of them broke at least once by the rate of 40 mm/s. The white slime only broke twice during the trials. Histograms of the break lengths for the slime samples across different strain rates are shown in Figure 6. If a slime sample did not break, it was put in the 'no breakage' bin.

The fraction of samples that broke was plotted over strain rate, and then fit to a sigmoidal function, as shown in Figure 7. A line of best fit following the sigmoidal equation

$$y_0 + \frac{\Delta y}{1 + e^{-k\,(x - x_0)}} \tag{2}$$

was graphed, with the parameters y_0 and Δy set to 0 and 1, respectively. This allowed for the fit to find the critical strain rate x_0, which is the strain rate at which 50% of the samples are estimated to break.

Slime with a decreased amount of borax had a critical strain rate of 50.6 ± 20.0 mm/s, compared with a critical strain rate of 15.34 ± 2.01 mm/s for slime with an increased amount of borax, a rate of 24.8 ± 0.85 mm/s for slime with a regular amount of borax, and a rate of 6.11 ± 0.20 mm/s for slime with an addition of shaving gel. Figure 8 shows the graph of critical strain rate as a function of borax. Decreasing the amount of borax compared to the standard sample increased stretchiness.

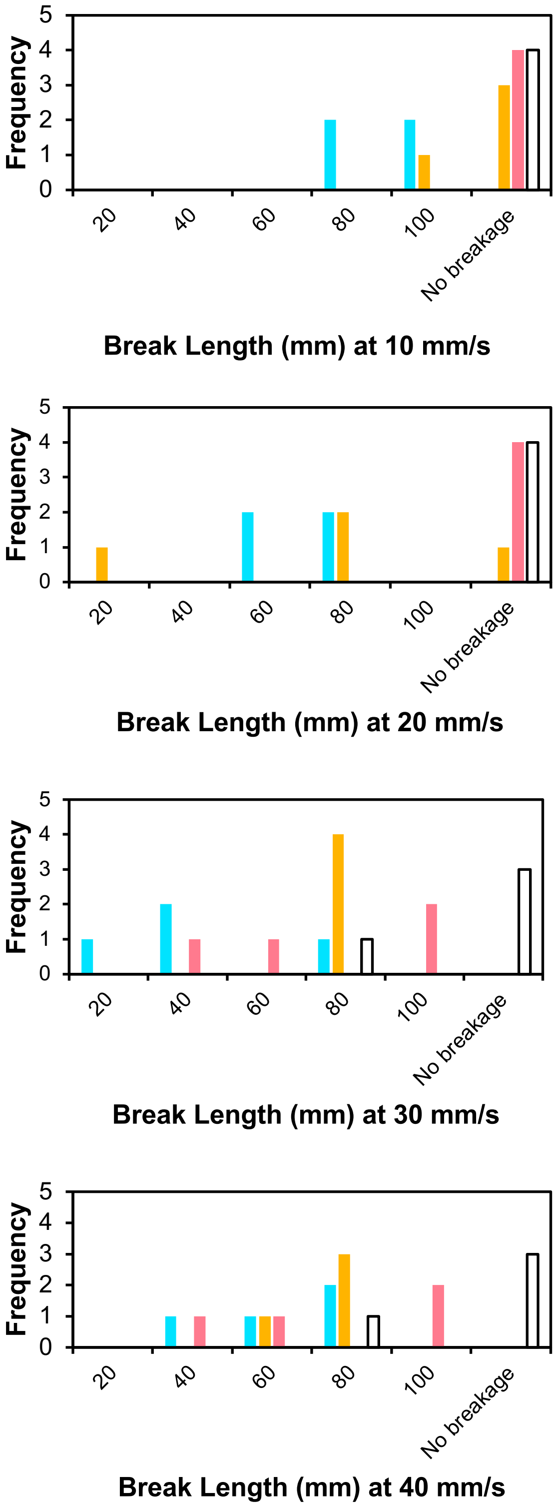

Figure 6: Histograms showing the distributions of break lengths for the aqua, orange, pink, and white slimes across different strain rates. From the histograms, we can see that the white slime most often was able to stretch to the maximum length.

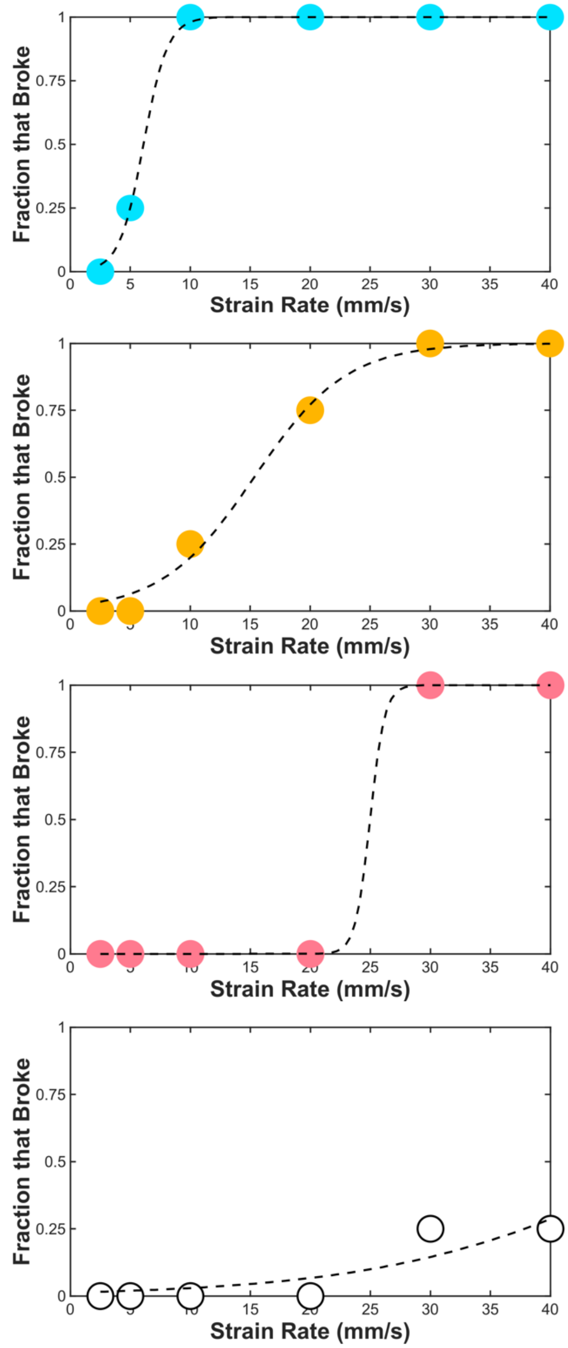

Figure 7: Graphs of fraction of the samples that broke versus strain rates for the aqua, orange, pink, and white slimes. A sigmoidal fit was applied to find the critical strain rate, the strain rate at which 50% of the samples are predicted to break.

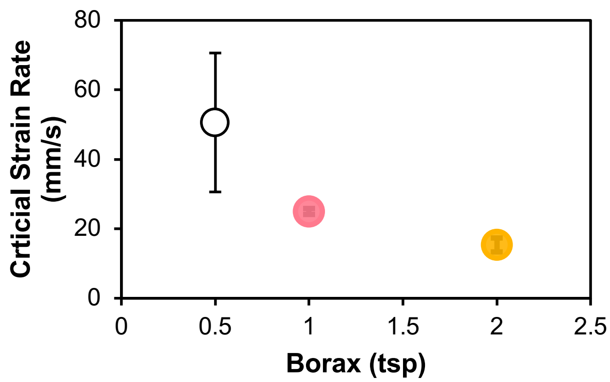

Figure 8: Critical strain rate versus borax for orange, pink, and white slimes.

CONCLUSION

Decreasing the ratio of borax added to the stretchiness of the slime. The sample with the least amount of borax had the most trials where it was able to be stretched to maximum length, only snapping twice. As expected, the slimes broke more at increasing strain rates. At the minimum tested strain rate, 2.5 mm/s, none of the slimes broke during the trials. At the texture analyzer's maximum rate of 40 mm/s, all of the slimes broke at least once.

Slime with a decreased amount of borax had a critical strain rate of 50.6 ± 20.0 mm/s, higher than the other slime samples. A greater critical strain rate corresponded to a greater stretchiness in the slimes. Decreasing the amount of borax increases the slime stretchiness across different strain rates. However, the critical strain rate for the decreased amount of borax involved some extrapolation, as the maximum strain rate of the texture analyzer was 40 mm/s and at that rate only 25% of the samples had broken. In future experiments, a texture analyzer with higher strain rate capabilities should be used.

Borax was the main ingredient altered in the slime composition, as direct conclusions between its effects as the cross-linking agent and the stretchiness of the slime can be drawn. Further experiments could analyze the effects of altering the ratio of glue and water on slime stretchability. While test samples with differing amounts of glue and water were created, the resulting substance did not behave the same way as slime and was not able to be stretched on the texture analyzer. Developing a way to consistently alter these ingredients so that the change in stretchability can be measured without changing the fundamental material properties of slime would involve further research. Further research could also include quantifying the viscoelastic and memory effects of slime as it is stretched, and finding an ideal composition for the stretchiest slime.

The standard slime recipe should be modified to include a decreased amount of borax to maximize consumer satisfaction. This key behind stretchy slime will improve slime creation in the consumer product industry and will help researchers develop slime that will better benefit their experiments.

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