Cornell University

MAE 4900 Final Report

Cornell Creative Machines Lab

Wax Actuation and Material Application

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Abstract

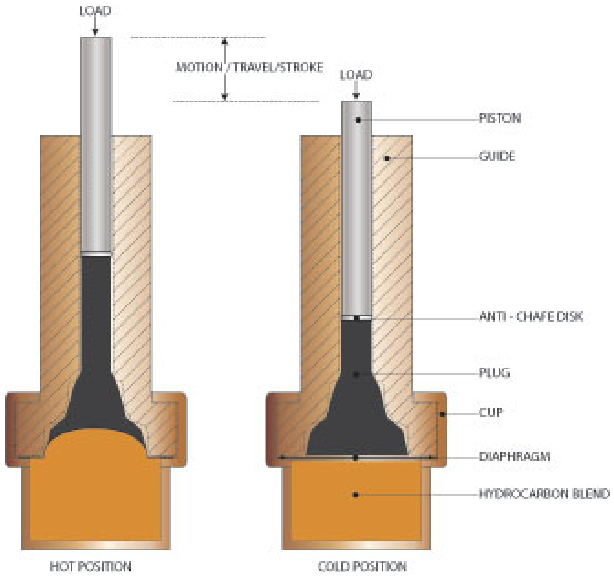
An actuator translates energy into mechanical activity, and is the most basic form of a motor. This project aims to create an actuator which uses wax to convert electric energy into motion, and can eventually be printed on a 3D printer. Wax has a high coefficient of thermal expansion, meaning it increases dramatically in volume when heat is applied, as it transitions from solid to liquid. Mixing this with silicone creates a soft solid material, which expands with heating with little leakage. For this material to be useful, we have characterized it and showed potential applications of its unique properties.

Background

'Wax' is an umbrella term that describes many different substances. In this project, we have used petroleum derived waxes, focusing later on common paraffin wax. Paraffin is a soft solid at room temperature, and melts at around 100 °F. It also exhibits large expansion as it transitions from solid to liquid, on the order of tens of percents.

Wax actuators, or wax motors, are frequently used in industry. See Figure 1a. A small reservoir of wax sits in a chamber. Above the chamber is a flexible diaphragm (or O-ring) and above that a piston. When the wax heats and expands, the full volume change is exhibited by the narrow piston's vertical displacement. These actuators are used in two applications. In greenhouses, they are used to open windows, with heat provided by sunlight. In dish and clothes washing machines, electric current powers the motor to push a button. A common wax motor, used in a Maytag dishwasher is displayed in Figure 1b.

The reader may notice that the motor contains a restrictive diaphragm or O-ring, seemingly increasing the friction encountered by the piston. This is extremely necessary when working with paraffin wax. The material leaks through nearly every material - even through plastic walls! Silicone rubber, however, provides a barrier wax cannot pass through. In this project thus far, we have needed to coat nearly every wax adjacent surface with silicone so that the wax is contained.



(a) Actuator Diagram

(b) Wax Motor

Figure 1

Goals and Motivation

The first and foremost goal of this project is to create a wax powered device, fabricate it on a 3D printer, attach it to an electrical power source, and have it 'walk' out of the printer. To help accomplish this, I identified four subgoals.

- Test wax expansion force and volume change
- Create plastic, silicone, and wax actuator heated by hot plate
- Adapt design so that heating source is electric current
- Adapt design to be 3D Printed

This would make the actuator a sort of simplistic robot. However, any device we could print and immediately induce motion could be extremely useful. It is essentially the last piece that must be developed for walking robots to be fully printable. Paired with computer algorithms already developed, this will allow computers to design, create, and test robots, without human interaction at any stage.

It is worth mentioning that actuators developed in this project may also have use in the soft robotics field because, though not the primary reason for using wax, the materials used in creating these actuator prototypes are very pliable. The devices we are working to create are quite comparable to air pressure driven soft robots. Wax also exhibits variable stiffness as it changes state from solid to liquid. This property can easily be taken advantage of to create variable stiffness actuators, commonly used to make joints or other devices in soft robots.

Literature Review

As discussed above, wax actuators are rather common. A good amount of research has been done in finding new applications for wax actuators, primarily in microfluidics. In 2006, a paper between Carnegie Mellon and Columbia University's Mechanical Engineering departments on "Complianced-Based Latchable Microfluidic Actuators Using a Paraffin Wax" [1] was published. It found that paraffin could be used to actuate a valve, effectively closing off a small channel. The wax actuator designed took advantage of two key elements: PDMS(a silicone rubber)'s flexibility and wax sealing capability, and wax's tendency to 'bulge' when heated in such a flexible membrane. Though these findings tell us that wax actuators are plausible and useful, they are not particularly applicable to our goal of making actuators which move linearly and significantly.

In 2007, Marcus Lehto at Uppsala University published a paper on "Paraffin Actuators in Microfluidic Systems" [2]. This thesis discussed mainly the plausibility of using wax actuators in MEMS applications. This paper discusses using paraffin as a linear actuator, but for the most part only expects displacements of micron scale for actuators centimeters large, with maximum expansive force of about 10N. The paper also discusses rapid prototyping, but not in the context of printing an entire actuator, rather as a way of designing actuators quickly. It does, however, once again emphasize the need to use a silicone membrane on wax adjacent surfaces.

Another useful resource is Tammy Meichun Ho's paper on the "Preliminary Design, Manufacturing, and Characterization of a Novel Paraffin-Based Microactuator for Microfluidic Applications" [3] out of University of Utah. It explores the possibility of using an inlaid heater, much like we intend to do in the later stages of our actuator design. It concluded that PDMS was the best silicone rubber for this kind of design, but more importantly, found that the so called 'in-situ' heater was possible. They were able to develop an actuator using a mix of graphite within wax, thus allowing current to be used to heat the wax compartment. Though it seems like a bit more work would need to be done to implement this technique with consistent results, it shows promising development for our actuation heater design.

Technical Approach

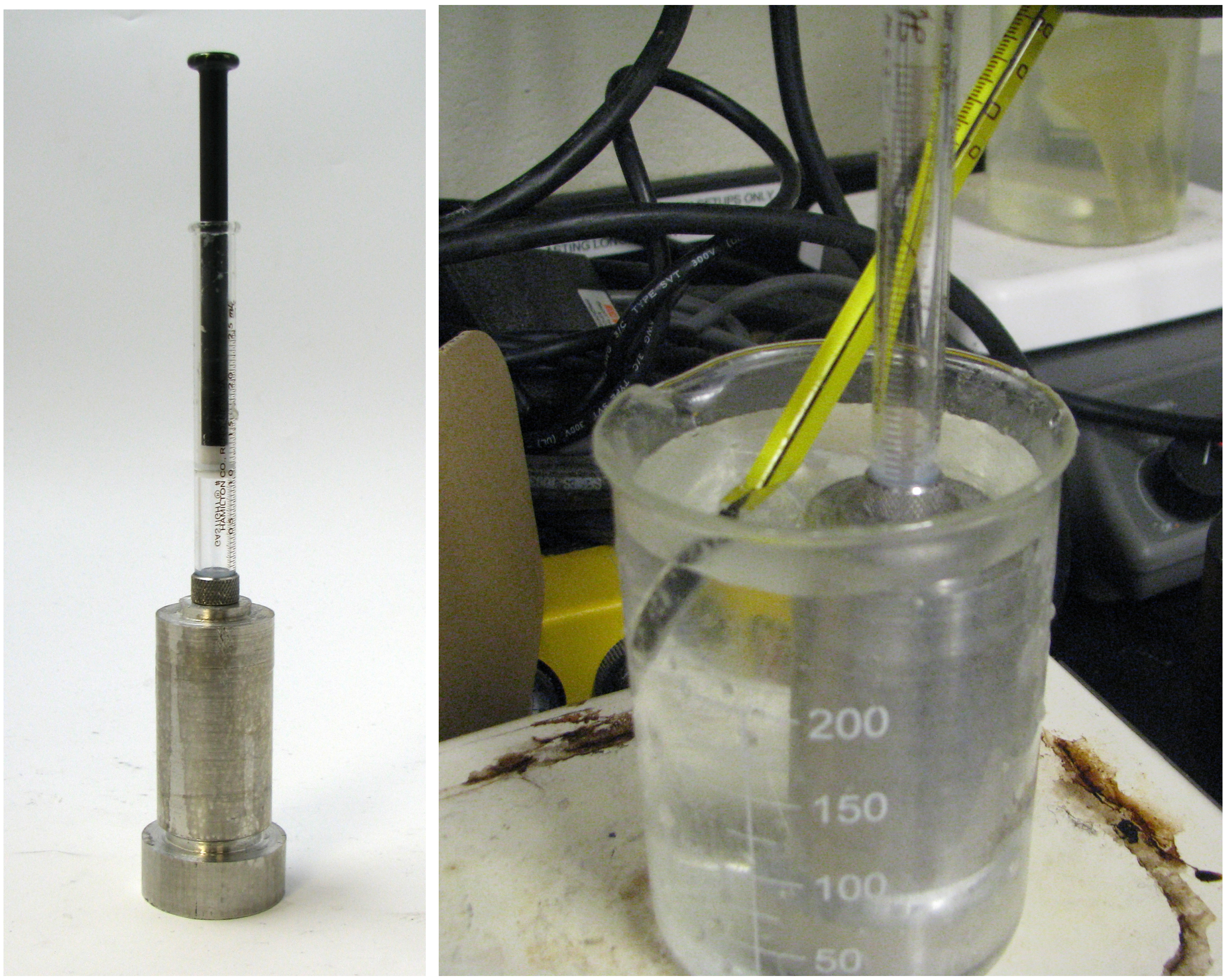
I. Tests of Wax Properties

To begin, we wished to identify two basic mechanical properties of wax, the percent expansion it displayed under phase change, and the force is could apply when doing so. We had four wax samples. The first, basic paraffin wax, in this case packaged as nurdles intended for spa therapy. A picture of this wax, straight from the package, is found below, see Figure 2. The other three were Astorstat brand waxes. Lent to us by Rob Maccurdy in the Creative Machines Lab, these samples are all petroleum derived products.

Figure 2. Paraffin wax nurdles.

To begin testing, we designed an experimental setup. The basic concept was very similar to the simple wax motors shown in the Introduction. Essentially, we created an aluminum chamber with a piston in a volumetric measuring cylinder at the top. This would allow us to measure volumetric change of a wax sample inside the cylinder upon heating. It would also allow us to put pressure on the wax sample, so that we could measure the expansive force it produced. To manufacture this, we cut an aluminum chamber (which holds exactly 10 mL) and chamber plug on a lathe, and purchased a medical grade gas tight syringe to be used as the piston piece. Silicone sealant was then used to seal the connections between these three parts. A picture of the setup is found in Figure 3a.

We then tested for heat expansion. To do this, we filled the chamber with melted wax, constantly topping it off as the wax solidified, so to get a plug of the correct volume. Then the plug was sealed onto the chamber with silicone, and the syringe screwed in and sealed as well. The entire setup was then placed in a hot water bath, supposedly allowing the now heated wax to expand into the syringe above. See Figure 3b. However, during this testing, we noticed the seal on the chamber plug broke under the pressure of the expanding wax, and now leaked liquid wax.



(a) Testing setup **(b)** Heating Procedure

Figure 3

To remedy this, we created a new plug for the chamber. We made this one threaded (and threaded the lower section of the aluminum chamber) so that it would have better sealing and durability. We also sealed these threads with plumbing tape as well as silicone. Still, when we tested again, these seals leaked wax. It seemed like we need to come up with a simpler procedure.

So, we opted to simply test the volumetric change between the solid and liquid stages of each wax sample. First, we measured liquid density. We noted the mass of a sample of the wax nurdles we were testing. Then, placing these in a graduated cylinder and heating, we easily found the liquid volume of the sample, and calculated from this the liquid density. Finding the solid density of the wax was a bit more difficult. To do this, we cast a block of wax by pouring a liquid sample into a small plastic tray. Then, we cut from it a rectangular prism. Knowing that this prism was fully solid wax (without pockets of air), we measured its mass and then calculated its volume using a ruler. Finally from there we obtained a density. By comparing these two values we found the percent volumetric expansion for each sample. They are tabulated below.

Table 1. Wax Density Values

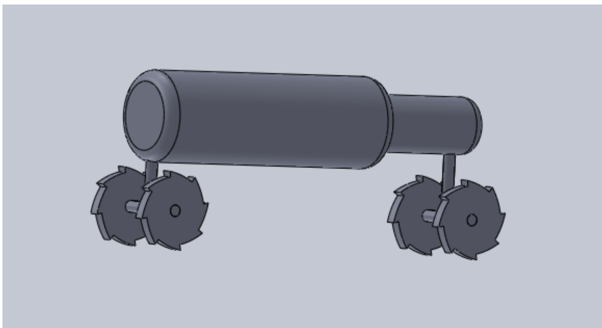
Sample	**Solid Density**	**Liquid Density**	**Volumetric Change**
Paraffin Wax	0.900	0.769	.30
Astorstat 6920	0.890	0.646	.38
Astorstat 75	0.530	0.672	<0
Astorstat HA-20	0.630	0.739	<0

Because the paraffin's expansion is significant, and nearly as high as the more specific sample, we chose to use it over more costly and harder to obtain waxes.

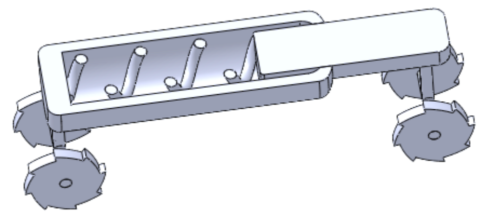
II. Initial Actuator Prototype Design

Now knowing the basic expansion we could expect from paraffin wax, we began to design prototype actuators. Our goal was to design a device that moves, flexes, or in some way changes with applied heat. Because we planned to bring these designs to a 3D printer in the next stage, we tried to design these prototypes using shapes and materials that would be possible to adapt to a printer. This meant using primarily plastic, silicone, and wax. We expect the final heating element to be a resistive element running current through the wax deposit, though this was a much easier design goal to meet.

My initial design for an actuator was quite complex. It comprises a piston cylinder, connected by a spring, with directionally frictioned wheels on its base. See Figure 4. However, when seriously looking to created this actuator, it became clear that it was too complex. On the modifiable 3D printers, we can only print a small amount of complexity, and especially not in all three dimensions. It would also not be possible to coat the inside of the actuator with the necessary silicone. For this reason, the actuator idea was heavily modified.



(a) CAD Model. Note directionally frictional wheels.

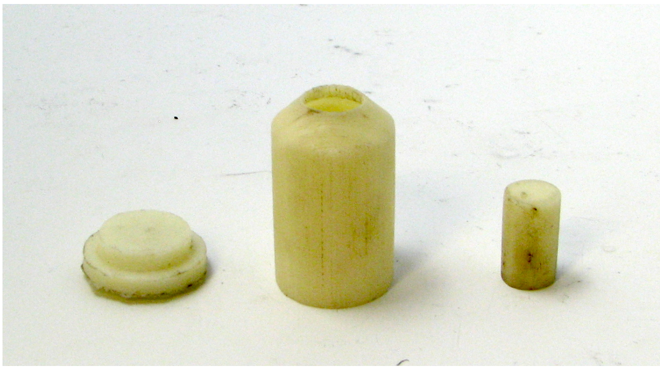


(b) Actuator Cutaway. Note internal spring.

Figure 4. Initial Actuator Design.

Next, I modified the above idea to a simpler device, one that would test the 'piston actuation' I was trying to implement. This first actuator comprised a piston, cylinder, and cylinder cap. These were designed in Solidworks, then printed on the Up! printer in the Creative Machines Lab. See Figure 5. I coated the plastic pieces in silicone rubber sealant, then inserted wax, and then sealed the pieces together.

I expected that, when heated on a hot plate, the expanding wax would generate enough force to stretch the silicone and push the piston rod upwards. However, in running this experiment, I was able to bring the device up to a temperature where the wax was clearly liquid, but there was no observable or measurable change in the piston's height. Thus we moved on to another design.



(a) Printed Plastic Pieces Before Assembly.

(b) Assembled Actuator. Piston moves freely up and down.

Figure 5. Piston Actuator Design.

The next design concept was the creation of a wax bimorph. Bimorphs are objects using two materials which expand at different rates under heating. When heated, the bimorph then bends to accommodate for the more voluminous material on one side. See Figure 6.

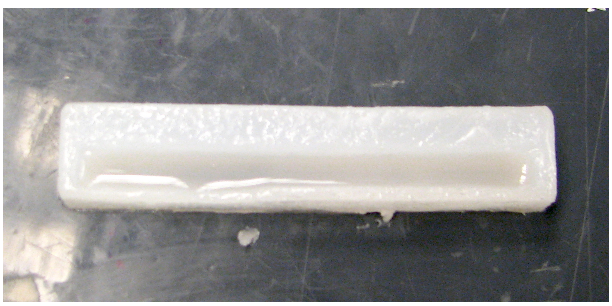
(a) Before Heating.

(b) After Heating.

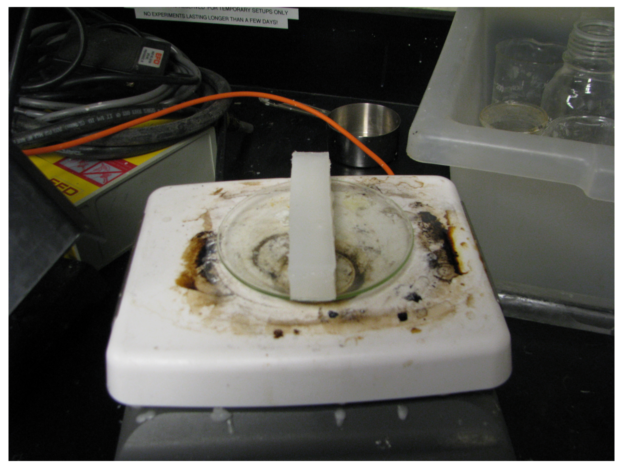
Figure 6. BiMorph Device. Brown material is more expansive than yellow material.

So, essentially the idea for my bimorph was to cast a brick of silicone rubber, with a well along one side for wax. See Figure 7a. To produce, I first had to make mold negatives on the Up! from ABS plastic, which the silicone was then cast in. From there, liquid wax was poured into the well, and refilled until it was a solid prism. Then, a thin sheet of the silicone was placed on top and 'cold cured,' a process in which the silicone is solidified by letting it sit in a cool environment for about 24 hours (allowing the wax to stay solid) rather than heating it and allowing it to cure in about half an hour. By doing this, we kept the bimorph in its cool state, that is, where it is unbent and untensioned. If the wax were melted in the curing process, it would have leaked through the seal, rather than bending the device.

Once the silicone had cured, I put the entire device on a hot plate to allow it to heat to the wax's melting temperature. See Figure 7b. I expected the bimorph to slowly bend or lean to one side, however, this did not occur. Our (mine and Jeff Lipton's) thought of why this did not occur was due to bulging. Essentially, it is easier for the wax to expand by pushing out slightly on the thin silicone walls - causing the rectangular prism to bulge out, rather than force the entire brick into bending tension.



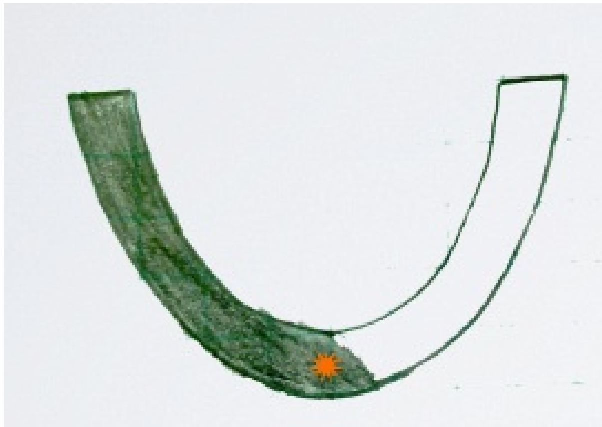
(a) Silicone Mold. Liquid wax is poured into the well and a silicone top is sealed on.



(b) Assembled Actuator. Testing on hot plate, but no bending measured.

Figure 7. BiMorph Actuator Design.

If this thought was true, there are a couple things we could try. First, it is possible to change the bimorph material. In the one above, wax forms the expansive compartment, while silicone forms a stable compartment. I could replace the silicone with air, which would be easier to compress, or even with one of the waxes which shrinks when melted. Second, we could try a new kind of actuator, one which changes its center of mass. Essentially, the actuator would be U-shaped, with one side of its curve bounded in plastic. As the wax heated and expanded, its added volume would push into the unbounded side, as this is the so called lowest energy state, the easiest place for the wax to go. When it moves to this side, the device's center of mass changes, and it rolls. See Figure 8.



(a) Before Heating. COM at center.

(b) After Heating. COM is skewed and device rolls.

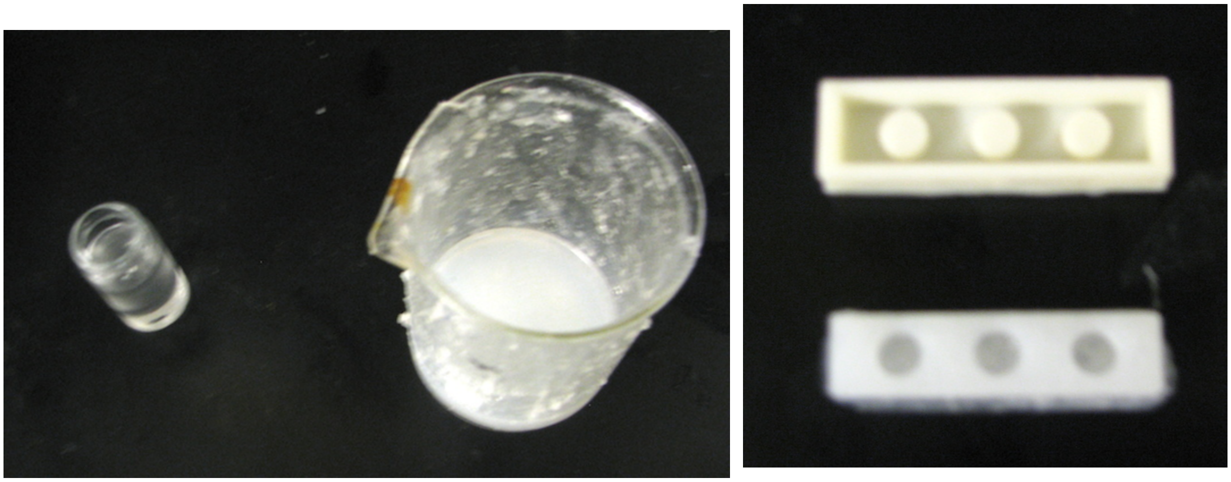
Figure 8. Changing Center of Mass Actuator Concept. Darker regions are bounded by plastic, lighter ones by silicone.

Another thought is to try to harness the expansive power of the wax a little differently. Essentially, instead of having a large deposit of wax, which can push against the walls containing it, we could create a way for the wax's expansion to be limited. That is, if the wax were to expand, it would have to do it in a certain direction (or all of them) rather than bulging only in certain areas. This idea is what we pursued next.

III. Silicone - Wax Material

Moving past the obstacles encountered in designing the first few actuators, it seemed the most important design objective was to create a wax device that is forced to keep its shape as it expands. Jeff Lipton suggested that I try mixing the paraffin wax with the pre-cured PDMS.

To begin with, I mixed the two parts of EcoFlex PDMS, and directly after, mixed in a sample of melted paraffin wax. To create the mixture, I had to stir vigorously, but after doing so, the wax and PDMS seemed well combined, and no part of the mixture settled out. Then I treated the mixture as PDMS, putting it in an ABS plastic mold and heating it for a half hour. After curing, the material generally felt like the normal PDMS/silicone rubber, though it definitely has a slightly softer and more flexible feel to it. See Figure 9.



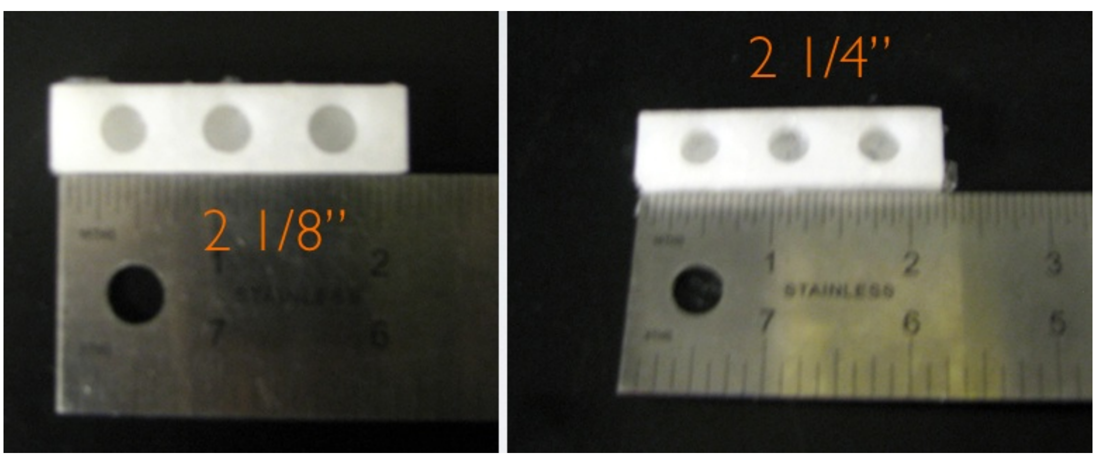
(a) Wax (left) and Ecoflex (right) Before Mixing.

(b) New Wax-Silicone Material After Curing. Mold pictured above.

Figure 9

I next wanted to test how this new material combination behaved under heating. Like the other designed actuators, I put this on a hot plate, meanwhile measuring its overall length to see if there was significant change. For the first time, there was. The original length of the device was $2\frac{1}{8}$", while the final length was $2\frac{1}{4}$". This gives us a length change of about 5.7%. See Figure 10.

Figure 10. Before and After Photos of Wax-Silicone Actuator.



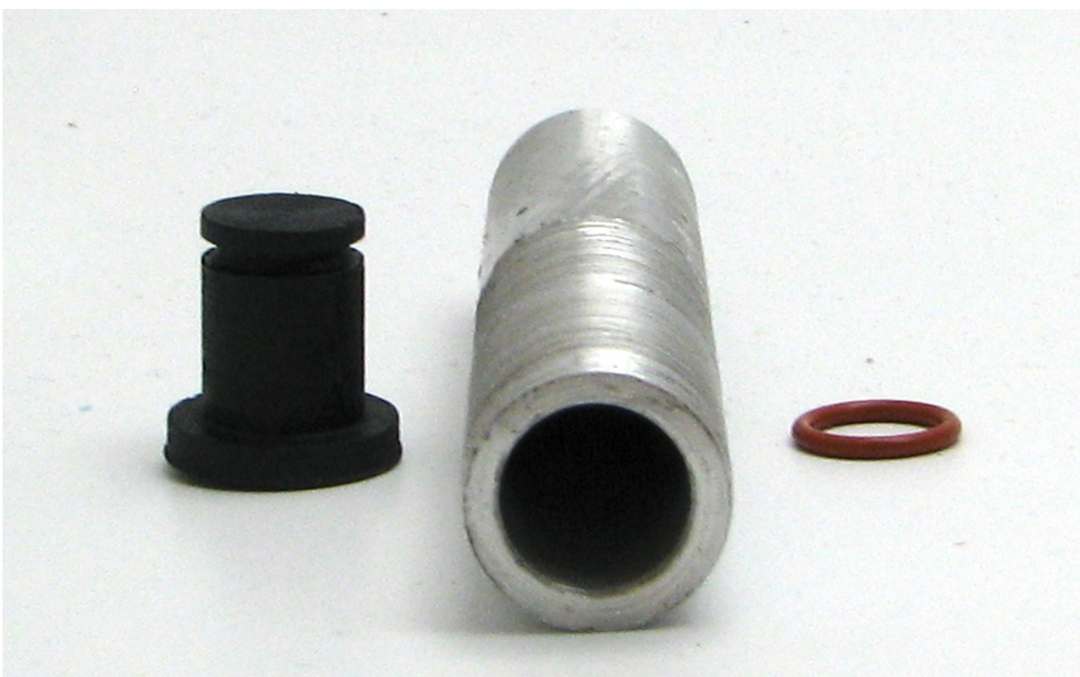
However, I noticed some other affects on this actuator from heating. Small amounts of liquid wax tends to leak out of the silicone brick. Also, small bubbles of liquid wax begin to form on the surface of the actuator. These bubbles provide a good insight as to what the complex structure of this material looks like. I believe the PDMS forms a porous structure, which the wax then fills in. Thus, why the wax may leak out, and why bubbles form. This can also explain the comparatively small expansion of the material. The silicone rubber structure can absorb a good amount of the expansion, simply by deforming internally. However, this material can expand more so than any other wax actuator we developed. It can still expand even when it is covered in a thin silicone layer, preventing wax leakage over many trials.

IV. Characterization of New Material

After inventing this new material, we wished to define its material properties. This would allow for its evaluation as an actuating material. Several properties must be analyzed to characterize the material: stroke, expansive force, temperature strain, and concentration. These must be compared with each other.

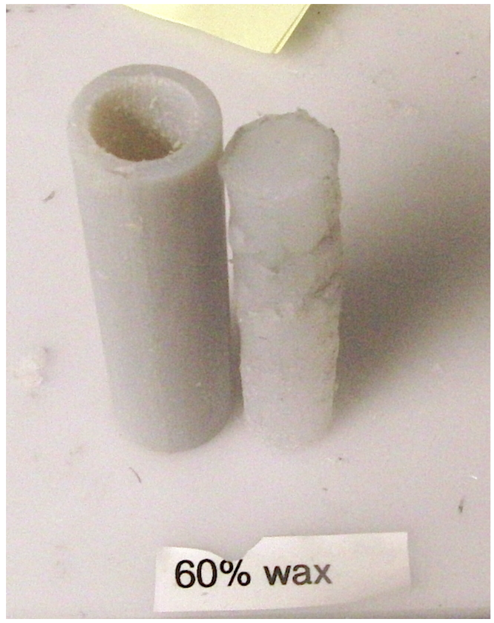
To test this, a setup needed to be developed which eliminates wax leakage. An aluminum tube and plastic cap were created, where a silicone O-ring seals the silicone-wax sample. The cap and chamber were machined in Cornell's Emerson machine shop.

Figure 11. The cap, chamber, and O-ring.



Samples were made using ECO-FLEX 00-50 silicone, chosen because it gave the greatest volumetric expansion in preliminary tests. Samples were made to fit in the testing chamber using a 3D-printed plastic mold.

Figure 12. The plastic tube and removed sample.



Now the samples had to be tested. We first wanted to examine the linear displacement of samples, simply by measuring maximum cap displacement when the material is heated. The sample is inserted into the chamber, then is hammered in to ensure that no air is trapped. A wrap heater then surrounds the testing setup, and is set to about 190° F. Cap displacement then is equivalent to the change in sample length. In this test,the samples created displayed a maximum strain of around 5-10 percent.

The next data set we wished to collect was the expansive force vs. the temperature of a sample. To do this, the tester was modified to be mounted on a pressure sensor. The chamber's outer diameter was threaded, and a crossbar piece was machined to fit the existing setup's mounting system.

Figure 13. The threaded tester.

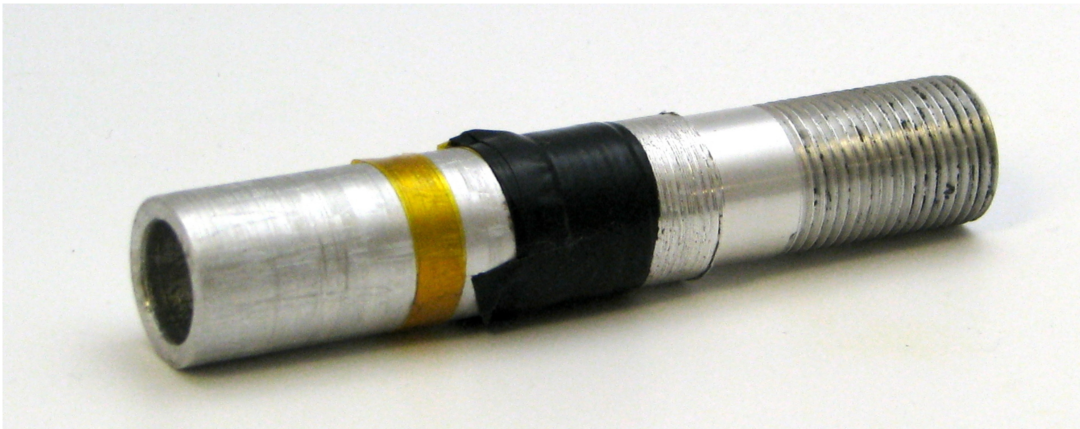
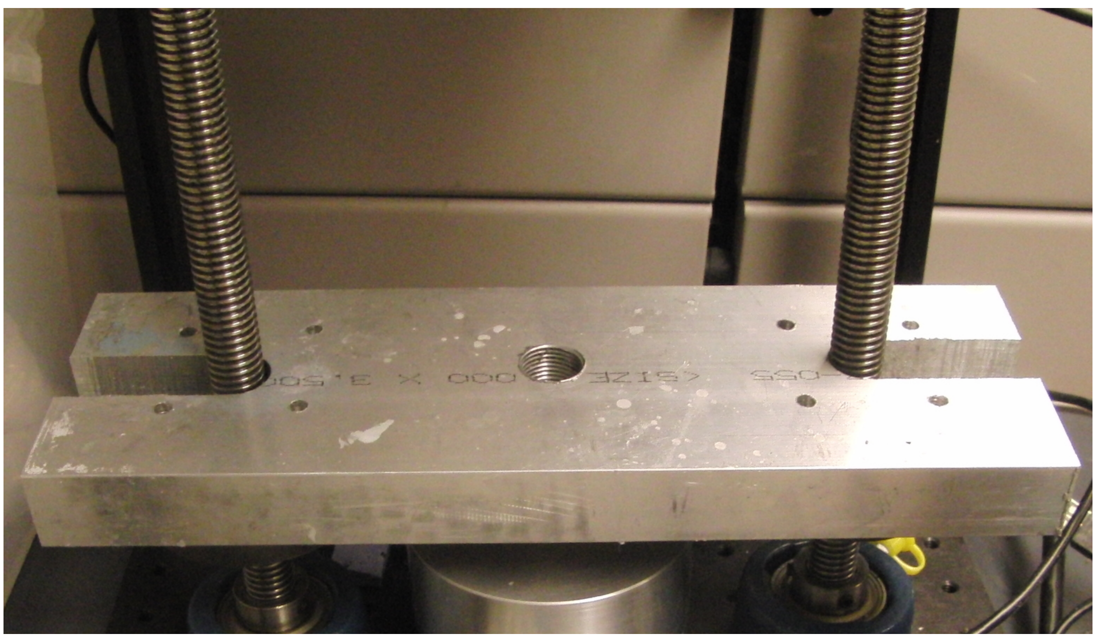


Figure 14. The crossbar mounting which the tester screws into.

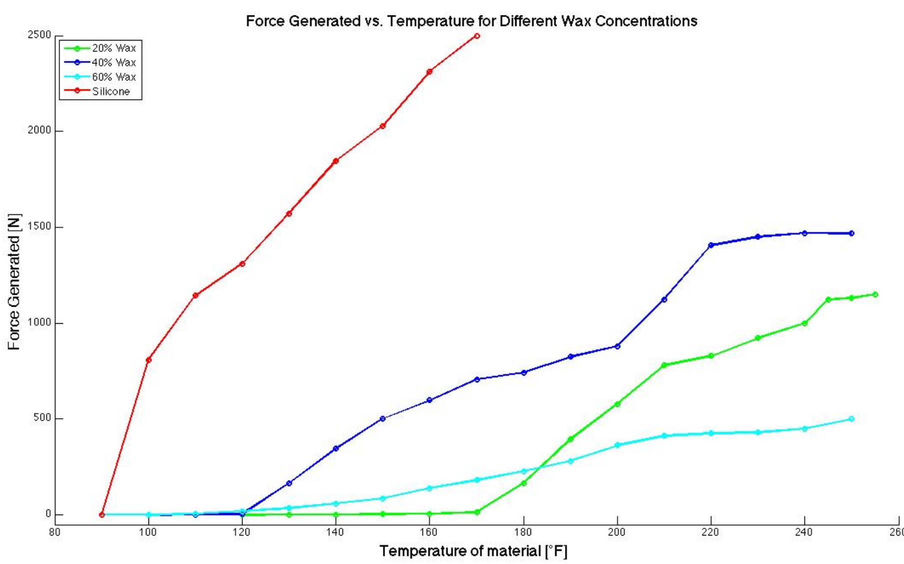


However, this pressure gauge did not work well for our purposes. It measured at too low a force. Thus, we moved to a different force gauge, the Mark-10. Additionally, a new cap was made from aluminum, as the plastic cap had developed a compromising hole. An aluminum mount was also created to secure the tester to the bottom of the gauge

(a) The aluminum cap. O-ring fits very well in groove.

(b) The Mark-10 Gauge with aluminum mount.

This new setup allowed for testing of force v. temperature. This property was tested for samples with a variety of wax concentrations. The graph below contains the compiled results.



The silicone (0% Wax) has a very high force. This is because silicone undergoes some thermal expansion, but does not expand nearly as much as this material. However, the results of higher percentage wax samples do not seem correct. Over many tests, results of samples with wax concentration above 20% do not perform consistently or as expected. Leakage is likely the reason for this (occurring when air is bled from the test chamber.) Jeff Lipton also noticed this when doing tests concerning the material stroke. It seemed 20% wax expanded more than 30 or 40%! For this reason, we are currently developing a new cap that allows for resealing after releasing air, so that tests can be verified as non-leaking.

V. Applications of New Material

At this stage of the project, we wished to show the potential of the incredible material we created. To do this, we brainstormed two applications: a rock crushing device and a robotic leg. While Jeff Lipton primarily worked with the robotic leg, I focused on designing a device which would use the force generated by the wax-PDMS to crack or crush a rock.

The crusher is designed around the material chamber/piston used during characterization, which crushes a sample held in place. It is intended to work with a rock sample about 2 inches in diameter.

Figure 16. The rock crusher as designed in SolidWorks.

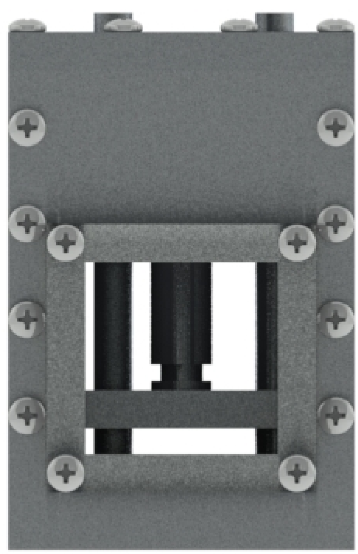
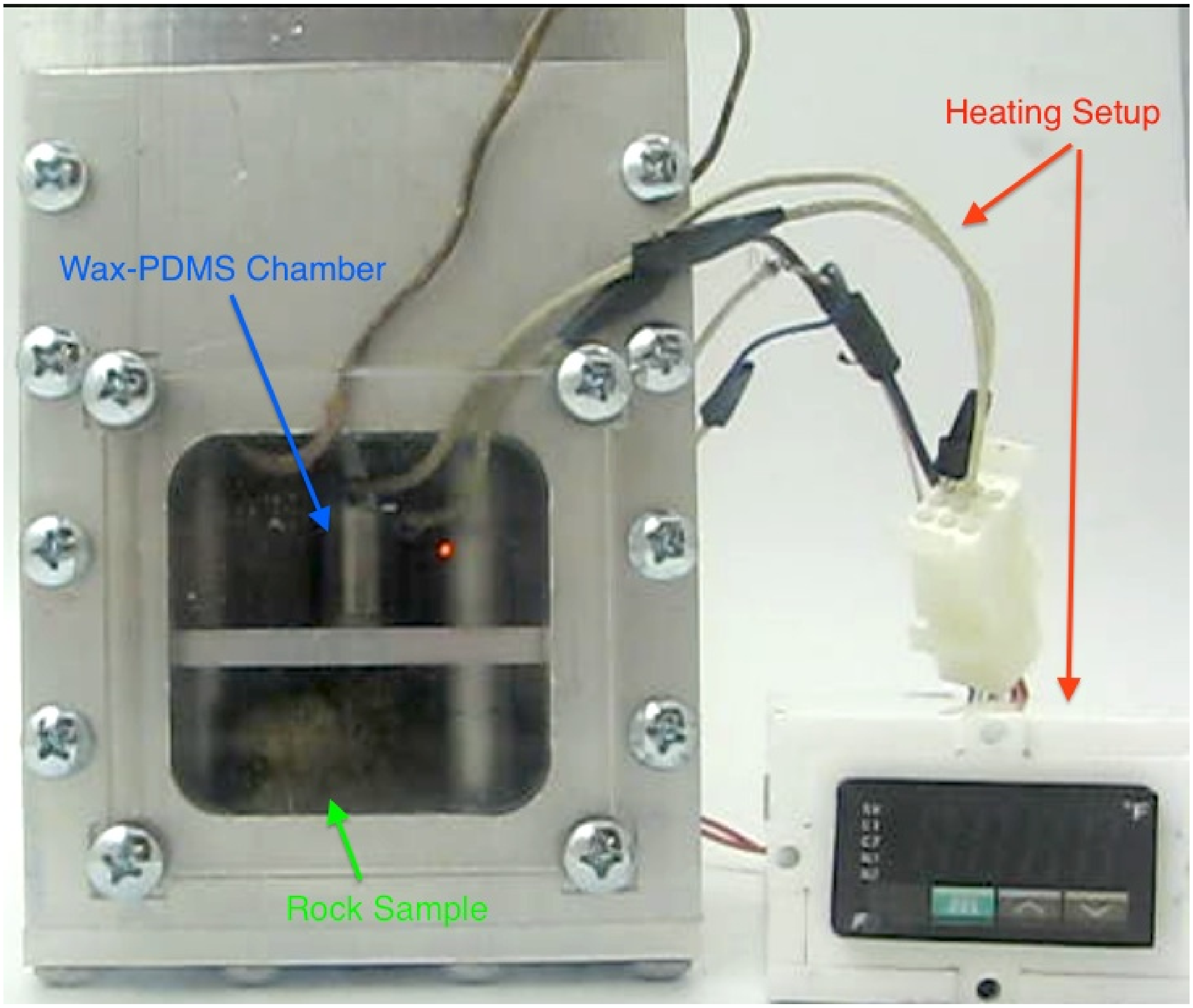


Figure 17. The completed rock crusher as used in testing.



The wax-PDMS will generate a force of 500 - 1000 lbf. For many common rocks, this is around the required force to cause a fracture. Because the material generates such a large force, there are a fair number of safety concerns involved. As seen in the figure above, the opening for the rock sample is covered by a piece of laser cut acrylic to prevent shrapnel being projected outside of the crusher. Additionally, the frame of the crusher is made to withstand a force up to 2000 lb before seeing any deformation or failure of screws.

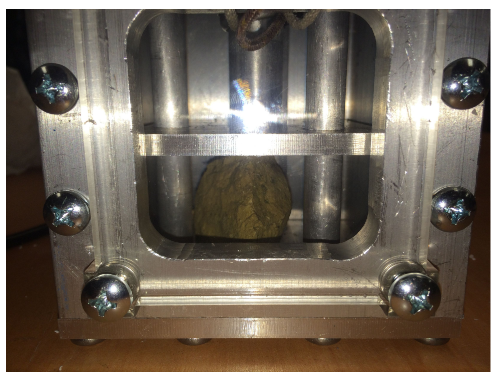
Originally, we looked to contract out the machining work for building the rock crusher, but the high cost (over 3000 dollars) made this impossible. Instead, I was able to machine all parts required in Cornell's Emerson Machine Shop for under 200 dollars of parts.

Once the machine was assembled, a heating setup very similar to that used in the characterization tests was implemented. A cartridge heater wraps around the chamber of wax-PDMS, and a temperature controller regulates the heater to a user-defined temperature. A wax concentration between 40 and 50 percent was used in samples for all of the rock crushing tests.

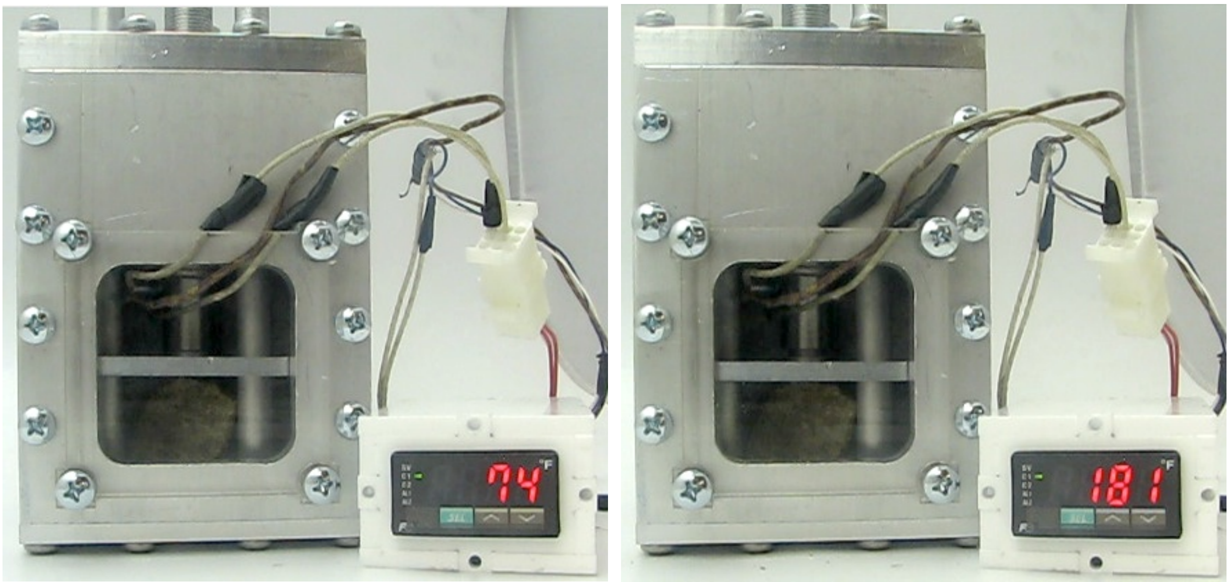
With the entire tester set up, rock samples were gathered. A few early tests used granite and similar samples, none of which showed any stress or deformation from the crusher.

Thus, some different types of samples were collected. These were found by breaking rocks with a hammer, and taking samples that would break from a small impact. Unfortunately, many of these rocks, when tested, tended not to crack, but to break into powder at the site of impact from the material expansion. While this clearly showed the power of the material, it was very hard to see, and far from impressive.

Figure 18. Testing the powdering rock.



So, we needed to find a rock sample that was not too strong (so we could break it,) and brittle (so that it would crack.) Cinder block is a readily-available material that seems to fit both these criterion. When we tested a first sample of cinder block, small parts of it cracked off, but there were no major fractures. In another test of a cinder block sample, there were major fractures in the rock, but none which were visible to the recording device.



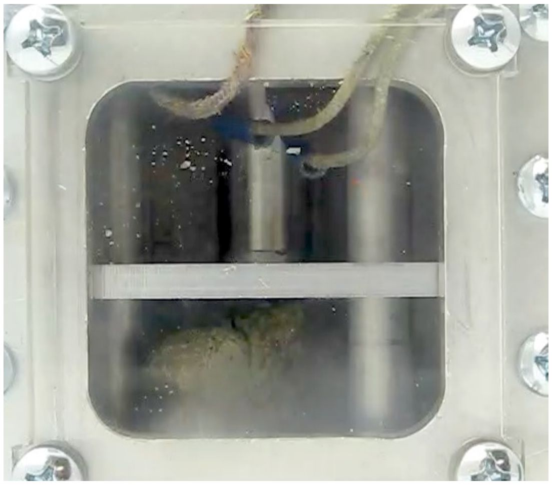
(a) Before heating. Beginning of test. **(b)** After heating. End of test.

Figure 19. Before and after heating to break cinder block. Note the extension of the wax-PDMS material.

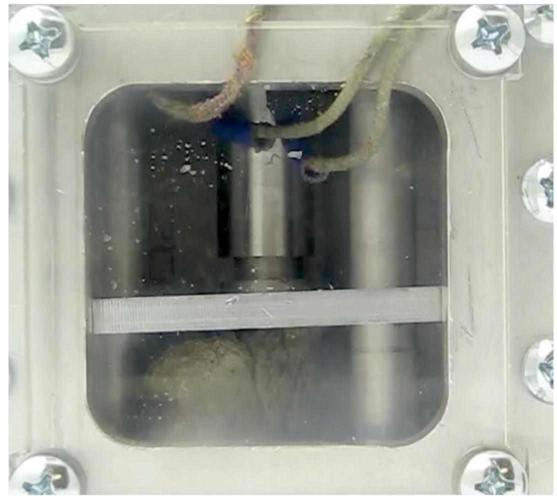
Because the cinder block material seemed to easily be split by the wax-PDMS, we kept trying samples, hoping to get one which would crack cleanly in view of the camera recording. Luckily, one sample did do this. The images below show this quite clearly.

The video of this test is available at this CornellBox link:
https://cornell.box.com/s/phubvv1a3zir81oryi5mae2uyv5wmvww

In about 2 minutes, the first major split in the rock had developed. By 6 minutes, the rock was broken into separate pieces. Over the final 20 minutes of the test after this point, there was some more extension of the material, further crushing the rock. Overall, there was approximately 5-6 mm of travel by the piston in the wax-PDMS material sample.



(a) Before heating. Beginning of test.



(b) After heating. End of test.

(c) Rock sample before test.

(d) Rock sample after test.

Figure 20. Before and after heating to break cinder block. Note the cracks in the rock sample .

This test's success is a great showcase of the power and energy contained in our new material. Though there is a not a large travel (a strain of at most 5-10 percent,) the force contained in a small sample of this material is enormous. Cylinders of the material about as large as an index finger are strong enough to crack rock; a few cylinders could easily lift a car. This wax-PDMS material is the first soft actuator of its kind which can perform feats like this.

Conclusions

One of the main things I've learned in working with this project is that wax is a very finicky material, creating problems with leakage, less than expected expansion, and low expansive force. Still, it has a lot of potential use in actuation, supported by this and previous research.

The most important results we have found however, are those from the new material we have created, a PDMS and paraffin mixture. I think this substance has gotten us much closer to developing a actuating device that can 'walk out of the printer.' It expands significantly under heat (though far less than pure paraffin wax) while maintaining its shape. This allows us to manipulate it to move in useful ways, that is, in specific directions or linearly, rather than simply bulging or deforming its container.

Though they do not pertain specifically to the goals outlined in the beginning stages of this project, this new material has many potential uses. It could be used as a variable density actuator, as a porous structure for other materials, or as an expansive soft material. This could have applications in soft robotics as thermal actuators and heat dependent valves. Our thorough testing of this material gives us the information we need to make useful devices or motors from it. Finally, we can see in the last stage of experimentation that this material has a decent amount of strength, and could fulfill a unique set of requirements which no current actuator does.

Future Work

Applications are the main goal of the future for this project. Making a reliably consistent material would be the first step in allowing wax-silicone to be used in ours and other labs.

Additionally, the material is to be developed to be powered by current. That is, by doping it with silver and carbon, it can be made to conduct some current and heat with electrical power. This would increase the usability of the actuator and give it a faster heating cycle. In this stage we would like to begin developing simple actuators and valves. The robot leg currently in development should show the usefulness of this material as a soft motor.

Finally, future work may be able to develop this material into a 3D printable motor. As the first real soft actuator, wax-PDMS may be the best candidate for 3D printed motion.

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