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Team #23 *In-Vitro* Model
Model Material Analysis
ME 476C-3

Introduction

As in vitro models progress, along with endovascular devices and biomaterials, understanding the model material properties is critical in creating an accurate simulation of the neurovasculature. NAU's Bioengineering Devices Lab (BDL) developed various models that test stability and function of artificial blot clots, capture devices, catheters, and new aneurysm filling devices and materials. To test how closely the model represents real vessels, the use of a high-precision Hybrid Rheometer tested the selected material. This poster focuses on the properties of the in-vitro vessel model such as elastic modulus and shear modulus. The material used for this capstone project is the focus of this analysis.

Initial qualitative evaluation

The materials used to form these neurovascular models must accurately replicate vessel properties to help simulate medical device delivery and endovascular surgical techniques. The in vitro model material properties depend on the type of polymer used and the curing process. Further testing was performed on two potential polymer candidates seen in Figure 1. Clear Flex 50 by Smooth-On, left, and Mold Max 15T by Smooth-On, left.

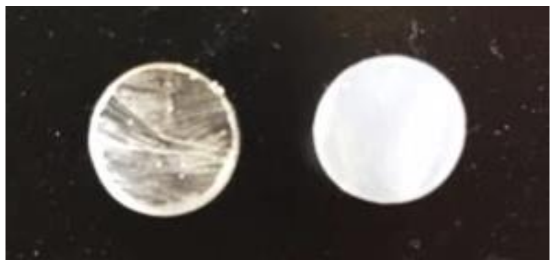

Figure 1: 20mm Material Test Samples

Mold Max 15T proved unworkable as a mold making material. Because of its soft nature, it was difficult to prepare, too opaque to visualize in an *in vitro* model, and did not respond to the mold release such that it became one piece instead of the intended two piece mold. Clear Flex 50 produced the most reliable models.

2-Part Model Casting Procedure

Below are the steps detailing the current method the BDL is utilizing to create *in-vitro* models. Though the capstone project focuses on 3D printed aspects, the creation and materials used in the 2-part model are applicable.

1. Vessel geometries are made by rolling flex wax to the correct geometries and sizes.
2. Nozzles (for subsequent hose attachment for flow model) are inserted onto the ends of the wax vessels.
3. The first layer of casting is poured into the mold and allowed to set long enough for the substance to have enough strength to support the wax vessels
4. The wax vessels are pressed (halfway) into the mold material along with latex rings for proper model alignment. The mold is allowed to set per manufacturer's directions.
5. A layer of mold release is applied to the cured model. A second layer of mold material is poured into the container and allowed to set per the manufacturer's directions shown in Figure 2.

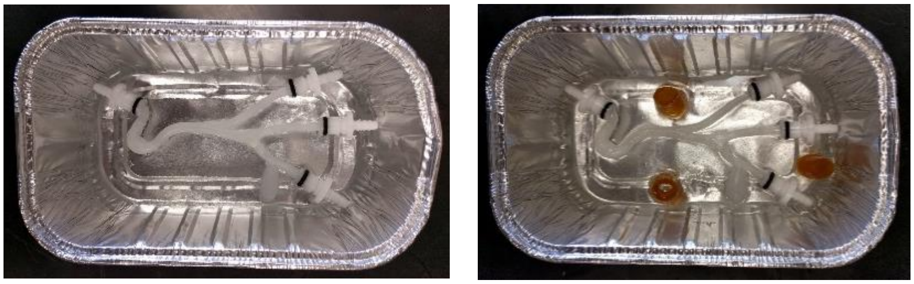

Figure 2: ICA/MCA model-making in progress

Selected Model Material Testing
Rheological measurements (shear modulus and elastic modulus) of Clear Flex 50 and comparisons to blood vessel properties were conducted using a Discovery HR-2 rheometer. [5] For the shear modulus testing, the head applies a constant compressive force and rotates the sample surfaces at various rates. For the elastic modulus testing, the head moves vertically (dynamic oscillation) at various rates. For both tests, a 20mm flat plate head and a Peltier plate bottom (allowing for body temperature (37°C) testing) are used seen in Figure 3.

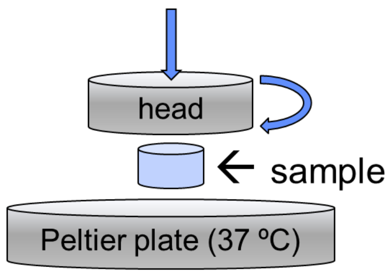

Figure 3: Sample Testing Setup

Samples are created using an 8mm hole-punch. Because the bottom and top of the samples must be parallel for most accurate results, swatches of model material were inspected for the flattest, most consistent areas. Samples need to be loaded concentric to the top plate for best results and surrounded by water. Surrounding the sample with water allows the sample to further be tested closer to human body conditions and in most cases water is flowing through the models.

Each test duration is 60 seconds with an axial strain of 1 % at a frequency of 1 Hz. Applied compressive axial force is 0.1 N and each sample was tested at least five times. The data points are taken at intervals of radians per second, meaning how much the sample gives with the force and turning of the head. The main difference is how the force is applied based on what the test is finding.

Mechanical properties as compared to vessels
Because Clear Flex 50 became the front running candidate for a model material, only its material properties were explored with the rheometer. The material does have some post-processing tunability; it could be room temperature cured only (>16 hours), post-cured once in a ~60°C oven for 8 hours, or post-cured twice in a ~60°C oven for 8 hours each time. All three sample types were explored.

The shear modulus curves (Figure 4) and elastic modulus curves (Figure 5) of each sample were compiled. As seen in the graphs below, the air cured and once cure models have very similar values. The model that underwent two cures had a significantly higher value that is roughly twice as stiff as the other samples.

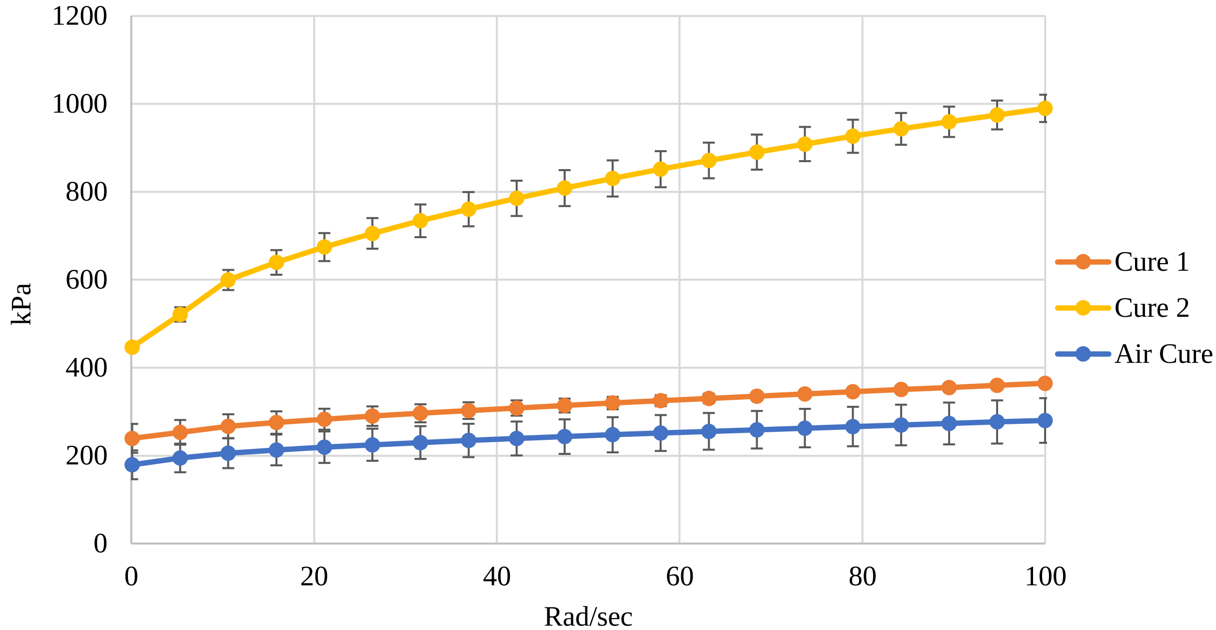

Figure 4: Shear Modulus

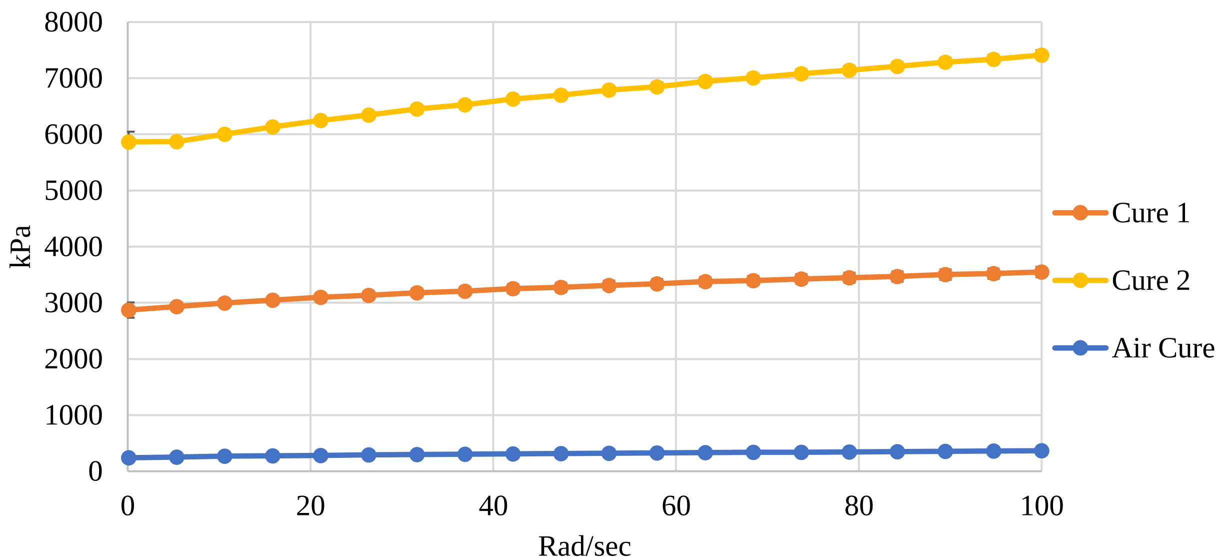

Figure 5: Elastic Modulus

The lower strain rate results (1 to 30 rad/s) were in phase and 30 to 100 rad/s shifted out of phase. Therefore the low strain rates maintained contact between the testing head and the sample, whereas higher strain rates may have begun to slip around 30 rad/s. However, the phase change did not affect the data trend. Error caused by concentricity and surface defects. All materials were compared at a physiologic strain rate of approximately 1 Hz (6.3 rad/s, see Fig. 6 & 7).

Rheometer data compared to Bank's values [6] for vessel wall stress and elastic modulus. Vessel wall stresses are compared to shear modulus (Figure 6). Laplace's Law is used to convert shear modulus to wall stress. Wall stress is calculated using pressure, radius, and vessel wall thickness. Using the approximate dimensions of the in vitro model (Radius = 2mm and Thickness =0.5mm).

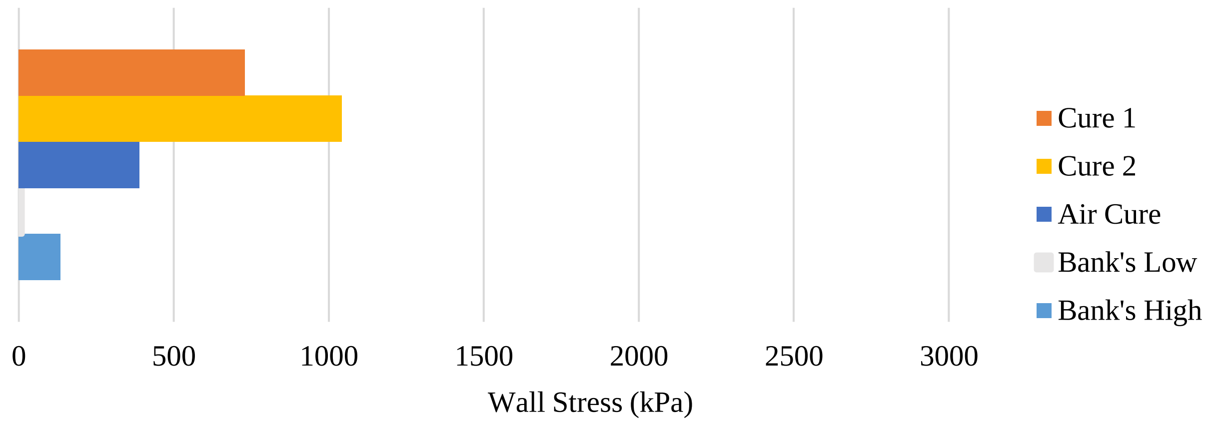

Figure 6: Wall Stress Comparison

It is important to note that Bank's data is from bronchial vessels. The vessels inside the brain are more delicate than the bronchial artery since they have thinner walls and smaller diameters. "Bank's Low" represents thinner, relaxed vessels, whereas "Bank's High" represents stiff vasoconstricted vessels. For neurovasculature, a lower stiffness, between the Banks High and Low range, is desired.

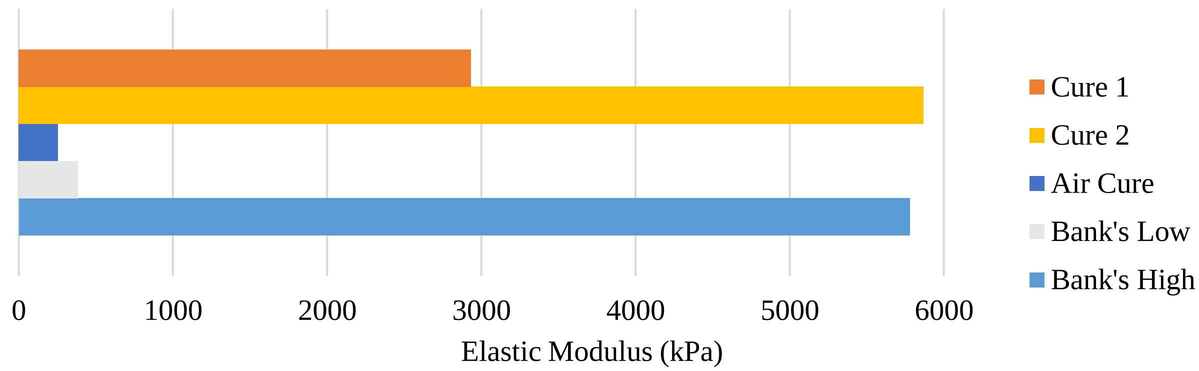

Figure 7: Elastic Comparison

BAM Material Comparison

A potential material that can be used in the model is in development in the lab. It is a polyacrylamide-alginate (PAAM-Alg) with some binding agents. This material has been named BAM, standing for Bill and Anne Marie, who are the two students who have continually worked with the material. BAM is highly elastic and could be a useful for the model. Its elasticity would potentially make it easier to remove the core of the *in-vitro* model which is a desirable aspect. Below in Figure 8 is the BAM material elastic properties added to the elastic graph above. The extremely low bar on the graph for high and low BAM values show how much more elastic this material is compared to the other material. Though it is more elastic than human vessels, this will not affect the overall purpose of the model.

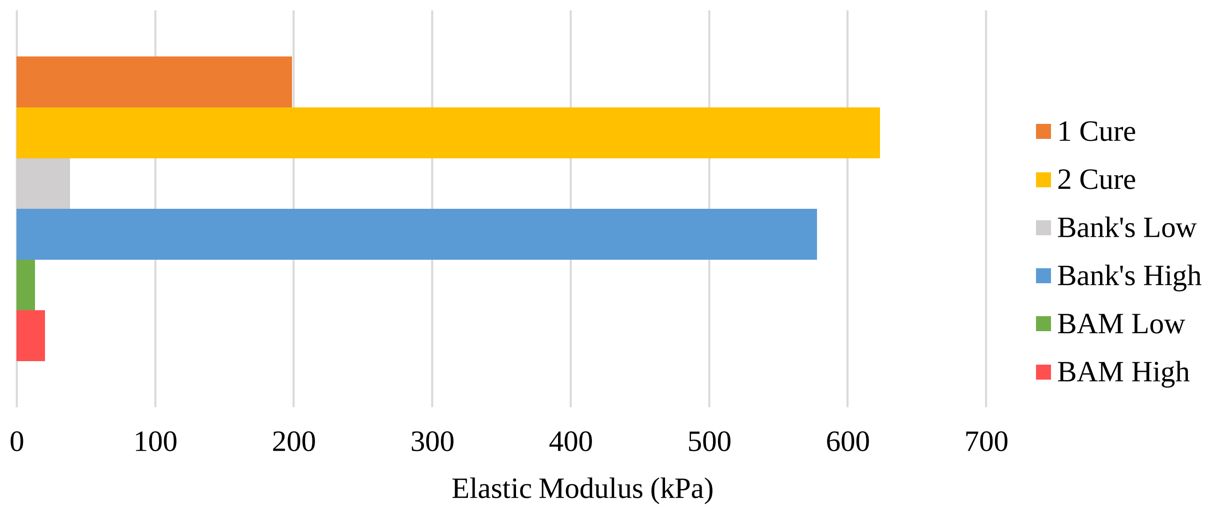

Figure 8: BAM Elastic Comparison

Conclusion
Overall, the Cure 1 materials have properties closer to human vessels (Figure 6 & 7), and are half as stiff as a Cure 2 material. The in-vitro model created using Air Cure has smaller, less stiff, and more elastic vessels to better simulate the neurovasculature. Cure 2 material is not desirable due to its increased stiffness. Utilizing the BAM material is currently the best material for the 3D printed model but the Clear Flex will be an alternative material.

Application
With confidence in the material selection, mold casting procedures, and understanding of mechanical properties, this model is ready for biomaterials characterization and testing. The model will test the BDL's biomaterials for aneurysm treatments and for synthetic thrombus for the following:

- Blood flow effects (flow rates and pressures monitored with a LabView DAQ system)
- Material fatigue (rheological testing with a rheometer)
- Particulation and/or downstream migration (particle counting and in-line filter system)
- Deployment of endovascular thrombus removal devices

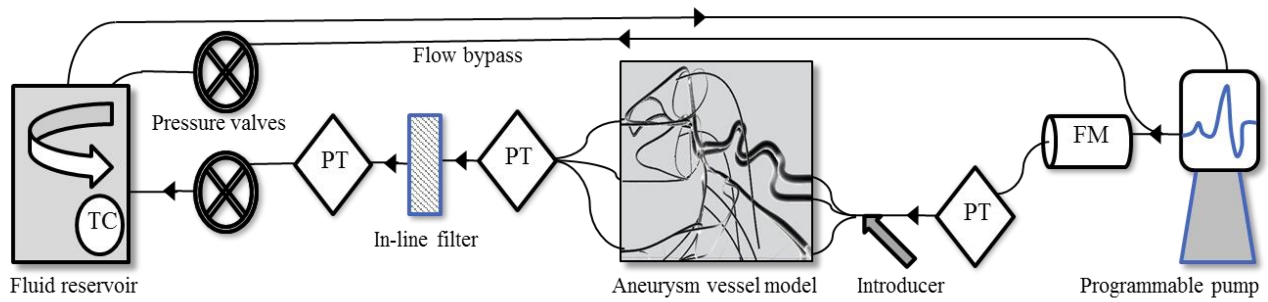

Figure 8: Graphical depiction of complete in vitro model

References

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