Shear-Thickening Fluid

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Shear-Thickening Fluids (STFs) are a special Non-Newtonian Fluid that act like a solid when they experience a force. A simple example of this is a mixture of cornstarch and water. In this experiment, I text this mixture's STF properties by using a ball drop to simulate an impact. By varying the ball drop height (and thus the force upon impact), and observing the bounce height, I determined where this solution stops acting like a liquid and starts acting like a solid. In addition, I did several subjective tests involving manipulating the fluid and observing how it reacted.

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INTRODUCTION

There are several types of Non-Newtonian Fluids, which behave in ways that contradict Newton's original theories. These fluids changes their state or properties in situations where most fluids would remain constant.

A Shear-Thickening Fluid (henceforth known as STF) is a specific type of Non-Newtonian Fluid whose viscosity is dependent on shear stress (or the strain rate) [1]. In other words, it is a fluid that acts like a solid when it experiences a shear force, like an impact (see Fig 1). This is extremely fascinating, because it does not require any temperature or pressure change to shift from liquid-like to solid-like. There are currently two theories as to why the STF's act like this, both of which have to do with the STF's molecular structure. One theory is when these liquids are hit by a force, they shift their structures into a crystalline shape, which is extremely hard. This is why they only act like solids when acted on by a shear force, and why they return to liquidity when that force stops. The other theory is that the fluid experiences hydroclustering when it is struck. This means that upon feeling a stress, the fluid realigns itself to form long chains (see Fig. 2). These chains then overlap to form a mesh, which is hard to break apart. STFs have a number of uses, both simple and extremely complex.

One simple example of a STF is Silly Putty. One of Silly Putty's properties is its moldability; it is easy to bend or smooth with your hands. However, if you try to throw Silly Putty against a wall, it bounces back. This is because upon impact, it hardens enough to bounce off the wall. In addition, if you grab two ends of a piece of Silly Putty and pull them away from each other, it will slowly stretch until it gets extremely thin. But if you grab both ends and suddenly yank in opposite directions, the Silly Putty will break cleanly, like a solid would.

A more complicated application of STFs is the attempt to create "Liquid Body Armor." In these projects, Kevlar, nylon, and other fabrics are impregnated with a complex STF consisting of silica nano particles. The treated fabrics provide much more protection than their neat counterparts, yet there is no major loss in flexibility.

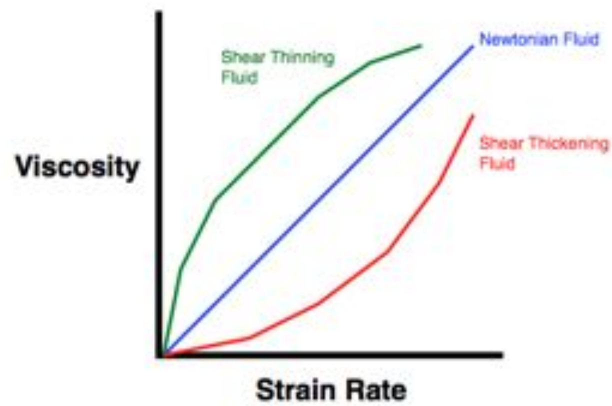

FIG. 1: A graph of how both Newtonian and Non-Newtonian fluids react under stress.

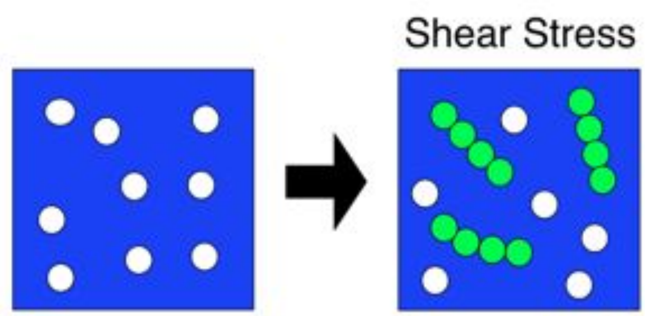

FIG. 2: A drawing of how the molecules shift when the STF experiences hydroclustering [2].

This can be used to protect the neck, elbows and knees of soldiers, where a certain level of flexibility and protection is needed. This method can improve the strength of specific fabrics to nearly 7 times the penetration protection [2]. Because it only takes a tiny fraction of a second for the STF to harden, the treated fabrics are only hard for the small amount of time they feel the stress, which means these fabrics will not lock up upon stress.

It is also believed that the solution 'Oobleck' from

Dr. Seuss's children's book "Bartholomew and the Oobleck" is a STF. In fact, the solution I use is commonly called oobleck. Oobleck is described as being a sticky solution that trapped whatever it fell on. No matter how hard people struggled, it was impossible to break free of this strange liquid [3]. The only way that people could get out of the oobleck was when the rain came and washed it away. This is certainly indicative of my STF, which was nearly impossible to escape from if you tried to use force. However water does rinse it away very well.

EXPERIMENT

Materials and Synthesis of the Shear-Thickening Fluid

The STF I created was incredibly simple. I merely mixed cornstarch and water in approximately a 4:3 ratio, respectively. The original formula I used called for a 5:2 ratio, but after mixing and testing, I felt the need for a higher amount of water. I used deionized water for purity, and just standard cornstarch from Wal-Mart. After repeated mixing attempts, I found the best way to make the STF was to add all the water at once, then gradually add the cornstarch little by little while mixing. If I started with too much cornstarch, it became very difficult to mix properly, although still possible. I also decided that using any mixing tool (like a mixer or a spoon) would actually not work very well, because the mixer would spin too quickly and the spoon had a tendency to skip over the surface of the solution. I found the best way to mix it was to place my hands in the solution and slowly mix it up myself, paying special attention to any pieces of un-moistened cornstarch.

One difficulty was determining the exact right ratio of cornstarch to water. My test for the appropriate ratio was to first poke the solution as hard as I could. If it repelled me like a solid, and my finger was still dry, I decided it had enough cornstarch. I then attempted to rest my finger on the solution and let it sink. If my finger sunk quickly without resistance, I decided it had enough water.

Subjective Testing

Before I began my impact testing, I attempted to gain an understand of what it meant that this solution was a shear thickening fluid. I started off by just resting my finger on the surface of the solution, and letting it sink slowly. When I attempted to move around quickly my finger was held tightly, but if I moved slowly I was able to extract my finger with no problem. I also experimented using a spoon to try and move the solution. If I pressed hard and attempted to scoop out the solution, it turned into a chalky solid. But if I left the spoon on the surface unattended, it would quickly sink and be difficult to extract. I also found it interesting that bubbles formed in the solution when I mixed it, and when I popped the bubbles there was a small crater in the surface that was caused by the pressure of the bubble. I also experimented with a flat head screwdriver, which produced very interesting results. The screwdriver could be stabbed into the fluid, cutting through it like a solid. When I attempted to drag the screwdriver through the solution quickly, the liquid actually fractured around the screwdriver.

Impact Testing

Before I did any tests where I measured the exact impact force, I used the high speed camera to observe the impact of a 1.69 kg ball dropped from roughly one meter above the solution. As my video shows, there was clear evidence that upon the first impact, the solution solidifies and craters under the ball's weight. The ball also clearly bounces up, and then lands again and begins to sink. I also placed the ball directly on the surface of the solution, and it clearly sinks slowly into the water. These effects demonstrate the STF's unique properties as both a solid and a liquid.

I then set up an apparatus that would allow me to use a camera to observe the fall of the ball from various heights and measure their bounce heights. As a control, I dropped the ball onto a wooden board to gather data on how a solid would react in this situation. I then dropped the ball into the solution every 10 cm from 0 to 1 m and recorded it with my camera. I then used LoggerPro to capture the bounce height, and analyzed it in Igor Pro. As a second trial, I recorded the bounce height of the ball dropped in 1 cm increments from 1 to 15 cm.

For the 1 cm trials, I used an apparatus consisting of the ball being suspended by a string over the solution, which had a meter stick next to it (Fig. 3). This allowed me to measure the drop height more accurately, and prevented friction, which was an issue with the pole.

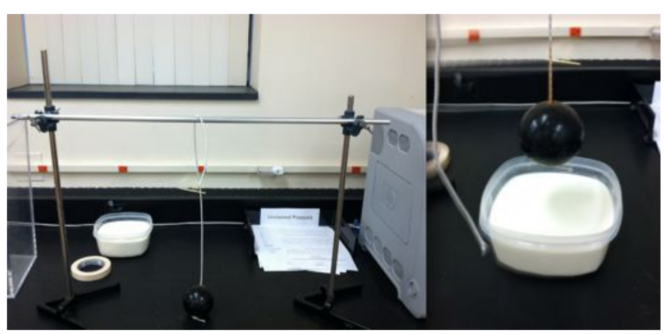

FIG. 3: My apparatus. On the left is the setup I used to suspend the ball, and on the right is an image of the ball suspended over the solution.

I also tried multiple impact tests without recording any data. I found that a bouncy ball would bounce off the surface, but had to be thrown with a great deal of force. While I was doing this, I noticed something interesting. It appeared that the ball would bounce much better when it was thrown at an angle then when it was thrown straight down. Because of this, I made sure to always drop my test ball directly down, to prevent discrepancies. It would be interesting to repeat the experiment using a controllable firing device (like a small air cannon) to shoot the ball from multiple angles and observe the bounce heights.

I also tried using a very light plastic hollow ball. I found that I was incapable of throwing this ball with enough force for it to bounce, which is why I ultimately chose the 1.69 kg ball as my testing piece.

RESULTS

Using Igor Pro, I determined the bounce height of the ball as a function of the height I dropped it from. First, I tested the way the ball bounced on a solid. As Fig. 4 shows, as drop height increases, so does bounce height. This makes sense physically, as it means that a ball with more momentum will bounce higher.

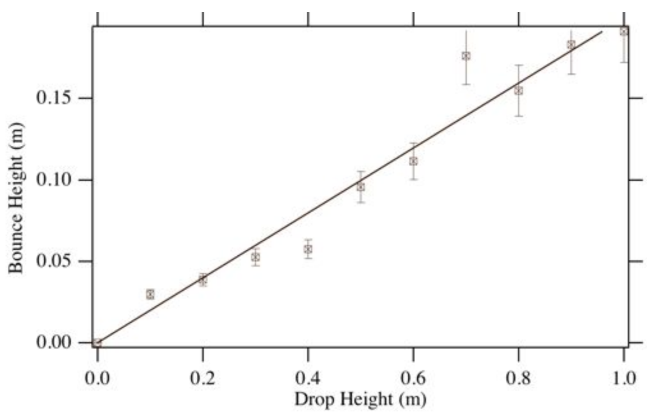

FIG. 4: The bounce height versus drop height of a ball onto a wooden plank.

I then repeated the same analysis for the two trials on the STF, one in 10 cm increments and one in 1 cm increments. Both Fig. 5 and Fig. 6 show that when dropping from a low height, there is little to no bounce. However, once a certain height is reached, the fluid starts acting like a solid and gives a bounce height proportional to the drop height.

It is important to note that the scale of Fig. 4, Fig. 5, and Fig. 6 are different. Fig. 7 shows both the wooden plank and the STF on the same scale. Clearly, the wood causes the ball to bounce much more, but it is also clear that once the STF gets out of the 'liquid regime,' it starts

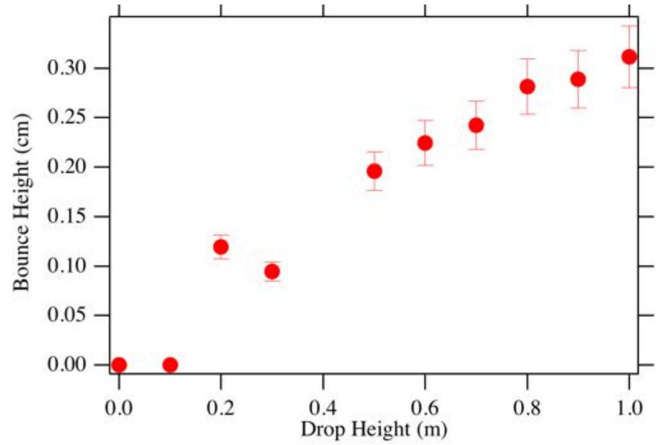

FIG. 5: The bounce height versus drop height of a ball onto my first STF solution.

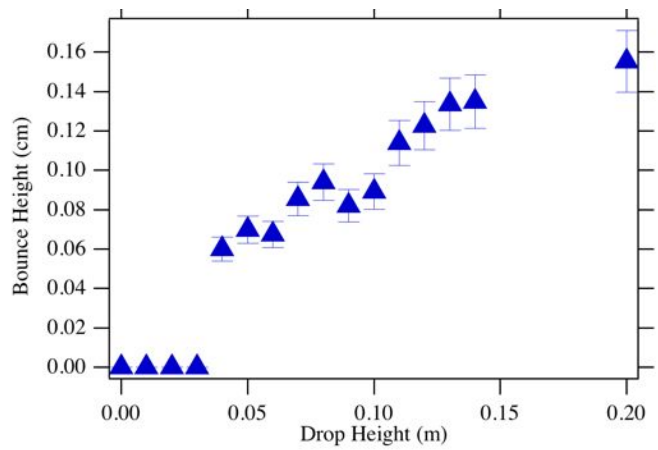

FIG. 6: The bounce height versus drop height of a ball onto my second STF solution.

acting like a solid and its bounce height increases proportional to the drop height. I believe that if I used a softer solid, like a type of chalk, I would observe a similar bounce to drop slope.

CONCLUSION

I think that my data is consistent with the theory, and when I interacted with the STF outside of tests I could defiantly tell that it was no ordinary liquid. When I slowly rested my finger on the on the surface of the solution, I sank with no problem. However, the instant I attempted to remove my finger or move in any direction quickly, I found myself stuck, and unable to force my way out.

There were several sources of potential error in my report. For starters, I made the mistake of dropping the ball on the same wooden plank for my entire test. This means that the wood was dented, and that could have

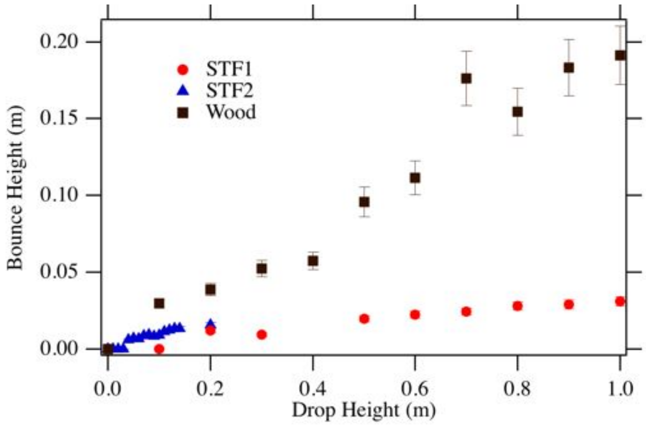

FIG. 7: The bounce height versus drop height of a ball onto both my STF solution and the wooden plank.

reduced the bounce height. Midway through the experiment I noticed this was happening, and tried to compensate by flipping the board over and striking a new position. Additionally, it was difficult to drop the ball from an exact height. My original apparatus involved using a pole to drop the ball straight down, but it ended up getting slightly gummed up by the solution that stuck to the ball after each run.

Another potential source of error was my inability to use the same solution throughout the entire experiment. The first day, I made my STF mixture and tested its properties without doing any drop tests. I left it in a sealed container over the weekend, and when I reopened it I found that it had molded, and was not usable. To prevent this, I refrigerated my sample between testings. Even with this precaution, by the end of the experiment I was forced to make another replacement mixture. It is possible that because I used different amounts of cornstarch and water, my second and third solutions had different properties, and thus gave different results. If I redid the experiment, I would do all drop trials on the same day with the same apparatus to attempt to prevent these errors.

FUTURE RESEARCH

There were severals avenues of research that I wish I could have experimented with, but I ran out of time. This "oobleck" mixture has become a celebrity on the internet because of its interesting properties. One interesting experiment involves placing the solution on an acoustic speaker and vibrating it. Because of its hardening properties, the oobleck starts to grow "fingers" out of the speaker that wave around as if alive. I would like to test this personally, and determine what proportion of cornstarch to water gives the optimal response.

Also, the attempts to impregnate fabrics with STFs is fascinating, and getting very good results. I would like to attempt to recreate these results, and construct strengthened fabrics that could have everyday use, in addition to military applications. However, it requires a much greater monetary investment than my current experiment. This is because it would be necessary to obtain silica nano particles, a special fluid to mix them in, and several other expensive components [5].

It would also be interesting to redo everything I did, but while tightly controlling the cornstarch to water ratio. The experimenter could then vary that ratio and determine what gives the best result. Also, I mentioned before the apparent angle dependence on the bounce height. It would be interesting to observe this effect in a more quantifiable way.

It would also be interesting to observe the effects of other Non-Newtonian Fluids. A magnetorheological fluid is another Non-Newtonian Fluid which is usually an oil containing pieces of iron. When a magnetic field is applied, the fluid's iron pieces align and it forms a solid. This effect can be used to create a flexible piece of fabric that can become rigid at will. I would love to attempt to impregnate fabrics and articles of clothing (like gloves or boots) with this fluid, and see if I can create fabric that can change its flexibility.

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