GECKO ADHESION ON SOFT SURFACES

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GECKO ADHESION ON SOFT SURFACES

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Thesis

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ABSTRACT

Geckos are impressive creatures due to their ability to easily attach to various surfaces from smooth leaves to rough textured walls and rapidly detach their toes as they climb. The micro-hierarchical structure of gecko toe pads allows them to interact and adhere to nearly any surface without the use of liquids. While this ability of geckos is equally related to gecko toe pads and the surface they are moving on; any change in each can affect the adhesion system. In this work, we briefly describe the gecko adhesion system and the forces involved, as well as detail the experimental setups. We also discuss how geckos perform on different soft substrates and investigate parameters such as friction, softness and surface free energy of the materials used, to study some parameters that can be the cause of changes in gecko's performance on these surfaces.

ACKNOWLEDGEMENTS

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CHAPTER I

INTRODUCTION

In this chapter we will discuss the fundamental concepts of this study needed to understand the experiments explained in chapter 2.

1.1 Mechanisms of Adhesion in Geckos

Geckos are fascinating creatures with amazing capabilities such as defying gravity during moving along vertical surfaces even with the head downwards and upside down on the ceilings. This repeated and rapid detachment of the feet without significant detachment forces is beyond the capability of any current synthetic adhesives making geckos toe's skin a unique system to study. These phenomena require parallel frictional forces equal to or greater than gecko's body weight ($\sim$ 50 g) and some details of the adhesion mechanism are still unknown. An even more complex and important problem is how they detach from the surface. Many researchers believe that the secret of the gecko's adhesive capability originates from their foot/toe morphology (surface chemistry, microstructure, etc.). The structure of the gecko toe is well-known and its multi-scale morphology is shown in figure 1.1. [1] The supporting concepts of this study, which include gecko foot structure and van der Waals forces are discussed in chapter 1. Also, the previous work done which led us to this study has been explained in chapter 1. The following chapter explains all the experimental methods that were employed in this research. Data analysis and results of the study are presented in Chapter 3. Finally, in the Conclusion, we will summarize the process of the experiment and outline the findings and implications of the study.

1.2 Gecko Toe Multiscale Morphology

The fact that geckos can overcome gravity relies on their foot structure. Studies over gecko toe morphology shows that gecko toes have a hierarchical structure yielding to a smart adhesive. Each gecko toe pad is covered with ridges (Scansors; Fig 1.1-B) which have long beta-keratin (with bulk Young's modulus $\sim$ 2 GPa. [2],[3]) hairs (Setae; Fig 1.1-D) which are each one tenth the diameter of a human hair. These setae are vertically aligned with each other, and are gathered into arrays in each individual lamellae, with a density of 5000 to 140000 setae/mm^2 [4],[5],[6],[7]. These hairlike stalks are then subdivided into hundreds of branches themselves and there are triangular plate-like structures on the tip of each branch (Spatula,; Fig 1.1-F) which come in contact with the surface and are the primary reason why the geckos can hold on to any surface.[6] A single seta of the tokay gecko (*Gekko* gecko; Fig 1.1-E) is roughly 110 microns long and 4.5 micrometers in width. [5],[8] Spatulae are 500 nm long and approximately 200 nm at the widest edge of the triangle and 10 nm thick [5],[8],[9]

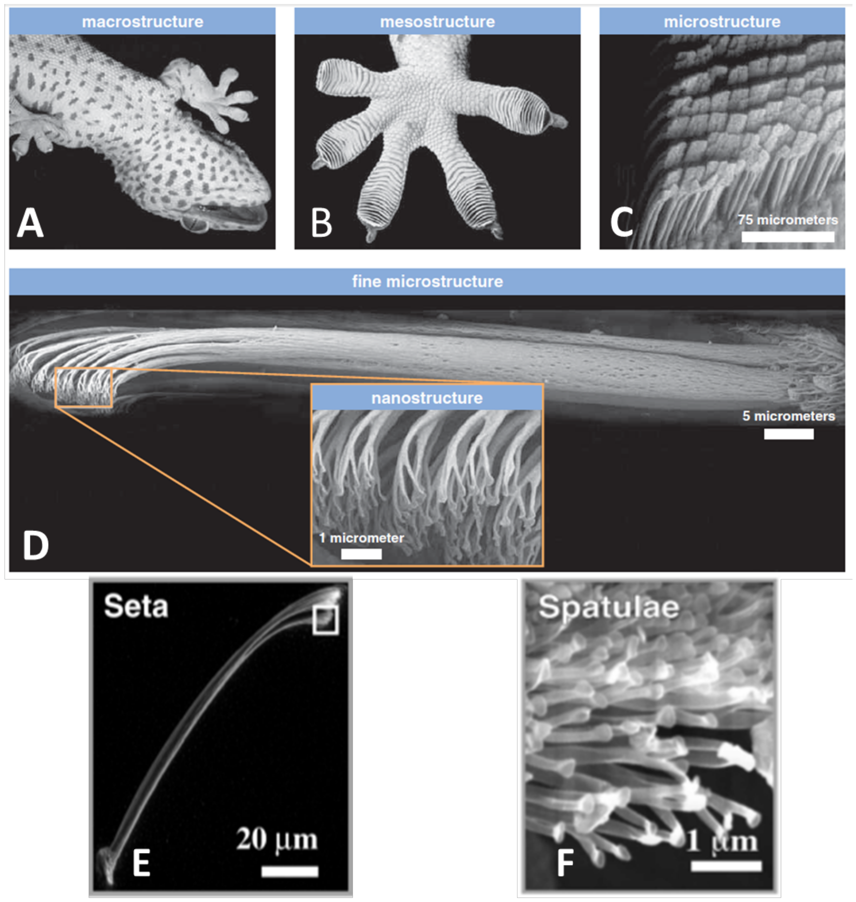

Figure 1.1: Hierarchical structure of the gecko toe pads leads to different new features at each scale. At the micro-scale picture a tokay gecko (*Gekko* gecko) is shown while with a closer look at the foot (mesostructure), many ridges can be seen crossing each toe. In the micro-scale picture, densely packed projections (setae) can be easily observed. The fine microstructure of a single gecko seta shows that each of these beta-keratin fibrils subdivides into hundreds of smaller branches, each of which having a triangled shape plate at its end (spatula). Figure modified from [5] and [10]

Different parameters of this hierarchical structure such as setal length, degree of branching, and spatular density all vary across the gecko toe. Setae with larger spatulae can be seen in the more distal lamellae, while the spatulae which belong to the very proximal lamellae are very small, such that no spatula can be found in some cases. [5]

In this work, we have used the lamellae chosen from the middle to distal sections of the gecko toes. The lamellae are refreshed approximately once a month when the gecko sheds its skin. The shed skin has been collected and frozen for later use, as in isolated lamella testing.

1.3 Adhesive Mechanism

Despite all the information about the morphological properies of gecko toes, a full understanding of their functionality and mechanism of adhesion is still unknown. In the early 20th century, Haase [11] hypothesized that adhesion process occurs due to intermolecular forces meaning that the attractive forces will increase as the space between the feet and the substrate decreases. Later there were some new postulates declaring that seta-surface physical engagements play the key role in gecko adhesion. Dellit in 1934 [12] proposed a microinterlocking hypothesis expressing that the seta's curved structure acts like a hook attaching to surface microstructures while the spatulae lie flat against the substrate, increasing the surface area in contact with the surface resulting in increased frictional forces. All these theories imply that adhesion should be stronger on rougher surfaces and inverted motion should be much harder, as friction mostly occurs parallel to the plane of locomotion which leaves no opposing force to gravity. Later it was observed that geckos can adhere to polished glass and polished silicon oxide while inverted [4], proving that surface irregularities are not necessary for adhesion.

Hiller (1968-1975) [13] refuted microinterlocking and friction hypothesis and suggested that the surface materials physiochemical properties are instrumental to gecko's adhesion strength regardless of the surface texture. In other words, gecko adhesion arises from molecular interactions rather than being a mechanical phenomenon. It was demonstrated that the adhesive force was correlated with the surface energy of the substrate, providing the first direct evidence that intermolecular forces are responsible for adhesion in geckos. However, there is no clear understanding what the molecular mechanism underlying adhesion is in setae since there are at least 11 different types of intermolecular surface forces at the interface between solids [14] which cannot always be distinguished from friction. Furthermore, a number of these interactions may have operated simultaneously to generate these significant amounts of forces. Other possible mechanisms are eliminated such as suction and glue discharge during the adhesion since geckos were found to stick strongly to a surface under vacuum and in ambient conditions and due to lack of other experimental evidence.[12],[15] Also, regarding intermolecular interaction mechanisms, electrostatic forces (Schmidt, 1904)[16] were proposed as a possible mechanism for adhesion in gecko setae which was later refuted (Dellit, 1934) [12] by eliminating electrostatic attractions via X-ray bombardment showing that geckos were still able to adhere in ionized air. Regardless, electrostatic forces can enhance the major attractive force acting between the surface and the gecko toe. Also, polarity of the surface might be an important factor in the strength of adhesion, however adhesive forces did not decrease completely to zero on all hydrophobic surfaces showing that polar-polar interactions are not the major driving force for gecko adhesion either. The role of capillary forces is also investigated, however there is no general system-independent study linking the adhesion mechanism to capillary effects regardless of other important parameters such as surface chemistry.

An alternative mechanism is that geckos adhere by van der Waals interactions which may sound counterintuitive since van der Waals interactions are the weakest of all intermolecular forces. However, it has been demonstrated that an individual seta operates by van der Waals forces.[4] An isolated seta, sheared in-plane on a substrate and detached out-of-plane, showed over an order of magnitude increase in the measured force compared to a case in which the seta was not sheared. Since the strength of van der Waals interactions depends on the contact area between the organism and the substrate and the distance between the surfaces, these experimental findings support the proposed gecko adhesion process. Furthermore, Autumn [10] demonstrated that a gecko can adhere effectively to both hydrophobic and hydrophilic surfaces strongly showing that van der Waals forces are sufficient for gecko adhesion since other mechanisms cannot explain this phenomenon. Therefore, geckos can adhere to wide range of chemistries accepting the van der Waals forces as the main adhesion mechanism.

1.4 Influence of Substrate Modulus on Gecko Adhesion

Previous reports showed that gecko adhesion on soft substrates depends on film thickness (modulus) since geckos did not stick to 10 μm thick films while they stuck to 2 nm thick films.[17] Based on this observation, authors hypothesized that gecko adhesion is only a function of softness and it is irrelevant to surface chemistry. Given these speculations we predicted that there should be a critical film thickness transition point for the adhesion of gecko films. Although it is not clear how softness can be defined quantitatively for a system like a gecko toe, we chose the length scale of spatula as a reasonable range to inspect the above-mentioned criteria. Thus, we used the spin-coating method due to its robust control of film thickness and produced PDMS films in a wide span of thickness from micrometer to tens of nanometer thick films. Surprisingly, no adhesion was observed to all these films, proving the hypothesis wrong. Moreover, we tested different materials and observed that gecko adhesion ability does not depend on the substrate modulus.

In this work, we started establishing a more general design rule for gecko adhesion by investigating various soft materials with different surface chemistry, since the previous hypothesis that gecko adhesion is only a function of softness seems oversimplified and was not confirmed for a variety of surface chemistries.

1.5 Surface Energy Estimation

Fowkes method

It was demonstrated that adhesive force was correlated with the surface energy of the substrate [18], providing the first direct evidence that intermolecular forces are responsible for adhesion in geckos. Fowkes pioneered a surface energy component approach based on the hypothesis that the total surface energy can be estimated by the sum of various surface energy components, which originate from specific kinds of intermolecular interactions. In the most common case the total surface energy γ can be divided into two main components: dispersive and non-dispersive surface energy components, [19].

$$\gamma = \gamma^D + \gamma^h + \gamma^{di} \tag{1.1}$$

where γ^d, γ^h, and $\gamma^d i$ are, respectively, dispersive surface tension component, and non-dispersive surface tension components due to hydrogen and dipole-dipole bonding. This equation is usually rearranged into:

$$\gamma = \gamma^D + \gamma^P \tag{1.2}$$

in which γ^d is the dispersive surface tention and γ^P is the non-dispersive (polar) component of the surface tension. Dispersive forces result from molecular interactions ascribed to London forces and the non-dispersive forces are an outcome of all non-London forces (dipole-dipole bonding, hydrogen bonding, etc.). Furthermore, Dupre's definition of adhesion energy is [20]

$$I_{SL} = \gamma_S + \gamma_L - \gamma_{SL}, \tag{1.3}$$

Wherein I_{SL} = energy of adhesion per unit area between a liquid and a solid surface. In Fowkes theory, the adhesive energy between a solid and a liquid can be separated into interactions between the dispersive components of the two phases and the polar components for the two phases.

$$I_{SL} = 2[(\gamma_L^D)^{\frac{1}{2}}(\gamma_S^D)^{\frac{1}{2}} + (\gamma_L^P)^{\frac{1}{2}}(\gamma_S^P)^{\frac{1}{2}}] \tag{1.4}$$

A very fundamental equation in the surface energy calculations is Young's equation which is an equilibrium relation between the equilibrium contact angle θ of a liquid on a solid surface and the interactions between solid surfaces and liquids:

$$\gamma_L \cos\theta = \gamma_S - \gamma_{SL} \tag{1.5}$$

For a solid-liquid system combining equations (1.3) and (1.4) with Young's Equation, yields the primary equation of the Fowkes' surface energy theory(1.5)

$$(\gamma_L^D)^{\frac{1}{2}}(\gamma_S^D)^{\frac{1}{2}} + (\gamma_L^P)^{\frac{1}{2}}(\gamma_S^P)^{\frac{1}{2}} = \frac{\gamma_L(\cos\theta + 1)}{2} \tag{1.6}$$

Experimental contact angles of different liquids with known dispersive and non-dispersive (polar) forces can be used to calculate the two components of the solid surface and therefore its total surface energy can be estimated. In this work, we have used diiodomethane and water as standard probing liquids with known surface energy components. (${\gamma_{\text{Water}}}^P$ = 48.6 mJ/cm^2, ${\gamma_{\text{Water}}}^D$ = 24.8 mJ/cm^2, ${\gamma_{\text{Diiodemthane}}}^P$ =

0.0 $\mathrm{mJ/cm^2}$, $\gamma_{\mathrm{Diiodemthane}}{}^{D} = 46.5\ \mathrm{mJ/cm^2}$). By measuring the contact angle of a solid with a liquid that has only a dispersive component to its surface tension, equation (1.6) reduces to (1.7):

$$\gamma_S^D = \frac{\gamma_L(\cos\theta + 1)^2}{4}. \tag{1.7}$$

In this work, we measure the contact angles of water and Diiodomethane to determine the surface energies of solids.

CHAPTER II

EXPERIMENTAL METHODS

In this chapter, we present the experimental method in details. We will introduce the materials, the friction test cell setup that was used for force measurements, the contact angle measurements that were used to calculate surface free energy of the substrates, the Durometer test that was employed for obtaining the sample's softness and, finally, the shear adhesion test of gecko toe lamellae on different substrates.

2.1 **Materials**

Neoprene (60 Duro), latex (38-40 Duro) and natural rubber (40 Duro) were purchased from McMaster-Carr company (Elmhurst, IL). The SEBS block copolymer used in this work is Kraton G1657 M which is a clear, linear triblock copolymer based on styrene and ethylene/butylene with a polystyrene content of 13%. Deionized water was used from the house deionized water system from Millipore. Diiodomethane (ReagentPlus, 99% contains copper as stabilizer) was purchased from Sigma-Aldrich. The PDMS used was the same material as it was used in Klittich et. Al [17].

2.2 **Sample Preparation**

2.2.1 Gecko Lamella

In order to test adhesion, we used lamellae from three Tokay geckos individuals (*Gekko* gecko); (there are large geckos, with correspondingly large toe pads) and mounted them on a piece of glass (0.25 inches thick) using glue. The lamellae separation process takes place under an optical microscope. First, a single lamella is isolated from the gecko shed which has been collected and stored in a -20 degree Celsius freezer. Then, a very thin underlying layer of skin is separated from the lamella in a way that the setae (hairs) do not get damaged. A single lamella perfectly separated from the Gekko gecko toe skin in our biology laboratory is shown in figure 2.1. After separation comes the mounting process in which all lamellae were mounted on a glass slide with 0.25 inch thickness with a cyanoacrylate superglue and allowed to cure for at least 2 days in ambient conditions before further tests. Moreover, pictures are taken from each mounted lamella for area measurement which is required for later adhesion calculations.

2.2.2 Soft Materials

Neoprene, Latex and a natural rubber sheets were first cut into pieces of 0.5×1.0 inches and then were soaked in toluene, Chloroform, acetone and ethanol for two hours each to remove any contaminants. They were then stored in a vacuum oven for an hour to dry out. The dried samples were left in a petri dish for at least one

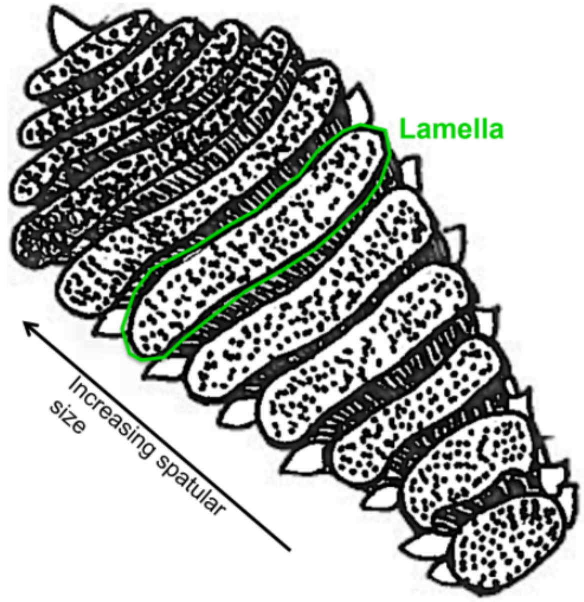

Figure 2.1: Annotated underside of a Tokay gecko's toe, showing the lamellae (with an outlined example). Based off of SEM and optical microscopy images from [21],[17] and personal observation.

night. The PDMS lenses used for the friction measurements were prepared by mixing Sylgard 184 at a 10:1 ratio of base to crosslinker, which is standard procedure for the preparation of our PDMS lenses [22]. Bubbles were evacuated by a vacuum dessicator, and the lenses were formed by extruding hemispheres of the mixture underwater onto a polystyrene petri dish. The PDMS samples were made with 10:1 ratio of base to crosslinker as well and were made by pouring the evacuated mixture into a polystyrene petri dish. The PDMS was put in an oven at 60 ^{c}ircC for 4 hours. The lenses and sheets were placed into glass petri dishes poured with toluene for two weeks and the solvent was changed every two days. They were dried out in the hood overnight after the last time the solvent was removed, vacuum dried at 60$\circ$C for four hours and kept there overnight. [17]

2.3 Surface Characterization

In order to characterize surface properties of the soft materials that are being examined in this research, we performed friction and contact angle tests.

2.3.1 Friction measurements

To understand the friction of gecko toe on substrates,we used PDMS lenses mimicking the gecko toe shed shearing on the surface of each substrate. This was done using a home built instrument.[22] In this instrument, the normal and shear forces applied to the surface can be mimicked as if they were being applied by the gecko. The calibration of the instrument is possible by applying different amounts of weight to it and reading the relative voltage. The more shear or normal force id applied to the instrument (weights from 1 gr to 50 gr have been hanged from the machine), the closer two capacitors placed inside the instrument will become and the less the voltage between the plates will be. A schematic of the setup used in our experiment is shown in figure 2.2. We measured the friction force and calculated the coefficient of friction between PDMS lenses and each surface by applying forces of 5, 10, 20 and 30 mN to the Latex, Natural rubber (NR), Polydimethylsiloxane (PDMS) and Styrene-Ethylene-Butylene-Styrene(SEBS) substrates. For Neoprene rubber samples, forces of 35 and 40 mN were also tested since, from the 5 and 10 mN tests no reasonable results could be inferred due to significant noise. To complete this task, we mounted each of the rubber sheet samples on glass pieces and mounted the glass on the instrument in a way that the normal and shear force motors can barely touch the samples. Prior to each test one must estimate the voltage in which the normal force motor will be in contact with the sample so that the shear force and, subsequently, the friction force are readable for calculating the coefficient of friction. PDMS lenses were mounted on glass pieces using tapes, and the normal force was applied in the normal direction by bringing into contact the rigid arms of the instrument by picometer motors. The shear force was then applied to each sample for collection of at least 400 data points. This is done to make sure that the experiment is running until the force reaches a plateau and we collect enough data points, so that we can take an average over at least 50 data points to get an average shear force for each applied normal force. A more detailed description for calculation of the coefficient of friction is given in chapter 3.

2.3.2 Contact angle and surface energy measurements

Scientists have used a wide variety of techniques to study different aspects of surfaces, however, only a few of these techniques have actually helped them get the most information about physical and chemical properties of surfaces. Surface properties of a solid can be understood by knowing the surface energy of that solid and the surface free energy of the solid can be determined from the contact angle of a pure liquid drop on that solid. [19]

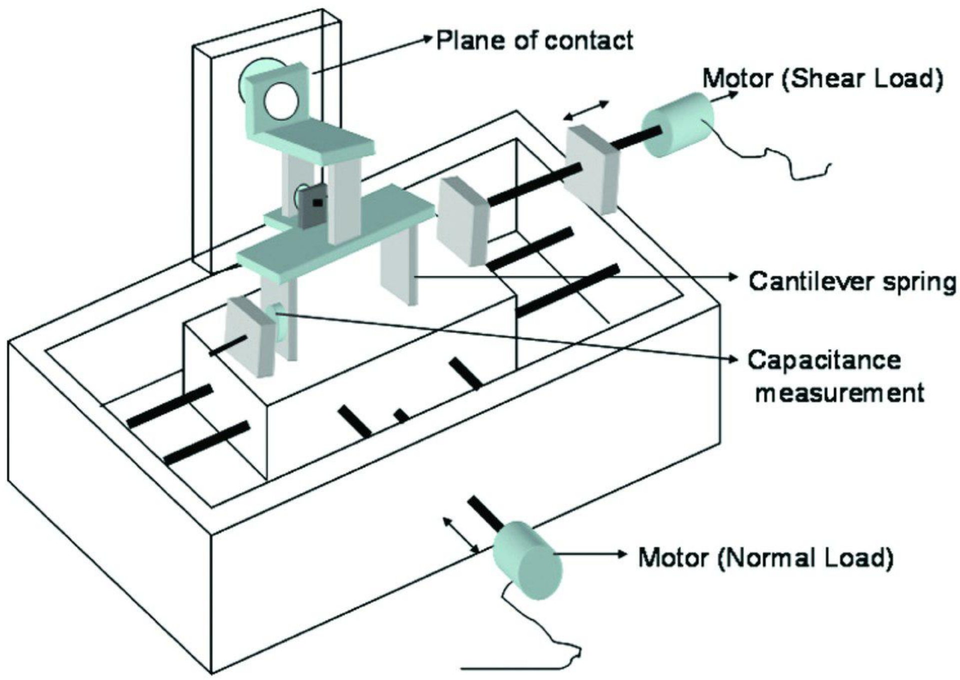

Figure 2.2: Schematic of the friction cell developed in house to measure friction coefficients.[22]

Pendant drop

A pendant drop technique is used to calculate the surface tension of the probing liquids to make sure that the solutions we were using were clean. To complete this task, we used a KRUSS Drop Shape Analyzer. More than 5 droplets of each probing liquid were suspended from the syringe and the surface energy was estimated based on, the Young- Laplace equation by the instrument. Water and diiodomethane have been used as our probing liquids.

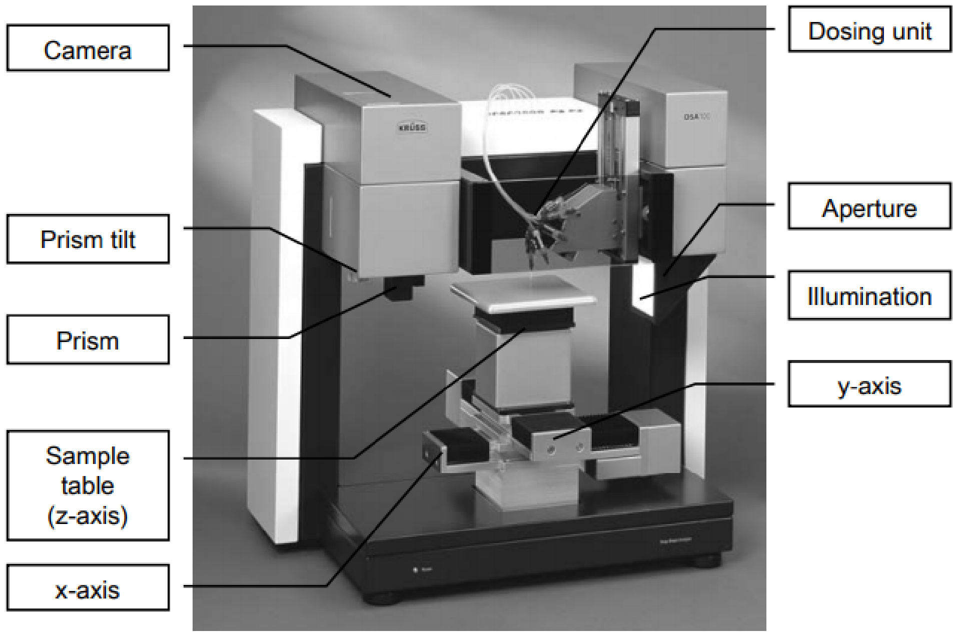

Figure 2.3: The Drop Shape Analizer instrument used for pendant drop and contact angle measuremets in the laboratory. [23]

Contact Angle

In this work, we have measured contact angles by the sessile drop method. The drops were formed on a sample positioned on the instruments stage using a microsyringe and the drop size was chosen to be less than 3 microliters to avoid interference by gravitational forces with the droplet's shape. Drops are illuminated by LEDs and the image is recorded through a side camera, see Figure 2.3. Evaluation of contact angles was performed by the Drop Shape Analyzer Software developed by the manufacturer (KRUSS). The probing liquids used were diiodomethane and water deposited at room temperature. Three pieces of each material (PDMS, SEBS, Neoprene, Latex, and NR) with at least 5 droplets of each probing liquid were used to determine the contact angle variability. Figure 2.4 shows examples.

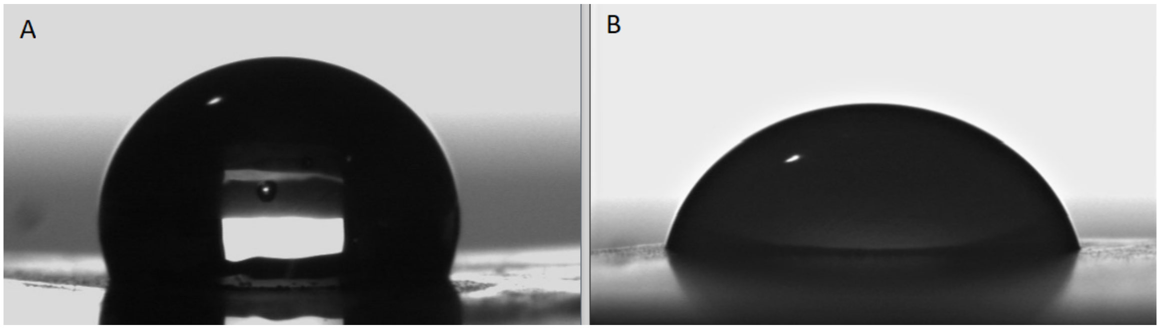

Figure 2.4: Example of two drops of (A) water on neoprene and (B) diiodomathane on neoprene, analyzed with the drop shape analyzer.

2.4 Adhesion Measurement

Shear adhesion measurements were a fundamental process for this research as they showed that geckoes show adhesive behavior to the soft substrates examined in this work.

2.4.1 Single lamella adhesion

The shear adhesion force was measured with the same house-made friction cell discussed in section 2.3.1. Mounted lamellae were first tested on glass pieces to make sure that each lamella being used sticks to glass showing that the separation and mounting process were successful. For the actual test process, the substrate and lamella were brought in contact by a motor in the normal force direction and loaded to a force of 5 mN. The shear force between the chosen lamella and the sample was recorded after the lamella was loaded in the shear direction with a velocity of 5 μ m/s in such a way that the substrate was moving in the direction toward the tip of the toe to simulate the gecko body weight shearing its toe. The test was ended manually when either of these cases happened: after watching a significant drop in the shear force, after the shear force was maintained constant for a couple of minutes (at least one minute), or when the lamella reached the end of the substrate. The measurement was repeated for six different lamellae on each of the five materials under study.

2.5 Durometer Measurements

Durometer tests were performed on neoprene, latex and NR to determine the exact hardness of the rubber sheets being used in this study. For this purpose, we put rubber pieces of 1×1.5 inches in a ccsi [24] durometer and let the indentor penetrate into the material. The force required to cause the indentor movement is inversely proportional to the hardness value of the test specimen. Hardness measurements were not done on PDMS and SEBS as their thickness was not enough for such measurements. The conversion of the durometer values to Young's moduli were then calculated with the following equation [25]:

$$E = \frac{0.0981 \times (56 + 7.62336 \times S)}{0.137505 \times (254 - 2.54 \times S)} \tag{2.1}$$

in which E is Youngs modulus in MPa and S is the ASTM D2240 Type A durometer hardness. This equation is considered a good first-order approximation to Youngs modulus from a hardness of 80 to 20 which correlates to the range that we obtained for the materials we are using.

CHAPTER III

RESULTS AND DISCUSSION

In this chapter, we present all the results from the experiments done for this study and further discuss these results.

3.1 Shear Adhesion Force

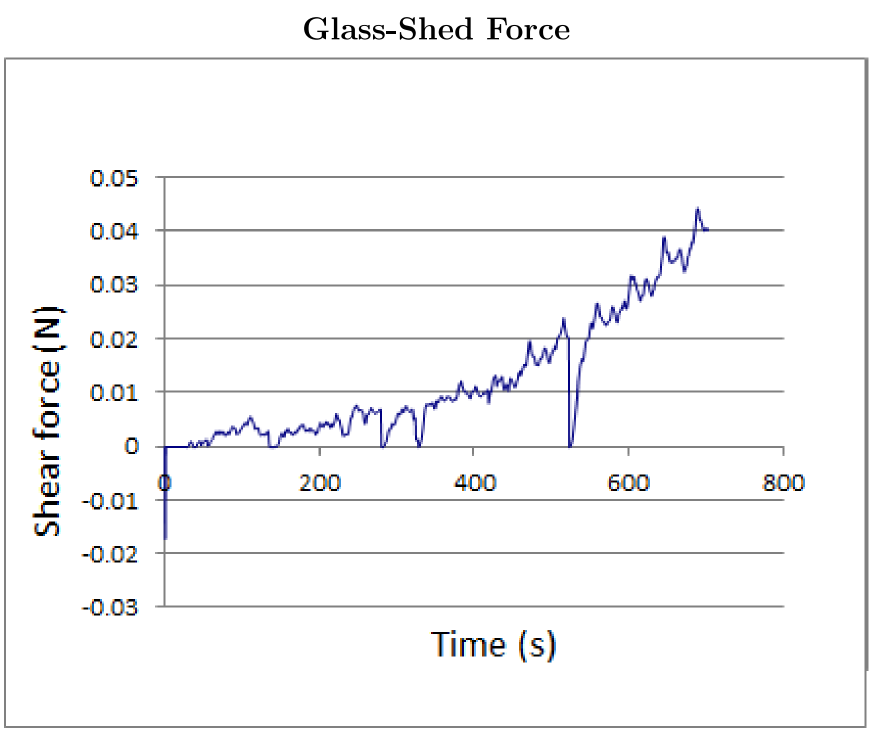

Figure 3.1: The shear force vs time curve for a single gecko lamella on glass.

The force-time graph of the isolated lamella on glass in figure 3.1 shows the fact that the force is increasing as a function of time, meaning that the lamella has been sticking to the glass. As the shed was obviously sticking well to the surface, the experiment was stopped after collection of 700 data points to avoid damaging the shed.

Rubber-Shed Force

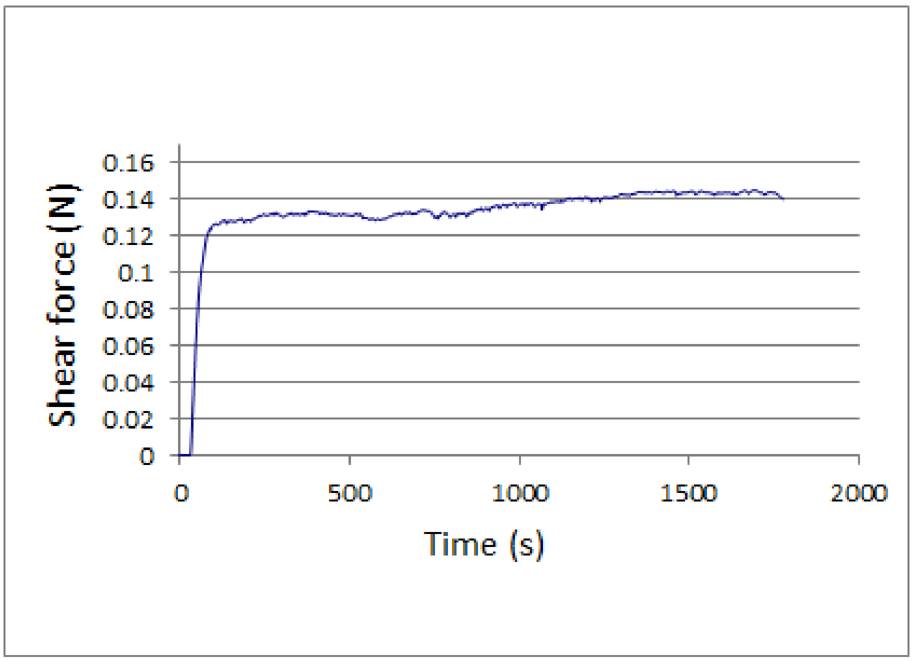

Figure 3.2: The shear force vs time curve for the same gecko lamella as in figure 3.1 on latex.

Figure 3.2 shows the shear force as a function of time for a lamella on latex. In this adhesion experiment, at the very beginning, the force is increasing until eventually it gets to a point where there is enough force that it starts sliding. It can be seen that, as the gecko shed slides along the latex substrate at the velocity of 5

μm/s, the shear force increases until it plateaus to a certain point. The average of that plateau has been taken to be the accepted shear force. This is done to prevent any spike being counted as the maximum force. A minimum of six successful runs has been collected with six different lammellae for each sample. Similar results have been obtained for neoprene, latex and natural rubber samples.

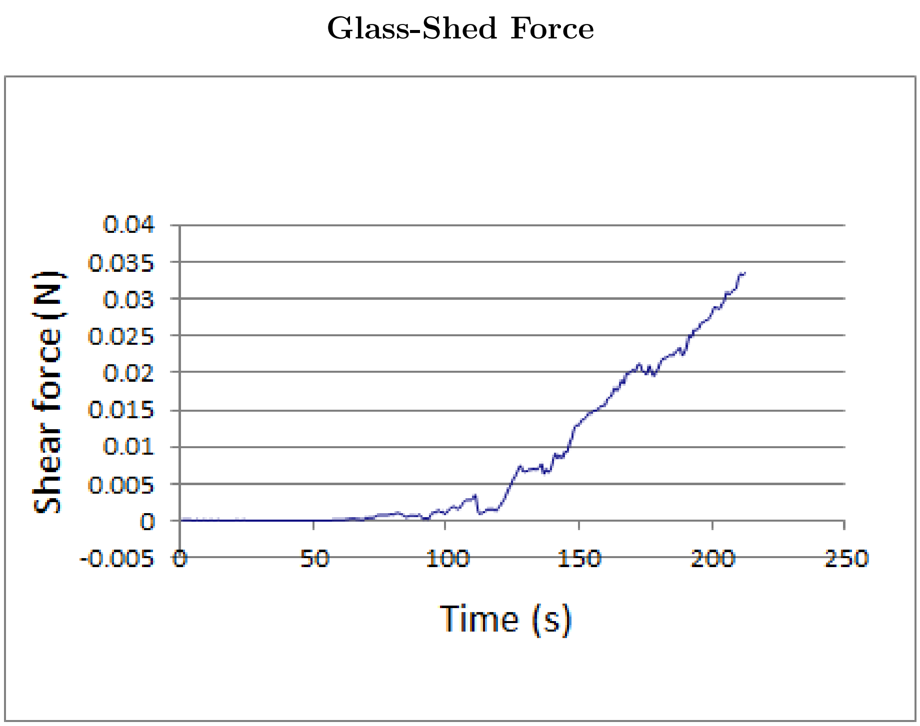

Figure 3.3: The shear force vs time curve for a single gecko toe shed on glass.

The gecko sheds were tested for a second time after some time (~2 month) on a glass substrate to make sure that they could still show the adhesion force on the materials. As can be seen in figure 3.3, an example of the accomplished experiments, the force-time graph of the isolated lamella on the glass shows that the lamella is behaving as it was before, meaning that it is still sticking to the glass.

Rubber-Shed Force(PDMS)

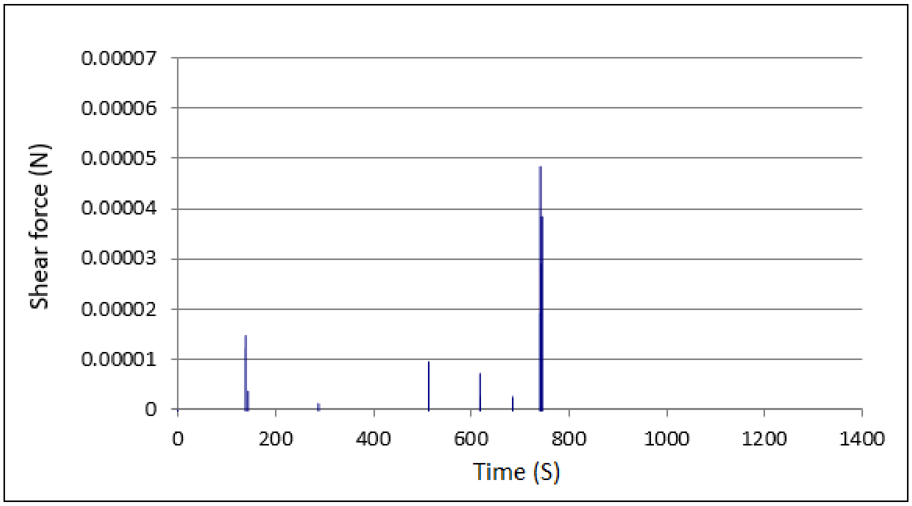

Figure 3.4: The shear force vs time curve for the same lamella as in figure 3.3 on PDMS.

Figures 3.4 shows a shear force result for a lamella on PDMS. This result was expected as scientists have seen no sign of geckos adhering to PDMS substrates before. Figure3.5 reveals an interesting result about SEBS, showing no adhesion to the gecko shed as well. Since the shed was perfectly adhering to glass, it can be interpreted that SEBS is another surface that might be able to be eliminated from the list of surfaces that geckos can adhere to.

Rubber-Shed Force(SEBS)

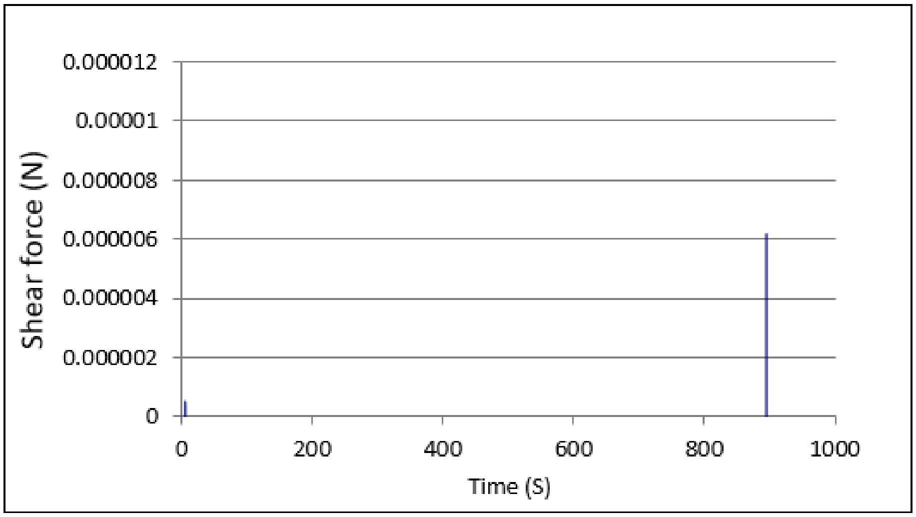

Figure 3.5: The shear force vs time curve for the same lamella as in figure 3.3 on SEBS.

A minimum of six runs have been performed on each material to reduce any possible error and the average of the force recorded while the shed was sliding on the sample has been taken to be the shear force for each sample of each material. The shear force, Averaged over the six experiments, is used to compare the adhesion between substrates. In figure 3.6 we present the average shear force with their standard errors. It can clearly be seen in figure 3.6 that the gecko lamella did not stick to either the PDMS or the SEBS samples, while the other materials show reasonable adhesion force for a single lamella. NR seems to be the best adhesive between the materials studied in this work.

Average Shear Adhesion

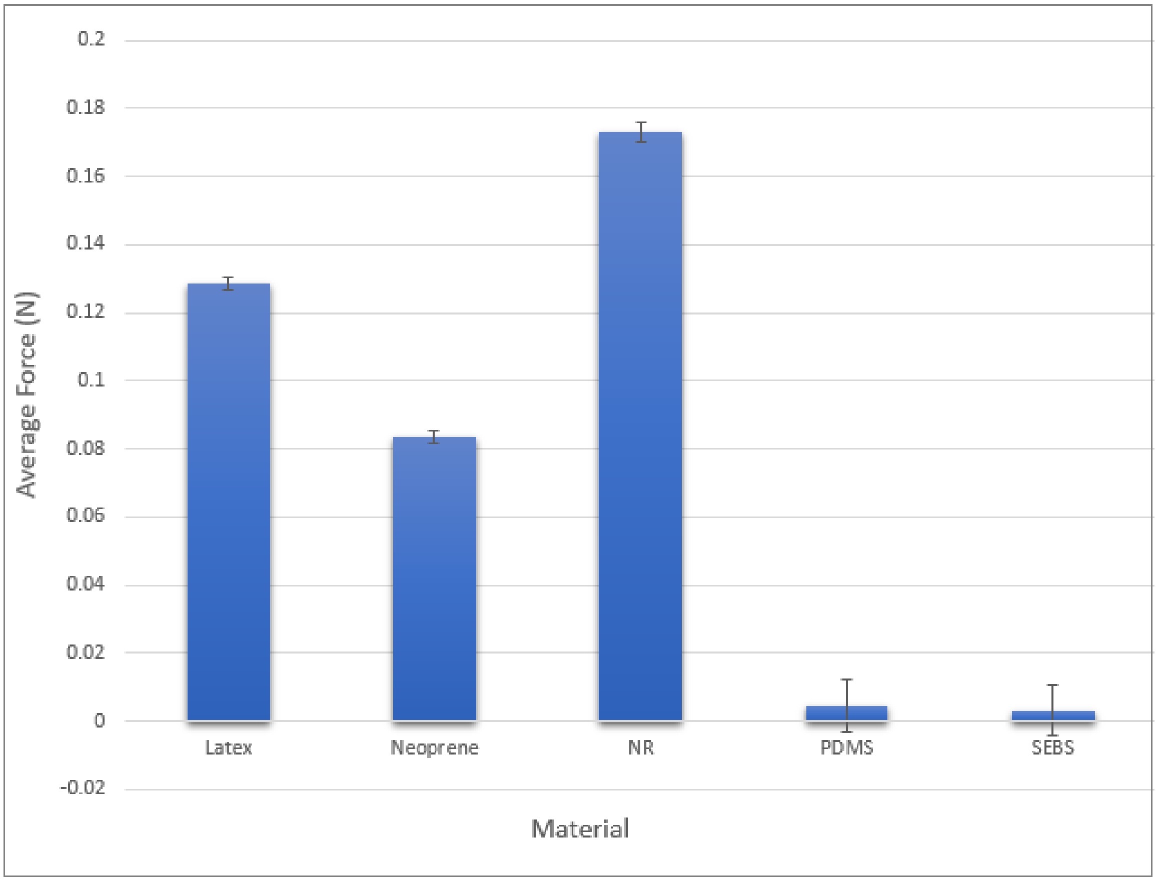

Figure 3.6: Comparison of the average shear adhesion for all materials. The bars represent the mean and the error bars represent the standard error of six experiment for each material.

These results are interesting since it has been thought that softness is the reason why geckos are not able to stick to PDMS. The figures above and other results in section 3.4 show that materials with a Young's modulus close to that of PDMS, behave differently in the sense that geckos are able to adhere to such materials. Since they can stick to some soft materials, why do they stick to some but not others? That is why we look at the coefficient of friction and the surface energy to see if there is any other parameter which can help us understand why they stick to some rubbers but not all.

3.2 Coefficient of Friction

Coefficient of Friction

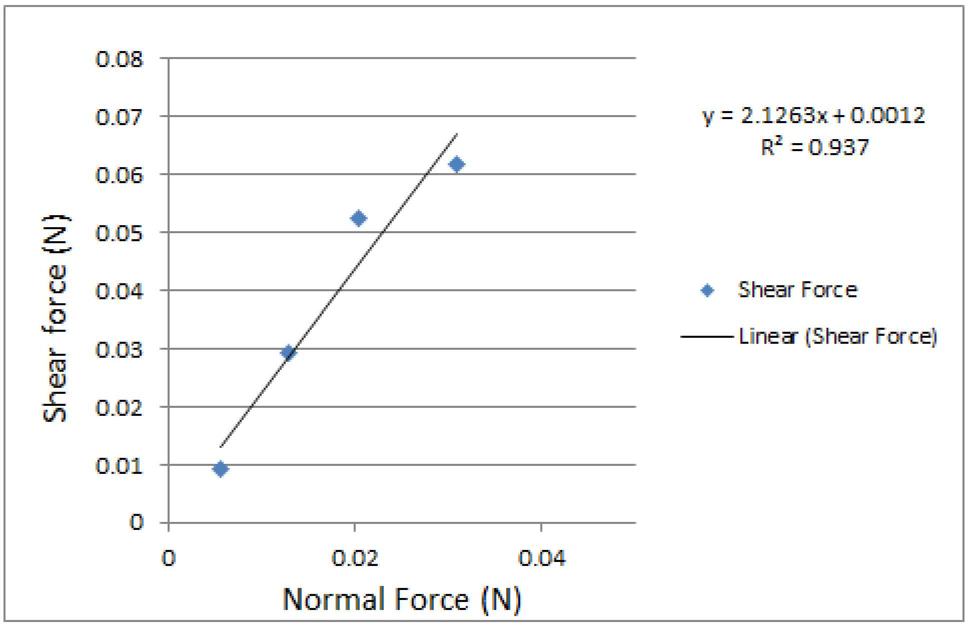

Figure 3.7: Shear force vs normal force for one latex sample from applying normal forces of 5, 10, 20, and 30 mN. The slope of the fitted line is the coefficient of friction for the sample.

The coefficient of friction between a pdms lense and the materials is the first parameter that we measured for each of these materials to see if there is any relation between friction and the amount of adhesion. Four different shear forces were recorded by applying different normal forces for each sample of each material.

The coefficient of friction was then calculated from the slope of a trend line of the measured values. Figure 3.7 is an example of this calculation for a latex sample.

Average Friction Coefficient

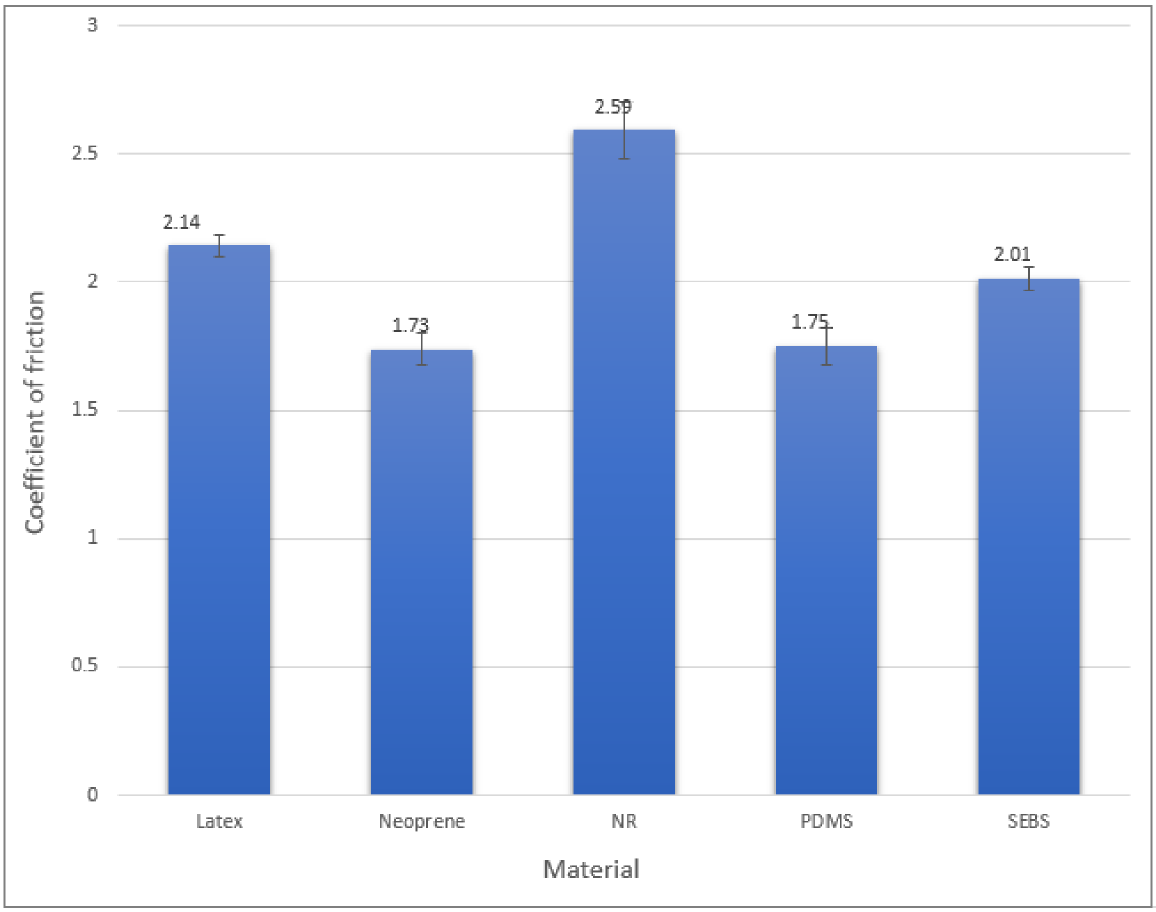

Figure 3.8: Comparison of the average coefficient of friction between the materials and PDMS for all materials. The bars represent the mean and the error bars represent the standard error over three measurements.

Figure 3.7 shows the result for all tested samples. Comparing with figure 3.6 on the average shear adhesion, it first seems that the higher the coefficient of friction, the higher the shear force for the geckos. However, SEBS and PDMS have coefficients of friction close to that of the rubbers to which the geckos can stick. It shows that friction cannot be a parameter that plays the important role in the adhesion of geckos to soft surfaces.

3.3 Contact Angle

The contact angles of water and diiodomethane have been measured on each surface and the collected data is presented in table 3.1. The surface energies are then calculated from equation (1.7).

Table 3.1: Average contact angle of materials.

Material	**Water Contact Angle**	**Diiodomethane Contact Angle**
Neoprene	102.38 ± 0.31	92.88 ± 03
Latex	95.48 ± 1.04	53.9 ± 0.54
Natural Rubber	92.58 ± 0.64	62.45 ± 0.64
PDMS	99.72 ± 0.32	92.88 ± 0.25
SEBS	93.5 ± 0.42	53.69 ± 0.42

Average Surface Energies

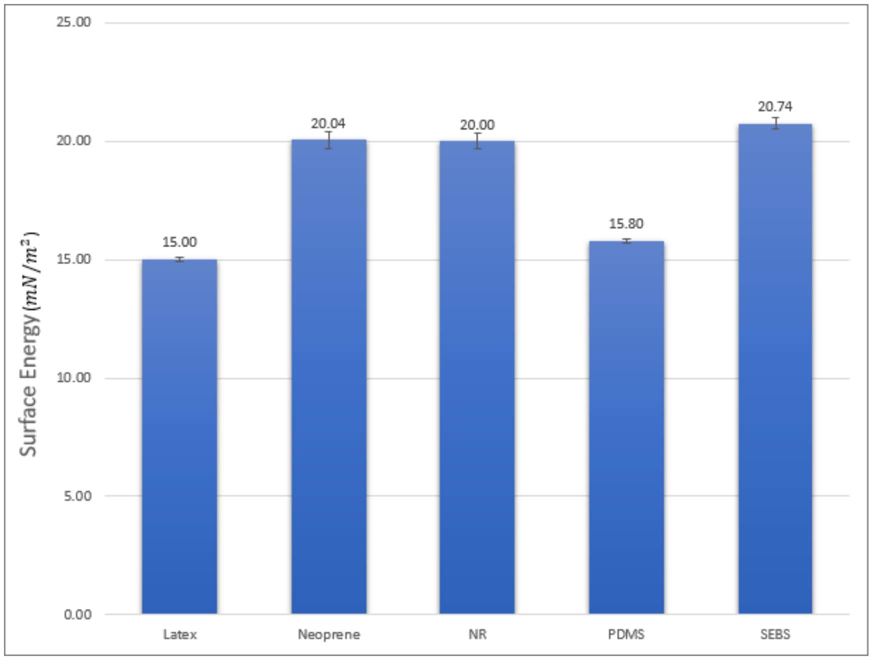

Figure 3.9: Comparison of the average surface energy of all materials.

Surface energies have been calculated by having contact angle values for each material and the average values and standard errors are presented in figure 3.9. All surface energies reside in low surface energy region and we believe their proximity make them comparable. As it can be seen in figure 3.9, all surface energies are close to each other, showing that the surface energy of the material is also not the parameter responsible for the differences seen in the adhesion of geckos on these soft surfaces. please note that the value calculated for PDMS is a little lower than seen in the literature. [17]

3.4 Hardness

Table 3.2: Shore A (Scale of hardness measeurement for materials with hardness less than 90) hardness of five materials and their calculated modulus. Moduli for all materials were calculated from the Shore A measurements, using equation (2.1).

Material	**Shore A Hardness**	**Young's Modulus (MPa)**
Neoprene	68	5.04
Latex	41.75 ± 0.25	1.32
Natural Rubber	33.75 ± 0.25	1.80
PDMS	70.9 ± 0.2 [17]	5.8 ± 0.1 [17]
SEBS	47 [26]	2.41 [26]

Another parameter that should be investigated about the surfaces is their hardness. The main concept of this work was based on our observation that geckos can hold on to the rubber sheets that we are working with – unlike PDMS –. To show that they have the same hardness, we performed durometer measurements and calculated the moduli with equation (2.1). The hardness measurements and the corresponding moduli are reported in table 3.2. It can be seen that all materials are soft and have similar values for their moduli. This can be interpreted to mean that softness is not the reason why geckos cannot stick to surfaces such as PDMS since they are able to stick to other soft surfaces, such as neoprene or latex.

CHAPTER IV

CONCLUSION

In this thesis we have reviewed the general concepts of gecko adhesion including gecko foot structure and their adhesion mechanism in addition to the previous work which led us to this study. We also introduced the experimental methods that were employed in this research. Gecko's performance on different soft surfaces were discussed and parameters, such as friction, softness, and surface free energy of the materials used, have been investigated in this work. As the collected data shows, geckos can hold on to neoprene, natural rubber and latex surfaces but are not able to stick to PDMS and SEBS substrates. The purpose of this work was to show that, unlike what had been thought before, the inability of geckos to adhere to surfaces like PDMS cannot be entirely due to softness. Our result for the coefficient of friction, surface energy and the modulus of neoprene, NR, latex, PDMS, and SEBS show that none of these parameters have a direct effect on surface adhesion, This leaves the question of "why geckos do not stick to some surfaces?". A parameter that may be considered in future work is the roughness of these surfaces, which is an important factor in studying adhesion. The whole animal experiment can also be done to have a better understanding of the amount of force geckos apply to the surface while they are trying to climb or hold on to that surface.

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