Properties of Spider Web Adhesion

An experiment with the viscosity of fluids

Background information: Spiders have used webs as a method to catch food for thousands of years. Spiders spin webs using silk as a means to trap their prey so that they do not have to move around and chase their prey. The spiders use different glands to produce different kinds of silk. How do the flies and insects stick to the webs? The main way the prey is stuck to the silk is through tiny drops of glue that are produced and placed on the silk fibers as pictured below. This is referred to as "beads-on-a –string" and consist of adhesive polymeric glycoproteins.[1, 2] Why do the beads form at specific ordered locations throughout the entire strand? Imagine when the water is turned off at a faucet, instead of a steady stream of water coming out, the water forms drops. This is the main principle behind Raleigh Instability, that is, that liquids because of their surface tension tend to minimize their surface area. This means the liquids will naturally tend to form drops when the wavelength reaches a certain maximum. This forms the specific pattern you see pictured below in Figure 1. The wavelength is the distance from one point to the next similar point. For example, in the picture below, the wavelength could be measured starting with the far left side of the bead on the left and go to the left most side of the bead in the center as indicated by the arrow in Figure 1.

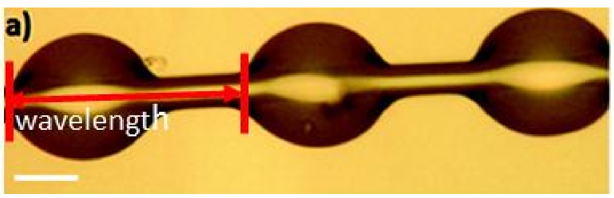


Figure 1. Wavelength of a droplet pattern on a fiber. Adapted with permission from reference 1.Copyright 2012 American Chemical Society."

What factors may influence the size of the drops? One of the main factors is the viscosity of the glue that the spiders use. Viscosity is the resistance of a fluid to flow. The higher the viscosity of a fluid the harder it is for the material to flow. For example, water would have a low viscosity because it is easier to move than honey which would have a high viscosity.

Experimental Question: Compare the two pictures below in Figure 2 and notice how the size of the doplet is different as well as the wavelength of the drops. What variables might impact the size of the drop on the string? How does type of material (viscosity) affect droplet size and wavelength of drops? How does the speed of the string through the solution affect the droplet size?

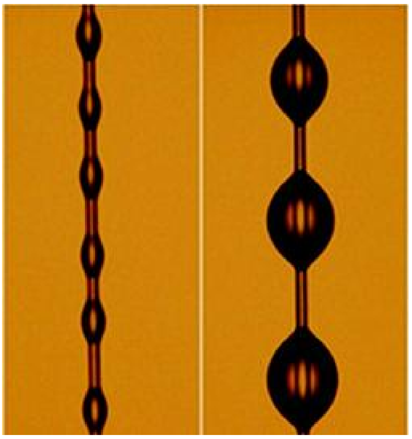


Figure 2. Different sized droplets formed on equal diameter nylon fibers. Adapted with permission from reference 1.Copyright 2012 American Chemical Society."

Materials needed: castor oil, olive oil, tomato juice, milk, corn syrup, nylon string, ruler

Instructor Setup: You will need to cut 5 pieces of nylon string for each lab group. The string length should be about 15 inches for each piece. The students should have access to rulers at their lab station. Place an appropriate amount of solution in a plastic container for the students to run their strings through. Depending on the class size you may want to do 2 solution containers for each one and split the class up. An alternative method would be to have the students use beakers for the solution at their individual lab stations.

Procedure:

Part I: How does the type of solution impact the number of drops and wavelength of drops? For this part of the experiment you will be testing 5 different solutions and moving the string at a constant velocity through the solution.

1. Take a piece of string. Hold onto both ends of the string and dip and then slide the center of the string through the solution bath.
2. Once it is submerged, pull on the string allowing it to move at a constant velocity out of the solution. Be sure to make a mental note this speed at which you are using to pull the string because it will be used for the rest of the solutions.
3. Count the number of drops along any segment of the string. Try to count along a good segment where the drops are easy to see and you can count several drops in a row. Record this in column 3 of Data Table 1.
4. Now measure the length of string along which you counted the beads. Record this in column 4 of Data Table 1.

5. Do 2 trials for each solution and then repeat for the rest of the solutions. Be sure to *not* change the speed at which you pull the string out of the solution.
6. Determine the wavelength of the “beads- on -a -string” (column 5) by taking the length of string you counted the drops along/number of drops. (column 4/column 3)
7. Find the average wavelength of the “beads-on-a- string” (column 6) by averaging the two trials in column 5.

Part II: How does the speed of the string impact the number of drops and wavelength of drops? For this part of the experiment you will be testing 2 different speeds of string and moving it through the same solution each time.

1. Determine what solution you want to use. You will be using the same solution type for all parts of this experiment.
2. Take a piece of string. Hold onto both ends of the string and dip and then slide the center of the string through the solution bath just like you did for part I.
3. Once it is submerged, pull on the string allowing it to move at a constant velocity out of the solution at a slow speed.
4. Count the number of drops and along any segment of the string. Try to count along a good segment where the drops are easy to see and you can count several drops in a row. Record this in column 3 of Data Table 2.
5. Now measure the length of string along which you counted the beads. Record this in column 4 of Data Table 2.
6. Do 2 trials and then repeat for the fast speed.
7. Determine the wavelength of the “beads- on-a-string” (column 5) by taking the length of string you counted the drops along/number of drops (column 4/column 3)
8. Find the average wavelength of the “beads-on-a-string” (column 6) by averaging the two trials in column 5

Figure 3. Spider and web. Reproducedwith permission from reference 1.Copyright 2012 American Chemical Society."

Viscosity values:

Olive oil = 0.081 Pa·s

Castor oil = 0.985 Pa·s

Corn Syrup = 1.38 Pa·s

Milk = 0.003 Pa·s

Tomato juice = 0.180 Pa·s

Data Sheet & Questions

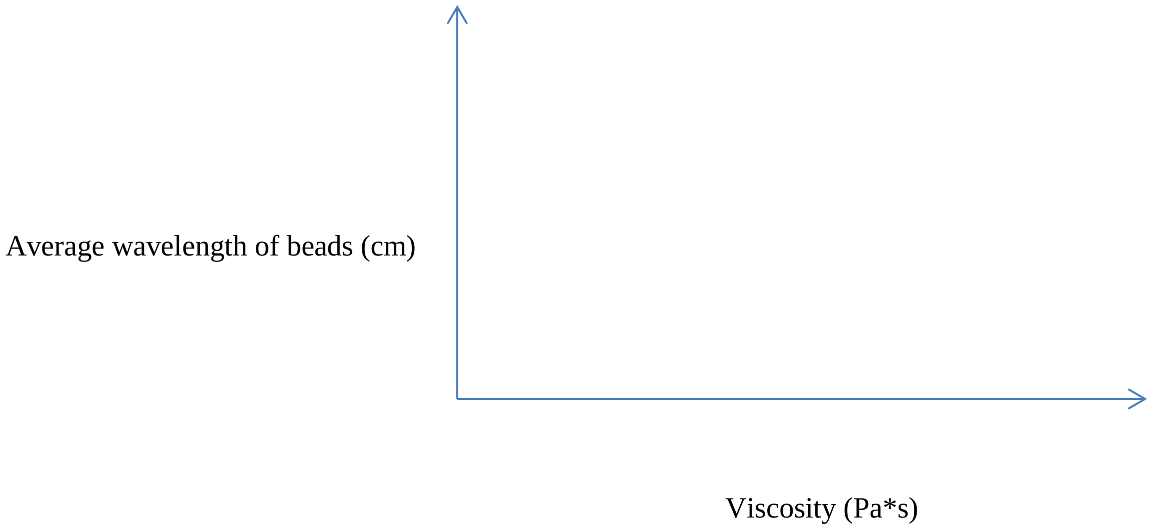
1 Type of solution	2 Trial number	3 Number of drops	4 Length of string you counted the drops along (cm)	5 wavelength of "beads-on-a-string" (length of string/number of drops) (cm)	6 Average wavelength of "beads-on-a-string" (average of Column 5)
Olive oil	1				
	2				
Castor Oil	1				
	2				
Corn Syrup	1				
	2				
Milk	1				
	2				
Tomato juice	1				
	2				

Data Table 1

1. Which type of solution produced the largest sized drops?
2. Which type of solution produced the shortest wavelength of "beads-on-a-string?"
3. Which type of solution has the lowest viscosity (least resistance to flow)? Which type of solution has the highest viscosity?

4. Comparing question #3 above to question #2 is there any relationship between the wavelength for the "beads-on-a-string" and viscosity?

5. Make a graph below of viscosity vs. average wavelength of beads:



1 Speed of string	2 Trial number	3 Number of drops	4 Length of string you counted the drops along (cm)	5 wavelength of “beads-on-a-string” (length of string/number of drops) (cm)	6 Average wavelength of “beads-on-a-string” (average of Column 5)
Slow	1				
	2				
Fast	1				
	2				

Data Table 2

6. Which speed produced the largest drop size?
7. Which speed produced shortest average wavelength?
8. What is the relationship between speed of string and average wavelength of “beads-on-a-string?”

Application questions:

9. You want to create a string with the smallest average drop size. Which solution do you choose? With what speed would you pull it with?

10. If a spider is trying to catch large flies and wants to produce large drops of glue how will he spin it to make the largest drops? (discuss both viscosity and speed here)

Going Further: Mathematical Models of "beads-on-a –string"

It is possible to calculate the wavelength array for the "beads- on-a-string" by knowing some common physical properties of the substance as well as some parameters of the experiment. The first thing that needs to be calculated is the capillary number, Ca. The capillary number is based upon viscosity, surface tension, and velocity of coating. After the capillary number is calculated it is possible to calculate the thickness of the entrained cylindrical film, e. This is done by using one of the two formulas below based upon the capillary number for the solution.[3]

$$\mathrm{Ca} = \eta \mathrm{V}/\gamma$$

$$e = \begin{cases} 1.34d\mathrm{Ca}^{2/3}, & \mathrm{Ca} \ll 1 \\ \dfrac{1.34d\mathrm{Ca}^{2/3}}{1 - 1.34\mathrm{Ca}^{2/3}}, & \mathrm{Ca} \sim 1 \end{cases}$$

where, d = radius of uncoated fiber, η = viscosity, γ = surface tension, V = velocity of the coating

After calcuating the thickness of the entrained cylindridal film it is possible to calculate the wavelength of array using the equation below[4,5]:

$$\lambda > 2\pi(d + e)$$

Example Problem: Olive oil has a surface tension of 32 mN/m and the velocity of the solution is 0.005 m/s. If the diameter of the string that you are using is 30 µm calculate the following:

11. The capillary number, Ca:

12. The thickness of the entrained cylindrical film, e:

13. The wavelength of array, λ:

Teacher Guide

Typical Results:

Higher viscosity means larger beads: if you look at Figure 4d below the largest viscosity fluid is on the right (largest beads) and the lowest viscosity fluid is on the left (smallest beads)

Faster velocities mean larger beads: if you look at Figure 4c below the beads-on-a-string for a faster velocity are pictured on the right (largest beads) and the slow velocity is pictured on the left (smallest beads).

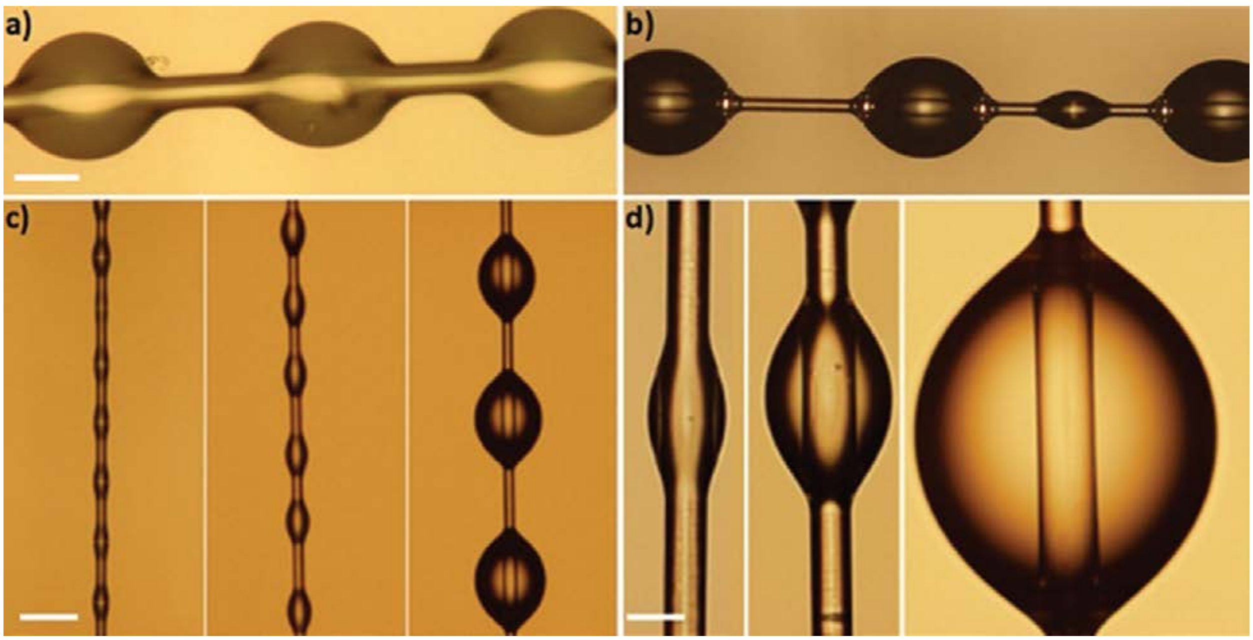


Figure 4. Fabrication and tuning of functional threads. (a,b) Capture spiral thread spun by Argiope trifasciata (scale bar is 30 μm) and a thread produced by withdrawing a nylon thread out of a reservoir filled with PDMS, respectively. (c) Effect of velocity of coating on drop dimensions when nylon threads are coated with PDMS of kinematic viscosity 1000 cst at velocities of 690, 2460, and 9460 $\mu m \cdot s^{-1}$ (left to right). (d) Effect of PDMS viscosity on drop dimensions. Nylon threads are coated, at 9460 $\mu m \cdot s^{-1}$, with PDMS of kinematic viscosities 10, 100, and 1000 cst (left to right). Capillary number increases from left to right. Scale bars in c and d are 150 and 50 μm, respectively. Reprinted with permission from reference 1.Copyright2012 American Chemical Society."

References and other readings:

(1) Sahni, V.; Labhasetwar, D. V.; Dhinojwala, A. *Langmuir*. **2012**, *28*, 2206−2210.

(2) Sahni, V.; Blackledge, T. A.; Dhinojwala, A. *J. Adhes*. **2011**, *87*, 595−614.

(3) Ryck, A. D.; Quere, *D. J. Fluid Mech.* **1996**, *311*, 219.

(4) Plateau, J. *Statique Experimentale et Theorique des Liquides Soumis aux Seules Forces Moleculaires*, 1st ed.; Gauthier-Villars: Paris, 1873; Chapter 2

(5) Lord Rayleigh. *Philos. Mag*. **1892**, *34*, 145.